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# **Evaluation of low-frequency façade insulation down to 20 Hz**

Measurement of low-frequency façade insulation down to 20 Hz and subjective assessment of synthesized cruise ship noise

Master's thesis in Master Program Sound and vibration

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**DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING**

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CHALMERS UNIVERSITY OF TECHNOLOGY  
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MASTER'S THESIS 2023

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## Abstract

Low-frequency noise has become a growing concern due to its potential adverse effects on human health. However, existing measurement standards and calculation software typically do not cover frequencies below 50 Hz, despite the human hearing threshold extending down to 20 Hz. The knowledge gap regarding sound insulation in the lower frequency range has prompted the need for further research. Recent regulations allow for industrial noise to exceed permissible levels near dwellings as long as indoor requirements are met, creating opportunities for construction in previously unsuitable areas. An example of such a location is Värtahamnen in Stockholm, where cruise ships regularly dock and generate noise from their ventilation systems and onboard electricity generation. These ships are expected to produce low-frequency noise that may pose challenges for nearby planned dwellings. This raises questions about evaluating low-frequency sound insulation and establishing reliable measurement methods, considering that sound pressure levels within rooms can vary significantly due to room modes.

This thesis utilizes a field-tested measurement method to assess the sound insulation of façades down to 20 Hz. The measurements also include a subjective assessment of synthesized cruise ship noise and its perception by the auditory system. Additionally, a finite element model was utilized to analyze room modes and gain further insights into their influence on the acoustic environment.

The results of the measurements indicate that common façade structures exhibit a moderate sound insulation capability down to 20 Hz. Among the various parameters that affect sound insulation below 100 Hz, room modes and windows were found to have the most significant impact. The subjective assessment revealed that when the synthesized cruise ship noise is barely audible in the receiving room, its frequency contents below 80 Hz lie below the human hearing threshold; however, as the noise levels increase to the point of being disturbing, this frequency limit is lowered to 31,5 Hz. These results indicate that modern façades may have adequate sound insulation below 50 Hz considering the human hearing threshold. However, achieving this requires careful planning and construction.

Keywords: low-frequency noise, room modes, façade, hearing threshold, level difference, measurements, dwellings



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# 1

## Introduction

Low-frequency noise, defined as sound waves with a frequency range of 20 Hz to 200 Hz, has been a growing concern in recent years due to its potential adverse effects on human health. Unlike high-frequency noise, which is easily absorbed by buildings and other structures, low-frequency noise can more easily penetrate walls and floors, making it a particular problem in residential areas near sources such as highways, ports, and industrial facilities. Additionally, low-frequency noise is often inaudible to the human ear, making it difficult to identify and mitigate. Research has shown that exposure to low-frequency noise can have a number of negative effects on human health, including sleep disturbance, cardiovascular disease, and cognitive impairment [12]. In particular, exposure to low-frequency noise at frequencies below 50 Hz has been linked to increased blood pressure, heart rate, stress hormone levels, decreased cognitive function, and decreased quality of life [17]. The Swedish public health agency (FoHM) has guideline values for low-frequency equivalent SPL levels regarding permanent residences in the range 31.5 Hz to 200 Hz [5]. While measurement standards for low-frequency sound insulation do not currently extend below 50 Hz, the potential health effects of exposure to these frequencies make it an important area of research.

In 2015, the Swedish regulations regarding industrial noise in PBL (Plan- och bygglagen) were revised (SFS 2015:668)[15]. The new regulations allowed industrial noise to be exceeded around dwellings, thereby enabling the construction of homes closer to industries, as long as they meet indoor requirements [3]. The new regulations operate similarly to those regulating traffic noise. If a building is located in a noisy area, it must have at least one side which is noise dampened with lower noise levels. The new regulations have opened up new possibilities for the construction of dwellings in previously unsuitable locations. One such example is Värtahamnen in Stockholm, where cruise ships regularly dock. These ships generate noise from their ventilation systems and from the generators used to produce their own electricity. The resulting low-frequency noise has a fundamental frequency ranging from 31.5 to 125 Hz, which is of particular concern for nearby dwellings. Today measurement standards and calculation software such as Insul and Bastian do not cover frequencies below 50 Hz, which makes it difficult to determine the risks of noise disturbances.

When evaluating sound insulation at low frequencies, it is important to consider several factors. Due to the longer wavelengths of low-frequency noise, standing waves can occur in rooms, resulting in significant spatial variations in SPL. Making

it challenging to assess sound insulation reliably. [11]

### **1.1 Purpose**

The purpose of the thesis is to evaluate a measurement method for reliably assessing low-frequency façade sound insulation down to 20 Hz and what parameters affect the sound space. Additionally, the purpose is to explore what frequencies are perceived concerning cruise ship noise.

# 2

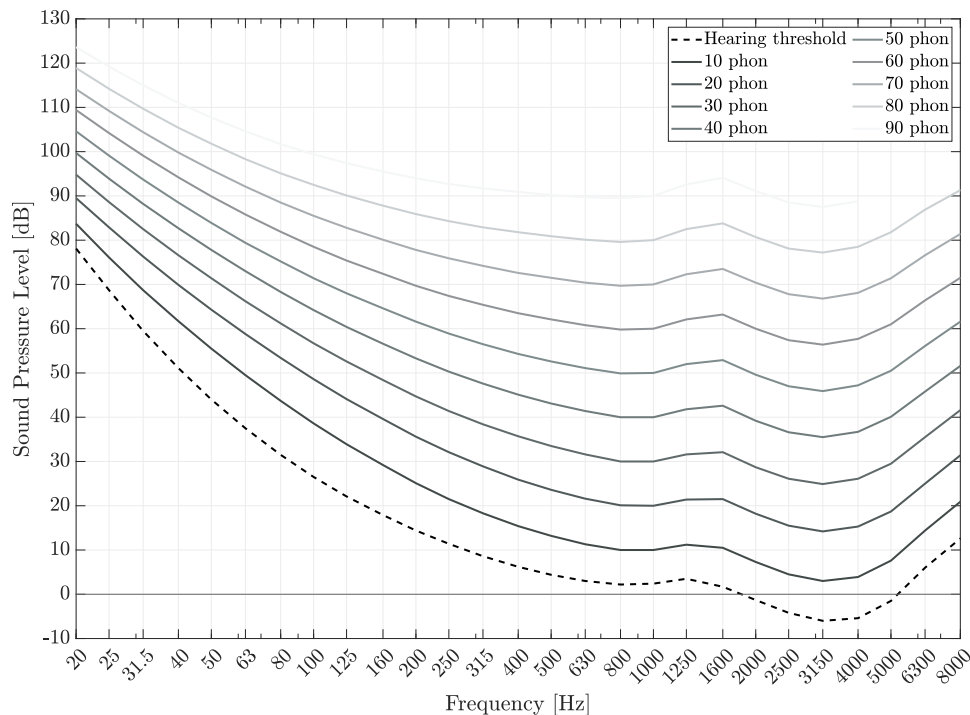
## Theory

### 2.1 Human hearing threshold and equal-loudness contours

The human hearing threshold is the minimum sound intensity level that can be perceived by the human ear at different frequencies. The threshold of hearing varies depending on the frequency of the sound, with a normal ear being sensitive to frequencies between 20-20 000 Hz, and most sensitive in the range 2000 to 4000 Hz.

The equal loudness contours show that the human ear is not equally sensitive to all frequencies at the same sound pressure level. The human auditory system is less sensitive to low and high frequencies at low sound pressure levels and more sensitive to mid-range frequencies. As a result, the ear becomes more sensitive to low and high frequencies at higher sound pressure levels and less sensitive to mid-range frequencies as seen in Figure 2.1. Loudness refers to the subjective perception of sound. It can be helpful to compare the loudness of sounds to a standard reference sound. The most commonly used reference sound is a binaurally presented 1000 Hz sine wave in a free field, emanating directly in front of the listener. The loudness level of a sound is determined by the intensity level of the 1000 Hz sine wave that sounds equally as loud as the sound being measured. The unit used to measure loudness level is called a "phon". Therefore, the loudness level of any sound in phons corresponds to the sound pressure level in decibels (dB) of the 1000 Hz sinusoidal wave that is perceived to be as loud [14].

Note that the International standard ISO 226:2003, where the normal equal-loudness level contours are determined has been revised in 2023. The human hearing threshold and phon curves used in this report are based on ISO 226:2023 [8].



**Figure 2.1:** Equal-loudness contours in phon with the human hearing threshold, computed in Matlab based on [8].

### 2.1.1 Low-frequency noise effects on humans

Low-frequency noise and vibrations in the range of approximately 0.5 Hz to 200 Hz have been shown to have significant impacts on human health and well-being. While most of the noise is perceived by the normal hearing system, vibrations of the body can also result from low-frequency noise and vibrations in the surrounding area, which can influence human perception of and reaction to low-frequency noise [2] [17].

One of the most common effects of low-frequency noise on humans is annoyance, which can depend on individual factors such as activity at the time of exposure and predictability of the noise. The effects of vibrations on the human body can also be complicated, as they can be mistaken for noise and result in people "hearing" more noise than is actually present. Exposure to low-frequency noise has been linked to negative effects on the cardiovascular system, such as a slight increase in the risk of heart disease among individuals living in areas highly exposed to road noise and a greater prevalence of cardiovascular diseases among those exposed to aircraft noise [2].

Additionally, exposure to low-frequency noise can lead to sleep disturbance, stress, and negative effects on cognitive function, communication, and social behavior. Studies show that noise-sensitive subjects exposed to low-frequency noise during work performance exhibited an increase in cortisol levels, indicating a stress response [17]. These findings highlight the importance of understanding and mitigating the effects of low-frequency noise and vibrations on human health and well-being.

When measuring noise levels, choosing an appropriate weighting filter is essential to accurately assess the impact of noise on human health and well-being. The A-weighting filter is commonly used to approximate how the human ear perceives sound, but it may not be suitable in situations where low-frequency noise is the primary source of disturbance. In such cases, the C-weighting filter, which only moderately attenuates low-frequency noise, may be more appropriate and could be used as a complement.

## 2.2 Room Acoustics

### 2.2.1 Reverberation time

Reverberation time (T) is a measure of the time required for the sound pressure level (SPL) to decrease 60 dB from its initial value after a sound source has ceased. It represents the amount of time that an acoustic space retains its sound energy, which is determined by the space's physical characteristics, such as its volume, surface area, and absorption properties of its materials. The reverberation time is based on the assumption that a diffuse field is present, which means the sound propagation is uniform in all directions. This criterion is never perfectly fulfilled in a practical situation but is still a useful approximation [10]. The most common formula used to calculate the reverberation time is Sabine's formula [14].

$$T = \frac{0.161V}{S\alpha + 4mV} \quad (2.1)$$

where  $V$  is the volume of the room and the denominator term describes the total absorption area in units of Sabine,  $S$  is the area of all surfaces and  $\alpha$  is the frequency dependant absorption coefficients of the materials. Typical absorptive materials trend towards higher absorption for higher frequencies, making the reverberation time shorter at higher frequencies and longer at lower frequencies. The reverberation time can therefore be controlled by changing the room's volume and the amount of absorption on the surfaces. The term  $4mV$  describes the sound absorption in air, which is the conversion of sound energy into heat as it interacts with the air molecules [10].

