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# Sound Reflection from Building Facades

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# Problem description

It is very important in room acoustics and in outdoor noise measurements to have a good description of the reflections from a wall. This can be investigated by doing impulse response measurements, and analyse and compare the direct and the reflected sound signal. Measurements in front of a wall may produce destructive interference for some frequencies, depending on the positions of the loudspeaker and the microphone.

The task is to determine if it is possible to measure a reflection coefficient for a surface of an outdoor building facade. It is also desirable to find out if interference is an existing problem for this type of measurement, and what effect interference has for sound measurements.

# Acknowledgment

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# Abstract

This report describes a method for measuring the reflection coefficient in situ for perpendicular sound incidence. The impulse response is measured in front of a surface. In this experiment the surface is an outdoor building facade. A freefield impulse response is subtracted from the measured impulse response, canceling the direct impulse in the measured response. This results in an impulse response for the reflected sound. To avoid parasitic reflections, the reflected impulse response is multiplied with a time window of suitable size. The frequency response of the direct and reflected impulse response is obtained by fast Fourier transform of the windowed time signals. The reflection coefficient is calculated by dividing the absolute value of the frequency response of the reflected signal with the absolute value of the frequency response of the freefield signal. The absorption coefficient is found by subtracting the reflection coefficient from one, and average over the desired frequency bands. Here one third octave frequency bands are used.

The method proves to be valid for measuring the reflection coefficient of building facades in a frequency range from 250 Hz to 2500 Hz. No interference effects are found in this frequency range.

# Samandrag

Denne rapporten skildrar ein metode for å måle refleksjonskoeffisienten på staden for 90 graders innfallsvinkel for lyden. Impulsresponsen er målt framfor ei overflate. I dette ekperimentet er overflata ein utandørs bygningsfasade. Ein frittfeltsimpulsrespons er trekt frå den målte impulsresponsen, og kansellerar den direkte impulsen i den målte responsen. Dette resulterer i ein impulsrespons for den reflekterte lyden. For å unngå parasittiske refleksjonar er den reflekterte impulsresponsen multiplisert med eit tidsvindauga med ein passende storleik. Frekvensresponsen for den direkte og reflekterte impulsresponsen er funnen ved bruk av fast Fourier transform av tidssignala multiplisert med tidsvindauga. Refleksjonskoeffisienten er utrekna ved å dividere absoluttverdien av frekvensresponsen av det reflekterte signalet med absoluttverdien av frekvensresponsen av frittfeltssignalet. Absorpsjonskoeffisienten er funnen ved å trekke refleksjonskoeffisienten frå ein og ta gjennomsnittet over dei ønska frekvensbanda. Her er eintredelsoktavfrekvensband brukt.

Metoden er gyldig for måling av refleksjonskoeffisienten til bygningsfasadar i eit frekvensområde frå 250 Hz til 2500 Hz. Ingen effektar frå interferens er funne i dette frekvensområdet.

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# Chapter 1

## Introduction

Sound absorption coefficients can be measured using different types of measurement methods, with different limitations and advantages. It is not always easy to measure the sound absorption coefficient, especially not in situ, i.e. at the site.

The most common way to measure is by using a reverberation room. For a room, the sound absorption can be found by measuring the reverberation time. The sound absorption is calculated from the reverberation time, volume and the absorption area of the room. The absorption factor obtained from this measurement is an average for the entire room, and is not specific for any of the materials in the room. If the sound absorption coefficient is known for some materials, the equivalent sound absorption area can be calculated for others. This method for measuring the sound absorption coefficient of acoustical materials is described in ISO 354:2003 Acoustics - Measurement of sound absorption in a reverberation room [1].

Another method for measuring the absorption coefficient is the standing wave tube technique. It is described in ISO 10534-1:1996 Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes - Part 1: Method using standing wave ratio [2]. This method evaluates the standing wave pattern of a plane wave in a tube to determine the sound absorption coefficient, reflection factor, surface impedance or admittance of a material or an object.

Neither of the above two mentioned methods can measure the sound absorption coefficient in situ. Sometimes it is necessary to measure the sound absorption coefficient for a surface or material in situ. The surface may not be placed in a reverberation room or possible to move into a laboratory. Two different methods for in situ measurements of the sound absorption coefficient are the subtraction method and the transfer function method. These two methods are compared in [3]. The conclusion in [3] is that the results of the two methods differ. They are similar for some frequencies, but have deviations for high and low frequencies. The subtraction method needs two measurements. One with only the direct sound, an approximate freefield measurement. The second measurement has both a direct sound and a reflected sound. The first measurement is subtracted from the second and only the reflected sound remains in addition to possible parasitic reflections. How the subtraction method can be used for measurements of absorption coefficients for road surfaces is described in ISO/FDIS 13472-1, Acoustics - Measurement of sound absorption properties of road surfaces in situ - Part1: Extended surface method [4]. The subtraction technique is described both for perpendicular and oblique sound incidence in [5]. The method is here improved by using digitally preemphasized pseudonoise signals.

When performing sound measurements in front of a surface, the time delayed reflected signal is added to the direct sound. This delayed signal may interfere with the direct signal causing the signal to be ampli-

fied for some frequencies if the interference is constructive, or attenuated if the interference is destructive. Theoretical calculations indicate that interference may be a problem for sound measurements in front of a reflecting surface. The possibility of destructive interference in front of a reflecting surface has been investigated in [6]. Hopkins and Lam, [7], have studied the sound field in front of, and close to a building facade. These studies are done in connection with environmental noise and sound insulation. This article refers to [8], where experiments on facades are done. Some of the results indicate problems with interference effects from the ground surface. In a study of in situ measurements of reflection index and sound insulation index of noise barriers [9], it has been noticed that scattering effects of the surface and ground reflection could influence the measurement results and introduce errors.

Sound insulation measurements is a type of sound measurement where interference effects may be a severe problem. Berandi has investigated possible effects of interference in front of a building facade [10], [11]. The measurement method for field measurements of airborne sound insulation for outer walls of buildings is described in NS-EN ISO 140-5, Akustikk Lydforhold i bygninger Del 5: Feltnåling av luftlydisolasjon av bygningsdeler i yttervegg og av yttervegger [12]. According to this standard, the sound pressure level should be measured directly on the building surface or 2 meters in front of the building facade. The reason why these positions are chosen, is most likely to avoid problems due to interference. In some situations it may be difficult or impossible to measure in these positions. It is desirable to be able to measure in other positions without having problems with interference effects.

The destructive interference occur at different frequencies depending on the positions of the microphone and loudspeaker relative to the reflecting surface. For sound insulation measurements, the effects of destructive interference is most evident at low frequencies, because the constructive interference did not overlap among bands [13]. Destructive interference is most severe for frequencies where the reflected signal is 180 degrees out of phase compared to the direct signal. The first frequency out of phase is the frequency delayed by half a wavelength. A possible solution to the problem may be to reduce or increase the distance to the reflecting surface, and move the interference out of the frequency range of interest.

Another work in progress, with a connection to this thesis, is a series of outdoor field measurements where a constant sound source and different microphone positions are used. The microphone positions used are fixed positions directly on the facade, fixed position in front of the facade and microphone sweep in front of the facade. The purpose of this thesis is to investigate if it is possible to measure sound insulation for a facade by using microphone positions in front of the facade, without having severe interference problems.

## 1.1 Outline of the report

Chapter 2 describes how sound propagates and different phenomena related to this. A summary of the standard ISO/FDIS 13472-1, Acoustics - Measurement of sound absorption properties of road surfaces in situ - Part1: Extended surface method is given in chapter 3, and a summary of NS-EN ISO 140-5, Akustikk Lydforhold i bygninger Del 5: Feltnåling av luftlydisolasjon av bygningsdeler i yttervegg og av yttervegger is given in chapter 4. These two chapters are describing a method for measuring sound absorption in situ, and how to measure sound insulation in building facades. How the experiment is done is described in chapter 5. Results are presented in chapter 6, discussed in chapter 7 and a conclusion is given in chapter 8. Technical specifications are given in appendix A, more detailed measurement results are given in appendix B and Matlab code for calculations are given in appendix C.

## Chapter 2

# Outdoor sound propagation

Sound is variation of pressure travelling as a wave through a medium, such as air, water or solids. In air sound propagates as longitudinal waves. When a sound wave is travelling in a medium, phenomena like reflection, interference, refraction or diffraction may occur. In outdoor environments factors like geometrical spreading, atmospheric effects, and surface effects may affect the propagation of the sound. These phenomena are described below.

### 2.1 Geometrical spreading

When a wavefront travels from a source in a lossless medium with no reflection with an increasing distance from the source, it will lead to spreading of sound power due to distribution of the sound power over an increasing area. This geometrical spreading is independent of frequency. For a point source radiating sound equally in all directions, the intensity  $I$  in a distance  $r$  from the source is given by equation 2.1

$$I = \frac{p^2(r)}{\rho c} = \frac{P}{4\pi r^2} \quad (2.1)$$

where  $p^2(r)$  is the sound pressure at distance  $r$ ,  $\rho c$  is the acoustic impedance and  $P$  is the power of the source in watt [14]. The logarithmic relationship between sound pressure level  $L_p$ , sound power level  $L_W$  and distance  $r$  is given in equation 2.2.

$$L_p = L_W + 20 \log r - 11 [dB] \quad (2.2)$$

For a point source this corresponds to a 6 dB decrease for a doubling of distance [14]. A point source is omnidirectional. For a directional source, the directivity index  $DI$  is added to account for the distribution of intensity depending on the direction. This results in equation 2.3.

$$L_p = L_W + 20 \log r - 11 + DI [dB] \quad (2.3)$$

The directivity index is given by  $10 \log DF$ , where  $DF$  is the directivity factor. The directivity factor is a ratio between the actual sound intensity and the sound intensity from a omnidirectional point source.

## 2.2 Atmospheric effects

### 2.2.1 Air absorption

When a sound wave is travelling through air, some of the sound energy is converted to heat. The amount of sound energy loss is dependent of the temperature and humidity of the air. The sound absorption in the air is also strongly dependent of frequency. The air absorption is significant for high frequencies at long range. For a plane wave, the distance  $r$  from where the sound pressure is  $p_0$ , the sound pressure  $p$  is given by equation 2.4.

$$p = p_0 e^{-\alpha r/2} \quad (2.4)$$

$\alpha$  is the attenuation coefficient for air absorption, which is dependent of frequency, humidity, temperature and pressure [14]. Air absorption is normally negligible, except for long distances and for very high frequencies.

### 2.2.2 Speed of sound

The speed of sound is determined by the properties of the medium which the sound wave is travelling in. For air, the speed of sound depends on the properties of the air, like the temperature, humidity and altitude/density. The main factor affecting the speed of sound in air is temperature. An approximate formula for calculation of speed of sound in dry air at sea level is given in 2.5

$$c_{air} = 331 + 0.6T_c \quad (2.5)$$

where  $c_{air}$  is the speed of sound in air in m/s and  $T_c$  is temperature in Celsius. At 20 degrees Celsius, the speed of sound in air is approximately 343 m/s [15].

### 2.2.3 Refraction

A medium may contain different temperatures. As described above, the speed of sound changes with temperature. When a medium has layers of different temperatures, the sound travels with different speed and the direction of the sound waves changes. This change of direction of propagation for a wave is called refraction. Refraction also occurs in change of media. This is described below in the section about surface effects and refraction.

## 2.3 Surface effects

### 2.3.1 Reflection

When a travelling acoustical wave encounters a surface, some of the sound is absorbed and some is reflected. A hard smooth surface reflects the sound wave with the same shape and characteristics as the incident wave. The angle of incidence for the wave is equal to the angle of reflection, where the angle is between a normal to the surface and the incidence and reflected wave. This is illustrated in figure 2.1, where  $\theta_i$  is the incidence angle and  $\theta_r$  is the reflection angle. It can be seen that  $\theta_i = \theta_r$ .

Reflection can be described by the ratio between amplitudes of the reflected and the incident wave. This ratio is often called the reflection coefficient.

$$R = \frac{(Z_2/Z_1) - \sqrt{1 - (n-1)\tan^2\alpha_i}}{(Z_2/Z_1) + \sqrt{1 - (n-1)\tan^2\alpha_i}} \quad (2.6)$$

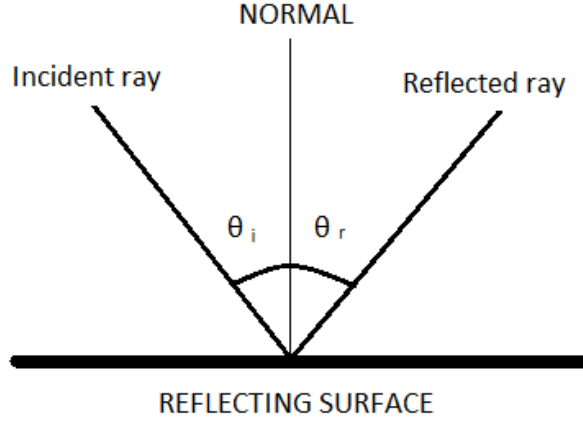


Figure 2.1: Specular reflection.

where  $Z_1$  and  $Z_2$  are the acoustic impedances for the first and the second medium,  $n = (c_2/c_1)^2$  and  $\alpha_i$  is the incidence angle. The acoustic impedance is given by the density  $\rho$  and speed of sound for the medium,  $Z = \rho c$  [16]. For a normal incidence situation where  $\alpha_i = 0$ , equation 2.6 can be simplified to 2.7.

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (2.7)$$

If the surface is not hard and smooth, the reflections may be diffuse. An uneven surface with irregularities will not reflect sound in a specular way as described above, with angle of reflection equal to the angle of incidence. In a diffuse reflection, the sound will be reflected in different directions. Whether a sound wave is reflected in a specular or diffuse way is decided by the size of the irregularities of the surface compared to the wavelength of the sound wave. If the wavelength is large compared to the irregularity in the surface, the irregularity is ignored and the sound is reflected in a specular way. Sound waves with small wavelengths are most affected by irregularities in an uneven surface.

### 2.3.2 Refraction

When a sound wave in one medium encounters a boundary of another medium, the wave is both reflected and transmitted. Refraction is when a wave is bent away from the straight way of travel. This is illustrated in figure 2.2.

The correlation between the angle of incidence and the angle of the transmitted wave is given by equation 2.8

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2} \quad (2.8)$$

where  $\theta_1$  is the angles of incidence,  $\theta_2$  is the angle of the transmitted wave,  $c_1$  is the speed of sound in first medium and  $c_2$  is the speed of sound in the second medium. This equation is called Snell's law [17].

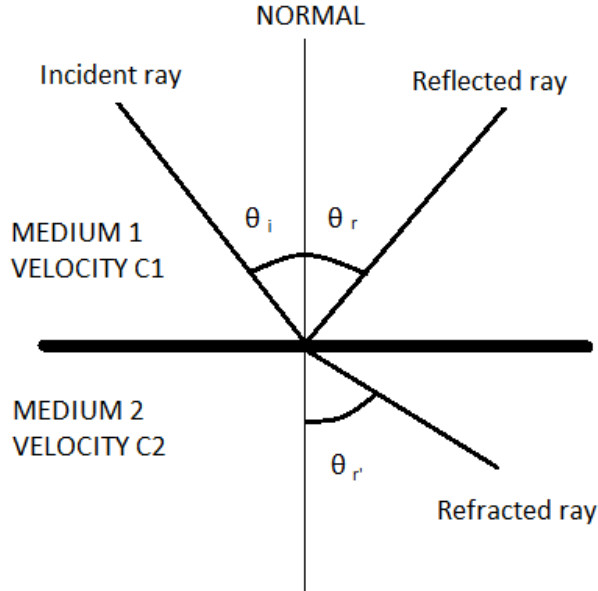


Figure 2.2: Reflection and transmission of an acoustic wave from one medium to another.

### 2.3.3 Interference

When two sound waves are added together, they interfere with each other. The interference can be either constructive or destructive. Whether the interference is constructive or destructive depends on the phases of the sound waves added together. Two waves of same frequency but out of phase gives destructive interference. If one wave is 180 degrees out of phase, the waves cancels each other out. If the waves are in phase, the interference is constructive. An example of how in phase and out of phase signals add together are illustrated in figure 2.3.

When a sound source is placed close to a reflecting surface the comb filter effect may occur. What happens is that the signal is added to a delayed version of itself. The delayed signal can be in phase or out of phase with the original signal. This gives constructive or destructive interference, which can lead to amplification of some frequencies and cancellation of others. The delayed signal will be in phase with the original signal for those frequencies that are delayed by a whole number of wavelengths. It will be 180 degrees out of phase and cancel the original signal out for the frequency delayed by half a wavelength. This is better described by equation 2.9 for in phase and 2.10 for out of phase delayed signals

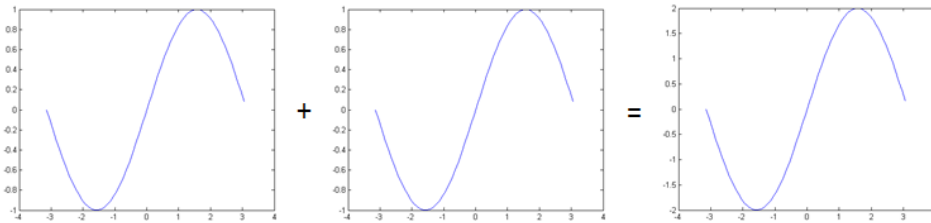
$$2d = n\lambda \tag{2.9}$$

$$2d = (n - 0.5)\lambda \tag{2.10}$$

where  $d$  is the distance from the reflecting surface to the listening or measurement point,  $n$  is a whole number and  $\lambda$  is the wavelength. The frequency can be found by using equation 2.11



In phase:



Out of phase:

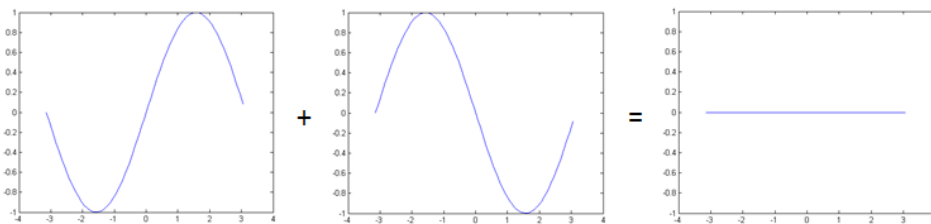


Figure 2.3: Constructive and destructive interference.

$$f = \frac{c}{\lambda} \quad (2.11)$$

where  $f$  is the frequency,  $c$  is the speed of sound and  $\lambda$  is the wavelength.

### 2.3.4 Ground absorption

When sound waves travel over ground, there is an energy loss due to reflection. How much the sound is absorbed in the ground depends on the surface and material of the ground, frequency of the sound and distance to the ground. When the source and receiver is placed close to the ground, the reflected sound may interfere with the direct sound. This is called the ground effect. This effect is normally noticed for frequencies between 200 and 600 Hz and for distances of some meters [18].

### 2.3.5 Diffraction

Diffraction is bending of wave due to a barrier, object or a small opening. When sound waves meet a barrier, some of the sound is reflected, some of it continues and some is bent or diffracted around the barrier. When meeting objects smaller than or about equal to the wavelength, the wave is diffracted around the object. Low frequency waves are more likely to be diffracted and bent around the object, and high frequencies are reflected or absorbed.

## Chapter 3

# Sound absorption measurements in situ (ISO/FDIS 13472-1)

How sound absorption for surfaces can be measured in situ is described in ISO/FDIS 13472-1 [4]. A loudspeaker is placed in front of the surface under test and a microphone is placed between the loudspeaker and the surface. The overall impulse response consists of a direct impulse, a time delayed impulse reflected from the surface and later reflections from the environment. The direct and reflected impulse response can be separated by temporal separation or signal subtraction technique. The sound absorption coefficient is found by using the Fourier transform of the direct sound and the sound reflected from the surface under test,

$$\alpha(f) = 1 - Q_W(f) = 1 - \frac{1}{K_r^2} \left| \frac{H_r(f)}{H_i(f)} \right|^2 \quad (3.1)$$

where  $Q_W(f)$  is the sound power reflection and  $K_r = \frac{d_s - d_m}{d_s + d_m}$  is a factor due to geometrical spreading.  $d_s$  is the distance from the sound source to the surface under test and  $d_m$  is the distance from the microphone and the surface under test. The complex reflection factor is given by 3.2

$$Q_p(f) = \frac{1}{K_r} \left| \frac{H_r(f)}{H_i(f)} \right| e^{i2\pi\Delta\tau} \quad (3.2)$$

where  $\Delta\tau$  is the time difference between the direct and the reflected impulses.

### 3.1 Signal separation techniques

The impulse response consists of a direct impulse, a reflected impulse and parasitic reflections. Two methods for separating the different components are described in [4], temporal separation and signal subtraction technique.

#### 3.1.1 Temporal separation

If there is an appropriate time difference between the direct, reflected and parasitic signals, a time windows can be used to separate the signals. The idea of this method is illustrated in figure 3.1.

