SUBWAY AND TRAIN-INDUCED VIBRATION CHARACTERISTICS IN BUILDINGS AND ADJACENT OPEN FIELDS IN THE BOSTON AREA

A thesis
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CERTIFICATE OF FITNESS

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have examined the candidate's thesis/dissertation (or papers) on the subject:

Subway and Train-Induced Vibration Characteristics in Buildings and Adjacent Open Fields in the Boston Area

and have found it satisfactory.

June 15th, 2012
Date of Defense

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Pradeep Maurya
June 15, 2012

To my parents, Savitri and Shiv Shankar,

who taught me patience at difficult times

Thanks for your support and motivation

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CHAPTER 1 INTRODUCTION

Urbanization in cities has compelled building developers to inhabit real estate available near subway and railway lines. Subway and train-induced building vibrations are a consequence of closeness of buildings to subway and railway tracks. Research laboratories and precision manufacturing facilities quite often accommodate highly vibration-sensitive equipment. Proximity to subways and railways affect proper operation of equipment due to building floor vibration. In the field of Nano-technology where precision manufacturing becomes extremely important, these vibrations have become a serious issue. Human comfort in residential and office buildings is also affected.

Many researchers have developed possible techniques to mitigate floor vibrations to the level at which proper functioning of vibration sensitive equipment and manufacturing at Nano-scale, is not hampered. Additionally, vibration mitigation systems are also required for residential and office buildings near subways and railways. The base isolation technique adopted at the structure is popular in reducing the vibration level. Incorporation of this technique is expensive and there is a need for a cost effective technique to mitigate vibrations in buildings. Sanayei et al. (2012) proposed an approach to mitigate subway-induced vibrations in building by increasing the thickness of a lower floor termed, “blocking floor”. In order to validate this approach, a four-story scale model building had been subjected to shaker-induced vertical vibrations at the base of center column. An impedance model for the prediction of vibration had also been developed and validated by comparing predicted velocity levels to measured velocities at each floor level. Predicted velocity levels for models using a “blocking floor” at the first floor indicated reduction in the vibration at the higher floor levels. However, this prediction model had assumed that subway-induced vibrations have a stronger vertical vibration component than horizontal components. It also assumed that contribution of significant vibration level which is associated with subway-induced vibration is within the frequency range of 500Hz.

In this research, vibrations data from full-scale buildings subjected to train and floor vibration in the foundation slab and in the adjacent open field have been measured. Three sites have been selected for train-induced vibration measurements and another three have been selected for subway-induced vibration study. Measurements from all six sites have been considered for validation of the above assumptions. Other findings from the study have also been discussed.

The main contribution of this thesis has been presented in Chapter 2, which will be submitted as a journal paper. Chapter 3 presents additional data from train-induced vibration measurement sites and Chapter 4 presents the results of additional information from subway-induced vibration measurement sites. Chapter 5 concludes learning and findings from this research. Detailed information about the data acquisition (DAQ) system and data processing have been presented in Chapter 6. Additional details about the subway and train vibration measurement setups have been detailed in Chapter 7.

CHAPTER 2 SUBWAY AND TRAIN-INDUCED BUILDING AND GROUND VIBRATION IN BOSTON AREA

The introduction of cutting edge technologies in laboratories and precision manufacturing facilities quite often includes the operation of vibration sensitive equipment. When these buildings are located near a railway track, the buildings are prone to subway and train-induced floor vibration. Human comfort in the residential and office buildings near subway and railway lines is also an issue of prime concern. It is thus imperative to mitigate these vibrations to the acceptable levels with the design of an efficient vibration mitigation system for buildings. The incorporation of a vibration mitigation system in a building in design phase requires understanding and characterization of subway and train-induced vibration before and after construction of a structure to meet serviceability criteria.

In this research, an exploration of vibration levels is performed on six sites in the Boston area. Three sites are selected for measuring train-induced vibration and another three are considered for subway-induced vibration study. Vibration measurements are performed on the building grade slab as well as in open field adjacent to the building. Findings from the comparison of the vibration characteristics are also concluded, revealing important information for the design of vibration mitigation systems for new buildings.

2.1 Introduction

Technologically advanced precision manufacturing facilities and medical laboratories require the uses of precision devices and equipment. Urbanization has often pushed construction of such facilities in the vicinity of railway lines. Operation of vibration sensitive equipment in such buildings is interfered with due to subway and train-induced floor vibration. Human comfort is also compromised in residential and office buildings. It is thus imperative to better understand, quantify, and mitigate these vibrations to the level at which operations inside the building is not affected.

Base isolation techniques are most widely adopted vibration mitigation systems in buildings but have proved to be an expensive approach. Sanayei et al. (2012) developed a building vibration prediction tool based on the impedance model and proposed a mitigation technique based on "blocking floor theory". Validation of the blocking floor theory was done through a four-story scale model building. However, the validation of the model was based on the assumption that the foundation of building columns subjected to subway-induced vibration has a vertical vibration component stronger than horizontal components with main transmission mode by axial waves through columns. It was also assumed that subway and train-induced vibrations are significant in the frequency range of 10-500 Hz. In order to validate this prediction and mitigation technique on full-scale building in design phase, there is a need to study the characteristics of subway and train-induced building floor vibration at grade slab as input to the building. This research is focused on understanding and quantification of subway and train-induced vibrations.

Background. Train or subway-induced vibrations emanating from tunnels and at-grade railway act as a transient line source. Hassan (2006) reported two patterns of propagation depending on the location of railways: (1) propagation of vibration due to surface railways, and (2) propagation as due to subways. The movement of train induces vibrations which were carried mainly in the form of a) compression waves with particle motion in the direction of propagation,

b) shear waves, with particle motion in a plane normal to the direction of propagation, c) Surface waves, with the particle motion elliptical in the plane vertical to the direction of propagation.

Adam and Estroff (2005) stated that most of the vibration energy generated due to a surface train passage is carried by Rayleigh waves that propagate close to the soil surface and transmit the vibrations to the structures via their foundations. Yang and Hung (2008) reported that in the case of subways, when the subway passes through a tunnel, vibrations of the tunnel structure are produced due to a number of factors along the paths of wave propagation, including the load generation mechanism of the train-track system, the geometry and location of the tunnel structure, and the irregularity of soil layers. Hassan (2006) stated that vibrations propagate through the ground and set the load bearing elements of the building into motion. These motions spread through the building to upper structural elements producing vibrations.

Eitzenberger (2008) stated that the amount of vibrations transmitted into the building depends on coupling between the ground and the foundation. Usually a reduction in the vibration level occurs due to impedance mismatch when waves from soil impinge on the structure foundation. This results in a reflection of a portion of energy at the interface and the loss in the vibration level is termed as a coupling loss between soil and foundation. Remington et al. (1987) reported that Grade slabs are in contact with the underlying soil and will be subjected to similar vibrations as the ground, and the coupling loss is therefore determined to be 0 dB for frequencies lower than the resonance frequency of the slab. Kurzweil (1979) determined that the coupling loss for lightweight buildings is also 0. He also determined that for a building supported directly on rock the coupling loss is 0. Remington, 1987 and Kurzweil, 1979) reported that for the other foundations types, the coupling loss varies between 2 and 15 dB depending on frequency and foundation type. This explains the reason for lower vibration levels inside some buildings than in open fields.

The discussion about significant component of subway and train-induced vibration has been an important consideration in the design of building vibration mitigation system. Rainer et al. (1988) investigated six one-story wooden houses in Kamloops, British Columbia, Canada and reported that both horizontal as well as vertical components of train-induced vibration can be significant. Chen et al. (2009) studied the characteristics of train-induced vibration acceleration responses in the seasonally frozen region of Daqing, China to reveal that vertical vibrations were prominent. Wei et al. (2011) measured subway-induced vibration in tunnels and a six-story masonry building in Shanghai to conclude that subway-induced vibrations should primarily focus on the vertical vibration control.

The objective of this research is to investigate which component of subway and train-induced vibration is greatest inside the building on the grade slab as well as in open area adjacent to the building. The vibration levels of inside these buildings on the grade slab are compared with the adjacent open field vibration levels. The range of frequency for significant vibration level is also explored through a set of experimental measurements made near MBTA commuter rail and subway line around Boston area, MA. Lessons learned from the train-induced and subway-induced vibration measurements are presented.

2.2 Vibration measurement sites in the Boston area

Six sites in for vibration measurements are identified around the Boston area. Site classification is done depending on the location of railways i.e. (1) train-induced vibration, and (2) subway-induced vibration. Selected sites for the train-induced vibration include building in

Medford, Somerville and MIT-Cambridge. Sites for subway-induced building vibration include buildings in Cambridge, Boston and Jamaica Plain. General information about each building site is summarized in the Table 2.2.1.

Table 2.2.1. Site details

Site	**Medford**	**Somerville**	**MIT-Cambridge**	**Cambridge**	**Boston**	**Jamaica Plain**
Source	Train	Train	Train	Subway	Subway	Subway
Activities	Research	Residential	Research	Research	Hospital	Teaching
Floors	B+4	B+6	8	8	8	B+3
Const.	Conc./steel	Masonry	Conc./ steel	Conc./ steel	Conc.	Conc.
Surficial Geology	Glacial fluvial	Glacial-fluvial	Artificial fill	Artificial fill	Glacial-fluvial	Glacial-fluvial

Conc.: Concrete; B: Basement

2.3 Site instrumentation and vibration measurements

The direction parallel to the track is labeled as longitudinal and that perpendicular to the track is transverse. Figure 2.3.1 shows the instrumentation of a tri-axial accelerometer setup on asphalt. Measurements are made at a sampling rate of 2,560 Hz. Figure 2.3.2 presents a sample train-induced vertical vibration measurement at 6.9 m from the centerline of the track in Medford. A typical train consisted of 5 to 6 cars and speed varied from 65 km/h to 96 km/h for trains. Figure 2.3.3 presents a sample subway-induced vertical vibration measurement on the ground surface above the tunnel in Cambridge. The measurements are presented as acceleration (g) vs. time (seconds).

Figure 2.3.1. Tri-axial accelerometer setup

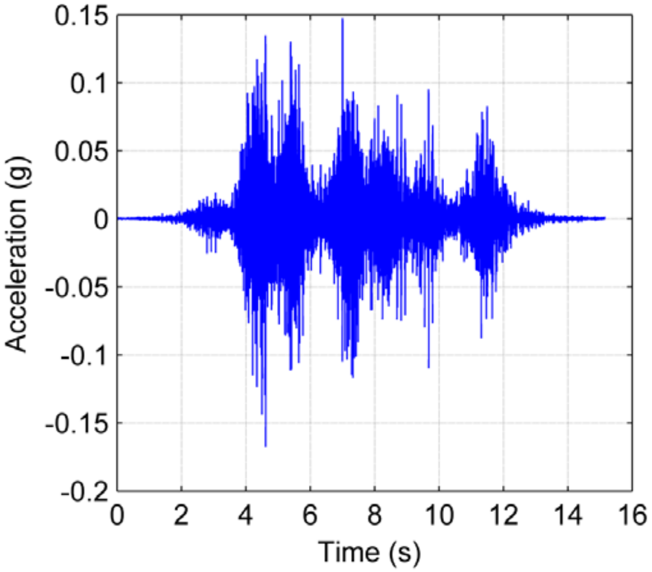


Figure 2.3.2. Train-induced vertical acceleration in Medford

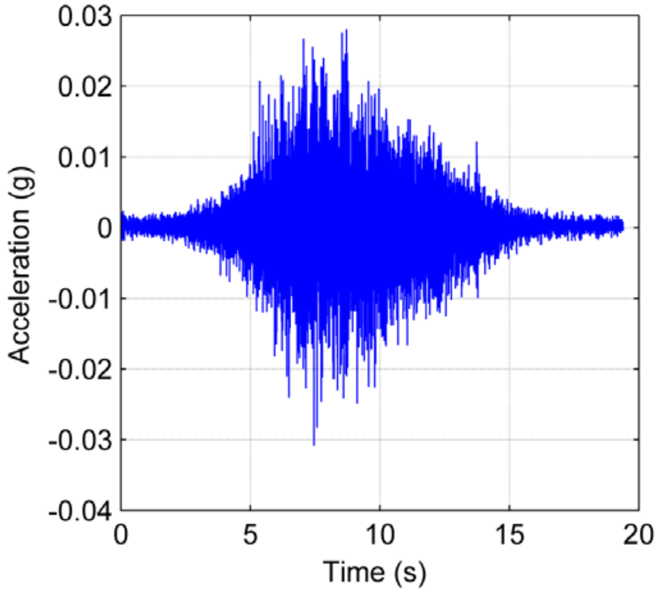


Figure 2.3.3. Subway-induced vertical acceleration in Boston

Subway and train-induced vibrations are transient events. For detailed analysis, FTA (2006) recommends expressing these vibrations in terms of one-third octave band velocity spectra described in the terms of maximum root mean square (RMS) vibration velocity level with one-second averaging time. This type of vibration analysis is termed as "Peak hold FFT spectrum". Peak hold FFT spectrums are generated by: (1) vibration data is divided into segments of 1 second time intervals, (2) each time domain segment is converted into RMS vibration level in frequency domain, and (3) maximum magnitude associated with each frequency among all these segments is stored.

The conversion of acceleration (A) to velocity (V) and further to velocity level in dB scale (VdB) is done using (1) and (2) (FTA, 2006).

$$V = \frac{A}{i(2\pi f)} \tag{1}$$

$$VdB = 20\log_{10}\left(\frac{V}{V_{ref}}\right) \tag{2}$$

where f is frequency, V_{ref} is 10^{-6} in$/s$ as reference velocity, and V is the velocity in in/s. As a reference, dB increases of 20, 10, 1, -1, -10, and -20 correspond to a multiplication by 10, 3.16, 1.12, 0.89, 0.32, and 0.10 on the linear scale, respectively.

Adjustments for the train speed in dB is incorporated using Equation (3) (FTA, 2006).

$$\text{adjustment}\left(dB\right) = 20\log_{10}\left(\frac{speed}{speed_{ref}}\right) \tag{3}$$

FTA (2006) illustrates some of the common vibration sources along with human and structural response to the ground-borne vibration. The range of interest is approximately from 50 VdB to 100 VdB. It specifies 65 VdB as the threshold for the most of vibration sensitive equipment and human perception of vibration. In the case of extremely sensitive equipment for lithography in printed circuits and inspection activities 54 VdB is considered appropriate and for the operation of electron microscopes, 48 VdB is considered. But in the most demanding criterion for the extremely vibration sensitive equipment, 42 VdB is considered.

2.4 Train-induced vibration measurement

Figure 2.4.1, Figure 2.4.2 and Figure 2.4.3 show buildings identified for the train-induced vibration measurements in Medford, Somerville and MIT-Cambridge.

Figure 2.4.4 shows different setups of measurements at Medford site. Measurements at train-induced measurement sites are categorized in three setups A, B and C.

In these vibration measurements, setup A is used for comparison of vertical vibrations in open field near tracks with tri-axial measurements inside of the building at the lowest level on the grade slab. Setup B is used for comparison of vertical vibrations in open field near tracks with tri-axial measurements in open filed. Setup C is used for comparison of vertical vibrations in open field near tracks with and array of vertical measurements in open field. All of these accelerometers are aligned perpendicular to the tracks. Table 2.4.1 shows the measurement setup and distances from the centerline of the tracks.

Figure 2.4.1. Vibration measurement site in Medford, MA

Figure 2.4.2. Vibration measurement site in Somerville, MA

Figure 2.4.3. Vibration measurement site in MIT-Cambridge, MA

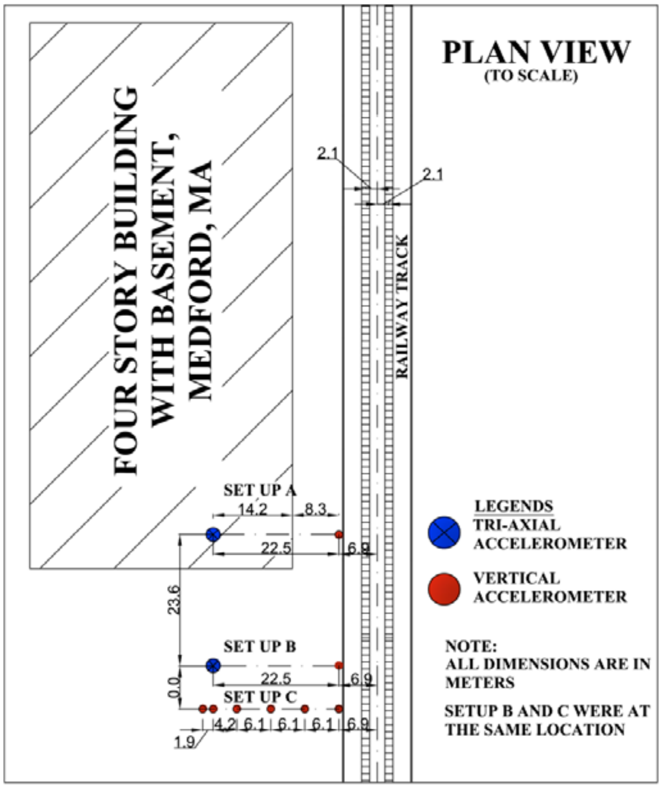


Figure 2.4.4. Measurement setups A, B, and C in Medford

Table 2.4.1. Setup classifications and details (Train)

Site =>		**Medford**		**Somerville**		**MIT-Cambridge**	
Location =>		**Dist. (m)**	**Surface**	**Dist. (m)**	**Surface**	**Dist. (m)**	**Surface**
Setup A	**Single**	6.9	asphalt	7	soil	1.7	asphalt
	Tri-axial	29.4	concrete	14	concrete	13.9	concrete
Setup B	**Single**	6.9	asphalt	7	soil	NA	NA
	Tri-axial	29.4	asphalt	14	soil	NA	NA
Setup C	**Single vertical**	6.9,13,19.1, 25.2,29.4, 30.3	asphalt	7,9,11,13, 15,17,22	soil	NA	NA

The speed of the trains is monitored using a speed radar gun. In Medford site, speed of the trains ranged from 65 km/h to 78 km/h and in Somerville, it was as high as 96 km/h. Adjustment for speed in dB level is made using Equation (2) for the speed of 74 km/h. These small adjustments ranged from 0.45 to 1.12 dB. Train-induced vibrations are measured from both the direction in both of the tracks. Mean of the train-induced vibration events obtained from each accelerometer is used for the comparison in frequency domain.

