Masteroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for informasjonsteknologi og elektroteknikk
Institutt for elektroniske systemer

Øyvind Fjeld

# The use of balconies for facade noise attenuation

Masteroppgave i Elektronisk Systemdesign og Innovasjon
Veileder: Guillaume Dutilleux
Medveileder: Tore Killengreen
Juni 2021

NTNU
Norwegian University of
Science and Technology

Øyvind Fjeld

# The use of balconies for facade noise attenuation

Masteroppgave i Elektronisk Systemdesign og Innovasjon
Veileder: Guillaume Dutilleux
Medveileder: Tore Killengreen
Juni 2021

Norges teknisk-naturvitenskapelige universitet
Fakultet for informasjonsteknologi og elektroteknikk
Institutt for elektroniske systemer

NTNU
Norwegian University of
Science and Technology

# The use of balconies for facade noise attenuation

Øyvind Fjeld

June 2020

# Abstract

The goal of the thesis is to investigate the ability of various types of balconies to reduce incoming noise on the building facade. This have been done through field measurements and estimates using Catt Acoustics, Nor96, ISO 12354-3 and guideline 517.521 from *Byggforskserien*.

The measurements show that the presence of a hard surfaced balcony with closed parapet can lead to an average sound reduction of around 3 dB across the facade behind the balcony compared to not having a balcony present. By also installing absorbing cement-bonded wood wool panels at the ceiling, an additional sound reduction of 1-2 dB, to a total SPL reduction of 4-5 dB compared to not having a balcony can be achieved.

Comparing the results show a good agreement between the measurements and estimates by Catt Acoustics, while Nor96 underestimates the screening effect of the balcony compared to the measurements. The 517.521 guideline overestimates on the sound reduction of a balcony without a ceiling compared to the measurements, particularly for high frequencies. The estimate by ISO 12354-3 is quite conservative compared to the measured results, but can be considered an indication of the minimum expected SPL reduction of a balcony.

# Sammendrag

Målet med masteroppgaven er å undersøke støydempningseffekten til balkonger på fasaden. Dette har blitt gjort gjennom feltmålinger og estimater ved bruk av Catt Acoustics, Nor96, retningslinje 517.521 av *Byggforskserien* og standarden ISO 12354-3.

Målingene viser at en balkong med kun harde overflater og tett rekkverk kan redusere lydtrykksnivået på fasaden bak balkongen med rundt 3 dB. Ved å installere treullsementplater i himlingen på bakongen kan lydreduksjonen økes med ytterligere 1-2 dB, til totalt 4-5 dB lydreduksjon sammenlignet med ikke å ha en balkong foran fasaden.

Sammenligning av resultatene viser en god overensstemmelse mellom målingene og estimatene i Catt Acoustics, mens Nor96 underestimerer skjermingen til balkongen. Retningslinje 517.521 overestimerer skjermingseffekten av en balkong uten tak sammelignet med målingene, spesielt for høye frekvenser. Estimatet gitt av ISO 12354-3 er ganske konservativt sammenlignet med måleresultatene, men kan anses som en indikasjon på den minste lydreduksjonen man kan forvente av balkongen.

# Contents

# Chapter 1

# Introduction

## 1.1 Background

The balcony is a common facility in urban area apartment blocks. In addition to offering the habitats an easily accessible outdoor area, it is believed that it can work as a sound blocker that protects the apartment against noise from outdoor sound sources. As the regulations for permitted sound levels in dwellings have became more comprehensive during recent years [1], the sound screening effect of the balcony can play an important role in fulfilling the requirements for indoor noise in buildings located in noisy regions. Additionally, according to the United Nations, it is projected that the segment of the worlds population living in urban areas will continue to increase from 55% in 2018 to 68% in 2050 [2]. This indicates that residential blocks in population dense areas will continue to be built and that the use of balconies for sound abatement will continue to play an important role in future city development.

A new version of the Norwegian guideline for treatment of noise in outdoor area planning, T-1442/2021, was released this June 2021. Chapter 1.2 of the new guideline states that a facade exposed to noise exceeding the allowed upper sound values for new constructions, can be dampened and thus comply with the requirements, through the use of screening at or close to the facade [3]. This method have been used for some time already, but it has not been formalized as an official way of fulfilling noise requirements until now. The screening specifically should result in a noise level within the allowed limits outside any openable windows or/and balcony-doors. One such measure of screening is the installment of balconies. There are several factors that determine the amount of noise a balcony can prevent. By doing measurements and comparing the results of the measurements with results from simulations and standards, the aim of this thesis is to investigate the screening effect of balconies of different types, as well as to determine the accuracy of different prediction methods in cases without access to measurements.

## 1.2 Earlier work

The concept of using balconies to shield from noise has been examined multiple times in the past. Different approaches, such as simulations and lab measurements, have been used for investigating the effect of various parameters of balconies. An overview of a few of these studies and the results they obtained will now be given.

A study by Y. G. Tong of a full scale balcony tested in lab [4] showed the effect of absorbing materials in the ceiling and walls of the balcony. It was found that the ceiling is the most effective place to put absorbing materials when using the balcony for noise protection.

S. K. Tang have conducted experiments with 1:10 scale models and line sources [5] [6]. In the papers Tang find among other things that balconies with highly reflecting interior walls have poor sound insulation, particularly if the balconies have a ceiling.

H. Hossam El Dien have done simulations of the sound field inside the balconies using pyramid ray tracing [7] [8]. In ([7]), different inclinations of the ceiling was tried, and it was found that the optimal inclination for maximized attenuation depended strongly on the elevation of the balcony. In ([8]), the effect of different balcony widths and different inclinations of parapets were investigated.

Numerical calculations have been conducted by D. Hothersall to calculate the effect of balconies using the boundary element method (BEM) [9]. Hothersall estimated that an attenuation of 5-8 dB on the sound field inside the balcony is achievable by treating the ceiling or rear wall with absorbing material, while up to 10 dB attenuation is possible by treating all the surfaces inside the balcony.

Lastly, field measurements of high-rise balconies have been conducted by Daryl N. May [10]. The measurements show that it is possible to get 4-5 dB attenuation by treating the ceiling alone with acoustic material, and 7-8 dB attenuation by treating one third of the interior surface area of the balcony.