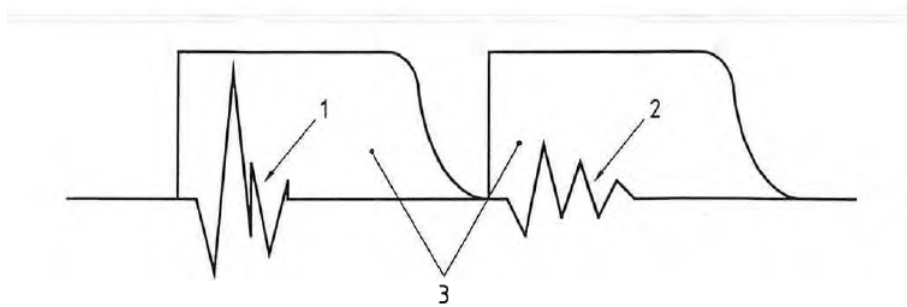


Figure 3.1: Separation using time window. 1. is the direct component, 2. is the reflected component and 3. are time windows. (From [4])

### 3.1.2 Signal subtraction technique

This technique requires an exact representation of the direct signal. This can be achieved by doing freefield measurements with the same equipment and same conditions. The freefield measurement can be subtracted from the overall response, resulting in the reflected response alone. This is illustrated in figure 3.2.

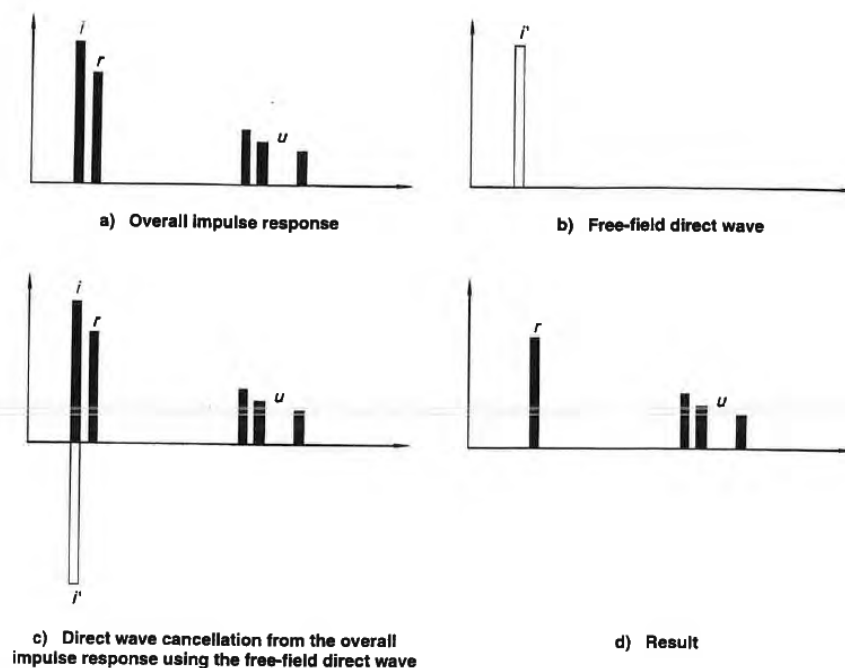


Figure 3.2: Separation using signal subtraction.  $i$  is the direct incident wave,  $r$  is the reflected wave,  $u$  is the unwanted parasitic reflections and  $i'$  is the freefield direct wave. (From [4])

With this technique, measurements can be done closer to the surface and with a longer sampling interval, than with the temporal separation technique.

## 3.2 Radius of the maximum sampling area

To avoid parasitic reflections, surrounding reflecting objects must be kept at a distance from the surface area under test. This area is a circle with center in the point of incidence and radius given in 3.3

$$r = \frac{1}{d_s + d_m + cT_W} \sqrt{(d_s + d_m + \frac{cT_W}{2})(d_s + \frac{cT_W}{2})(2d_m + cT_W)cT_W} \quad (3.3)$$

where  $c$  is the speed of sound in air and  $T_W$  is the width of the temporal window used to isolate the sound pressure wave reflected by the surface under test.

## 3.3 Physical principle of the measurement

The physical principal of the measurements can be described by the overall microphone response,  $h_m(t)$ , in 3.4

$$h_m(t) = h_i(t) + K_r h_i(t) * r_p(t - \Delta\tau) + \sum_j K_{r,j} h_i(t) * r_{p,j}(t - \Delta\tau_j) + h_n(t) \quad (3.4)$$

where  $h_i(t)$  is the impulse response of the direct path,  $r_p(t)$  is the reflection factor of the surface under test,  $h_n(t)$  is the background noise response,  $*$  is the convolution sign,  $j$  denotes the parasitic reflections,  $K_r$  is the geometrical spreading factor and  $\Delta\tau = 2d_m/c$  is the path length difference between the direct and the reflected path.

## Chapter 4

# Sound insulation in building facades (ISO 140-5)

Methods for field measurements of airborne sound insulation of facade elements and facades is described in NS-EN ISO 140-5 [12]. Two methods is described, the loudspeaker method for building parts and the global loudspeaker method. The loudspeaker method for building part gives an estimate for the field measured sound reduction index, and can be compared with valued measured in laboratory. The global method is measuring airborne sound insulation for an entire facade or building in a given situation, and is not comparable with laboratory measurements.

The average sound pressure level is measured directly on the building surface or 2 m in front of the building facade, and in the receiver room. From the measurements the field measured sound reduction index or sound pressure level difference is calculated.

### 4.1 Sound reduction index

Sound reduction index,  $R$ , is given by equation 4.1

$$R = 10 \log\left(\frac{W_1}{W_2}\right) dB \quad (4.1)$$

where  $W_1$  is the sound effect on the building facade and  $W_2$  is the sound effect transmitted through the building. Sound reduction index measured in the field,  $R'$ , is given by equation 4.2

$$R' = 10 \log\left(\frac{W_1}{W_2 + W_3}\right) dB \quad (4.2)$$

where sound effect from flanking or other building parts,  $W_3$ , is taken into account.

When a loudspeaker is used as sound source and placed with an incidence angle of  $45^\circ$ , the sound reduction index is given by equation 4.3

$$R'_{45^\circ} = L_{1,s} - L_2 + 10 \log\left(\frac{S}{A}\right) dB - 1.5 dB \quad (4.3)$$

where  $L_{1,s}$  is average sound pressure level on the building surface,  $L_2$  is average sound pressure level in the receiver room,  $S$  is the area of the building surface and  $A$  is sound absorption area in the receiver room.

Sound absorption area is calculated by Sabine's formula,  $A = \frac{0.16V}{T}$ , where V is the volume and T is the reverberation time in the receiver room.

## 4.2 Sound pressure level difference

Sound pressure level difference  $D_{2m}$  is the difference between outdoor sound pressure level 2 m in front of the building facade  $L_{1,2m}$  and the average sound pressure level in the receiver room  $L_2$ . It is given by equation 4.4.

$$D_{2m} = L_{1,2m} - L_2 \quad (4.4)$$

# Chapter 5

## Experiment

This chapter describes how the experiment is performed. It gives details about the equipment used, the measurement method and how the post processing is done.

### 5.1 Equipment

ISO13472 [4] states that the test system should consist of an signal generator, a power amplifier, a loudspeaker, a microphone with amplifier and a signal analyzer. Equipments used in this experiment:

#### **Measurement PC with WinMLS**

Lenovo  
ThinkPad T400

#### **Sound card**

Type: USB Audio  
Model: D-audio  
Serial number: 009900095

#### **Power amplifier**

Brül & Kjær  
Type: 2716  
Serial number: 2098846

#### **Loudspeaker-microphone probe**

Zircon  
Acoustic Engineering  
Serial number: 1004

#### **Sound level meter**

Norsonic  
Precision Sound Analyser Nor140  
Serial Number: 1404010

A measurement PC with WinMLS software was used for signal generator and analyser. Zircon loudspeaker-microphone probe is well suitable for measuring in situ sound reflection, absorption

properties of large surfaces, and airborne sound insulation properties of large walls [19]. The loudspeaker unit is a LS14. The microphone is a DPA 4060-B prepolarized omnidirectional miniature condenser microphone. The microphone was placed on a mast to keep a constant distance between microphone and loudspeaker. The distance used was 1.00 meter. Specifications for loudspeaker and microphone are given in table A. More detailed information on the Zircon probe can be found in [19]. The measured data was analysed further using Matlab.

## 5.2 Measurement method

Impulse response measurements were done using the software WinMLS. A typical impulse response generated by the Zircon probe using WinMLS is shown in figure 5.1.

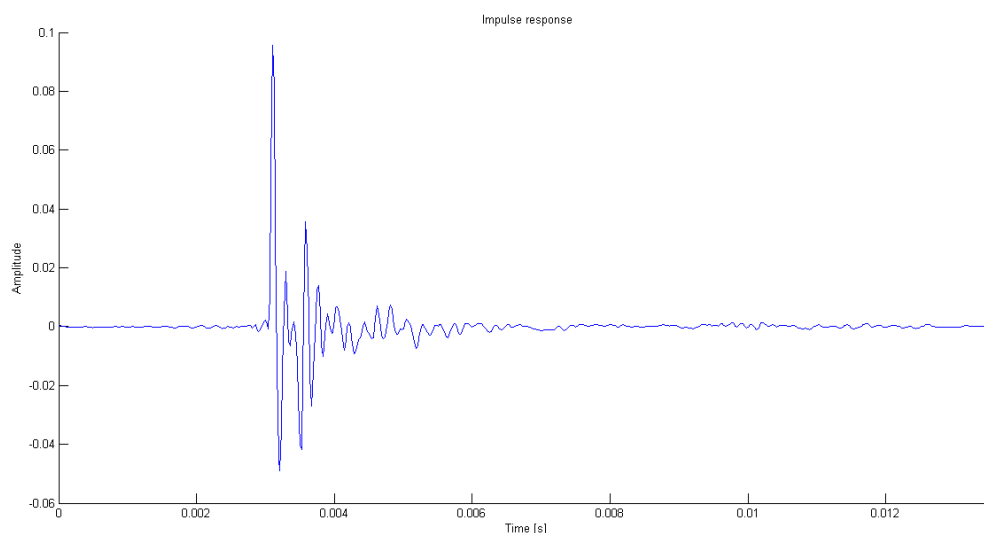


Figure 5.1: Impulse response

The freefield measurement was done by placing the Zircon probe a distance from any reflecting surface and pointing the loudspeaker up into the approximately free air. ISO 13472 [4] recommends to at least measure and average 50 impulse responses in order to minimize variations and to get an as accurate as possible representation of the freefield response. All measurements should be performed within an as short as possible period of time. This is to avoid variations of meteorological conditions, like the temperature, which affect the speed of sound. Five freefield measurements were performed. This amount of measurements was chosen to minimize the duration of the total measurement time of the experiment. Five measurements will still give some basis for comparison.

To do the reflection measurement, the loudspeaker and microphone was placed normal to the plane of the surface under test. Impulse response measurements were done for different distances. Three measurements were done for each distance. These measurements were made sure not to have large irregularities, and then averaged.

An example of an impulse response measurement in front of a surface is shown in figure 5.2, with the



direct impulse, the reflected impulse and some later small parasitic reflections. The reflected impulse is time delayed and attenuated compared to the direct impulse, but it is similar in shape.

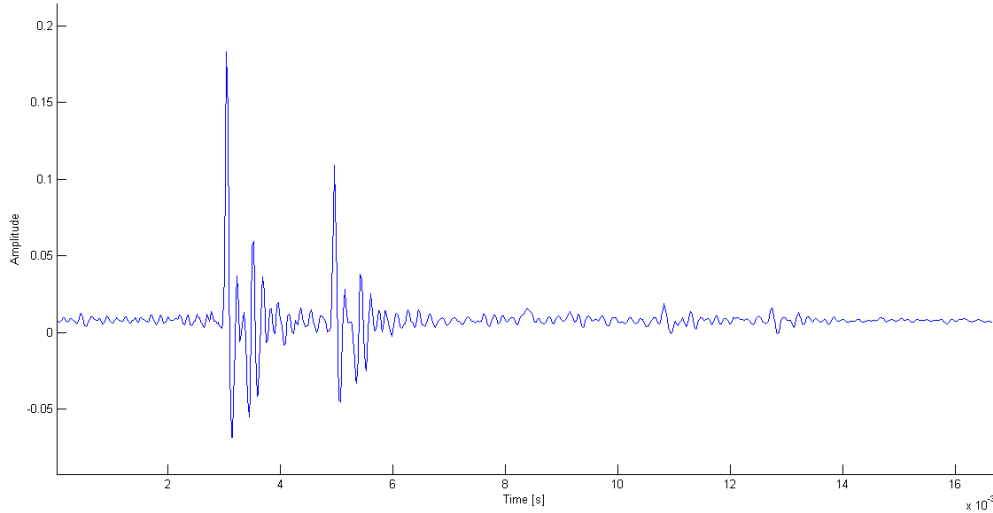


Figure 5.2: Impulse response measured in front of a surface.

### 5.2.1 Measurement setup

The microphone was placed 1.00 m from the loudspeaker. This distance was held strictly constant due to the mast of the Zircon probe. The measurement setup is illustrated in figure 5.3, where  $d_s$  is the distance from the loudspeaker to the surface,  $d_m$  is the distance from the microphone to surface and  $h_s$  is the distance from the ground to the loudspeaker.

The measurement PC was connected to an external sound card. The output from the sound card was connected to the amplifier and then to the loudspeaker. The input to the sound card was connected to the microphone via the loudspeaker of the Zircon probe.

### 5.2.2 Test site

The measurements were done outside on building facade surfaces. ISO 13472 [4] states that the surface under test should be visually homogenous and free of changes in material properties. The material also needs to be dry. The speed of the wind should not exceed 5 m/s, and the air temperature is recommended to be between 0 and 35 degrees Celsius during the measurement.

Two series of measurements were performed on two types of building facades. One on a brick building facade and one on a facade of slate material. The different types of surface material are shown in figure 5.4.

The measurements performed on the brick facade were done on March 14, 2013, in Oslo, Norway. The weather was sunny, the temperature was about 0 degrees Celsius and the wind was below 5 m/s. Pictures of the measurement site for the brick facade and setup of the instruments is shown in figure 5.5. A

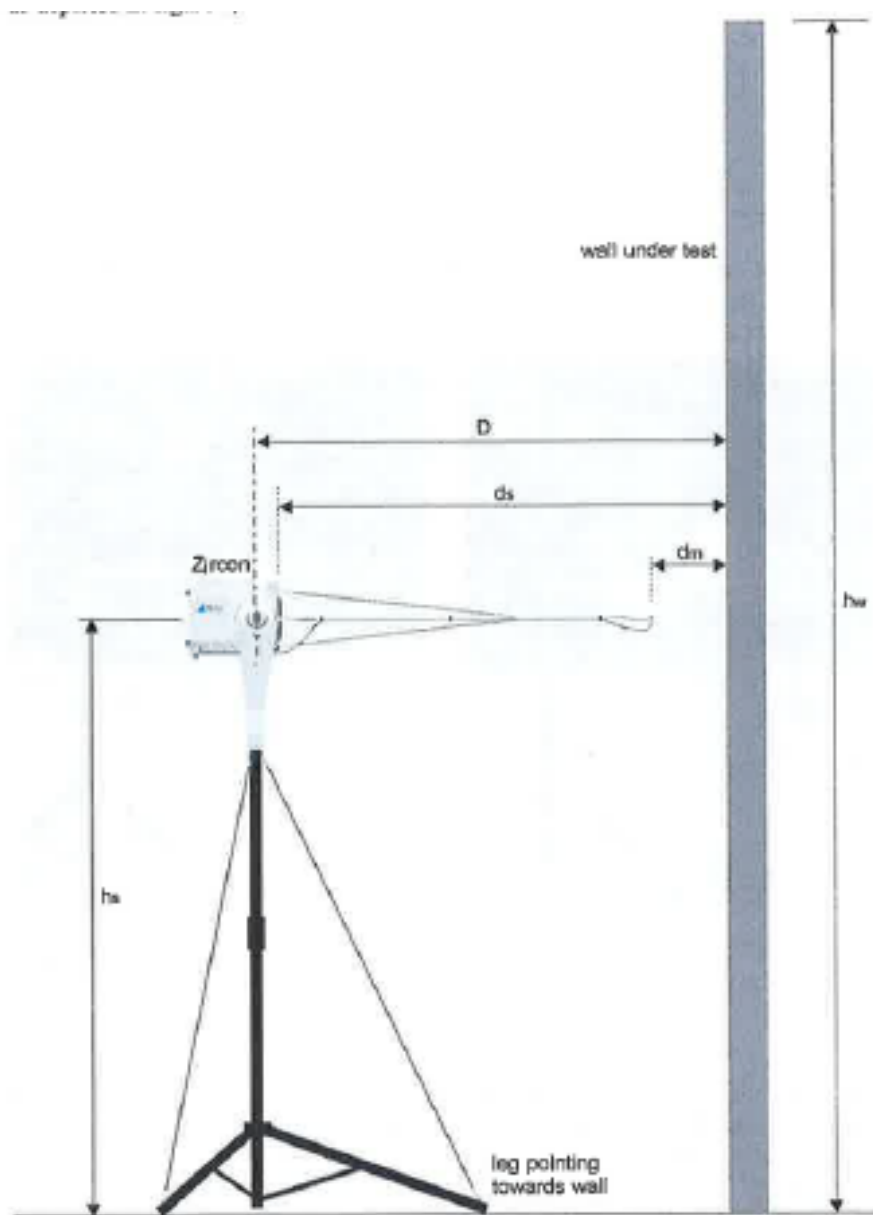


Figure 5.3: Measurement setup, from [19].

temperature of 0 degrees gives a speed of sound of  $c_{air} = 331 + 0.6 \cdot 0 \text{ m/s} = 331 \text{ m/s}$ , according to equation 2.5.

The measurements on the slate facade were done on April 24, 2013, in Oslo, Norway, on a sunny day with a temperature of about 10 degrees Celsius. There was a bit more wind this day, and there might have been periods of time where it exceeded 5 m/s. Pictures of the slate building facade measurement site and instrument setup are shown in figure 5.6. 10 degrees Celsius corresponds to a speed of sound of  $c_{air} = 331 + 0.6 \cdot 10 \text{ m/s} = 337 \text{ m/s}$ .



(a) Brick



(b) Slate

Figure 5.4: Building facade materials



Figure 5.5: Test site and measurement setup for brick building facade.

Reflecting surfaces and objects can interfere with the measurement and cause parasitic reflections. These need to be kept out of the maximum sampled area with radius according to equation 3.3.

The radius of the area with center in the measurement point to surrounding reflecting surfaces and objects was about 1.5 meters for both measurement series. Equation 3.3 was used to find the maximum distance from the measurement surface, giving valid results sure not to be affected by parasitic reflections.

For the brick surface, measurements were performed for distances 10 cm, 15 cm, 20 cm, 25 cm, 27 cm, 30 cm, 35 cm, 40 cm, 50 cm and 60 cm. Distances measured in the slate surface measurement series were 12 cm, 23 cm, 32 cm, 40 cm and 51 cm.

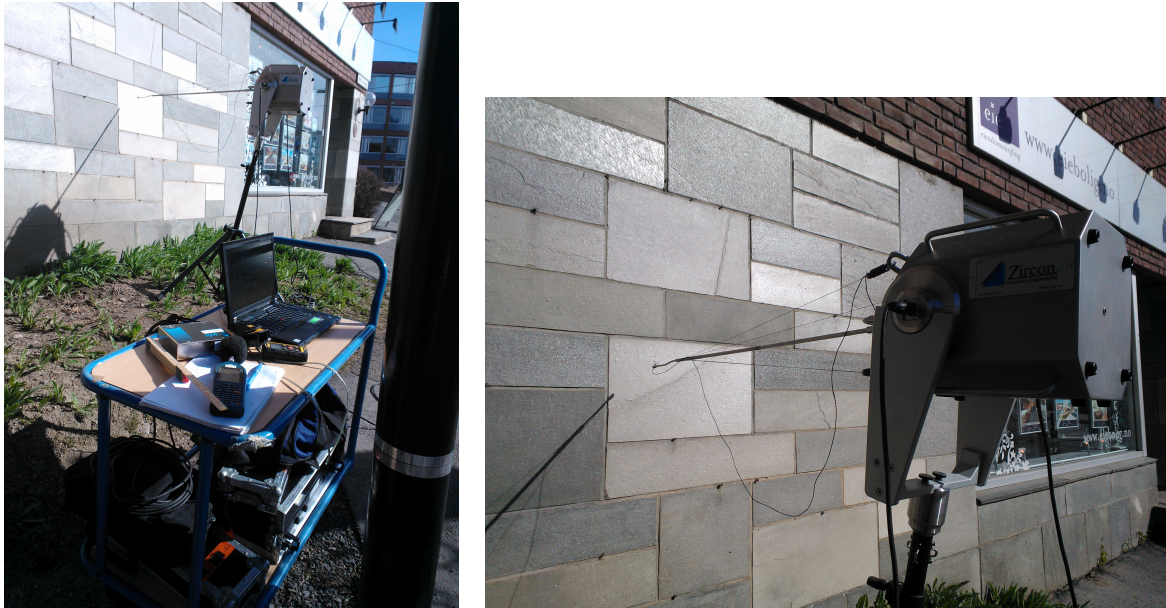


Figure 5.6: Test site and measurement setup for slate building facade.