### 2.2.2 Schroeder frequency

Schroeder frequency is a parameter defined as the frequency at which the reverberant sound field in a room transitions from a modal to a diffuse sound field. It can be defined as the frequency at which the reverberation time of a room transitions from being dominated by the decay of the modal resonances to being dominated by the decay of the diffuse sound field. At frequencies below the Schroeder frequency, the sound field in a room is dominated by room modes or eigenfrequencies, which are resonant frequencies that correspond to standing waves in the room. Above the Schroeder frequency, the sound field becomes more diffuse, with sound energy distributed more evenly throughout the room. The Schroeder frequency can be expressed as

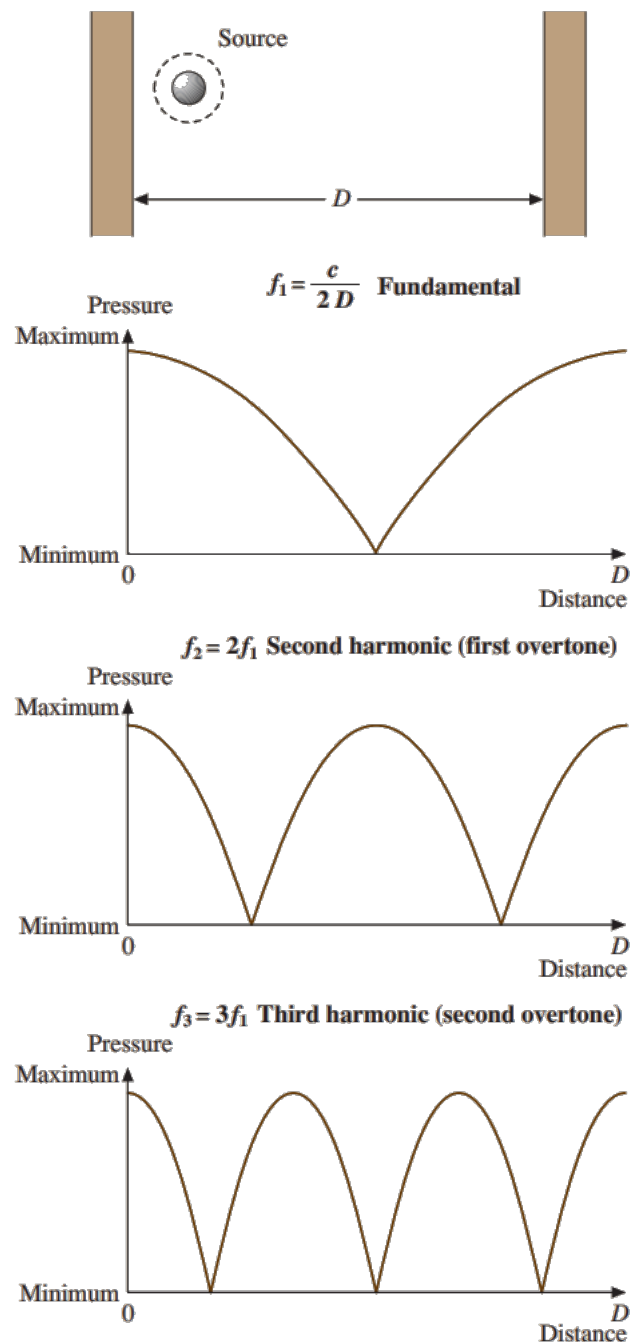
$$f_s \approx 2000\sqrt{\frac{T}{V}} \quad (2.2)$$

where it is noted that it is related to the volume of the room and the reverberation time, also meaning the absorption characteristics of the surfaces within the room. As the size of a room increases, the Schroeder frequency decreases, indicating that the modal resonances become more dominant at lower frequencies. Similarly, as the amount of sound-absorbing material within a room increases, the Schroeder frequency also decreases. A common characteristic of large halls is the presence of a strong modal overlap across the frequency range of interest due to the Schroeder frequency typically falling between 20 to 30 Hz, thus assessing any of the eigenfrequencies unnecessary as they lie below the threshold of hearing. In contrast, the Schroeder frequency of smaller rooms usually falls between 100 and 200 Hz, resulting in a higher number of eigenfrequencies below this range, thereby increasing the complexity of their acoustic characteristics [10].

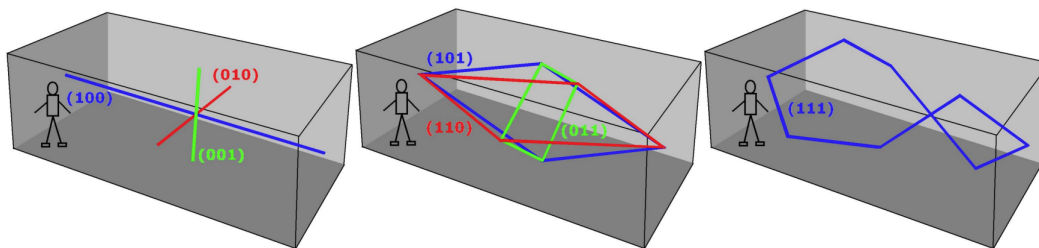
### 2.2.3 Room modes in shoe box shaped rooms

In acoustics, room modes refer to the specific frequencies at which sound waves can resonate within a closed space, such as a rectangular room with rigid boundaries. Room modes, also referred to as standing waves, arise when sound waves coincide and interfere with the original sound wave in the same phase, after two or more reflections from the boundaries of the room. As the sound travels along the same path indefinitely, the sound pressure level is greatly dependent on the location. Room modes emerge at certain frequencies known as eigenfrequencies or room resonance frequencies where the length of the above-described path is a multiple of the wavelength as seen in figure 2.2. In a room mode, fixed points exist where the waves reinforce each other to produce antinodes (high sound pressure), and other locations where complete or partial cancellation of sound results in a node (zero sound pressure). These points determine the highest and lowest sound pressures in the room. In spaces with parallel walls, little or no furniture, and low sound absorption, repeated reinforcement and cancellation may cause powerful nodes and antinodes.

In a rectangular room, room modes are determined by the dimensions of the room and the speed of sound, and they correspond to specific geometric standing wave patterns that can be excited by a sound source. For a rectangular room with rigid boundaries, the room modes are classified based on their wavefront patterns, which can be described using three integers ( $l$ ,  $m$ ,  $n$ ) that represent the number of half-wavelengths along each of the three axes of the room. As shown in figure 2.3, axial modes refer to room modes along one axis, tangential modes refer to two-dimensional modes, and oblique modes correspond to three-dimensional modes.



**Figure 2.2:** First axial modes in a room with rigid boundaries [14].



**Figure 2.3:** Left) Axial modes. Center) Tangential modes. Right) Oblique mode [11].

The resonance frequency of each mode is given by the equation

$$f_{lmn} = \frac{c_0}{2} \left[ \left( \frac{l}{L_x} \right)^2 + \left( \frac{m}{L_y} \right)^2 + \left( \frac{n}{L_z} \right)^2 \right]^{\frac{1}{2}} \quad l, m, n \geq 0 \quad (2.3)$$

where  $f$  is the frequency,  $c_0$  is the speed of sound,  $L_x$ ,  $L_y$ , and  $L_z$  are the dimensions of the room, and  $l$ ,  $m$ , and  $n$  are the integers that define the wavefront pattern. The first few modes of a rectangular room with rigid boundaries are relatively low in frequency and are mostly responsible for sound pressure level variations within the room [11]. These SPL variations and low-frequency modes are troublesome regarding the evaluation of reverberation time. The reverberation time is typically defined based on the assumption of a diffuse sound field that exists above the Schroeder frequency. This assumption requires at least three eigenfrequencies to be present within the bandwidth. However, at lower frequencies, the number of room modes decreases successively, and individual modes tend to dominate the sound field, which can significantly affect the accuracy of the reverberation time measurement. Although there may be a limited number or absence of modes in a given frequency range, sound absorption still occurs, making it relevant to measure and analyze decay time below the Schroeder frequency. Due to the absence of a diffuse sound field, decay time may be a more fitting term than reverberation time [13].

## 2.3 Building Acoustics

### 2.3.1 Reduction index and standardized level difference

In order to characterize the sound insulation properties of a building element, various quantities have been introduced in the literature. One such quantity is the reduction index  $R$ , which is a logarithmic value defined as

$$R = 10 * \lg \left( \frac{W_i}{W_t} \right), (dB) \quad (2.4)$$

where  $W_i$  represents the incident sound power on the surface of the element, and  $W_t$  is the transmitted sound power through the element. However, this quantity is mostly used for laboratory measurements, where it assumes that all sound energy is transmitted solely through the building element. In reality, the actual performance

of a building element is affected by flanking paths caused by cracks, openings and poor construction. To account for flanking transmission, the equation is rewritten as

$$R' = D + 10 * \lg\left(\frac{S}{A_R}\right), \quad (2.5)$$

where  $D$  is the sound pressure level differences between the two rooms expressed as

$$D = L_1 - L_2, \quad (2.6)$$

where  $L_1$  is the sound pressure level at the façade and  $L_2$  the sound pressure level in the receiving room and  $S$  is the area of the building element, and  $A_R$  the equivalent absorption area of the receiving room, in square meters. This way of expressing the reduction index is called the apparent sound reduction index, representing a more realistic situation.

There are still other ways of expressing sound insulation. The quantity  $D_{nT}$ , standardized level difference which refers to a given reverberation time  $T_0$ , takes flanking transmission more comprehensively into account as it is not as focused on the partition element. The standardized level difference is expressed as

$$D_{nT} = D + 10 * \lg\left(\frac{T}{T_0}\right), \quad (2.7)$$

where  $T$  is the measured reverberation time and  $T_0$  is set to 0.5 seconds for dwellings [16].

### 2.3.1.1 Façade insulation

For façades, the apparent sound reduction index of a building element is expressed as

$$R'_{45^\circ} = D + 10 * \lg\left(\frac{S}{A_R}\right) - 1.5dB, \quad (2.8)$$

when the sound source is a loudspeaker at an angle incident of  $45^\circ$ [7].

In situations where low-frequency level differences are being evaluated, the criterion for a diffuse field may not be met, and the reverberation time unable to assess. Hence, as mentioned by [9], it is more appropriate to consider the level difference solely and incorporate a -6 dB correction to account for façade reflections, expressed as.

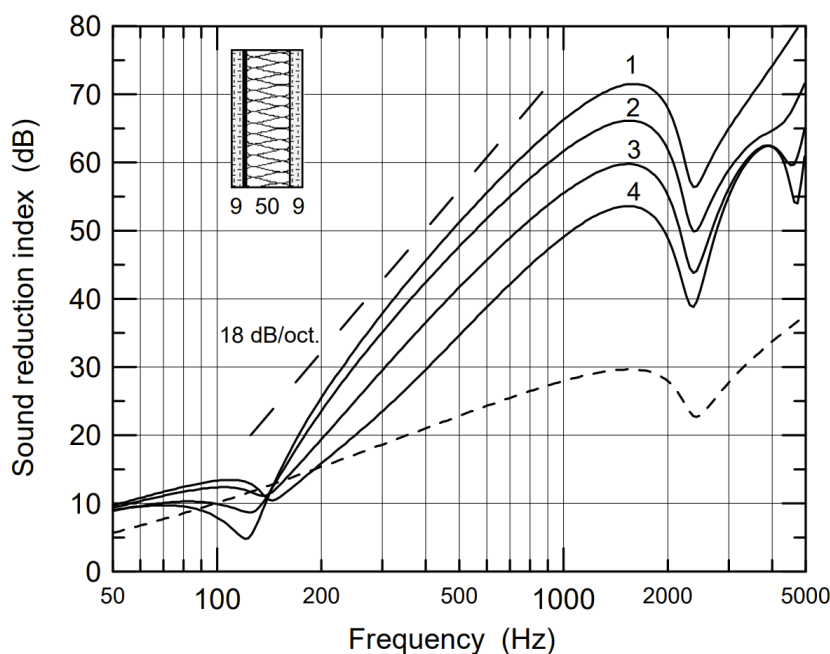
$$DL = L_1 - L_2 - 6, \quad (2.9)$$

### 2.3.2 Sound insulation at low frequencies

Effective sound insulation of low frequencies is a challenging aspect of noise control, particularly in building design. Low-frequency sounds have longer wavelengths and are less easily absorbed by typical sound insulation materials, making it difficult to

achieve satisfactory levels of sound reduction. Therefore, a multi-layered approach that includes a combination of heavy mass barriers, acoustic absorption materials, and structural decoupling techniques is often necessary to effectively reduce the transmission of low-frequency sounds through walls, floors, and ceilings [6].