## 1.3 Focus and layout of text

The text has two main aspects of interest. The first is to investigate the sound reducing effect balconies can have through field measurements. While the effect of absorbing materials in balconies as described in Section 1.2 have been investigated several times before, most of the papers discuss scale models or lab measurements, which could deviate from actual field measurements. The sound reduction effect of adding an absorbing ceiling to a balcony is investigated in the octave bands from 125 Hz to 4000 Hz for cases where the balcony is subjected to noise from either a point source or a line source. Additionally, the A-weighted sound reduction that can be achieved through covering various surfaces of the balcony with absorbing materials is investigated, primarily through simulations.

The second aspect of interest is to investigate the accuracy of different prediction methods of the screening effect of a balcony compared to the measured results. While the computer has allowed for simulation programs that can be indispensable tools for making an approximation of sound field where measurements are unpractical or unavailable, the value of such tools is largely dependent on their accuracy [11]. The estimated screening effect of various balcony types is investigated using the Nor96 prediction method and with the room acoustic prediction program Catt Acoustics and is compared to each other and the field measurement of the same balcony. The average and standard deviation between the two prediction methods is also determined. Finally calculations using guideline 517.521 of Byggforskserien [12] and ISO 12354-3 [13] is done to determine their accuracy in comparison to the field measurements. Ideally, the comparison between the results of the different prediction methods can provide useful information in terms of what methods can be used to make accurate predictions of sound reduction effects, and give an idea of what sound reduction effect can be expected by covering other surfaces than the ceiling with absorbing materials.

The paper assumes the reader is familiar with basic acoustic concepts such as sound pressure, sound pressure level, frequency of sound, and resonance frequency.

In Chapter 2 theory regarding relevant concepts for sound interactions in balconies is presented. This includes outdoor sound propagation, diffraction and specular reflection. Additionally, theory regarding point sources and line sources is presented. Chapter 3 describes the methods and conditions for measurements performed in balconies. Furthermore the parameters for the various prediction methods are outlined. Chapter 4 presents the results of the measurements, simulations, and calculations. Chapter 5 discusses the differences and similarities between the measurements, simulations and estimations based on standards. The uncertainty factors involved in the field measurements and prediction methods are also discussed. Finally, conclusions are drawn in Chapter 6.

# Chapter 2

# Theory

## 2.1 Outdoor sound propagation

This thesis revolves around outdoor sound measurements, which does have its implications. However, the measurements have been done at a relatively short distance, which means that the effect of refraction (curvature of waves due to meteorological conditions) can be dismissed. The same can be said for air absorption (sound energy getting converted into kinetic molecular energy), which even for high frequencies is not very significant at distances less than 100 meters. The outdoor sound propagation topics that are relevant for this thesis will be presented in the following sub chapters. For a more comprehensive description of outdoor sound propagation, see *Tutorial on sound propagation outdoors* [14], which is the source of most of the information of this chapter.

### 2.1.1 Geometrical divergence

When the sound source is small compared to the distance considered, the waves spread spherically and the SPL decreases by 6 dB with a doubling of distance. This source type is referred to as a point source. All sources can be considered point sources, assuming the listener is far enough away. ISO 9613-2 [15] gives an equation for predicting the attenuation of sound by a point source due to geometrical divergence, $A_{div}$:

$$A_{div} = [20 \lg(\frac{d}{d_0}) + 11] \text{ dB} \tag{2.1}$$

where

$d$ is the distance from the source to the receiver, in meters;

$d_0$ is the reference distance, equal 1 meter.

Line sources radiate sound along a line, which causes cylindrical spreading of sound, assuming the distance from the listener to the source is not far greater than the length of the line source. In this case, the SPL decreases by 3 dB per doubling of distance. A line source can be represented by an array of point sources. The sound of each of these point sources may be either coherent or incoherent with one another. When a line of point sources is coherent, it means that the sources radiate sound of identical frequency [16]. An example of a coherent line source could be a loudspeaker array, where each loudspeaker generates sound of identical frequency. When a line of point sources are incoherent, it means they radiate sound of varying frequency. This is the most common line source type in real world situations. An example of an incoherent line source could be a trafficked road where the sound is generated by different vehicles driving at different speeds.

A study by P. Jean et al. [17] investigates sound field and insertion loss of different different source types. It was found that the coherent line source overestimated the insertion loss of a barrier compared to the incoherent line source. The study also shows that coherent line sources are likelier to have systematic variations in sound level based on the distance to the source, whereas the incoherent sources are decreasing more linearly with the distance.

### 2.1.2 Ground effect

The effect of the ground is smaller in the case of measuring balconies than in normal outdoor measurement situations, because most ground effects only apply for waves traveling more-or-less horizontally near the ground. As the balconies considered in this thesis is elevated well above ground level, the waves reaching the balcony will only be close to the ground near the source position. Specular reflections right next to the source will thereby have an impact and can be a cause of interference, something that will be described in further depth in Section 2.2.3.

## 2.2 Specular reflection

As described in Section 1.2, multiple studies show a significant relation between the absorption coefficient of the ceiling and the sound level at the balcony. This indicates that the reflection of the ceiling plays a large role for the measured sound level inside the balcony. An illustration of waves generated by a source reaching a receiver inside a balcony through specular reflection is shown in Figure 2.1.

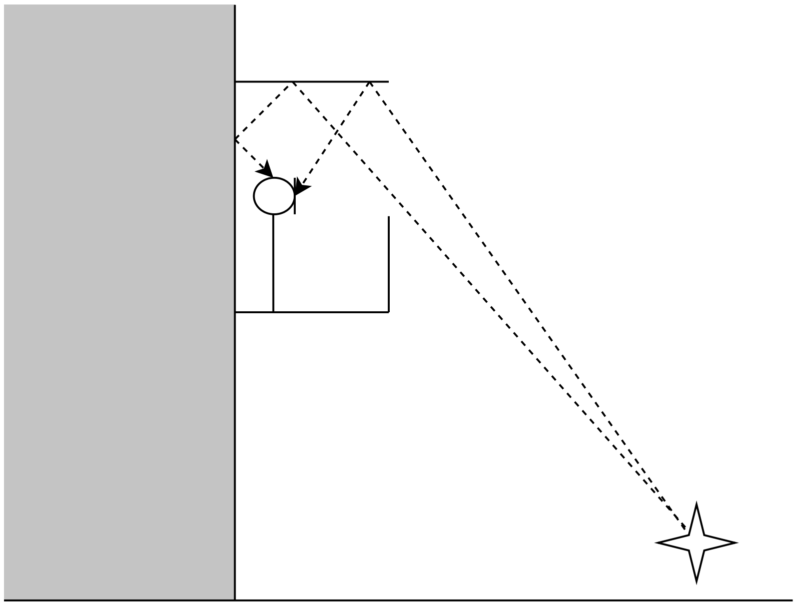


**Figure 2.1:** Illustration of rays reaching the receiver through specular reflections at surfaces of the balcony.

Rays of higher order reflections may also be reflected at the parapet, the floor and the facade. Additionally, as mentioned in Section 2.1, sound waves can also be reflected off the ground and up towards the ceiling of the balcony.