### 5.2.3 Test signal

The test signal produced by the software WinMLS was a swept sine, with signal duration of 20 seconds. The start and stop frequencies were 50 Hz and 10 kHz. The sampling frequency was set to 48 kHz.

### 5.2.4 Background noise

The background noise was measured by using a sound level meter. It was measured for third octave bands between frequencies 50 and 10 kHz. The duration of the measurement was set to 20 seconds. Background noise measurements were done both before and after the reflection measurements to check for variations in background noise. The background noise level was compared to the sound level of the reflection measurements. It was made sure that the signal to noise ratio did not exceed 10 dB for at least third octave bands between 250 Hz and 4 kHz.

The test site for the slate surface measurements was close to a road, and measurements were therefore more affected by background noise from traffic than measurements performed at the test site for the brick building facade. Background noise measurements were done at the slate surface test site, but not at the brick surface site.

## 5.3 Data processing

Most of the data processing is done using Matlab. Code for this can be found in appendix C. Impulse responses measured using WinMLS was loaded into Matlab. The freefield impulse responses were averaged by adding the time signals together and dividing by the number of measurements. The same was done for the reflection impulse responses.

### 5.3.1 Geometrical spreading

Geometrical spreading is partly compensated for. It is compensated for relative to the measurement with the shortest distance from the microphone to the surface. The geometrical spreading from the microphone to this distance is not compensated for.

The sound pressure arriving at the microphone should be the same for any distance, if it is assumed that the absorption of the surface is the only loss of sound pressure. A geometrical spreading factor is calculated by taking the root mean square of the particular impulse response and dividing it by the root mean square of impulse response with the shortest distance to the surface. The impulse response is multiplied by this factor after the time shift and the subtraction, but before the time windowing. Code for this is given in the Matlab function `spreading.m` in the appendix C.3.

### 5.3.2 Time shift

The freefield impulse compared to the direct impulse may have a small time shift. The reason may be because of variation in temperature during the measurement or it may be caused by an offset in the loudspeaker cone due to change in orientation [4]. Before subtraction of the time signals, it is necessary to correct for this time shift. The time shift is most likely not equal to a whole multiple of samples. The time shift is therefore checked from -0.5 sample to +0.5 sample with a step size of 0.001. The shift that gave the smallest difference around the peak of the impulse was used. The code for this is found in the Matlab function `timeshift.m` in appendix C.2. An example of a signal where the freefield impulse response is subtracted is shown in figure 5.7. The blue line is the signal without a time shift and the red line is with a time shift.

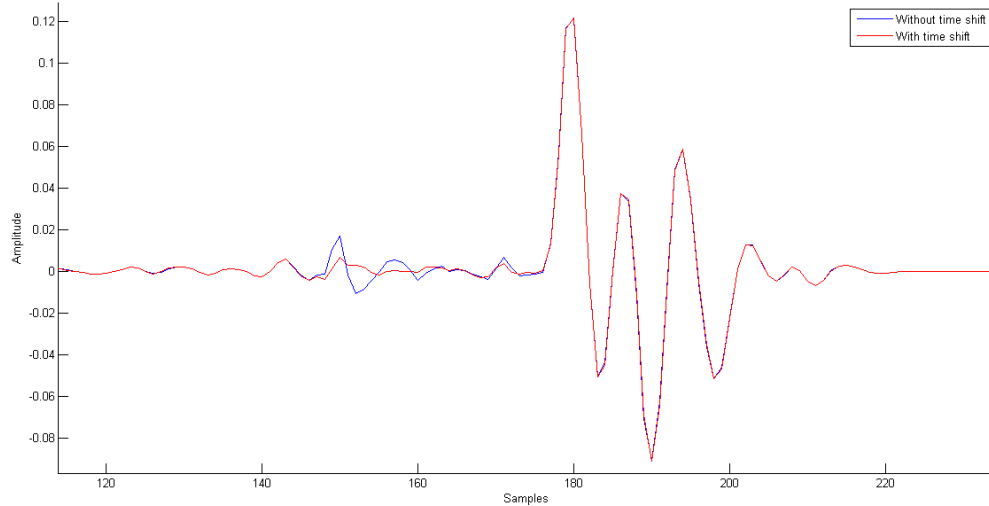


Figure 5.7: Subtracted signal, with and without time shift.

### 5.3.3 Signal separation

To separate the reflected impulse from the direct impulse, the signal subtraction method was used. The freefield impulse response should be nearly identical to the direct impulse in the reflection measurement.

After the time shift, the freefield impulse can therefore be subtracted from the reflection measurement containing both a direct and a reflected component, and only the reflected impulse will remain.

### 5.3.4 Time window

Time windows were multiplied with the impulse responses, both the freefield response and the reflection response with the direct signal subtracted. This was done to extract the parts of interest from the measurement, for instance to avoid reflections from surfaces other than the one under test. When the distance to the surface under test is smaller than the distance to other surfaces, the parasitic reflections arrive later than the wall reflections, and a time window may be used.

In this experiment a time window with a sharp leading edge, a flat portion and a Blackman-Harris trailing edge was used. The shape of the time window used is shown in figure 5.8. The Blackman-Harris edge is to suppress signal oscillations in the frequency domain.

Two types of time windows are used, where the difference is the length of the window and where it starts. The first type of time window is only used to avoid reflections arriving after a period of time. The total length of the time window used for the freefield response equals the time it takes for sound to travel from the loudspeaker to the wall and back to the microphone. This is the time before any reflections arrive at the microphone. The total length of the time window used for the reflection response is the time of the freefield window added the time it takes for sound to travel from the surface to the microphone. The second type of window extracts only the impulse from each measurement. The window starts where the impulse begins.

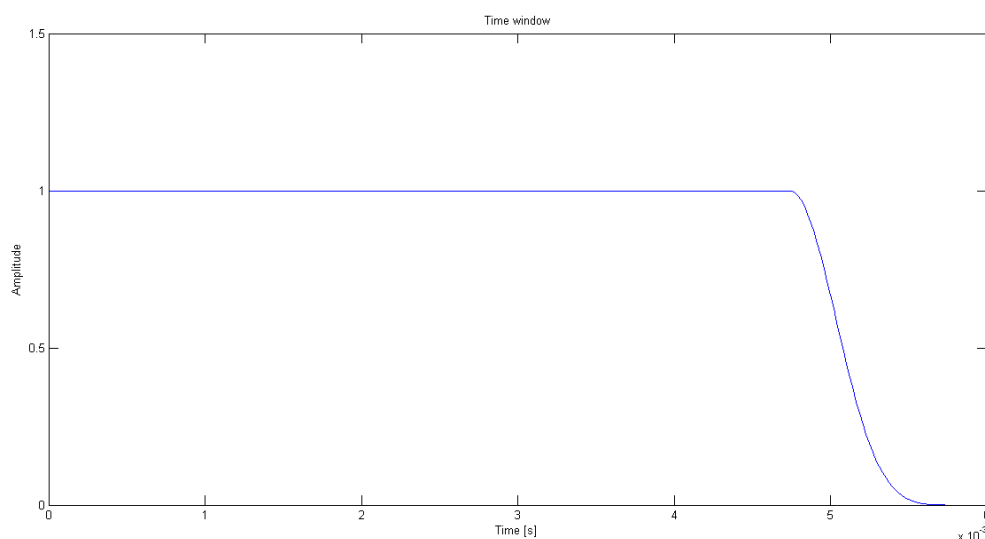


Figure 5.8: Time window

### 5.3.5 Reflection coefficient

The reflection coefficient is calculated by first taking the fast Fourier transform of the windowed impulse responses for the direct and the reflected signal. The absolute value of the reflected signal's Fourier transform

is divided by the absolute value of the direct signal's Fourier transform. This results in a frequency dependent reflection coefficient.

### **5.3.6 Absorption factor**

The absorption factor is found by subtracting the reflection factor from one, and then calculated for one third octave bands. This is done by averaging the values of the absorption factor for the one third octave bands.

# Chapter 6

## Results

This chapter presents the results from the experiment described. More details of the results are given in appendix B.

### 6.1 Valid measurements

Not all the measurements are valid because of possible reflections from surfaces or objects other than the surface under test. The distance from the surface to the microphone giving valid measurement results can be calculated by equation 3.3 in chapter 3. Constant parameters in the equation are the radius of the maximum sampling area,  $r = 1.5m$ , and the speed of sound  $c = 331m/s$  for the brick surface or  $c = 337m/s$  for the slate surface. The size of the temporal window,  $T_W$  is dependent on the distance to the surface. Measurement conditions for the measurement of the brick surface gave a maximum distance of about 30 cm from microphone to surface. With the given conditions for the measurement series of the slate surface, a distance from microphone to surface up to about 30 cm would give reliable results. This means that the measurements with distances 20 cm, 25 cm and 30 cm from the brick surface are valid, and only the measurement 23 cm from the slate surface is valid.

Even though the measurement 32 cm from the slate surface is not one of the valid measurement, it is included in the results. The reason it is not a valid measurement is because of possible reflections from other surfaces or objects than the one under test, but when examining the time response for this measurement, no obvious signs of paracitic reflections in the time windows used are found. The reason for including this measurement is to have a basis for comparison and it will give valuable information about the reflection coefficient and absorption coefficient.

The reflection coefficients and absorption coefficients for all measurements are included in some figures and tables in the results. The reason for this is to compare the valid measurements against measurements from a variety of distances. It is also desirable to check these measurements for interference effects.

For the reflection coefficient it is decided to focus on the method with temporal separation and signal subtraction. These curves are smoother than the curve for the signal subtraction method, and is therefore more suitable for evaluations of the reflection coefficient. The reflection coefficient obtained from this method is also used for calculating the absorption coefficient. wWhen calculations are done for one third octave bands, oscillations are smoothed.



## 6.2 Background noise

Measured background noise level in one third octave bands is presented in table 6.1. BN 1 is background noise measured in the start of the measurement series given in dB, and BN 2 is background noise measured at the end of the measurement series. M is the sound level of the loudspeaker output and SNR is the difference between the sound pressure level of background noise and the measurement signal. A more detailed table is given in appendix B.1.

Table 6.1: Background noise measured before and after measurement, compared to sound pressure level of measurement.

Frequency [Hz]	BN 1 [dB]	BN 2 [dB]	M [dB]	SNR [dB]
250	54.9	54.5	74.5	19.6
315	54	54	75.5	21.5
400	54.5	52.5	77.1	22.6
500	54.8	51.2	75.3	20.5
630	53.2	51.1	76.8	23.6
800	55.6	52.7	77.3	21.7
1k	55.3	53.2	77.8	22.5
1.25k	53.5	50.9	78.9	25.4
1.6k	51.5	48.5	77.4	25.9
2k	49.8	49.1	77.5	27.7
2.5k	47.8	50.3	77	26.7
3.5k	46.8	52.9	74.4	21.5
4k	44.4	52.3	76.3	24

## 6.3 Reflection factor

From the brick facade measurements, measurements from distances 20 cm, 25 cm and 30 cm from the surface is presented in figures 6.1, 6.2 and 6.3. From the slate facade measurements, measurements from distances 23 cm and 32 cm from the surface are presented in figures 6.6 and 6.7. The first two plots are time responses of the freefield measurement in red and the reflection measurement with direct component subtracted in blue. The first plot is the time windowed time response of the subtraction method. The second plot is the time response of temporal separation combined with the subtraction method. The third plot is the reflection factor for both methods, signal subtraction method in blue and temporal separation in red. Reflection factors for the valid measurements are plotted together in figure 6.4 for the brick surface and in figure 6.8 for the slate surface. Reflection factors for all measurements for both methods are presented in figure 6.5 for the brick surface and in figure 6.9 for the slate surface. Results from all measured distances are given in appendix B.2.

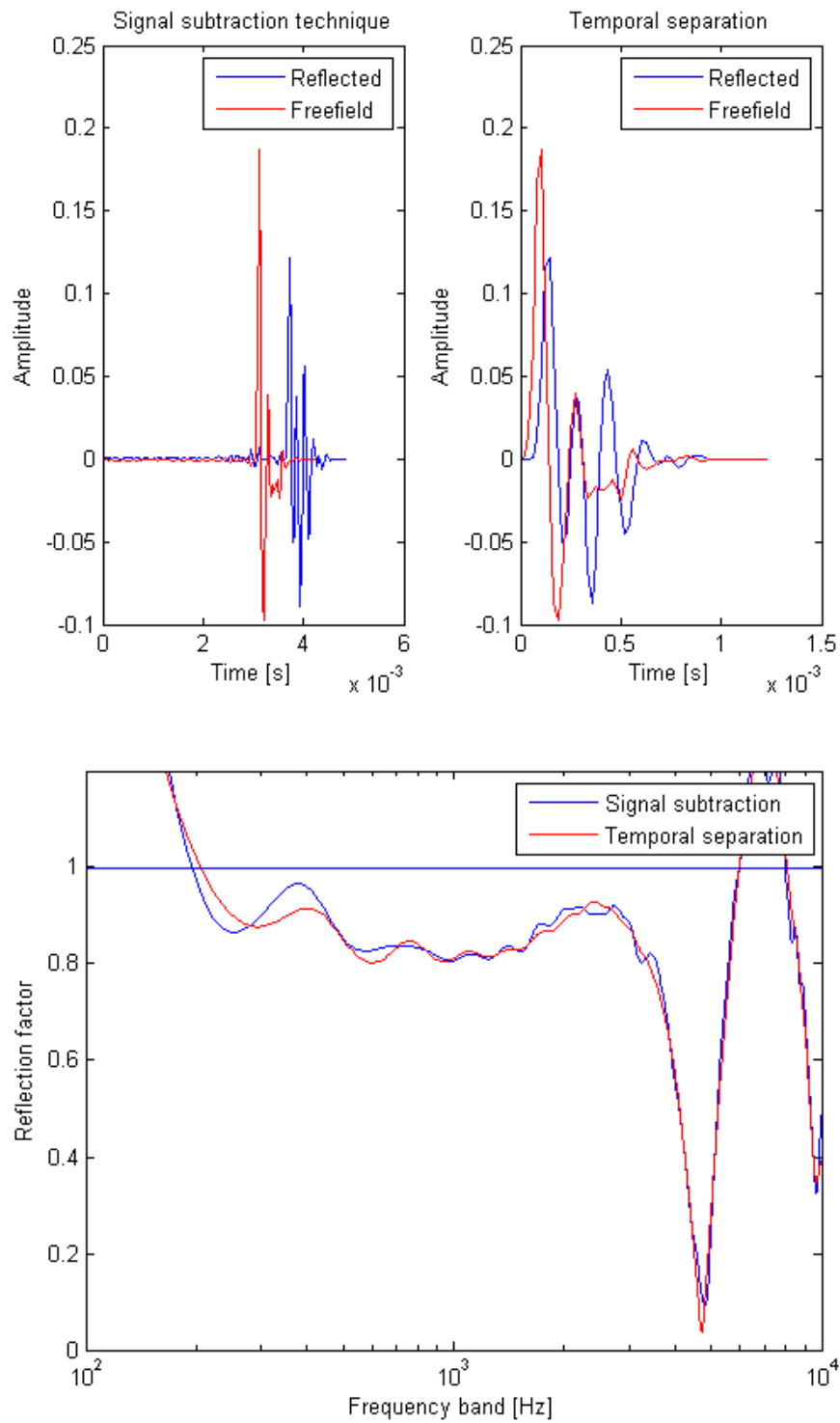


Figure 6.1: Time responses and reflection factor 20 cm distance from brick building facade.

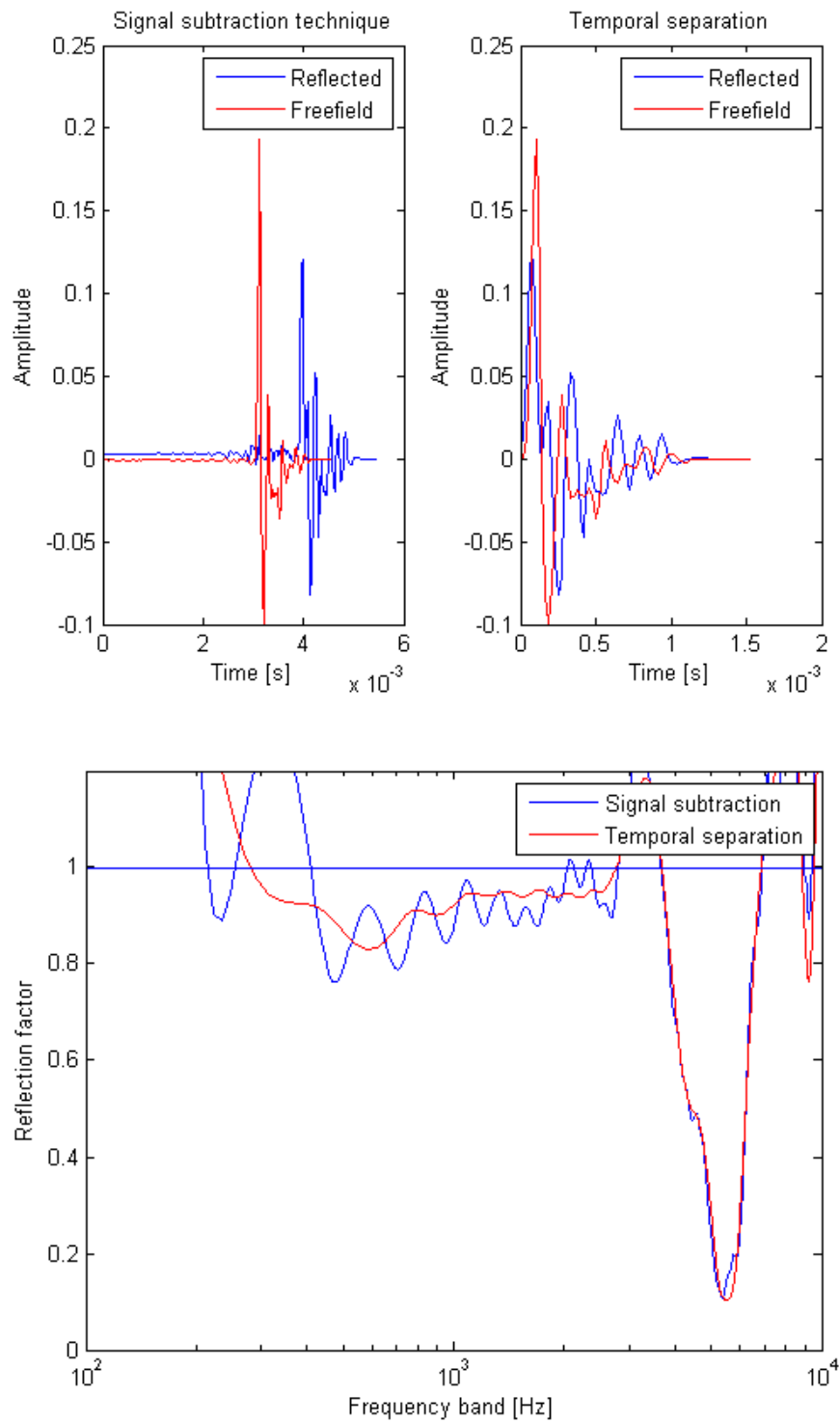


Figure 6.2: Time responses and reflection factor 25 cm distance from brick building facade.