2.4.1 Observations from train-induced vibration measurements

Figure 2.4.5 compares the mean velocity components in open field on asphalt in Medford at 29.4 m from the centerline of train track. Ambient velocity components are shown using dash lines with the same markers. The train-induced vibrations are 10 to 30 VdB greater in magnitude as compared to the ambient vibrations indicating low noise to signal ratio resulting in robust measurements in robust measurements. It is observed that all the measured mean velocity components in the open field on asphalt are comparable in magnitude between 20 to 100 Hz. Above 100 Hz, vertical velocity component exhibit 10 to 15 VdB greater velocity level as compared to horizontal velocity components. Horizontal components become greater than vertical component by 10 to 15 VdB below 20 Hz.

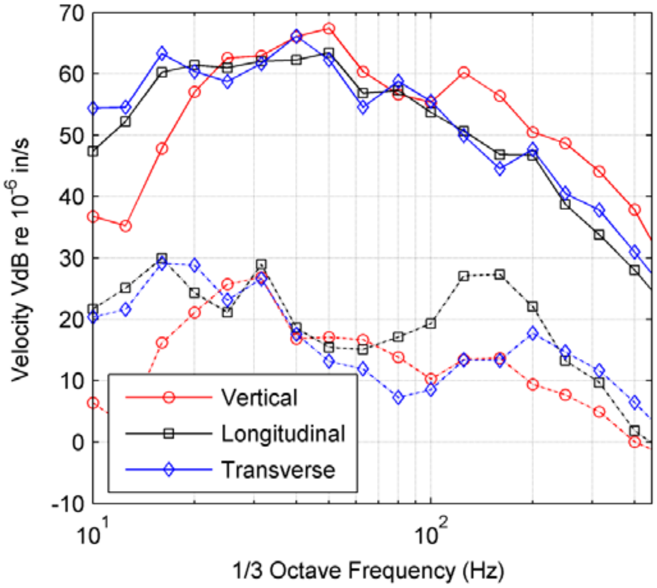


Figure 2.4.5. Train-induced mean velocity components in open field, Medford

Figure 2.4.6 compares the train-induced velocity components at Medford site shown in the solid lines at 29.4 m from the centerline of track. It is observed that the vertical component is greater than the horizontal (longitudinal and transverse) components by around 10 VdB in the frequency range of 30 Hz to 200 Hz. Transverse and longitudinal velocity components show comparable magnitude throughout the frequency spectrum.

It is also observed that the difference in vibration level between horizontal and vertical components vary throughout the spectrum. The components become comparable in magnitude at higher frequency ranges beyond 200 Hz. Horizontal components (transverse and longitudinal) are greater than the vertical component below 25 Hz. This can be related to the contribution of surface waves (Rayleigh waves) to the horizontal components of vibration at low frequencies. Thus care shall be taken concerning the frequency range of interest, while designing building vibration mitigation system for any particular component of vibration. The observations from Somerville and MIT-Cambridge site inside the building are shown in Figure 2.4.7 and Figure 2.4.8. It is observed that the vertical velocity component is 5 to 15 VdB greater as compared to horizontal velocity components below 300 Hz. Velocity level is observed significant within the frequency range of 20 Hz to 200 Hz.

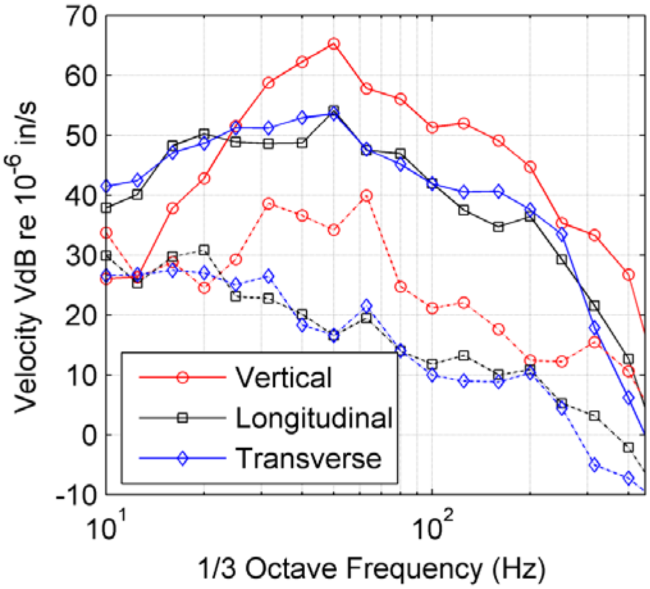


Figure 2.4.6. Train-induced mean velocity components inside building, Medford

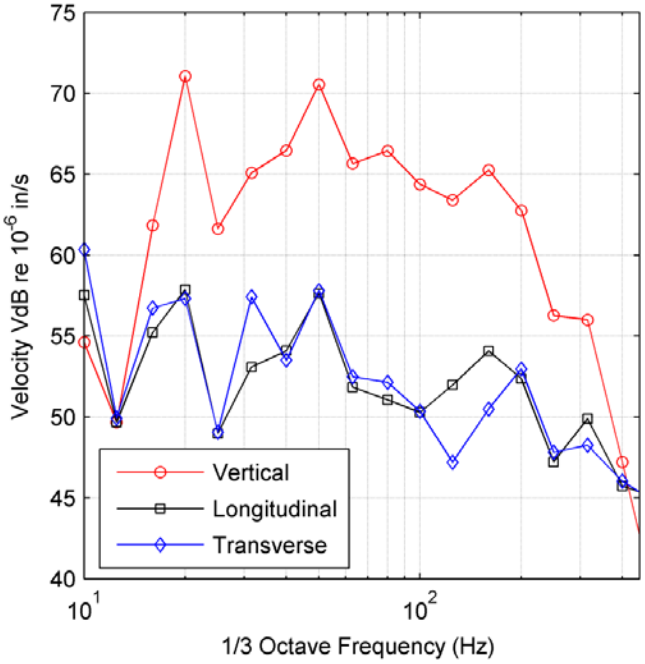


Figure 2.4.7. Train-induced mean velocity components inside building, Somerville

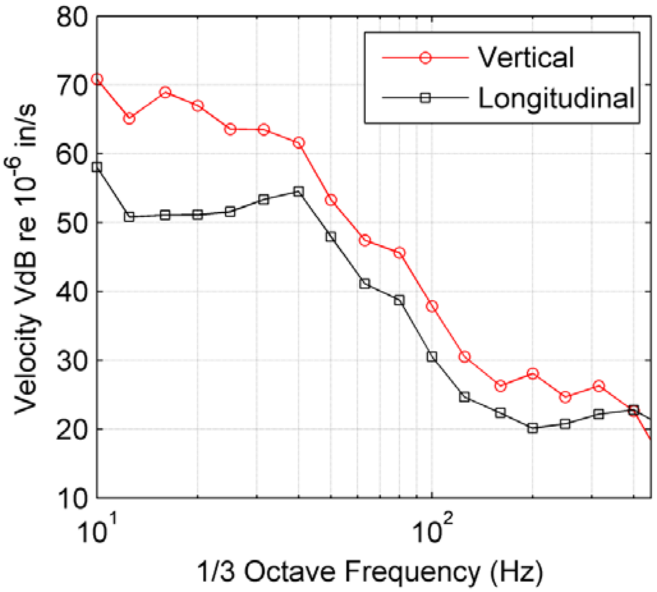


Figure 2.4.8. Train-induced mean velocity components inside building, MIT-Cambridge

Velocities are induced by the mixture of surface and body waves. In the case of train-induced vibration, surface and body waves were generated at the source. Eitzenberger (2008) stated that the surface waves contain Rayleigh waves that it does not propagate far deeper into the medium, since the velocity decreases with increased depth, and at a depth of 1 to 2 wavelengths, velocity is negligible. The effect of Rayleigh waves is reduced in the building basement vibration measurement at about 3 m depth as compared to the effect pronounced on the surface. In this case, P-waves (body waves) contribute to the vertical component in the basement at lower frequencies.

Most of the vibration sensitive equipment such as lithography and MRI has their sensitivities defined between 8 to 100 Hz. Logarithmic differences of mean vertical velocity inside the building and open field is compared in Figure 2.4.9. These vertical velocity levels are at 29.4 m and 14 m away from the centerline of track in Medford and Somerville site, respectively. It is observed that the responses in both the sites are similar in magnitude in the frequency range of

30 to 100 Hz. Both graph lines show negative numbers in the range of 10 to 100 Hz indicating that the vertical vibration measurements inside the building on the grade slab are smaller than the open field levels ranging between 0 to -14 dB. Based on the observations from these two sites, it can be inferred that perhaps train-induced open field ground vibration measurements can conservatively be used for vibration mitigation system of a new building in the design phase below 100 Hz. For this purpose, more measurements are recommended at desired new sites.

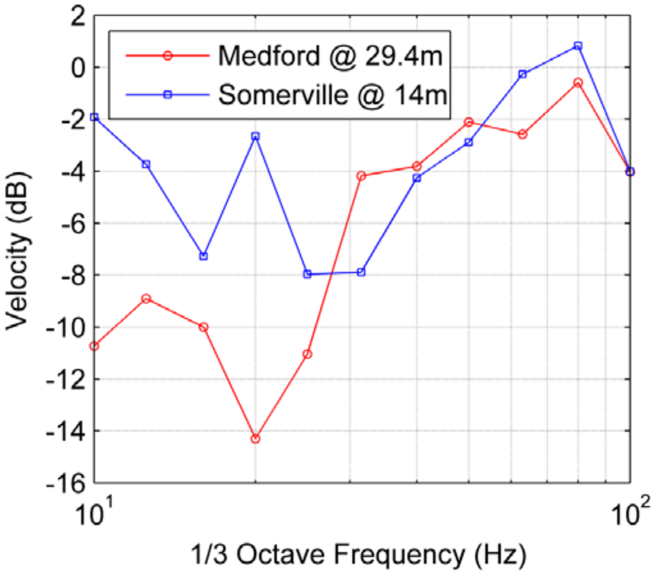


Figure 2.4.9. Vertical velocity difference: Inside Building - Open Field

In order to understand the behavior of train-induced open field vertical vibration levels, responses from the accelerometers at the increasing distances from source is compared in Figure 2.4.10. It shows that with the increase in the distance from source of vibration, vibration level decreases. At higher frequencies, a sudden increase in the velocity level is observed at some points. This is probably due to the local site response. The peak in velocity level is observed at 50 Hz. In Figure 2.4.11, the peak vertical velocity attenuation with respect to distance is graphed. It is observed that vertical velocity level reduces by around 25 VdB with the increase in distance of 25 m at 50 Hz. Similarly, a 15 VdB reduction over 15 m distance was observed in Somerville site at 50 Hz which is a frequency associated with peak velocity level. Form these measurements, it is observed that there is an attenuation of about 1 VdB per meter as distance from railway line. However, the attenuation is not varying linearly with distance.

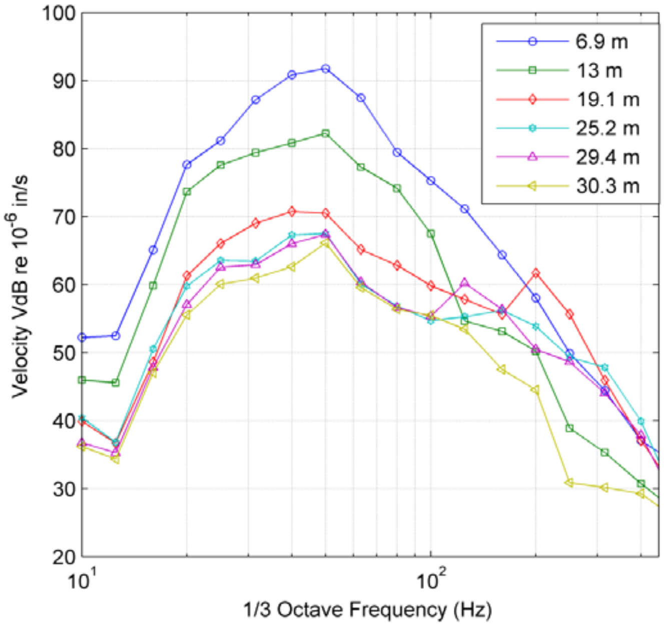


Figure 2.4.10. Train-induced mean vertical velocity in open field, Medford

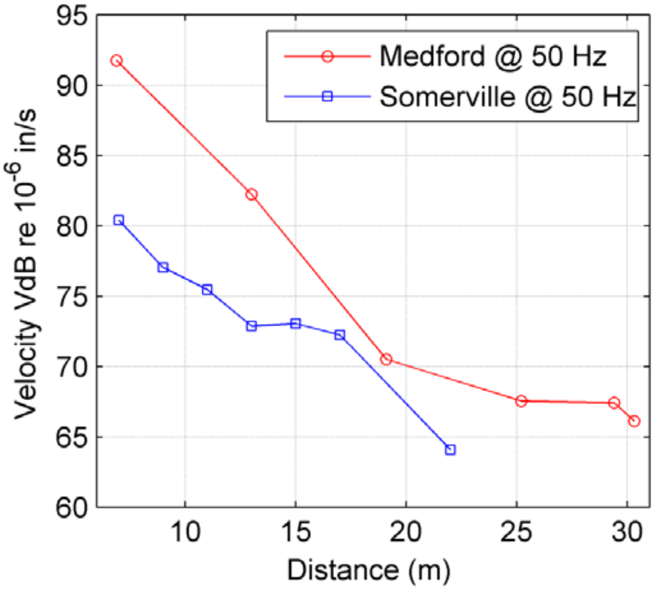


Figure 2.4.11. Train-induced mean vertical velocity in open field

2.5 Subway-induced vibration measurement

Subway-induced vibration measurements site in Boston, Jamaica Plain and Cambridge are shown in Figure 2.5.1, Figure 2.5.4 and Figure 2.5.7, respectively. Figure 2.5.2 and Figure 2.5.3 show plan and elevation of different setup of measurements taken at the Boston site. Similarly, Figure 2.5.5, Figure 2.5.6, and Figure 2.5.8, Figure 2.5.9 show plan and elevation sketches at Jamaica Plain and Cambridge site, respectively. Measurements have been classified in three setups A, B, and C.