The typical behavior of a double wall (seen in Figure 2.4), includes the double wall resonance and the critical frequency where higher transmission losses occur. When low-frequency sound waves with much smaller wavelength than the distance between the leaves encounter a structure consisting of multiple leaves, the stiffness of the air in the cavity between the leaves can cause them to become strongly coupled. Even if a porous absorber is present, this coupling can still occur. This results in a weakness in the reduction index, called the double wall resonance. However, if the vibrations of the leaves are controlled by mass, i.e., for frequencies lower than the double-wall resonance frequency, the wall can behave like a single leaf with a mass equivalent to the sum of the masses of the individual leaves [16].



**Figure 2.4:** Sound reduction index of an unbound double wall. Two 9mm plasterboards with a critical frequency 2250 Hz. The lower dashed curve presents reduction index for a single board [16]. Below ca 140 Hz, the vibrations are controlled by mass.

### 2.3.3 Previous studies on low-frequency façade insulation

There have been other studies on low-frequency façade insulation down to as far as 5 Hz, utilizing a custom built infrasound loudspeaker and presenting the level difference  $DL$  as results. Down to 20 Hz, approximately a mean level difference through the façades of 15 dB is observed for a wide range of façade structures [9]. The emphasis lies on how many and which measurement positions in the receiving room are relevant, as room modes affect the sound environment at low frequencies. Additionally, the measurement period gains increased importance due to temporal variations in sound sources for low-frequency noise [11].

Measurements at low frequencies present challenges due to the limited frequency response of most loudspeakers, necessitating less common equipment. Furthermore, the presence of background noise, particularly low-frequency disturbances like nearby construction or traffic, can pose additional difficulties [9].

### 2.3.4 Measurement standards

The standard "Field measurement of sound insulation in buildings and of building elements - Part 3: Façade sound insulation" (ISO 16283-3:2016) describes the measurement procedure and different methods for evaluating façade sound insulation. The standard is intended for room volumes ranging from  $10m^3$  to  $250m^3$  in the frequency range of 50 Hz to 5000 Hz.

For frequencies below 100 Hz the low-frequency procedure intends to be used in addition to default measurements. According to [7], the low-frequency procedure shall also be used when the receiving room is smaller than  $25m^3$ . The low-frequency procedure requires four corner position measurements, two at ground level and two at ceiling level [7]. Measurements can be done by either using traffic as a sound source or a loudspeaker, loudspeakers are more practical as they are not dependent on traffic producing sufficiently high sound pressure levels.

## 2.4 Regulations and recommended SPL levels

There are regulations and recommendations regarding noise in both dwellings and offices to ensure a healthy and safe environment for people to live and work in. Regulations regarding noise in dwellings are primarily focused on reducing noise from outside sources, such as traffic or industry, to levels that are not harmful to people's health or quality of life. The regulations are set by the Swedish Environmental Protection Agency (Naturvårdsverket) and are based on EU directives. The regulations set limits for noise levels in different areas, such as residential, commercial, and industrial areas, and require municipalities to monitor noise levels and take action to reduce noise pollution when necessary.

In addition to regulations, there are also recommendations regarding noise levels in dwellings. The National Board of Housing, Building and Planning (Boverket) recommends that the indoor noise level should not exceed 30 dB(A) during the day and 25 dB(A) at night in bedrooms to ensure a good sleep environment.

Regulations and recommendations regarding noise in offices are also in place to protect workers' health and safety. The Swedish Work Environment Authority (Arbetsmiljöverket) sets regulations for maximum noise levels in the workplace, which depend on the type of work being carried out. For example, the maximum noise level for office work is 55 dB(A), while the maximum for industrial work is 85 dB(A) during an eight-hour workday [4].

### 2.4.1 Swedish Public Health Agency (FoHM)

The Swedish Public Health Agency (FoHM) has guideline values for low-frequency indoor noise. These apply to various living spaces, including living rooms in per-

manent residences and holiday homes, rooms designated for sleep, rest, and daily socializing, and dining rooms used as bedrooms. Additionally, the guidance extends to teaching facilities, care centers, and other temporary accommodations, including bedrooms [5]. The guideline values in third-octave bands are shown in Table 2.1.

**Table 2.1:** FoHM guideline values for low-frequency noise [5].

3rd octave bands [Hz]	31.5	40	50	63	80	100	125	160	200
SPL [dB]	56	49	43	42	40	38	36	34	32

### 2.4.2 Swedish Work Environment Authority

Arbetsmiljöverket is the Swedish Work Environment Authority responsible for setting requirements and guidelines for working conditions in Sweden. The authority has established regulations regarding low-frequency and infrasound in the workplace. According to the Swedish Work Environment Authority's regulations, the exposure of workers to low-frequency and infrasound should be limited to prevent adverse health effects. These regulations set limits for the exposure of workers to low-frequency and infrasound in the workplace, measured in terms of sound pressure levels. In table 2.2 the values used as assessment basis when there is a risk of high noise exposure are shown [4].

**Table 2.2:** Exposure values for infrasound and low-frequency sound [4].

Center frequency 1/3- octave band [Hz]	SPL [dB]	Center frequency 1/3- octave band [Hz]	SPL [dB]
2	130	25	71
2.5	126	31.5	61
3.15	122	40	54
4	118	50	49
5	114	63	47
6.3	110	80	45
8	106	100	43
10	102	125	41
12.5	98	160	39
16	94	200	37
20	90		

### 2.4.3 Ordinance (2015:216) on traffic noise in residential buildings

The Swedish Regulation (2015:216) on traffic noise at residential buildings describes the rules and requirements for protecting residents of new residential buildings from

traffic noise. The regulation sets noise level limits for different times of day and for different types of noise, such as aircraft noise, road traffic noise, and railway noise. Noise from rail traffic and roads should not exceed 60 dBA equivalent sound level at the façade of a residential building.[1]

If a residential building is constructed in an area with high noise exposure, such as near a busy road or railway, the regulations require that the building is designed to provide adequate sound insulation to protect residents from external noise. However, if one side of the building is not exposed to high external noise levels, (below 55 dBA equivalent sound level), it is possible to take advantage of this and design that side of the building to have lower sound insulation requirements while still meeting the overall sound insulation requirements for the entire building. While the noise exposed side still cannot be exposed to sound levels above 70 dBA between 22:00 and 06:00 during the day.[1]

#### 2.4.4 Guidance on industrial noise

Similar to traffic noise, industrial noise is regulated close to dwellings. In 2015, the Swedish regulations regarding industrial noise in PBL (Plan- och bygglagen) were revised (SFS 2015:668)[15]. The new regulations allowed industrial noise to be exceeded around dwellings, thereby enabling the construction of homes closer to industries, as long as they meet indoor requirements. Noise from cruise ships docked in harbors is classified as industrial noise and follows these guideline values. These guideline values are a bit stricter than the Ordinance on traffic noise and divided into three zones, A, B, and C, as shown in Table 2.3. In zone A, dwellings can be built without a need for a quiet side. Zone B allows dwellings to be built if the façade is exposed to sound levels up to levels seen below, and a quiet side fulfills the guideline values. In zone C, construction of dwellings should not be allowed. [3]

**Table 2.3:** Highest equivalent sound levels from industrial activity, expressed as free field value outdoors at the façade of residential buildings [3].

	Zone A	Zone B		Zone C
		Exposed side	Quiet side	
Day	50 dBA	60 dBA	45 dBA	>60 dBA
Evening	45 dBA	55 dBA	45 dBA	>50 dBA
Night	45 dBA	50 dBA	40 dBA	>50 dBA



# 3

## Method

Several measurements were conducted to evaluate how well a range of typical façade structures isolate against low-frequency noise. The measurements were conducted using the low-frequency procedure given by ISO 16283-3:2016 but extended based on [9] and [11], higher frequencies were also measured with the same method. Instead of measuring  $R'_{45^\circ}$  (Equation 2.8), which requires the rooms reverberation time, the level difference described in Equation 2.9 is used. During the measurements, subjective evaluations regarding the disturbance of low-frequency noise were noted. For further understanding of the measured results, finite element modeling of room modes was conducted in Comsol.

### 3.1 Façade measurements

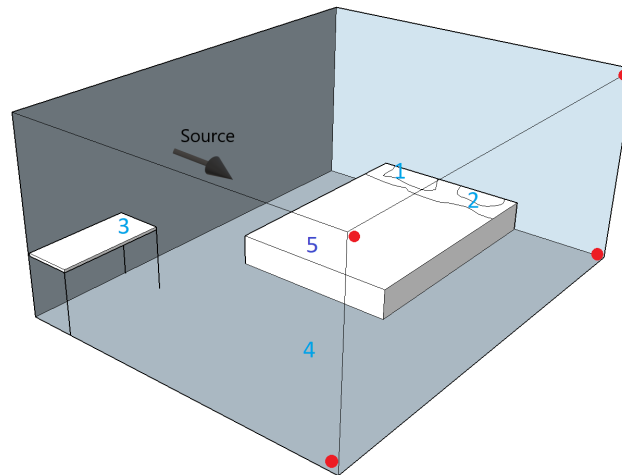
A modified version of the industry-standard measurement procedure ISO 16283-3:2016 was utilized to determine the level difference  $DL$  in one-third octave bands ranging from 20-3150 Hz. The measurement method employed the global loudspeaker approach, and drew inspiration from [9] and [11]. To generate sufficiently high sound pressure level in the lower frequency bands 20-200 Hz, a subwoofer model EAW Otto™ was used playing pink noise, and between 160-3150 Hz, a Yamaha DHR 15 loudspeaker was used (see Figure 3.1). To take the measurements, a Brüel & Kjær type 2270 sound level meter and a Brüel & Kjær type 4189 prepolarized free-field microphone were used. Note that some measurements range from 20 to 200 Hz as only the subwoofer was present at those measurements.



**Figure 3.1:** Speaker setup used during measurements, a) subwoofer EAW Otto™, b) loudspeaker Yamaha DHR 15.

The following described positions were all taken during 30 seconds time per position. The sound pressure level on the façade  $L_1$  (dB) was measured in five different positions and energy averaged. Similarly, the sound pressure level  $L_2$  [dB] was measured, and energy averaged over five positions in the receiving room. One position was located in the center of the room, while the other four positions were in areas where occupants are likely to be, as indicated by furnishing or the architectural floor plan, such as sleeping and dining locations (see Figure 3.2). These positions, including the central position, are further referenced as diffuse positions in the thesis. In addition, four corner positions at the wall on the opposite side of the façade were measured, and energy averaged. These positions were taken approximately 0,3-0,4m from any boundary, according to [7]. The corner measurements were then evaluated separately from the diffuse positions [9]. For each  $L_2$  position, the background noise was also measured in the same spot to secure that a sound pressure level difference of at least 6 [dB] was fulfilled; if this was not the case, that position was discarded and not included in the energy average. In Figure 3.2 a model illustrating how the measurement positions were taken is shown.

