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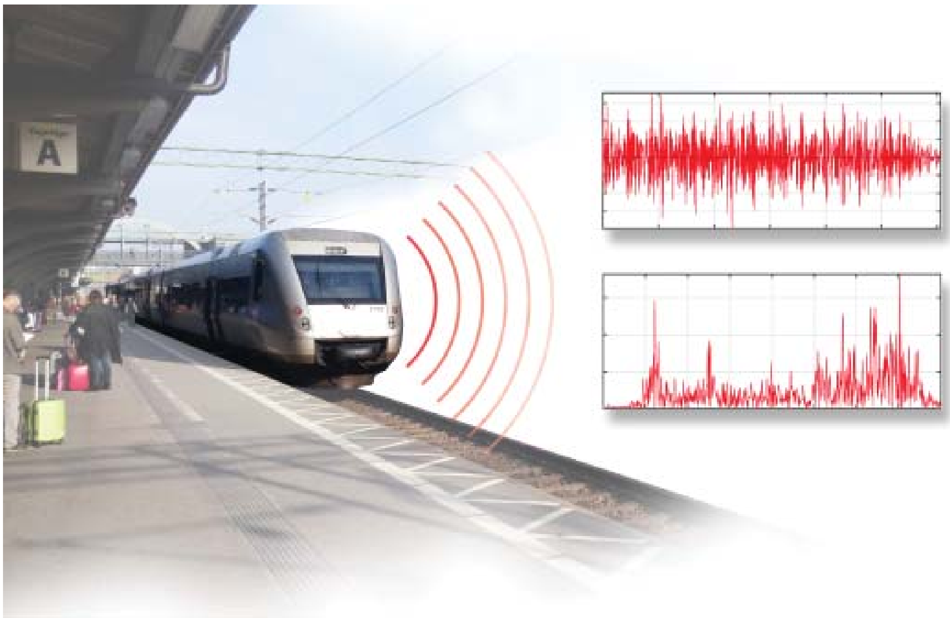

EXPERIMENTAL INVESTIGATION OF STRUCTURE-BORNE NOISE INDUCED BY RAILWAY TRAFFIC IN A MULTI-STOREY BUILDING

ADAM CEDERQUIST

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MASTER'S DISSERTATION

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Abstract

One of the modern cities environment issues is noise and vibration created by train traffic, especially since cities today strive towards being more dense. Urbanization leads to new areas built with pre existing railway tracks. This puts a lot of pressure on the structures built on those areas regarding vibrations. Heavy concrete buildings are more resilient against vibrations than light-weight structures, that are becoming more and more popular. More knowledge is needed to create buildings that is resistant towards vibrations and noise.

The main objective in this report is first of, to get a better understanding of how vibration impact the inhabitants of structures. This through evaluating a building in Helsingborgs Campus which is known to be exposed to vibration caused by trains. The evaluation is executed by doing measurements using seismometer and sonometers placed on different positions in the vicinity of the building. The seismometers used are omni-directional where the train direction are named north, second horizontal direction named east and lastly the normal direction, named normal. The measurements were executed simultaneously to properly be able to evaluate the data.

The evaluation of the result shows that the type of train definitely has an impact on the vibration levels. Also the speed is of great importance, although it does not impact the normal direction for unknown reasons. The highest amplitudes measured is always in the normal direction within the building which is a expected result due the measurements are executed on floors. The result in every measurement position follows the same pattern where the highest amplitude is the in normal direction, followed by the east and lastly the north direction not counting the measurement position close to the facade. This may be due to stabilization from the concrete wall.

Sammanfattning

En av det moderna samhällets städers miljöproblem är oljud och vibrationer skapat av tågtrafik. Detta speciellt sedan dagens städer strävar efter en mer och mer tät innerstad. Dagens urbaniseringen leder till att nya områden skapas där förr tågrälsen ensamt ringlade fram. Detta ställer högre krav på dagens byggnader med hänsyn till vibrationer. Robusta betongbyggnader är mer beständiga mot vibrationer än lätta träbyggnationer, som blir allt mer populära. Mer kunskap om området är därför en nödvändighet för att skapa byggnader som är beständiga mot vibrationer.

Huvudsyftet med rapporten är att först och främst få en större förståelse för hur vibrationer från tåg påverkar byggnaders stomljud. Detta genom att utvärdera en byggnad i Helsingborgs Campus var det sägs att vibrationer kan kännas när tågen mullrar förbi utanför. Utvärderingen genomförs genom mätningar med seismometerar och sonometrar som placeras ut i byggnaden. Seismometerna mäter i tre riktiningar benämnt nordlig, östlig och den normala riktningen vilket nordlig riktning är den riktning tågen färdas i. Det är viktigt att mätdatan är synkroniserad för att kunna göra en noggrann utvärdering.

Utvärderingen av resultatet visar att tågtypen spelar roll m.h.t vibrationsnivåerna. Även hastigheten är viktig, dock inte i normal riktningen som är opåverkad av okänd anledning. De största uppmätta amplituderna i byggnaden är normalen vilket är ett väntat resultat eftersom mätningarna på våningsplan utförs på bjälklagen vilka naturligt tenderar att röra sig mer i normala riktningen. Alla mätpunkterna följer samma mönster där normalen har störst amplitud följt av östligt och sist nordlig riktning förutom mätpunkten nära fasaden. Detta kan ha att göra med stabiliseringen som väggen ger.

Acknowledgements

This master thesis was written for the faculty of acoustic, LTH. It was carried out during 5 months, 30 hp and is the last part of the Civil engineering program. I've got a lot of help to write this report and would like to give a special thanks to the persons helping me.

I would like to give a special thanks to one of my supervisors Juan Negreira which helped me a lot during this period. I would also like to thank Peter Person for all the help. Also Peter Johnsson for learning me the equipment along with Brian Norsk Jensen for letting me borrow the equipment. I'm also thankful for the help and knowledge of which Sigmund Olafsen and Nils Persson could provide.

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Contents

Chapter 1

Introduction

1.1 Background

Lately more and more people tend to move to cities and this is an ongoing trend [1]. Cities grow not only in size but tend to densify. This requires sometimes that unbuilt land is committed for building purposes. The latter makes that buildings are often erected near transportation hubs. The public transportation gets more advanced and efficient. However. the latter brings alongside noise and vibration transportation related problem and such challenges must be addressed if vibroacoustic comfort in dwellings is to be achieved. Noise exposure is, according to the World Health Organisation (WHO), the second largest environmental cause of health problem (just after the impact of air quality) and should therefore be kept in mind when designing and constructing [2].

But it is not only existing structures that is affected. Previously rural areas where only highways and railways tracks pathed through the empty landscape are now shifting into urban areas. These built tracks are more complex to modify which now puts extra pressure on the new structures built nearby the tracks. Public transportation is a must for the districts on the edge of the cities and the closer to a hub the facility is the more attractive it is. A facility in the design phase is easier to modify than an existing track, since the earlier in the process the vulnerabilities are counter measured, the better. Therefore a greater understanding of how the noise is created and transmitted by the trains and what measures to take is of great interest.

1.2 Objective and method

The goal of the master thesis is to gain a greater understanding on how train induced vibrations affect buildings and their occupants. This was done by developing and evaluating an adequate measuring method well suited for a multi-storey building in Campus Helsingborg built in the vicinity of a railway track and subjected to high levels of structure-borne noise at certain locations. The influence of the train type, rolling speed, et al, was investigated thoroughly by using the measurement method developed.

To get a better basis, fundamental vibroacoustic theory is studied along with how it can affect humans. Similar projects will be studied in a literature review to create a greater understanding on possible reduction methods. Different types of reduction methods describing how to deal with the noise created by trains are listed. The following research questions are adressed in the thesis.

- How should the measurement procedure be designed to give adequate results?
- What are the main factors affecting the vibroacoustic comfort in the building?
- What conclusions can be drawn by the result?

1.3 Limitations

The primary focus of the master thesis was to carry out measurements in a building were vibration issues were orally reported by some co-workers (from railway traffic). Evaluating one building narrowed the study to factors affecting that particular building. No comparison in between different building materials can be executed since just one building was evaluated. Only the last storey of the building was studied, not the intermediate ones since, this was the one where vibrations were reported. The literature study includes different measures to take but does not put any emphasis on practically testing them. It can be hard to tell how measures will affect the building in reality and how effective they are with no real testing site.

1.4 Outline

The report is structured as follows:

- **Chapter 2**: Contains background in acoustics which describes fundamental theory of sound. The difference between airborne sound and structure-borne sound is discussed along with wave propagation in the ground. Some notes on how sound affect humans is also presented.

- **Chapter 3**: A literature study of similar projects are included in the thesis to study different measurement techniques and how to reduce the vibration levels in dwellings in different ends of the transmission path.

- **Chapter 4**: Details the measurement technique employed, the sensors placement as well as several concepts about signal processing that were used in the measurement campaign.

- **Chapter 5**: The collected data is presented from the measurements in Helsingborg in different ways and compared in different aspects, such as speed and train type.

- **Chapter 6**: The results from chapter 5 is discussed and possible sources of error are stated. Suggestions for further research can be found in the end of the chapter.

Chapter 2

Theory of sound and vibration

The main focus in this thesis will be on vibrations created by trains. This chapter contains a theoretical background about fundamental acoustics, vibration transmission, wave propagation and also about human perception of sound and vibrations. The idea is to provide the reader with knowledge needed in order to be able to follow what has been performed though the course of this project.

Vibration transmission can be divided into three sub-parts, the noise source, the medium and the receiver which each will be gone through, seen in Figure 2.1.

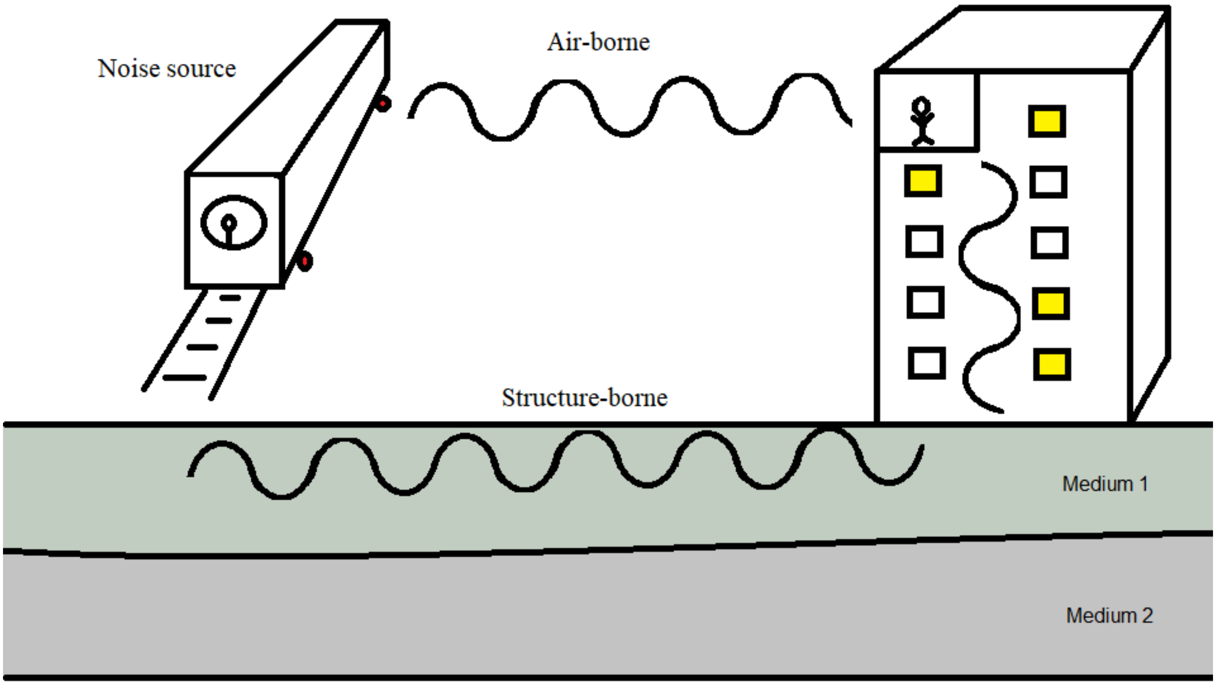


Figure 2.1: Visualization of vibration transmission.

- The source which can be either outdoors or indorrs, which noise and vibration created by trains will be the main focus in this master thesis.
- The medium in which vibrations travel can either be the ground outside of a building or the slab of a buildings foundation. On longer distances the waves travel down through the soil to the bedrock, with a lower attenuation.
- The receiver in this case is a building, which with its occupants with a threshold of annoyance.

2.1 Fundamentals of sound and vibration

It is important to know the basics of acoustic to fully understand this thesis. This section will focus on just this.

2.1.1 Waves

Both sound and vibrations is defined as mechanical vibrations travelling through a fluid and a solid medium, respectively. The limit between both domains is hard to establish, as it is complex problem. In board strokes, sound is what is heard whereas vibrations are oscillations that is perceived as movement in our body.

Basics

The simplest representation of a wave is a harmonic wave, which can be seen in Figure 2.2. It has the period T, the frequency f and a time dependent amplitude of sin$(\frac{2}{\pi \cdot T} \cdot t)$.

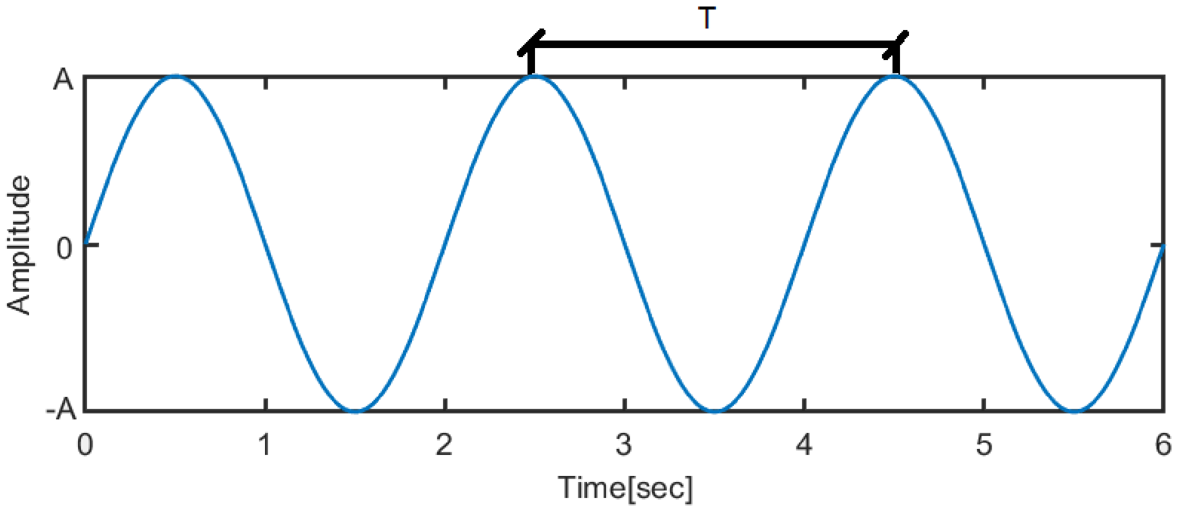


Figure 2.2: A harmonic sound wave illustrating the wavelength, frequency and amplitude

The frequency has the unit Hertz where the relation between wavelength and frequency can be seen in Equation 2.1.

$$f = \frac{1}{T} \tag{2.1}$$

in which:
f is the frequency in Hertz,
T is the period in seconds.

The relation between velocity, wavelength and frequency are shown in Equation 2.2 and is commonly used in acoustics.

$$\lambda = \frac{c}{f} \tag{2.2}$$

in which:
λ is the wavelength in m,
c is the velocity in m/s,
f is the frequency in 1/s.

Time Domain and frequency domain

The previous section explained a harmonic wave comprised just one frequency (i.e. it is called a tone). In reality, when common sound/noise and or vibrations occur, they contain a lot of frequencies. Therefore, when analysing structures and/or when we want to analyse how those signals affect people, it is useful to know which frequency components they contain. To that end, and algorithm called Fast Fourier Transformation (FFT) is used. This mathematical tool allows us to decompose any periodict time singal, as an infinite sum of simple harmonic signals (sinus and cosinus). Thus, a signal can be looked at from two different angles. The time and frequency domain c.f. Figure 2.3.

Figure 2.4 shows three different signals and how a combination of two creates a new more complex signal. The last part of the figure shows a Fast Fourier Transformation, FFT, executed on the third time signal, in order to see the frequency content of the time signal. The FFT used in this master thesis can be found in appendix. An Inverse Fast Fourier Transformation, IFFT can be used if one want to go from the frequency domain to the time domain.

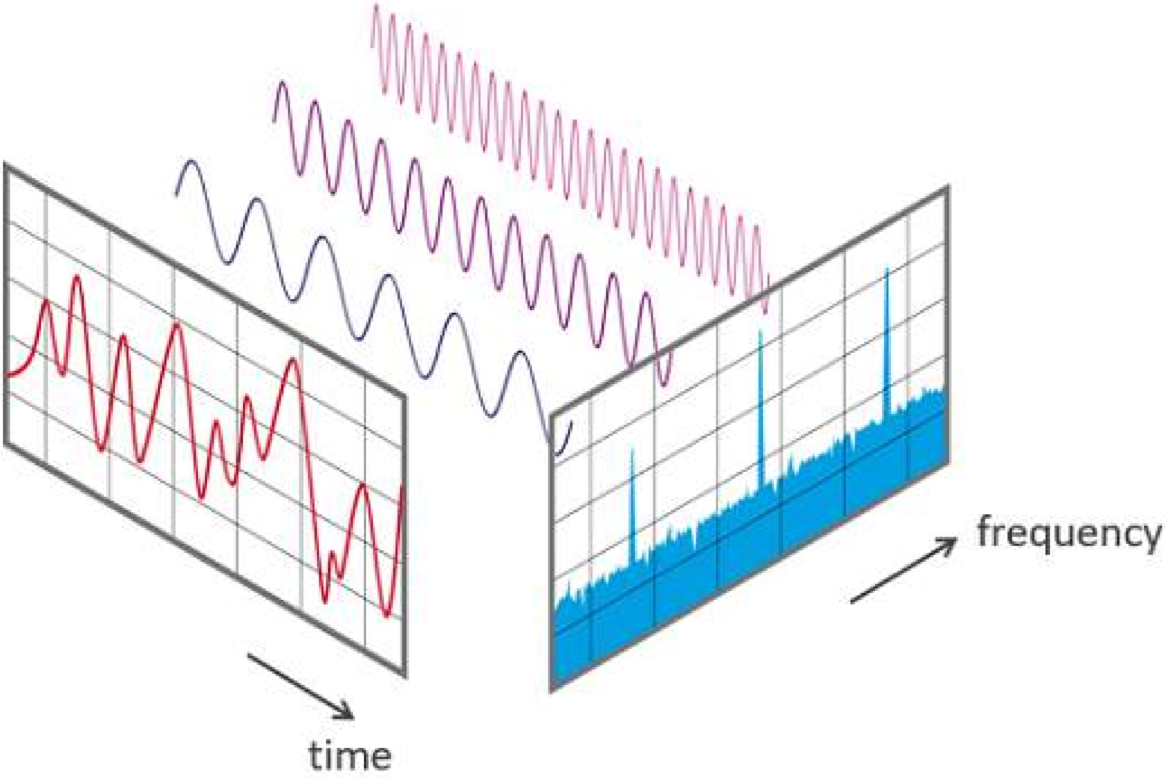


Figure 2.3: A picture illustrating a time singal in the time and frequency domain [3]

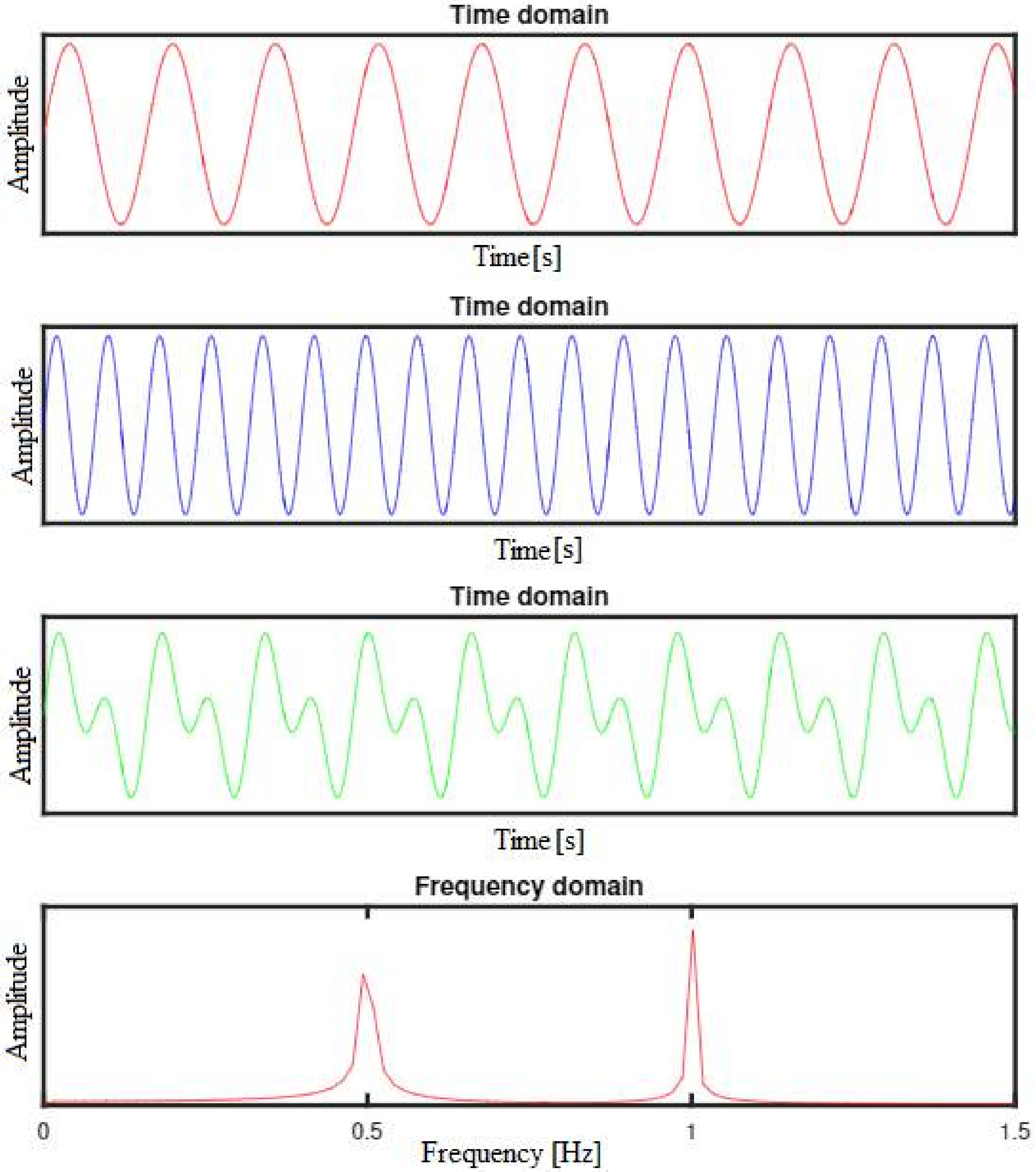


Figure 2.4: An example of different signals in time domain and frequency domain

RMS

The root mean square, RMS, is a quantity used to compare time varying and frequency domain singals in between each other. The objective with the quantity is to transform a varying time signal/ frequency domain into a single, representative value, to more easy compare it to other ones. The RMS can be used on different quantities such as displacements, sound pressure and acceleration. How to calculate the RMS in the time domain can be seen in Equation 2.3.

$$P_{RMS} = \sqrt{\frac{1}{T} \int_{\Delta t}^{T+\Delta t} p^2(t)dt} \tag{2.3}$$

in which:
T is the required time interval in seconds,
p(t) is the time signal, time dependant,

How to calculate the RMS in frequency domain can be seen in equation 2.4

$$X_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} X(f)_i^2} \tag{2.4}$$

in which:
X(f) is the magnitude of the function X at each frequency,
N is the number of frequencies of X,

In this master thesis, the RMS values were used in order to compare signals from different trains.

Sound quantities

Sound, defined as oscillation of air particles creating a pressure wave is often measured using a microphone in which the sound pressure level, defined by L_p, can be calculated with Equation 2.5.In order to make the pressure units a bit more practical, sound is often expressed in decibels, for which a reference quantity is used (20 μPa) [4]. The latter reference quantity was set to that value because it is approximately the smallest value our hearing spectrum can defect. In broad strokes, 0 dB would be our limit of hearing, whereas the threshold pain would lie somewhere around 120-130 dB. Note that our hearing is frequency sensitive. For more information, see e.g [4].

$$L_p = 10 \log \frac{P_{RMS}^2}{p_0^2} \tag{2.5}$$

in which:
$\mathrm{p_0}$ is a reference value of 20 μPa,
$\mathrm{P_{RMS}}$ is the RMS pressure level,
$\mathrm{L_p}$ is the sound pressure level, in dB.

Leq

Leq represents a value known as equivalent sound pressure level. This since sound pressure level measured changes over time but sometimes a representativ SPL value is required. Therefore a value that produces the same energy over time is needed. Leq,24h is the average sound pressure level over a span of 24h and is a common value.

$$\mathrm{L_{eq}} = 10\log\left(\frac{1}{n}\sum_{i=1}^{n} x \cdot 10^{\frac{Leqi}{10}}\right) \tag{2.6}$$

in which:
$\mathrm{L_{eq}}$ is the measured value for a certain time interval in dB,
x is the measured time for a certain interval,
n is the number of measurements.

Weighting

A weighting is a frequency dependent filter added to the spectrum of sound content. The A-weighting is developed to correlate to how humans perceive sound, indicated as dBA. This is done because our hearing is frequency dependent and for example, in low frequencies humans need a lighter sound pressure level (in general) to be equally affected of higher frequencies. There are other types of frequency weightings such as C-weighting designed for high level aircraft noise and Z-weighting with zero frequency weighting.

Octave bands

When one performs an FFT of a time signal the resolution of the frequency axis can be chosen by the user. However sometimes in acoustics it can be a bit unpractical and time-consuming, since our hearing is not able to distinguish in narrow band(e.g. differences in 1 Hz). To that end, frequencies are grouped in ”boxes” and some sort of ”average” value is assigned to each interval. Depending on the resolution of those ”boxes” we can distinguish between octave bands and third octave bands (standardised in the ISO266). This weighting can be assigned to different intervals. The most common used are the octave, and the third-octave. The different intervals can be calculate using the formula in Equation 2.7.

$$\frac{f_{n+1}}{f_n} = 2^K \tag{2.7}$$

in which:
$\mathrm{f_{n+1}}$ is the cut-off upper frequency,
$\mathrm{f_n}$ is the cut-off upper frequency,
K is either 1 for octave bands and 1/3 for third-octave.