### 2.2.1 Absorption

When reflection of sound happens at a boundary, a fraction of the sound energy is absorbed, either by being converted into heat or by being transmitted through the boundary. The sound reduction when this happens is given by Equation 2.2 [18]

$$\Delta SPL = 10\lg(|R|^2), \tag{2.2}$$

where

$$|R|^2 = \frac{p^2_{rms,reflected}}{p^2_{rms,incident}}.$$

The energy absorption coefficient $\alpha$ can be expressed through $|R|^2$ as [19]

$$\alpha = 1 - |R|^2. \tag{2.3}$$

Combining Equation 2.2 and Equation 2.3 the following relation between the decibel sound reduction and $\alpha$ can be made:

$$\Delta SPL = 10\lg(1-\alpha). \tag{2.4}$$

$\alpha$ is dependent on the complex impedance of the material, as well as the frequency of the sound and incident angle of the waves. For simplicity it is common to operate with octave band diffuse field values of $\alpha$ for different materials.

### 2.2.2 Surface scattering

Scattering of sound can happen when sound waves are hitting an uneven surface. ISO 17947-1 [20] defines the scattering coefficient $s$ as the amount of reflected energy which is not reflected specularly. Simulations by Embrechts [21] demonstrate that there is a non-linear relation between the scattering and the ratio between the roughness (the rms-value of the height variations of the surface) $\delta$ of a material, and the wavelength of the sound $\lambda$. The experiments show that when $\delta$ is much smaller than $\lambda$, the scattering is close to 0, while when $\delta$ approaches the same order of magnitude as $\lambda$, the scattering coefficient rapidly approaches 1. This indicates that sound of higher frequency will be scattered to a larger degree than sound of low frequency. Similarly to the absorption coefficient, scattering of sound also depends on the angle of incident wave. For simplicity it is common to operate with diffuse field values of scattering.

High scattering on a building facade will cause more sound energy, especially of high frequencies, to reach the balcony. An illustration of this is shown in Figure 2.2. Another implication is that high scattering in the balcony ceiling could cause less sound to reach the inside of the balcony, as some of the sound that would normally reach the inside of the balcony through specular reflection at the ceiling could instead get scattered away from the balcony.

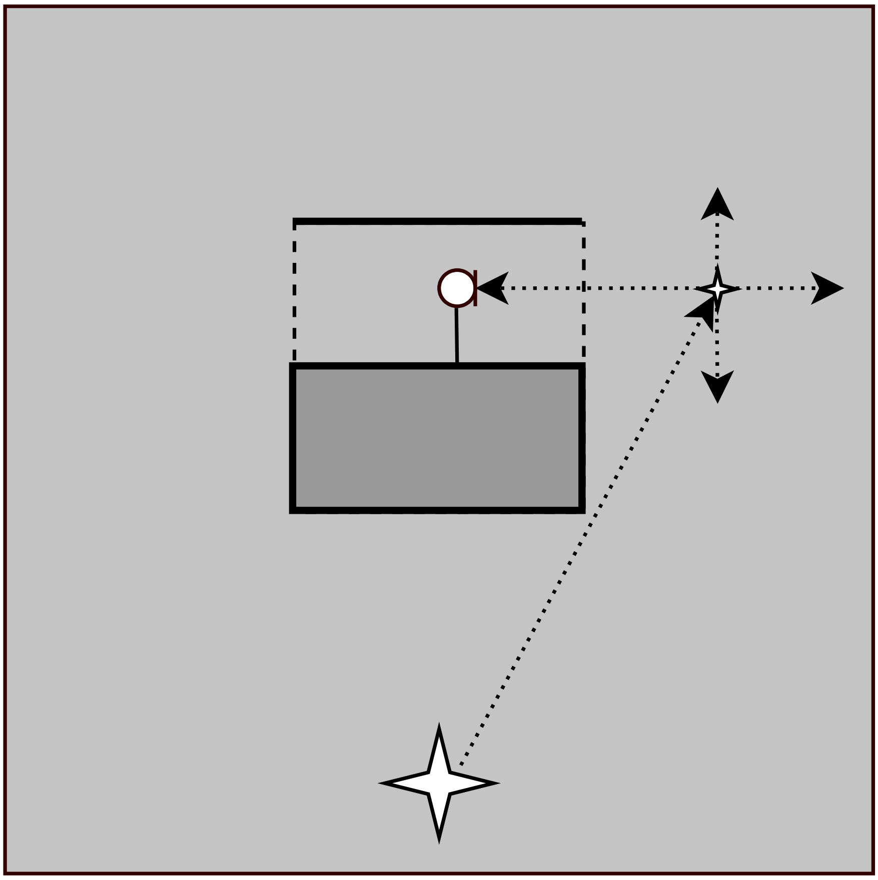


**Figure 2.2:** Illustration of rays getting scattered when reaching the facade, causing some sound to reach the balcony.

### 2.2.3 Interference

When a direct wave interacts with a reflected wave, interference happens [22]. The reflected wave can either serve to amplify or cancel the direct wave, depending on the phase relationship between the two at the position of the receiver.

In the case of a balcony with a source positioned close to the ground, interference can occur between the direct wave from the source and the waves reflected at the ground close to the source. Such a case, where the delay between the reflected and direct wave is equal to half a period and thereby causing destructive interference, is illustrated in Figure 2.3. Another possibility is interference between waves getting reflected by the ceiling and waves getting diffracted over the parapet. Diffraction will be discussed in detail next.