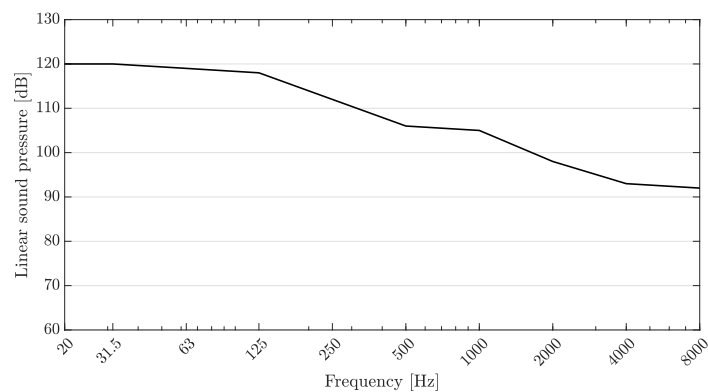
The level difference was then evaluated according to Equation 2.9, the -6 [dB] correction is due to reflections on the façade as the microphone was positioned on the façade [11].



**Figure 3.2:** Model illustrating the 9 total measurement positions in a room, where blue nr 1-4 show diffuse positions, nr 5 the central position, red dots indicate corner positions and source the façade wall.

### 3.1.1 Subjective assessment

For three of the measured façades, a synthesized cruise ship noise signal, seen in Figure 3.3, was generated to simulate the sound spectra emanating from cruise ships located in Värtahamnen. This noise signal was fed to the subwoofer and spanned a frequency range of 20 Hz to 200 Hz. The lower frequencies were deemed more interesting to both human perception and the sound insulation of the façades. Participants were positioned in the receiving room at diffuse positions and were asked to listen while the sound pressure level was gradually increased until it was perceptible but non-disturbing. The corresponding sound pressure levels were recorded both in the receiving room and on the façade. Additionally, the sound pressure level was increased further until the noise was deemed disturbing, and the corresponding measurements were also recorded.



**Figure 3.3:** Spectrum shape of the synthesized cruise ship noise signal.

## **3.2 Room mode analysis and finite element modeling**

The sound insulation at low frequencies can be significantly affected by the shape of a room. To investigate this further, the room modes of the shoe box shaped rooms were evaluated using Equation 2.3. Room modes for more complex shaped rooms were calculated using Comsol 6.1 software. The room geometries were based on on-site measurements, and all surfaces were considered to be acoustically hard boundaries. The study focused on frequencies ranging from 1 to 200 Hz, which includes the first room modes. The mesh size was set to be five times smaller than the corresponding wavelength of the highest frequency of interest, which in this case was 200 Hz.

# 4

## Results

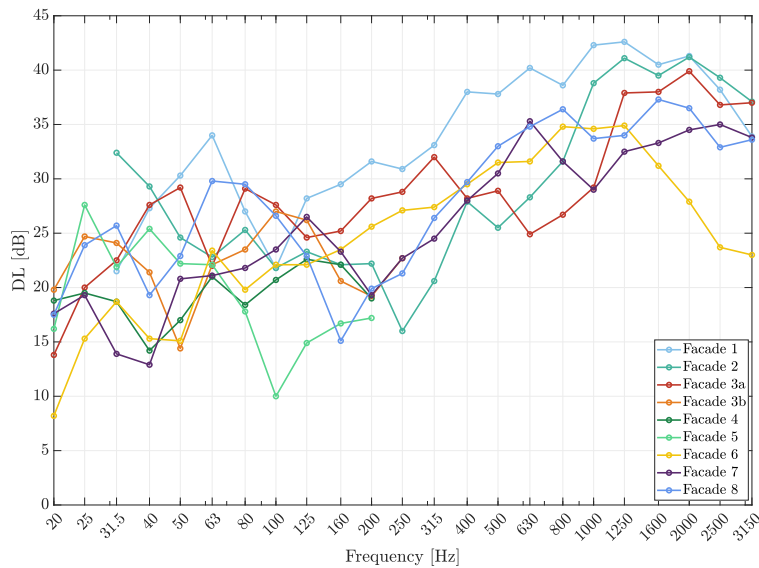
### 4.1 Low-frequency façade insulation measurements

In Table 4.1, the measured façades are presented. F is the index for a studied façade, Y is the construction year, [H] or [L] indicates if its a heavy or light façade, W is the percentage of window surface on the façade, S is the partition area and  $f_1$  the first predicted resonance frequency. The receiving rooms on the inside of façades 1, 2, 3b, 5, and 6 were unfurnished, while 3a, 4, 7, and 8 were furnished.

**Table 4.1:** Properties of the measured façades.

F	Y	Construction details outside to inside	Thickness (mm)	W (%)	Volume ( $m^3$ )	S ( $m^2$ )	$f_1$ (Hz)
1	2023	[H] plaster (20), putsbärskiva (50), EPS graphite (150), concrete (150)	370	39	68	11.5	22.2
2	2023	[H] plaster (10), mineral wool (90), mineral wool (100), concrete (150)	350	41	23.5	6.8	49
3a	2020	[H] plaster (10), mineral wool (100), concrete (150)	350	36	63	12.8	31
3b	2020	[H] plaster (10), mineral wool (100), concrete (150)	350	31	60	8.8	25
4	2002	[H] plaster (5), mineral wool (100), concrete (120)	225	70	98	23	21
5	2023	[H] terrazzo (32), plasterboard (40), pir insulation (150), concrete (150)	372	25	47	15	39
6	1958	[L] glass cassette, mineral wool (120), gypsum	≈ 140	50	201	29	18
7	2006	[L] wood panels(13), batten(24), studs and mineral wool (170), gypsum(13)	220	36	43	10	38
8	1962	[L] lightweight concrete (200)	200	41	36	8	39

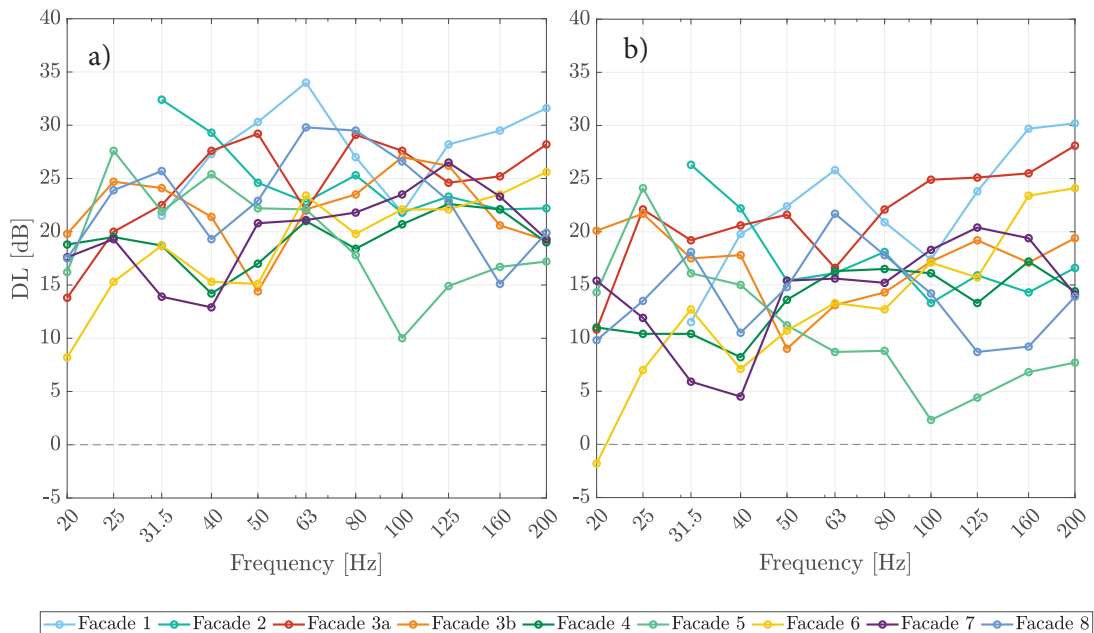
Figure 4.1 illustrates the resulting level difference  $DL$  defined in Equation 2.9, in the frequency range 20-3150 Hz for all façades presented in Table 4.1. Measurements of façades 3b, 4, and 5 are limited to 200 Hz.



**Figure 4.1:** Energy averaged level difference  $DL$  measured in diffuse positions, with a frequency span of 20-3150 Hz.

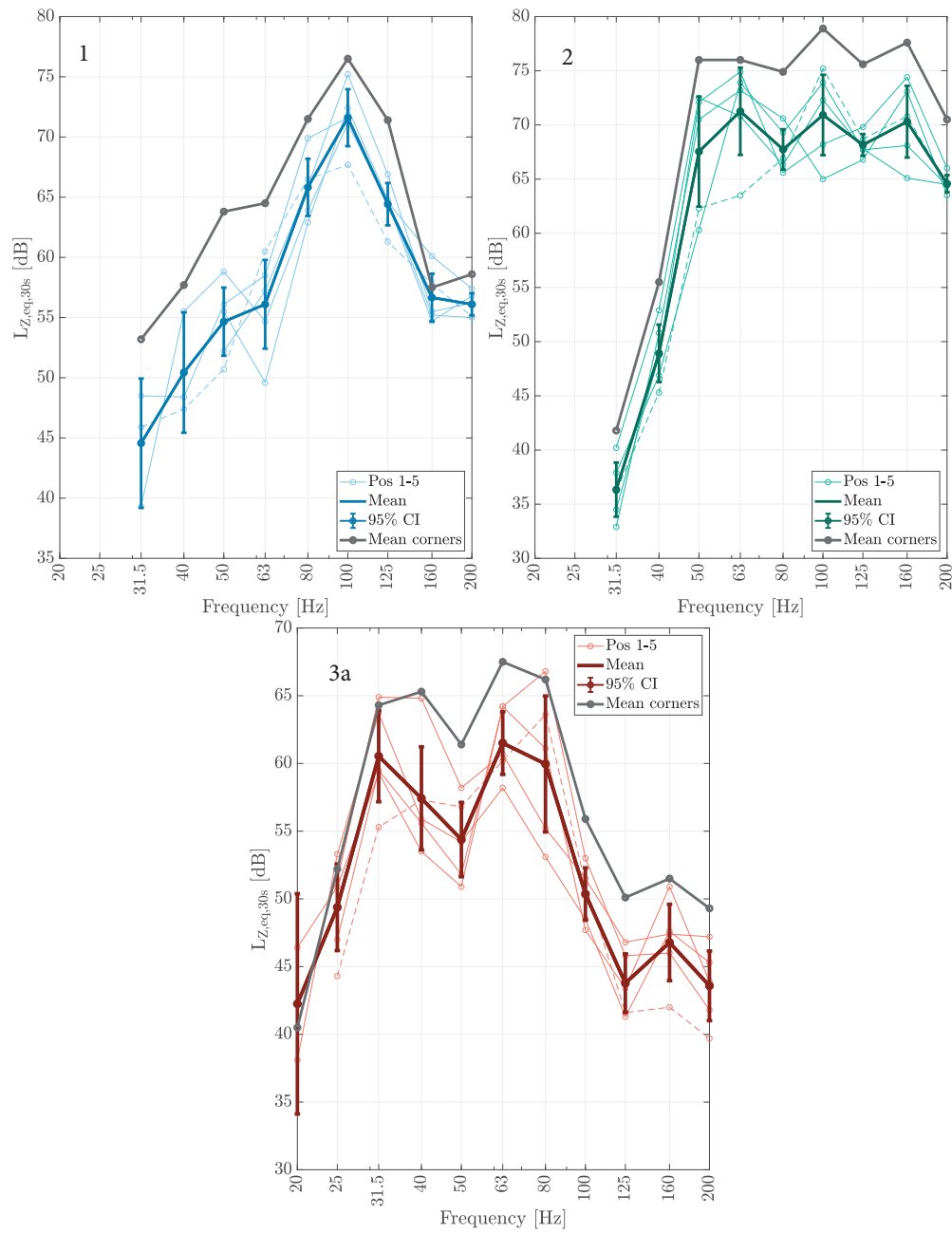
## 4. Results

In Figure 4.2, the same level differences  $DL$  as shown in Figure 4.1 is illustrated, but with a frequency range of 20-200 Hz. The corner positions are also included here; these generally show lower values for the level difference. At 20 Hz, the different façades show similar values, even heavy concrete façades (1-5) and the lighter façades (6-8), an exception is façade 6, which is an old glass façade. A greater spread can be seen between 31,5 and 80 Hz. Façades 4 [H] and 7 [L] show similar  $DL$  even though the construction type is different, the reason behind this could be the amount of window surface at façade 4, since the similar constructed heavy façades show overall better  $DL$ .