To convert octave bands to the 1/3 octave, Equation 2.8 is used.

$$L_p = 10 \cdot \log(\frac{1}{3}) \tag{2.8}$$

in which:
$\mathrm{L_p}$ is the sound pressure level, in dB.

Convert from 1/3 octave to octave is shown in Equation 2.9

$$L_{oct} = 10 \cdot \log(\sum_{i=1}^{3} 10^{\frac{\mathrm{L_{p,i}}}{10}}) \tag{2.9}$$

in which:
$\mathrm{L_{oct}}$ is the sound pressure level, in dB.

Eigenfrequencies and resonance

Imagine a simply supported beam as in Figure 2.5 when the beam is set into vibrations, there will be some frequencies of which the wavelength is a multiple of the length of the beam. In those cases, standing wave occur as a result of a constructive interference. There will be some points (called nodes) where no vibrations will occur, whereas others where the vibration levels will be very high. This phenomenon is called resonance and the frequencies at which it occur are called eigenfrequencies of the structure. The number of eigenfrequencies for the beam in question has an infinite number of eigen frequencies determined by $\mathrm{L} = \frac{\lambda}{2} \cdot \mathrm{n}$

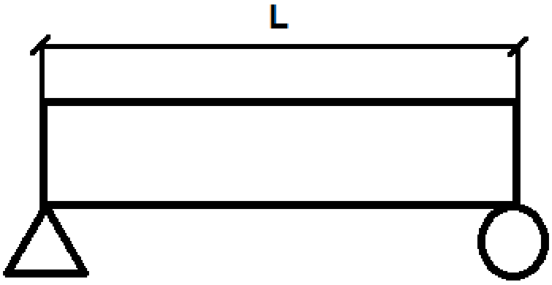


Figure 2.5: A simply supported beam with length L

In reality some form of **damping** is connected to the system makes the vibration vanish with time. This means a system can have a certain eigenfrequency it is extra vulnerable to in which most cases some sort of damping is added to avoid resonance. A system is most often more complex with a number of elements connected. A building has both a foundation, pillars and floor slabs which within themselves has even more elements. The process gets complicated quickly where a frequency analysis could be necessary.

An empty square room has two easy-to-see eigenfrequencies, between top-bottom and between two opposing walls. Furniture in the room acts as damping and could also creates other eigenfrequencies.

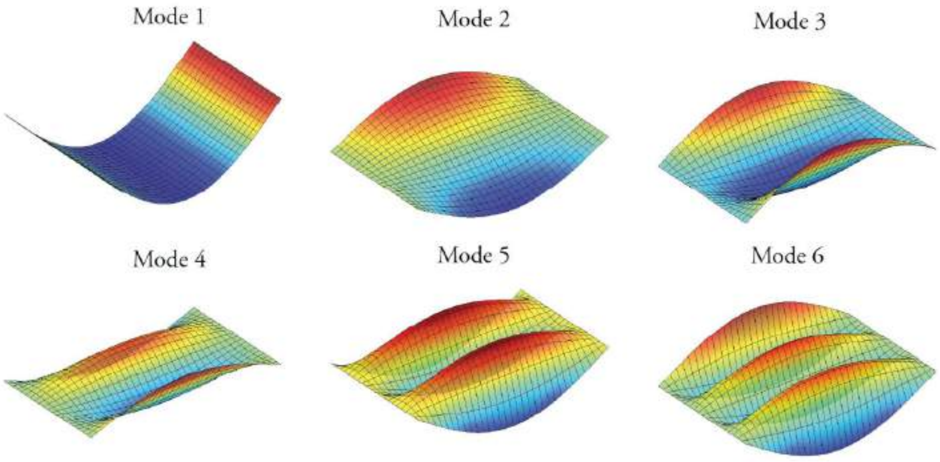


Figure 2.6: The first six eigenfrequencies of a floor, Figure source: [5]

The first mode of a floor in buildings can be seen in Figure 2.6. This mode often occurs many times in different variations just as the beam does.

2.2 Sound transmission

Sound is waves moving through an element. This element could be anything from a fluid to a solid material. The source creating the sound can either be a vibrating body, changing airflow, time-dependant heat source or a supersonic flow.

The vibration can either be transmitted through the air, called airborne or through vibration in solids called structure-borne. This is illustrated in Figure 2.1 in the beginning of this chapter. Measurements most often contain sound from both transmission paths and can be difficult to separate. Although the importance of separating them could be vital, since the measures to take are different [6]. Walls and floors are tested how good they are against airborne sound insulation and impact sound insulation.

2.2.1 Airborne sound

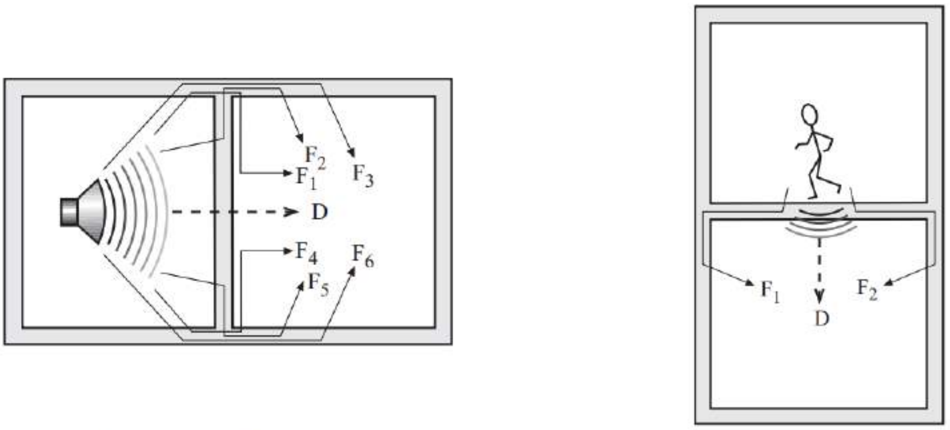
This type of transmission where most of the energy is travelling through air and just a bit through strucutre is called airbborne sound transmission. When the wave hits an element it causes it to radiate and create pressure difference on the other side that propagates and create noise [7]. There are also distance loss present which is vary for different wavelenghts. This means lower frequencies tend to travel longer distances than higher ones [8].

2.2.2 Structure-borne sound

The direct impact of an object striking an element of a structure causing it to vibrate and to generate sound waves through the medium and to its adjacent surfaces is called structure-borne sound. This could be a train generated vibrations travelling through the soil to the building foundation and through the frame to the floors [5]. This thesis will mainly focus on the low frequency content of structure-borne sound.

Trains cause vibrations that are transmitted through the substructure of the railway into the surrounding ground. The vibrations can affect nearby buildings. If they are strong enough they can affect building occupants, but not only from directly feeling the vibrations but through the structure and also from building components becoming audible, called radiated sound.

Both types of sound transmission can be direct and flanking transmission which are illustrated in Figure 2.7. Flanking transmission can be described as when a generated sound travels around the primary element separating two spaces. Sound will always find ”the weakest link” and spread in between spaces.



(a) Airborne sound transmission

(b) Impact sound

Figure 2.7: Visualization of transmission paths where F is flanking and D is direct, Figure source: [5]

When measuring the structure-borne noise the velocity and/or acceleration levels are of interest. The relation between acceleration and velocity is determined using Equation 2.10 [4]. Both velocities and acceleration levels can be measured with the appropiate transducers, as it will be seen in Chapter 4.

$$|a| = \left|\frac{dv}{dt}\right| = \left|\frac{d(\hat{v}\cdot e^{j\omega})}{dt}\right| = |\, j\omega\cdot v| = \omega\cdot|v| \tag{2.10}$$

in which:
a is the acceleration in $\mathrm{m/s^2}$,
v is the speed in m/s,
ω is angle velocity in rad/s.

2.3 Wave propagation

There are plenty of factors influencing the propagation of waves in the ground. The properties of the ground have an influence on how the waves propagate, e.g. damping parameters, on soil type, layering and ground water level. Bedrock exhibits a low level of damping while a marshy soil has a strong damping effect [4].

2.3.1 Wave types

There are two types of waves that occur to the response to dynamic loading , body and surface waves [9]. Those are divided into sub parts cf. Figure 2.8. Body waves travel within the body of the ground with a high velocity in most mediums and therefore the wavelengths are usually very short in comparison to the element producing the waves. The movement of the particles during a body wave is parallel to the direction of the wave [10]. Variations in physical properties such as seismic velocity and density occur both laterally and with depth in the earth. Body waves are divided into compressional waves, referred to as p-waves and s-waves, referred to as secondary-waves. The secondary waves have a perpendicular movement in relation to the direction. This leads to a lower velocity compared to the Body waves, therefore the wavelength is shorter [4].

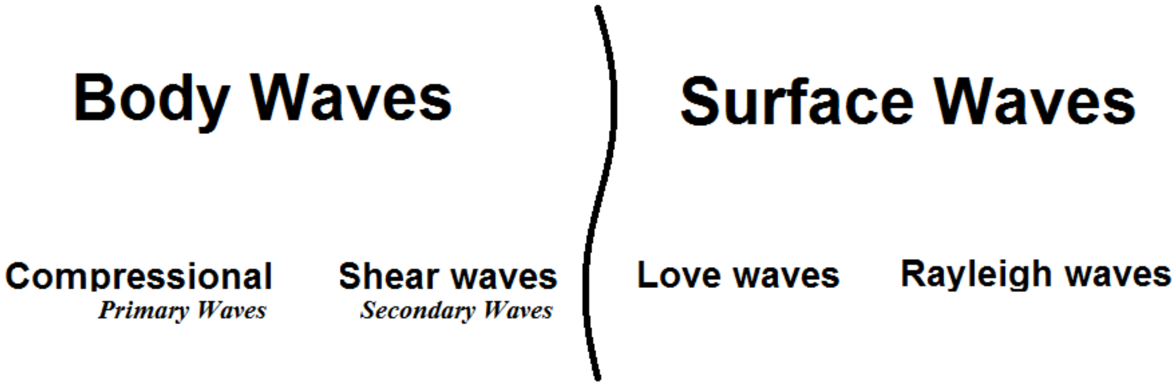


Figure 2.8: visualization of the wave relations

The surface-waves on the other hand, travel on the ground surface. Love and Rayleigh waves are two example of surface-waves. The proportions between surface- and body waves change with increasing depth were the deeper it is the more body waves there are. The surface waves consist on a mix of both of longitudinal and transversal movement and act roughly analogously as waves on water [10, 4, 8].

The primary waves are restrained to a the particle motion in the direction of the wave propagation. However the particles are only able to move in x-direction with no shear stress, although in reality there is always shear stress present [11]. The secondary waves are assumed to be waves of distortion were the volume expansion is zero in which the volume cannot change but the boundaries can. The wave displacement in y-direction varies with time and a scale factor $\sqrt{G/\rho}$ [12, 13].

The velocity of a wave does not have to be the same as the velocity of the particles in the material. Most often the velocity of the wave is called group velocity or bulk velocity [9]. In Equation 2.11 the relationship between velocity and material parameters are shown for the primary waves.

$$c = \sqrt{\frac{E}{\rho}\frac{1+\nu}{(1+\nu)(1-\nu)}} \tag{2.11}$$

in which:
E is Young's modulus in MPa,
c is the velocity in m/s,
ν is the Poisson's ratio,
ρ is the density in $\mathrm{kg/m^3}$.

The velocity of secondary waves are shown in Equation 2.12. An estimation that shear waves have a velocity of 48% of primary waves can often be used as an approximation [11]. Otherwise a more thorough/accurate expression is given by:

$$c = \sqrt{\frac{G}{\rho}} \tag{2.12}$$

in which:
G is Shear modulus in MPa,
ρ is the density in $\mathrm{kg/m^3}$.

The velocity of Rayleigh waves is about 90% of the velocity of shear waves, although the constant changes with properties of the medium [11].

2.3.2 Reflection

When a wave travelling through a medium into another with a set boundary in between, some percent of the energy will be reflected and some will travel forward into the second medium. The reflection coefficient R/R_0 describes how much energy is reflected from the medium.

$$\frac{\mathrm{R}}{\mathrm{R_0}} = \left(\frac{\rho_1 \mathrm{c}_1 - \rho_2 \mathrm{c}_2}{\rho_1 \mathrm{c}_1 + \rho_2 \mathrm{c}_2}\right)^2 \tag{2.13}$$

in which:
R is the reflected energy in joule,
$\mathrm{R_0}$ is the incident energy in joule,
ρ density of each material in $\mathrm{kg/m^3}$,
c is the velocity in m/s.

Equation 2.13 is theory based and defined as two infinite materials with a set boundary in between. If there are any discontinuities the relationship is no longer fulfilled. Therefore, a proper way to find out the actual reflection can be by experiment. In the formula, the impedance is used, which is the wave speed multiplied by the density. The impedance is defined as the resistance of the medium for a wave travel through it [11, 12].

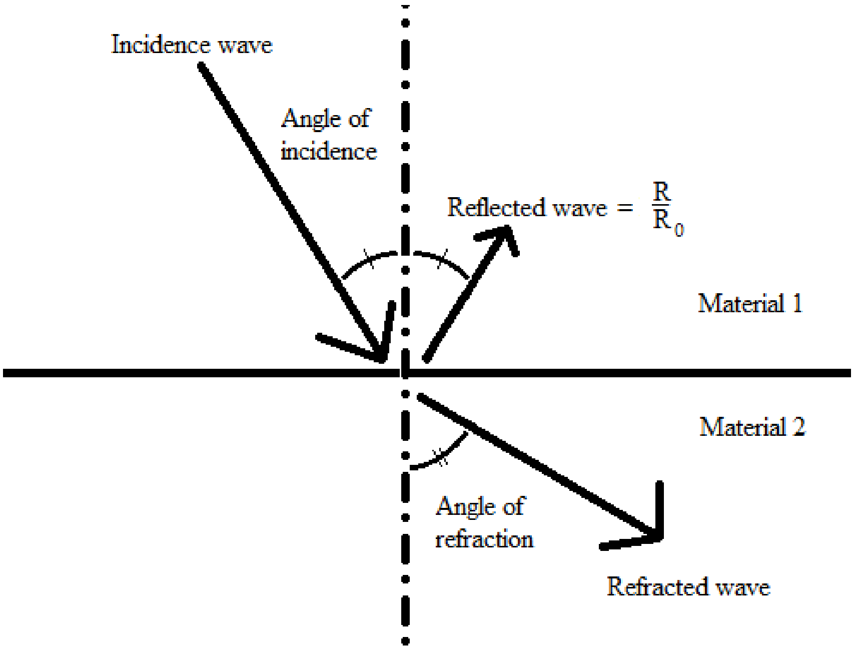


Figure 2.9: An illustration of reflection and refraction of a wave

2.3.3 Refraction

The refraction is the transmitted waves into another medium. The angle of the wave reflecting into a surface is of importance when travelling through mediums. The refracted angle is decided by the velocity of propagation of the sound of the two materials which the sound travel through and also the incidence angle. Equation. 2.14 shows exactly this.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{c_1}{c_2} \tag{2.14}$$

in which:
θ_1 is the angle of incidence,
θ_2 is the angle of refraction,
c_1 is the velocity of the first medium,
c_2 is the velocity of the second medium.

A value of θ_2 greater than 90 leads to fully reflection and appears when the sound travels through a light material into a material were the travel velocity is higher [11].

2.4 Effects of sound & vibrations

In recent years, noise has been recognised as one of our critical environmental pollution problems [2]. Humans are not only affected by the noise within the hearing spectrum but also the span outside of it. Interestingly enough, the noise produced by e.g. a car, is approximately less than 10 ppm of the total power produced by the engine [14].

2.4.1 Human effects

All sources create pressure waves which can be picked up by human hearing [14]. But the hearing spectrum of humans is limited, approximately 16 Hz - 16 kHz. The sounds below 16 Hz are still picked by humans but outside of the perception range of hearing. Not only sound affects human, but also vibration. How railway noise and vibration affects sleep was investigated [15]. With increasing vibration amplitude an increased hearth rate was monitored and had affect on perceived sleep quality. The vibrations and noise also interfere with the normal rhythms of sleep and can cause sleep disturbance.

There are three main reasons how vibrations affect humans. The vibrations perceived as motion of the floor are uncomfortable and give rise to fear of damage to the building. The second reason is somewhat connected to the first. Vibrations in the building lead to sound radiated from the surfaces of the room. This sound has mainly low frequency content and is perceived as disturbing. The last is the vibrations lead to rattling of glass and movement of paintings hanging on the walls [6]. Vibrations from trains contributes to disturbance of sleep and have negative effect on performance and attention span [16].

How a person is disturbed by noise and vibration depends if they are both present at the same time, which is the worst case scenario [17]. The direction of the vibration is also of interest since a standing or laying person is less resilient to different vibrations. A person laying down is more resilient to vertical vibrations than horizontal. Also what type of activity is being performed affects the disturbance level [9]. However, the human exposure to vibration are described more detailed in ISO 2631-1 [18].

Table 2.1: Guidelines for rail-traffic-induced vibrations from *Trafikverket*

Hall type	Equivalent SPL L_{eq24h}	maximum vibration level scaled RMS value
New dwellings	60 dBA	0.4 mm/s
Existing dwellings	65 dBA	1.4 mm/s

Rail-traffic-induced vibrations have guidelines on maximal vibration levels by *Trafikverket*. These levels are recommendations and they depend on if the structure is a new or existing, c.f Table 2.1 [19]. The levels are set in the worst RMS value of the duration of one second with the frequency range 1-80 Hz in acceleration or velocity, unless substantial peaks, discussed in ISO-2631-2 [20].

The Swedish standard SS 460 4861 [21], which is based on ISO 2631-2 [20] describes the guidelines for comfort related assessments c.f. Figure 2.10. The perception threshold starts at 0.4 mm/s and is defined as moderate up to 1 mm/s with a high likeliness above 1 mm/s. The standard depends on various building types, c.f. Figure 2.11

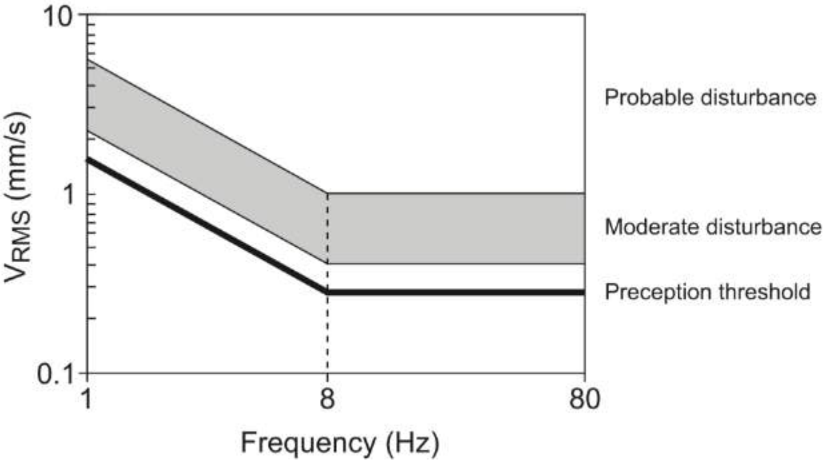


Figure 2.10: Human perception threshold from vibration, Figure source: [9]

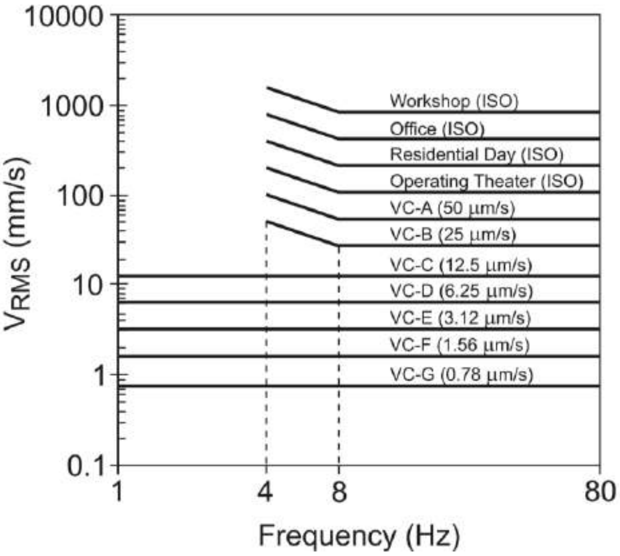


Figure 2.11: VC-curves and ISO guidelines, Figure source: [9]

2.5 Noise sources in buildings

2.5.1 Outdoor sources

The built environment can withstand a lot of different disturbing noise sources. They can either be internal or external sources. Internal are located in the building, which can be people walking, dropping objects, installations like HVAC system and pumps etc. External can be sources from traffic or an industry. In this thesis the main focus are noise created by rail traffic. Noise and vibrations created by railroad traffic are affected by a lot of different factors such as train type, speed, length of the train and number of wagons connected [19].

2.5.2 Indoor sources

Indoor noise sources can be created by industries, such as engines and other loud machines. Engines tend to oscilate and create vibration spread in the building depending on weight and the angular velocity. It is not only engines generate but could be other building occupants which through weaknesses in the structure creates resonances to affect other inhabitants. This thesis puts no real emphasis on those indoor noise sources since the main focus lies on noise created by trains.

Chapter 3

Literature review

This chapter contains information collected from different studies, articles and PhD thesis. The first section discuss how to reduce the noise and vibrations affecting humans. The later sections focus on how to make adequate measurement techniques.

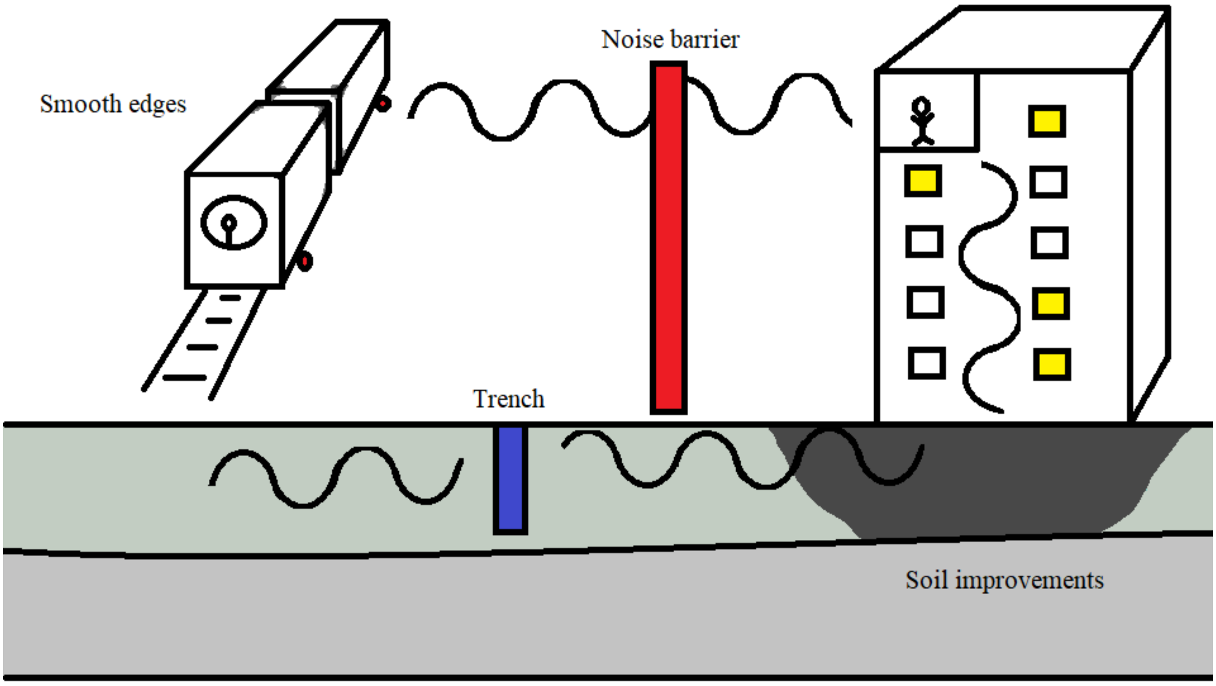


Figure 3.1: visualization of different vibration measures.

3.1 Vibrations reduction measures

There are plenty of ways to reduce the noise and vibrations created by trains. The noise source can be damped as early on in the chain as possible having smooth passages of the trains. Or can be damped of by the soil before it even hits the facade of the building nearby. This may not always be a suitable method and measures have to be done within the building. Different types of measures can be seen in Figure 3.1 and explained hereafter.

3.1.1 Propagation through the soil

The noise travels thought the soil as vibration until it reaches structures. To stop those vibrations from hitting the building or reduce the vibrations hitting structures there are different types of measures. The most important ones are summarised in this section from the literature. Different reduction methods to reduce rail traffic induced vibration are studied, e.g. a PhD dissertation of reduction measures at MAX IV laboratory.

Trench as wave barrier

Using a trench as a wave barrier at the test Max IV Laboratory site was studied by means of finite element simulation performing a parametric study. In the study, the trench depth, width and distance from the source were parameters that were varied. Both the width and distance from the noise source had slight effect on the vibration transmission from one side to the other, while the depth on the trench had a stronger effect on the vibration levels. This was due to the fact that a barrier reflects incident waves, but also contributes to disturbance in the wavefront. The waves propagate downwards into the bedrock and then excite the soil layer. If the trench is filled with water, the height of the water level is of interest. Since S-waves cannot propagate through water the water acts as a barrier, although P-waves are enabled to. Higher water levels are beneficial in this study for the P-waves [22]. Trenches can be effective but is not always the best alternative from an economical and practical point of view.

Solid trench barrier

Instead of a trench, a solid barrier can be considered since both the safety aspects along with difficulties with water infiltration. In a study the Poisson's ratio, the mass density, the loss factor and the elastic modulus were varied. Optimal is having the elastic modulus as low as possible. For frequencies in the range from 5-25 Hz with higher elastic modulus (20-50 GPa) the reduction was neglectable. The size of the trench gave the other parameters only a slight impact. The distance to the barrier has slight impact were a placement closer to the noise source is beneficial. The distance between the trench and the protected facility is of interest because the study shows that some frequencies (10-25 Hz) is amplified after a certain distance [22].

Filler material

Waves in soil are damped out faster than in the bedrock. At longer distances the waves follow the vertical motion of the bedrock. Therefore a reduction of waves propagating into the bedrock is of importance. A filler material in the soil can be used were the velocity being the parameter of importance [23]. A soft filler material can increase the effectiveness of the trench. The effectiveness of a barrier were found not to have a appreciably effect within practical values of the parameters of the filling material.

Shaped landscapes

An architectural landscape containing hills and valleys in combination or separate can act as a wave obstacle. This has been examined through a parameter study with different combination of hills and valleys. Both 2 and 3 dimenstional models are developed were the result can give both a reduction and an amplification of the vibrations. The best reduction was using a combination of the two of them [24].