Figure 2.5.1. Measurement site in Boston, MA

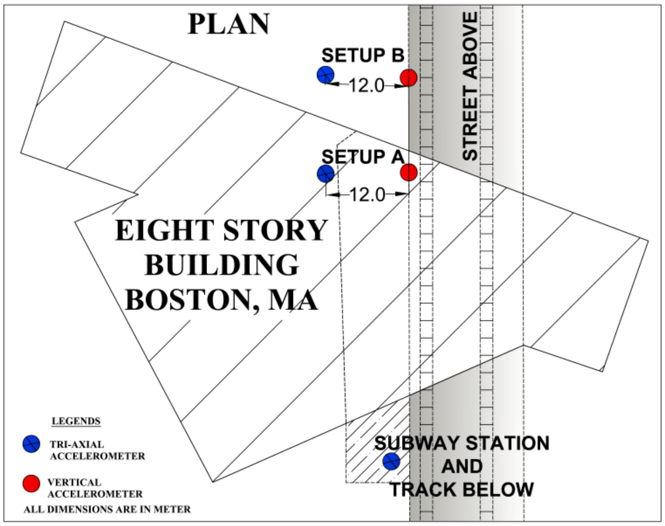


Figure 2.5.2. Measurement setups in Boston: Plan

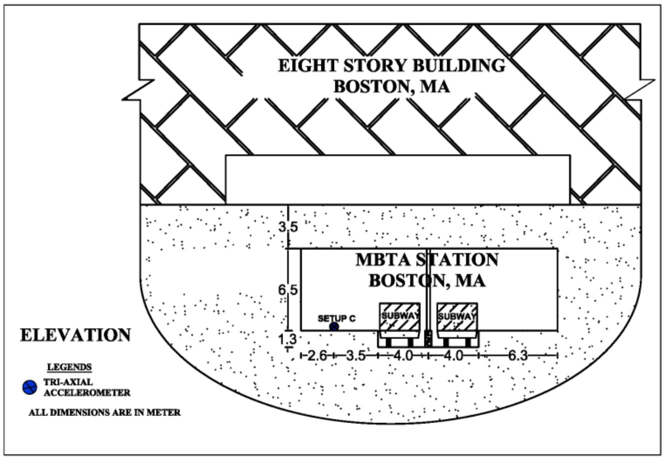


Figure 2.5.3. Measurement setups in Boston: Elevation

Figure 2.5.4. Measurement site in Jamaica Plain, MA

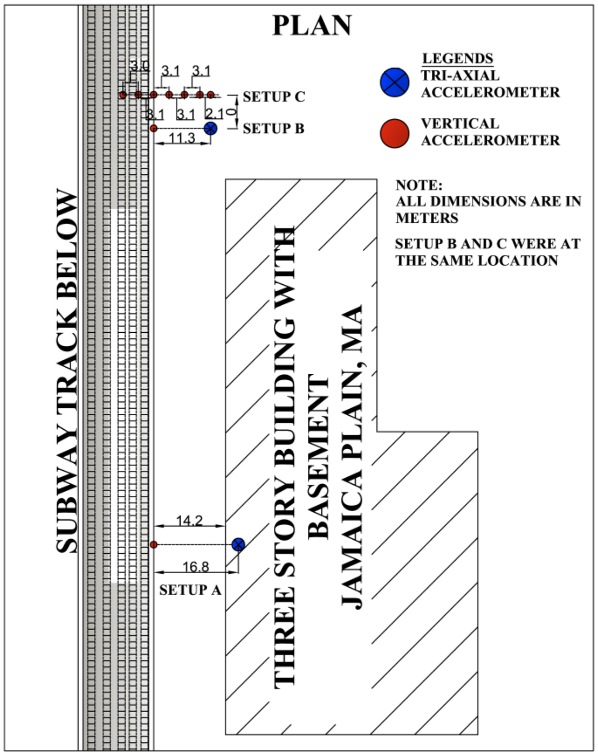


Figure 2.5.5. Measurement setups in Jamaica Plain: Plan

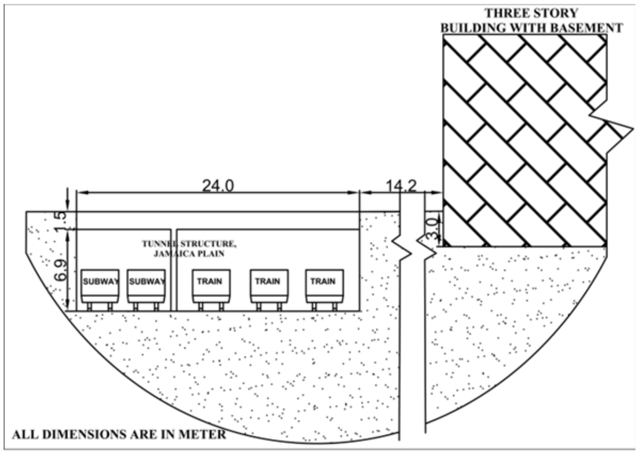


Figure 2.5.6. Measurement setups in Jamaica Plain: Elevation

Figure 2.5.7. Measurement site in Cambridge, MA

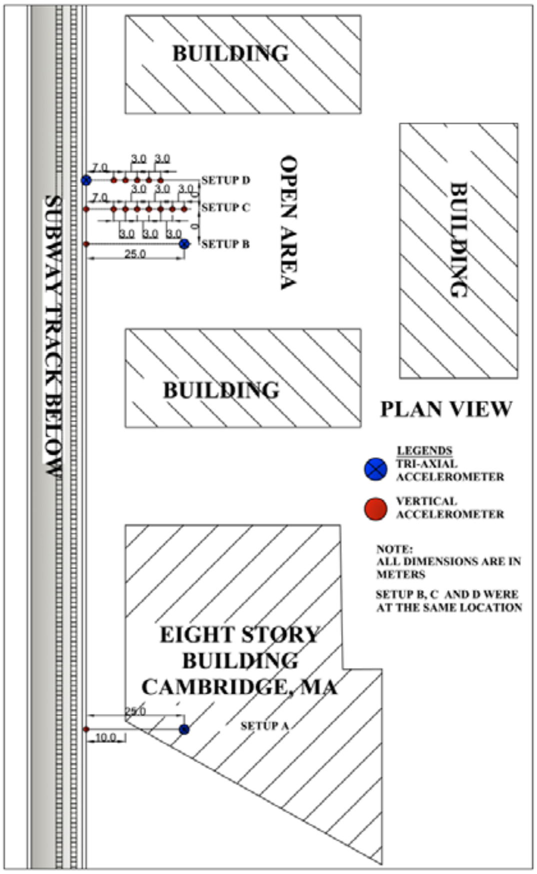


Figure 2.5.8. Measurement setups in Cambridge: Plan

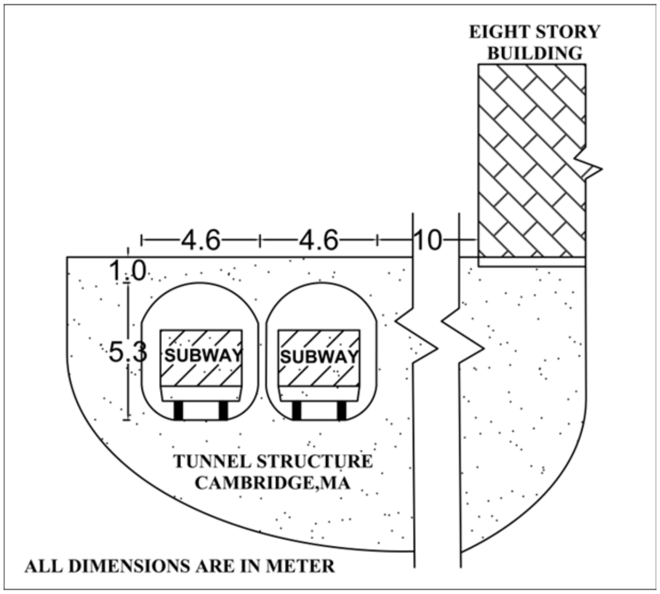


Figure 2.5.9. Measurement setups in Cambridge: Elevation

In these vibration measurements, setup A is used for comparison of vertical vibrations in open field near tracks with tri-axial measurements inside of the building at the lowest level on the grade slab. Setup B is used for comparison of vertical vibrations in open field near tracks with tri-axial measurements in open filed. Setup C is used for comparison of vertical vibrations in open field near tracks with and array of vertical measurements in open field with the exception at Boston site where setup C is used to measure tri-axial vibration inside MBTA station. All of these accelerometers are aligned perpendicular to the tracks. Table 2.5.1 shows the measurement setup and distances from the centerline of the tracks.

Table 2.5.1. Setup classifications and details (Subway)

Site =>		**Boston**		**Jamaica Plain**		**Cambridge**	
Location =>		**Dist. (m)**	**Surface**	**Dist. (m)**	**Surface**	**Dist. (m)**	**Surface**
Setup A	**Single**	0	asphalt	0	soil	0	asphalt
	Tri-axial	12	concrete	16.8	concrete	25	concrete
Setup B	**Single**	0	asphalt	0	soil	0	concrete
	Tri-axial	12	asphalt	11.3	soil	25	soil
Setup C	**Single vertical**	NA	NA	0,3,6.1,9, 12.1,15.2, 17.4	soil	0,7,10,13, 16,19,22, 25	soil
	Tri-axial	7.5	asphalt	NA	NA	NA	NA

Vibration measurements for subways on both the tracks are recorded. Speed measurement is only done inside MBTA station at Boston site but not at other site due to inaccessibility. Thus, adjustment due to speed in dB is not made in any of the subway sites due to consistency

2.5.1 Observations from subway-induced vibration measurements

Figure 2.5.10 compares subway-induced velocity components inside MBTA station. Ambient velocity components have also been shown using dashed line with the same markers. Subway-induced vibrations are 10 to 35 VdB larger in magnitude as compared to the ambient vibrations indicating low noise to signal ratio resulting in robust measurements. It is important to note that the vertical component is greater than horizontal components in the frequency range of 10 to 300 Hz.

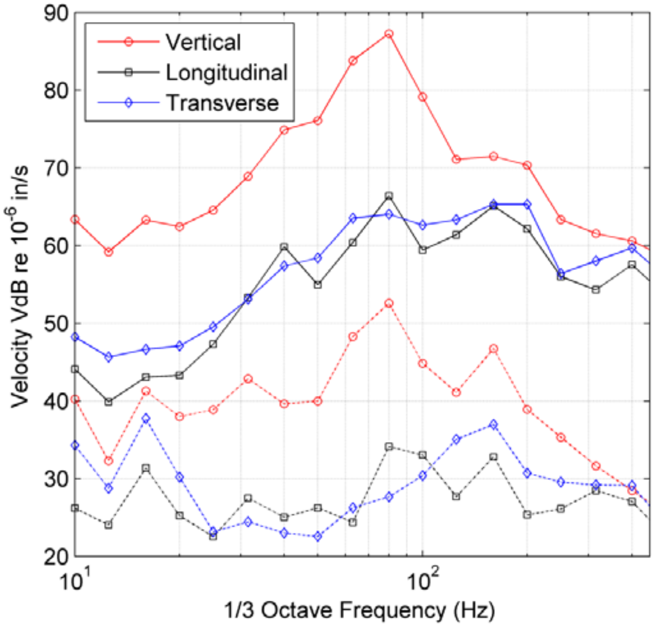


Figure 2.5.10. Subway-induced mean vertical velocity inside MBTA station, Boston

Figure 2.5.11 compares the subway-induced velocity in open field on asphalt, 12 m away from the subway line. It is observed that vertical velocity component is greater than horizontal components by 5 to 10 VdB within the frequency range of 10 to 300 Hz. Peak level of velocity level is associated with 40 Hz.

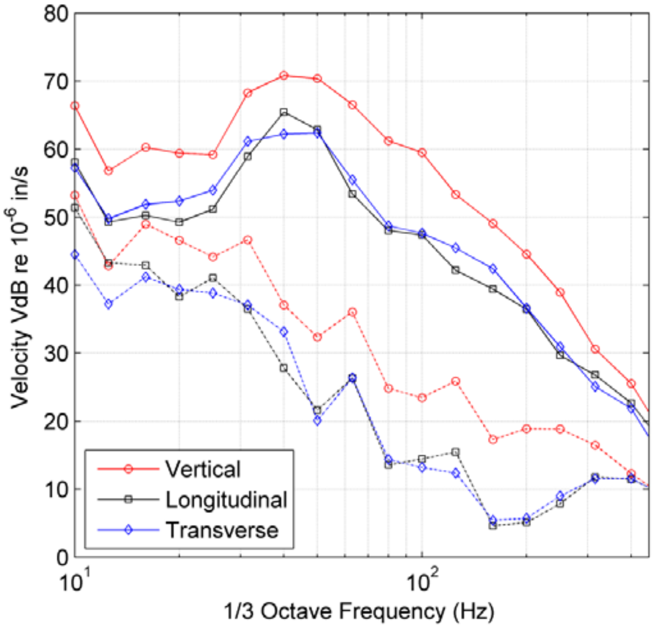


Figure 2.5.11. Subway-induced mean velocity in open field, Boston

For the Boston site, Figure 2.5.12 compares subway-induced vibration components inside the building 12 m away from the subway track. It shows that the vertical velocity component is greater than horizontal components by 10 to 15 VdB in the frequency range of 20 to 200 Hz inside the building. Transverse and longitudinal components show comparable velocity levels. For the Jamaica Plain site, Figure 2.5.13 shows the measurements from inside the building 16.8 m away from the subway track. It also shows that the vertical velocity component is greater than horizontal components by 10 to 15 VdB in the frequency range of 20 to 200 Hz. But in case of Cambridge site in Figure 2.5.14, transverse velocity component exhibited velocity magnitudes comparable to vertical component. Both these components are measured 10 to 15 VdB higher than longitudinal velocity component below 200 Hz.

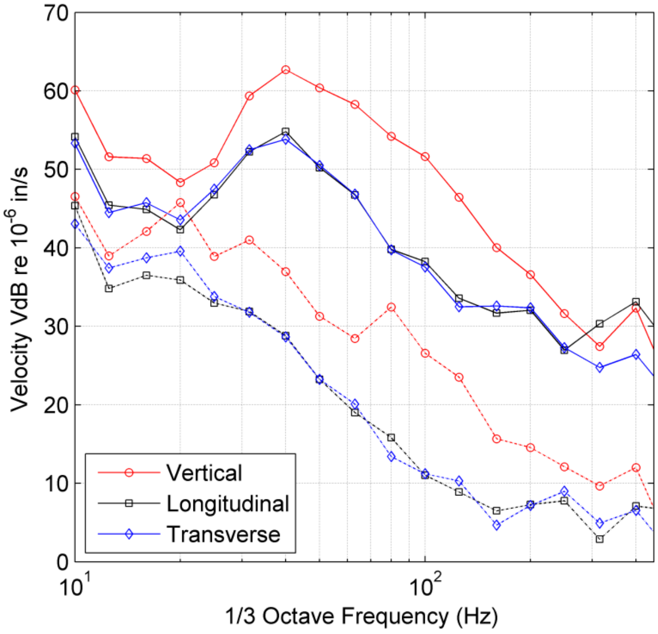


Figure 2.5.12. Subway-induced mean velocity inside building, Boston

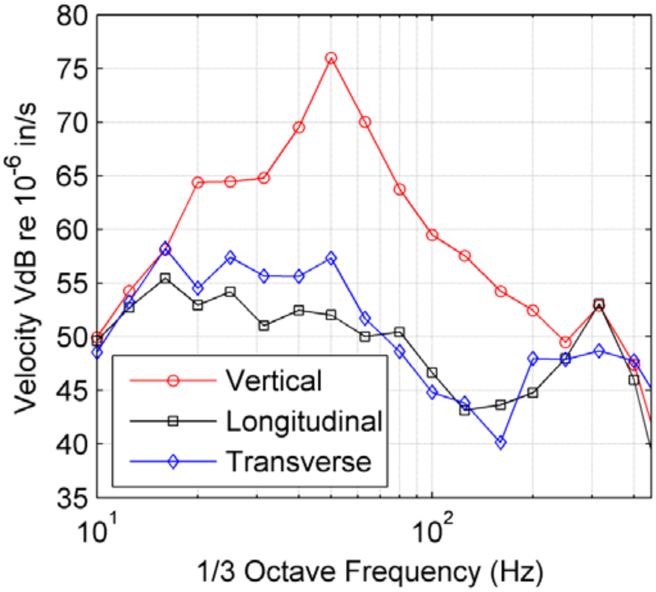


Figure 2.5.13. Subway-induced mean velocity inside building, Jamaica Plain

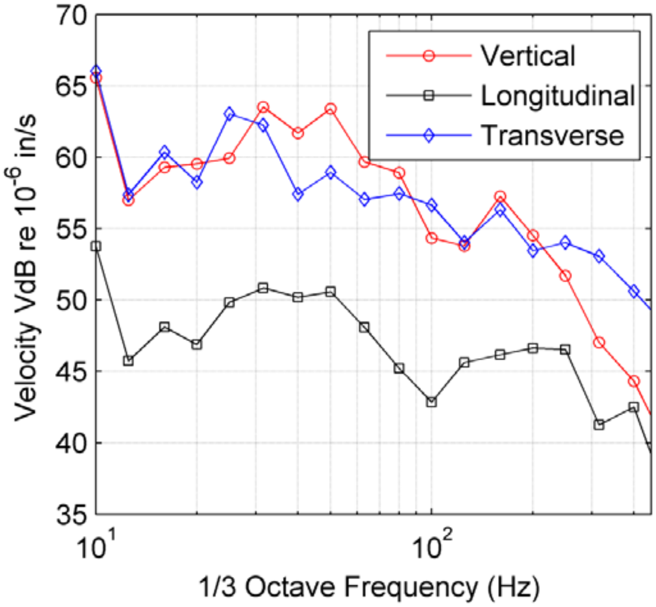


Figure 2.5.14. Subway-induced mean velocity inside building, Cambridge

Figure 2.5.15 compares the logarithmic differences in subway-induced mean vertical velocities inside building and open field measured at Boston, Jamaica Plain, and Cambridge sites. In Boston site, vertical velocity level inside the building is measured 10 dB lower than open field vertical velocity level. Vertical velocities in Jamaica Plain as well as Cambridge show 0 to 15 dB greater velocity level inside the building compared to open field velocity measurements.

It is evident from the observations made in these subway-induced vibration measurement sites that velocity level after the construction of building can be greater that the measured before the existence of building at site on ground surface. Open field vibration measurement may not necessarily always be greater than the vibration level after the construction of building. Thus care shall be taken while designing vibration mitigation system for buildings to be constructed at site subjected to subway-induced vibration.