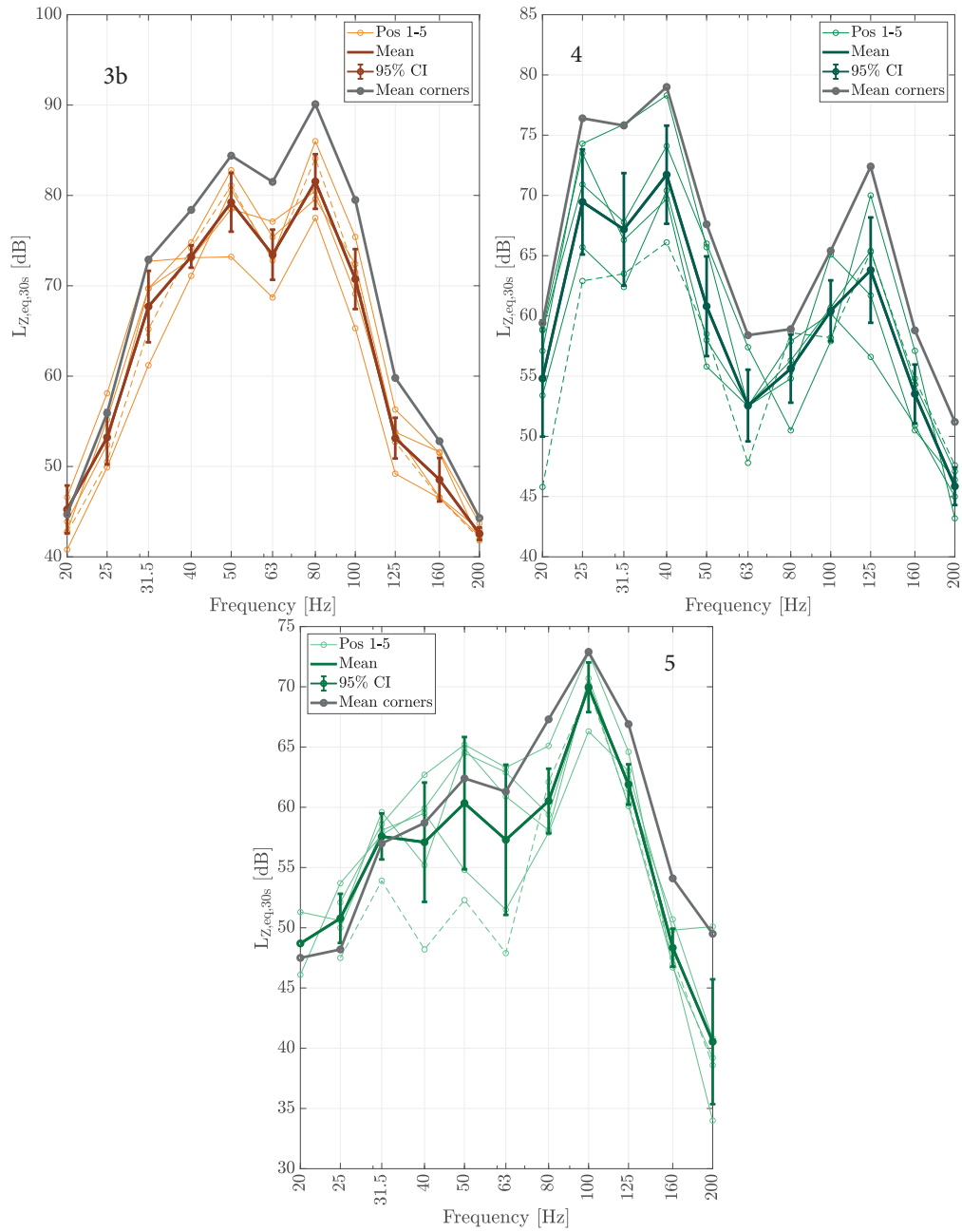
**Figure 4.2:** a) Energy averaged level difference  $DL$  measured in diffuse positions, with a frequency span of 20-200 Hz, b) Corner positions.

In Figures 4.3, 4.4 and 4.5, the measured sound pressure levels in the receiving room  $L_2$  are presented with the mean and 95% confidence intervals, where there are less than five points present, that position did not fulfill a 6 dB level above the background noise. This is, however, only the case for façades 1, 3a, 5, and 6. The energy averaged corner positions are represented as a gray line. For most measurements, the sound pressure level of the corner positions were a bit higher than the diffuse position levels, which is consistent with the acoustic theory and the lower calculated level difference  $DL$  in Figure 4.2.

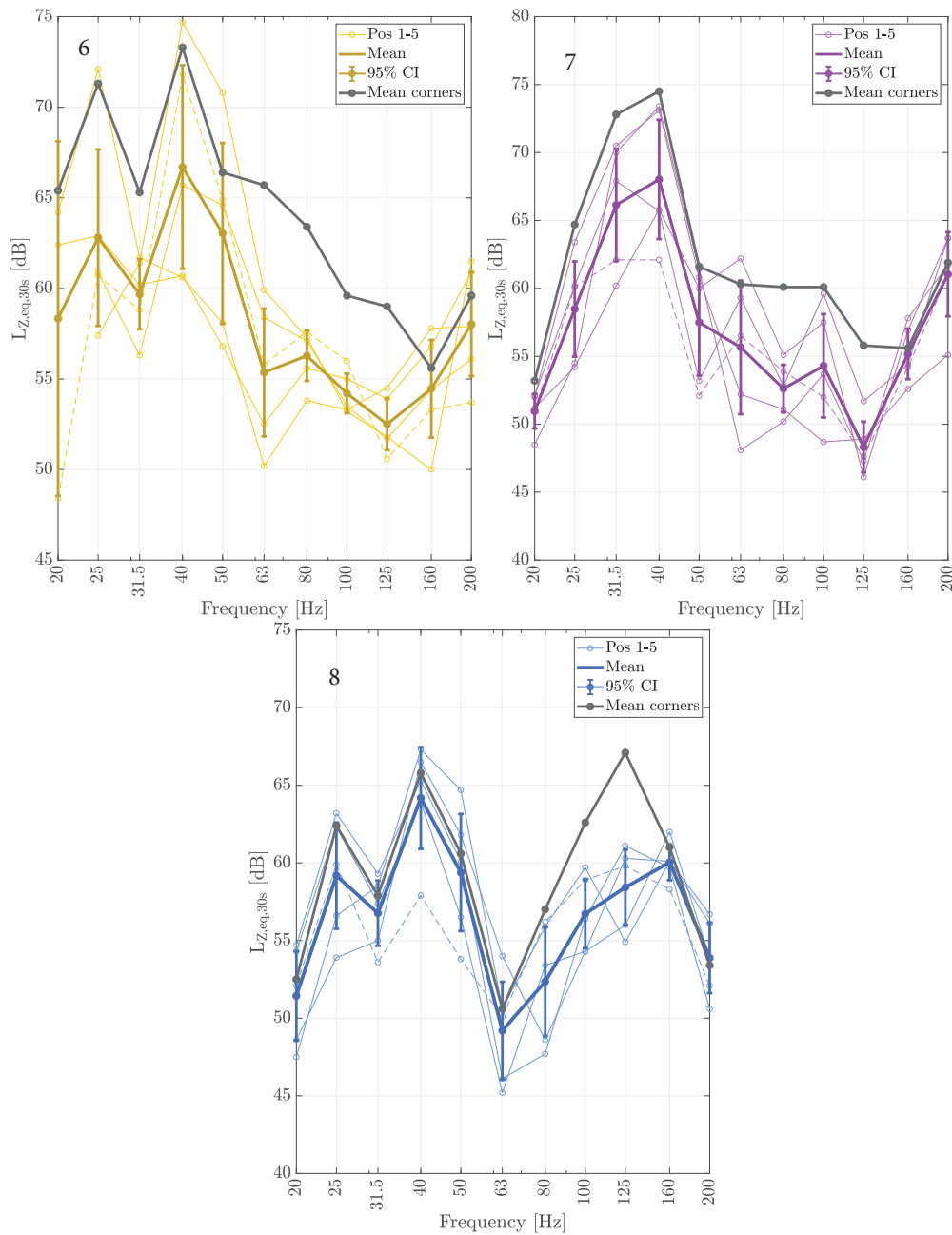


**Figure 4.3:** Façades 1, 2, 3a. Equivalent unweighted sound pressure level in all diffuse positions  $L_2$ , with arithmetic mean and energy averaged corner positions mean in gray color. The 95% Confidence interval is presented as a vertical line. The central room position from each measurement is seen as a dashed line.

## 4. Results

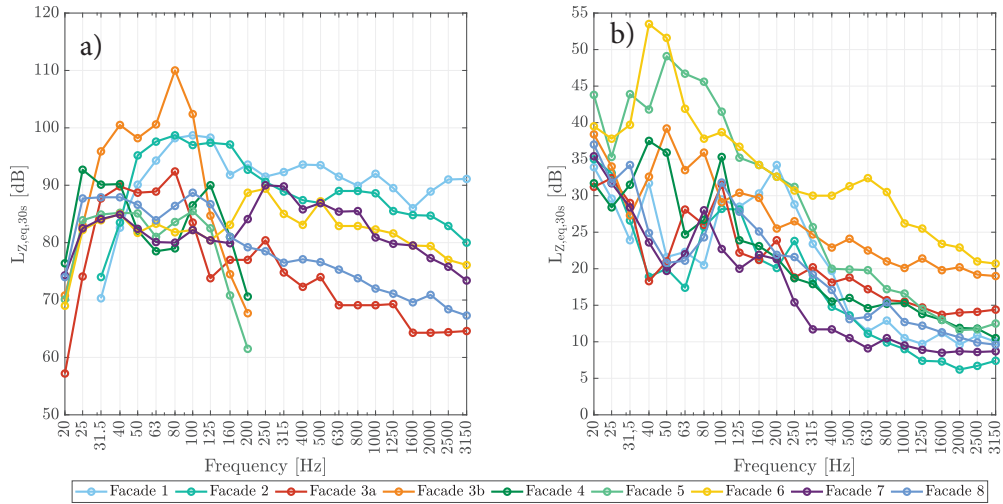


**Figure 4.4:** Façades 3b, 4, 5. Equivalent unweighted sound pressure level in all diffuse positions  $L_2$ , with arithmetic mean and energy averaged corner positions mean in gray color. The 95% Confidence interval is presented as a vertical line. The central room position from each measurement is seen as a dashed line.



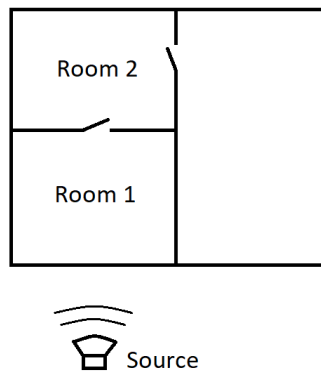
**Figure 4.5:** Façades 6, 7, 8. Equivalent unweighted sound pressure level in all diffuse positions  $L_2$ , with arithmetic mean and energy averaged corner positions mean in gray color. The 95% Confidence interval is presented as a vertical line. The central room position from each measurement is seen as a dashed line.