Soil improvements

A Danish study [25] showed that improving the soil under the train track reduced the ground vibrations. They found that soil improvement by increasing the elastic modulus of the soil was especially efficient at reducing ground vibrations at and close to the track compared to trenches. A study were soil improvements were performed in the foundation of a structure with a combination of them both works better, since a higher elastic modulus works in favour of the trench as well. The reason to mix soft soil with binders is to higher the elastic modulus. It could be cement, lime, blast furnace slag and fly ash. Both internal and external induced vibrations may be reduced using this technique [23].

Slab stabilisation

A parametric study were performed in order to find what parameters of a concrete slab on soil is the most important. When using a slab as stabilisation for the noise source the width of the foundation is important. The foundation is more effective at reducing Rayleigh waves at wavelength of 5-15 m. The width of the slab should be approximate 2-4 times the dominant Rayleigh wavelength. A high degree of vibration reduction is achieved using high elastic modulus and a large depth of the stabilisation. Stabilising the soil had a great impact on reducing the vibrations caused by pedestrians inside a building [23].

3.1.2 Train design

Smoothen edges

The railway system in Japan is more developed compared to Sweden [26]. High speed trains are built between the big urban areas to unite the country. Those urban areas expand into areas where the railway was built and the noise from the train traffic has started to become a problem. One vibration measure is to lower the speed limits in those areas since the speed is affecting the vibrations levels negativelly. Therefore a lot of tests have been made in order to find out how to reduce the noise without having speed limits. A lot of the noise is created by the aerodynamic noise, especially from the gap between the cars [27]. Therefore, a wind tunnel testing was performed on Shinkansen train on models on a scale of 1/8 but also applied in field tests. The gap between each car had originally a sharp edge and the idea was to smoothen the edges in order to lower to noise level. The model was tested in 200-300 km/h wind tunnel and the smoothen edges between the cars were effective for noise reduction. The technique was therefore applied in a field test were the noise level was reduced by 6-7 dB [28].

Noise barrier

Due to diffraction a noise barrier maximum reduction is limited to 15 dBA [14]. In order for a barrier to work, the barrier must break the line of sight between the source and the listener. Although a barrier typically provides a minimum of 3-5 dBA of noise reduction the effectiveness can be larger if set up correctly [14]. The performance of a noise barrier improves when being either very close to the source or the receiver.

3.1.3 Noise sources

There are different factors affecting the vibrations created by trains. Hereafter some of them are named from different studies.

Ruggedness noise

An uneven wheel traveling on a track will generate noise. This noise will be the main factor when a train is travelling with a velocity over 30 km/h and under this speed limit the engines are the dominating factor. A train wheel that is not perfectly round rolling on a rail will create vibrations and noise. The more rugged the wheel is the more noise it will create. One travel way for the noise will be through the air and hit the facade of the buildings nearby. The vibrations created will also travel through the rail and ground towards buildings nearby. Modern passenger trains have more sophisticated wheels, whose purpose is to generate less noise. Other types of trains, such as the freight cars, has a certain breaking mechanism that require another type of wheel with even more ruggedness creating more vibrations than the regular passenger trains [19].

Rail corrugation

Rails do not always have the same height, it has a vertical difference in between the rail tracks, this is called rail corrugation. The idea that rail corrugation has an influence on noise from rails and wheels is not new. A quote from Sigmund Olafsen PhD on tramcars in Oslo: “The roughness of the rail is the main source of the noise emission of the tramcar”. A more recent source talking about the effect of rail grindings on railways indicates that the effect is much more pronounced on new and modern rolling stock than on older vehicles [6]. Danish railway authorities use rail corrugation measurements for maintenance programs as well as for noise control [29].

Other type of noise

The train can generate a lot of different noises such as turning noise, break squeal, noise from shifts but also from turnouts. There could be loose parts on the train which also could be a noise source. Acceleration and breaking of the train are other factors that could have an impact on the noise levels in an area. When a train travels with great velocity aerodynamic noise due to turbulence is a noise source. Although it is only of importance with a speed over 300 km/h [19].

The local geometry of the rail has been considered in some prediction models. The German method Shall 03 adds a correlation of 8 dB for curve radius below 300 m and 3 dB for radius in between 300 and 500 meters [6]. The curve squeal is a known phenomena but happens occasionally and is therefore not always considered. There are no predictions methods considering vertical gradients. They have been investigated but no studies on the subject have found an inclusion into official models.

The importance of velocity

Studies show that not only does the velocity of the trains affect the noise level, but also the frequency of the noise is affected. A study in Germany on a surface railway line on two different train types shows exactly this. Measurements were carried out in the ground adjacent to the track in order to show the impact on the noise spectrum. The result shows a correlation where higher velocities increases both the general velocity level and also an increase in the peak frequency [4].

$$f_s = \frac{v}{3{,}6 \cdot s} \tag{3.1}$$

in which:
f_s is the peak frequency in Hz,
v is the speed in km/h,
s is the sleeper spacing, axle spacing and wheel perimeter, in m.

The peak frequency for structure-borne noise excitation is calculated by Equation 3.1. The study varied the velocity with related sleeper spacing in order to re-create the same peak frequency for different velocities showing increased dB with increasing velocity. There was a couple of different test sites in the study with different mass in the system, wheel spacing and sleeper spacing leading to different excitation frequencies for different sites. All tests lead to the same conclusion that velocity has an impact on the sound pressure level [4].

3.2 Measurements

A measurement sensor records a non-electrical quantity (e.g. velocity, acceleration) and transforms it into an electrical current. This is the signal which can be picked up by a computer and used to be post-processed such as amplified, filtered, recorded and displayed in many ways [30]. The seismometers are sensors recording the velocity of the ground for evaluation. But prior to the evaluation of the measurements have to be executed correctly to collect the proper data.

3.2.1 Collecting data using seismometers

The purpose of the master thesis was not only to measure vibration levels at each level, but also to come up with a measurement procedure which allowed simultaneous measurements at different locations and levels which could eventually be further developed and refined in order to use as calibration data to develope, e.g. numerical prediction tools.

Ideally, vibrations should be measured in three orthogonal directions outside, on the building foundation and a few places in the building. This is not always possible and might need a lot of instruments. In this case, there also was a time limitation to do so. To know which of the floors the vibration were most severe, instead people who used the building were asked where the noise and vibrations levels were the highest. This is usually in the midpoint of the longest span in the structure and in this case the 7th floor of the building [6, 31].

The transmission paths of the vibrations are usually underground and inside the building structures and this cannot be observed during the measurements. The data collected during the measurements collects mainly surface waves since they are placed on the ground. There does not have to be any clear correlation between the surface waves on the ground and the vibrations inside the house. There is likely that vibration found deeper in the ground are better correlated with the vibrations in the house [6].

Nyquist-shannon theorem

A computer is a digital machine of which have to interpret a analog signal from measurement correctly. In order to get an accurate signal from a measurement, enough sample frequency have to be collected. The Nyquist-shannon theorem states that the sample rate must be twice the highest frequency of interest. This shows that one must have knowledge of the situation at hand beforehand. Otherwise a phenomenon called aliasing, can be found as a result which is illustrated in Figure 3.2.

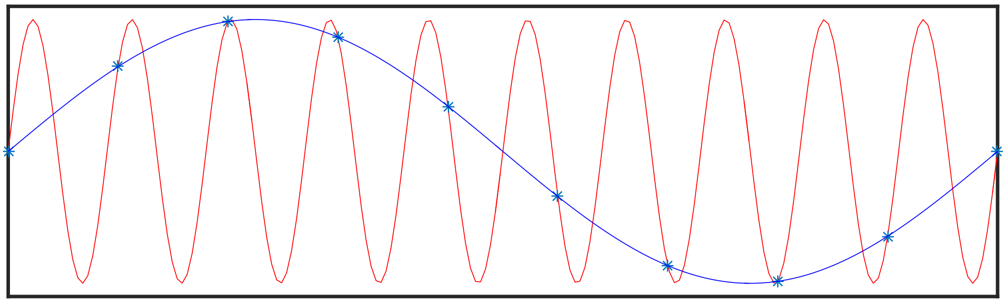


Figure 3.2: An example of a bad sample rate

$$F_s = 2B \tag{3.2}$$

in which:
V is the bandwidth in Hz,
F_s is sampling frequency in Hz.

In order to pick up all the needed frequencies the sample size must be at least twice the highest frequency. The frequency content of interest is between 0.5 Hz and 80 Hz of which a sample rate of 160 is needed. In the measurement a sample rate of 250 samples/s was used to make sure all frequencies were collected.

3.2.2 Collecting data using sound level meter

When measuring the sound pressure level on the facade of a building there are three typical ways of execution.

- Directly on the facade
- Sweeping at a distance of 0,25 m or 0,5 m in front of the facade
- Mounted in front on the facade

It is not always possible to mount the microphone directly on the facade and other methods has been tested and showed almost equally precise. Although there have to be enough reflections in the area in order to a enough sound field that is quite close to a diffuse field [6].

3.2.3 The impact of seasons

During studies made by Sigmund Olafsen influence seasonal variations were discovered. During his measurements, some the residence owners have claimed that the vibration levels vary significantly between winter and summer. In particular many of the house owners claim increased vibration levels during especially cold periods. The author states ”It is quite possible that this is correct, as it is quite conceivable that the mechanical properties of the soil change with the seasons”. The latte, in turn will have an impact on the speed propagation of sound [6].

Chapter 4

Method

The measurements were perfomed at a seven-storey building of the LTH Campus in Helsingborg, Sweden. The building is rougly 100 years old with a concrete framework and was originally designed as a factory by Tretorn. Nowadays the building contains both offices and classrooms where vibration from the rail/trains are experienced acording to some people working there, especially on the 7th floor and on ground level. In the vicinity, of ground level, a railroad is located alongside the building roughly 20 m away. There are three tracks running close by to the building passing in NNW direction. Between the tracks and the building is a smaller one-way road with low amount of traffic. A fence separates the tracks and the road which a certain permission is required to cross. The trains passing by have different speeds since the station is nearby. Most of them travel at moderate speed, 60-80 km/h while others are waiting for a free track at the station and pass by slowly, e.g 20km/h.

Figure 4.1: A map generated by Google, Kartdata, Geobasis-DE/BKG [32]

Figure 4.2: A photo of the building in Helsingborgs Campus, Photograph: Adam Cederquist

4.1 The area

The area is in the harbour of Helsingborg c.f Figure 4.1, which typically contains a lot of fillers. The Geological Survey of Sweden (SGU) provides a map of the area in terms of the overburden and the bedrock [33]. The rock type beneath the building is mica-rich sedimentary rock. The building stands on fillers with an under laying layer of post-glacial sand-gravel with a depth of 10-20 m.

4.1.1 Type of trains

There are three tracks running alongside the building. Three different types of trains use these tracks, all with different speed, length and weight. Öresundståg and Pågatåg are pretty similar trains with most passes in these tracks. The heavier SJ trains pass less frequently and is presumably the train causing the most vibrations in the area. All the statistics of the train types can be found in Table 4.1.

Table 4.1: Technical specs of the different trains passing by from [34, 35, 36]

	Öresundståg	Pågatåg	SJ
Kerb weight[Tons]	156	155	370
Max. Speed[km/h]	180	160	200
Train length[m]	78.9	74.3	165
Kerb weight per m [tons/m]	1.98	2.09	2.24

Figure 4.3: The setup outside Helsingborgs Campus with an Öresundståg in the background, Photograph: Juan Negreira

A Öresundståg can be seen in the background of the setup in Figure 4.3. A better photo of the Öresundståg can be seen in Figure 4.4 which is the lightest train per meter on the tracks beside the building in Helsingborg.

Figure 4.4: A photo of the lightest of the trains on the distance, the Öresundståg, Photograph: Adam Cederquist

Figure 4.5: A photo of the most common of the trains on the distance, the Pågatåg, Photograph: Adam Cederquist

The blue Pågatåg is the most common train in southernmost region of Sweden where is Helsingborg is located and is therefore expected to be fairly frequent on the tracks. This train can be seen in Figure 4.5. The less frequeny train is the SJ train which is mostly used for long distances. It travels with a higher speed and it carries the most weight per meter. The SJ train is shown in Figure 4.6.

Figure 4.6: A photo of the heaviest train on the distance, the SJ train, Photograph: Adam Cederquist

4.2 Measurement equipment

Two different types of equipment were used in the measurements. Seismometers, measuring the velocities in the area and sound level meters, measuring the sound pressure levels.

4.2.1 Guralp, seismometers MAN-C3E-0004

The MAN-C3E-0004 is a three-axial digital seismometer consisting of three sensors measuring in North/South, East/West and vertical direction. The sensor has its frequency range in between 1/120 and 50 Hz [37]. It is supplied with a 12 V DC power supply. The sensor needs a computer in order to store the data. The instrument can also be controlled from the computer, for instance controlling the mass locking process. A seismomter contains a mass hanging in a spring which movements are registered. The instruments extremely sensible sensors has to be locked in place while moving the seismometer. It needs to be unlocked before starting the measurements in order to get accurate data. It is very important that the seismometer is in even plane when measuring in order to collect the data and to function correctly.

Figure 4.7: A seismometer seen from above, Photograph: Adam Cederquist

The seismometer has external connectors and controls and can be found on the top of the instrument seen in Figure 4.7.

- An Ethernet connector, labelled NET
- A general purpose input/output connector, labelled GPIO
- A universal serial bus connector, labelled USB
- A spirit-level
- A power and data connector, labelled DATA
- A GPS receiver connector, labelled GPS
- The handle, with an arrow indicating “North”

Figure 4.8: A Seismometer with all cables connected, Photograph: Juan Negreira

4.2.2 Associated equipment

The seismometers need a number of different components to start measuring. First of the instruments needs power supply, a 12 V DC power source. They also need to be synchronised, this through a GPS time signal. Lastly the seismometer sends out data which either are stored in a external USB or using a cable connected to a computer. Using this setup every seismometer has to be connected to a GPS antenna of their own, which was not possible on site. Therefore a separate system was built in-house where only one GPS antenna was needed. This is explained in the next subsection ”Separate box system”. All the equipment used in the setup of the seismometers are listed below.

- 4 Guralp Seismometers
- A laptop with the software SCREAM
- 4 Guralp batteries with cables
- 6 Ethernet cables
- 3 built boxes named RX A
- 1 built boxes named TX
- 1 built boxes named RX T
- A Guralp GPS receiver
- A linksys router
- 4 cables to connect with Seismometer the boxes

Separate box system

The circuit diagram showing the separate box system can be found in Figure 4.9. The system was built in-house to synchronise the seismometers even though they are positioned inside and still be able to measure. This due to the fact that the available GPS antennas only have a 25 m long cable. The GPS antenna needs to be mounted outdoors and therefore a separate box was built. Only one GPS antenna is connected to the system, in one of the ends of the serie-connected system in Figure 4.9. The GPS is collecting the time and the system sends and feeds all the seismometers with a GPS signal, which is needed for them to work. The serie-connected system contains one more box than seismometers, since the box connected to the external GPS has no data output, called TX Box. The boxes that receive and send the GPS signal are called RX A and each of them connects to a seismometer. The end box is only receiving a signal and has therefore a special design, called RX T. One advantage with this system is that it can be monitored at the same time from one computer and all the data can be downloaded and stored simultaneously. The seismometers feed the box system with power through the GPS cable and sends out its data to the box system through a net cable. Lastly the system needs to be connected to a router in order to feed an IP number to each seismometer in order to collect the data. The computer is then connected to the router or any of the boxes to monitor the process.

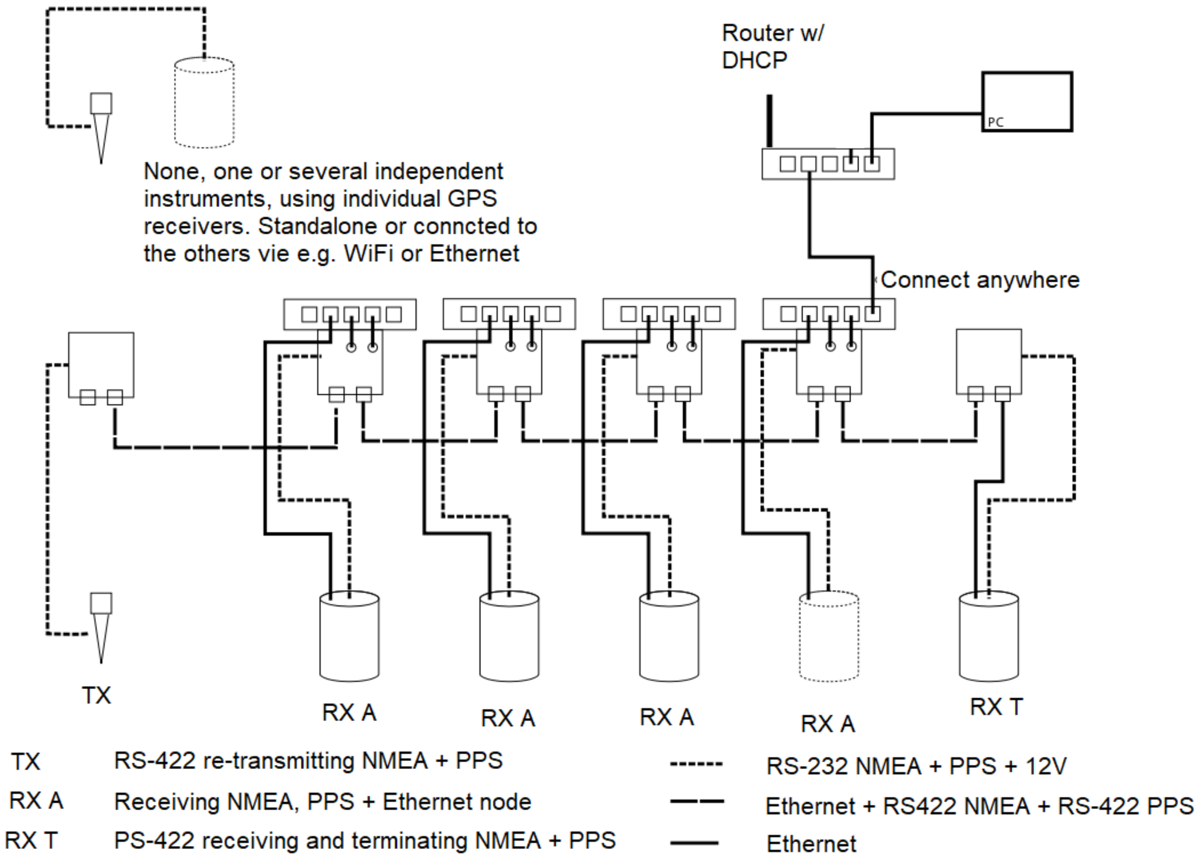


Figure 4.9: Scheme over the seismometers setup.

4.2.3 Norsonic, Nor140

The Nor140 sound analyser is a handheld instrument for sound measuring. The instrument contains all from the microphone sensor to a SD memory card to easily transfer recorded data to a PC. It can measure in octave band, third-octave band and up to 120 dB. In order for a accurate measurement no noise from other sources should be present, such as stepping from people nearby. The sonometer has built in weighting and other commonly used standards [38].

Figure 4.10: A sonometer used in the measurements, Photograph: Adam Cederquist

4.3 The site setup

The setup consists of four seismometers and some other equipment needed plus three sonometers. These should be placed at different locations in the structure to give an adequate measurement.

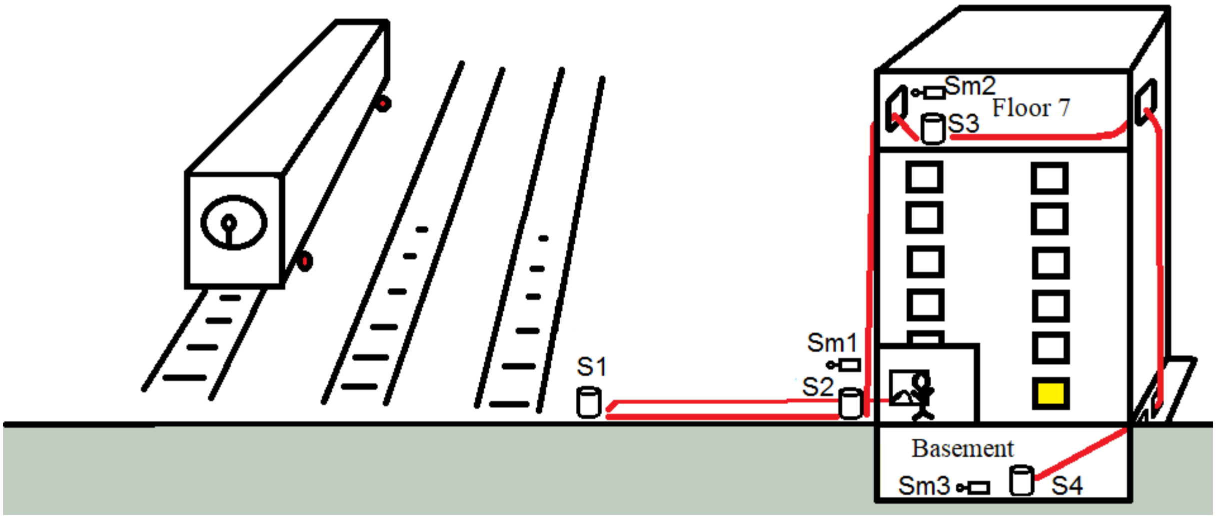


Figure 4.11: A total number of four seismometers (named S) and three sound level meters(named SM) were distributed around the building

4.3.1 Preparation

The setup for on the Campus consists of four seismometers and three sonometers. The placement of the sensors are of big importance. In order to get meaningful results all the sensors should be placed in a vertical line. This is so the all measurement point are perpendicular to the tracks so the time difference only depends on the time delay on of the wave travelling within the building in a somewhat 2d dimension.

One seismometer should be placed in the basement to avoid picking up any airborne noise and to use as a reference point [6]. One should be placed on one of the top floors were building occupants experienced vibrations in order to catch how the building is affected to the trains. The last two should be placed outdoors, one closer to the track and the other closer to the facade. This in order to pick up a clear signal from the track and to be able to see what happens in the soil before the waves hit the structure.

The sonometers should be placed at different locations, one outdoors, one on one of the top floors and the last one in the basement. All placements of the sensors can be seen in a floor plan, Figure 4.12 and 4.13. All the more precise sensors measurements can be seen in Figure 4.14

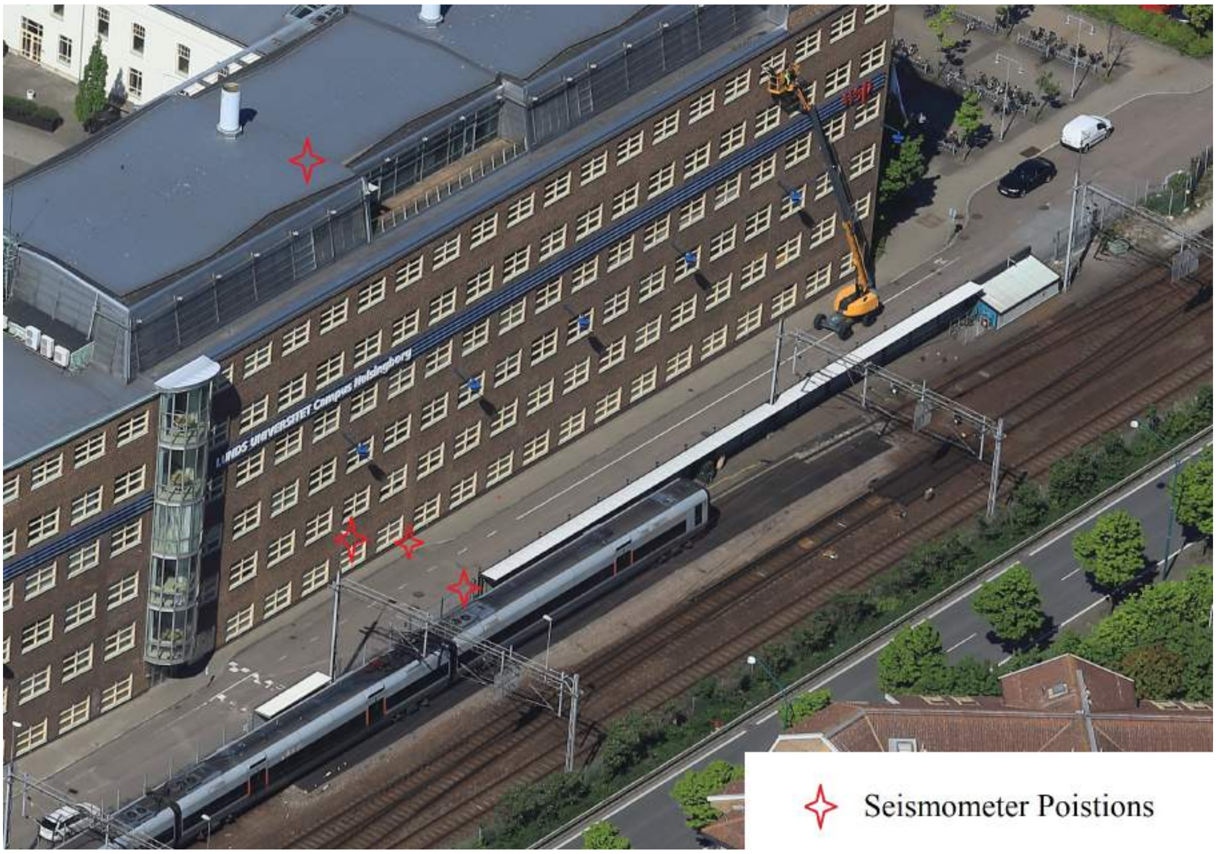


Figure 4.12: A photo showing the seismometers positions, marked with a red star, aerial photographer: Perry Nordeng.

4.3.2 On site

The facility was first analysed to see possible positions for the equipment. Outdoors, the issue with the road between the building and the tracks which had low amount of traffic had to be solved. The cables were going to cross the road somehow The disturbance from the road seemed low and were therefore solved by adding 4 planks, 2 for each wheel of each side of the cables. Next to the track and on the sidewalk by the facade, the pavement was in good condition that the seismometers could be placed directly on that even surface. The latter was assured by the spirit-levels of each seismometer.

The basement of the building had an open plan view which made the positing very convenient. No windows towards the trains, and windows towards the courtyard. This is a perfect setup since the basement is the end of a serie-connected system which will be discussed in Section 4.2.2. The basement seismometer is fully isolated from the tracks meaning that no airborne noise gets through and an opportunity to lead the cables out through the windows to the courtyard and up to the top floor.

The objective for the top floor was to have a clear way for the cables to exit on both ends of the building since the system was in the middle of the serie-connection. The 7th floor of the building had a open plan to it with balconies on both ends of floor. The plan was to lead the cables on the outside of the facade down to the road between the track and facade where the other two seismometers were positioned. All this can be seen in Figure 4.11

4.3.3 The measurements

The measurements were carried out during one hour, catching 15 train passages. The type of train, direction, time for the train to pass and number of carriages were carefully noted together with its length to get the velocity of the trains. The measurements were performed the evening of a Thursday, August 23rd (2018) between 19 and 20. The time of the year was chosen in late summer, off season, meaning there should not be students or staff there during evening/nighttime. A few vehicles crossed during the measurements which some were noted. Some boards were placed on the road to protect the cables, although they did not isolate the cables from impact. The setup can be seen in Figure 4.14 along with the measurement plan view.