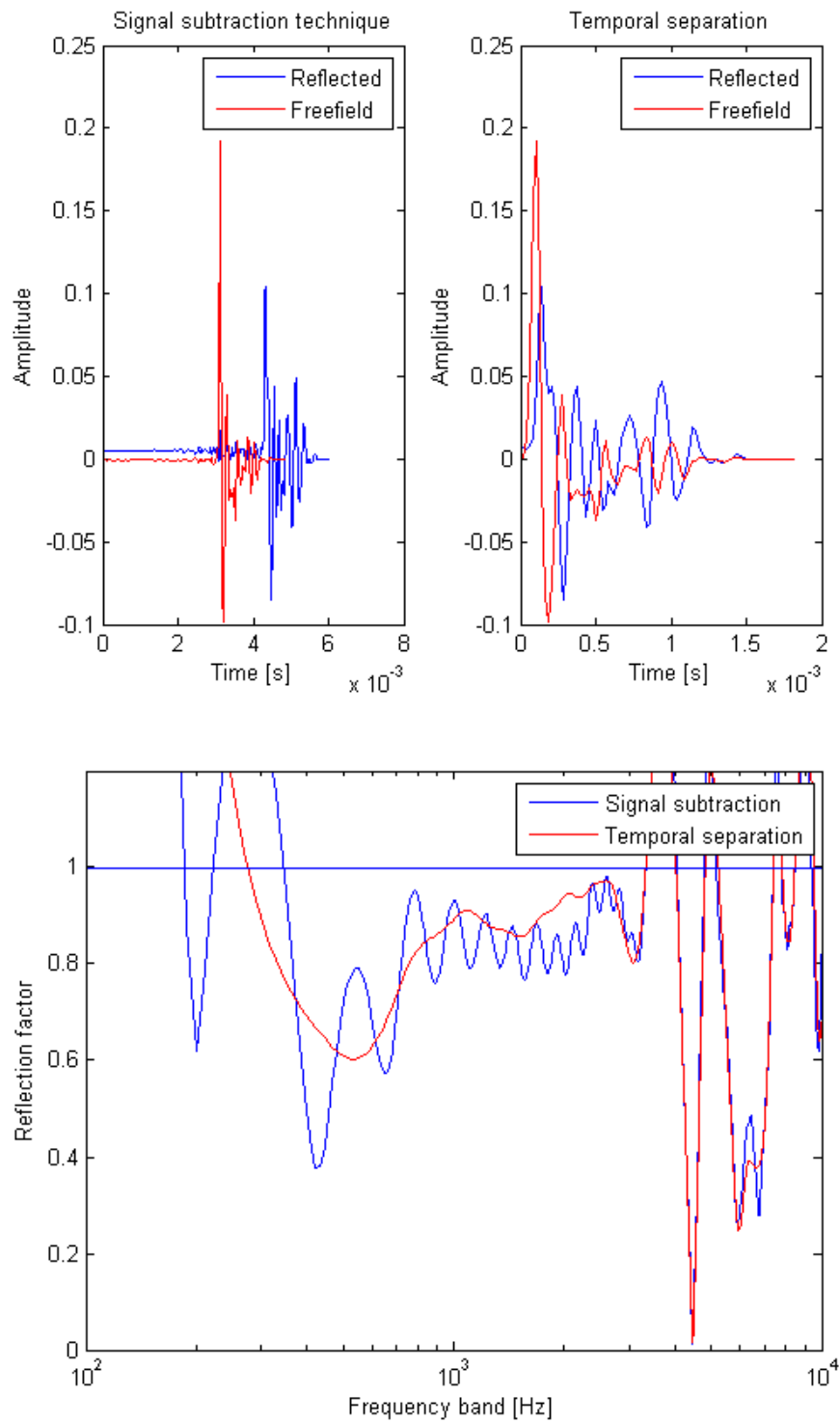


Figure 6.3: Time responses and reflection factor 30 cm distance from brick building facade.

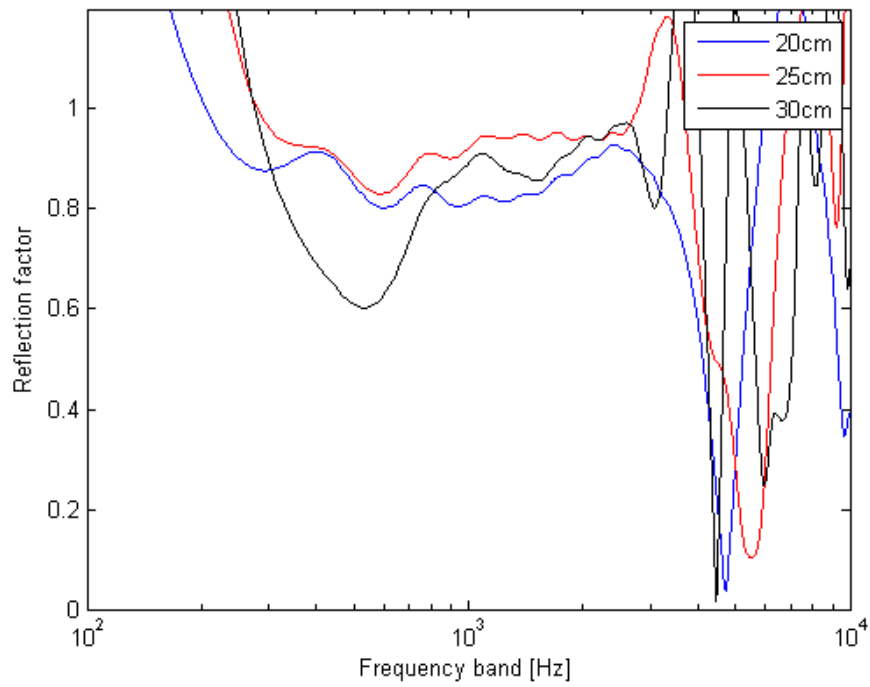
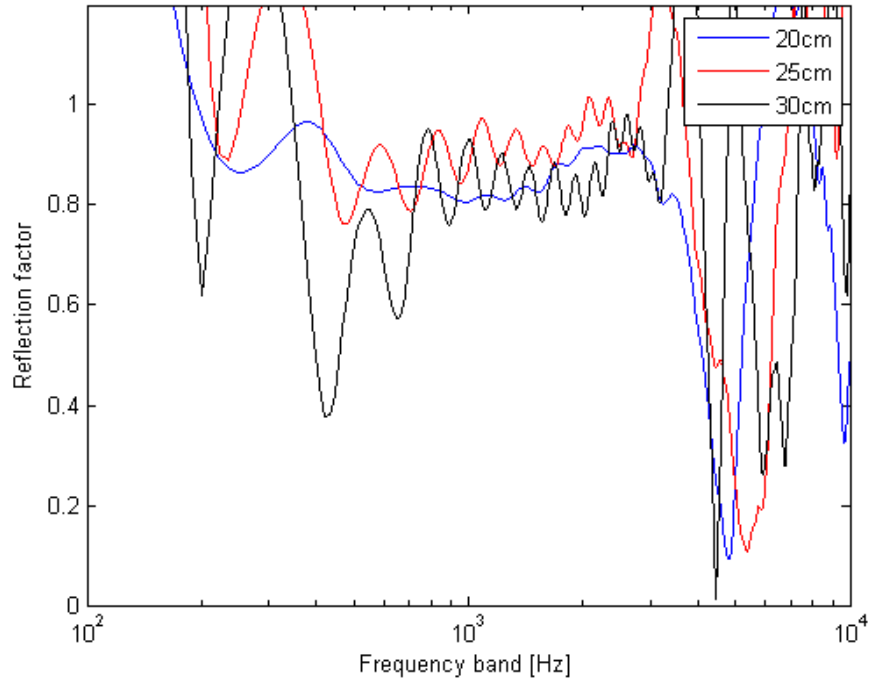


Figure 6.4: Reflection factor for valid measurements, brick surface.

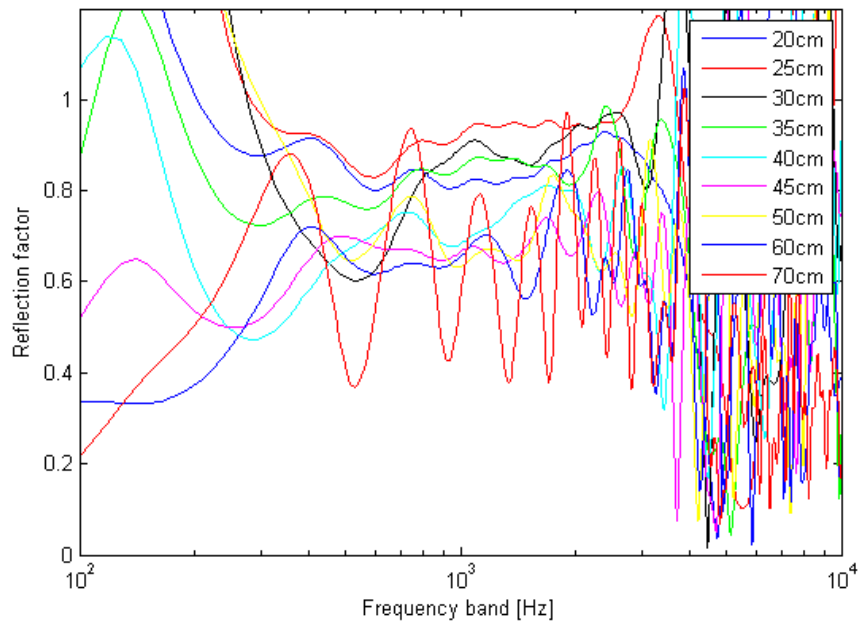
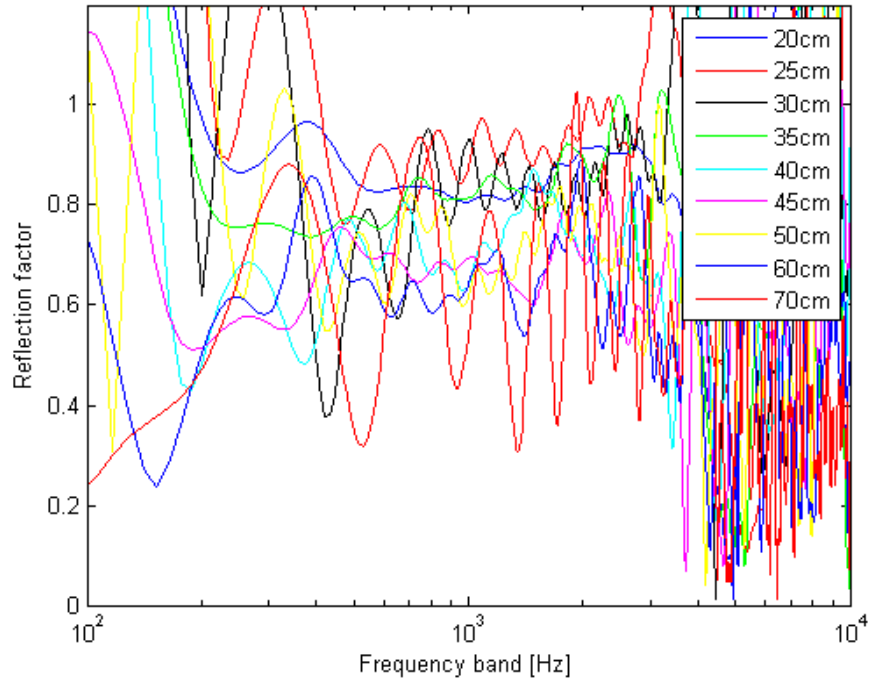


Figure 6.5: Reflection factor for all measurements, brick surface

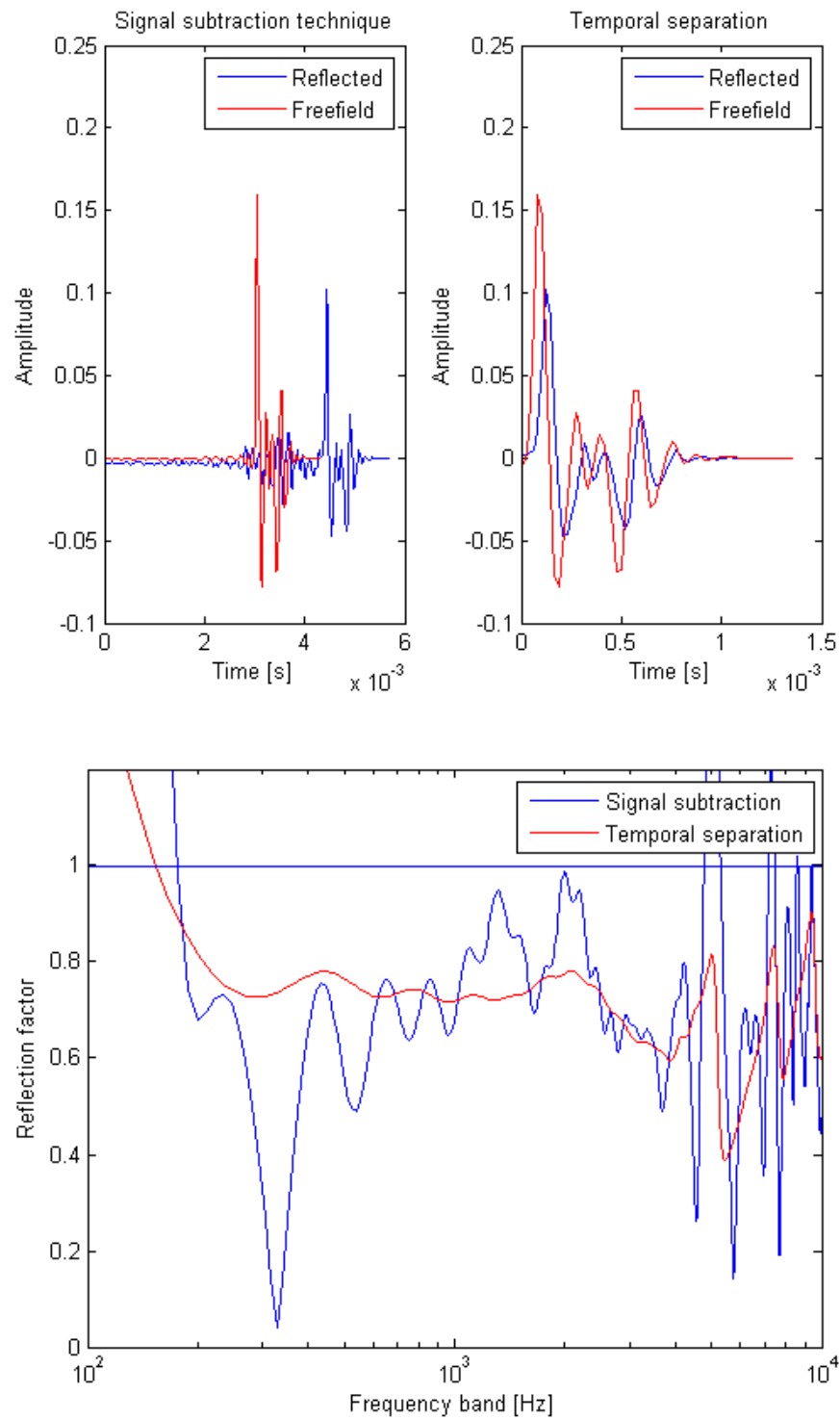


Figure 6.6: Time responses and reflection factor 23 cm distance from slate building facade.

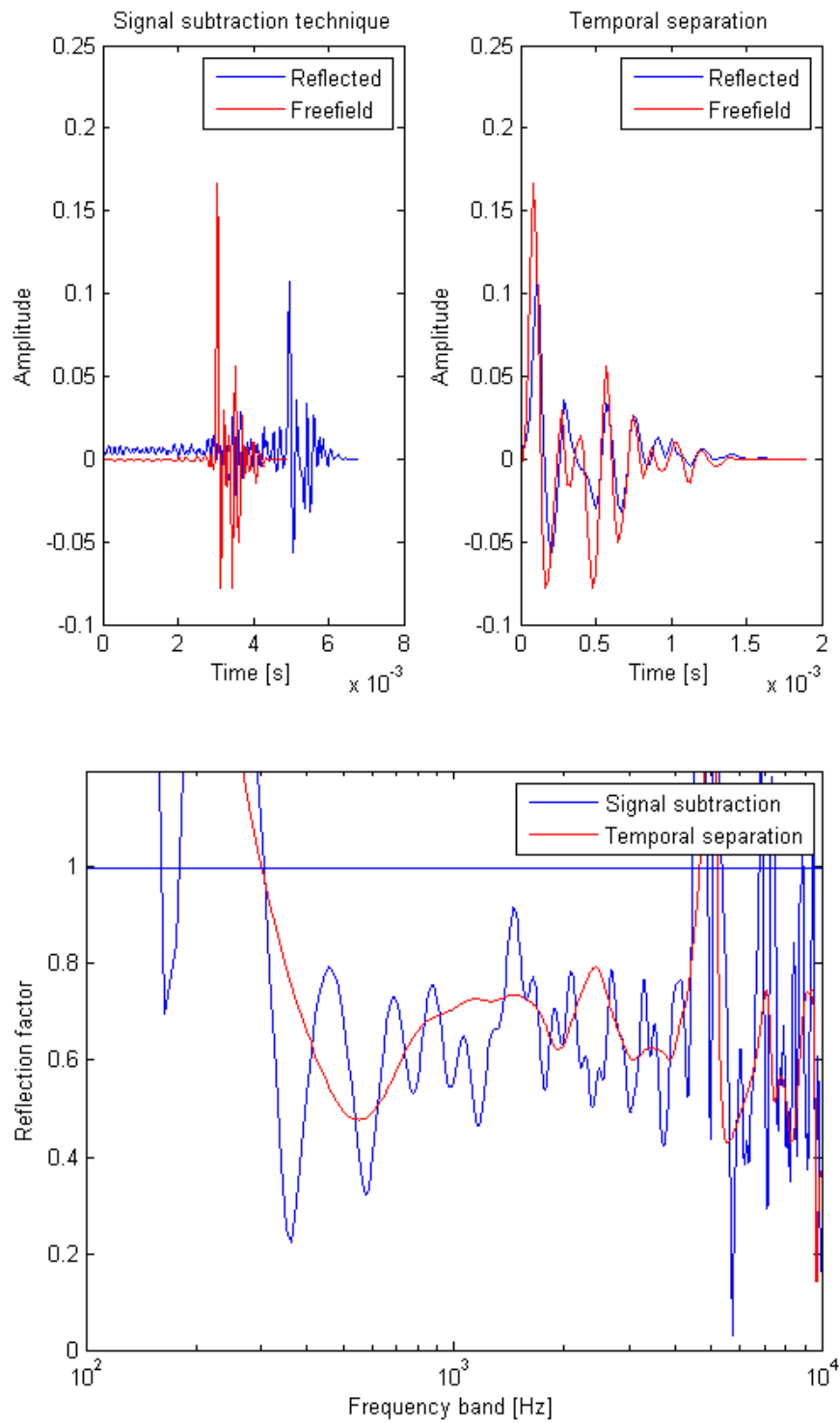


Figure 6.7: Time responses and reflection factor 32 cm distance from slate building facade.



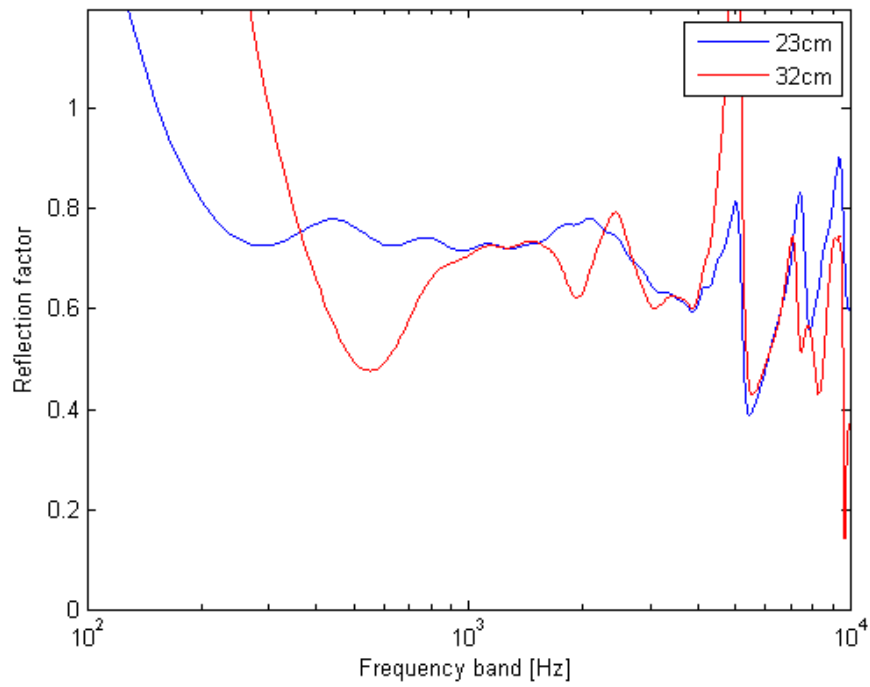
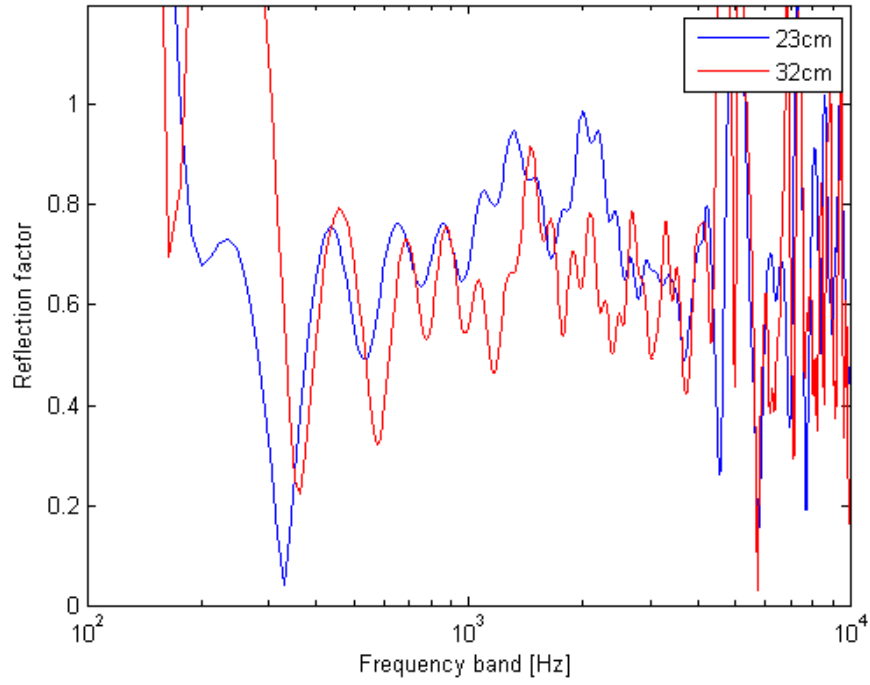