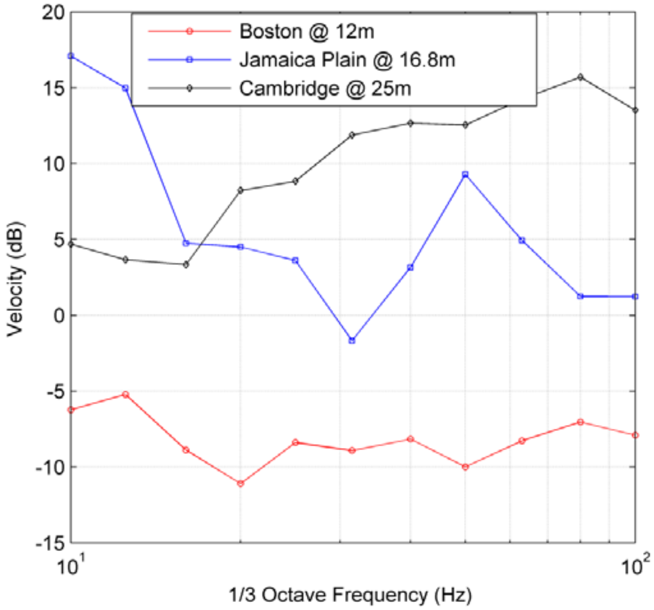


Figure 2.5.15. Vertical velocity difference: inside building - open filed

Figure 2.5.16 shows variation of subway-induced vertical vibration with respect to distance at Cambridge site. It can be observed that the peak of vibration is associated with 63 Hz. In Figure 2.5.17, the peak vertical velocity attenuation with respect to distance is graphed. The Cambridge site a drop of about 25 VdB is observed at 63 Hz as the distance from subway line increases from 0 to 25 m. Similarly, in Jamaica Plain site, a decrease of about 18 VdB is observed with the increase in distance of 17.4 m at 50 Hz associated with level of peak velocity level. From these measurements, it is observed that there is an attenuation of about 1 VdB per meter as distance from subway line. However, the attenuation is not varying linearly with distance.

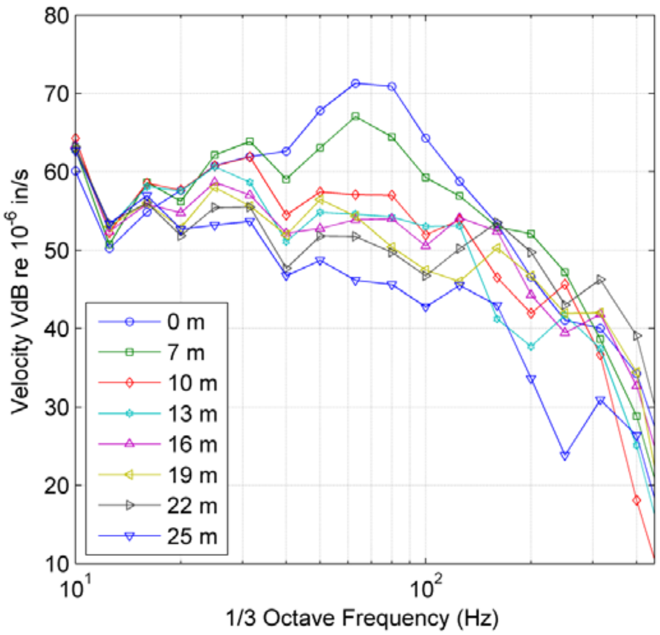


Figure 2.5.16. Subway-induced vertical vibration in open field, Cambridge

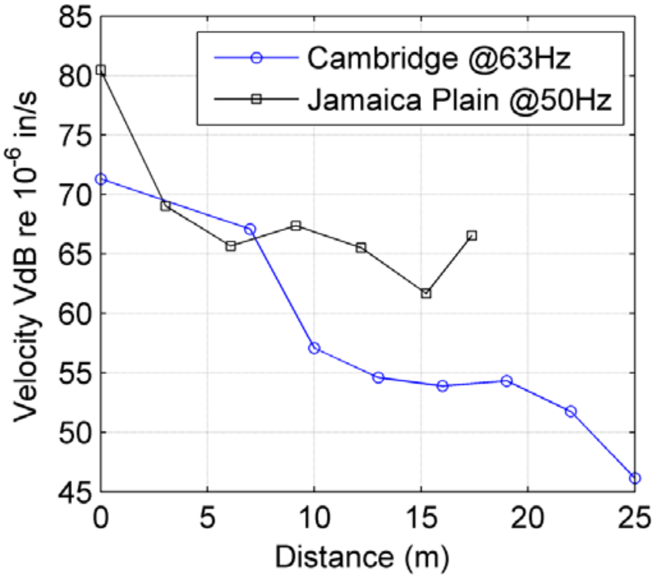


Figure 2.5.17. Subway-induced vertical Velocity in open field

2.6 Conclusions

Subway and train-induced vibrations were successfully measured inside building on grade slab and in the adjacent open field in different setups. Frequency range and magnitude of vibrations at which operation of sensitive equipment is hampered should be the prime concern for vibration mitigation system. Following conclusion can be drawn from the observations made from the measurements.

- Common to both subway and train-induced vibrations:
    - For all six sites, the measured vertical velocity was higher than horizontal components inside the building on grade slabs. On the buildings grade slabs, the maximum vertical velocities ranged from 63 to 70 VdB and the horizontal velocities from 51 to 57 VdB. Thus vertical components which are greater need to be considered while design of vibration mitigation system for a building.
    - Frequency range of significant velocity level on ground surface was contained was 10 to 250 Hz.
    - Velocity level on ground surface at the frequency associated with peak velocity level decreased by approximately 1 VdB per meter with the increase in distance perpendicular from subway and railway tracks.
- Specific to train-induced vibrations:
    - The largest magnitude of vibration switched between the vertical and horizontal components in various frequency ranges. Therefore, the mitigation system shall be designed to mitigate the largest component of vibration which can be horizontal at lower

  frequencies and vertical at higher frequencies. Thus care shall be taken while designing building vibration mitigation system of the building.

  - Below 100 Hz, train-induced vibration sites showed greater vertical vibration in open field than inside the building. Based on these two sites, open field vertical vibration measurements can be used for the design of vibration mitigation system of buildings.
- Specific to subway-induced vibrations:
  - Vertical velocity components measured inside the building exhibited lower velocity levels in Boston site but it was measured greater at Cambridge and Jamaica Plain site. Open field vibration thus may not necessarily always be greater than vibration inside the building. Thus care shall be taken in design of building vibration mitigation system for sites subjected to subway-induced vibrations in concern with the depth of tunnel with respect to the foundation of the building.

In the future, full-scale testing of buildings subjected to train and subway-induced vibrations will be used for validation of impedance modeling of structures and “blocking floor theory”.

2.7 Acknowledgements

Authors would like to thank Dr. Laurie G. Baise and Dr. Eric Thompson at Tufts University for reviewing this paper. This research would not have been successful without the coordination and permission from Gladys Unger from Acentech Inc., Dr. Gary Leisk at Tufts University, Gerry Desmond at MIT-Cambridge, Ted O’Leary at Alexandria properties, Edward Pitts at Tufts Medical Center, Michele D. Taylor at Pearl Street Park, Dr. Sito Narcesse at English High School, and Claudia Smith-Reid, Sorrenia Dillon from MBTA. Sincere thanks to graduate

students K.P.Anish, Merve Iplickcioglu, and Sagar D. Shetty at Tufts University for their significant contribution and help throughout the experimental process.

CHAPTER 3 ADDITIONAL TRAIN-INDUCED VIBRATION MEASUREMENT INFORMATION

3.1 Vibration measurement site in Somerville, MA

Vibration measurements at all sites are made using Wilcoxon seismic 731A accelerometers and Data Acquisition system (RION DA20 data recorder). Speed monitoring of the trains is done using Bushnell Speedster III speed radar gun. At each site 3 to 8 train events are measured in each setup. Mean value of all train events is considered in representing data along each velocity component. Figure 3.1.1 shows a sample mean vertical velocity plotline passing through the mean values of absolute values of train events.

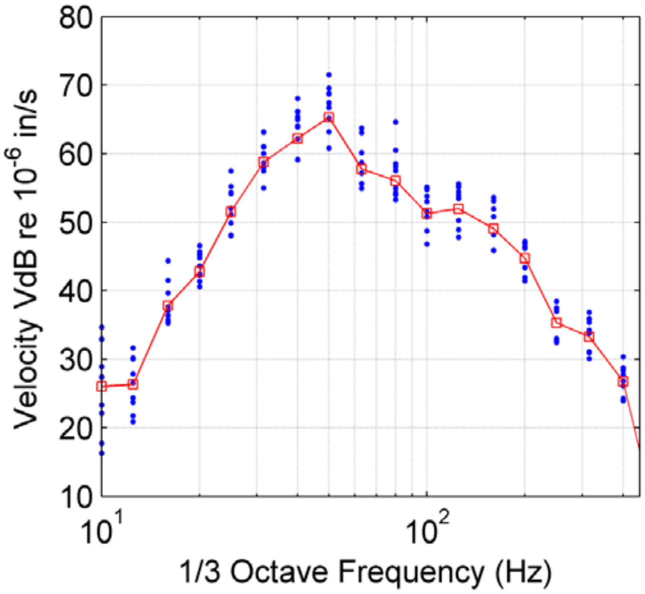


Figure 3.1.1. Mean and absolute vertical velocity levels, Medford

Measurement site at Somerville is a residential apartment for elderly or disabled individuals. It is a six story building with basement. Figure 2.4.2 presents a view of commuter train passing near the site. Vibration measurement inside the building is taken on grade slab in the basement.

Figure 3.1.2 presents a plan view of measurement setups performed at the site. Setup A has a tri-axial accelerometer placed in the building basement 14m away from the centerline of tracks and a single vertical accelerometer outside the building 7m away from the centerline of tracks. Grade slab in the building basement is 3m below the open filed ground surface. Both the accelerometers are aligned in a straight line perpendicular to the tracks. Setup B has tri-axial as well as single vertical accelerometer aligned in a straight line perpendicular to the track at the same distance as in setup A but it is in the open field adjacent to the building. Setup C has an array of seven single vertical accelerometers aligned in a direction perpendicular to the track. These are placed at 7m, 9m, 11m, 13m, 15m, 17m and 22m from the centerline of tracks. Setup A and B is performed at the same time and measured six trains. Setup C is performed at the same location of setup B at different time and measured vibrations due to six trains. Trains events are measured from both the directions and on both of the tracks.

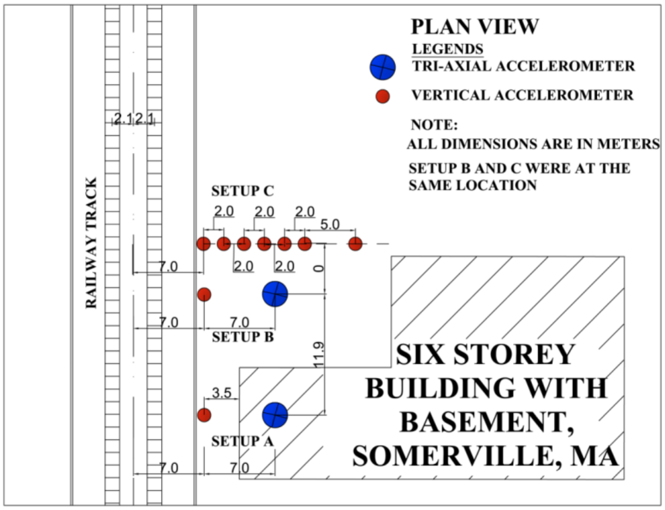


Figure 3.1.2. Measurement setup A, B, and C

Figure 3.1.3 shows the tri-axial accelerometer setup with aluminum block mounted over iron-wedge in open field. The aluminum block with accelerometers on the iron wedge behaves like a single degree of freedom structure on being subjected to train-induced vibrations. And due to low contact stiffness of wedge with the soil, horizontal measurements are affected by resonance of this setup in the lower frequency range. This phenomenon contaminates data obtained from horizontal accelerometers. However, data from vertical accelerometer in this setup is not affected. Locations where tri-axial accelerometer is setup either on asphalt or concrete, measurements are not contaminated due to a strong contact provided by epoxy between the aluminum block and asphalt/concrete. The resonance behavior was not observed inside the building with tri-axial accelerometer setup on the grade slab.

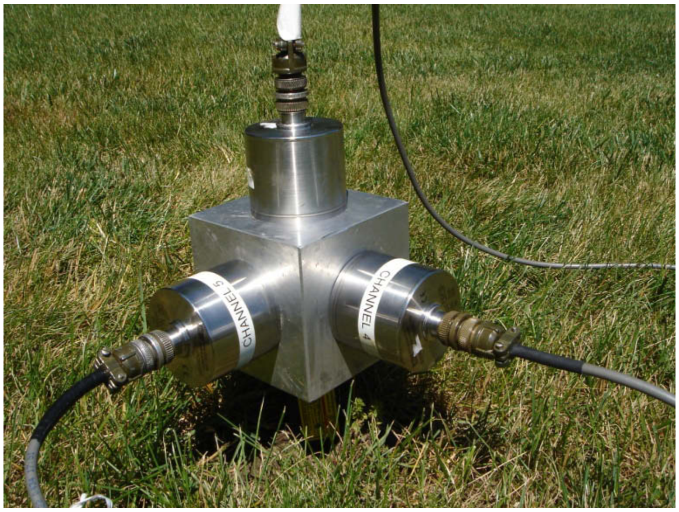


Figure 3.1.3. Tri-axial accelerometer setup in open field

3.1.2 Observations from Somerville site:

Comparison of mean velocity level components from the tri-axial accelerometer is presented in Figure 3.1.4. It shows that the mean vertical velocity level is 5 to 15 VdB greater than horizontal velocity components below 300 Hz. Longitudinal and transverse velocity components exhibit comparable velocity levels and similar shapes to each other.

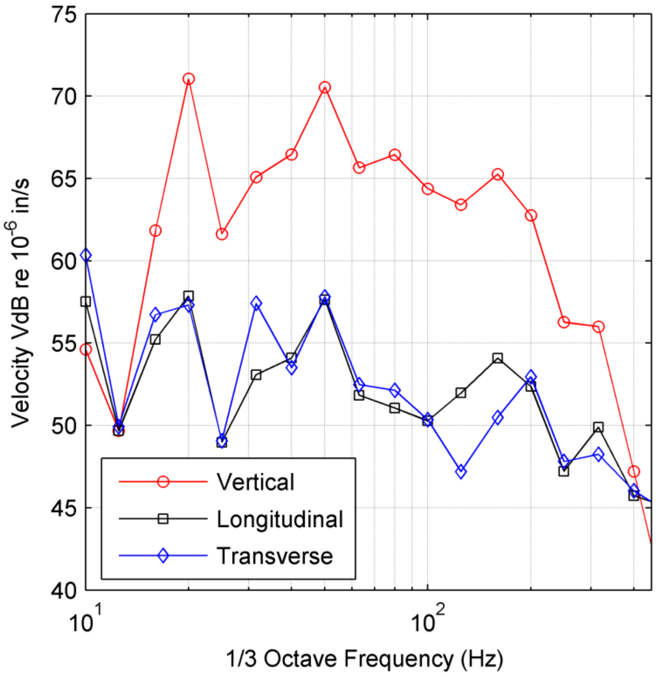


Figure 3.1.4.Train-induced mean velocity components inside building

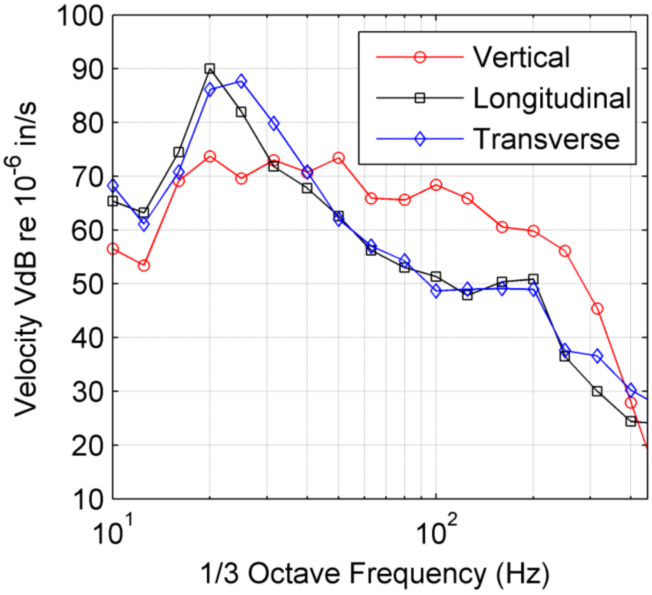


Figure 3.1.5.Train-induced mean velocity components in open field

Figure 3.1.5 compares velocity components measured in open field adjacent to the building. It is observed that in the frequency range of 50 to 300 Hz, vertical velocity component is greater than the horizontal velocities (longitudinal and transverse) by 10 to 15 VdB. Greater value of horizontal velocities than vertical velocity below 50 Hz is due to the resonance of horizontal accelerometers on tri-axial setup over iron-wedge acting as single degree of freedom system. Thus horizontal velocity levels below 50 Hz cannot be used for comparison purposes. An alternative technique for horizontal vibration measurements shall be adopted for future measurements in open field to avoid capturing data contaminated with resonance of the system.

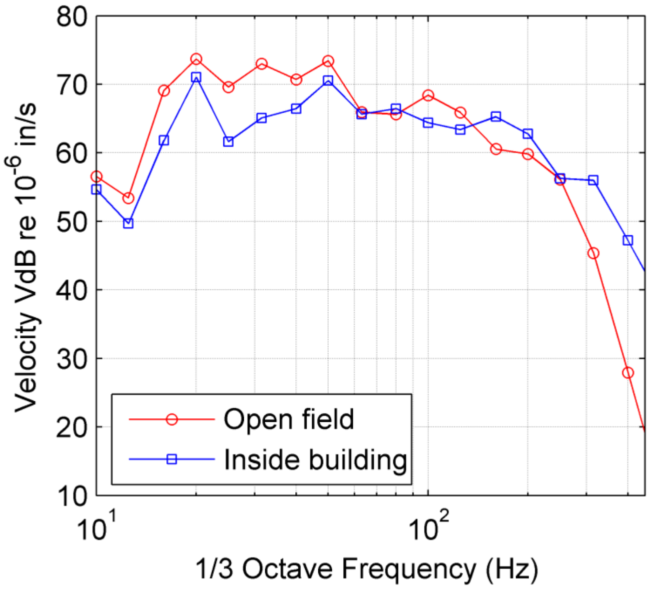


Figure 3.1.6. Train-induced mean vertical velocity

It is observed from Figure 3.1.6 that the vertical velocity component in open area adjacent to the building is 0 to 10 VdB greater than that observed inside building basement up to the frequency of 150 Hz. Open field measurement drops sharply beyond 150Hz.