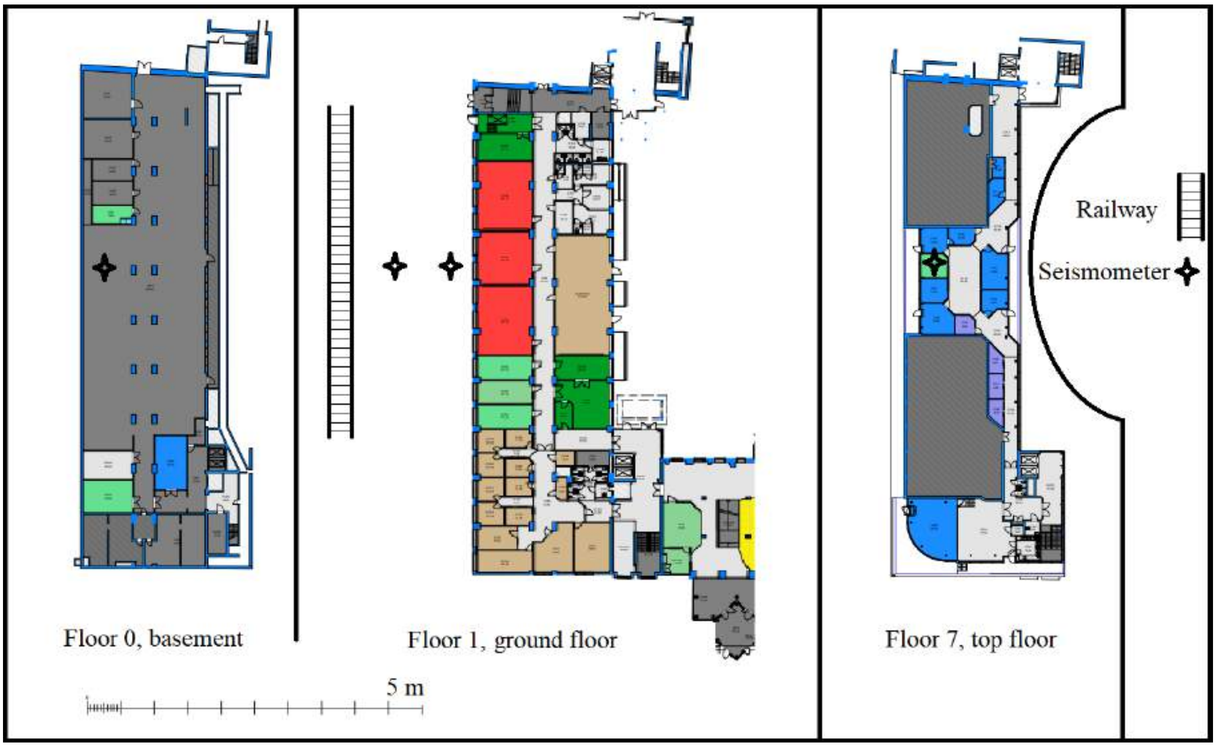
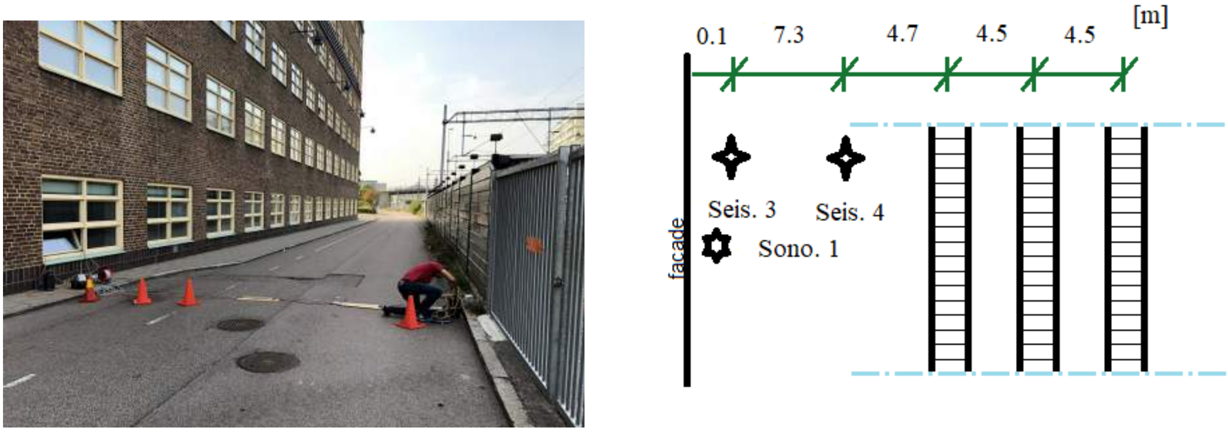
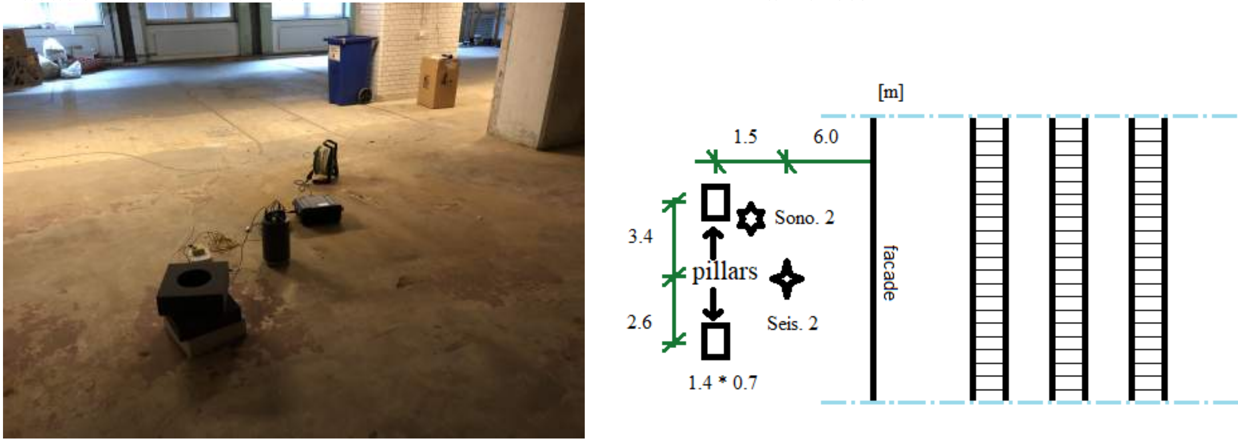


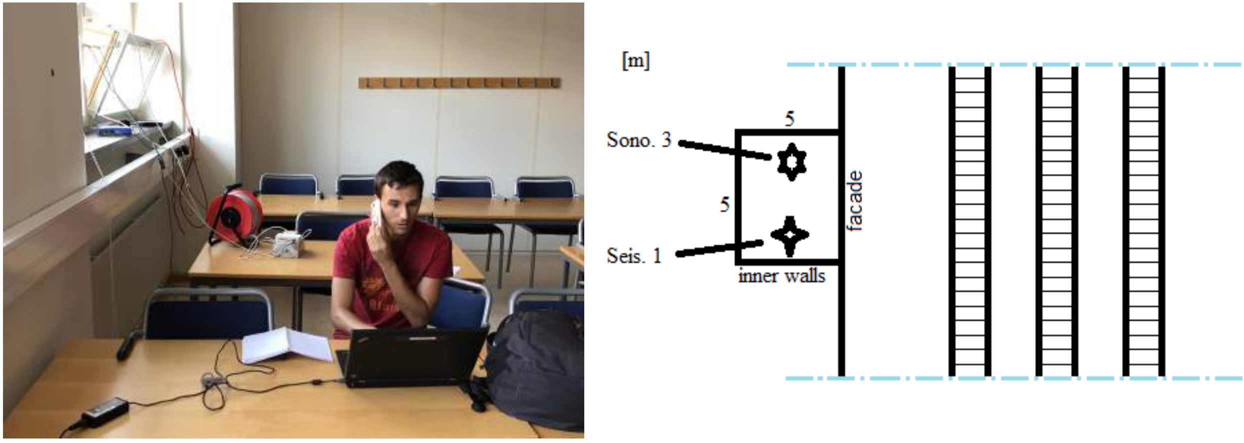
Figure 4.13: Floor plan, where the seismometers were positioned, market with a black star.



Facade rail seismometer Rail sketch



Basement seismometer Basement sketch



1st floor setup 7th floor sketch

Figure 4.14: A collection of photos and sketches from the site

4.4 Signal processing

The raw data files are not always clear enough to be used straight off. There could be a lot of disturbances to the raw signal which have to be filtered, e.g. people walking by and cable crossing itself. This section will go through how to remove the issues that were encountered and how they were solved. In this section, train number two will be used as an example to study on how the signal processing works.

The seismometers measure in three direction, north, east and normal direction, all shown in Figure 4.15.

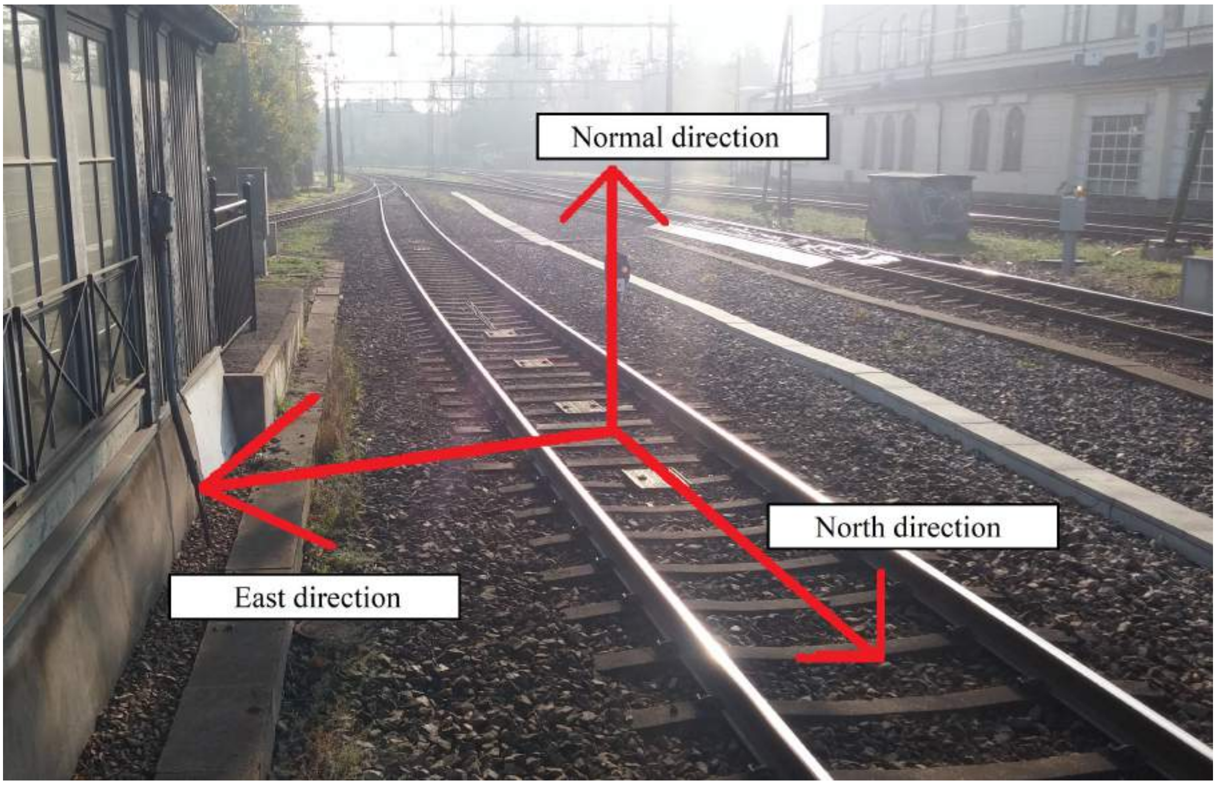


Figure 4.15: The setup outside Helsingborgs Campus with an Öresundståg in the background, Photograph: Adam Cederquist

4.4.1 Train extraction

The data from the seismometers comes in files of 15 min and with a sample size of 250 samples per second. Therefore the first thing in the process is to manually cut the train signal out from the the measurement data. Every train passes with a different velocity and the time signal differ in length in between the different trains. A train passage can be seen in Figure 4.16. The signal, in the time domain, is not centered around 0 which it should. This since the signal had some kind of disturbance. Therefore filters were added to remove the disturbance.

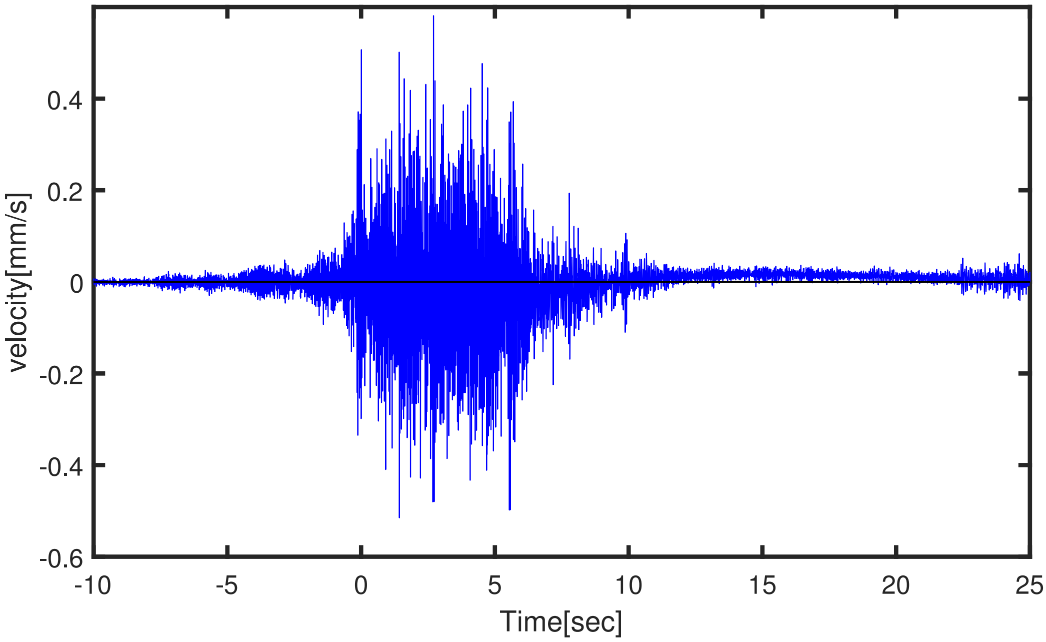


Figure 4.16: Example of a unfiltered time signal showing one train passage

Figure 4.16 shows the raw data signal from a train. In order to analyse the signal a manual cropping process need to be executed on each signal. This is not always a straight forward process since some signals have less protruding signals. Those signals were not used in the analyse since the train signals should be easy to find and crop The extracted train signal of the signal in Figure 4.16 can be seen in Figure 4.17 in a plotted time domain and frequency domain.

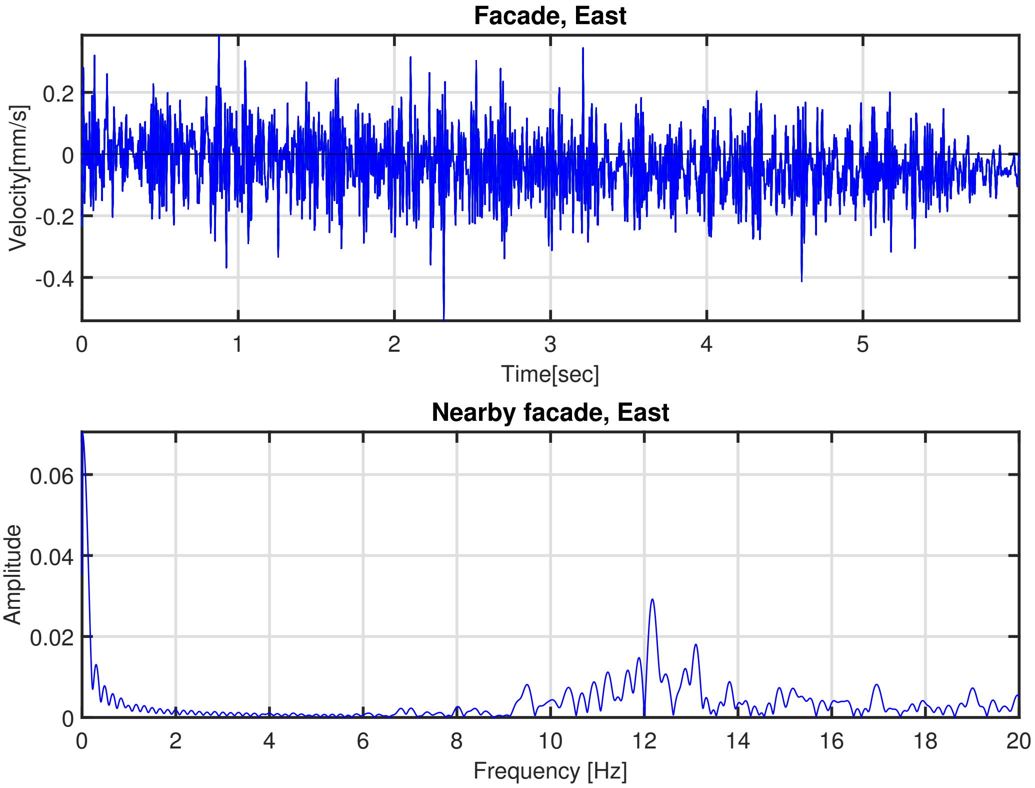


Figure 4.17: Time domain and frequency domain of the unfiltered signal of a Pågatåg, east direction

4.4.2 Filtering the signal

A filter can be used to remove any unwanted content of signals. This may be due to disturbance to the signal or that the frequency range of interest is definite. Sometimes it can be hard to find the right filter since there are many different, simple ones and more complex ones. This could be filtering such as Butterworth filter, Kaiser window or Parks-McClellan filter. This to remove any content of the signal which is not of interest or noise interfering with the signal.

On all of the train signals, the frequency domain, most of the acquired signals presented ripples in the lowest frequencies which can be seen on the unfiltered signal in Figure 4.17. The value was spiking towards the 0 Hz interval interfering with the rest of the frequencies. To eliminate this type of disturbance a high pass filter of type Butterworh was added to the signal were frequencies from 0-1 Hz were filtered out. Filtering our those frequencies can make the analyse miss out on the first global node of the building but on the other hand this range can be amplified by something else than the trains. The raw signal also contains some high frequencies which are not of interest. Therefore a low pass filter of type Parks-McClellan filter was also added in order to filter out the higher frequencies. The modified signal after the filters were added can be seen in Figure 4.20.

Parks-McClellan filter

The Park-McClellan filter is used as a low pass filter were all the low frequency content is unchanged and the high frequencies is filtered out. This due to the frequency range of interested is from 1 to 80 Hz. The idea with was that somehow the ripples on the frequency content was impacted by the higher frequencies. This was not the case but the filter was still used to make sure to be in the right interval. The filter can be seen in Figure 4.18.

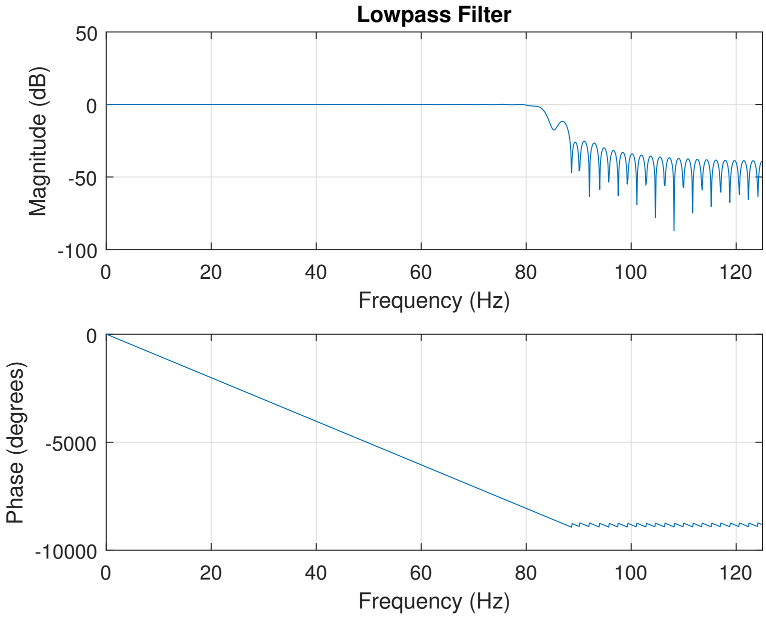


Figure 4.18: Low pass filtering using Parks-McClellan filter.

Butterworth filter

The ripples were filtered out with the Butterworth filter. The objective with the filter is to remove the ripples in the frequency domain. Through testing different intervals a filter filtering out from 1 Hz did the job, all frequency content under 1 Hz was damped. This is shown in Figure 4.19.

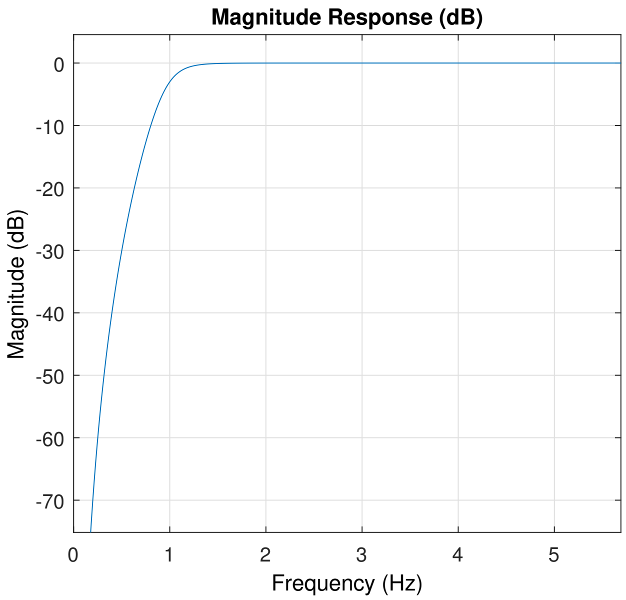


Figure 4.19: High pass filtering using Butterworth filter.

Using the filters on the signals

A closer look of the filtered signal time domain and frequency domain can be seen in Figure 4.20. Note how the time domain signal is centered around 0 which it was not before the filters were added. Also note how the frequency domain ripples are gone. Now the signal can be analysed since the disturbance is filtered. The frequency domain is used to spot certain eigen frequencies for the structure which get resonated from the train. A structure is a number of elements connected. If all those elements have the same weak points, the system starts to resonate. The idea with the frequency domain is to spot those weak points and somehow remove those points from the system.

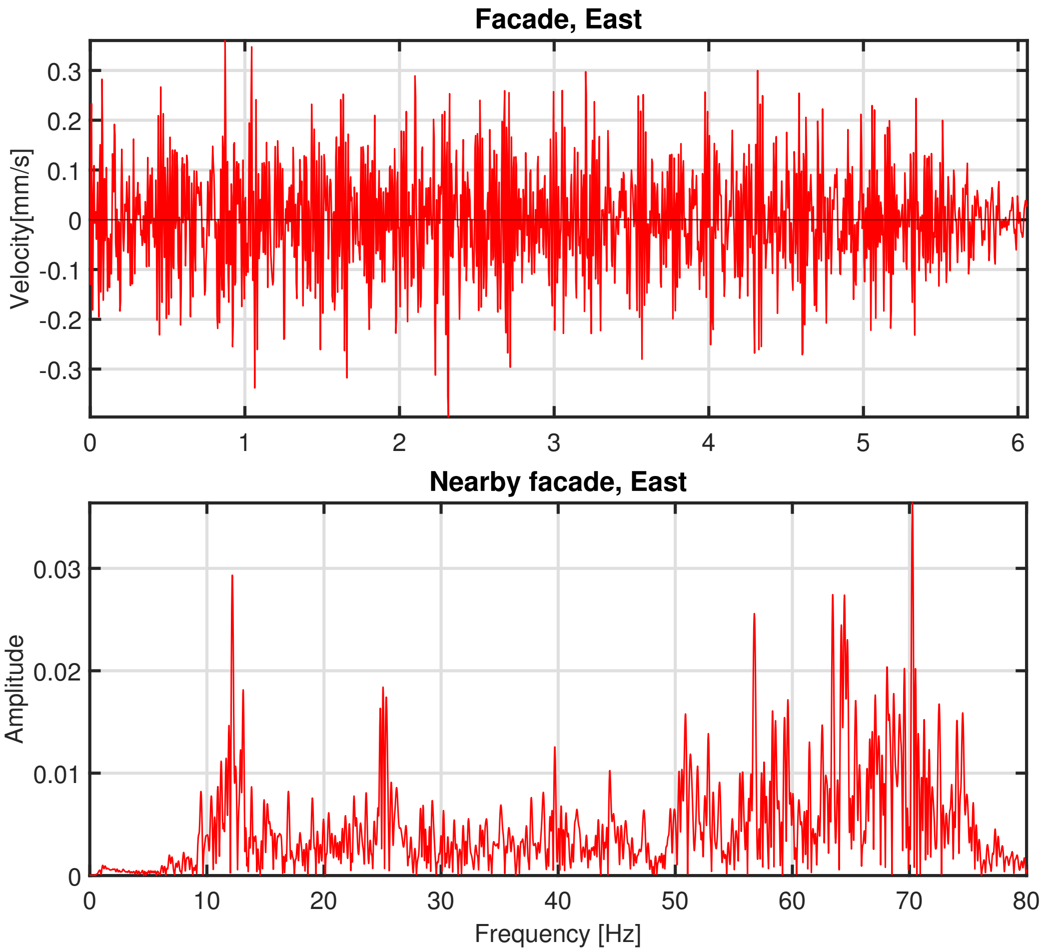


Figure 4.20: Filtered signal in time domain and frequency domain on train #2 in Table 5.1

Chapter 5

Results

All the measurements results collected from the measurement campaign are presented in the following chapter alongside discussions. The data is presented and organised in different ways in order to check the influence of different parameters o vibration levels.

5.1 Train information

When all the equipment was set, the data were captured during one hour. A total of 15 trains passed: 2 SJ trains, 4 Öresundtåg and 9 Pågatåg. All the information of the trains can be found in Figure 5.1. Since the time was not measured for train number 5 and 6 they had special treatment. The velocity of train 6 is an average of train 4 and 15 since the speed were roughly the same. Train number 5's velocity was a visual estimation of roughly 20 km/h.