Figure 6.8: Reflection factor for valid measurements, slate surface

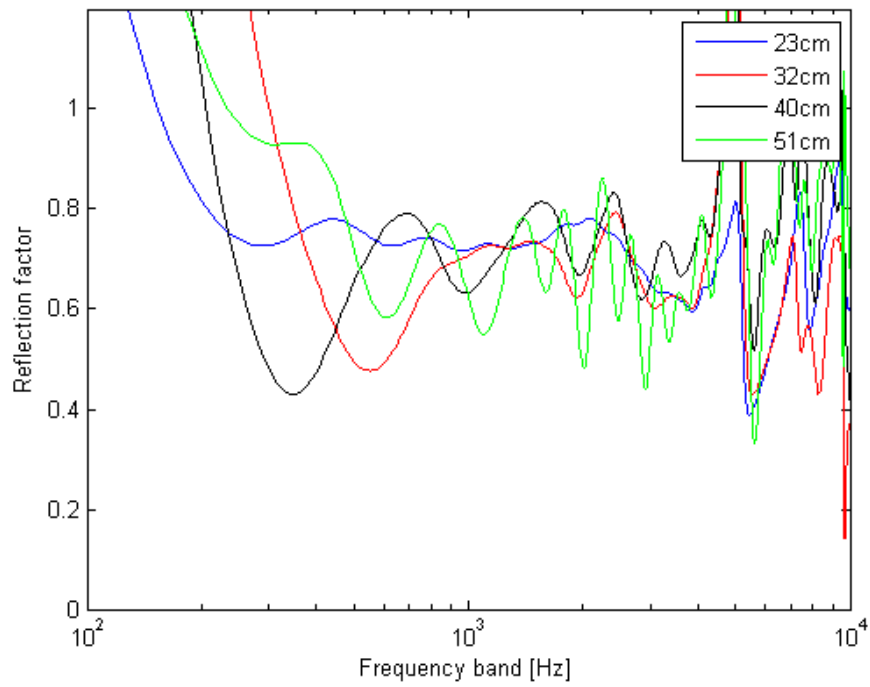
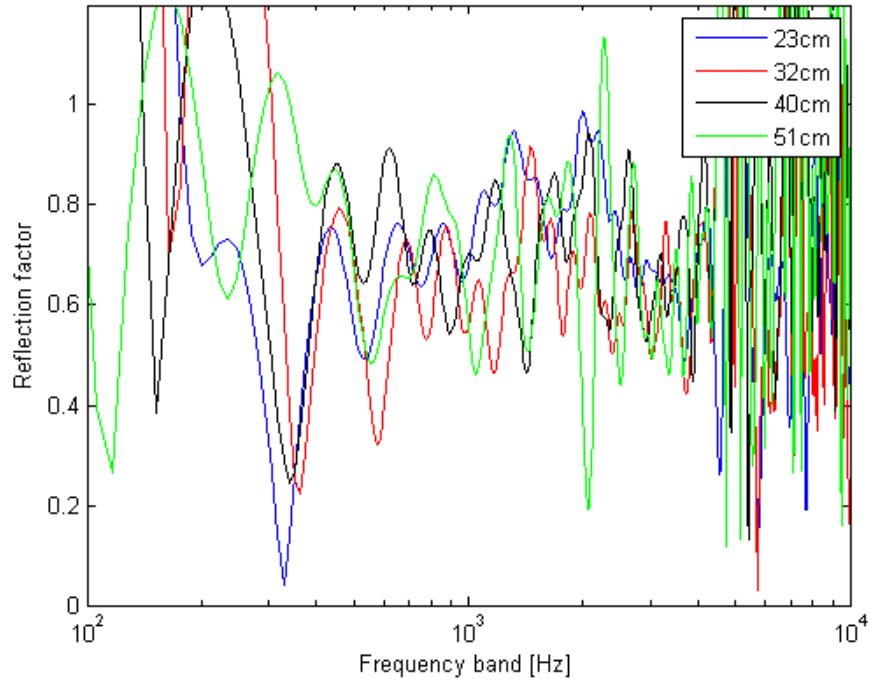


Figure 6.9: Reflection factor for all measurements, slate surface.

## 6.4 Interference

Table 6.2 and 6.3 show the first frequencies that may be affected by interference due to the delayed signal reflected from the building facade. The frequencies are calculated by using equations 2.9, 2.10 and 2.11, for the distances used for measuring in the experiment. Table 6.2 is calculated for the brick building facade and table 6.3 for the slate building facade.

Table 6.2: Frequencies where the delayed signal creates destructive and constructive interference.

d [cm]	$0.5\lambda$	$\lambda$	$1.5\lambda$	$2\lambda$	$2.5\lambda$	$3\lambda$
20	413.8 Hz	827.5 Hz	1241.3 Hz	1655 Hz	2068.8 Hz	2482.5 Hz
25	331 Hz	662 Hz	993 Hz	1324 Hz	1655 Hz	1986 Hz
30	275.8 Hz	551.7 Hz	827.5 Hz	1103.3 Hz	1379.2 Hz	1655 Hz
40	206.9 Hz	413.8 Hz	620.6 Hz	827.5 Hz	1034.4 Hz	1241.3 Hz
50	165.5 Hz	331 Hz	496.5 Hz	662 Hz	827.5 Hz	993 Hz

Table 6.3: Frequencies where the delayed signal creates destructive and constructive interference.

d [cm]	$0.5\lambda$	$\lambda$	$1.5\lambda$	$2\lambda$	$2.5\lambda$	$3\lambda$
23	366.3 Hz	732.6 Hz	1098.9 Hz	1465.2 Hz	1831.5 Hz	2197.8 Hz
32	263.3 Hz	526.6 Hz	789.8 Hz	1053.1 Hz	1316.4 Hz	1579.7 Hz
40	210.6 Hz	421.3 Hz	631.9 Hz	842.5 Hz	1053.1 Hz	1263.8 Hz
51	165.2 Hz	330.4 Hz	495.6 Hz	660.8 Hz	826 Hz	991.2 Hz

## 6.5 Absorption coefficient

The calculated absorption coefficient for one third octave band frequencies 250 Hz to 10 kHz is given in table 6.4 for the brick building surface and in table 6.5 for the slate building surface. The absorption coefficient is calculated for all measured distances. The tables also give the mean absorption values and standard deviations.  $\mu_1$  is the mean of all distances and  $\sigma_1$  is the standard deviation for all distances.  $\mu_2$  is the mean of the valid measurements and  $\sigma_2$  is the standard deviation calculated from these measurements. These results are plotted and illustrated in figure 6.10 for the brick surface and in figure 6.11 for the slate surface.

Table 6.4: Absorption coefficient for the brick building facade.

f [Hz]	0.2m	0.25m	0.3m	0.35m	0.4m	0.45m	0.5m	0.6m	0.7m	$\mu_1$	$\sigma_1$	$\mu_2$	$\sigma_2$
250	0.08	0	0	0.22	0.48	0.49	0	0.56	0.39	0.25	0.22	0.03	0.22
315	0.11	0.04	0.12	0.27	0.51	0.47	0.04	0.43	0.21	0.24	0.17	0.09	0.16
400	0.09	0.08	0.29	0.23	0.43	0.36	0.20	0.30	0.20	0.24	0.11	0.16	0.13
500	0.14	0.13	0.38	0.22	0.34	0.31	0.33	0.34	0.52	0.30	0.12	0.22	0.14
630	0.19	0.15	0.34	0.22	0.28	0.32	0.29	0.38	0.37	0.28	0.08	0.23	0.10
800	0.17	0.10	0.19	0.16	0.27	0.34	0.25	0.36	0.22	0.23	0.08	0.15	0.09
1k	0.19	0.08	0.11	0.15	0.31	0.34	0.35	0.34	0.41	0.25	0.12	0.12	0.14
1.25k	0.18	0.06	0.12	0.13	0.26	0.35	0.34	0.33	0.42	0.24	0.12	0.12	0.14
1.6k	0.16	0.05	0.13	0.14	0.20	0.29	0.26	0.36	0.41	0.22	0.11	0.11	0.12
2k	0.11	0.06	0.07	0.16	0.23	0.30	0.25	0.26	0.25	0.19	0.08	0.08	0.11
2.5k	0.08	0.04	0.04	0.11	0.26	0.33	0.38	0.32	0.32	0.21	0.13	0.05	0.16
3.5k	0.17	0	0.10	0.16	0.45	0.36	0.29	0.46	0.47	0.27	0.16	0.09	0.20
4k	0.47	0.27	0.26	0.41	0.24	0.56	0.51	0.42	0.29	0.38	0.11	0.34	0.10
5k	0.62	0.73	0.24	0.77	0.19	0.30	0.40	0.36	0.69	0.48	0.21	0.53	0.22
6.3k	0.02	0.38	0.62	0.30	0.43	0.36	0.43	0.54	0.69	0.42	0.19	0.34	0.26
8k	0.08	0	0.07	0.17	0.05	0.49	0.34	0.61	0.63	0.27	0.24	0.05	0.22
10k	0.60	0.07	0.12	0.33	0.20	0.27	0	0.51	0.59	0.30	0.21	0.26	0.24

Table 6.5: Absorption coefficient for the slate building facade.

f [Hz]	0.23m	0.32m	0.4m	0.51m	$\mu_1$	$\sigma_1$	$\mu_2$	$\sigma_2$
250	0.25	0	0.27	0.02	0.13	0.12	0.12	0.12
315	0.27	0.07	0.51	0.06	0.23	0.18	0.17	0.12
400	0.23	0.31	0.52	0.09	0.29	0.16	0.27	0.04
500	0.23	0.49	0.37	0.25	0.33	0.10	0.36	0.13
630	0.27	0.48	0.24	0.39	0.34	0.10	0.38	0.11
800	0.26	0.35	0.26	0.27	0.29	0.04	0.31	0.05
1k	0.28	0.29	0.35	0.36	0.32	0.04	0.29	0.04
1.25k	0.27	0.27	0.27	0.32	0.29	0.02	0.27	0.01
1.6k	0.26	0.28	0.20	0.28	0.26	0.03	0.27	0.02
2k	0.23	0.33	0.29	0.33	0.29	0.04	0.28	0.05
2.5k	0.27	0.26	0.25	0.31	0.27	0.02	0.27	0.01
3.5k	0.36	0.38	0.31	0.43	0.37	0.04	0.37	0.01
4k	0.37	0.33	0.27	0.33	0.32	0.04	0.35	0.03
5k	0.37	0.19	0.16	0.17	0.22	0.09	0.28	0.11
6.3k	0.44	0.43	0.21	0.23	0.33	0.11	0.44	0.11
8k	0.30	0.45	0.18	0.17	0.27	0.11	0.37	0.12
10k	0.20	0.46	0.27	0.14	0.27	0.12	0.33	0.15

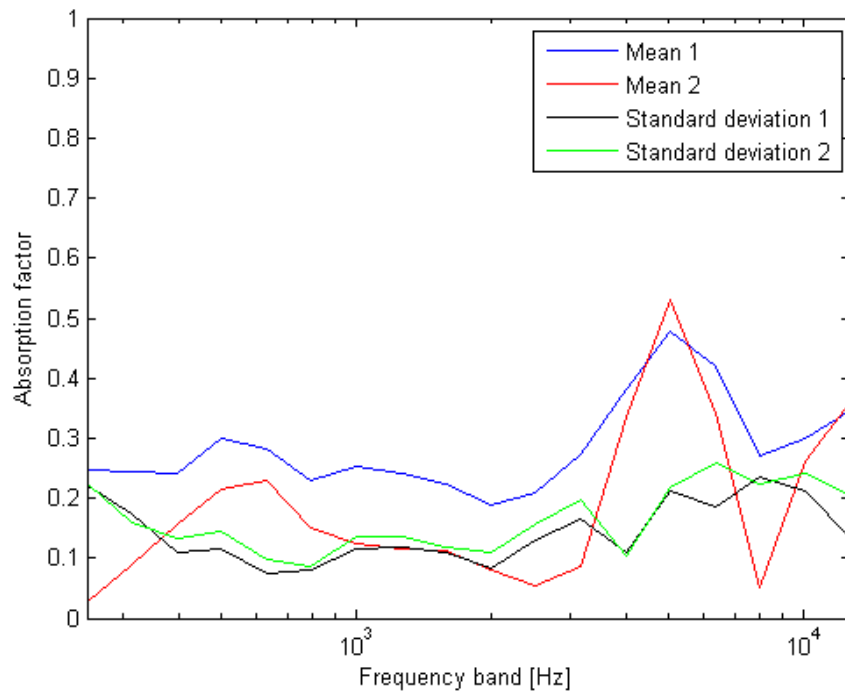
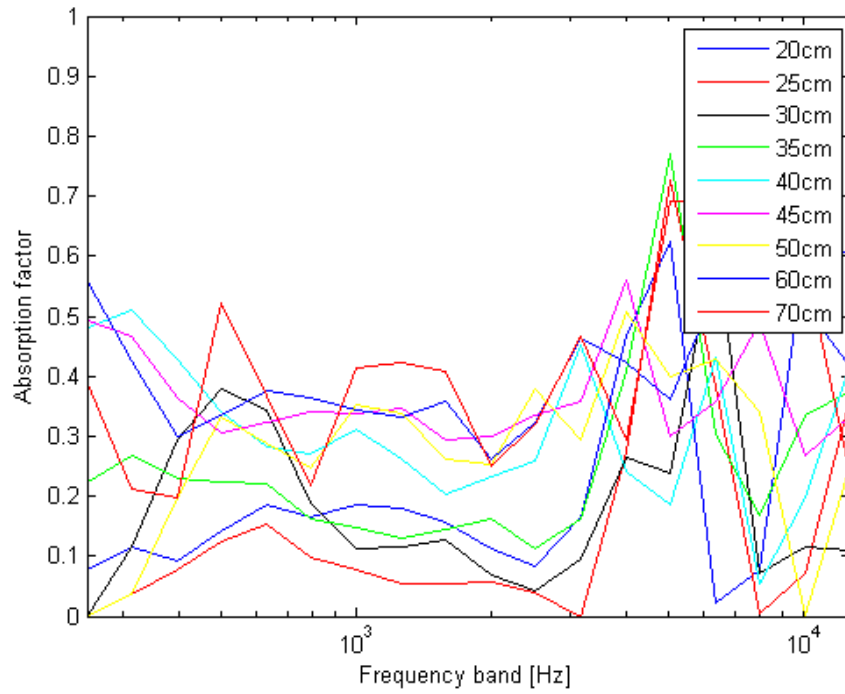


Figure 6.10: Absorption factor for all measurements, mean values and standard deviations, brick surface.

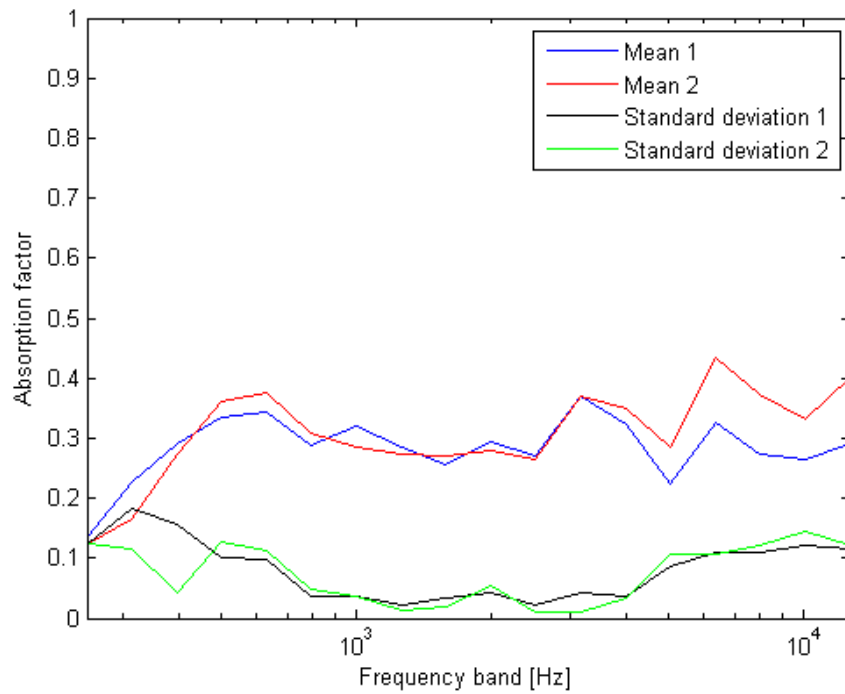
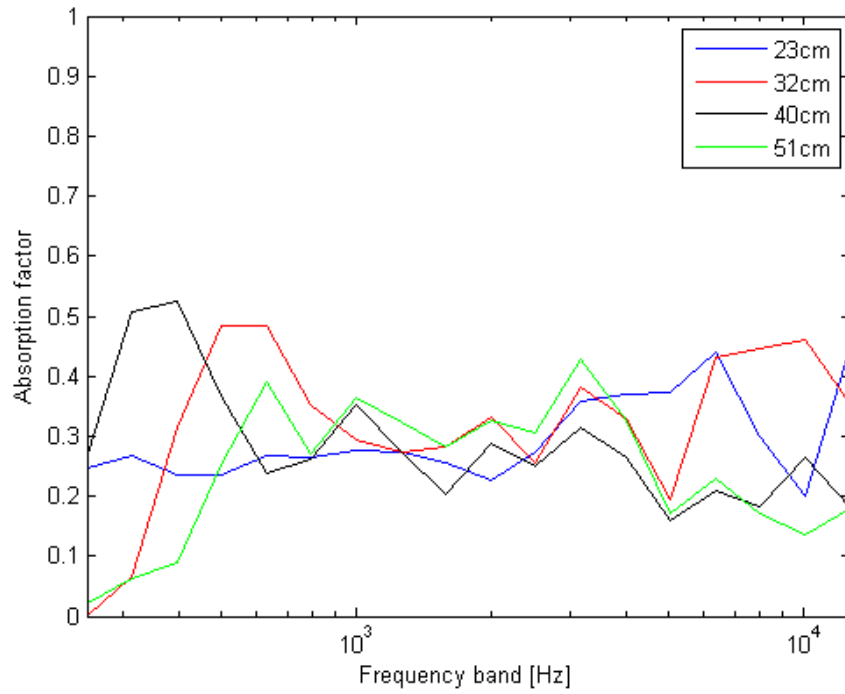


Figure 6.11: Absorption factor for all measurements, mean values and standard deviations, slate surface.

# Chapter 7

## Discussion

This chapter discuss the results presented in the previous chapter, obtained from the experiment. Possible sources of error and measurement uncertainty are identified and discussed. Some suggestions for improvements of the measurement method and further studies are given.

### 7.1 Time response

The time responses for the brick building surface show that the signal subtraction has almost canceled out the direct response of the reflection measurement, but there are still some minor residue from the direct response. Comparing the shape of the reflected response against the freefield response, there are some differences. Also the reflected signal for the different distances have differences in shape. This means that the reflected sound wave is not just a delayed attenuated version of the direct sound wave. The reason for this may be that the brick surface is not smooth and will not reflect sound in a specular way for all frequencies.

The time responses of the measurements for the slate building surface show that the signal subtraction is less successful. There is still some of the direct response which is not canceled out by the signal subtraction. The shapes of the direct and reflected response are very similar. This may be because of the fairly smooth and hard surface of the slate facade.

### 7.2 Reflection coefficient

The reflection coefficient calculated with the signal subtraction method have more oscillations than the reflection coefficient calculated with the temporal separation method with signal subtraction. These oscillations may be caused by the swept sine measurement signal. If it is too fast, it may cause instability in the measurement. The shape of the time window affects the signal in the frequency domain. A Blackman-Harris edge for the time window will suppress signal oscillations [4]. If the direct sound is not canceled out and the paracitic reflections are not gated out, it affects the frequency response. This is a problem for the results of the reflection coefficient using the signal subtraction method where there are residues from the direct response. Disregarding the oscillation, both calculation methods have mostly the same shape.

For the brick surface at a distance of 20 cm, the reflection coefficient has a value above 1.00 for frequencies below 200 Hz. Between 200 Hz and 3000 Hz the reflection coefficient varies between 0.80 and 0.97. After 3000 Hz the curve of the reflection coefficient decreases down to almost zero, before it increases to exceed

1.00 at about 6000 Hz.

The reflection coefficient for a distance of 25 cm from the surface is below 1.00 for frequencies between 280 Hz and 2800 Hz for the temporal separation with signal subtraction method. In this area, the reflection coefficient varies between 0.83 and 1.00. After 2800 Hz, the curve has a top before it decreases down to about zero and then increases again.

At a distance of 30 cm from the brick surface, the reflection coefficient curve for the temporal separation with signal subtraction method is below 1.00 for frequencies between about 280 Hz and 3300 Hz. In this area, the reflection coefficient varies between 0.60 and 1.00. After 3300 Hz, the curve has many peaks and dips.

These measurements show valid results for the reflection coefficient in a frequency range from about 300 Hz to 2500 Hz. The high reflection coefficient of 0.80 to 0.90 is reasonable for the hard brick surface.