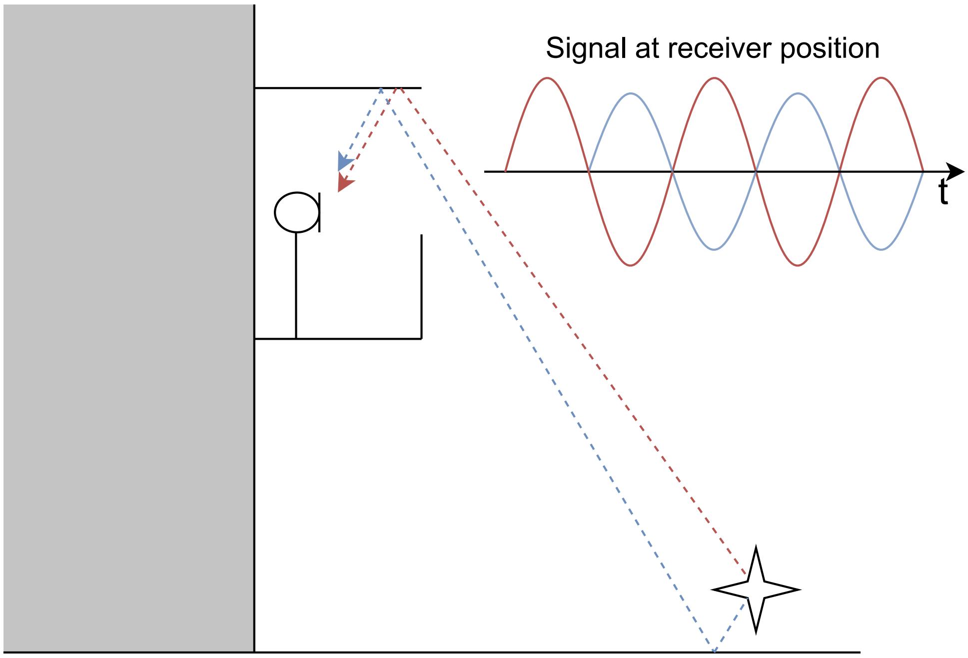



**Figure 2.3:** Illustration of destructive interference between a direct wave via the ceiling (red) and a wave reflected at the ground and via the ceiling (blue), leading to cancellation of certain frequencies at the receiver position.

## 2.3 Diffraction

Diffraction can occur when sound waves encounter gaps or edges. This causes the waves to bend out around the edge, spreading out spherically around the point of diffraction. In order for diffraction to happen, the object needs to be sufficiently large compared to the wavelength of the sound [23]. Waves of low frequency and thus high wavelength diffracts around objects more effectively than waves of high frequency and thus low wavelength.

### 2.3.1 Diffraction around barriers

Insertion loss describe the difference, in decibels, of the sound pressure level at a receiver position when a barrier is present compared to when it is not [24]. The insertion loss is limited primarily by the strength of the diffracted waves traveling around the edges of the barrier, assuming there are no gaps. The greater the size of the barrier, the longer the waves have to travel to go around the edge and the greater the sound reduction becomes.

The parapet of a balcony can work as a barrier. When the parapet is closed, with little transmission through the surface and no gaps between the floor and the parapet, the effect of the parapet is limited by the diffraction of the sound waves going over it. An example of how the waves can propagate in such a case is illustrated in Figure 2.4. The insertion loss depends on the extra travel length of the sound waves, which in this case is determined by the height of the parapet, the depth of the balcony, and the relative positions of the source, receiver and balcony.

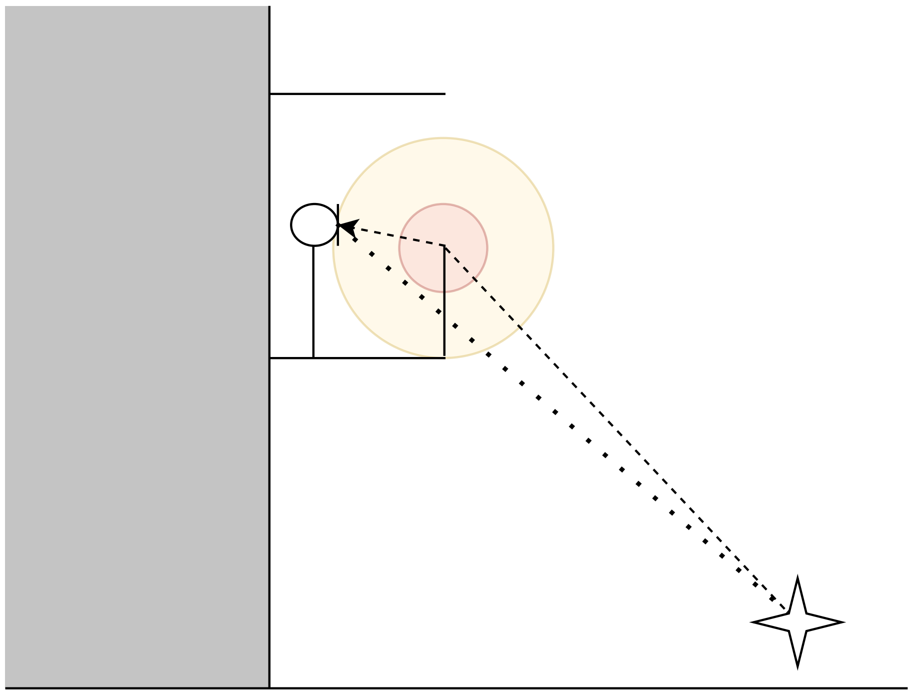


**Figure 2.4:** Illustration of the path difference between a direct path and the path of a diffracted ray.

### 2.3.2 Edge diffraction

When sound reaches the edge of an object, the edge acts as a sound source. The edge diffraction is strongest close to the edge, where the path difference between the direct wave and the diffracted wave is smallest. Continuing with the example of a balcony, edge diffraction is relevant particularly at balconies located close to the side edge of the facade. In addition, top balconies without roof will be affected edge diffraction happening at the top of the facade. An illustration of this is shown in Figure 2.5. In addition to the diffraction caused by the edges of the facade, edge diffraction will also happen at the edge of the ceiling when the balcony has one.