Table 5.1: Information of the different trains passages by

Train no.	Train Type	Time[sec]	Cars	Length [m]	**Speed[km/h]**
1	Pågatåg	4,66	4	74,3	**57,4**
2	Pågatåg	4,70	4	74,3	**56,9**
3	Pågatåg	4.75	4	74,3	**56,3**
4	Öresundtåg	9.03	6	157,8	**62,9**
5	Öresundtåg	Slow	-	-	**20,0**
6	Öresundtåg	Fast	-	-	**58,5**
7	Pågatåg	7,70	8	148,6	**69,4**
8	Pågatåg	4,70	4	74,3	**56,9**
9	Pågatåg	3,21	4	74,3	**83,3**
10	Pågatåg	4,11	4	74,3	**65,1**
11	SJ	6,82	4	165,0	**87,1**
12	Pågatåg	8,26	4	74,3	**32,4**
13	Pågatåg	9,57	8	148,6	**55,9**
14	SJ	6,50	4	165,0	**91,4**
15	Öresundtåg	10,5	6	157,8	**54,1**

Quality of the data

Looking at every train individually means that the signal should be centered around 0 after the filtering and the FFT should have no ripples, see section 4.4.2. Also the signal should be distinct so the train is easily extracted from the measurements. Trains number 8 and 9 had no distinct signal where it was difficult to see where the signal started and ended. The amplitude was also not very different from the overall noise of the signal. This could be due to a car driving by during a train passage or people walking on the cables. Therefore those two trains were discarded.

5.2 A train passage: time & frequency domain analysis

Every train passage data from four seismometers in three directions was acquired for. This is a large number of data and therefore in this section, train number two will be analysed, only in the normal direction. The rest of the train passages can be seen in appendix. The signal captured can be seen in Figure A.16. In the upper part of the figure the time domain can be seen, where the vibration level are strongest closest to the tracks and decays with distance. The basement has the lowest amplitude on signal response. Looking at the basement's FFT, the lower frequencies are more damped than the higher ones. The 7th floor has mostly low frequency content which also can be seen in the time domain, were the signal does not oscillate as frequent as in the basement.

Resonances

The frequency content has some peaks which correlate between the different measurement points. A resonance can be seen around 12 Hz on the 7th floor which also is spotted nearby the facade, although it is not that distinct nearby the track. This is a weak point of the system and could be the most important frequency to focus on when doing any kind of counter measure to reduce vibrations. Also another frequency of interest is one at 25 Hz which also can be found nearby the facade. This frequency can more easily be seen nearby the track.

Apart from the trains amplifying those resonances there could also be human activities (e.g. walking) which could excite them as well. Since walking is around 2 Hz and 12 Hz is a multiple it could get amplified. This could create discomfort within the building without the impact of the trains.

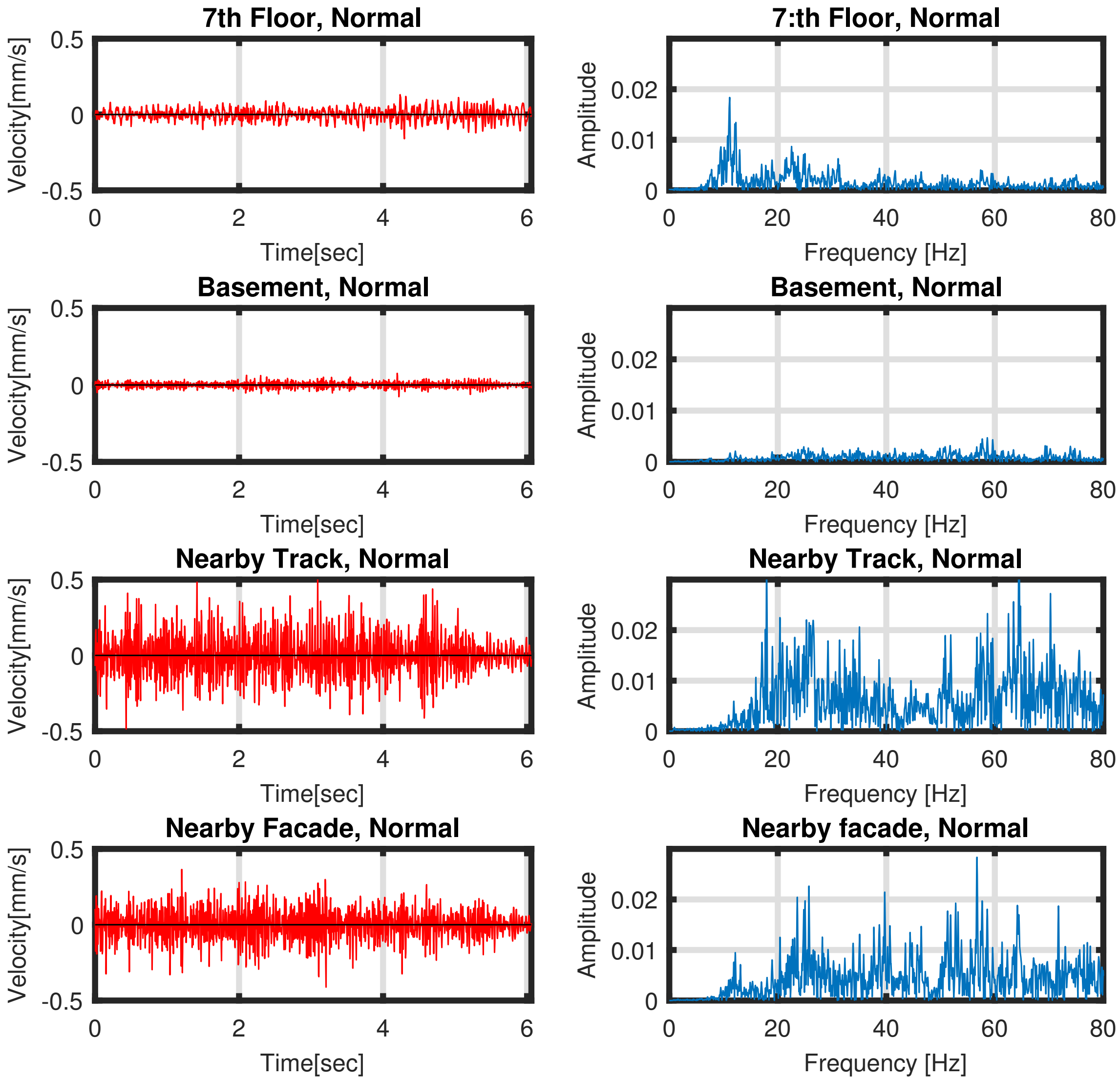


Figure 5.1: Time domain and frequency domain of train 2

5.3 RMS values

The RMS velocity values from each train passage are calculated according to Equation 2.3 & 2.4 and are plotted in Figure 5.2. It can be observed that if the train has a high amplitude in one direction, the same goes for all the directions. Although the relation in between the values do not scale linear in every direction which also can be seen in the figure. Hereafter, Pågtåg will be referred as Påga, the Öresundståg as Öre and the SJ trains as SJ.

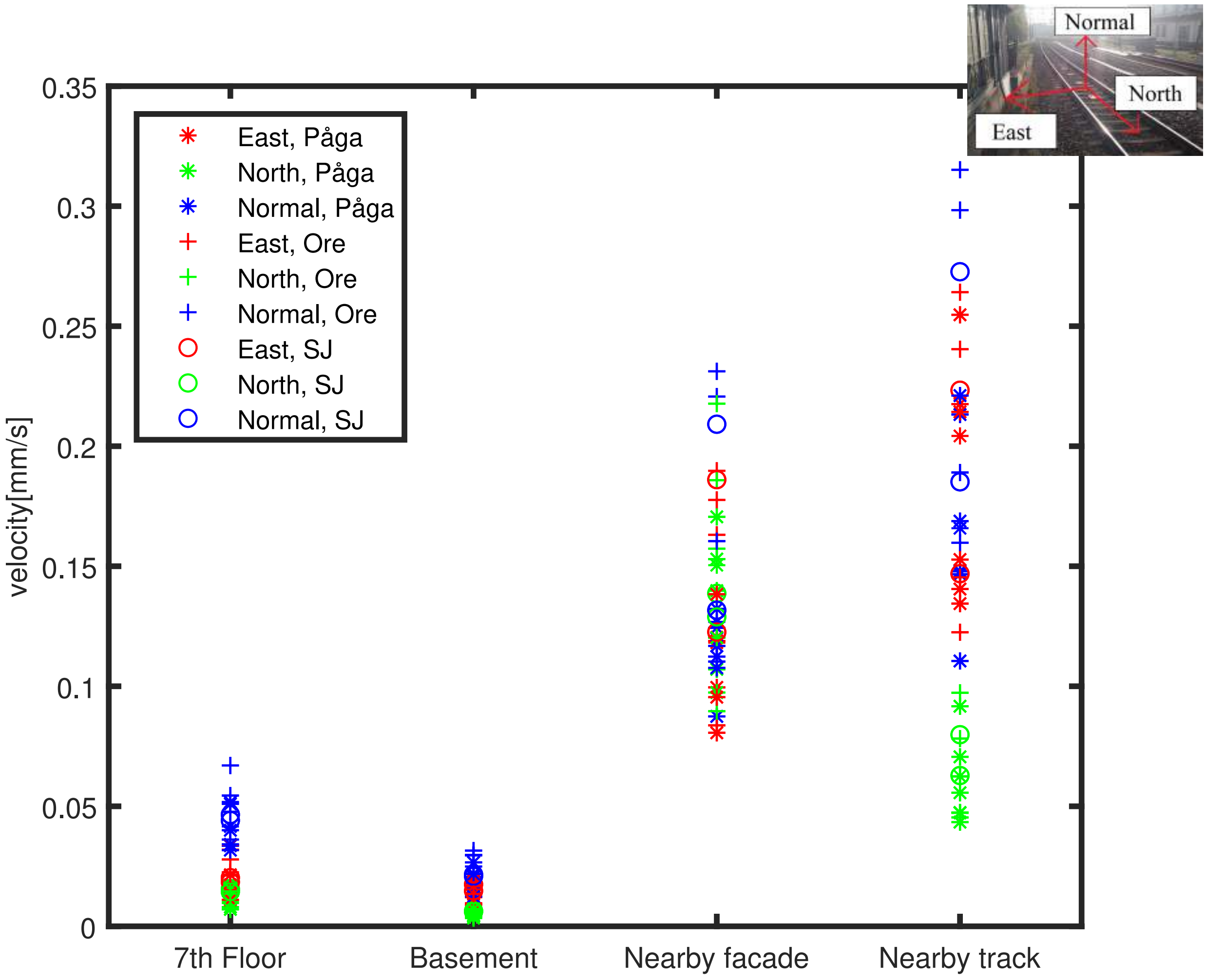


Figure 5.2: RMS of the Time domain for every train, in every direction

A closer look on each of the different locations can be seen in Figure 5.3. Notice that the amplitude of the normal direction is the dominating both for the basement and the seventh floor. This is not as significant nearby the track or the facade. But nearby the track the same pattern exists. Nearby the facade the result is more blended. Looking at the north direction, it has the lowest amplitude in all measurement positions except nearby the facade were all the values are seemed more random as the other three. This could be due to the fact that the wall is stabilising the ground around.

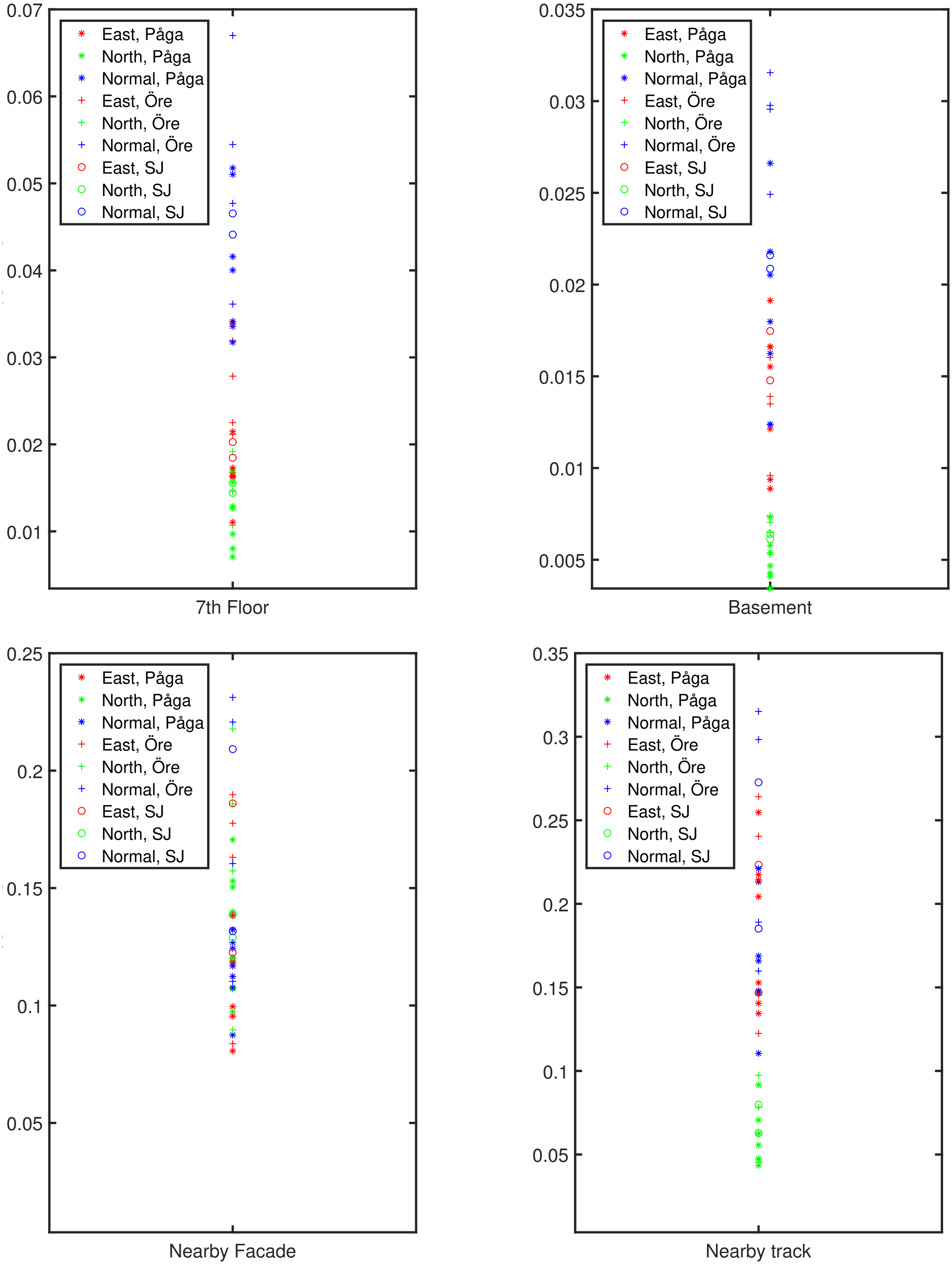


Figure 5.3: The figures show a closer look on the RMS values previously presented in Figure-5.2

RMS values in each direction

It can be a bit hard to spot the differences between the different directions the RMS values presented in Figure 5.2. The RMS values are shown in each individual direction in Figure 5.4. An even more zoomed in plot can be found in the appendix (Figure A.1, A.2 and A.3).

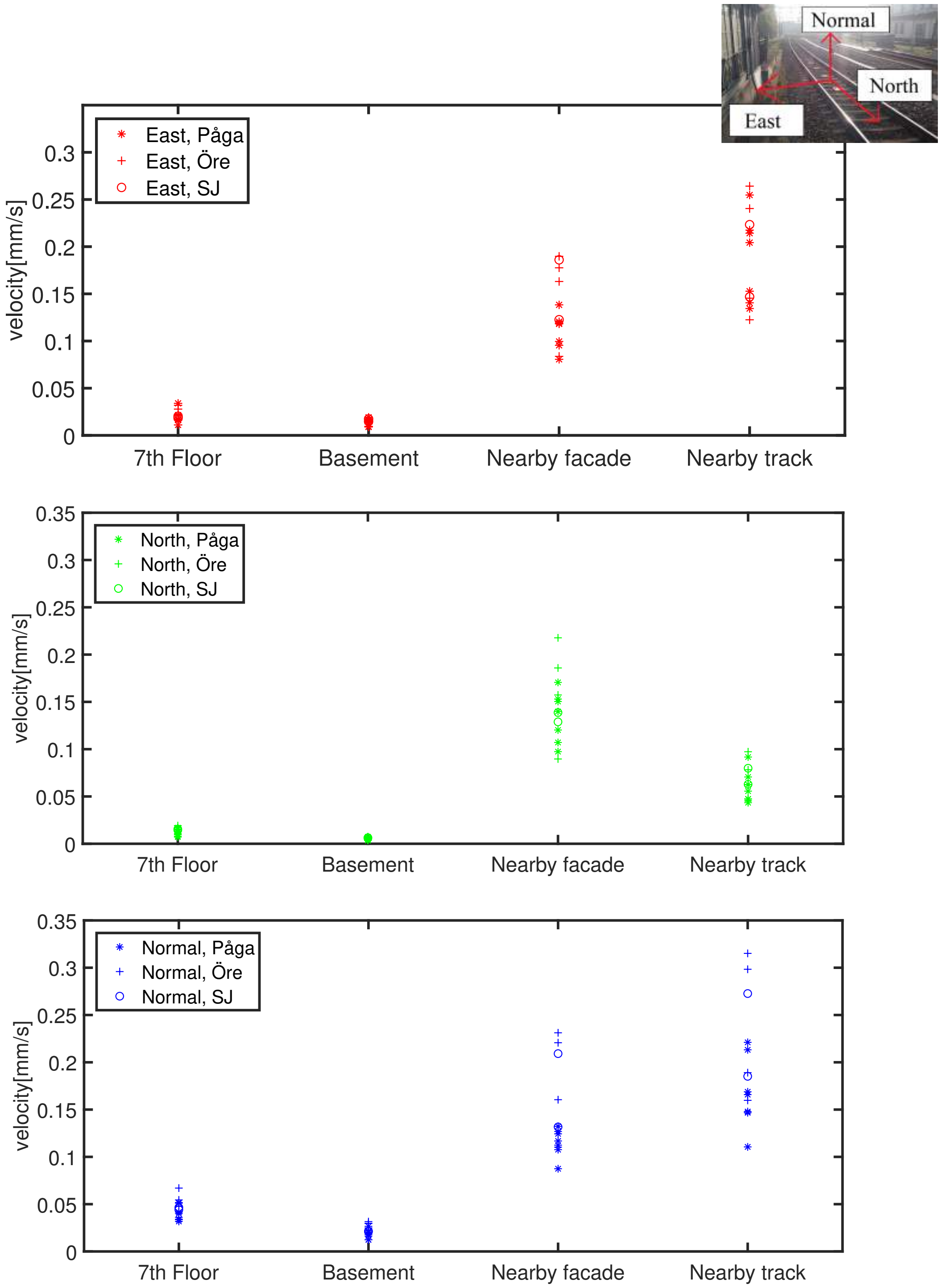


Figure 5.4: RMS for all the trains separated by direction

Train type average

A comparison between the average of the three directions where all 13 trains can be seen in Figure 5.5. The plot clearly shows how the 7th floor, the basement and the seismometer near the track follow a pattern. If a train has a high amplitude in one direction it implies that it has a high amplitude in all other directions too and the pattern follows for all the positions except near the facade, where it appears that the Pågatåg has a lower amplitude than the rest of the measurement points.

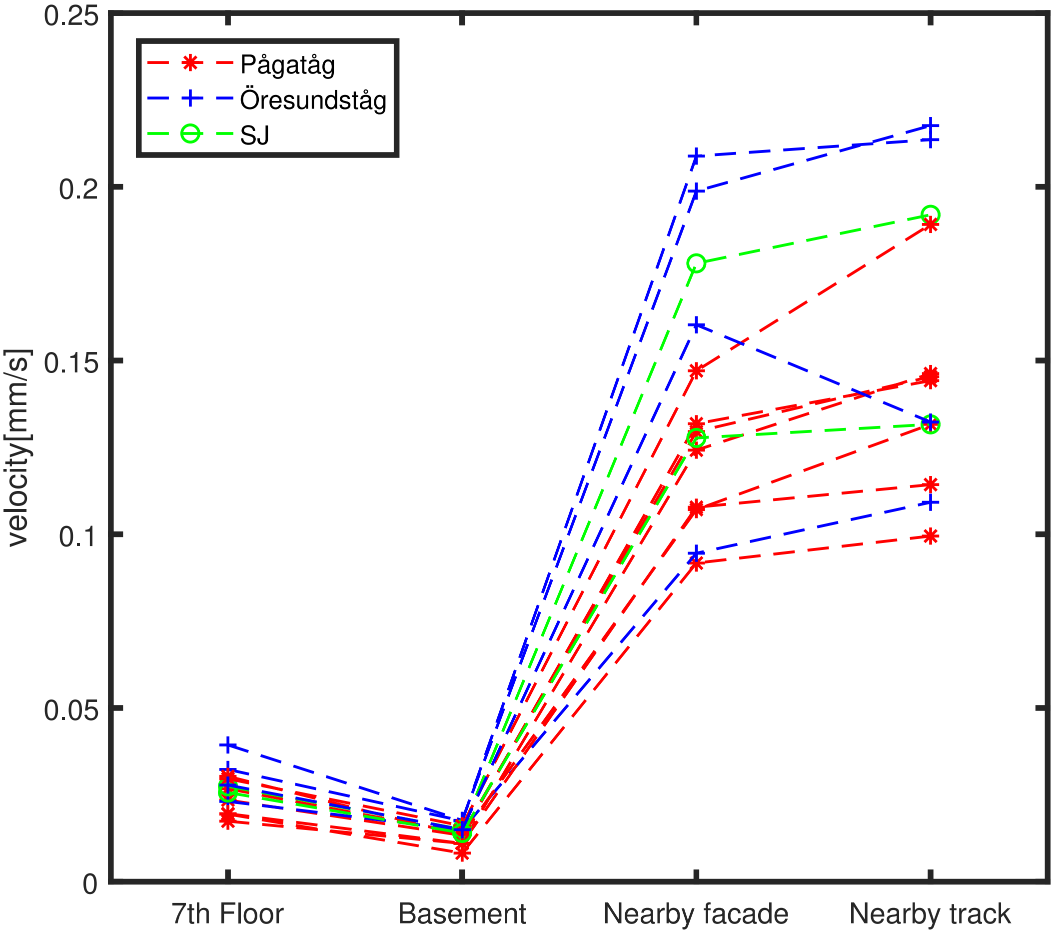


Figure 5.5: The average of the three directions for all 13 trains, coloured by train type

Mean train type

Figure 5.6 shows the mean value for every train type in every direction. There Öresundståg has a greater impact in all direction on the seventh floor. Although the result from the facade does not follow the same pattern. The Pågatag has the lowest amplitude in almost all the direction for every measurement point. Both the normal direction and for the east direction the amplitude decreases close to the facade compared to the other trains. This is not the case in the north direction though.

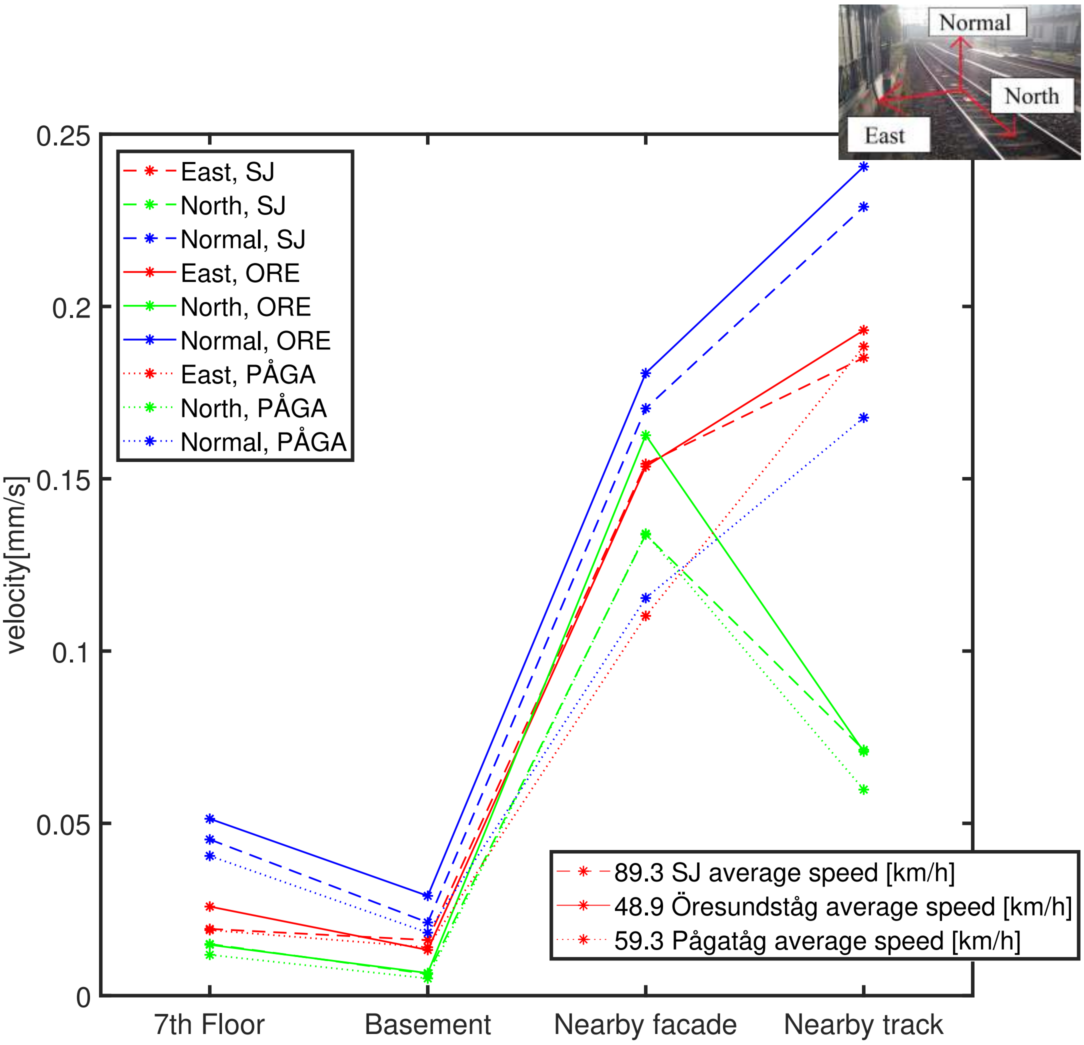


Figure 5.6: The average RMS of the time domain for every train type, in every direction

Speed comparison

A comparison between the fast trains and the slower ones was executed in order to find a correlation between speed and amplitude. Trains 7,11 and 14 were considered fast with a speed over 69 km/h and 5 and 12 were considered slow with a speed below 33km/h. The results show clearly that in the basement almost no difference is present. Both the north and east direction have greater impact on the 7th floor regarding faster trains. Closer to the facade slower trains have more of an impact.