For the slate surface at a distance of 23 cm, the reflection coefficient is below 1.00 for frequencies after 175 Hz for the signal subtraction method and about 150 Hz for the temporal separation method with signal subtraction. The curve for the temporal separation method with signal subtraction has values mostly varying between 0.7 and 0.8 up to 2700 Hz, where the curve begins to have larger decreases and increases.

The reflection coefficient for the distance 32 cm from the slate surface has values below 1.00 for frequencies between 300 Hz and about 4500 Hz. The values of the reflection coefficient vary mostly between 0.48 and 0.80 in this area. After 4500 Hz the curve also has larger decreases and increases.

These measurements show valid results for the reflection coefficients in a frequency range from about 350 Hz to 4000 Hz. The high reflection coefficient of 0.7 to 0.8 is reasonable for a hard surface such as the slate surface.

### **7.2.1 Interference**

Interference effects are most likely to be observed at low frequencies. It is also in the low frequency area that interference effects introduce most problems when an averaging over frequency bands is performed. The reason for this is that the frequency bands in the low frequency area are smaller than frequency bands in a higher frequency area. Interference effects will therefore affect a frequency band with low frequency more than a band with higher frequency.

The oscillations found in the signal subtraction method, but not in the temporal separation with signal subtraction, are not caused by interference. When comparing the dips and peaks of the reflection coefficient curves with the calculated frequencies that may be affected by interference, no clear relationship between them is found.

## **7.3 Absorption coefficient**

The mean absorption coefficient of the valid measurements for the brick surface lies between 0.03 and 0.23 for frequencies between 250 Hz and 2500 Hz. The standard deviations for these measurements are between 0.09 and 0.22. The highest values of standard deviation are found for low frequencies and high frequencies. Comparing these results with the mean absorption calculated from all the performed measurements, the mean absorption for the valid measurements is lower for almost all frequencies and the standard deviation



is higher for most frequencies.

The mean absorption coefficient of the measurements done for distances 23 cm and 32 cm from the slate building surface lies between 0.12 and 0.38 for frequencies between 250 Hz and 4000 Hz. The standard deviation for these measurements are between 0.02 and 0.13. Frequencies between 800 Hz and 4000 Hz have low standard deviations. The highest values of standard deviation is found for low frequencies and high frequencies. Comparing these results with the mean absorption calculated for all the performed measurements for the slate surface, the mean absorption is approximately the same and there is no large difference in standard deviation.

## 7.4 Measurement uncertainty

All measurements have some uncertainty, and especially outdoor measurements. Outdoor measurements can be unpredictable and have many factors which are difficult to control, like temperature, wind, weather and background noise.

The speed of the wind and the temperature was not measured at the test sites. This makes it uncertain if temperature and wind are within the recommended range. Wind may produce noise at the microphone. It may also influence the propagation of sound waves, but since the measurements are done for small distances, the effect of the wind on the sound wave is negligible. The temperature is used for calculating the speed of sound and the time sound use to travel a certain distance. This is used in the size, and start and stop of the time windows. The time windows are an important factor affecting the results, since they are supposed to extract the relevant parts of the measurements and gate out parasitic reflections. Time windows that do not match the measurements may cause errors and inaccuracies in the results. Different types and sizes of time windows give variation in the results. The time window may affect the low frequency area if it is not able to gate out the parasitic reflections [5].

Outdoor background noise is unpredictable and varies over time. The background noise at the test sites is mainly traffic noise. It is only measured at one of the test sites, but it is measured at the test site most exposed to traffic noise. Since the background noise measurements at this test site fulfilled the requirements of signal to noise ratio, it is assumed that the requirements are also fulfilled for the other, less noisy, test site. Even though the background noise averaged over time fulfill the requirements, there may be periods of time where the background noise levels are too high compared to the measurement signal. This may give uncertainty, inaccuracies or errors in the measurements.

ISO 13472 [4] states that the measurement surface should be visually homogenous and free of changes in material properties. The slate surface is fairly smooth and free of changes, but the brick surface has obvious changes of material and is uneven. The uneven surface may lead to diffuse reflection of the sound wave for some frequencies. High frequencies are most affected by irregularities in the surface. Uneven absorption properties of the surface gives a measurement uncertainty.

In the measurement setup, the loudspeaker is supposed to be placed perpendicular to the measurement surface. To ensure this, the angle of the loudspeaker relative to the measurement surface should have been measured. This was not done, because equipment not available. If the distance from the microphone to the surface is not measured accurately, it may affect the time window. Consequences of a time window not matching the measurement is described above.

Geometrical spreading is only compensated for relative to the measurement with the shortest distance to the surface. This means that there are some inaccuracy and measurement uncertainty due to geometrical

spreading.

When subtracting the freefield response from the overall response, there might be some small differences between the freefield response and the direct response. This means that the direct response is not completely canceled out, and leads to some measurement uncertainty. The measurement chain may not be stable. This may again lead to the direct response not being completely canceled out when subtracting the freefield response from the total response. If the direct sound is not completely canceled by subtraction, it can affect the results in the high frequency area [5].

## **7.5 Possible improvements of the measurement method and further work**

One improvement of the measurement method is to perform more measurements of the reflection response in the same position and of the freefield response. An average of more measurements may give a more accurate representation of the reflection response and freefield response. Another improvement is to include a better method for compensating for geometrical spreading of the sound waves. If geometrical spreading is taken into account for all measurements, it will give more accurate and comparable results. It would also be desirable to develop a user interface for the code used for calculations. The interface should be able to open the measurement program and perform measurements, and calculate and present the results directly. This would make the measurements easier to perform and the quality of the results could be evaluated immediately.

Further work will be to use the results obtained from these measurements and the analyses of interference effects in the study for improving the sound insulation measurement method.

## Chapter 8

# Conclusion

ISO 13472 [4] describes two signal separation techniques. One is called temporal separation, where the relevant components are extracted from the overall impulse response by time windows. This method requires a sufficient time delay between the direct and reflected component, so that they do not overlap. The other technique is called signal subtraction technique. This is a technique where the direct component is subtracted from the overall impulse response. This way it is not a problem if there is an overlap between the direct and reflected component.

In this experiment the signal subtraction technique described in ISO 13472 is used. The signal subtraction technique is also used in combination with the temporal separation. With this combination, measurements can be performed close to a surface and problems related to the signal subtraction not completely canceling out the direct component are avoided.

In this experiment, the temporal separation combined with temporal separation provides a better representation of the reflection coefficient than signal subtraction technique alone. It is much smoother and does not have the oscillations that are found in the results from the signal subtraction method alone. The experiments show a valid method for measurement of the reflection coefficient in a frequency range between 250 Hz and 2500 Hz. No interference effects are found in the valid frequency range.

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# Appendix A

## Technical specifications

Parameter	Condition	Min	Typ	Max	Unit
LS14 loudspeaker unit					
Operation frequency range	Third octave frequency bands	50		10000	Hz
Nominal impedance			8		$\Omega$
Power handling	Continuous		50		W
	Peak			80	W
Sound Pressure Level	At 1 m distance in front, at 50 W applied power		104		dB
Microphone power supply	PP3 battery		9		V
Power supply operation time	Starting from full battery		140		h
Connectors	Microphone input		Microdot		
	Microphone output		3-pole XLR		
	Loudspeaker output		Speakon		
Weight			9.5		kg
DPA 4060-B microphone					
Diameter	Prepolarized condenser element		5.4		mm
Operating frequency range	-3 dB	20		20000	Hz
Sensitivity	At 1 kHz	14	20	28	mV/Pa
Equivalent noise level	CCIR 468-1		35	38	dB
Source-microphone distance	Without microphone insert		1.00		m
	With microphone insert		1.25		m
Weight	Including microphone insert		0.9		kg

Table A.1: Specifications for Zircon probe, from [19].



# Appendix B

## Measurements

### B.1 Background noise

Table B.1: Background noise

Frequency [Hz]	BN 1 [dB]	BN 2 [dB]	M [dB]	SNR [dB]
20	59.8	64.9	70	5.1
25	61.3	65.1	66.5	1.4
31.5	64.4	64.5	66.6	2.1
40	65.5	58	66.5	1
50	67.2	61.3	70.1	2.9
63	62.7	59.5	67.1	4.4
80	57	63.6	67.4	3.8
100	57.3	63.6	71.8	8.2
125	56.6	52.5	74.6	18
160	57.8	57.5	75.6	17.8
200	57.2	57.2	76.3	19.1
250	54.9	54.5	74.5	19.6
315	54	54	75.5	21.5
400	54.5	52.5	77.1	22.6
500	54.8	51.2	75.3	20.5
630	53.2	51.1	76.8	23.6
800	55.6	52.7	77.3	21.7
1k	55.3	53.2	77.8	22.5
1.25k	53.5	50.9	78.9	25.4
1.6k	51.5	48.5	77.4	25.9
2k	49.8	49.1	77.5	27.7
2.5k	47.8	50.3	77	26.7
3.5k	46.8	52.9	74.4	21.5
4k	44.4	52.3	76.3	24
5k	40.8	49.9	74.1	24.1
6.3k	37.2	47.6	68.3	20.7
8k	33.7	43.6	58.6	15
10k	29.7	40	55.1	15.1
12.5k	24.4	34.6	54	19.4
16k	18.8	24.6	38.3	13.7
20k	12	<del>46.4</del>	31	16.6



## B.2 Reflection factor

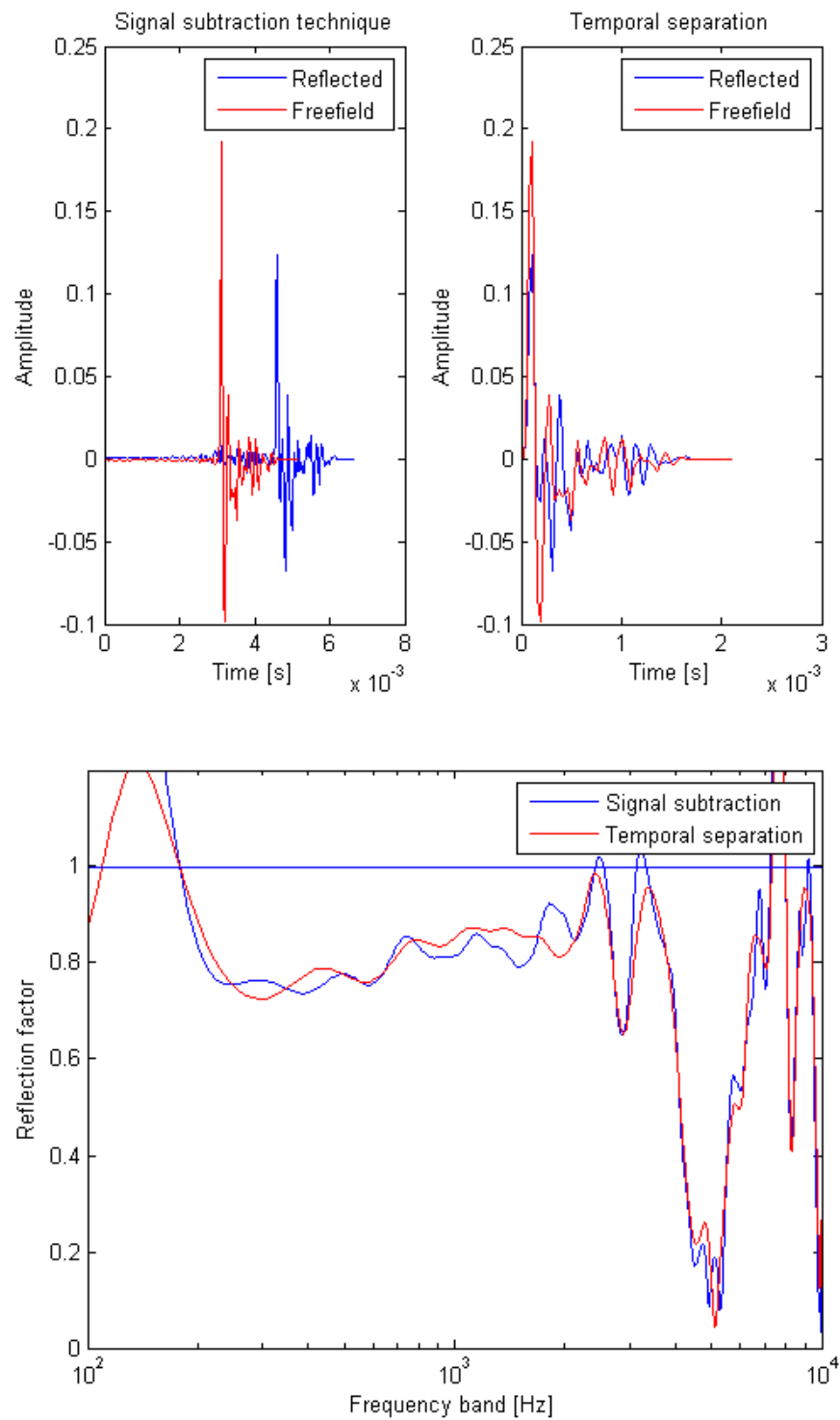


Figure B.1: Time responses and reflection factor 35 cm distance from brick building facade.

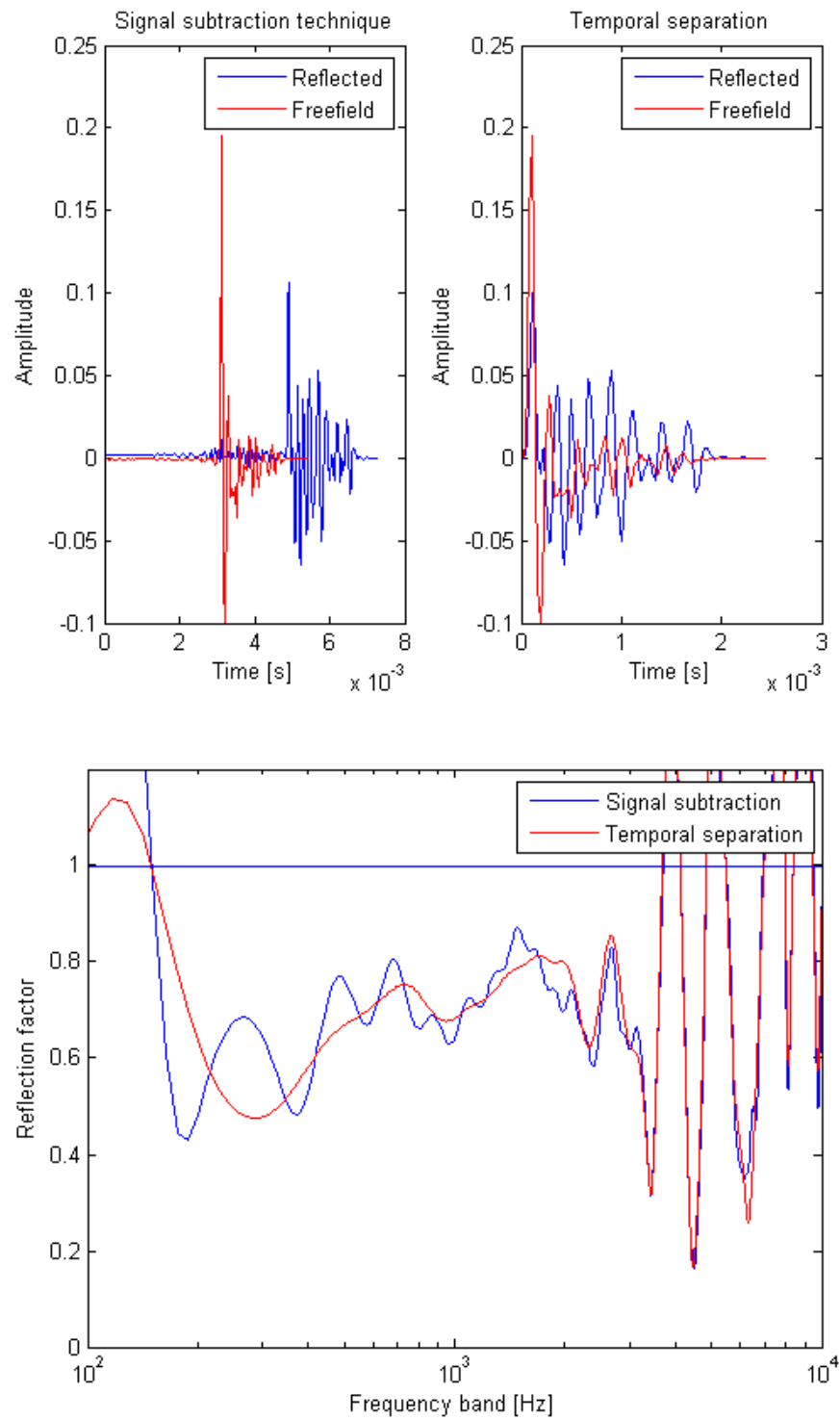


Figure B.2: Time responses and reflection factor 40 cm distance from brick building facade.

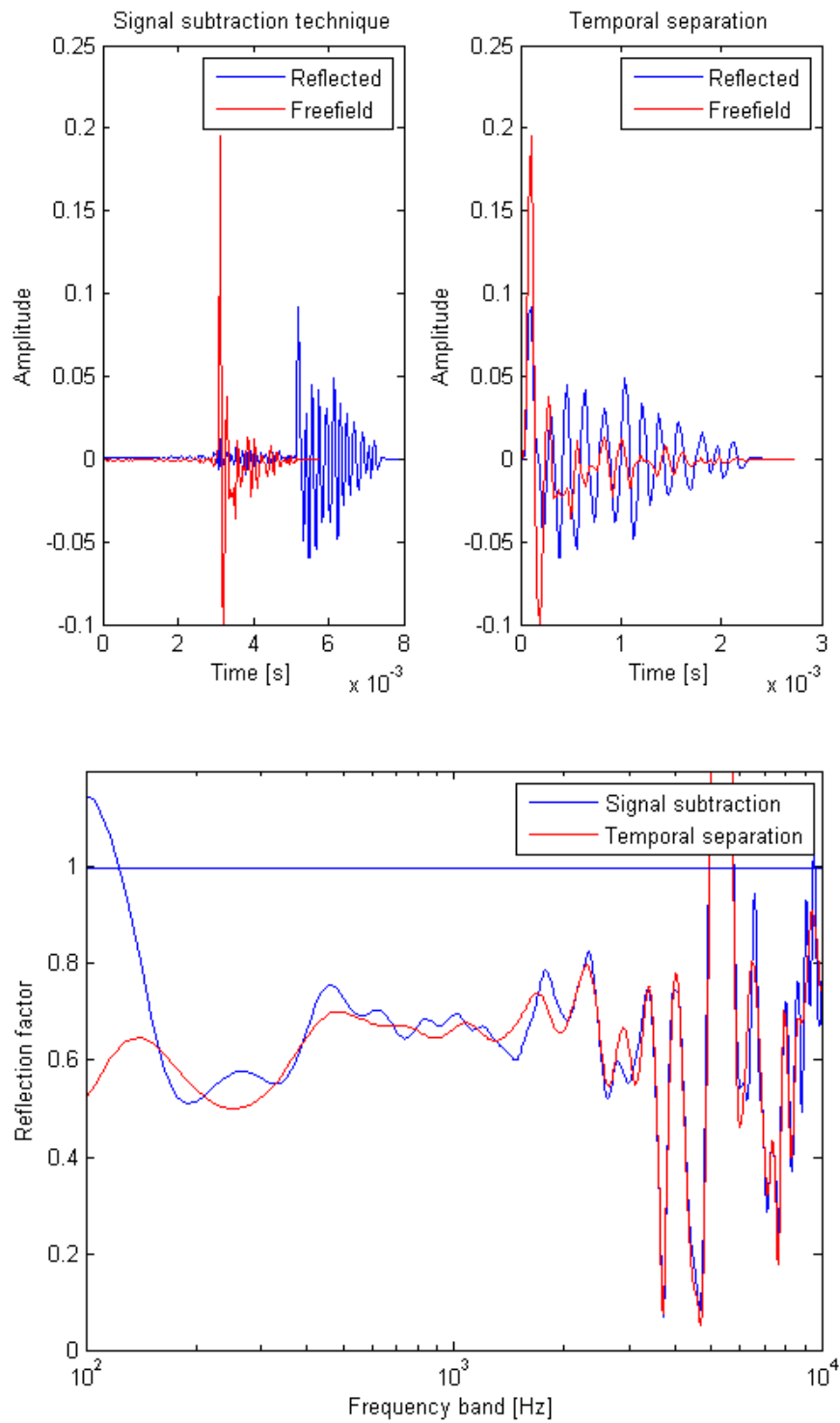


Figure B.3: Time responses and reflection factor 45 cm distance from brick building facade.