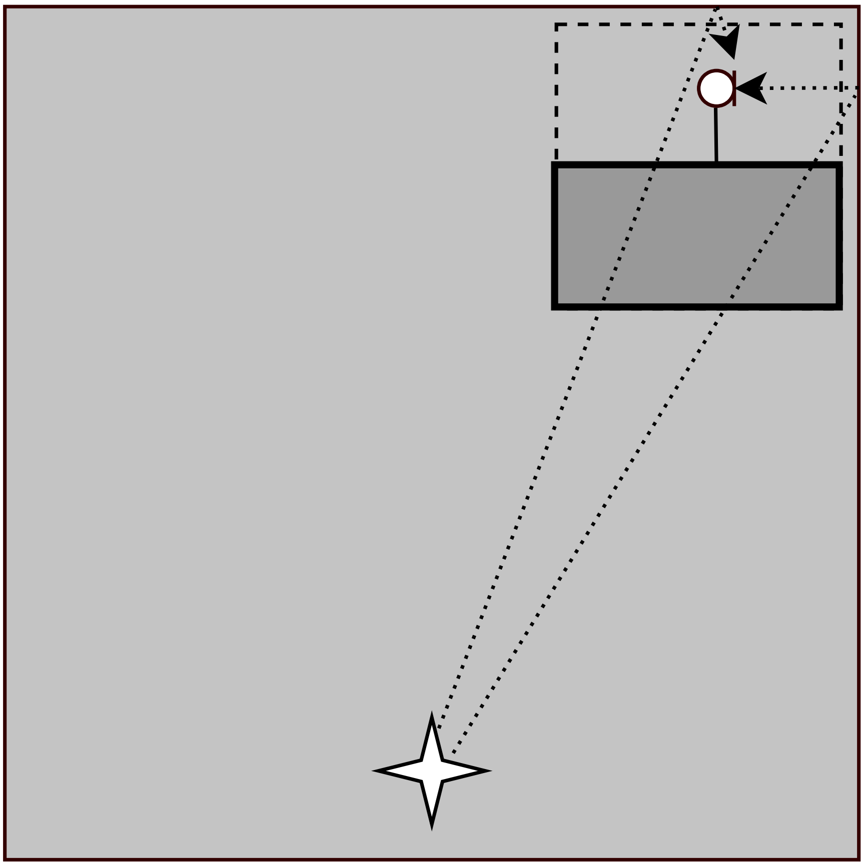


**Figure 2.5:** Illustration of how edge diffraction can diffract sound waves from the edge of the facade to the balcony.

### 2.3.3 Ray paths of diffraction and specular reflection

Waves can have multiple paths to reach a receiver of higher order generated by a source. In the case of a balcony, one possibility is a wave that diffracts from the edge of the parapet and reflect off a surface before reaching the receiver, as illustrated in Figure 2.6. This can cause interference, as described in Section 2.2.3.

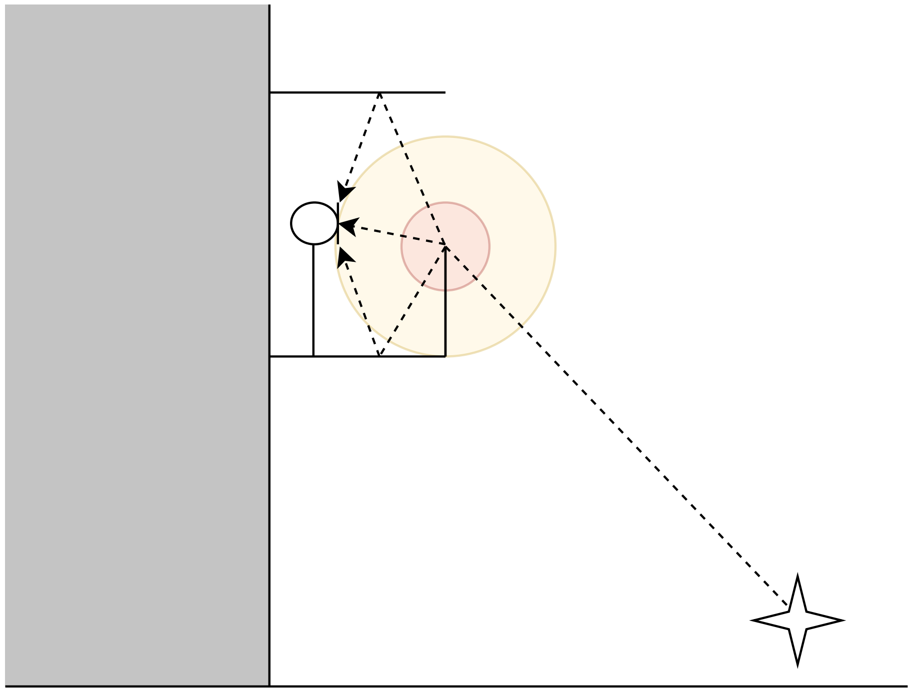


**Figure 2.6:** Illustration of various ray paths consisting of diffraction and reflection.

# Chapter 3

# Methods

A screenshot from the model used for retrieving information about the buildings and balconies is shown in Figure 3.1. The yellow crosses mark the balconies that have been measured. The dimensions of this model, confirmed by on-site distance measurements, is used to gather data regarding the propagation distances of the measurements and is also the basis for the estimations.

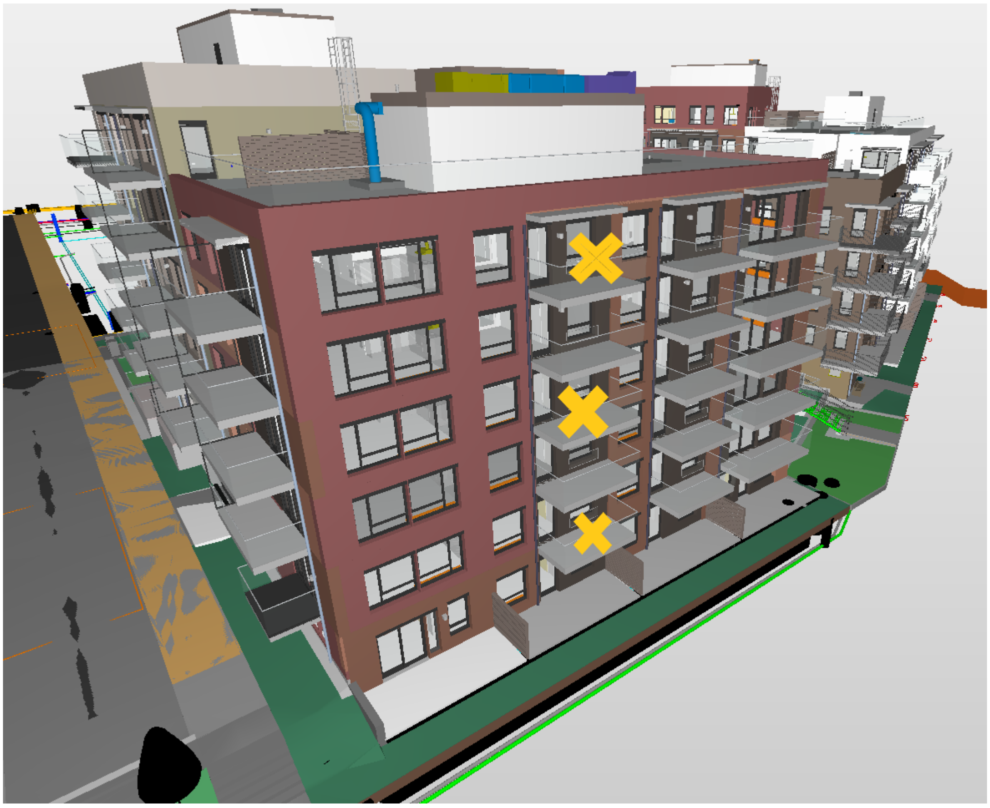


**Figure 3.1:** Screenshot from a Solibri model showing the finished balconies and buildings. The orange crosses signify the balconies that have been measured.