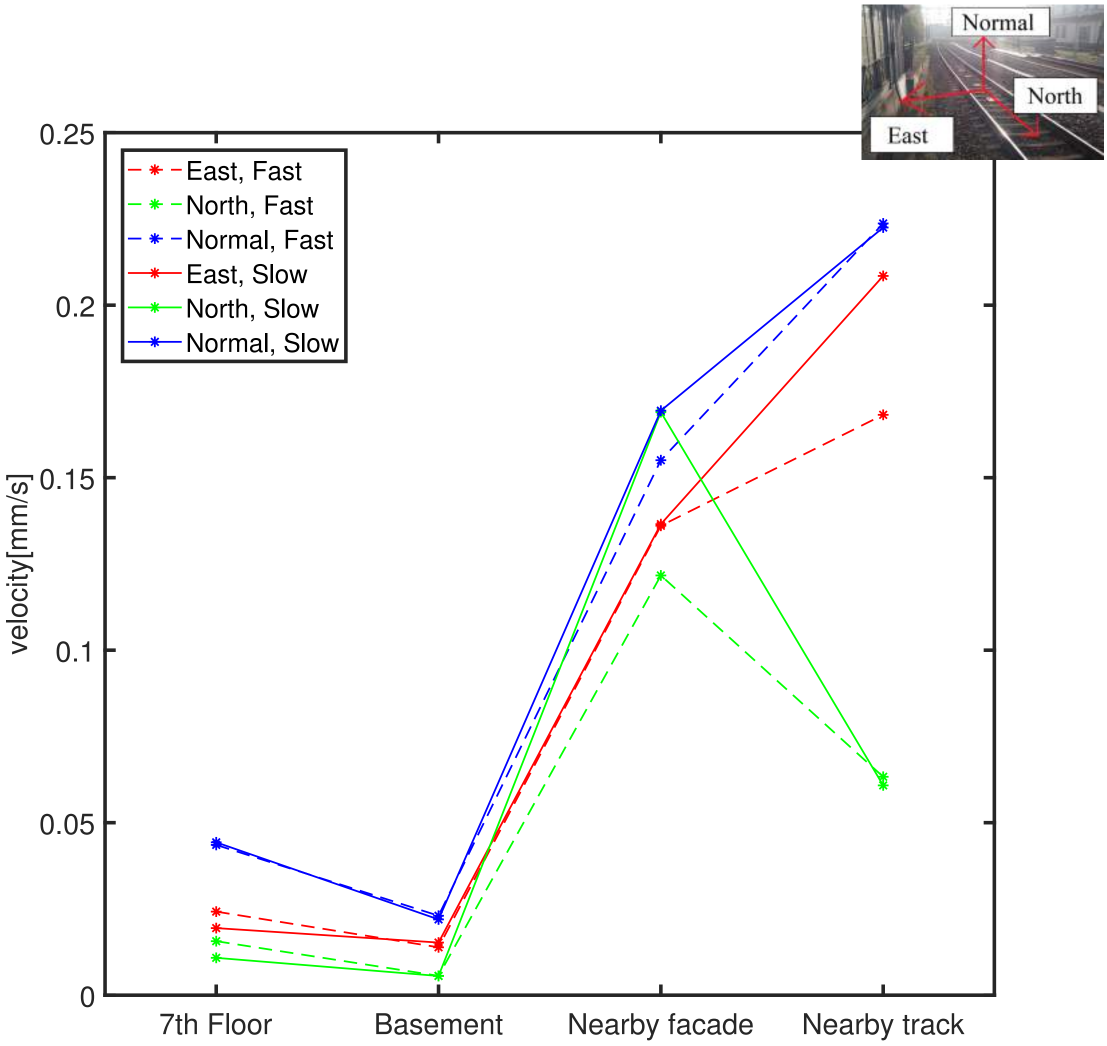


Figure 5.7: RMS comparing trains with higher velocities versus lower velocities

5.4 Sonometers

A sound level meter is a hand-held is an instrument which measures the sound pressure levels. The instrument consists of a microphone, a screen and a computer memory. The microphone, with known sensitivity is collecting the data and converted by the instrument from an electrical signal into sound pressure. The sound level meter measures airborne noise and can divide the sound into frequency content. Different types of analyses can be executed, octave analysis and third octave analysis. Every instrument needs to be carefully calibrated to give a high accuracy.

In the figure below, the equivalent sound pressure levels in third-octave bands during the time of the 15 train passages is presented. As expected, the sound level meter. As expected, the sound level meter by the façade outside captured the highest values, whereas in the basement the lowest sound pressure levels occurred. Higher values are depicted in the lower end of the spectrum, indicating that trains create more noise with low-frequency content.

It is hard to correlate the equivalent sound pressure levels with the resonances of the floors recorded by the seismometers by having equivalent sound pressure levels. Had I measured single train passages a better correlation between sound pressure and vibration levels would have been easier; however, due to logistics and time this was not possible. Interesting though is the descend of sound pressure level in the sound level meter placed in the 7th floor between 16 and 40 Hertz (since there are low-frequency components in the velocity spectrum), whereas the other two meters show an increase. Further analyses of the relation between sound pressure and vibration levels are of interest as further work.

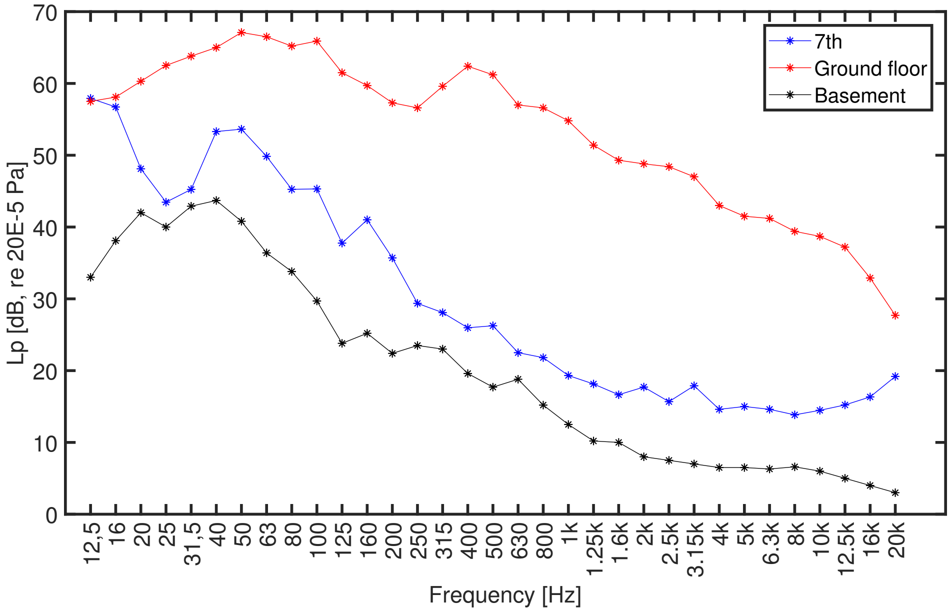


Figure 5.8: SPL during the train passages

Chapter 6

Conclusions & Discussion

6.1 Conclusion

In the master thesis, a measurement procedure to measure railway traffic and the vibration levels produced in a nearby building at different levels and three different directions was designed and implemented. The main conclusions are summarised below.

- It is important to measure the vibration levels from railway traffic in three direction in order to properly assess human comfort inside dwellings.

- Railway traffic can be a cause of discomfort, as the vibrations created can exceed the limits/guidelines stated in the norms.

- It is important, when designing building, to be aware of the dynamic properties of the buildings and the activities to be performed in them in order to avoid, e.g. resonances which could hinder the achievement of comfort inside for the ocoupants.

- Öresundtåg creates the highest amplitude in the building followed by the SJ train and last Pågatågen.

- The velocity levels in the building are highest in the normal direction.

- Faster speeds lead to higher amplitudes in east and north direction but the normal is unchanged within the building.

- If a train has a high amplitude in one direction, it implies that it will have a high amplitude in all the direction, exception for the measurement position close to the facade.

6.2 Discussion on the measurements

The result from the measurements show correlations, both between speed, train type and in different directions. North will be referred to as the train direction, east perpendicular in the horizontal plane and the normal direction as vertical direction.

The reason Öresundståg are the dominating train in terms of vibration may be because it carries the least weight per meter. The extra mass on the other trains may help to reduce the vibrations created. Also difference types of frequencies are amplified when a different mass is present.

The signal is strongest closest to the track and decays with distance. The lowest signal is in the basement, for all the measured trains. On the seventh floor the signal mostly contains lower frequencies which may excite the lower modes of vibration of the building. The amplitude in all directions follows a pattern were the normal has the highest amplitude followed by east and last the north direction. This is expected since a floors first eigen frequency are in the normal direction. This bending mode has the most displacement in the normal direction and may be the reason why the normal direction has the biggest amplitude.

The facade is a lot different than the rest of the measurement positions. The directional pattern which follows in the other points is not present close to the facade. This could be because the building is acting like some sort of damping stabilising the ground. There could be some interaction between the waves not connecting up close to the building were mostly body waves are affecting the building and therefore only surface waves are measured at the facade, with different frequency content since those have different resonances.

The speed comparison is interesting since it is mainly the seventh floor that presents a difference. When the velocity goes up, the peak frequency goes up, see section 3.1.3. It could be due to the fact that the frequency content is different for the different measurement positions. It could be that the faster trains peak frequency correlates with the peak frequencies of the seventh floor at 12 Hz. This could also explain why the other directions are almost undisturbed.

The building was built over 100 years ago in concrete. That said, it should withstand vibration from the trains better because of the extra mass from the concrete. The highest RMS value is roughly 25% of the guidelines in Table 2.1 which could be a warning to those building lightweight structures in the vicinity of the tracks. Maybe some sort of measurement on other structures should be done, to investigate if a lighter material were to be used for structures in the vicinity of the railway. This is no verification of that, but could be a warning to future projects.

The conclusion that faster trains have a greater impact on the structure is both known and proved in this thesis. Although it was expected to have a more distinct outcome on the result. That the normal amplitude was unaffected was a bit surprising. The reason could be that the seismometer was not placed in the middle of the concrete slab. But this should only have lead to different amplitudes on the seventh floor.

The sonometer outdoors had too much disturbances of people walking by and maybe a shorter measurement should be performed and not a measurement for a total hour. Instead the measurements should be divided in which each particular train has its own corresponding sound measurement. The total hour contains people walking by both step sound and talking is affecting the results.

The solution using boards to protect the cables was not as efficient as expected. The solution is more suited in a muddy terrain and not on a street were the board were moving around. Also the material was too light ending in the board moving and had to be reset to the original position after every car passed by. A more suited solution is to bring a real rubber product which the cables run under which separates the impact from the car from the cables.

6.3 Further research

In order to gain more knowledge of what happens in between the floors of the building more measurements could be carried out. The measurements should be done simultaneously on different floors and the data analysed to get knowledge on how different floor react in comparison to each other. Plausibly other floors could have higher RMS values depending on which modes of vibration are excited. This is of great interest to compare with the current regulation and guidelines. Also if the peak resonances on the different floors correlate which could imply that a retrofitting in the existing floors through adding extra partitions, mass for example, is the best solution for the building in question, if the owner wants a measure.

It is interesting that similar trains have so different values in the results. How much can trains vibration levels be reduced just by a carefully designed train? Creating a train with lower vibration level is beneficial for every structure along the track line and could be an easier measure to take in the long run than modifying every building along the track where problem occurs. This along with improving the ruggedness of the tracks in order to smooth the friction between the rail and wheels.

The values are close to the 25% of the government rules for this concrete building but how would they be modified in case of a lightweight structure? Investigations on different building materials and how they correlate in between each other could be investigated. If there is a clear correlation in between building materials the method would make the evaluation process of buildings easier. The latter could be done by use of numerical models, which would entail cost and time saving, while allowing to predict the building behaviour during its design phase, or without the need of constructing mock-ups or modifying existing buildings. To do so, through calibration of models with measurement data should be performed, in order to then use those models as prediction tools.

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Appendices

Appendix A

Plots

A.1 Closer look at RMS values all trains, different graphs for all directions

East direction

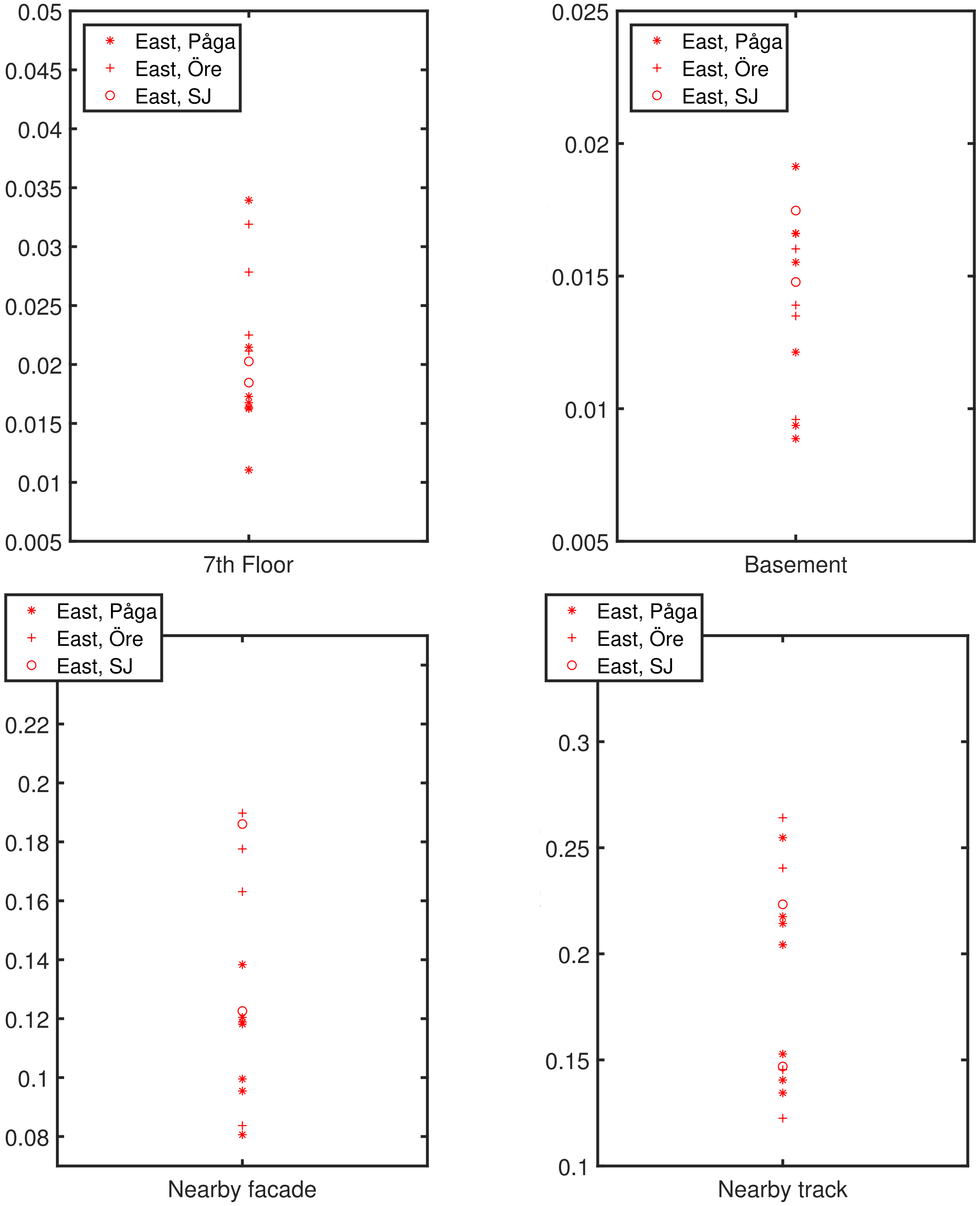

Figure A.1: The figures show a closer look on the RMS values in the east direction

North direction

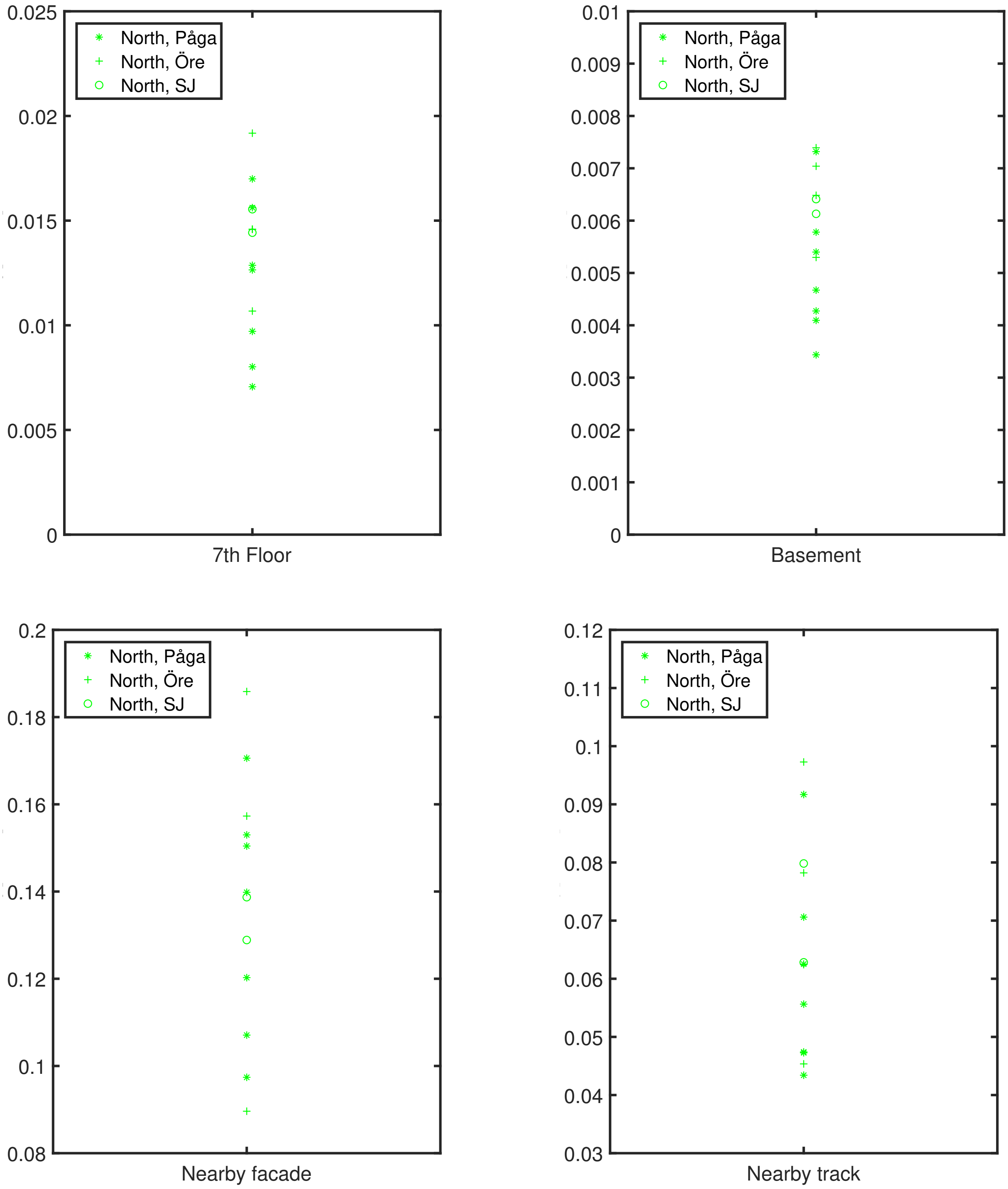

Figure A.2: The figures show a closer look on the RMS values in the north direction

Normal direction

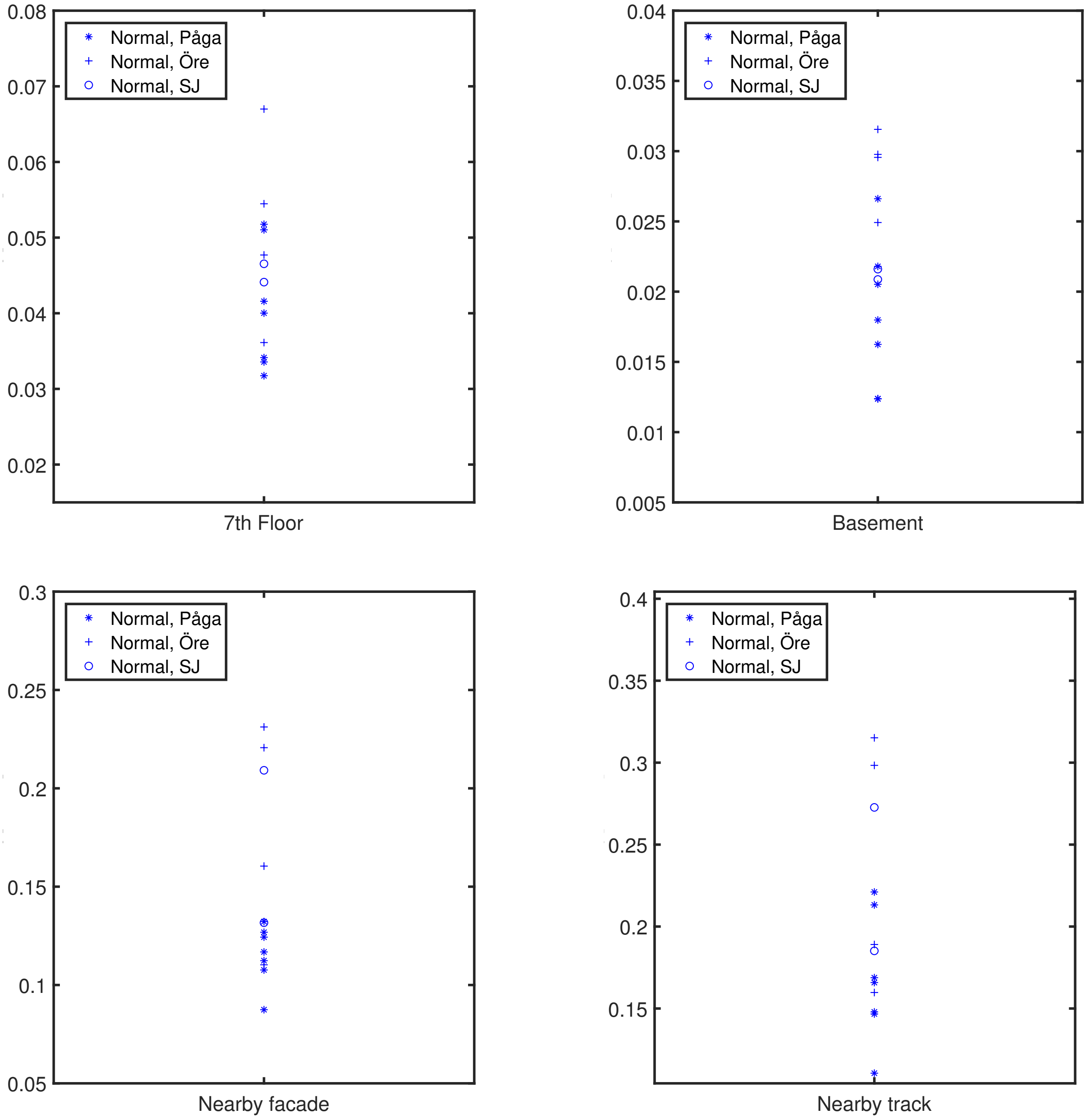

Figure A.3: The figures show a closer look on the RMS values in the normal direction