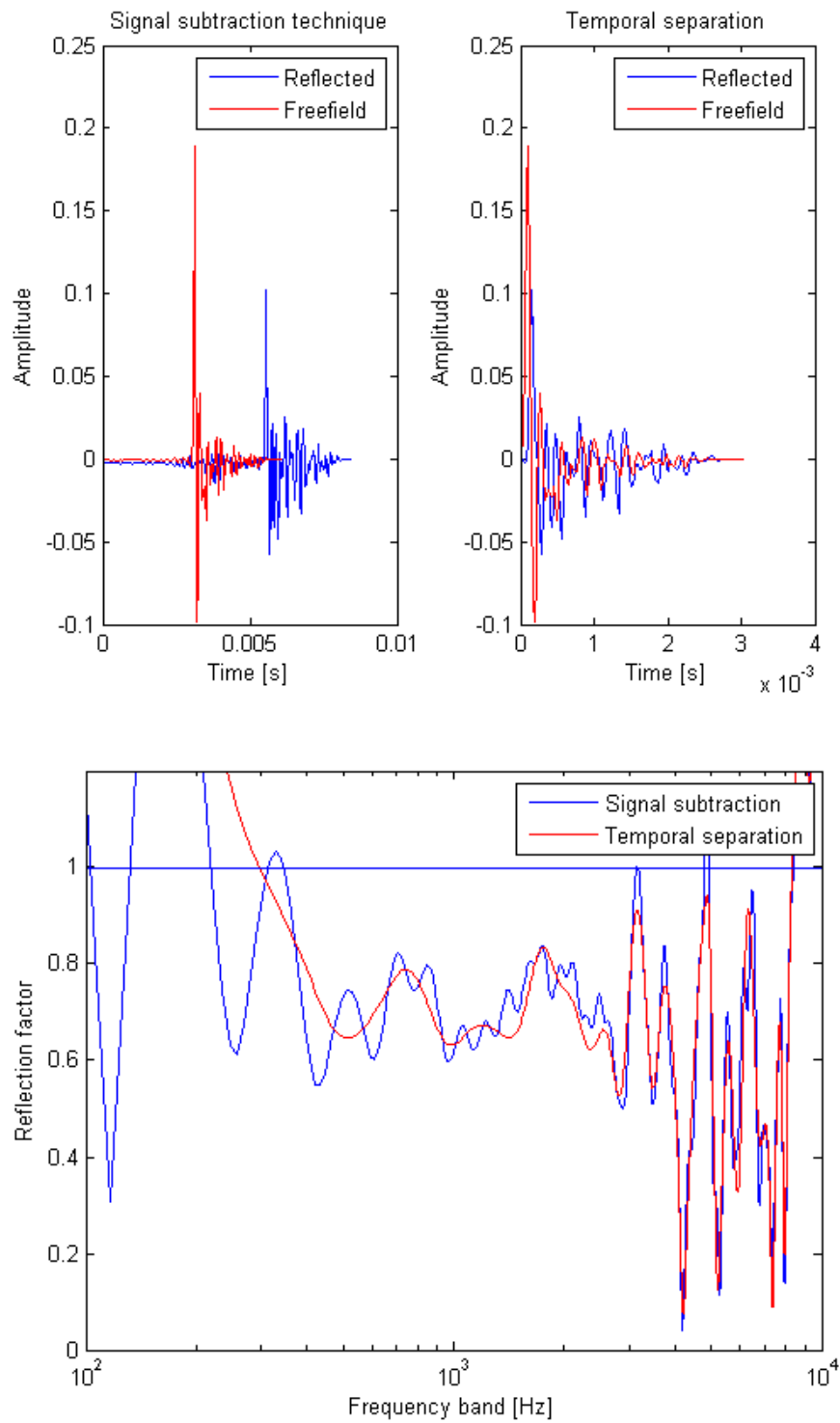


Figure B.4: Time responses and reflection factor 50 cm distance from brick building facade.

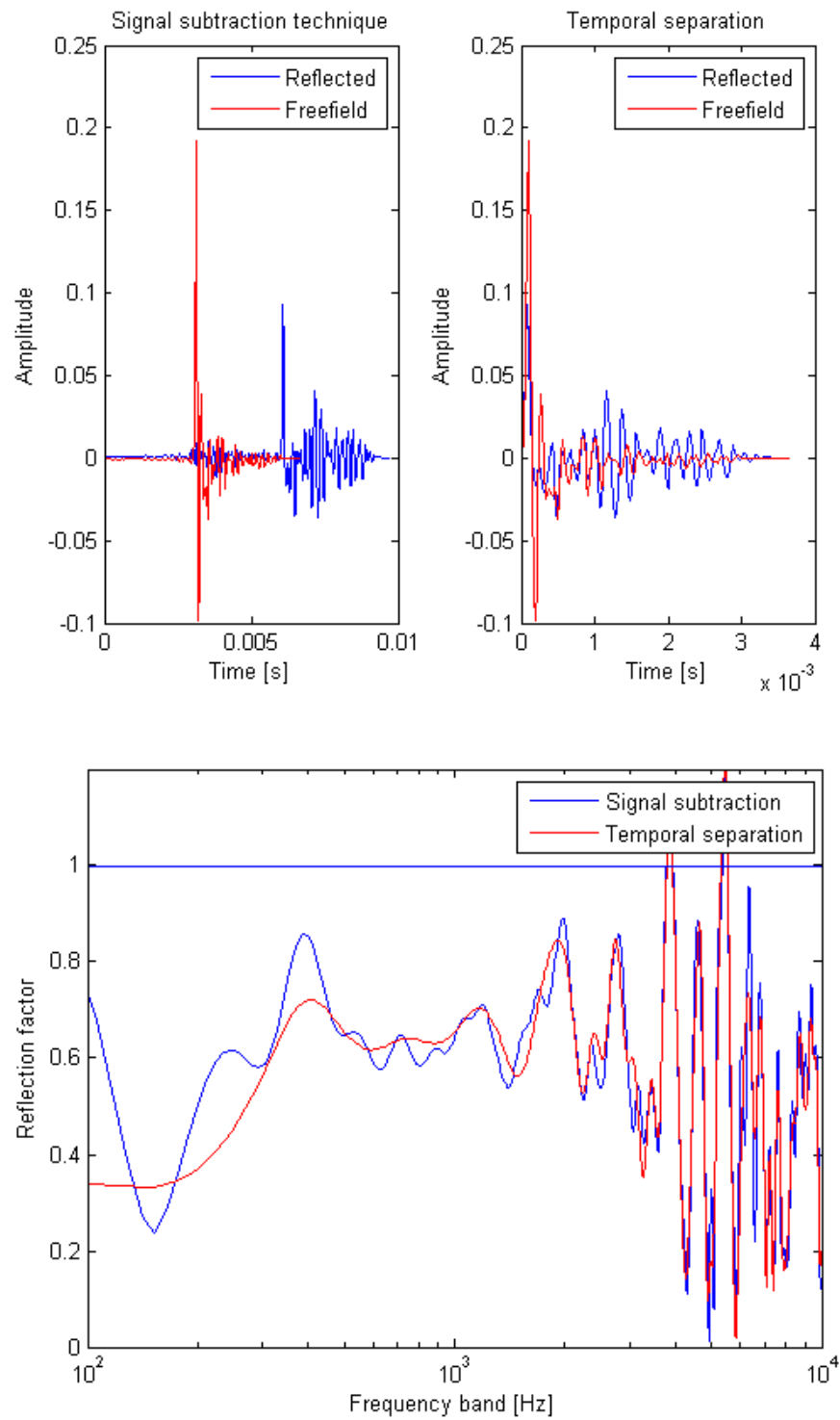


Figure B.5: Time responses and reflection factor 60 cm distance from brick building facade.

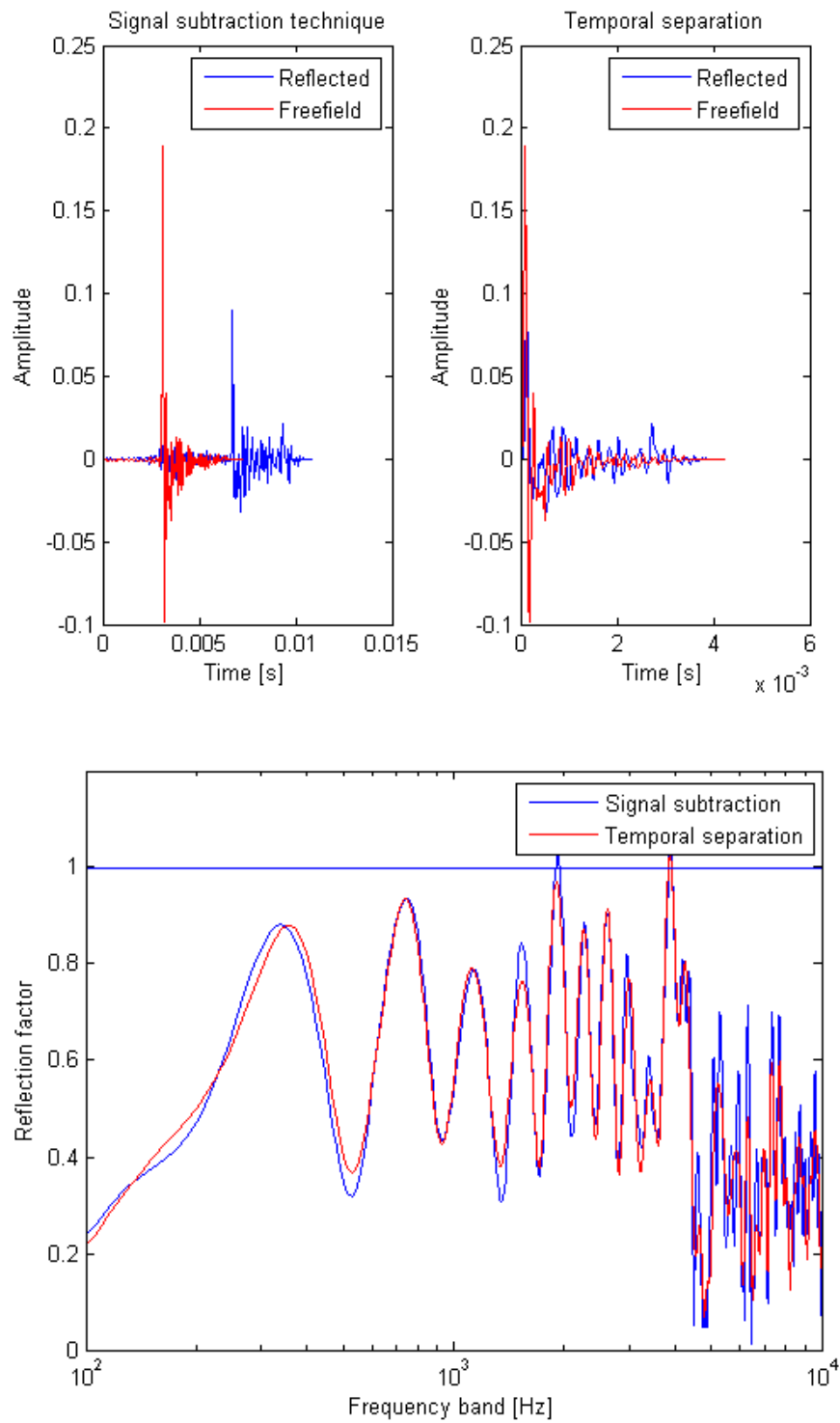


Figure B.6: Time responses and reflection factor 70 cm distance from brick building facade.

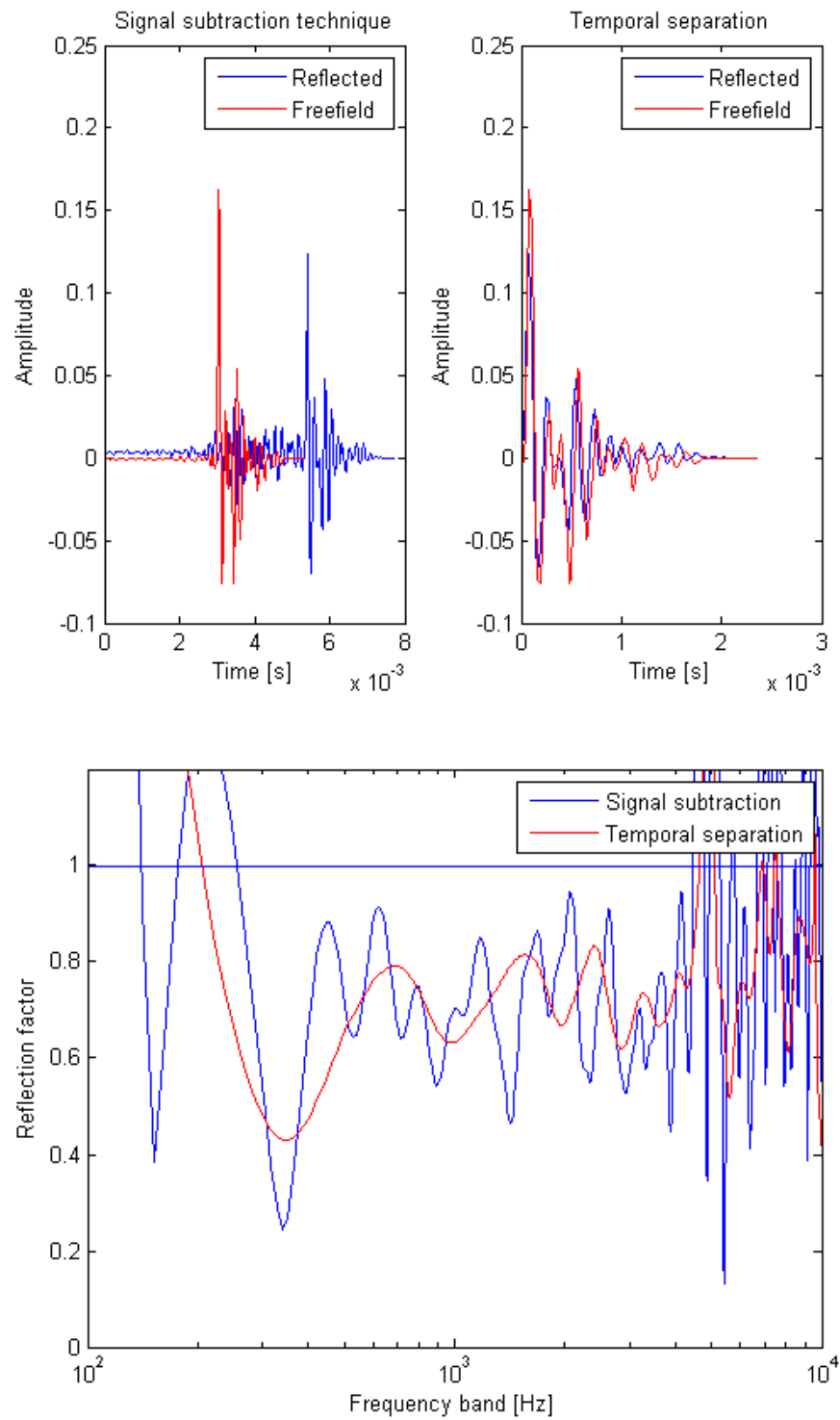


Figure B.7: Time responses and reflection factor 40 cm distance from slate building facade.

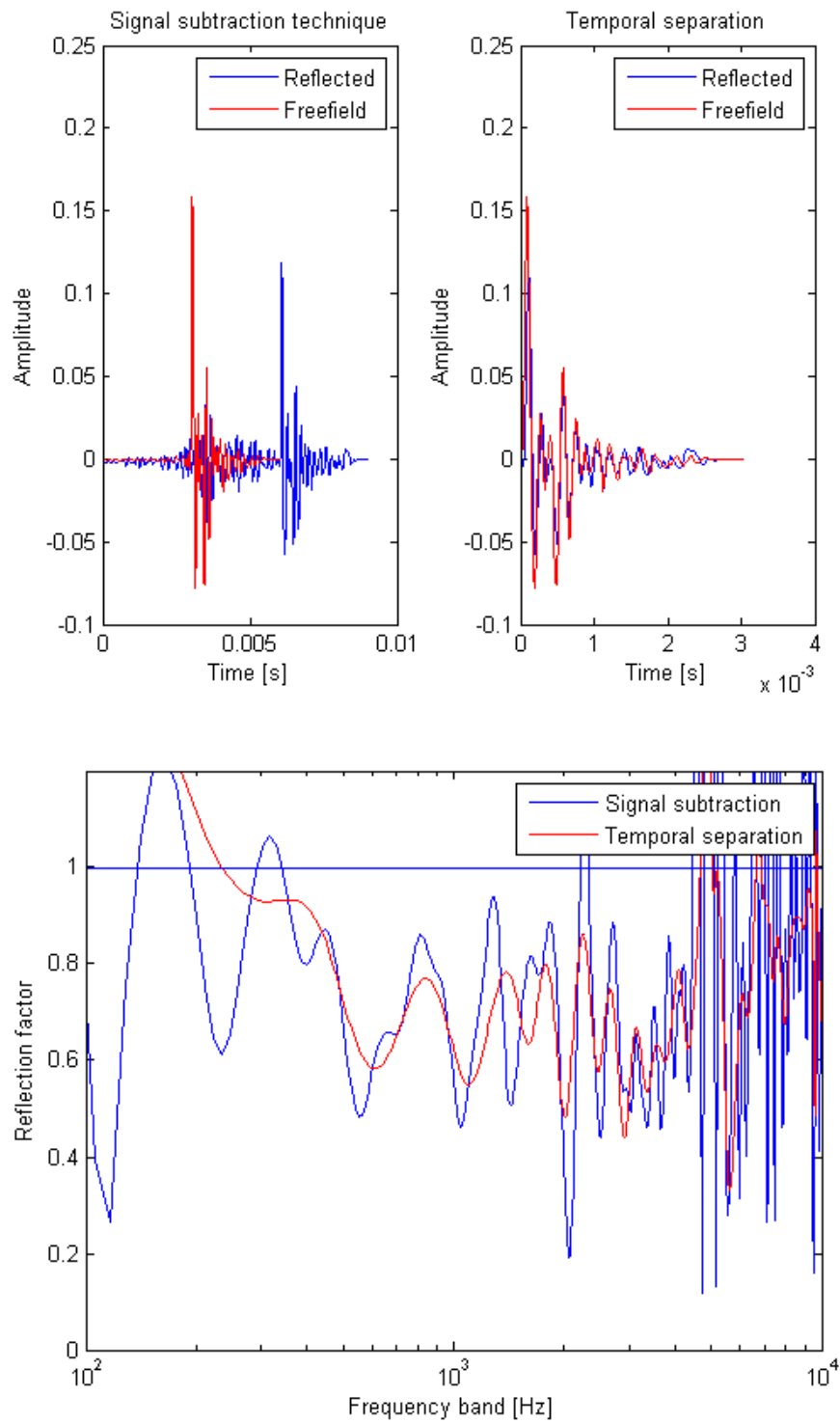


Figure B.8: Time responses and reflection factor 51 cm distance from slate building facade.