## 3.1 Measuring the SPL difference between balcony facade and parapet

### 3.1.1 Site

Measurements have been carried out in a construction site located at Vollebekk on two different occasions. The same balconies were measured both times. On the first occasion the ceiling of the balconies consisted only of concrete, while on the second occasion absorbing material had been installed on the ceiling of the balconies.

A satellite photo of the site is shown in Figure 3.2. The buildings were not built during the time of the photo, so the outline of the new building and balcony is drawn in blue. The distance from the balcony to the metro line that will be measured is shown, in addition to the distance to nearby 4-lane highway causing background noise. A picture showing the elevation of the metro line as compared to the construction site is shown in Figure 3.3.

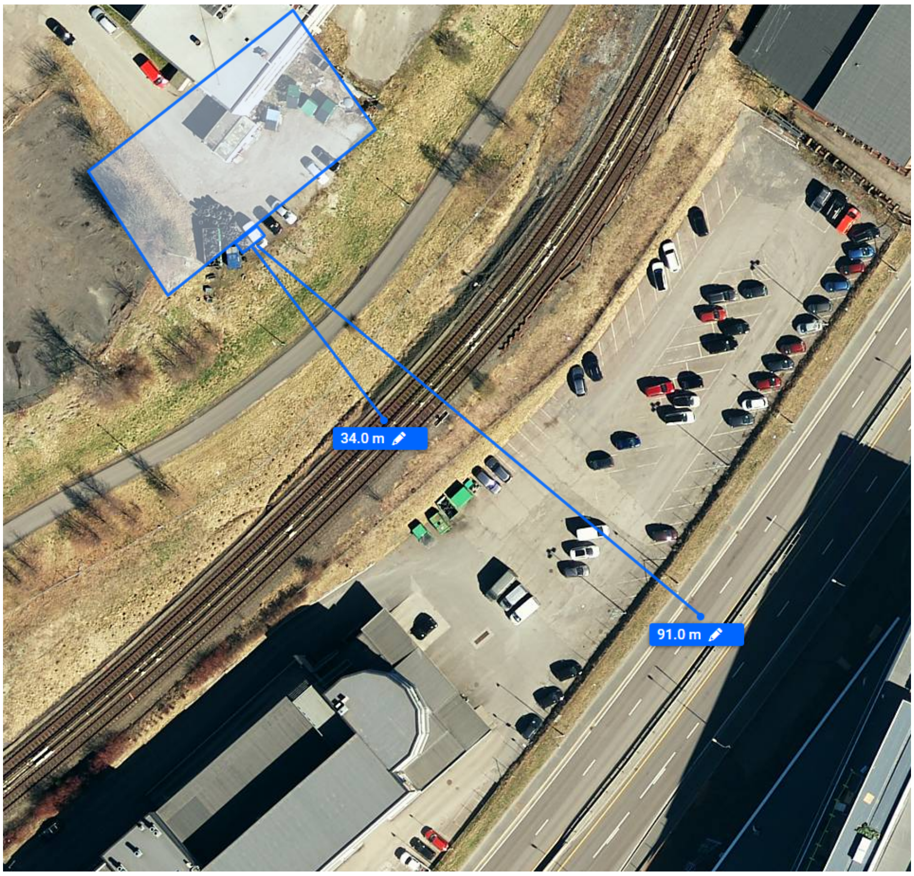



**Figure 3.2:** Satellite photo of the area around the balcony and nearby noise sources. The picture is a screenshot from "Gule sider".

**Figure 3.3:** Photo from the side of the metro line and construction site. The picture is a screenshot from "Google Earth".

The balconies that were measured had a width of 4 meters, a height of 2.8 meters and a depth of 2 meters. Measurements were done at the 2nd, 4th and 6th floor. The parapet in the 6th floor was measured to be 1.2 meters, while the parapet of the 2nd and 4th floor was measured to be 1 meter. The dimensions, microphone positions and loudspeaker position is shown in Figure 3.4. As can be seen, the balcony at the 6th floor has a ceiling that only covers half the balcony. This may be considered as an approximation to a balcony without ceiling, as the ceiling no longer is in direct sight of the loudspeaker.