Façade 6 is seen having large sound pressure level variations compared to the other measurements. Unfortunately, there was construction going on in the background disturbing the measurement (see Figure 4.6). However, a signal to noise ratio of at least 6 dB was fulfilled for all positions from 25 Hz and above, while individual positions might still have been influenced by construction noise. Façade 5 and 6 stand out from the rest regarding the background noise, while façade 5 was influenced by constant traffic noise which did not affect individual measurement positions.

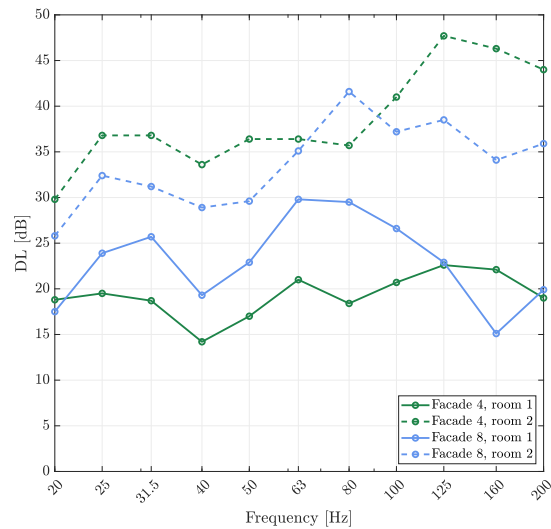


**Figure 4.6:** a) Energy averaged equivalent unweighted sound pressure level  $L_1$  measured on the façades. b) Equivalent unweighted background noise in central positions of the receiving room.

An additional measurement was included when conducting the measurement of façade 4 and 8. A separate room adjacent to the receiving room was measured on the opposite side of the façade. Figure 4.7 simply illustrates where the additional measurement was conducted (room 2), note that the doors were closed during measurements. Figure 4.8 presents the resulting level difference for both rooms. The same measurement method was used in room 2, following the floor plan or furnishing (diffuse positions), and a signal to noise ratio of at least 6 dB was fulfilled in all five positions. The extra rooms measured were separated by lightweight indoor gypsum walls and a door. Façade 4 had a better door separating the rooms (R'w 35), while façade 8 had a simpler door (R'w 15-20).



**Figure 4.7:** Simplified floor plan of how room 2 where located in relation to room 1 and the façade.



**Figure 4.8:** Level difference  $DL$  measured in receiving rooms 1 and adjacent rooms 2.

As seen in Figure 4.8, the adjacent rooms show significantly higher level difference  $DL$ , particularly façade 4 with the better door.

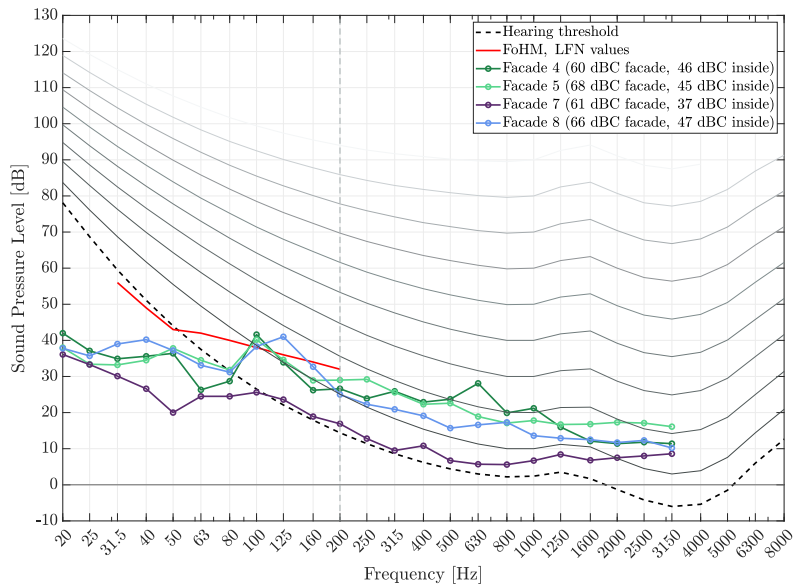
#### 4.1.1 Subjective assessment

For all subjective assessments, two persons were in the receiving room listening and assessing the non-disturbing and disturbing levels. The resulting measurements are presented in Figure 4.9 and 4.10. The results are presented overlaid on the equal loudness contours and human hearing threshold to illustrate better what frequency components were actually perceived. The gray lines represent the phon levels 10 to 90, and the red line denotes the guideline values by FoHM seen in Table 2.1. The two plots range from 20 to 8000 Hz, meanwhile, the subwoofer only generated noise between 20 and 200 Hz, beyond that, the recorded levels are the background noise. The sound spectra were made to imitate that seen in Figure 3.3, the actual spectra measured outside on the façades are shown in Figure 4.11. Unfortunately, due to the subwoofer's frequency response, there is an energy loss below 31,5 Hz, meaning that the spectra could not be imitated correctly for the 20 and 25 Hz bands.

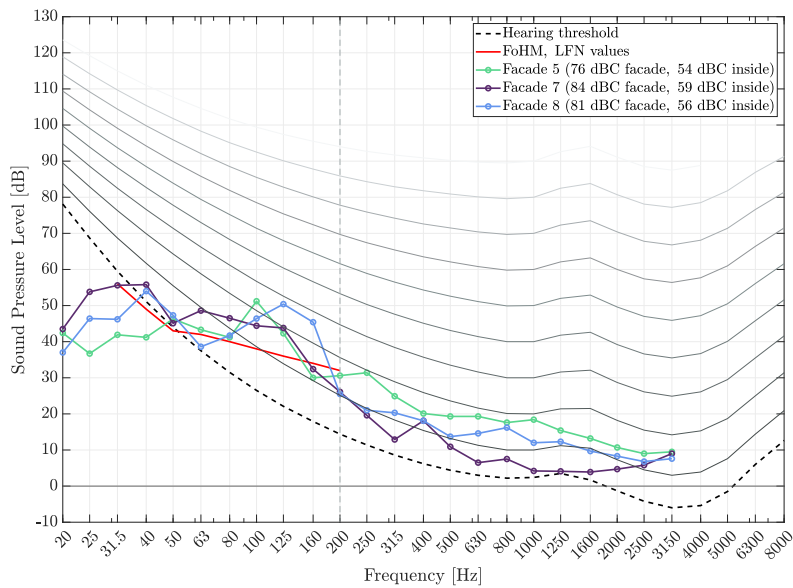
The subjective results regarding the non-disturbing noise levels in Figure 4.9 can be seen exceeding the FoHM guideline values around 100 and 125 Hz for façades 4, 5, and 8. Meanwhile, the noise levels at façade 7 barely reaches over the hearing threshold at the same range, indicating that the results are very subjective as different persons were present during different measurements and experienced the noise differently. The background noise also needs to be accounted for, at façade 7, the background noise was lower and, therefore might affect the results, as the low-frequency components might be easier to distinguish. Table 4.2 and 4.3 show the recorded noise levels in dBA and dBC values on the façades and inside the receiving

## 4. Results

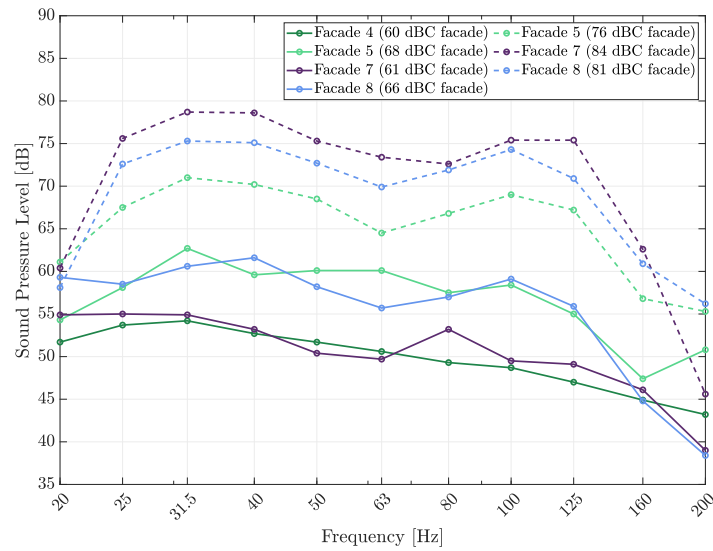
room. Interestingly, the measured sound pressure levels for frequencies below 80 Hz lie below the hearing threshold. This difference is even more notable below 50 Hz. Between 80 and 160 Hz seems to be the most problematic frequency range considering façades 4, 5, and 8. Looking at the disturbing levels in Figure 4.10, FoHM guideline values and the hearing threshold are exceeded between 40 and 160 Hz, and to a larger amount between 80 and 160 Hz. Even when the façades are exposed to these noise levels, frequencies below 31,5 Hz stay well below the hearing threshold.



**Figure 4.9:** Equal loudness contours in phon with the recorded non-disturbing noise levels inside. Data above 200 Hz corresponds to background noise.



**Figure 4.10:** Equal loudness contours in phon with the recorded disturbing noise levels inside. Data above 200 Hz corresponds to background noise.



**Figure 4.11:** Recorded sound pressure levels on the façades during the subjective assessment. Solid curves represents the non-disturbing measurements and dashed curves the disturbing

**Table 4.2:** Non-disturbing levels in dBA and dBC for different façades.

F	dBA Façade	dBA Inside	dBC Façade	dBC Inside
4	52	31	60	46
5	59	31	68	45
7	46	22	61	37
8	48	29	66	47

**Table 4.3:** Disturbing levels in dBA and dBC for different façades.

F	dBA Façade	dBA Inside	dBC Façade	dBC Inside
5	62	35	76	54
7	62	33	84	59
8	62	37	81	56

## 4.2 Room mode analysis and finite element modelling

Calculated room modes for the shoebox shaped receiving rooms of façades 2, 3b, 4, 5, 6, 7 and 8 can be found in the appendix. The finite element modeling of room modes was conducted on the receiving rooms of façades 1 and 3a. These rooms were not shoebox shaped and therefore the room modes could not be evaluated using formula 2.3. In Figure 4.12 a mesh for an example calculation is shown. In Figures 4.13 and 4.14, four of the first modes are illustrated for each receiving room.

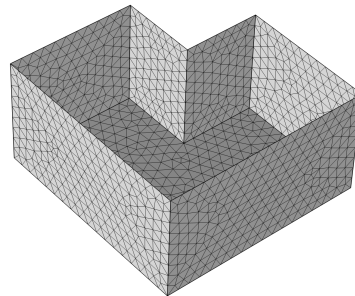


Figure 4.12: Example mesh, façade 3a.