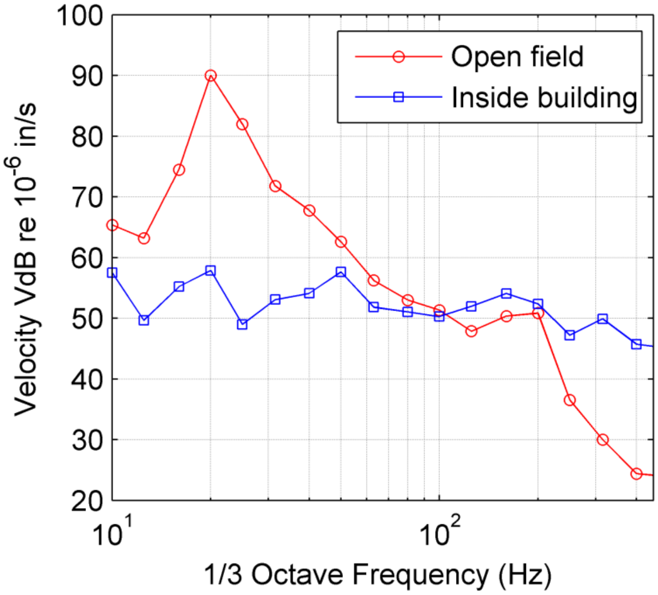


Figure 3.1.7. Train-induced mean longitudinal velocity

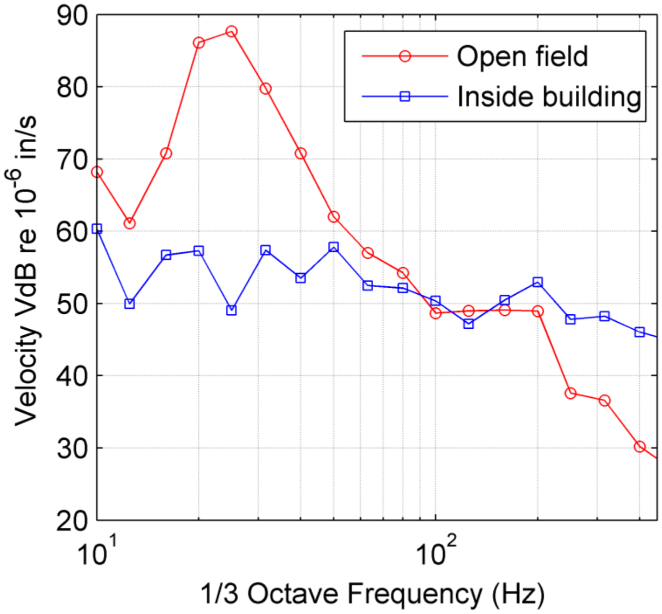


Figure 3.1.8. Train-induced mean transverse velocity

Figure 3.1.7 and Figure 3.1.8 captures resonance in the longitudinal and transverse velocity components measured in open field adjacent to building. It is thus difficult to comment on these figures with certainty. It is observed that at the frequency above 100 Hz, horizontal velocities measured in open field drops below the measurements inside the building. This observation is also made in Figure 3.1.6 for vertical velocity component.

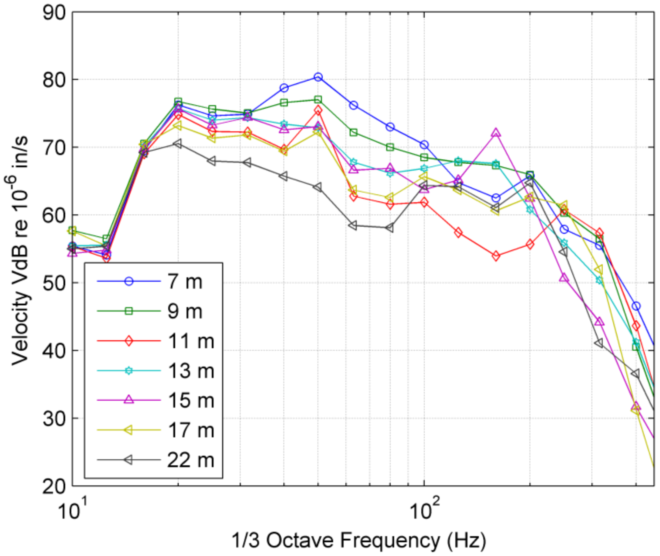


Figure 3.1.9. Train-induced open field mean vertical velocity

From Figure 3.1.9 it is observed that in general, peak velocity level decreases with the increase in distance from the track but at some point this observation differs probably due to local site response. Peak level of vibration is associated with 50 Hz. It is observed that the velocity levels at peak level of frequency dropped by 15 VdB over 15m distance. Thus it can be said that a drop of 1 VdB per meter is approximately observed at the frequency associated with peak velocity level.

3.2 Vibration measurement site in MIT-Cambridge, MA

Measurement site at MIT-Cambridge is research laboratory with sensitive equipment like MRI machines. It is an eight story building with a skywalk. Cargo trains, usually three in a day, passes through the building under the skywalk. Figure 2.4.3 presents a view of train passageway across the building. Vibration measurements inside the building are made on the grade slab in the first floor. The site has only one railway track and trains come from either directions. Three trains are measured at this site. Speed of only one train in the evening is recorded as the other two trains were scheduled late night.

Figure 3.2.1 shows plan of measurement setup A performed at the site. Setup A has a tri-axial accelerometer placed in the building 13.9m away from the centerline of track and a single vertical accelerometer outside the building 1.7m away from the centerline of track. Both the accelerometers are aligned in a straight line perpendicular to the track. Transverse direction accelerometer malfunctioned and readings are not made for transverse direction in setup A. Another tri-axial accelerometer is also setup near the column inside the building 13.9m away from the centerline of track. This is set to measure vibration near the column. In this setup, accelerometer in the longitudinal direction did not work properly and measurements are not recorded. This site had only 3 trains per day due to which other setups in open field on asphalt are not performed.

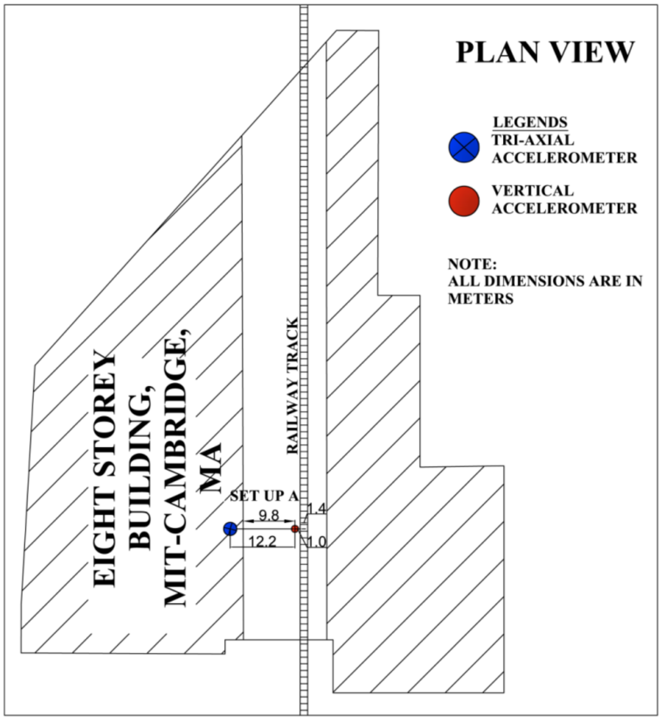


Figure 3.2.1. Measurement setup A

3.2.2 Observations from MIT-Cambridge site measurements

From Figure 3.2.2 it can be observed that the mean vertical velocity inside the building is greater than longitudinal velocity by 5 to 15 VdB in the frequency range of 15 to 300 Hz. Beyond 300 Hz, magnitude of velocity components become comparable. Figure 3.2.3 presents the vibration measurement near the column. It is observed that transverse velocity component is lower than the vertical velocity component below 60Hz. The velocity levels become comparable in magnitude above 60 Hz.

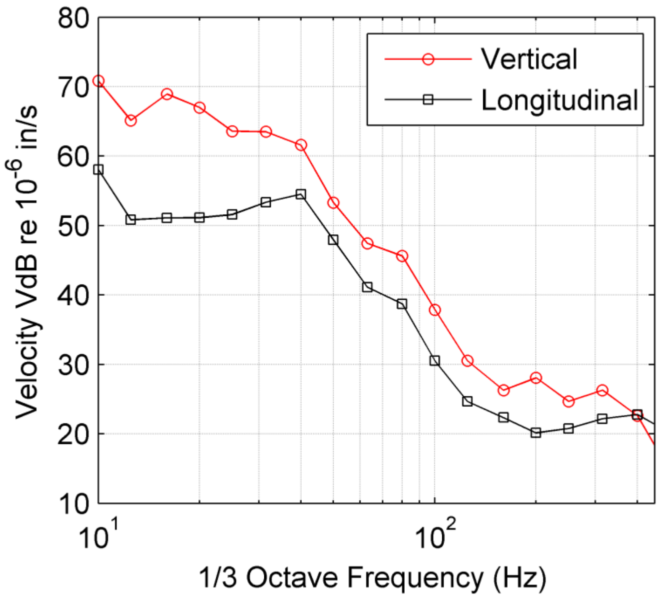


Figure 3.2.2.Train-induced mean velocity components inside building

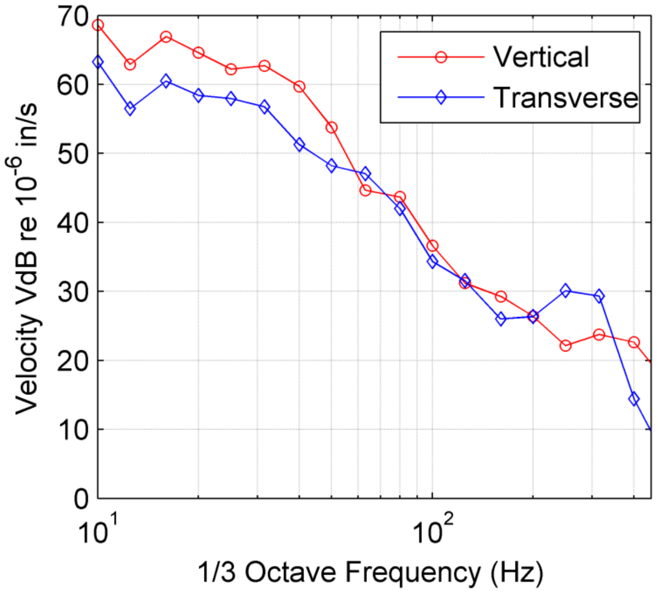


Figure 3.2.3.Train-induced mean velocity components inside building near column

CHAPTER 4 ADDITIONAL SUBWAY-INDUCED VIBRATION MEASUREMENTS INFORMATION

4.1Vibration measurement site in Jamaica Plain, MA

Vibration measurements at each subway-induced vibration measurement site are done for 8 to 30 subway events in each setup. Mean value of all subway events is considered in representing data along each velocity component. Figure 4.1.1 shows a sample mean vertical velocity plotline passing through the mean values of absolute values of subway events.

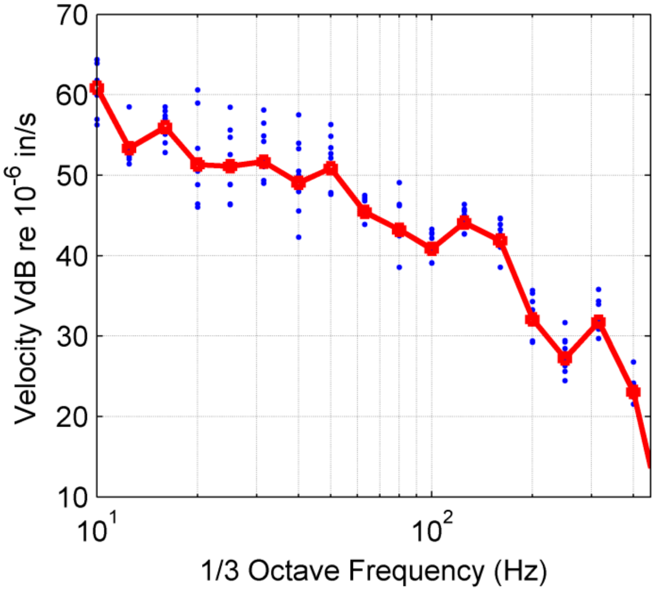


Figure 4.1.1. Mean and absolute vertical velocity levels, Cambridge

Measurement site at Jamaica Plain is institutional building. It is a three story building with basement. Commuter trains as well as orange line (subway) passes under the ground adjacent to the building. Location of orange line tacks are farther from the building as compared to commuter train trains. Thus vibration measurements due to subways are smaller as compared to the commuter trains measured underneath the ground. That is why measurements due to commuter trains passing under the ground are considered at this site. Figure 2.5.4 shows vibration measurement site in Jamaica Plain. Vibration measurement inside the building is performed in the building basement.

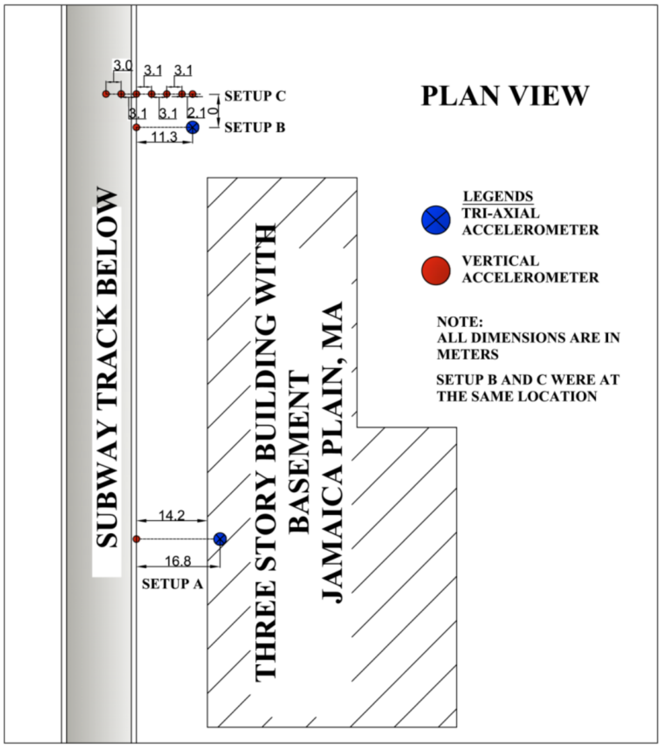


Figure 4.1.2. Measurement setup A, B, and C

Figure 4.1.2 shows plan of measurement setups performed at the site. Setup A has a tri-axial accelerometer placed in the building basement 16.8 m away from subway line and a single vertical accelerometer outside the building above the subway line. Both the accelerometers are aligned in a straight line perpendicular to the tracks. Setup B has tri-axial as well as single vertical accelerometer aligned in a straight line perpendicular to the track separated by 11.3 m from each other. The distances could not be maintained to be same as in setup A due to discontinuity in the surface of ground at 16.8m from the railway tracks. Tri-axial accelerometer in setup B is mounted over iron-wedge. Setup A and B is performed simultaneously and measured five commuter trains. Setup C has an array of seven single vertical accelerometers aligned in a direction perpendicular to the track. These were placed at 0 m, 3.0 m, 6.1 m, 9.1 m, 12.1 m, 15.2 m and 17.4 m on the ground surface above the subway line. Setup C is performed at the same location of setup B at different time and measured vibrations due to five trains.

4.1.2 Observations from Jamaica Plain measurement site:

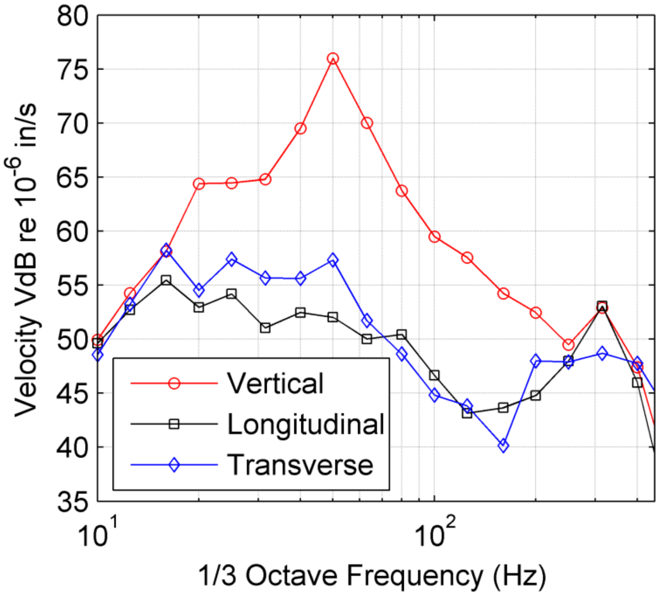


Figure 4.1.3. Subway-induced mean velocity components inside building

Figure 4.1.3 compares mean velocity components measured inside building basement. It is observed that the vertical velocity is greater than the horizontal components (longitudinal and transverse) by 10 to 15 VdB below 200 Hz. Above 200 Hz, velocity components become comparable in magnitude. Longitudinal and transverse velocity levels showed comparable magnitude.