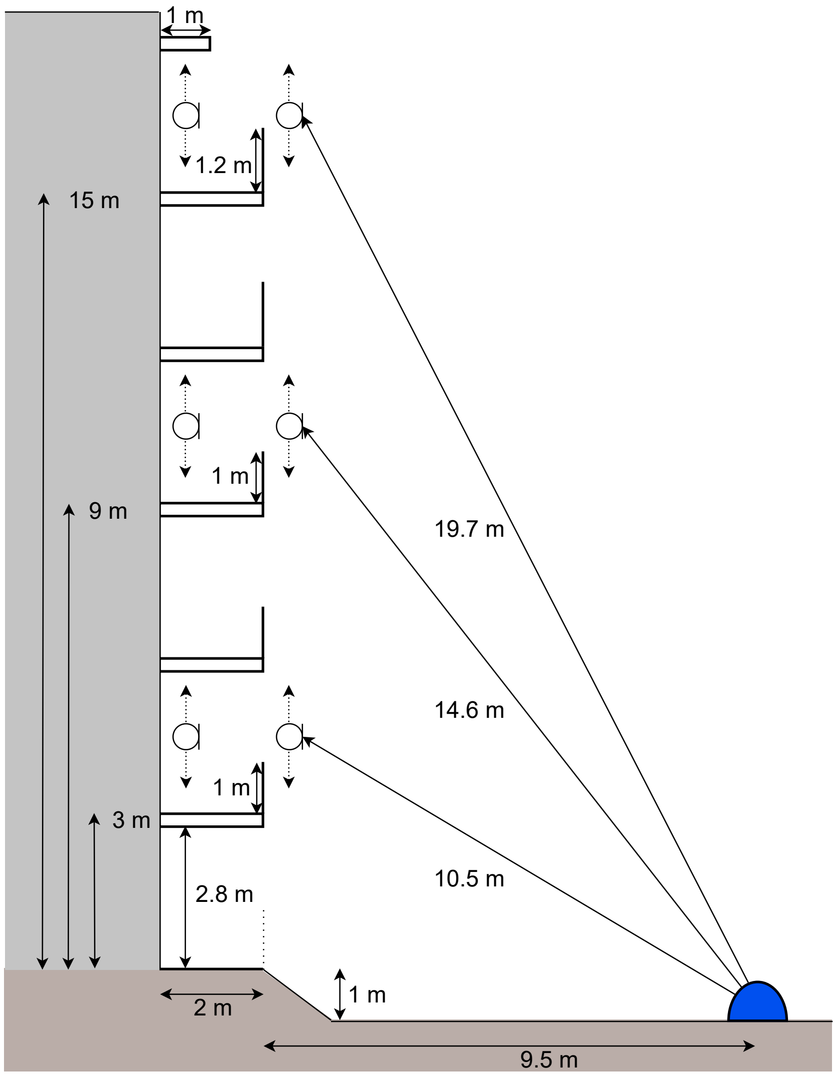



**Figure 3.4:** Illustration of the different balconies that were measured. The microphone positions indicate the center height of the microphone sweep, while the dotted arrows indicate the region of the sweep. The blue semicircle indicate the loudspeaker position.

Between the first and the second measurement, sound absorbing cement-bonded wood wool panes called *semullit* was installed on the ceilings of the balconies measured. The absorbing panel was mounted directly at the concrete, and the absorption coefficient for this configuration is shown in Figure 3.5. A picture showing two 4th floor balconies, where the closest has absorbing panel installed, is shown in Figure 3.6. The 6th floor balcony that was measured also had absorbing material installed. A picture from the top balcony is shown in Figure 3.7. As can be seen in the pictures, the absorbing material does not cover the entire ceiling, but rather an area of about 10 cm margin within the edge of the ceiling.

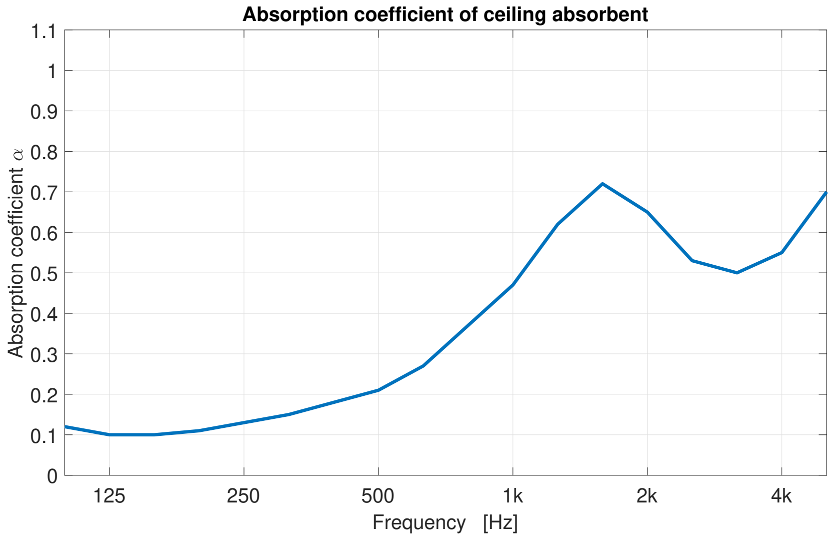



**Figure 3.5:** Absorption coefficient $\alpha$ of semullit when mounted directly on the concrete ceiling. The graph is made based on information found at the producers website, troldtekt.com.

**Figure 3.6:** Picture of the 4th floor balcony.

**Figure 3.7:** Picture of the 6th floor balcony.

As can be seen in Figure 3.6 and Figure 3.7, the main portion of the facade consists of unpainted brick, while the material at the part of the facade behind the balconies consist a combination of glass (windows and balcony door) and painted wood. The parapet is made of 8.76 mm thick laminated, tempered glass, with a frame of painted aluminum. There are gaps of about 1 cm between the glass and the crown of the parapet and between the front parapet and the side parapets.

On the fist measurement date, there was positioned a vehicle that could be a source of reflection behind the loudspeaker. On the second measurement date, there was no vehicle nearby, but there was a large pile of gravel to the right of the loudspeaker.

### 3.1.2 Meteorological conditions

The first measurements were done at May the 6th, from 10:30 am to 2 pm. The weather was clear and the temperate was 6-7 degrees. The air humidity was between 30% and 40%. The wind speed was 4-6 m/s to the south/southwest. This means that the measurements were done with headwind since the balcony is positioned to the north/northwest of where the loudspeaker was placed.

The second measurements were done at June the 15th, from 11 am to 1 pm. The weather was clear and the temperature was 18 degrees, while the air humidity was at 35%. The wind speed was 5-6 meters to the east, so the measurements were done with headwind or side-wind to the right.

### 3.1.3 Equipment

A hemi-dodecahedron loudspeaker of type Norsonic275 was used as the point source. The loudspeaker and amplifier characteristics can be found in Appendix A.

Different microphones were used for the two occasions of measurements. The microphones are of class 1, in accordance to IEC 61672-1 [25]. The microphones were equipped with a 3.5 cm radius windscreen, and were calibrated before and after the measurements were made. A table describing what microphone was used at what date and location, in addition to serial numbers, is shown in Appendix B.

### 3.1.4 Measurement method

The loudspeaker was placed on the ground 9.5 meters directly in the front of the ground position underneath the front of the parapet, emitting pink noise at 100 dB.

For the point source measurements, the measuring microphone was swept across an area 0.5 meters from the facade behind the balcony for up to 30 seconds in order to obtain an average value of the sound pressure level. Ideally for facade measurements, the microphone is mounted to the facade, but studies have shown that there is no great loss of accuracy in using sweeps outside the facade when other reflective surfaces (such as the balcony ceiling) is present [26]. In order to measure a reference level without any balcony present, measurements were additionally done outside of the parapets of the balconies, sweeping sideways and up/down in the region 0.5 meters outside the front parapet.