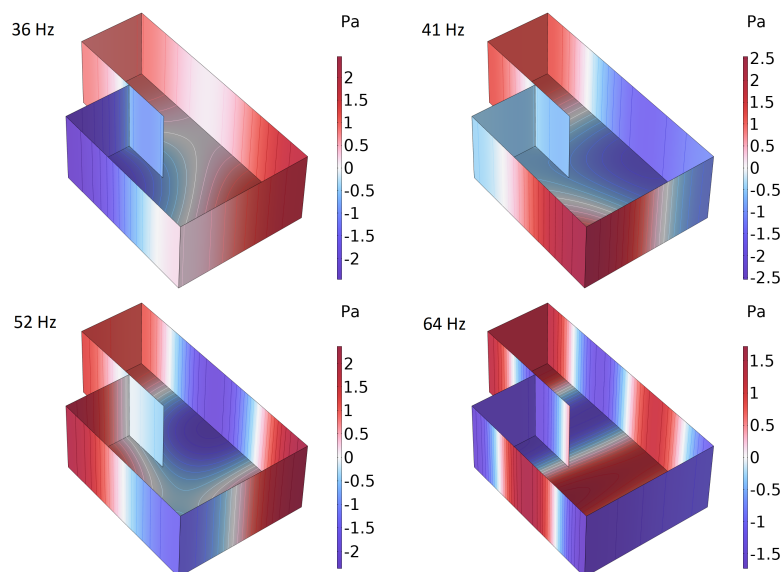
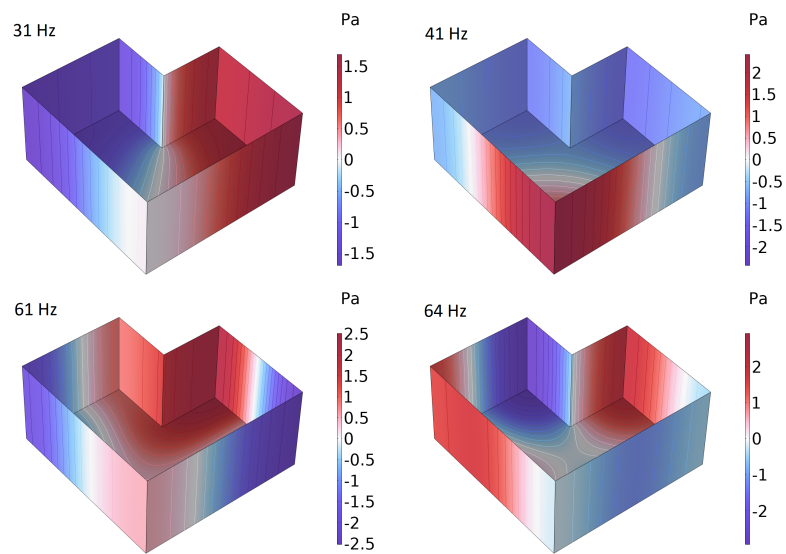


Figure 4.13: Room modes in the receiving room of façade 1.



**Figure 4.14:** Room modes in the receiving room of façade 3a.

The red and blue areas illustrate where the sound pressure level in the room will be strongest, and the white area between shows where partial cancellation will occur, also called nodes. In these white areas, lower sound pressure levels should theoretically be recorded. Several modes are seen having white areas in central positions, which corresponds with Figures 4.3, 4.4, and 4.5, where the central positions are often the lowest measured position.



# 5

## Discussion

The measurements were conducted according to the furnishing or floor plan. Therefore, several positions were taken in close proximity to a wall or corner. This is a more realistic scenario as people commonly place their furnishing close to walls, such as beds, sofas, and desks. Positions close to boundaries often mean higher sound pressure levels caused by room modes (see Figures 4.13 & 4.14). Still, there is a clear difference in the level difference  $DL$  when comparing the diffuse position measurements with the corner positions (see Figure 4.2b). Figures 4.3, 4.4, and 4.5 show that the corner positions exceed the diffuse positions for most frequency bands with some exceptions. In the same plots, the central positions are also marked, these usually show the lowest measured sound pressure levels. As a result of the measurement method used, where positions closer to boundaries were chosen, a lower level difference  $DL$  was calculated. Measurements down to 20 Hz can be heavily affected by the background noise, especially below 50 Hz. Problems did arise at some façades where disturbances from traffic or construction work influenced the measurements. Fortunately, most measurements were performed in secluded areas or later in the afternoon with minimal disturbances. Façades 5 and 6 were the most exposed to background noise, while the measurement of façade 5 still proved to be sufficiently reliable as the background noise was constant traffic noise.

All the level difference measurements indicate that there is moderate sound insulation in a range of common façade structures down to 20 Hz, aligning with previous studies. Even the lightweight façades show no significant difference in overall sound insulation capabilities compared to heavy structures (see Figure 4.2); one outlier is façade 6, which is an old glass façade with reportedly poor insulation properties. However, there are weaknesses in the level difference seen on every façade.

Multiple factors can contribute to weaknesses in the level difference  $DL$ . One example is strong room modes; these can cause variations in sound pressure level for the measured  $L_2$  positions within that particular frequency band and could result in a lower level difference. Façade 1 is seen as having a weakness in the level difference at 80 - 100 Hz (see Figure 4.2), while the difference between measurement positions is low (see Figure 4.3). In this case, the reduction index curve for the windows and window door is known, and the corresponding resonance frequencies lie at 80 and 100 Hz, creating a weakness in the sound insulation. Figure 4.13 illustrates some of the first room modes of façade 1; they correspond well with the assumption of larger sound pressure level variations at frequency bands 40, 50, and 63 Hz. The same can be said about façade 5, which is heavily influenced by room modes in the frequency

bands 40, 50, and 63 Hz; while there is no significant reduction in level difference caused by them, they are contributing to measurement uncertainty (see Figure 4.4). However, the most significant reduction of the level difference is observed at 100 Hz, which is caused by the window door.

For façade 2, the first room mode resides at 49 Hz and the second at 63 Hz, while none of the axial modes are near 80 Hz (see Appendix). The position spread at 80 Hz is notably smaller than the previously mentioned frequencies. Additionally, at 99 Hz, another axial mode resides, causing greater spread. These room modes are causing fluctuations in the level difference  $DL$  (see Figure 4.2). However, this pattern is not as visible for all measurements. For example, façade 3b, being an unfurnished shoebox shaped room, has quite small differences between measured  $L_2$  positions (see Figure 4.4). But the level difference  $DL$  is heavily influenced by the axial modes in the  $x$  direction (see Appendix). At 25 Hz, where the first room mode resides, a high level difference and relatively low spread among  $L_2$  positions are recorded. Meanwhile, the next axial mode in the same direction, found at 50 Hz could be responsible for the weakness in level difference at 50 Hz.

Overall, the room modes are identified to influence the sound insulation, as the most noticeable cases are observed below 100 Hz. At frequencies above this range, other factors can influence the sound insulation properties more, such as windows and the critical frequency of the construction. Windows and window doors usually have resonance frequencies between 100 and 250 Hz, which needs to be considered if there is a risk of disturbances. Therefore, it is likely to be the dominating factor regarding the reduction in level difference, as the most significant weaknesses recorded are caused by the windows and window doors.

Regarding the subjective assessment of the synthesized cruise ship noise, the resulting levels at which a person is disturbed or accepts the noise are highly dependent on the individual. A more systematic procedure, such as the "1 Up 2 Down" method, could have been used to establish the disturbance threshold, which can be deemed a more scientific psychoacoustics method. However, the results seen in Figure 4.9 and Table 4.2 show similar patterns, with façade values ranging within 60-68 dBC and 48-59 dBA. The recorded levels pass the hearing threshold at approximately 80 Hz and are experienced as loudest around 100-125 Hz. This is also where the guideline values from FoHM are exceeded. Measured sound pressure levels under 50 Hz are well below the hearing threshold for all façades, including a lightweight wood structure and heavy concrete buildings. The common factor is the windows, which are responsible for the lower level difference around 100-160 Hz. Unfortunately, no façade with windows with very high sound insulation was measured during the work. Looking at the disturbing levels in Figure 4.10, the hearing threshold is still not passed until approximately 31,5-40 Hz, while the most exposed area is around 100-160 Hz. With regard to the human hearing threshold, typical façades today seem to have sufficient sound insulation properties at frequencies below 50 Hz while not exposed to as high sound levels as shown in Figure 4.3. The frequency range

below 50 Hz is not that significant when dimensioning the façade construction, but rather windows should be the main focus. Regarding the noise from cruise ships in Värtahamnen, the noise levels on the projected façades are unknown, making it difficult to compare the results directly. To conduct a more comprehensive analysis of these types of disturbances, it would be valuable to utilize authentic recordings from the cruise ships and play them at the anticipated sound pressure levels on the façades for the subjective assessment.

The additional measurement conducted for façades 4 and 7, regarding the adjacent room (see Figure 4.8), indicate that sound reduction of frequencies down to 20 Hz inside dwellings is possible to achieve to certain extents. Installing indoor doors with better sound insulation properties, such as in façade 4, drastically improves the sound insulation against the exposed façade. When the noise source originates from one side of the building, and a quiet side is present, it is possible to design dwellings so that at least half the rooms are facing the quieter side. This approach can effectively reduce low-frequency disturbances and can be a good option against cruise ship noise when one side of the building faces the harbor. The sound levels found in PBL (Plan- och bygglagen) on industrial noise in residential buildings explained in Section 2.4.4 are, however, only specified in dBA values. As seen in Tables 4.2 and 4.3, even the disturbing levels almost fulfill the 60 dBA regulation on the façades, while still requiring a quiet side, the noise was deemed disturbing. Evaluating disturbances from sources with known low-frequency components with only dBA values can be risky as they may underestimate the low-frequency content, which can still contribute to disturbances. While indoor regulations still need to be met, underestimating the incident low-frequency noise on the façades could become troublesome in later stages of the construction process.

While much of the low-frequency components recorded during the subjective assessments did not seem to be noticeable by the human ear (see Figure 4.9), low-frequency noise can still affect the human body in other ways, for example, causing vibrations in the body which can influence the perception of the noise and increase annoyance. During the subjective assessments, all participants could experience a feeling of anxiety in the body and a little pressure in the ears, and when muting the subwoofer came a sense of relief. This sensation gradually increased with the sound pressure level of the noise while being negligible below the non-disturbing levels. Being aware of the specific sound they were searching for, participants might not have noticed it otherwise.

It is important to mention that when residing in a location with a sea view overlooking docks where cruise ships frequently arrive and depart, some individuals may actually desire to hear these sounds as they are considered part of the environment. However, addressing any potential disturbances caused by prolonged periods of the ships being docked is crucial.



# 6

## Conclusion

The conducted façade measurements have provided valuable insights into the sound insulation properties of common façade structures. The resulting level differences indicate a moderate sound insulation capability for various façade structures commonly seen in Sweden today. Several façades gave limited variation in the level difference  $DL$  between 20 and 50 Hz, while the human hearing threshold gradually increases towards lower frequencies. Frequencies below 50 Hz may not pose significant challenges regarding cruise ship noise if appropriate windows are installed and careful planning of room shape and size is undertaken to address room modes. While the auditory system could not perceive all low-frequency components recorded during the subjective measurements, it is worth noting that the body might perceive low-frequencies in other ways. Additionally, low-frequencies prove to be effectively attenuated by the indoor environment, indicating that a quiet side of the building could be a useful way to address low-frequency disturbances.

Regarding assessing the potential impact of low-frequency noise on buildings, current practices rely solely on using A-weighted sound pressure level (dBA) to describe noise levels. However, the subjective assessment conducted in this study revealed that low-frequency noise is often underestimated when disturbances predominantly consist of low-frequency components and are evaluated using dBA. As a recommendation, it is suggested that when low-frequency disturbances are anticipated, the use of C-weighted sound pressure level (dBC) should be included to ensure a comprehensive evaluation that does not underestimate noise exposure.

### 6.1 Further research

In order to advance the understanding of low-frequency sound insulation of façades, future research should focus on conducting measurements on heavy constructions equipped with high-quality windows with sound reduction indices ( $R'w$ ) of 48 dB and above. This could provide valuable insights into the performance of robust façade structures and their ability to attenuate low-frequency noise.

Developing computational models to calculate sound insulation at low frequencies, specifically for windows, and potentially extending ( $Rw$ ) curves below 50 Hz can be valuable during the planning phase in situations with a potential risk of low-

## 6. Conclusion

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frequency noise.

Additionally, it is important to acknowledge that the thesis did not account for the potential effects of low-frequency noise on the human body below the hearing threshold. This includes the perception of infrasound. Further research should explore the physiological and psychological impacts of low-frequency noise on individuals, considering factors beyond auditory perception. This may involve investigating how low-frequency vibrations affect human well-being, cognitive function, and overall comfort.