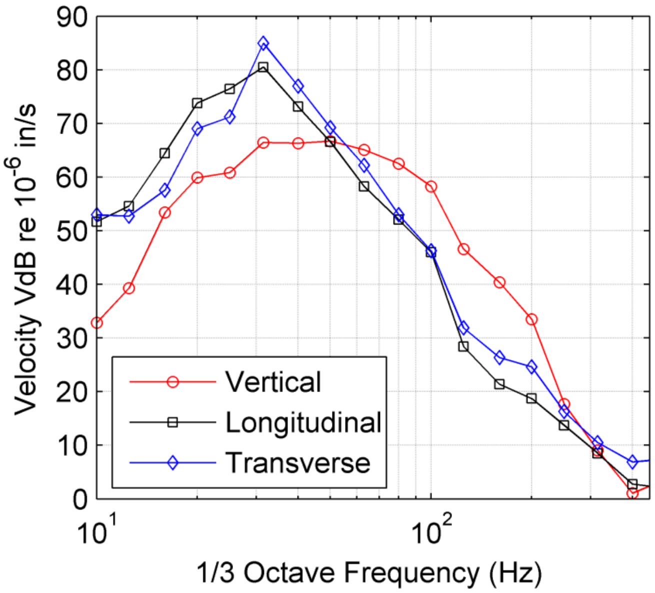


Figure 4.1.4. Subway-induced mean velocity components in open field

Figure 4.1.4 compares mean velocity components measured in open field. It is observed that vertical velocity level is 5 to 10 VdB higher than the horizontal components between 60 to 200 Hz. Above 200 Hz, velocity components become comparable in magnitude. Horizontal components exhibit resonance behavior of the system in horizontal direction below 50 Hz and thus the comparison below 50 Hz cannot be made.

Figure 4.1.5 compares vertical velocity in the building basement and in open field adjacent to the building. Observations from the figure showed that velocity levels in the building basement are 0 to 10 VdB greater than that observed in open field below 100 Hz. Above 100 Hz, vertical velocity inside building is greater by 5 to 40 VdB.

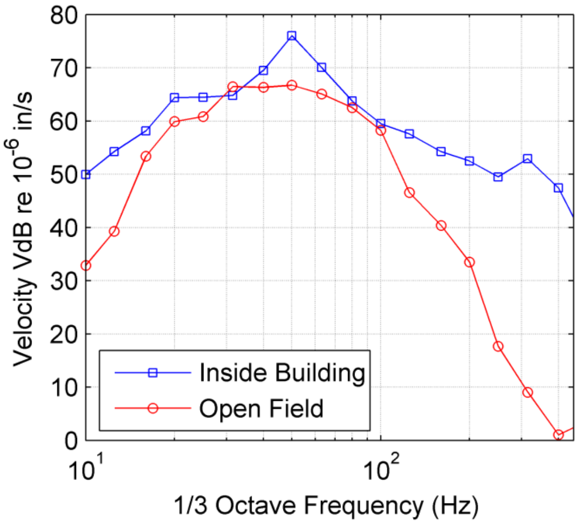


Figure 4.1.5. Subway-induced mean vertical velocity

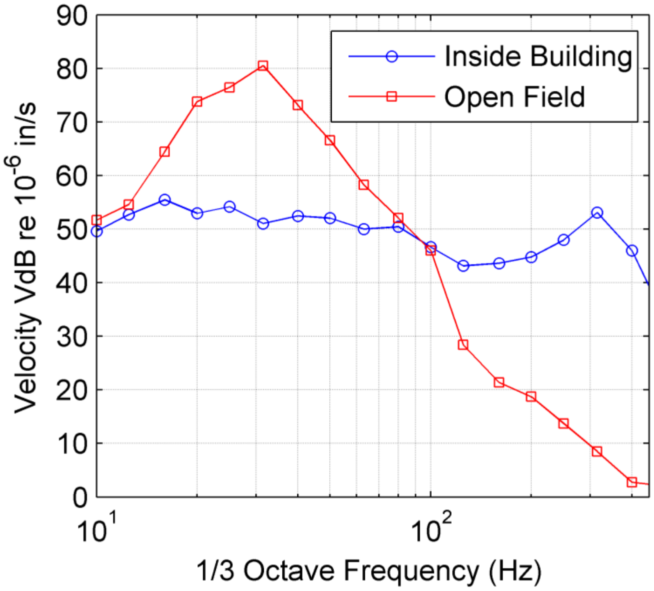


Figure 4.1.6. Subway-induced mean longitudinal velocity

The longitudinal and transverse velocity components in the building basement and adjacent open field are compared in Figure 4.1.6 and Figure 4.1.7, respectively. It is observed that horizontal components measured in open field are contaminated by horizontal resonance of the system and cannot be used for comparison.

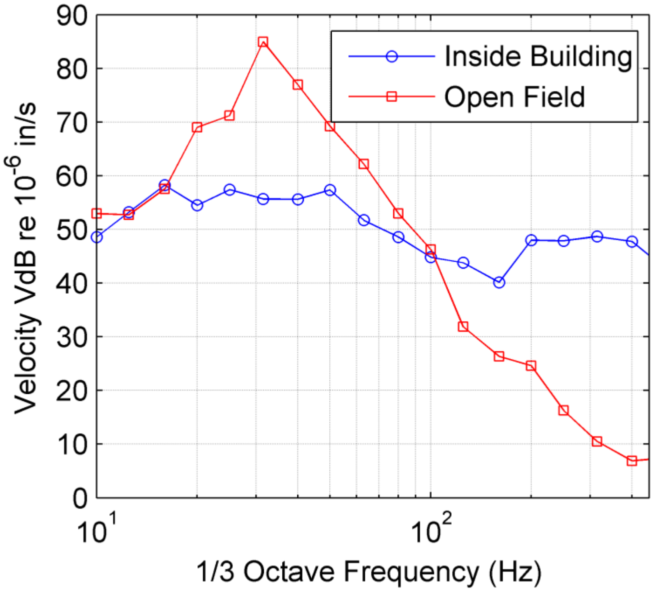


Figure 4.1.7. Subway-induced mean transverse velocity

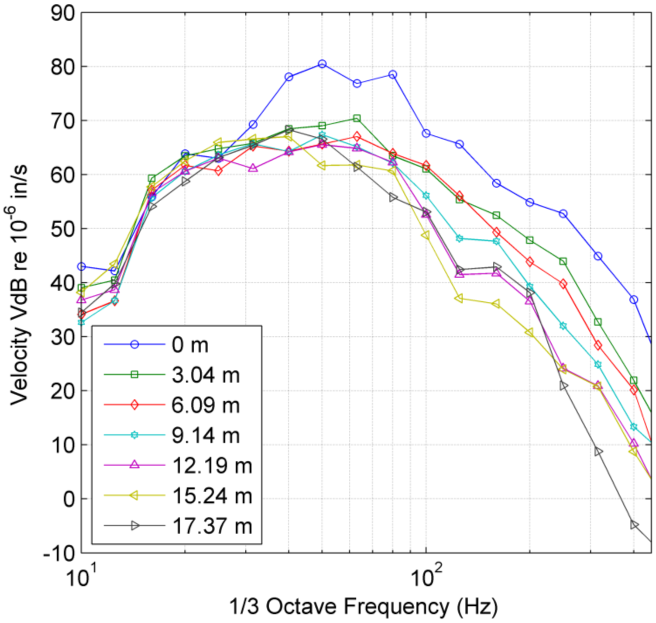


Figure 4.1.8. Subway-induced mean vertical velocity

Figure 4.1.8 compares variation of vibration level spectrum with the increase in the distance. Peak velocity level occurs between frequencies of 50 to 63.5Hz. A decrease of 17 to 18 VdB was observed with the increase in distance of 17.4m at 50 Hz associated with peak velocity level. Thus it can be approximated to have 1 VdB per meter attenuation with increase in distance from subway track.

4.2 Vibration measurement site in Cambridge, MA

Measurement site in Cambridge for subway is shown in Figure 2.5.7. The building is eight storied and has research laboratories sensitive equipment of bio-medical field. Redline goes underneath the ground adjacent to the building and measurements are made for that. There is a surface train track as well through which a few cargo trains pass by (three in a day). Due to the surface train track besides the building, tunnel structure for subway at this location is expected to be different from other locations. Also an underground storm water tank is found to be located near the building. Measurements inside the building are made in steam room on the first floor (lowest floor).

Figure 4.2.1 shows the plan view of measurement setups performed at the site. Setup A has a tri-axial accelerometer placed in the building basement 25m away from subway line and a single vertical accelerometer outside the building above subway line. Both the accelerometers are aligned in a straight line perpendicular to the subway track. Setup B has tri-axial as well as single vertical accelerometer aligned in a straight line perpendicular to the track at the same distance as in setup A but it is placed outside the building. Tri-axial accelerometer in setup B is mounted over the iron-wedge. Setup C has an array of seven single vertical accelerometers aligned in a direction perpendicular to the track. These are placed at 0m, 7m, 10m, 13m, 16m, 19m, 22m and

25m from the centerline of tracks. Setup D has tri-axial accelerometer above the subway line on walkway and an array of five single vertical accelerometers placed at a distance 7m, 10m, 13m, 16m and 19 m from the subway line. Setup C and D are performed at the same location of setup B at different times.

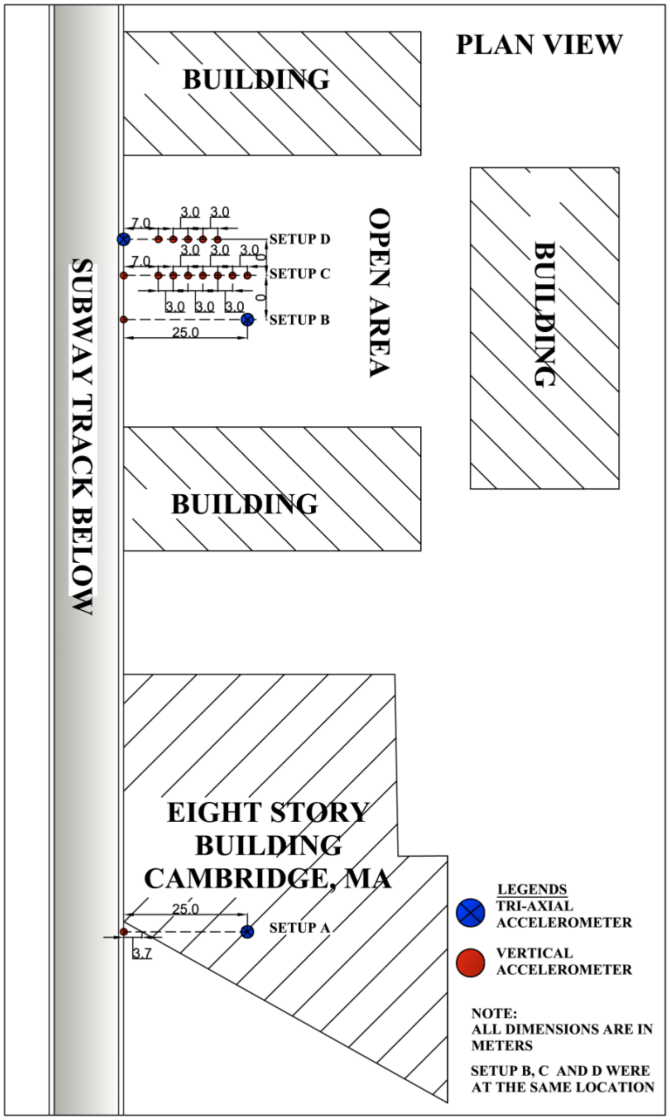


Figure 4.2.1. Measurement setup A, B, C, and D

4.2.2 Observations from Cambridge site measurements:

Figure 4.2.2 compares measured mean velocity components inside the building 25m away from the subway track. It is observed that the vertical velocity and transverse velocity component is greater than longitudinal velocity component by 10 to 15dB.

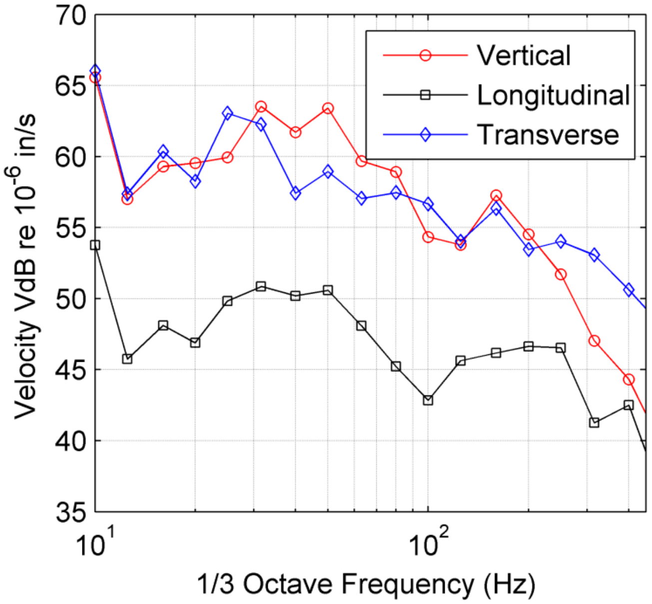


Figure 4.2.2. Subway-induced mean velocity inside building

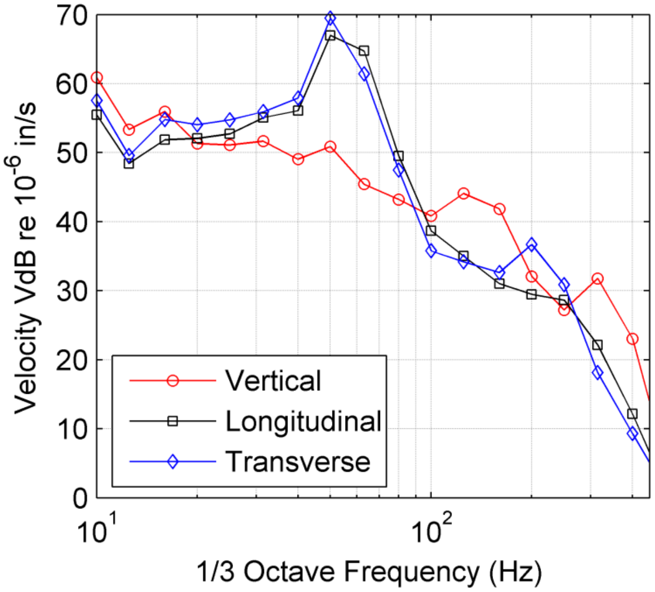


Figure 4.2.3. Subway-induced mean velocity in open field

Figure 4.2.3 compares mean velocity components in open field. Between 100 to 200 Hz, vertical component show 10 VdB higher velocity level compared to horizontal component. Above 200 Hz, velocity components show comparable magnitude for all components. However it is difficult to draw conclusion from this figure due to contamination of horizontal data below 100 Hz.

Figure 4.2.4 compares mean velocity components measured in open field near source as in setup D. Tri-axial accelerometer had been glued on walkway made of concrete. It is observed that the vertical velocity component showed 5 to 12 VdB greater velocity level compared to horizontal components.

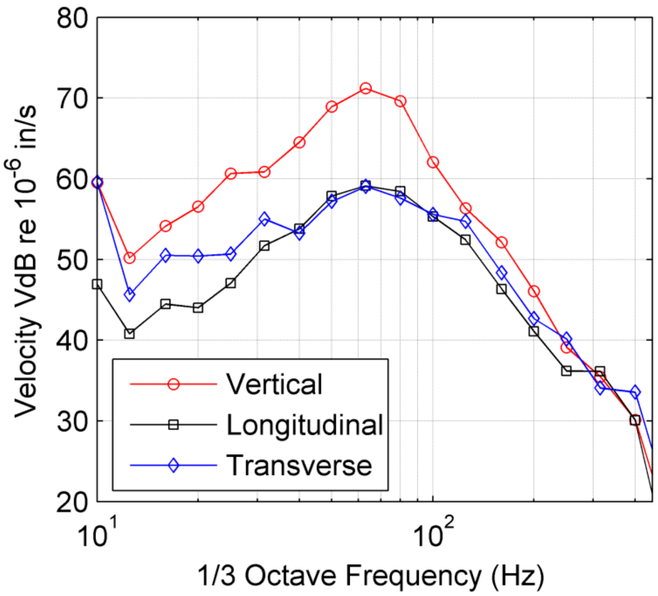


Figure 4.2.4. Subway-induced open field mean velocity near subway track

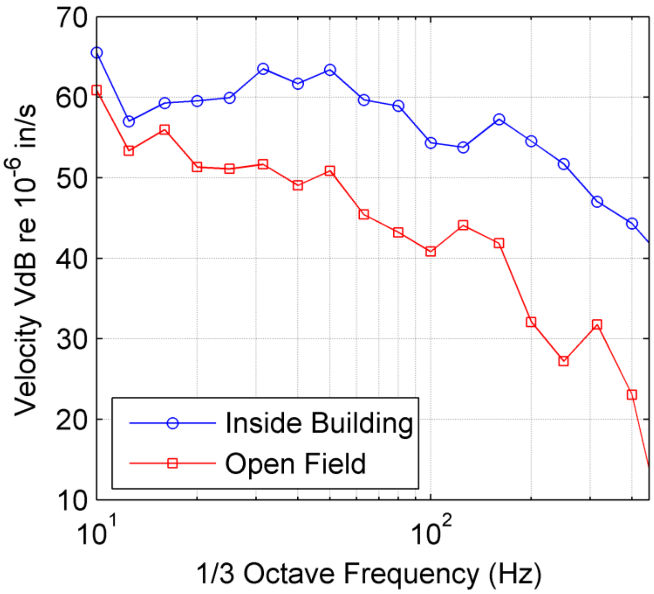


Figure 4.2.5. Subway-induced mean vertical velocity

Figure 4.2.5 compares mean vertical velocity components inside the building and in open field. Velocity level inside the building has been measured 5 to 30 VdB greater than the velocity level in open filed. It is unexpected behavior. In order to investigate further the vertical velocity levels near the source in setup A and B is compared in Figure 4.2.6. It is observed that the velocity near the source in the setup A is higher than that in setup B. It might be due to difference in the tunnel structure at that location to accommodate load due to surface train that also exist above on the ground surface. In addition to that an underground storm water tank also exists near the building. Thus it is difficult to comment about the reason of observations made from these figures.