A.2 The graphs for all studied trains, in the normal direction

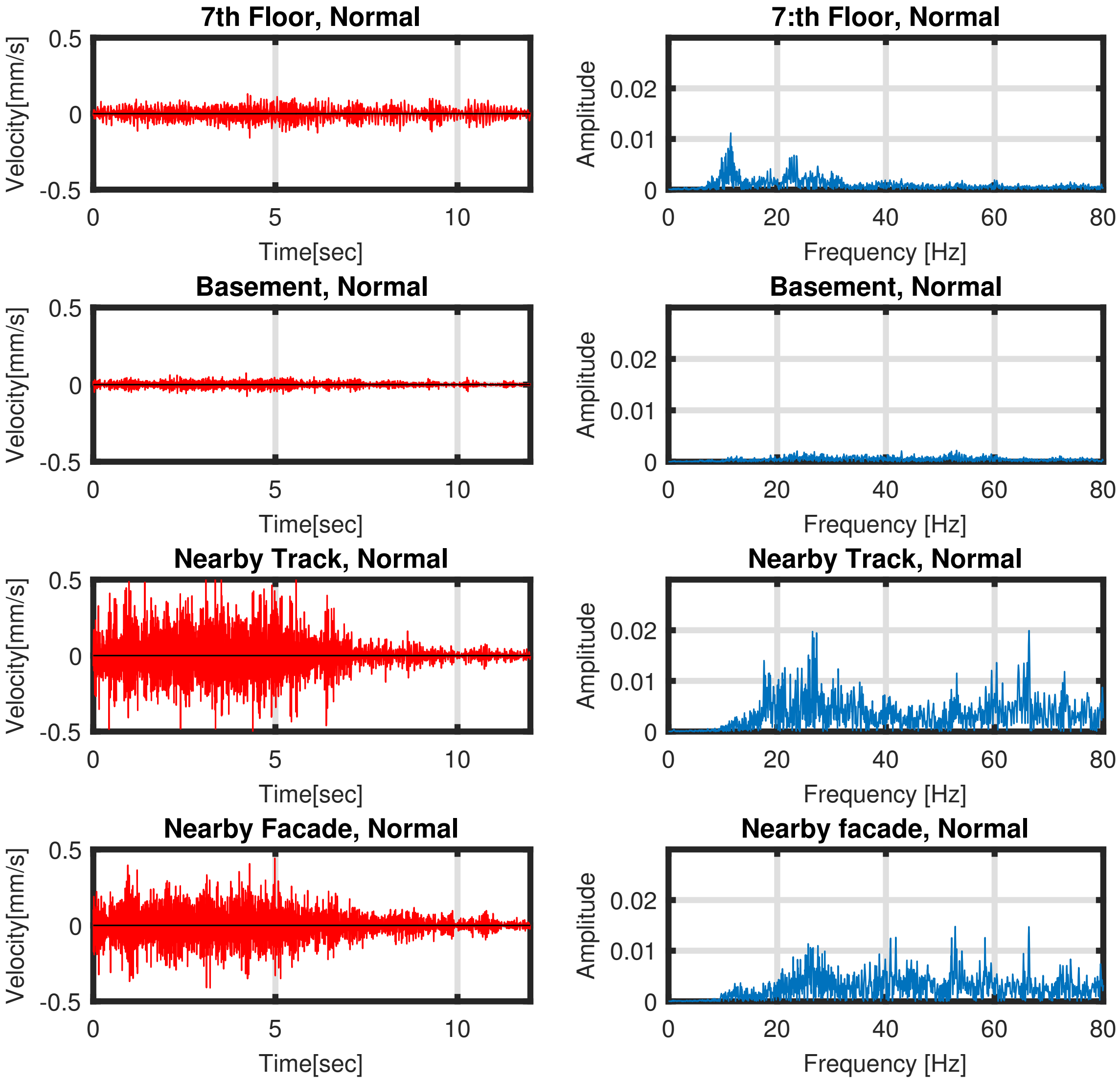

Figure A.4: Time domain and frequency domain of train no. 1

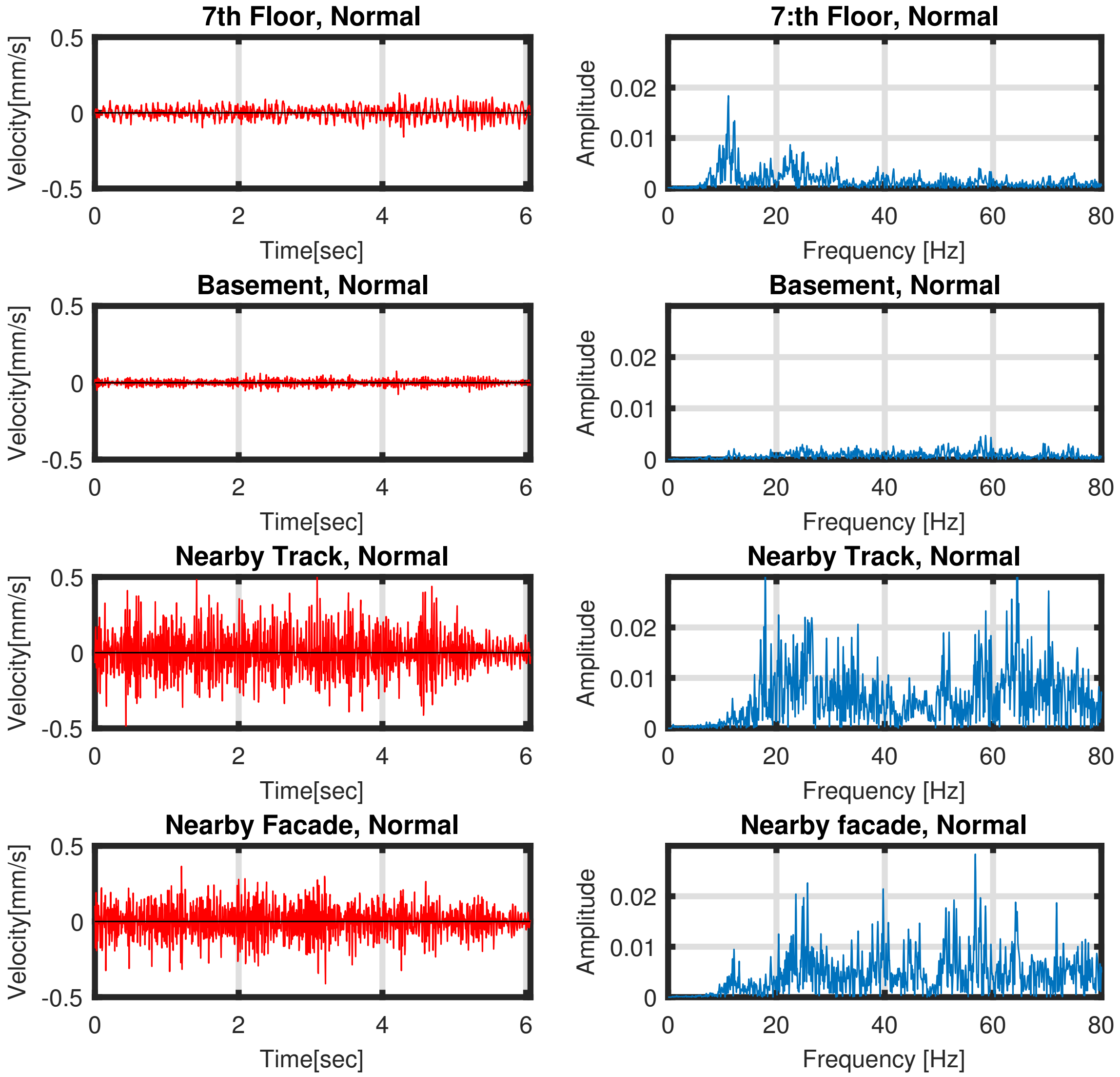

Figure A.5: Time domain and frequency domain of train no. 2

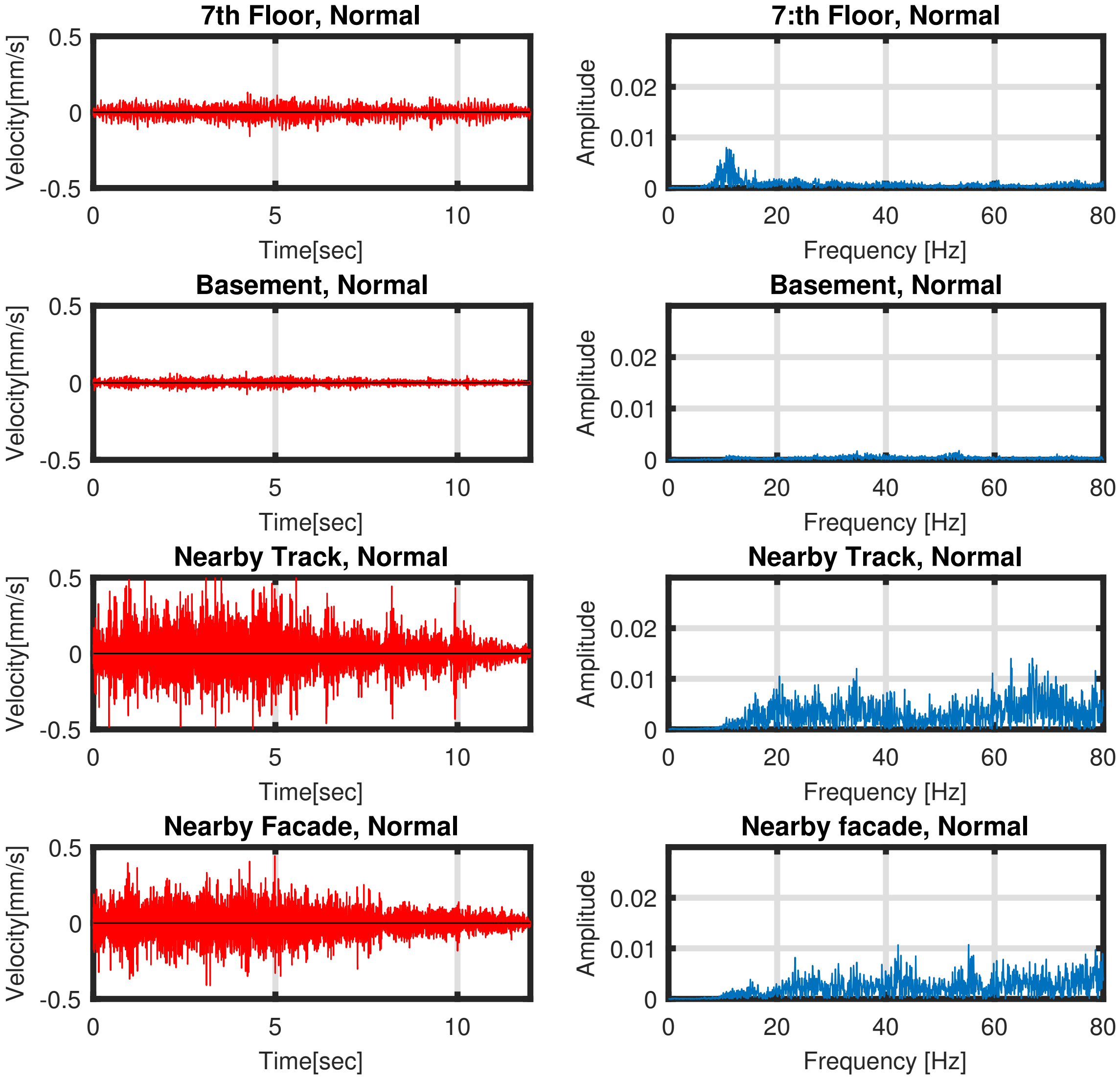

Figure A.6: Time domain and frequency domain of train no. 3

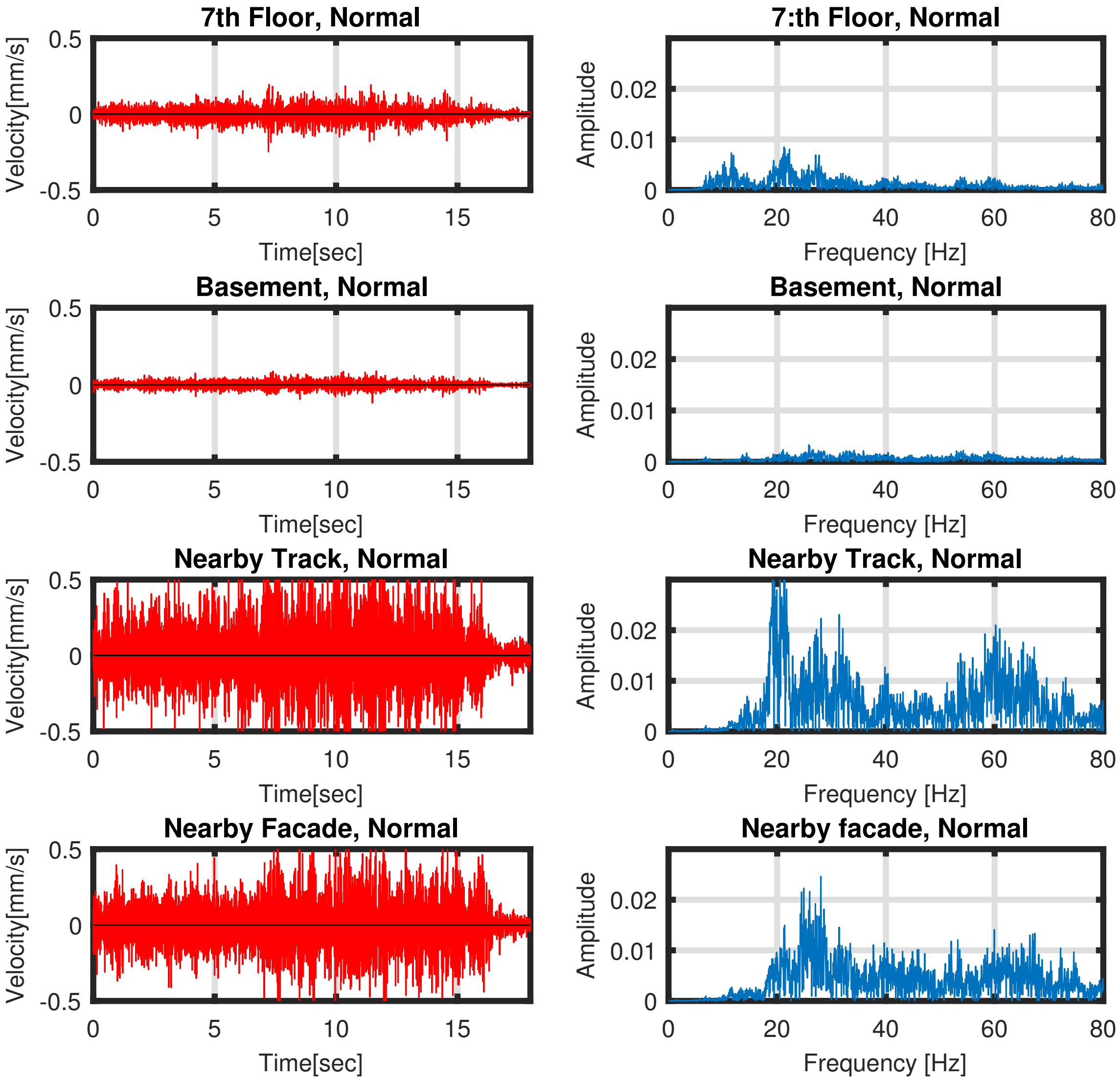

Figure A.7: Time domain and frequency domain of train no. 4

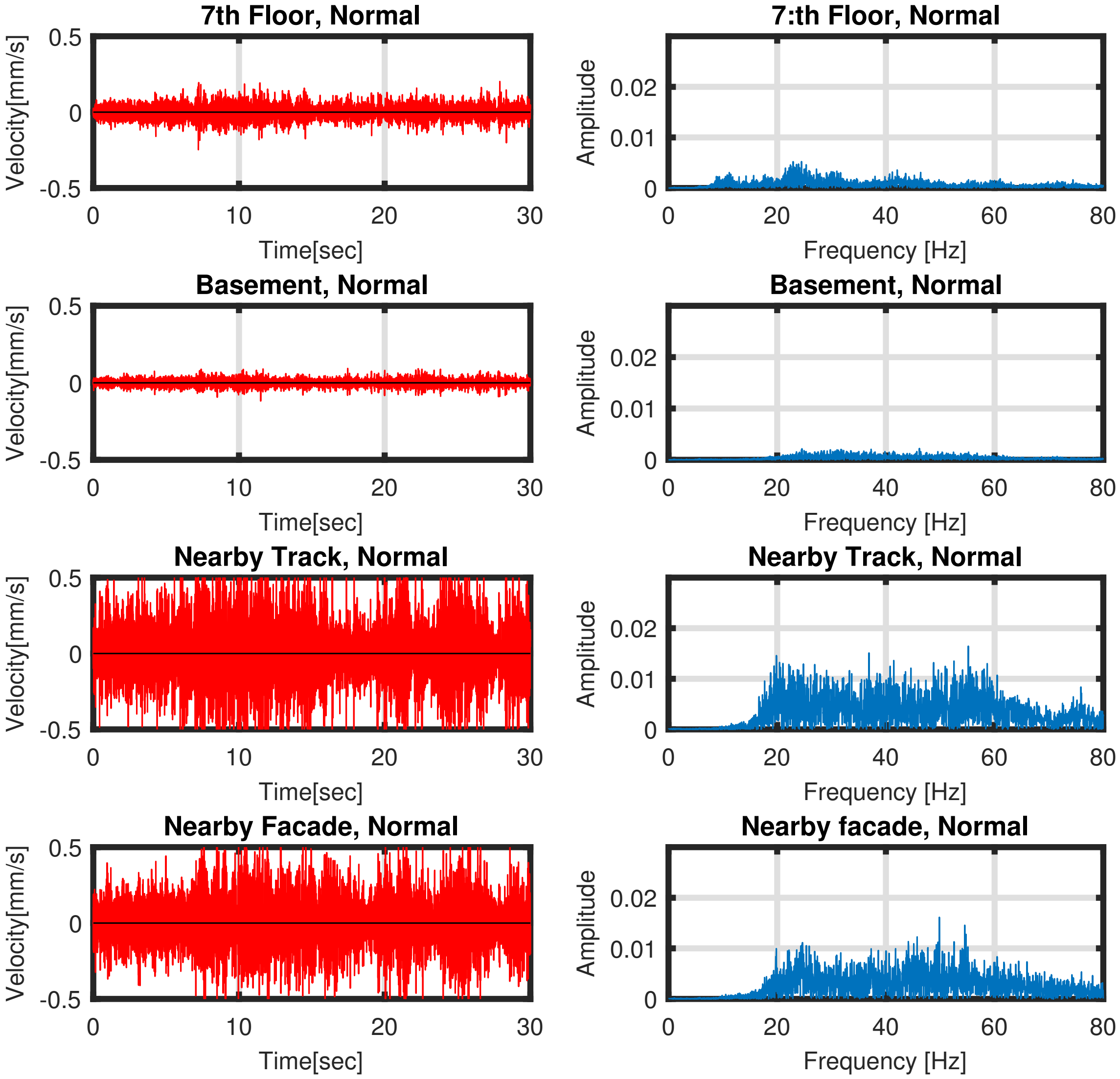

Figure A.8: Time domain and frequency domain of train no. 5

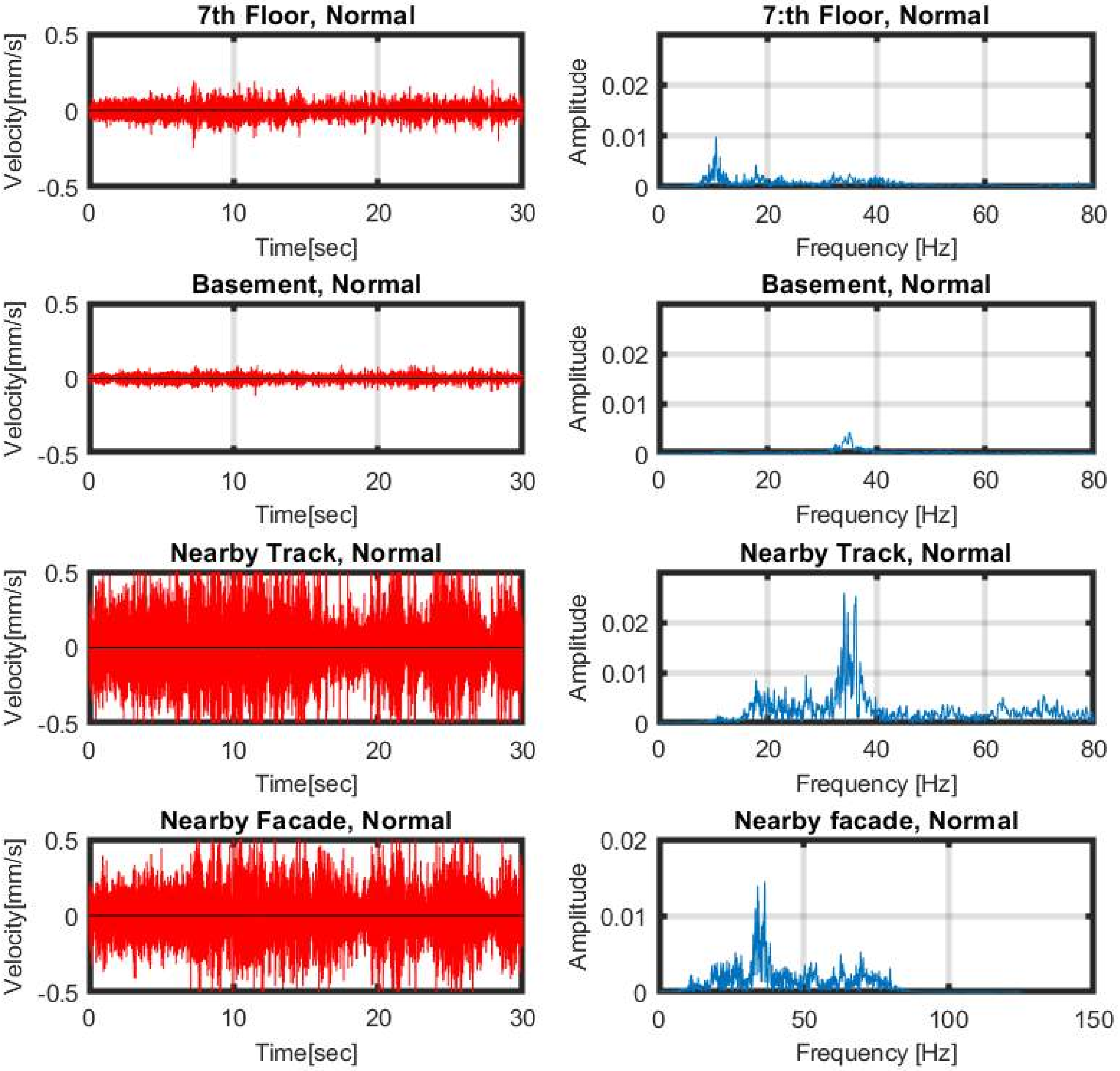

Figure A.9: Time domain and frequency domain of train no. 6

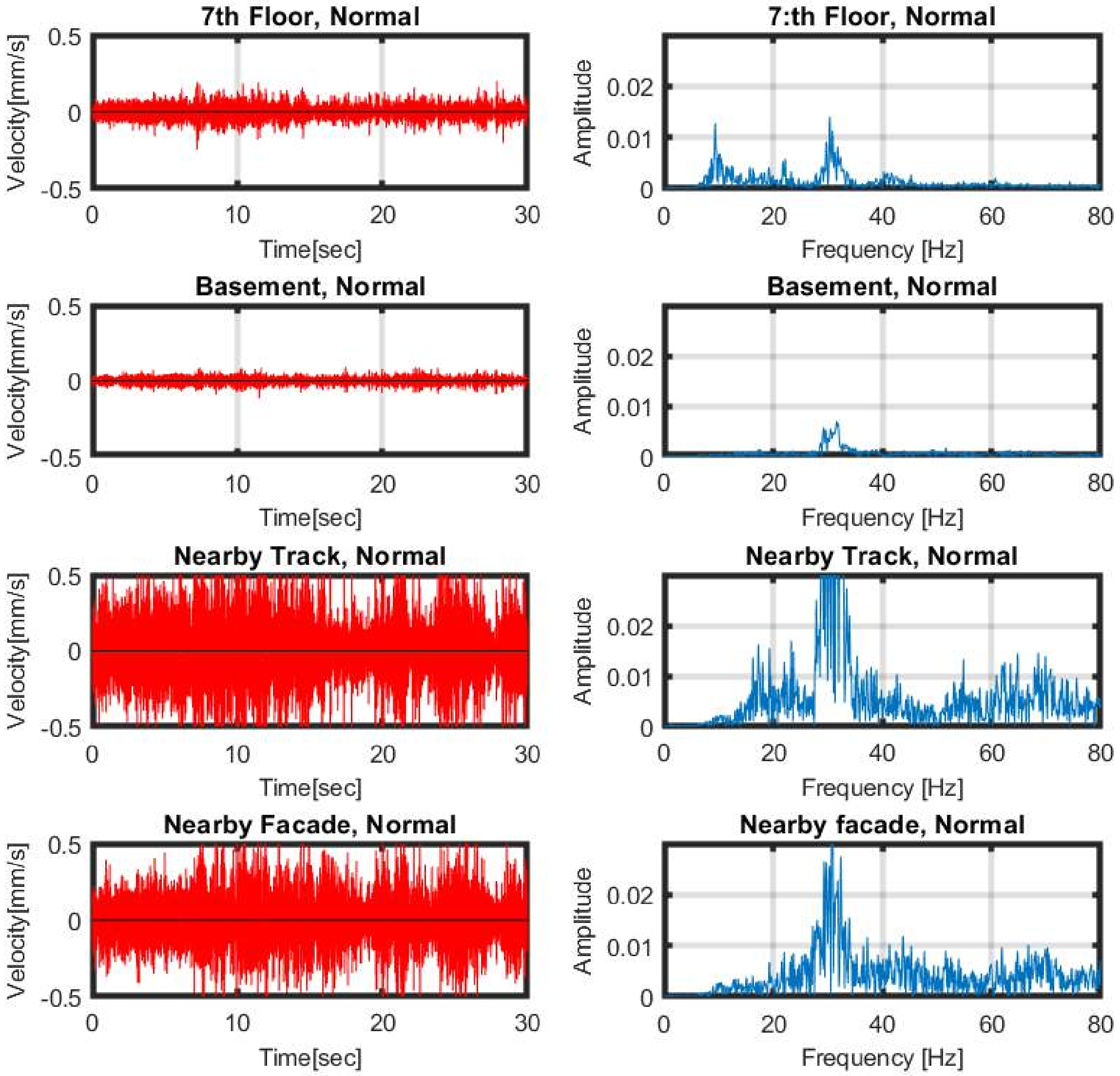

Figure A.10: Time domain and frequency domain of train no. 7

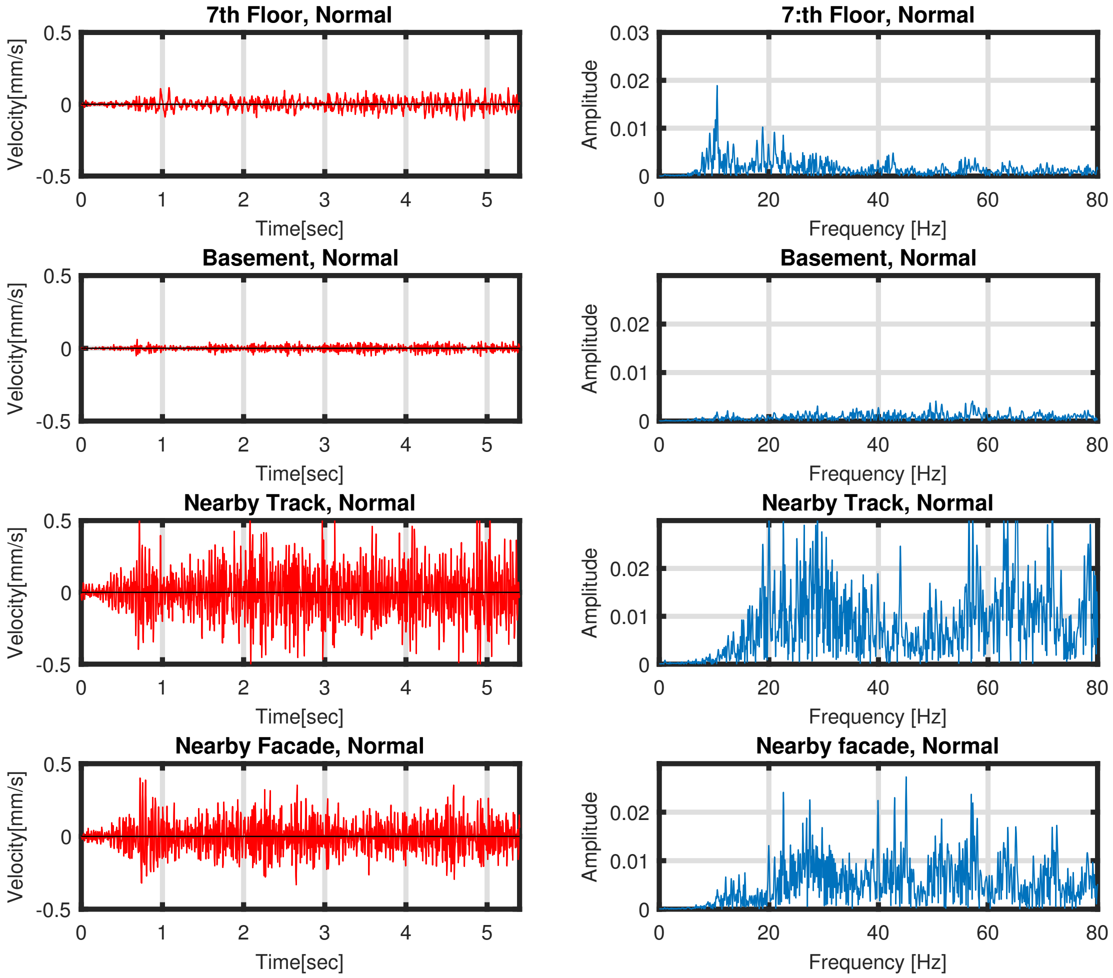

Figure A.11: Time domain and frequency domain of train no. 10

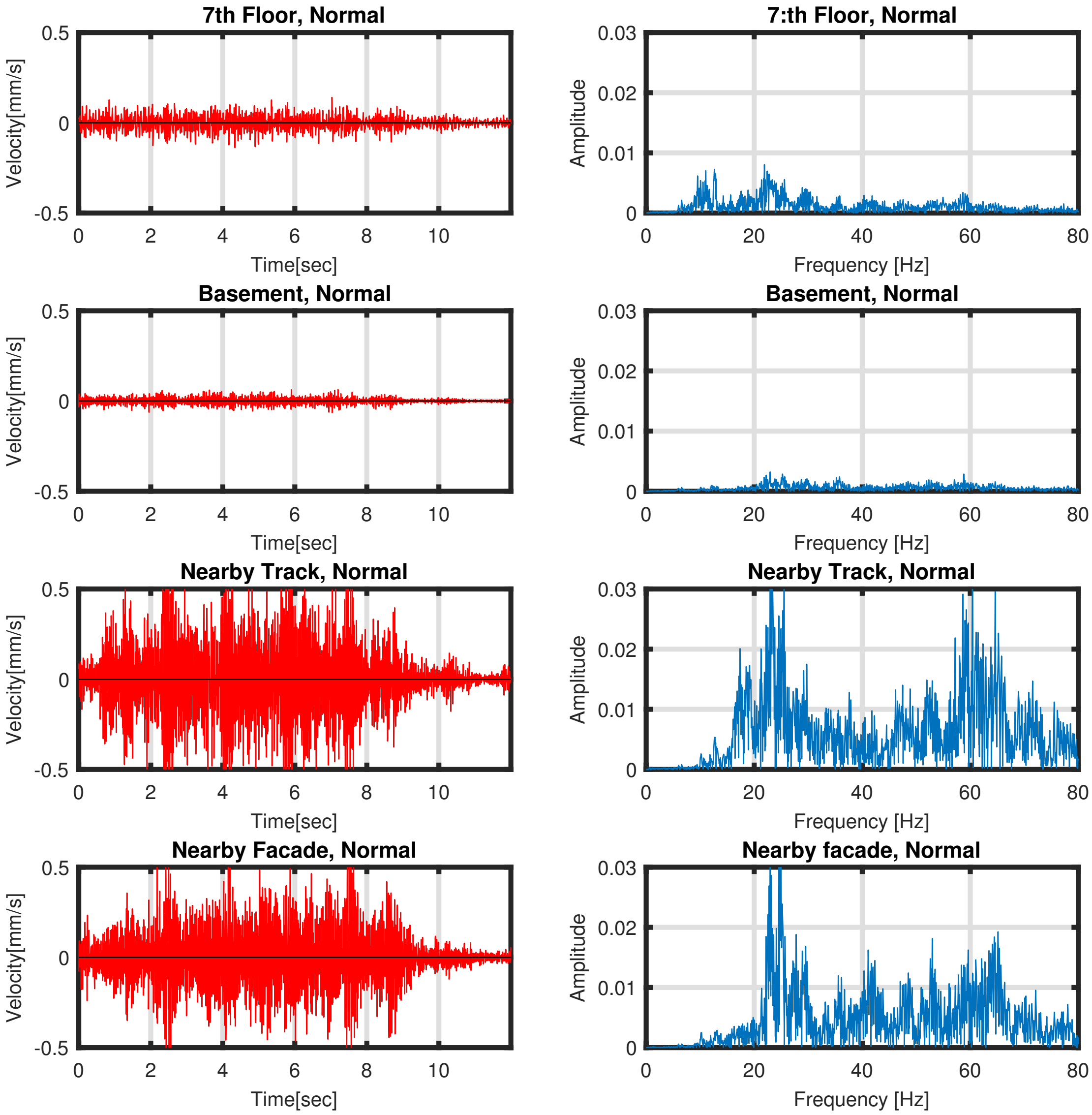

Figure A.12: Time domain and frequency domain of train no. 11

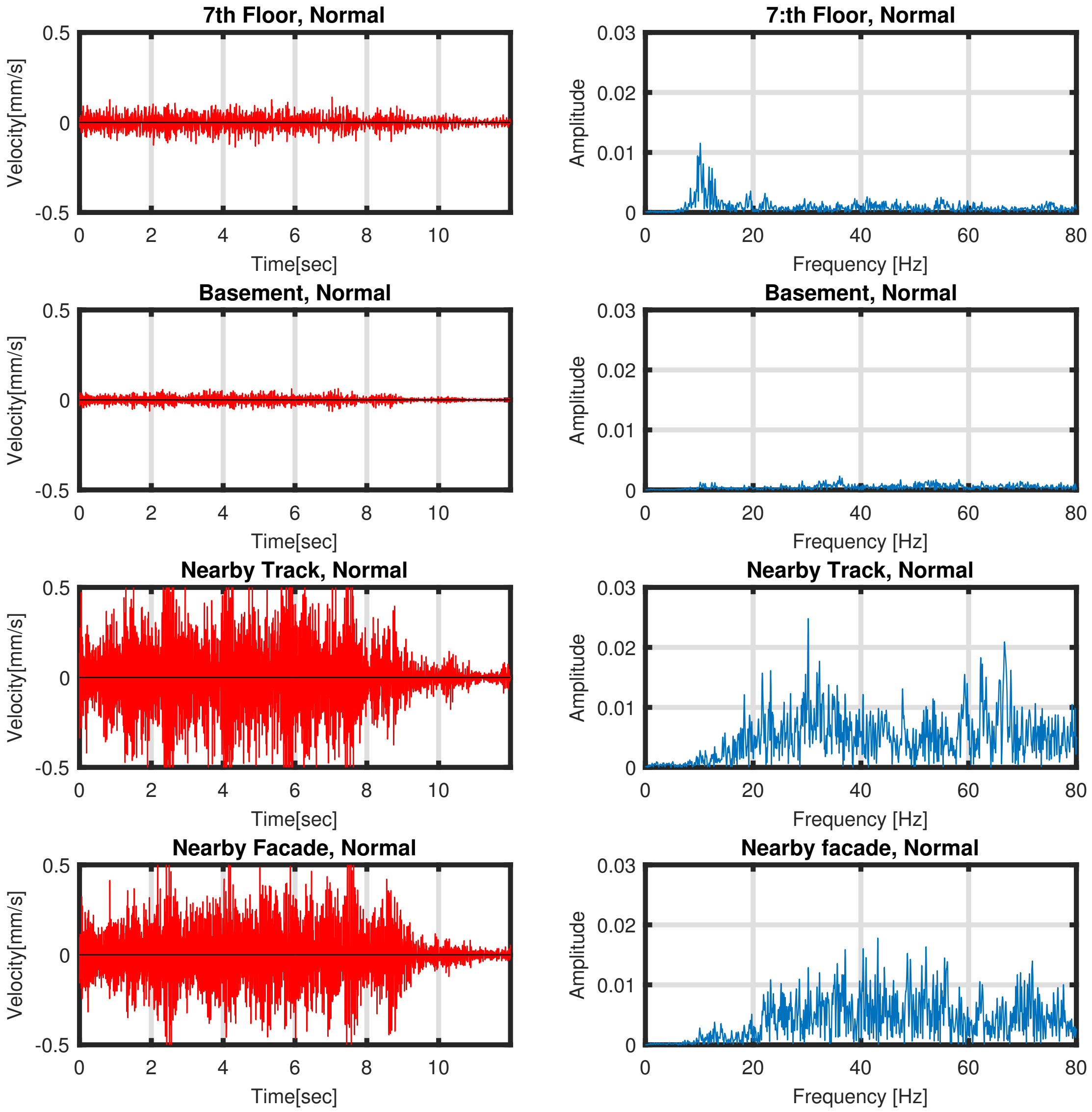

Figure A.13: Time domain and frequency domain of train no. 12

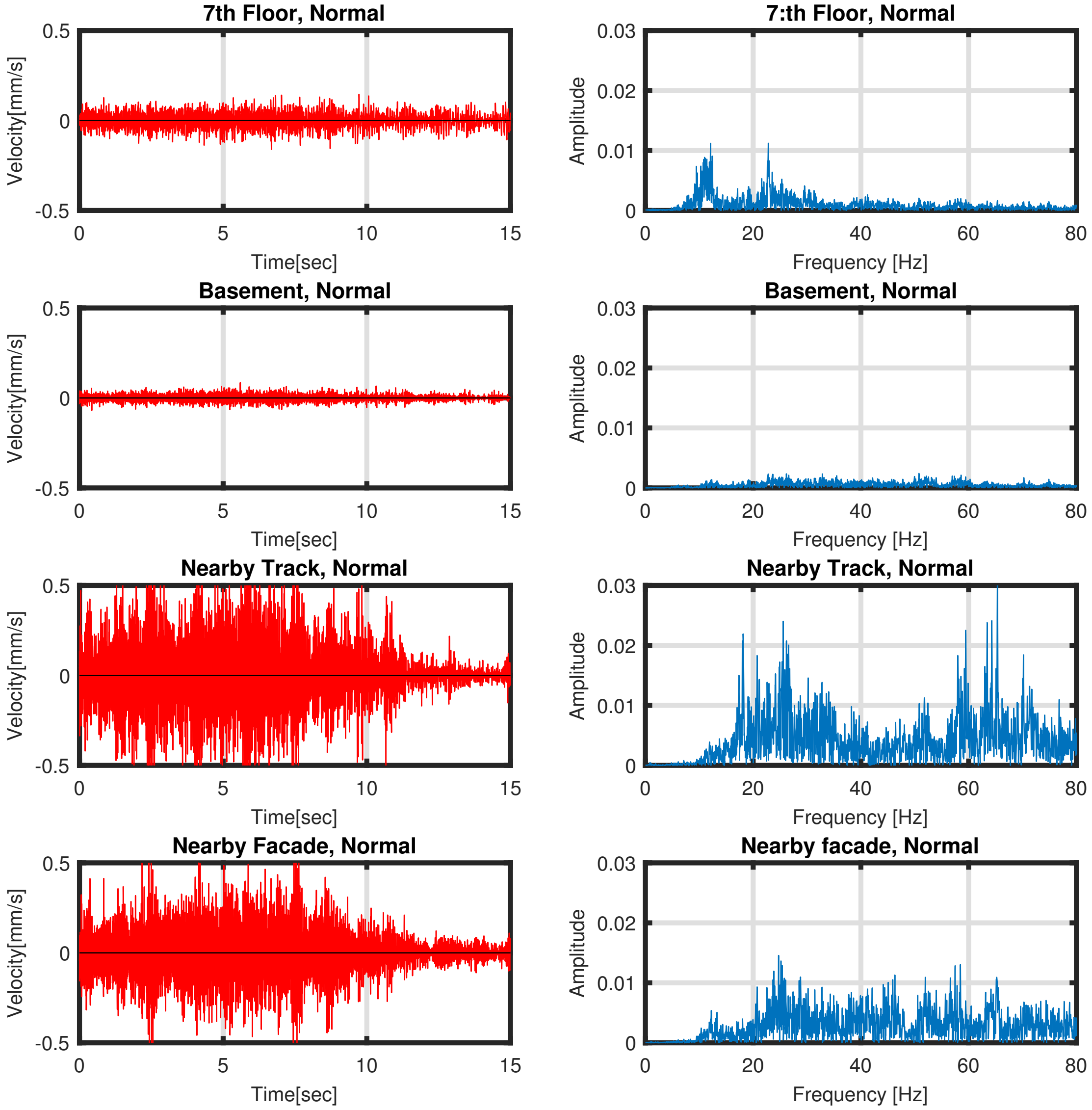

Figure A.14: Time domain and frequency domain of train no. 13

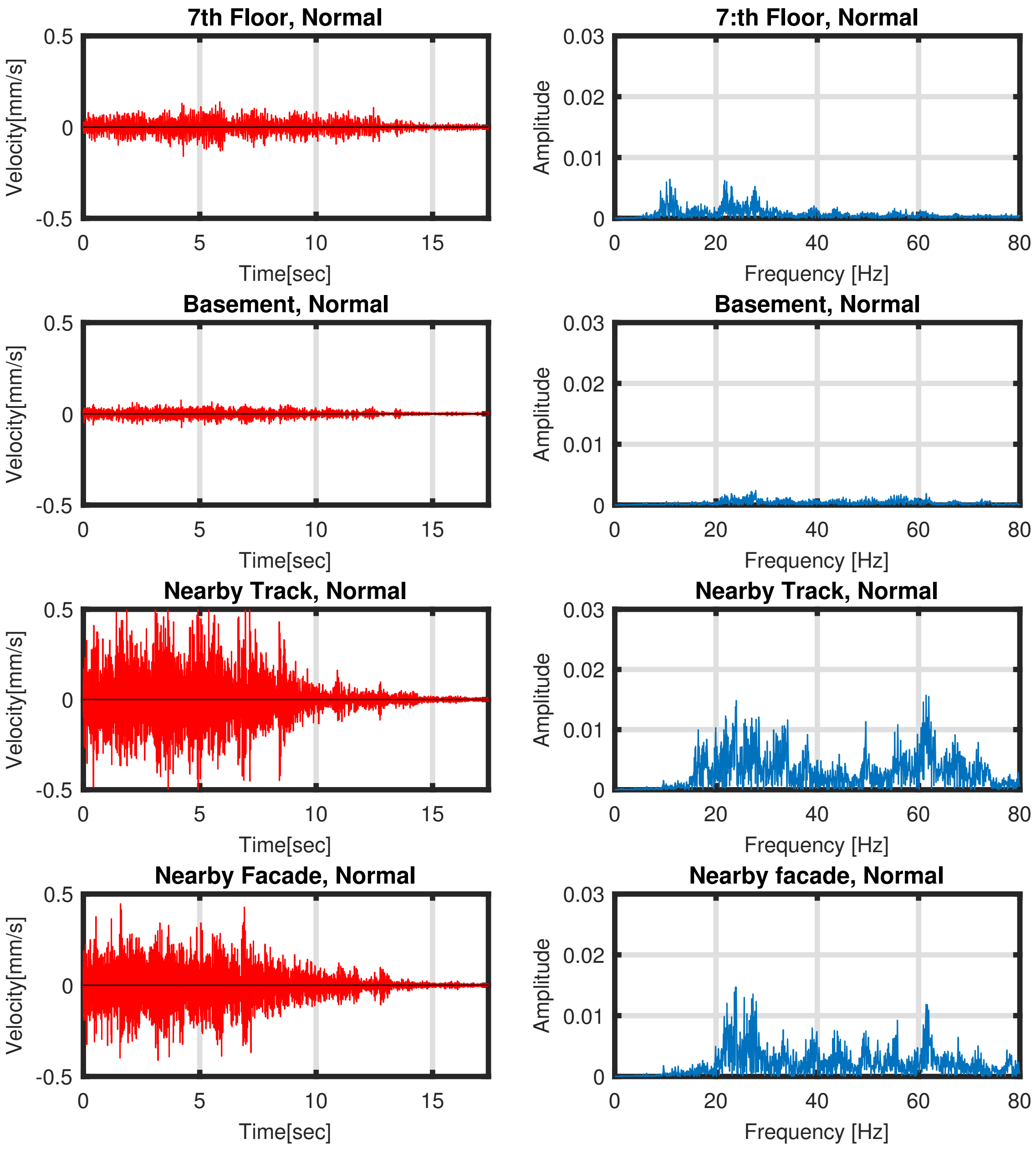

Figure A.15: Time domain and frequency domain of train no. 14

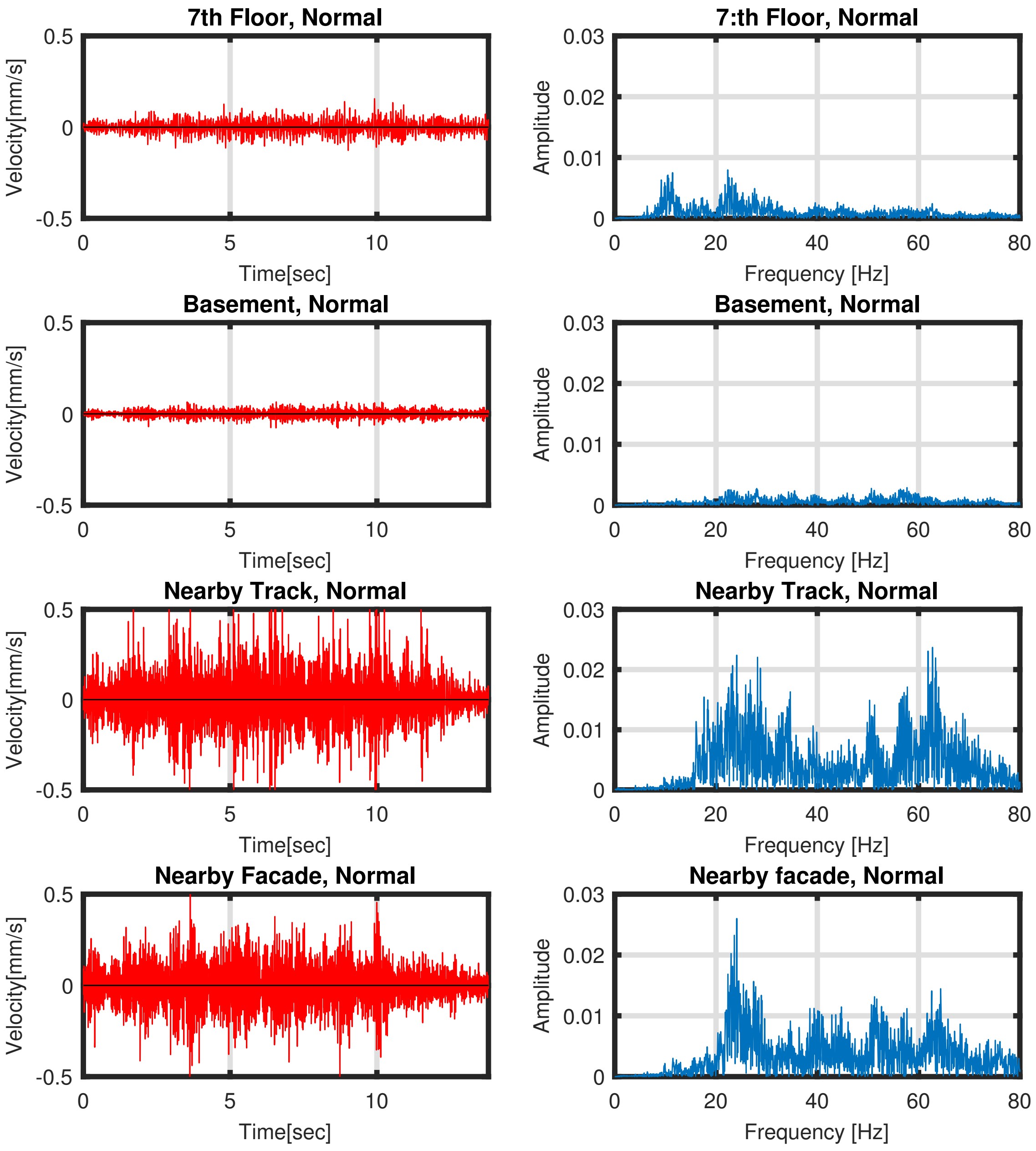

Figure A.16: Time domain and frequency domain of train no. 15

Appendix B

Matlab codes

All calculations were executed in MATLAB. Some of the code is presented in this chapter.

B.1 Train script

```
%% Train #2

%Train Specific Parameters
 Time=char('00');
 Starttime=6.95;
 Stoptime=7.05;

%%Parameters, direction and # seismometer
Rms=zeros(3,4);
D=char('e','n','z');
E=char('0','1','3','4');
 for r=1:3
     x=D(r);
     for g=1:4
         d=E(g);
         s=0;
         s = strcat(d,'20180823_17',Time,x);
         y = strcat(d,x);

%% Read Gcf files to MATLAB
         [SAMPLES,STREAMID,SPS,tStart] = readgcffile(s);

%% Extract correc train & correct unit
         Y=SAMPLES(250*60*Starttime:250*60*Stoptime);
         Y=Y*485e-9;

%% Create timevector
         c=linspace(0,(Stoptime-Starttime)*60,length(Y));

%% Low Pass Filter
% Input Parameters & saving old signal for plotting
         fp=75;
         fs=95;
         rp=0.00057564620966;
         rs=100;
         Fsamp=1/(c(5)-c(4));
         Hd=lowpasseqripp(Fsamp,fp,fs,rp,rs);
         Ygammal=Y;
```

```
%% Applying the filter to our signal

%Length of the impulse response (filter)
        lengthImpResp=length(Hd.numerator);

%Length of the sound
        lengthSound=length(Y);

%Delay of the filter (by definition: different if the filter is odd or even order)
        if (rem(lengthImpResp,2)==0) %rem : remainder after division
            delay=(lengthImpResp)/2; %If the filter length is even
        else
            delay=(lengthImpResp-1)/2; %If the filter length is odd

        end

%Convolution (to filter the sound)
        FilteredSound=conv(Y,Hd.numerator);

%Extracting (isolating) the sound (taking into account -deleting- the delay introduced by
% the filter at the beginning and at the end)
        FilteredSound=FilteredSound(delay+1:delay+lengthSound);
        FilteredOne=FilteredSound;

%% High pass filter, Butterworth:
        [b,a]=butter(5,0.008,'high');

%Filter the Data:
        FilteredTwo=filter(b,a,FilteredSound);

%% FFT operator % plotting
        [freq,Yfft]=fftoperator_2(c,FilteredTwo,g,r,Ygammal,FilteredOne,Starttime,Stoptime,Time);
     end
 end
```

B.2 Parks-McClellan filter

```
%% Filter designed with the toolbox "fdatool" (Matlab code generated automatically by the interface)

function Hd=lowpasseqripp(Fsamp,fp,fs,rp,rs)
%LOWPASSEQRIPP Returns a discrete-time filter object.

%
% MATLAB Code
% Generated by MATLAB(R) 7.11 and the Signal Processing Toolbox 6.14.
%