# Bibliography

- [1] 2015:216 (2015). *Förordning (2015:216) om trafikbuller vid bostadsbyggnader*. Landsbygds- och infrastrukturdepartementet SPN.
- [2] Berglund, B., Hassmen, P., and Job, R. S. (1996). Sources and effects of low-frequency noise. *The Journal of the Acoustical Society of America*, 99(5):2985–3002.
- [3] Boverket (2015). *Industri- och annat verksamhetsbuller vid planläggning och bygglövsprövning av bostäder*, volume 2015:21. Boverket - Myndigheten för samhällsplanering, byggande och boende.
- [4] Buller AFS 2005:16 (2005). *Arbetsmiljöverkets föreskrifter om buller samt allmänna råd om tillämpningen av föreskrifterna*. Arbetsmiljöverket.
- [5] Folkhälsomyndigheten (2014). *Folkhälsomyndighetens allmänna råd om buller inomhus*, volume FoHMFS 2014:13. Folkhälsomyndigheten - Myndigheten för folkhälsofrågor.
- [6] Hopkins, C. (2012). *Sound insulation*. Routledge.
- [7] ISO 16283-3:2016 (2016). Byggakustik - fältmätning av ljudisolering i byggnader och hos byggnadselement - del 3: Fasad ljudisolering. Standard, International Organization for Standardization.
- [8] ISO 226:2023 (2023). Acoustics-normal equal-loudness-level contours. Standard, International Organization for Standardization.
- [9] Keränen, J., Hakala, J., and Hongisto, V. (2019). The sound insulation of façades at frequencies 5–5000 Hz. *Building and Environment*, 156:12–20.
- [10] Kuttruff, H. (2016). *Room acoustics*. Crc Press.
- [11] Oliva, D., Hongisto, V., Keränen, J., and Koskinen, V. (2011). Measurement of low frequency noise in rooms. *Finnish Institute of Occupational Health, Helsinki*.
- [12] Peris, E. et al. (2020). Environmental noise in Europe: 2020. *Eur. Environ. Agency*, 1:104.
- [13] Pettersson, M., Ljunggren, F., and Simmons, C. (2022). The effect of furniture when measuring reverberation times at low frequencies from 31.5 Hz. *Building and Environment*, 223:109480.

- [14] Rossing, T. D. and Rossing, T. D. (2014). *Springer handbook of acoustics*. Springer.
- [15] SFS 2015:668 (2015). *Lag om ändring i plan- och bygglagen (2010:900)*. Landsbygds- och infrastrukturdepartementet SPN BB.
- [16] Vigran, T. E. (2014). *Building acoustics*. CRC Press.
- [17] Waye, K. P., Smith, M., and Ögren, M. (2017). Hälsopåverkan av lågfrekvent buller inomhus. *Medicinska institutionen, Göteborgs Universitet*.

# A

## Appendix 1

**Facade 2**

Lx	Ly	Lz	Hz
1	0	0	49
0	1	0	63
0	0	1	69
1	1	0	80
1	0	1	84
0	1	1	93
2	0	0	99
1	1	1	106
2	1	0	117
2	0	1	120
0	2	0	127
2	1	1	136
1	2	0	136
0	0	2	137
0	2	1	144
1	0	2	146
3	0	0	148
0	1	2	151
1	2	1	152
1	1	2	159
2	2	0	161
3	1	0	161
3	0	1	163
2	0	2	169
2	2	1	175
3	1	1	175
2	1	2	181
0	2	2	187
0	3	0	190
1	2	2	193
3	2	0	195
1	3	0	197
4	0	0	197
3	0	2	202
0	3	1	202
0	0	3	206

**Facade 3b**

Lx	Ly	Lz	Hz
1	0	0	25
0	1	0	45
2	0	0	50
1	1	0	52
2	1	0	68
0	0	1	75
3	0	0	76
1	0	1	79
0	1	1	87
3	1	0	88
2	0	1	90
0	2	0	90
1	1	1	91
1	2	0	94
2	1	1	101
4	0	0	101
2	2	0	103
3	0	1	106
4	1	0	111
3	1	1	115
0	2	1	117
3	2	0	118
1	2	1	120
4	0	1	125
2	2	1	127
4	1	1	133
4	2	0	135
0	3	0	135
1	3	0	138
3	2	1	139
2	3	0	144
0	0	2	149
1	0	2	151
4	2	1	155
0	3	1	155
3	3	0	155
0	1	2	156
1	3	1	157
2	0	2	157
1	1	2	158
2	3	1	163
2	1	2	164
3	0	2	167
4	3	0	169
3	3	1	172
3	1	2	173
0	2	2	174
1	2	2	176

4	0	2	180
0	4	0	181
2	2	2	181
1	4	0	182
4	3	1	185
4	1	2	186
2	4	0	187
3	2	2	190
0	4	1	195
3	4	0	196
1	4	1	197
4	2	2	201

**Facade 4**

Lx	Ly	Lz	Hz
0	1	0	21
1	0	0	38
0	2	0	41
1	1	0	43
1	2	0	56
0	3	0	62
0	0	1	64
0	1	1	68
1	3	0	73
1	0	1	75
0	2	1	76
2	0	0	77
1	1	1	78
2	1	0	79
0	4	0	82
1	2	1	86
2	2	0	87
0	3	1	89
1	4	0	91
1	3	1	97
2	3	0	98
2	0	1	100
2	1	1	102
0	4	1	105
2	2	1	108
1	4	1	111
2	4	0	112
3	0	0	115
3	1	0	117
2	3	1	118
3	2	0	122
0	0	2	129
2	4	1	130
3	3	0	130

**Facade 5**

Lx	Ly	Lz	Hz
0	0	0	0
0	1	0	38.87126
0	0	1	51.5015
1	0	0	53.59375
0	1	1	64.52426
1	1	0	66.20623
1	0	1	74.32829
0	2	0	77.74252
1	1	1	83.8789
0	2	1	93.25398
1	2	0	94.42558
0	0	2	103.003
2	0	0	107.1875
1	2	1	107.5574
0	1	2	110.0936
2	1	0	114.0181
1	0	2	116.1116
0	3	0	116.6138
2	0	1	118.9183
1	1	2	122.4454
2	1	1	125.1101
0	3	1	127.4801
1	3	0	128.3396
0	2	2	129.0485
2	2	0	132.4125
1	3	1	138.2876
1	2	2	139.7348
2	2	1	142.0756
2	0	2	148.6566
2	1	2	153.6547
0	0	3	154.5045
0	4	0	155.485
0	3	2	155.5905
2	3	0	158.3917

0	1	2	131
3	0	1	132
3	1	1	133
1	0	2	135
0	2	2	135
1	1	2	136
3	2	1	138
1	2	2	141
3	4	0	141
0	3	2	143
3	3	1	146
1	3	2	148
2	0	2	150
2	1	2	151
0	4	2	153
4	0	0	153
4	1	0	155
3	4	1	155
2	2	2	156
1	4	2	158
4	2	0	159
2	3	2	162
4	3	0	165
4	0	1	166
4	1	1	168
2	4	2	171
4	2	1	171
3	0	2	173
4	4	0	174
3	1	2	174
4	3	1	177
3	2	2	178
3	3	2	183
4	4	1	186
3	4	2	191
0	0	3	193
0	1	3	195
1	0	3	197
0	2	3	198
1	1	3	198
4	0	2	200

0	1	3	159.3192
3	0	0	160.7813
1	0	3	163.5357
0	4	1	163.7926
1	4	0	164.4624
1	3	2	164.5621
3	1	0	165.4134
2	3	1	166.5543
2	2	2	167.7578
1	1	3	168.092
3	0	1	168.8284
1	4	1	172.3377
0	2	3	172.9611
3	1	1	173.2455
3	2	0	178.5903
1	2	3	181.0741
3	2	1	185.868
0	4	2	186.508
2	0	3	188.0447
2	4	0	188.8512
2	3	2	188.938
3	0	2	190.9456
2	1	3	192.0203
0	3	3	193.5728
1	4	2	194.0554
3	1	2	194.862
2	4	1	195.7477
3	3	0	198.6187
1	3	3	200.8549

**Facade 6**

Lx	Ly	Lz	Hz
0	1	0	18
1	0	0	21
1	1	0	28
0	2	0	36
1	2	0	42

**Facade 7**

Lx	Ly	Lz	Hz
1	0	0	38
0	1	0	48
1	1	0	61
0	0	1	64
1	0	1	74

2	0	0	43	2	0	0	76
2	1	0	46	0	1	1	80
0	3	0	54	1	1	1	88
2	2	0	56	2	1	0	90
1	3	0	58	0	2	0	96
3	0	0	64	2	0	1	99
0	0	1	66	1	2	0	104
3	1	0	67	2	1	1	110
0	1	1	68	3	0	0	114
2	3	0	69	0	2	1	115
1	0	1	69	1	2	1	122
1	1	1	72	2	2	0	123
0	4	0	73	3	1	0	124
3	2	0	74	0	0	2	127
0	2	1	75	3	0	1	131
1	4	0	76	1	0	2	133
1	2	1	78	0	1	2	136
2	0	1	79	2	2	1	138
2	1	1	81	3	1	1	139
3	3	0	84	1	1	2	141
2	4	0	84	0	3	0	145
4	0	0	85	2	0	2	148
0	3	1	85	1	3	0	149
2	2	1	87	3	2	0	150
4	1	0	87	4	0	0	152
1	3	1	88	2	1	2	156
3	0	1	92	0	3	1	158
4	2	0	93	0	2	2	159
3	1	1	94	4	1	0	160
2	3	1	96	1	3	1	162
3	4	0	97	3	2	1	162
0	4	1	98	2	3	0	163
3	2	1	99	1	2	2	164
1	4	1	100	4	0	1	165
4	3	0	101	3	0	2	171
3	3	1	107	4	1	1	172
2	4	1	107	2	3	1	175
4	0	1	108	2	2	2	177
4	1	1	109	3	1	2	178
4	4	0	112	4	2	0	180
4	2	1	114	3	3	0	184
3	4	1	117	0	0	3	191
4	3	1	121	4	2	1	191
4	4	1	130	0	3	2	192
0	0	2	132	0	4	0	193
0	1	2	133	1	0	3	194
1	0	2	134	3	3	1	195
1	1	2	135	1	3	2	196
0	2	2	137	3	2	2	196
1	2	2	138	1	4	0	196

2	0	2	139	0	1	3	197
2	1	2	140	4	0	2	198
0	3	2	143	1	1	3	200
2	2	2	143				
1	3	2	144				
3	0	2	147				
3	1	2	148				
2	3	2	149				
0	4	2	151				
3	2	2	151				
1	4	2	152				
3	3	2	156				
2	4	2	156				
4	0	2	157				
4	1	2	158				
4	2	2	161				
3	4	2	164				
4	3	2	166				
4	4	2	173				
0	0	3	198				
0	1	3	199				
1	0	3	199				
1	1	3	200				
0	2	3	201				

**Facade 8**

<b>Lx</b>	<b>Ly</b>	<b>Lz</b>	<b>Hz</b>	
1	0	0	39	
0	1	0	52	
1	1	0	65	
0	0	1	70	
2	0	0	78	
1	0	1	80	
0	1	1	87	
2	1	0	94	
1	1	1	96	
2	0	1	105	
0	2	0	105	
1	2	0	112	
3	0	0	117	
2	1	1	117	
0	2	1	126	
3	1	0	128	
2	2	0	131	
1	2	1	132	
3	0	1	136	
0	0	2	139	
1	0	2	145	
3	1	1	146	

**Facade 1****Hz**

22  
36  
41  
53  
64  
68  
72  
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150  
151

**Facade 3a****Hz**

31  
41  
61  
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73  
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167	193
168	197
168	199
168	199
169	200
170	202
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