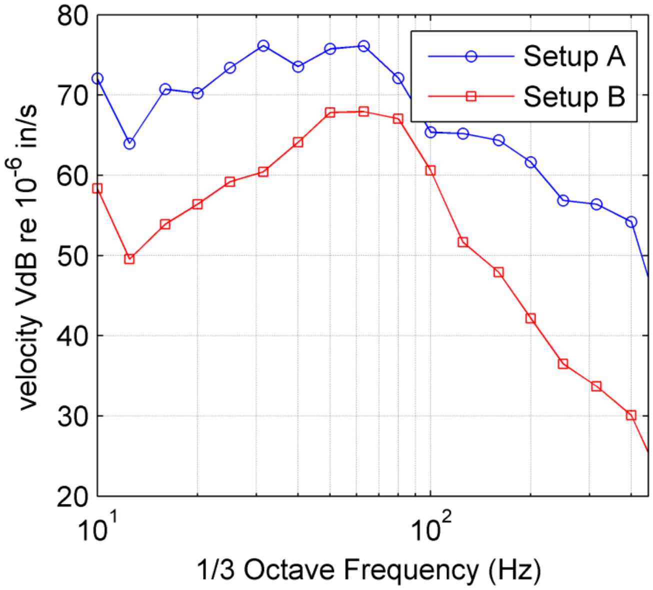


Figure 4.2.6. Subway-induced mean vertical velocity near the subway line

The longitudinal and transverse mean velocity in the building basement and adjacent open field are compared in Figure 4.2.7 and Figure 4.2.8, respectively. Above 100 Hz, open field measurements drops sharply below inside building measurements. However, below 100 Hz, horizontal velocity components measured in the open field show effect due to resonance and cannot be interpreted.

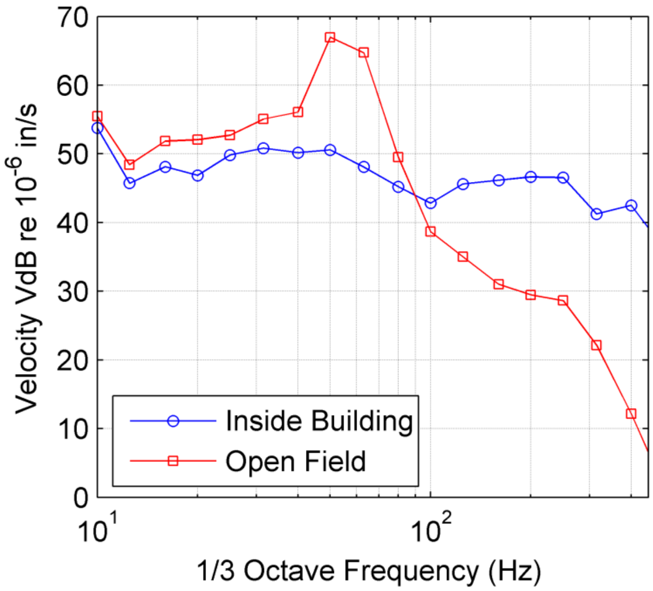


Figure 4.2.7. Subway-induced mean longitudinal velocity

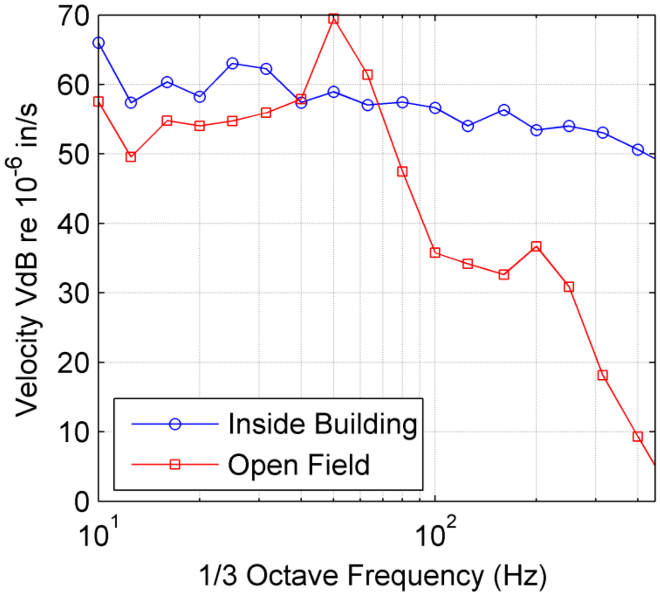


Figure 4.2.8. Subway-induced mean transverse velocity

CHAPTER 5 FUTURE WORK

This research is a supplement for the validation of impedance model for prediction of train and subway-induced building vibration and blocking floor theory for full scale buildings. Through the validation of assumptions of prediction model and analysis the characteristics of subway and train-induced floor vibrations, validation of prediction model and blocking floor theory in full scale building is the next step. This requires series of measurements in full-scale buildings subjected to subway and train-induced vibrations. Validation of blocking floor theory will provide an efficient method for mitigation of subway and train-induced vibrations in residential buildings, laboratories with sensitive measurement devices, and manufacturing plants for semiconductor devices, computer chips, and Nano-technology manufacturing facilities.

Additionally, it was observed that horizontal accelerometers when installed over iron-wedge in open fields in soft soil capture resonance of the system and vibration measurements become contaminated. Though solution to this problem exists to get a single set tri-axial accelerometer but alternatives to utilize available equipment is still desired. Additionally, effect of asphalt on horizontal measured accelerations need to be investigated. Also how the subway and train-induced vibration measurements change with depth, how the foundation type effect vibration received inside buildings need to be investigated.

CHAPTER 6 DATA ACQUISITION AND PROCESSING

6.1 Operational Instruction for RION DA20 data recorder

Equipment: RION 4-Channel Data Recorder DV-20

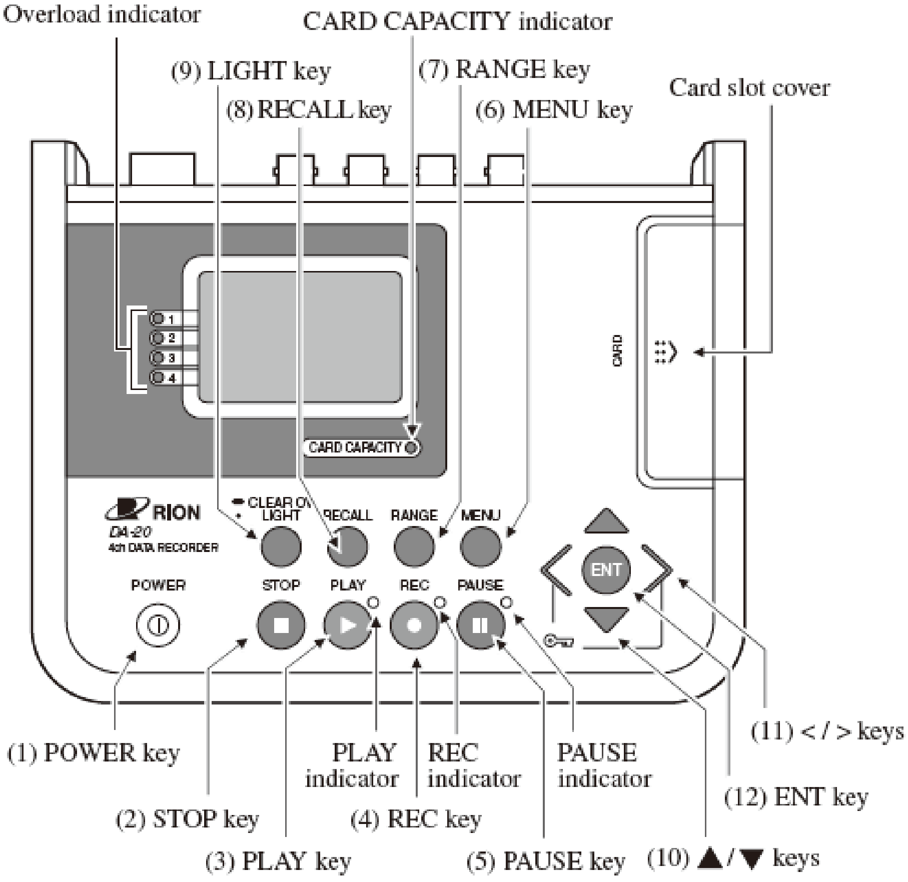


Figure 6.1.1. RION DA20 data recorder

Source: www.rian.co.jp (Instruction Manual, 4 Channel Data Recorder DA-20)

The figure above shows the front panel. In order to operate, please follow the following steps:

1. Connect one end of conditioner to accelerometer and another end to the RION.
2. Press POWER key for around 5 seconds to turn the instrument on.
3. A message appears of the screen, press STOP, to come out of it.
4. The following screen appears

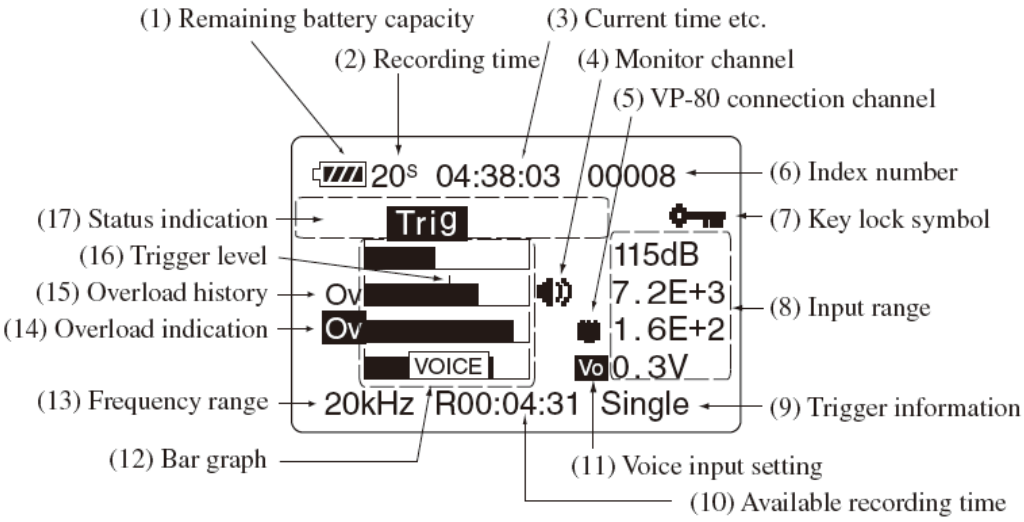
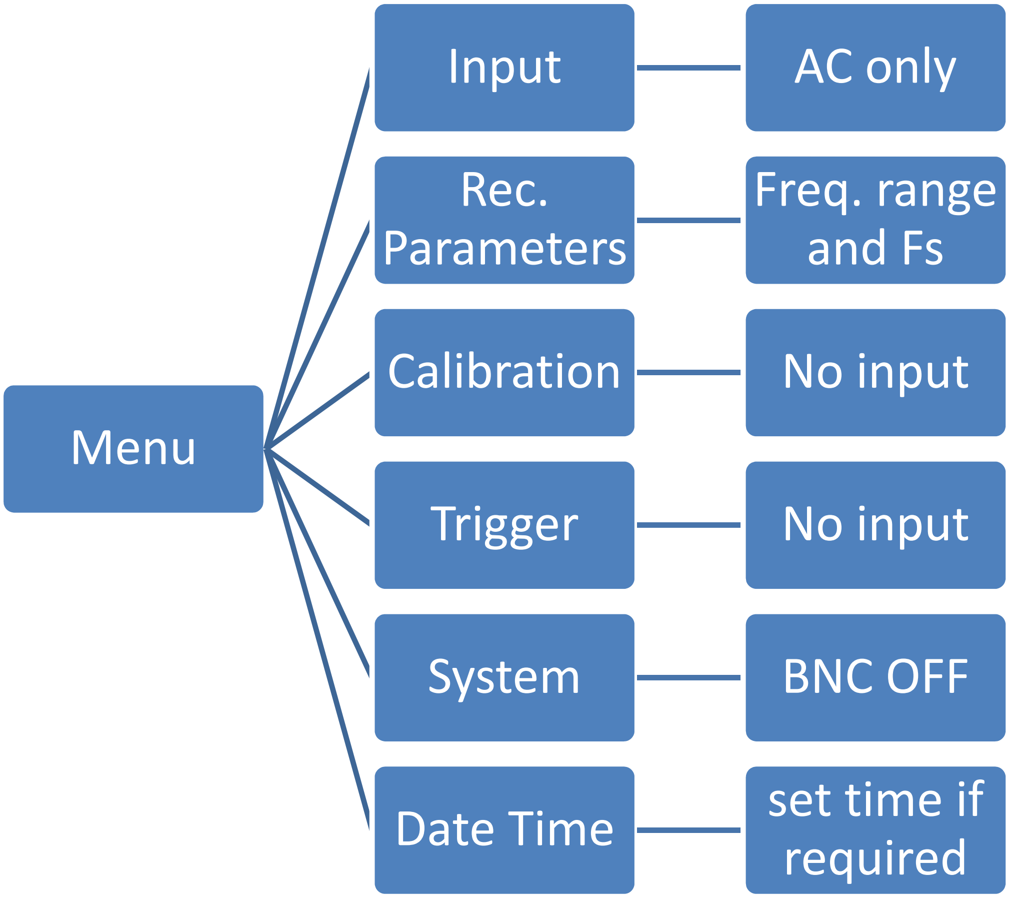


Figure 6.1.2. RION DA20 screen output

Source: www.rian.co.jp (Instruction Manual, 4 Channel Data Recorder DA-20)

5. Check remaining battery capacity before starting test.
6. Note the file number (index number) for current test
7. Scroll using up and down key and press ENT to select
8. Press MENU to get the following options



Note: the action corresponding to each option is mentioned above.

9. Press STOP to go back to Main Menu screen
10. Set the voltage range for each channel depending on the expected noise amplitude. In order to make sure the range is neither too high nor to low, trial with one of the train pass by is preferred. Select range so those trains pass by reaches 70 to 90 % of the selected vibration range.
11. Turn the conditioner power supply on and measure the vibrations continuously
12. The data is stored in the form of wave file in CF card and scaled in the range of -1 to 1
13. The RION DA-20 converts input voltages at the BNC connectors to numerical values in the wave file that fall between the values -1 to +1. The input A/D convertor incorporates

overload protection to 1.3 times the specified voltage range. An input range of +/-1.3 will scale to a value of +/-1 in the wave file. For greater input voltages the values in the wave file is limited to +/-1. The wave file values can be interpreted to give the corresponding input voltage to the Rion according to the following formula:

$$Input\ voltage = wavefile\ value \times 1.3 \times voltage\ range$$

6.2 Data Extraction from wave file

Measured accelerations due to subway and train-induced vibrations had been acquired through RION DA20. It stores measured data on a memory card (CF card) in wave file format. This data can be extracted in MATLAB using the command as below:

```
[y, Fs] = wavread(filename, [N1 N2])
```

where, *y* is the measured data, *Fs* is the sampling rate of the stored data, *filename* is the name of file for wave file format data, *N1* and *N2* is the start and end point of the samples from each channels of the file. Thus the measured data and its sampling rate can be obtained through the file in WAV format.