% Generated on: 19-Sep-2012 09:02:20
%

% Equiripple Lowpass filter designed using the FIRPM function.

% All frequency values are in Hz.
Fs=Fsamp; % Sampling Frequency

Fpass=fp;                % Passband Frequency
Fstop=fs;                % Stopband Frequency
Dpass=rp;                % Passband Ripple
Dstop=(10^(-rs/20));     % Stopband Attenuation
dens=20;                 % Density Factor

% Calculate the order from the parameters using FIRPMORD.
[N,Fo,Ao,W]=firpmord([Fpass, Fstop]/(Fs/2), [1 0], [Dpass, Dstop]);

% Calculate the coefficients using the FIRPM function.
b=firpm(N, Fo, Ao, W, {dens});
Hd=dfilt.dffir(b);

% [EOF]
```

B.3 Fft-operator

```
%
function [freq ,Yfft ,Rms]=fftoperator(time ,y,g,r ,ygammal ,One, Start ,Stop ,TrainTime)
% ------------------------------------------------------------------------------------------
%
%     PURPOSE
%       Obtain fft of timesignal y(t)- discrete fourier transform
%
%
%     INPUT:
%       time: row or column vector with n elements with constant increment
%       y: corresponding row or column vector with n elements of signal
%       g: # of the seismometer
%       r: # of the direction
%       ygammal: Old signal
%       One: Signal with one filter applied
%       Start: Starttime for the train
%       Stop: Stoptime for the train
%       TrainTime: Start time of the input file
%
%     OUTPUT:
%       freq: row or column vector with n elements with constant
%             increment [Hz]
%       yfft: corresponding row or column vector with n elements of
%             amplitudes
%       Rms: Maximum Rms value of the time signal over one second
%
%     REM.
%       Only the unique points are returned i.e. f lies in 0<=f<=Fs/2
%
%     REFERENCES
%       Juan Negreira; May 2011 mod. P-E Austrell 2018-02-01
%       mod. Adam Cederquist 2018-09-20
%-----------------------------------------------------------------------------------------
%
%
%
%% Plotting the time domain with all filters
Start=Start+str2num(TrainTime);
Stop=Stop+str2num(TrainTime);
Time=linspace(0,(Stop-Start)*60,length(ygammal));
UI={'7th Floor','Basement','Track','Fasade'};
UI2={', East',', North',', Normal'};
namn = strcat(UI(g),UI2(r));
figure(2*r-1)
  subplot (2,2,g)
   plot(Time,ygammal,'b');
   hold on
  plot(Time,One,'g');
   hold on
  plot(Time,y,'r');
   hold on
  plot([0 (Stop-Start)*60],[0 0],'black');
    title(namn)
  grid on
  xlabel('Time')
  ylabel('Velocity[mm/s]')

Yrms=y;
y=[y; 0*(1:length(y)*99)']*100;
dt=time(2)-time(1);
time=[time linspace(max(time)+dt,(max(time)+dt)*100-dt,length(time)*99)];
%% Introducing the time signal
xData=time;
yData=y;
%Calculating the FFT
%
%Number of points in input data
NFFT=length(yData);
```

```
%Nyquist frequency
Fn=1/(xData(2)-xData(1))/2;
%Absolute value of the FRF
FFTY=abs(fft(yData));
NumUniquePts=ceil((NFFT+1)/2 ) ;
% fft s~~tric , t hrow away second half
FFTY=FFTY(1:NumUniquePts) ;
% Take magnitude of Y
Yfft=abs(FFTY);
% Mult1ply by 2 to take into account the fact that we
% threw out second half of FFTY above
Yfft=Yfft*2 ;
% Account for endpoint uniqueness
Yfft(1)=Yfft(1)/2;
% We know NFFT is even
Yfft(length(Yfft))=Yfft(length(Yfft))/2;
% Scale the FFT so that it is not a function of the length of y.
Yfft=Yfft/length(yData);
%Frequencies
freq=(0:NumUniquePts-1)*2*Fn/NFFT;
%Name on plot
VectorG={'7:th Floor','Basement','Nearby Track','Nearby facade'};
VectorR={', East',', North',', Normal'};
namn = strcat(VectorG(g),VectorR(r));
k = find((freq-80) > 0);
k=k(1);
Var1=max(Yfft(1:k));
Rms=rms(Yfft);
Lengd=length(Yrms);
Stawp=floor(Lengd/250)*5-4;
S1=1;
RRms=[];
for i=1:Stawp
    i;
    S2=i*50+200;
    RRms(1,i)=rms(Yrms(S1:S2));
    S1=S2-249;
end
Rms=max(RRms);
figure(2*r)
subplot(2,2,g)
  plot(freq,Yfft)
  title(namn)
  grid on
  xlabel('Frequency [Hz]')
  ylabel('Amplitude')
  axis([0 80 0 Var1])
```