# Appendix C

## Matlab code

### C.1 loadimp.m

```
function [h, Fs, Format, Comment] = loadimp(filename)
%
%LOADIMP Load WinMLS measurement file.
% Supported file extensions:
% .WMB binary file containing impulse response and header
% .WMT ASCII (text) file containing impulse response and header
% (Please use wavread.m to read wav-files)
%
% If the file can not be read, an error message is given and the
% variables are returned as empty, that is <[]>;
%
% [h]=LOADIMP(filename) loads a .WMB or .WMT format file specified by "filename",
% returning the sampled data in variable "h". The extension
% must be included in the filename.
%
% [h,Fs]=LOADIMP(filename) loads a .WMB or .WMT format file specified by
% "filename", returning the sampled data in variable "h" and the
% sample rate in variable "Fs".
%
% [h,Fs,Format]=LOADIMP(filename) loads a .WMB or .WMT format file specified by
% "filename", returning the sampled data in variable "h", the
% sample rate in variable "Fs" and format information in the variable
% "Format". The format information is returned as a 6 element
% vector with the following order:
%
%           Format(1)      Sequence Order
%           Format(2)      Number of averages
%           Format(3)      Channel
%           Format(4)      Maximum level recorded during the measurement (percent)
%           Format(5)      # of bits used for record
%           Format(6)      # of bits used for play
%
% For version 3 files, more fields are present in the header. To change the
% arguments returned in the Format variable, selecting additional fields,
% change the line assigning to the variable in 'loadimp.m'. The line is marked (*).
%
% If the file cannot be read, an error message is given and h is returned as -1;
% This function uses the subroutine valstr.m which is included in this file.
%
```

```

% Copyright Morset Sound Development 1998-2003,
% update 21112001 - removed reading of extra header
% update 13062003 - support for file format version 4, problems
% update 23062003 - fixed problems with support for ver. 4
% Contact: www.winmls.com
%
% Example: [h1, Fs, Format, Comment]=loadimp('h1.wmb');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Change log
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% KP08012001: Updated for version 3 headers
% LM03072001: Made it work for Matlab ver. 4
% PS31032008: Included valstr in the file

VersionNumber=4; % Reads header version 3
VersionNumber.1=1; % Old files are version number 1

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Initialize return variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
h = []; Fs = NaN; Format = []; Comment = []; % Fs is scalar and cannot be []

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% OPEN FILE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fid=fopen(filename, 'r');
if isunix == 1,
    fid=fopen(filename, 'r','ieee-le');
else
    fid=fopen(filename, 'r');
end

if ( fid == -1 )
    disp(' '); disp('Error. Could not open a file with the the specified filename.')
    return
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% FIND EXTENSION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
l=length(filename);
if l<3 % check that length of string is larger than three.
    disp(' '); disp('Error. Wrong extension')
    disp('Either .WMB or .WMT must be used as file extensions,')
    return
end

ext=upper(filename(1-2:l));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% READ BINARY DATA FROM FILE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if strcmp(ext,'WMB')
    % Read format identifier
    id=setstr(fread(fid, [1,4],'uchar'));
    if (id~='WMLS')
        disp(' '); disp('Error. The file is not a WinMLS binary file!');
        fclose(fid);
        return;
    end
end

```

```

end;

% Read header data, check on header version first.
Version=fread(fid,1, 'ulong');
%if (Version ~= VersionNumber_1 & Version ~= VersionNumber)
if (Version<1 & Version>VersionNumber)
    disp(' '); disp('Error. Illegal version of file. ');
    fclose(fid);
    return;
end;

if (Version == VersionNumber_1)
% Read version 1 header
AvgNo=fread(fid,1,'ulong');
SeqOrder=fread(fid,1,'ulong');
Fs=fread(fid,1,'ulong');
RecBitsPerSample=fread(fid,1,'ulong');
PlayBitsPerSample=fread(fid,1,'ulong');
MaxRecLevel=fread(fid,1,'ulong');
Channel=fread(fid,1,'ulong');
Format=[SeqOrder AvgNo Channel MaxRecLevel RecBitsPerSample PlayBitsPerSample];

% read comment
len=fread(fid,1,'ulong');
Comment=(setstr(fread(fid, [1,len+1],'uchar')));
elseif (Version >= 3)
% Read version 3 header
Title = setstr(fread(fid,80,'uchar')); % Measurement title
Comment = (setstr(fread(fid,60,'char'))); % Channel comment
DateOfMeas = setstr(fread(fid,20,'uchar')); % Date of measurement
d_new_header_exists = fread(fid,1,'ulong'); % For internal use
Channel = fread(fid,1,'ulong'); % Channel number in measurement
NumberOfChannels = fread(fid,1,'ulong'); % Total number of channels in this measurement
Fs = fread(fid,1,'float'); % Sampling frequency
Length = fread(fid,1,'ulong'); % Length of measurement
UseFeedbackLoop = fread(fid,1,'uchar'); % Flag: Is feedback loop used?
Mixer = fread(fid,1,'uchar'); % Flag: Is WinMLS mixer used?

% Input settings
InputDevice = setstr(fread(fid,30,'uchar')); % Name of input device
MaxRecLevel = fread(fid,1,'float'); % Maximum recording level
RecBitsPerSample = fread(fid,1,'ulong'); % Number of bits per sample
MixerInputVolume = fread(fid,1,'ulong'); % Mixer input volume
MixerInputIsCalibrated = fread(fid,1,'uchar'); % Flag: Set to 1 if mixer input is calibrated
dummy = fread(fid,3,'uchar'); % SKIP 3 bytes of padding
MixerInputVol_db = fread(fid,1,'float'); % Mixer input volume in decibels.
HardwareInputIsCalibrated = fread(fid,1,'uchar'); % Flag: Set to 1 if hardware input is calibrated
InputUnitLabel = setstr(fread(fid,11,'uchar')); % Input Unit Label
InputConversionFactordB = fread(fid,1,'float'); % Input Conversion Factor

% Output settings
OutputDevice = setstr(fread(fid,30,'uchar')); % Name of output device
dummy = fread(fid,2,'uchar'); % SKIP 2 bytes of padding
PlayBitsPerSample = fread(fid,1,'ulong'); % Number of bits per sample
MixerOutputMasterVolume = fread(fid,1,'ulong'); % Mixer output master volume
MixerOutputVolume = fread(fid,1,'ulong'); % Mixer output volume
MixerOutputIsCalibrated = fread(fid,1,'ulong'); % Flag: Set to 1 if mixer output is calibrated
MixerOutputVol_db = fread(fid,1,'float'); % Mixer input volume in decibels.
HardwareOutputIsCalibrated = fread(fid,1,'uchar'); % Flag: Set to 1 if hardware output is calibrated
OutputUnitLabel = setstr(fread(fid,11,'uchar')); % Output Unit Label
OutputConversionFactordB = fread(fid,1,'float'); % Output Conversion Factor

```

```

SpeedOfSound = fread(fid,1,'float'); % Speed of sound in meters per second
MeasurementMode = setstr(fread(fid,257,'uchar')); % Measurement Mode
MeasurementSystemCorrection = fread(fid,1,'uchar'); % Flag: Is measurement system correction used?
PreEmphasis = fread(fid,1,'uchar'); % Flag: Is preemphasis used?
DeEmphasis = fread(fid,1,'uchar'); % Flag: Is deemphasis used?
EmphasisFileName = setstr(fread(fid,256,'uchar')); % Name of emphasis file
SeqOrder = fread(fid,1,'ulong'); % Sequence order
AvgNo = fread(fid,1,'ulong'); % Number of averages
NumberOfPreMLS = fread(fid,1,'ulong'); % Number of Pre-MLS
TypeOfMLS = setstr(fread(fid,11,'uchar')); % Type of MLS

    if (Version == 3)
        dummy = fread(fid,1,'uchar'); % Skip one byte of padding
    end;

% (*) Return selected information. Change this line to alter the informatng returned in the format a
Format=[SeqOrder AvgNo Channel MaxRecLevel RecBitsPerSample PlayBitsPerSample];

% read trailing informatng, skip extra header
% len_e=fread(fid,1,'ulong'); % Length of extra header
% extra_header = fread(fid,len_e,'uchar'); % Skip extra header
end;

% Read version 4 data
if (Version >= 4)
    dummy = fread(fid,6,'uchar'); % Skip one byte of padding
    MeasID = setstr(fread(fid,16,'uchar')); %20 MeasID = setstr(fread(fid,16,'uchar'))
    ExtraHeaderSize = fread(fid,1,'ulong'); % not used
    IsTransferfunction = fread(fid,1,'uchar'); % Flag: Is preemphasis used?
    SpecifyImpLen = fread(fid,1,'uchar'); % Flag: Is preemphasis used?
    Resample = fread(fid,1,'uchar'); % Flag: Is preemphasis used?
    SweepLenInSec = fread(fid,1,'double'); % Maximum recording level
    StartFreq = fread(fid,1,'double'); % Maximum recording level
    EndFreq = fread(fid,1,'double'); % Maximum recording level
    HPfiltered = fread(fid,1,'uchar'); % Flag: Is preemphasis used?
    if (Version == 4)
        dummy = fread(fid,7,'uchar'); %7 Skip 7 bytes of padding
    end;
end;

% read impulse response
h=zeros(1,Length); % initialize data to make it faster
h=fread(fid,Length,'float');
fclose(fid);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% READ ASCII DATA FROM FILE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
elseif strcmp(ext,'WMT')

% Read first line to check if it is a WinMLS Ascii file
string=fgetl(fid);
if strcmp(string, '#WinMLS datafile')==1
    disp(' '); disp('Error. The specified file either corrupt or not a WinMLS Ascii file')
    fclose(fid);
    return
end

% Ignore all lines starting with '#'
Version=str2num(valstr(fid));
if (Version>VersionNumber)

```

```

disp('Illegal version of file');
fclose(fid);
return;
end;

AvgNo=str2num(valstr(fid));
SeqOrder=str2num(valstr(fid));
Fs=str2num(valstr(fid));
RecBitsPerSample=str2num(valstr(fid));
PlayBitsPerSample=str2num(valstr(fid));
MaxRecLevel=str2num(valstr(fid));
Channel=str2num(valstr(fid));

% read comment
Comment=valstr(fid);
Comment=Comment(2:length(Comment)-1);

Format=[SeqOrder AvgNo Channel MaxRecLevel RecBitsPerSample PlayBitsPerSample];

%skip all lines beginning with '#'
string=fgetl(fid);
while findstr(string, '#')==1,
    string=fgetl(fid);
end;

% read impulse response
%imp_l=2^SeqOrder-1;
%h=zeros(1,imp_l); % initialize data
%h(1:imp_l)=fscanf(fid,'%f',inf);
h=fscanf(fid,'%f',inf);
fclose(fid);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% THE FILE EXTENSION IS NOT SUPPORTED
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
else
    disp(' '); disp('Error. The file extension you specified is not supported.')
    disp('Either .WMB or .WMT must be used as file extensions,')
    disp('Type <help loadimp> for more information')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% THE SUBROUTINE valstr
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [string]=valstr(fid)
% Skip all lines beginning with '#', return non-comment string
string=fgetl(fid);
s=findstr(string,'#');
if s==1,
    string=fgetl(fid);
end

```

## C.2 timeshift.m

```

function [target,target.ref] = timeshift(h.ref,h.obj,Fs)

%h.ref er mÅ¥lt frittfelt impulsrespons
%h.obj er mÅ¥lt impulsrespons til objektet
%Fs er samplingfrekvensen

```

```

%finner maksimalverdi og posison (i sample)
[max_val_ref,max_pos_ref]=max(abs(h_ref));
[max_val_obj,max_pos_obj]=max(abs(h_obj));
%vektor med normaliserte frekvensverdier.
k=(0:length(h_obj)/2)'/length(h_obj);
%initierer feilvektor, tar med fram til 1 ms etter toppen i impulsresponsen
feil=sum(abs(h_obj(1:max_pos_obj+Fs*1e-3)));
%ii teller fra -0.5 sample til +0.5 sample (tidsforskyvning)
for ii=-0.5:0.001:0.5
    %frekvensrespons til en tidsforskyvet impulsrespons
    g=exp(1i*2*pi*(ii+max_pos_ref-max_pos_obj)*k);
    %sÅrger for at fasen har verdi 0 ved aliasingfrekvensen, om ikke, vil man
    %kunne fÅ et imaginÅrt tidsignal.
    g(end)=1;
    %setter inn speilspekteret, (over aliasingfrekvensen)
    g=[g;conj(g(end-1:-1:2))];
    %trekker den tidsforsinkede referanseimpulsen fra impulsresponsen til
    %objektet
    temp=h_obj-iff(fft(h_ref).*g);
    %beregner avviket
    feil2=sum(abs(temp(1:max_pos_ref+Fs*1e-3)));
    %noen linjer for Å plotte
    % % plot([h_ref(1:max_pos_obj+Fs*5e-3),h_obj(1:max_pos_obj+Fs*5e-3),temp(1:max_pos_obj+Fs*5e-3)])
    % plot([h_obj(1:max_pos_obj+Fs*5e-3),temp(1:max_pos_obj+Fs*5e-3)])
    % pause(0.1)
    %gjÅr en sjekk pÅ om avviket er mindre enn forrige bergenet avvik
    if feil2<feil
        %target er den mÅlte impulsresponsen til objektet med
        %fritt feltsimpulsen trekt fra.
        target=temp;
        %target_ref er referansesignal med riktig tidsforsinkelse.
        target_ref=iff(fft(h_ref).*g);
        %avvik er tidsforsinkelsen i samples
        avvik=ii+max_pos_ref-max_pos_obj;
    end
    feil=feil2;
end

end

```

### C.3 spreading.m

```

function [K] = spreading(h_object)
% spreading.m calculated a factor for geometrical spreading, K, relative
% to the measurement with the shortest distance to the surface.

h_object1 = loadimp('Object_23_1.wmb');
h_object2 = loadimp('Object_23_2.wmb');
h_object3 = loadimp('Object_23_3.wmb');

h1 = (h_object1+h_object2+h_object3)./3;
h2 = h_object;

% Root mean square
rms1 = sqrt(mean(h1.^2));
rms2 = sqrt(mean(h2.^2));

% Geometrical spreading factor
K = rms1/rms2;

```

## C.4 Main code

```

% This Matlab calculates and plots the reflection factor and absorption
% factor using temporal separation with a signal subtraction technique.

% Measured impulse responses%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
h.freefield1 = loadimp('Freefield.1.wmb');
h.freefield2 = loadimp('Freefield.2.wmb');
h.freefield3 = loadimp('Freefield.3.wmb');
h.freefield4 = loadimp('Freefield.4.wmb');
h.freefield5 = loadimp('Freefield.5.wmb');

h.object1 = loadimp('Object.23.1.wmb');
h.object2 = loadimp('Object.23.2.wmb');
h.object3 = loadimp('Object.23.3.wmb');

% Averaging %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
h.freefield = (h.freefield2+h.freefield3+h.freefield5)./3;
%h.freefield = (h.freefield1+h.freefield2+h.freefield3+h.freefield4+h.freefield5)./5;
% h_object = (h_object1+h_object2+h_object3+h_object4+h_object5)./5;
h.object = (h.object1+h.object2+h.object3)./3;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ds = 1.23; % Distance between loudspeaker and surface under test
dm = 0.23; % Distance between microphone and surface under test

c = 337; % Speed of sound
fs = 48000; % Sampling frequency
N = 4096;

% Geometrical spreading %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Kr = (ds - dm)/(ds + dm);

K = spreading(h.object);

% Time constants %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
t1 = (ds-dm)/c; % Time 1 m
t1fs = ceil(t1*fs);

t2 = (ds + dm)/c;
t2fs = ceil(t2*fs);

t3 = dm/c; % Time microphone to surface
t3fs = ceil(t3*fs);

t4 = 0.001;
t4fs = ceil(t4*fs);

% Radius of maximum sampled area %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Tw = t2 + 2*t3;
r = 1/(ds+dm+c*Tw)*sqrt((ds + dm + (c*Tw)/2)*(ds + (c*Tw)/2)*(2*dm + c*Tw)*c*Tw);

% Time window %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
w.length = t2fs; % distance wall + distance mic wall
w.length2 = t2fs + 2*t3fs; % distance wall + 2*distance mic wall
w.length3 = 2*t3fs; % distance wall + distance mic wall

wb = ones(w.length,1);

```

```

windowfunc = blackmanharris(2*0.001*fs);
w_time = length(windowfunc)/2;
wb_edge = windowfunc(w_time:length(windowfunc));
wb(w_length-fs*0.001:w_length)= wb_edge;

% % Plot time window
% tid_window = 0:1/fs:(length(wb)-1)/fs;
% figure(4)
% plot(tid_window,wb)
% axis([0 0.006 0 1.5])
% xlabel('Time [s]')
% ylabel('Amplitude')
% title('Time window')

wb2 = ones(w_length2,1);
wb2(w_length2-fs*0.001:w_length2)= wb_edge;

wb3 = ones(w_length3,1);
if length(wb3) >= length(wb_edge)
    wb3(w_length3-fs*0.001:w_length3)= wb_edge;
end

% % Without time shift
% hr2 = h_object - h_freefield;
% hr2_w = hr2(1:length(wb2)).*wb2;

% Time shift %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% With time shift
[hr,h_freefield] = timeshift(h_freefield,h_object,fs);

hr = K*hr; % Geometrical spreading

hr_w = hr(1:length(wb2)).*wb2;
h_freefield_w = h_freefield(1:length(wb)).*wb;

hr_w3 = hr(t2fs:(t2fs+length(wb3)-1)).*wb3;
h_freefield_w3 = h_freefield(t1fs:(t1fs+length(wb3)-1)).*wb3;

% % With and without time shift
% hold off
% figure(5)
% hold on
% plot(hr2_w)
% plot(hr_w, 'r')
% legend('Without time shift','With time shift')
% xlabel('Samples')
% ylabel('Amplitude')

% Frequency response %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Hr = fft(hr_w,N);
Hi = fft(h_freefield_w,N);

Hr3 = fft(hr_w3,N);
Hi3 = fft(h_freefield_w3,N);

% Reflection factor %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Q = abs(Hr./Hi);
% Qw = (1/Kr)^2.*abs(Hr./Hi).^2;
Q3 = abs(Hr3./Hi);

one = ones(length(Q)/2,1);

```



```

% Absorption %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% a = 1 - Qw;
% a = 1 - Q;
a = 1 - Q3;

for i = 1:length(a)
    if a(i) < 0
        a(i) = 0;
    end
end

n = 18; % Number of frequency bands
j = 1;
f = zeros(n,1);
f(1) = 250; % First center frequency
f_low = zeros(n,1);
f_high = zeros(n,1);
f_low_fs = zeros(n,1);
f_high_fs = zeros(n,1);
A = zeros(n,1);

for j = 1:n
    f_low(j) = f(j)/2^(1/6);
    f_high(j) = 2^(1/6) * f(j);

    f_low_fs(j) = floor(((N-1)/fs) * f_low(j));
    f_high_fs(j) = ceil(((N-1)/fs) * f_high(j));

    A(j) = mean(a(f_low_fs(j):f_high_fs(j)));
    f(j+1) = 2^(1/3) * f(j);
    f(j) = ceil(f(j));
end

% Plot %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tid_direct = 0:1/fs:(length(h_freefield_w)-1)/fs;
tid_reflect = 0:1/fs:(length(hr_w)-1)/fs;
tid_direct3 = 0:1/fs:(length(h_freefield_w3)-1)/fs;
tid_reflect3 = 0:1/fs:(length(hr_w3)-1)/fs;
fрек = ((0:N-1)*(fs/N));
fAxis = фрек(1:length(фрек)/2)';

% Time response
figure(1)
% % Frequency response
% subplot(1,2,1)
% hold off
% plot(fAxis,abs(Hr(1:length(Hr)/2)))
% hold on
% plot(fAxis,abs(Hi(1:length(Hi)/2)),'r')
% hold off
% legend('Reflected', 'Freefield')
% xlabel('Frequency [Hz]')
% ylabel('Amplitude')
% title('Frequency spectrum')
subplot(1,2,1)
hold off
plot(tid_reflect,hr_w)
hold on
plot(tid_direct,h_freefield_w,'r') % Plots direct impulse response as a function of time
legend('Reflected', 'Freefield')
xlabel('Time [s]')

```

```

ylabel('Amplitude')
title('Signal subtraction technique')
subplot(1,2,2)
hold off
plot(tid.reflect3,hr_w3)
hold on
plot(tid.direct3,h.freefield_w3,'r')
legend('Reflected', 'Freefield')
xlabel('Time [s]')
ylabel('Amplitude')
title('Temporal separation')

% Reflection factor
hold off
figure(2)
semilogx(fAxis,Q(1:length(Q)/2))
hold on
semilogx(fAxis,Q3(1:length(Q3)/2),'r')
semilogx(fAxis,one)
axis([100 10000 0 1.2])
legend('Signal subtraction', 'Temporal separation')
xlabel('Frequency band [Hz]');
ylabel('Reflection factor');
% hold on
% axis([0 7000 0 1.2])
% semilogx(Q(1:length(Q)/2),'k')
% semilogx(Q3(1:length(Qw)/2))
% semilogx(one)

% Absorption
figure(3)
bar(A)
axis([0 19 0 1])
set(gca, 'XTick', (2:3:n)); % Label frequency axis on octaves.
set(gca, 'XTickLabel', f(2:3:length(f))); % MATLAB 5.1
xlabel('Frequency band [Hz]');
ylabel('Absorption coefficient');

```

## C.5 sd.m

```

% This Matlab script calculates and plots the mean absorption coefficient
% and the standard deviation.

% Absorption coefficients for different distances
A_23 = [0.246429288482987;0.266557543213536;0.234735815843621;0.234707985335729;0.267309994611192;0.263344710];
A_32 = [0;0.0665402809029716;0.314464185589832;0.485223406957227;0.484073761022172;0.352134005201296;0.292477];
A_40 = [0.265327979650172;0.506569956567461;0.524028054788400;0.366371435731227;0.236882990338421;0.262096079];
A_51 = [0.0200449195169417;0.0638337690698226;0.0896339706007874;0.253116952739192;0.389992425683925;0.269885];

i = 1;
for i = 1:length(A_23)
    A_mean(i) = (A_23(i)+A_32(i)+A_40(i)+A_51(i))/4;
    A_mean2(i) = (A_23(i)+A_32(i))/2;
    sd1(i) = sqrt(( (A_23(i)-A_mean(i))^2 + (A_32(i)-A_mean(i))^2 + (A_40(i)-A_mean(i))^2 + (A_51(i)-A_mean(i))^2 )/4);
    sd2(i) = sqrt(( (A_23(i)-A_mean(i))^2 + (A_32(i)-A_mean(i))^2 )/2);
end

% Frequency bands
f = [250;315;397;501;630;794;1001;1260;1588;2001;2520;3175;4001;5040;6350;8001;10080;12700;];

```

```

% Plot
figure(1)
semilogx(f,A.23)
hold on
semilogx(f,A.32,'r')
semilogx(f,A.40,'k')
semilogx(f,A.51,'g')
axis([250 12700 0 1])
legend('23cm', '32cm', '40cm', '51cm')
xlabel('Frequency band [Hz]');
ylabel('Absorption factor');

figure(2)
semilogx(f,A.mean)
hold on
semilogx(f,A.mean2,'r')
semilogx(f,sd1,'k')
semilogx(f,sd2,'g')
axis([250 12700 0 1])
legend('Mean 1', 'Mean 2', 'Standard deviation 1', 'Standard deviation 2')
xlabel('Frequency band [Hz]');
ylabel('Absorption factor');

```