6.3 Data Processing and Peak hold analysis

The extracted data *y* needs to be converted to measured acceleration. It can be done as follow:

$$\text{Acceleration}\left(A\right) = \frac{1.3 \times \text{measured data } \left(\text{y}\right) \times \text{selected range of RION}}{\text{Accelerometer sensitivity}}$$

Train pass by events are transient events. That is why measured acceleration (A) is now processed considering segment of 1 second at a time and updating the peak value at each frequency. This method is termed as peak hold spectrum. MATLAB routine “time2freq” has been used for the conversion of acceleration in time domain to velocity in frequency domain in VdB scale as below:

```
%% Program to convert time domain signal to frequency domain
% function [vel f] =time2freq(x,N,Fs,g,vref)

% The input parameters are:
% o  x is the signal in time domain
% o  N is the window size
% o  Fs is the sampling frequency
% o  g is the acceleration due to gravity
% o  vref is the reference velocity as recommended by FTA 2006

% The ouput parameters are:
% o  vel is the output in velocity
% o  f is the frequency

function [vel f]=time2freq(x,N,Fs,g,vref)
    df=Fs/N;

    vref=10^-6; %in/s2 reference velocity
    y=buffer(x,N,N/2,'nodelay'); % This divides x into small samples
                                   and overlaps the segment
    Ncolumn=size(y,2);
    for i=1:Ncolumn
        df=Fs/N;
        [Pxx,f]=pwelch(y(:,i),hanning(N),0,N,Fs);

        vel1(:,i)=20*log10(abs((((2*Pxx*df).^0.5)./(sqrt(-
        1)*2*pi*f))*g/vref)); % conversion to velocity in dB scale
    end

vel=max(vel1,[],2); % Peak hold Velocity

end
```

6.4 One-third octave frequency band

FTA (2006) recommends one-third octave band frequency spectrum to represent the detailed analysis of building response and performance of vibration mitigation methods. In one-third octave band representation, energy associated with each one-third octave band is summed and assigned to corresponding central frequency of each band. The velocity levels obtained in VdB scale is further converted in 1/3rd Octave band representation as below:

```
% function [one_third_freq,band] = onethirdoctave(frequencies,measurements)

% The input parameters are:
% o frequencies: frequency values (with a fixed of variable frequency step),
% o measurements: VdB values (corresponding to the frequency vector defined
% above).
%
% The output parameters are:
% o one_third_freq: center frequencies of 1/3 octave bands,
% o bands: VdB values in 1/3 bands

function [one_third_freq_preferred,bands] =
onethirdoctave(frequencies,measurements)

  one_third_freq_preferred = [16 20 25  31.5 40 50 63 80 100 125 160 200 250
...
                    315 400 500 630 800 1000 1250 1600 2000 2500 ...
                    3150 4000 5000 6300 8000 10000 12500 16000 20000];
  % Determine lower and upper limits of each 1/3 octave band
  one_third_freq = zeros(1,length(one_third_freq_preferred));
  one_third_bands = zeros(2,length(one_third_freq_preferred));
  for a = 1:length(one_third_freq_preferred),
    one_third_freq(a)  = (1000*((2^(1/3)))^(a-19));
    one_third_bands(1,a) = one_third_freq(a)/2^(1/6);
    one_third_bands(2,a) = one_third_freq(a)*2^(1/6);
  end

  % Converting input VdB values to energy values
   measurements=((10^-6)^2)*10.^(measurements/10); % Energy at each frequency
  % Compute Energy associated with each central frequency of 1/3 octave band
  for a = 1:size(one_third_bands,2),
    bands(a) = 0;
    idx = find( frequencies >= one_third_bands(1,a) ...
        & frequencies < one_third_bands(2,a) );
    % If we have no 'measurement' point in this band:
    if ( length(idx) == 0 )
      fprintf('Warning: no point found in band centered at
%4.0f\n',one_third_freq(a));
    % If we have only 1 'measurement' point in this band:
    elseif ( length(idx) == 1 )
      fprintf('Warning: only one point found in band centered at
%4.0f\n',one_third_freq(a));
      bands(a) = measurements(idx);
    % If we have more than 1 'measurement' point in this band:
    elseif ( length(idx) > 1 )
      for b = 1:length(idx)-1,
        bands(a) = bands(a)+ measurements(idx(b));% summation of energies
```

```
      end
      % Convert energy values back to VdB values
      bands(a) = 20*log10(sqrt(bands(a))/10^-6);
    end
  end
end
```

CHAPTER 7 SUPPLEMENTS TO TRAIN AND SUBWAY MEASUREMENT SETUP

7.1 Measurement data in Medford, MA

Test Setup A: Tri-axial accelerometer inside the building & Single Vertical accelerometer outside the building near the track

Measurement Location: G900 Textile Lab, Basement (Tri-axial) & Single Vertical (outside)

Table 7.1.1. Setup A: Accelerometers information, Medford

Label	**1**	**2**	**3**	**4**
Accelerometer	2353	2354	4026	2428
Sensitivity [V/g]	10.01	10.25	10.20	9.90
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Range [V]	1	1	1	3
RION Channel	2	1	3	4

Table 7.1.2. Setup A: Train data, Medford

Train No.	Type	Speed (km/h)	Direction	Track
1	Commuter	65	WM→NS	Near
2	Commuter	76	NS→WM	Far
3	Commuter	74	WM→NS	Near
4	Cargo	42	NS→WM	Near
5	Commuter	70	NS→WM	Far
6	Commuter	68	NS→WM	Far

NS: North Station and WM: West Medford

Test Setup B: Tri-axial accelerometer away from the track & Single Vertical accelerometer near the track, in open field

Measurement Location: Tri-axial far from track & Single Vertical near the track (Both outside)

Table 7.1.3. Setup B: Accelerometers information, Medford

Label	**1**	**2**	**3**	**4**
Accelerometer	2353	2354	4026	2428
Sensitivity [V/g]	10.01	10.25	10.20	9.90
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Range Amb. [V]	0.01	0.01	0.01	0.01
RION Range Train [V]	1	1	1	3
RION Channel	2	1	3	4

Table 7.1.4. Setup B: Train data, Medford

Train No.	Type	Speed (km/h)	Direction	Track
1	Commuter	69	WM→NS	Near
2	Commuter	75	NS→WM	Far
3	Commuter	71	WM→NS	Near
4	Commuter	69	NS→WM	Far
5	Commuter	64	WM→NS	Near

Test Setup C: Array of 6 vertical accelerometers

Measurement Location: Nearness to track is in this order: (Nearest) 4-5-6-A1-2-A2 (Farthest)

Table 7.1.5. Setup C: Accelerometers information, Medford

Label	**4**	**5**	**6**	**A1**	**2**	**A2**
Accelerometer	2428	2420	4091	2554	2354	3886
Sensitivity [V/g]	9.9	9.83	10.4	9.99	10.25	10.3
Location	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
RION Range Amb. [V]	0.01	0.01	0.01	0.01	0.01	0.01
RION Range Train [V]	3	3	3/1	1	1	1
RION Channel	J4	G1	G2	G3	J1	G4

Table 7.1.6. Setup C: Train data, Medford

Train No.	Type	Speed (km/h)	Direction	Track
1	Commuter	69	WM→NS	Near
2	Commuter	75	NS→WM	Far
3	Commuter	71	WM→NS	Near
4	Commuter	69	NS→WM	Far
5	Commuter	64	WM→NS	Near

7.2 Measurement data in Somerville, MA

Test Setup A: Tri-axial accelerometer inside the building & Single Vertical accelerometer outside the building near the track

Measurement Location: Garage, Basement (Tri-axial) & Single Vertical (outside)

Table 7.2.1. Setup A: Accelerometer information, Somerville

Label	**1**	**2**	**3**	**4**
Accelerometer	2353	2354	4026	2428
Sensitivity [V/g]	10.01	10.25	10.20	9.90
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Range Amb. [V]	0.01	0.01	0.01	0.01
RION Range Train [V]	0.3	0.3/1	0.3	0.3
RION Channel	2	1	3	4

Table 7.2.2. Setup A: Train data, Somerville

Train No.	Type	Speed (km/h)	Direction	Track
1	Commuter	72	NS→WM	Near
2	Commuter	89	WM→NS	Near
3	Cargo	24	NS→WM	Far
4	Commuter	85	WM→NS	Near
5	Commuter	76	NS→WM	Near
6	Commuter	96	WM→NS	Far

Test Setup B: Tri-axial accelerometer away from the track & Single Vertical accelerometer near the track, in open field

Measurement Location: Tri-axial far from track & Single Vertical near the track (Both outside)

Table 7.2.3. Setup B: Accelerometer information, Somerville

Label	**5**	**6**	**A1**	**A2**
Accelerometer	2420	4091	2554	3886
Sensitivity [V/g]	9.83	10.4	9.99	10.3
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Range Amb. [V]	0.01	0.01	0.01	0.01
RION Range Train [V]	1	1	1	3
RION Channel	2	1	3	4

Table 7.2.4. Setup B: Train data, Somerville

Train No.	Type	Speed (km/h)	Direction	Track
1	Commuter	72	NS→WM	Near
2	Commuter	89	WM→NS	Near
3	Cargo	24	NS→WM	Far
4	Commuter	85	WM→NS	Near
5	Commuter	76	NS→WM	Near
6	Commuter	96	WM→NS	Far

Test Setup C: Array of 7 vertical accelerometers

Measurement Location: Nearness to track is in this order: (Nearest) 4-5-6-A1-2-A2 (Farthest)

Table 7.2.5. Setup C: Accelerometers information, Somerville

Label	**A1**	**2**	**3**	**4**	**1**	**5**	**6**
Accelerometer	2554	2354	4026	2428	2353	2420	4091
Sensitivity [V/g]	9.99	10.25	10.20	9.90	10.01	9.83	10.4
Location	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
RION Range Amb. [V]	0.01	0.01	0.01	0.01	0.01	0.01	0.01

RION Range Train [V]	1	1	0.3	0.3	0.3	1	3/1
RION Channel	J4	J3	J2	J1	G3	G2	G1

Table 7.2.6. Setup C: Train data, Somerville

Train No.	Type	Speed (km/h)	Direction	Track
1	Commuter	81	NS→WM	Near
2	Commuter	69	NS→WM	Near
3	Commuter	76	NS→WM	Near
4	Commuter	93	WM→NS	Near
5	Commuter	78	NS→WM	Near
6	Commuter	94	WM→NS	Far

7.3 Measurement data in MIT-Cambridge, MA

Test Setup A: Tri-axial accelerometer inside the building & Single Vertical accelerometer outside the building near the track

Measurement Location: Storage Room, First Floor (Tri-axial) & Single Vertical (outside)

Table 7.3.1. Setup A: Accelerometers information, MIT-Cambridge

Label	**1**	**2**	**3**	**4**
Accelerometer	2353	2354	4026	2428
Sensitivity [V/g]	10.01	10.25	10.20	9.90
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Range [V]	0.3	0.3	10	1
RION Channel	2	1	3	4

Table 7.3.2. Setup A: Train data, MIT-Cambridge

Train No.	Type	Speed (km/h)
1	Cargo	53-37

7.4 Measurement data in Boston, MA

Test Setup A: Tri-axial accelerometer inside the building & Single Vertical accelerometer outside the building near the track

Measurement Location: Lobby, First floor (Tri-axial) & Single Vertical (outside)

Table 7.4.1. Setup A: Accelerometers information, Boston

Label	**1**	**2**	**3**	**4**
Accelerometer	2353	2354	4026	2428
Sensitivity [V/g]	10.01	10.25	10.20	9.90
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Range [V]	0.3	0.3	0.3	0.3
RION Channel	2	1	3	4

Test Setup B: Tri-axial accelerometer in open field on asphalt & Single Vertical accelerometer near the track in open field

Table 7.4.2. Setup B: Accelerometers information, Boston

Label	**2**	**1**	**3**	**A-4**
Accelerometer	2354	2353	4026	2984
Sensitivity [V/g]	10.25	10.01	10.20	10.17
Location	Triaxial-Vertical	Triaxial-Longitudinal	Triaxial-Transverse	Single-Vertical
RION Range Amb. [V]	0.01	0.01	0.01	0.1
RION Range [V]	0.1	0.1	0.1	0.1
RION Channel	1	2	3	4

Test Setup C: Tri-axial accelerometer inside MBTA station

Table 7.4.3. Setup C: Accelerometers information, Boston

Label	**6**	**5**	**4**
Accelerometer	4091	2420	2428

Sensitivity [V/g]	10.4	9.83	9.90
Location	Tri-axial Vertical	Tri-axial Longitudinal	Tri-axial Transverse
RION Range Amb. [V]	0.03	0.03	0.03
RION Range Train [V]	3	1	1
RION Channel	1	2	3

Table 7.4.4. Setup C: Train data, Boston

Train No.	Speed (km/h)	Direction	Track
1	43	SC→FH	Far
2	44	FH→SC	Near
3	39	SC→FH	Far
4	43	FH→SC	Near
5	49	SC→FH	Far
6	48	FH→SC	Near
7	36	SC→FH	Far
8	53	FH→SC	Near
9	39	SC→FH	Far
10	43	FH→SC	Near
11	34	SC→FH	Far
12	49	FH→SC	Near
13	34	SC→FH	Far
14	43	FH→SC	Near
15	36	SC→FH	Far
16	42	FH→SC	Near
17	35	SC→FH	Far
18	35	FH→SC	Near
19	29	SC→FH	Far
20	41	FH→SC	Near
21	28	SC→FH	Far
22	44	FH→SC	Near
23	33	SC→FH	Far
24	44	FH→SC	Near
25	35	SC→FH	Far
26	43	FH→SC	Near
27	31	SC→FH	Far
28	43	FH→SC	Near
29	35	SC→FH	Far

30	41	FH→SC	Near
31	36	SC→FH	Far
32	44	FH→SC	Near
33	35	SC→FH	Far

SC: South Cove and FH: Forest Hill

7.5 Measurement data in Cambridge, MA

Test Setup A: Tri-axial accelerometer inside the building & Single Vertical accelerometer outside the building near the track

Measurement Location: Steam Room, First floor (Tri-axial) & Single Vertical (outside)

Table 7.5.1. Setup A: Accelerometers information, Cambridge

Label	**1**	**2**	**3**	**4**
Accelerometer	2353	2354	4026	2428
Sensitivity [V/g]	10.01	10.25	10.20	9.90
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Amb. Range [V]	0.1	0.1	0.1	0.1
RION Train. Range [V]	0.1	0.1	0.1	0.3
RION Channel	2	1	3	4

Test Setup B: Tri-axial accelerometer away from the track & Single Vertical accelerometer near the track, in open field

Measurement Location: Tri-axial far from track & Single Vertical near the track outside

Table 7.5.2. Setup B: Accelerometers information, Cambridge

Label	**5**	**6**	**A-1**	**A-2**
Accelerometer	2420	4091	2554	3886
Sensitivity [V/g]	9.83	10.4	9.99	10.3
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Amb. Range [V]	0.03	0.03	0.03	0.03
RION Range [V]	0.1	0.1	0.1	0.3
RION Channel	2	1	3	4

Test Setup C: Array of 8 vertical accelerometers

Measurement Location: Nearness to track is in this order: (Nearest) 6-5-A1-A2-4-3-2-1(Farthest)

Table 7.5.3. Setup C: Accelerometers information, Cambridge

Label	**1**	**2**	**3**	**4**	**5**	**6**	**A-1**	**A-2**
Accelerometer	2353	2354	4026	2428	2420	4091	2554	3886
Sensitivity [V/g]	10.01	10.25	10.20	9.90	9.83	10.4	9.99	10.3
Location	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
RION Range Amb. [V]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
RION Range Train [V]	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3
RION Channel	J4	J3	J2	J1	G2	G1	G3	G4

Test Setup D: Tri-axial accelerometer nearest to the track and vertical array of 5 accelerometers

Table 7.5.4. Setup D: Accelerometers information, Cambridge

Label	**1**	**2**	**3**	**4**	**5**	**6**	**A-1**	**A-2**
Accelerometer	2353	2354	4026	2428	2420	4091	2554	3886
Sensitivity [V/g]	10.01	10.25	10.20	9.90	9.83	10.4	9.99	10.3
Location	S_V5	S_V4	S_V3	S_V2	T_L	T_V	T_T	S_V1
RION Range Amb. [V]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
RION Range Train [V]	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3
RION Channel	J4	J3	J2	J1	G2	G1	G3	G4

7.6 Measurement data in Jamaica Plain, MA

Test Setup A: Tri-axial accelerometer inside the building & Single Vertical accelerometer outside the building near the track

Measurement Location: Lobby, First floor (Tri-axial) & Single Vertical (outside)

Table 7.6.1. Setup A: Accelerometers information, Jamaica Plain

Label	1	2	3	4
Accelerometer	2353	2354	4026	2428
Sensitivity [V/g]	10.01	10.25	10.20	9.90
Location	Triaxial-Long.	Triaxial-Vertical	Triaxial-Trans.	Single-Vertical
RION Amb Range [V]	0.01	0.01	0.01	0.01
RION Train Range [V]	0.3	1	0.3	1
RION Channel	2	1	3	4

Test Setup B: Tri-axial accelerometer inside the garage & Single Vertical accelerometer near the track, in open field

Measurement Location: Tri-axial far from track, inside the garage & Single Vertical near the track outside

Table 7.6.2. Setup B: Accelerometers information, Jamaica Plain

Label	5	6	A-1	A-2
Accelerometer	2420	4091	2554	3886
Sensitivity [V/g]	9.83	10.4	9.99	10.3
Location	Triaxial-Longitudinal	Triaxial-Vertical	Triaxial-Transverse	Single-Vertical
RION Amb Range [V]	0.01	0.01	0.01	0.01
RION Train Range [V]	0.3	0.3	0.3	1
RION Channel	2	1	3	4

Test Setup C: Array of 7 vertical accelerometers

Measurement Location: Nearness to track is in this order: (Nearest) 4-3-2-1(Farthest)

Table 7.6.3. Setup C: Accelerometers information, Jamaica Plain

Label	4	3	A-2	2	1	5	6
Accelerometer	2428	4026	3886	2354	2353	2420	4091
Sensitivity	9.90	10.20	10.3	10.25	10.01	9.83	10.4

[V/g]							
Location	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
RION Range Amb. [V]	0.01	0.01	0.01	0.01	0.01	0.01	0.01
RION Range Train [V]	0.3/1	0.3	0.3	0.3	0.3	0.3	0.3
RION Channel	J1	J2	J3	J4	G1	G2	G3

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