In order to investigate the screening effect of the balcony when exposed to a line source, measurements of the nearby metro were also done. The measurements were done in accordance to the method described in NS 8177 [27]. The microphones were positioned stationary at 1.5 meters above ground, 1 meter from the facade and slightly to the left in the balcony to avoid any modal cancellations. On the first measurement date, the microphones were recording continuously for 30 minutes, which allowed for 7-8 metro passages, subsequently on each measurement floor. On the second measurement date, six microphones did recordings simultaneously for 75 minutes, which allowed for a total of 20 metro passages. To find an estimate on the sound level at the facade without a balcony, measurements were also done with the microphone positioned above the parapet during the second measurement date. In the 4th floor, the microphone was instead taped to the outside of the parapet, which may be a better approximation to the sound level of a facade without a balcony. Ideally, all the metro measurements outside the parapet -as well as the metro measurements at the facade- should have been done in this fashion, but this was not possible due to equipment limitations.

### 3.1.5 Post-processing

The measured A-weighted sum of sound pressure level and 1/3 octave band values of the recordings of the loudspeaker were exported to Excel via NorXfer. The octave bands were calculated in Excel, by logarithmically summarizing the belonging three 1/3 octave bands. The data was then read and plotted in Matlab.

The recordings of the metro were analyzed in NorReview in order to extract the measured A-weighted sum of sound pressure level and 1/3 octave band values from each passage. The data was then transferred to Excel, where the recordings were summarized logarithmically to find the average 1/3 octave band values and A-weighted sum of all the passages for each measured balcony. The 1/3 octave bands were converted to octave bands by logarithmic summation. Finally, the data was read and plotted in Matlab.

## 3.2 Estimating SPL reduction at balcony facade

Estimates on the SPL reduction have been made using Catt Acoustics and Nor96 through CadnaA, with parameters based on the balconies measured. First, the parameters common for both methods will be described. Afterwards, individual parameters for each simulation program will be outlined.

### 3.2.1 Common parameters

In both methods the elevation of the balcony being simulated is 10 meters above ground level, identical to the 4th floor balcony crossed out in Figure 3.1. The balcony is four meters wide, two meters deep and three meters tall from floor to ceiling. The height of the balcony parapet is 1 meter.

The parts of the balcony treated with absorbing material have the absorption factor equal "Semullit" in Table 3.1, which have been chosen based on the data in Figure 3.5. For surfaces not covered with absorbing material, glass have been used as the material of the parapet, and concrete as the material of the floor, ceiling and the facade. The absorption coefficient numbers for concrete and glass is based on studies conducted by Vorländer [28].

| **Material** | **Absorption coefficient $\alpha$** | | | | | |
|---|---|---|---|---|---|---|
| | 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz |
| Concrete | 0.02 | 0.02 | 0.03 | 0.03 | 0.04 | 0.05 |
| Glass, 86 mm | 0.10 | 0.06 | 0.04 | 0.03 | 0.02 | 0.02 |
| Semullit | 0.10 | 0.12 | 0.20 | 0.48 | 0.65 | 0.55 |

**Table 3.1:** Absorption coefficients of the different materials at different frequencies.

The simulations are done with absorbing material covering different inward facing surfaces of the balcony. In addition, simulations have been done for balcony without roof, balcony with an open parapet, and as a comparison the sound level on the facade with no balcony. The different variants used for the calculations is shown in Figure 3.8.

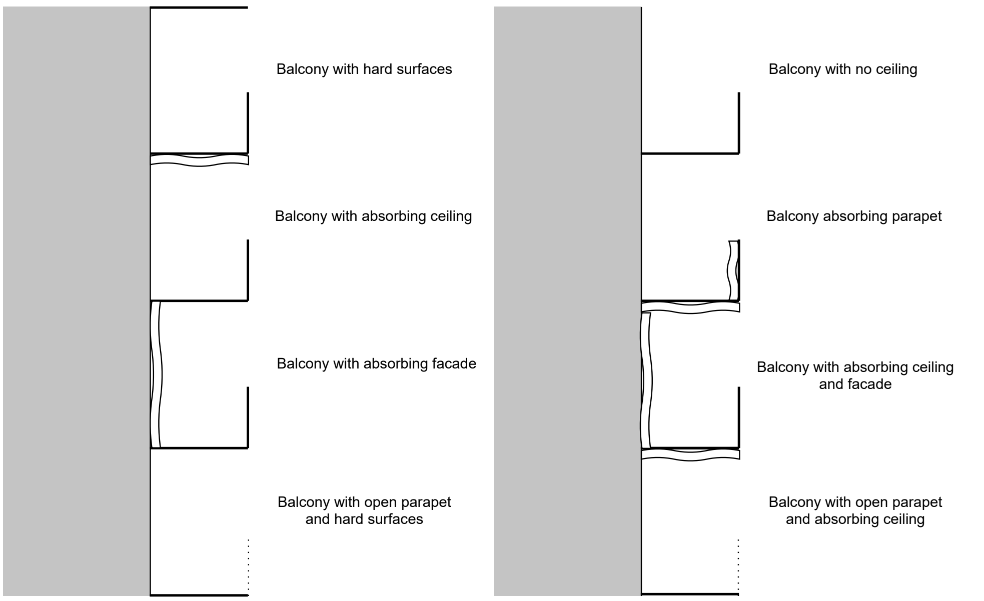



**Figure 3.8:** Variants of different balcony configurations.

### 3.2.2 Nor96 prediction method

Nor96, also called the Nordic prediction method, is a calculation method for outdoor sound propagation commonly used by acoustic consultants in Nordic countries. The prediction method can be used to calculate sound emission from railroads, roads with car traffic and industry noise. However, in this thesis only industry noise sources have been used. The method yields results in octave bands and among other things accounts for spherical divergence, reflections on vertical surfaces, screening, ground effect and air absorption [29].

Calculations based on Nor96 have been done using the noise prediction software CadnaA. A model of the area where the field measurements took place was provided by the architects and imported into the software. The dimensions of the buildings and environment is defined according to the imported model. The balcony parapet goes all the way down from the balcony to the ground, as the floor of the balcony, a "bridge element" do not properly screen sound coming from below.

Simulations of sound levels caused by a point source and two different line sources have been made. The point source have a pink noise spectrum. The first line source represents an imaginary road located 10 meters from the front of the balcony, running parallel to the building facade, and is used as a basis for comparison with simulations in Catt Acoustics. The road source has a frequency spectrum equal to the noise from a city road with a speed limit of 50 km/t, as defined in ISO 717-1 [30]. A plot in 1/3 octave bands of this spectrum is shown with the orange line in Figure 3.9. The blue line represents a the sound spectrum generated by a metros running over a rail close to the real-life construction site. The simulated metro line will work as a point of comparison to the real-life metro line. The frequency spectrum is based on field measurements done by Brekke & Strand at metros bypassing at 20-70 km/h.

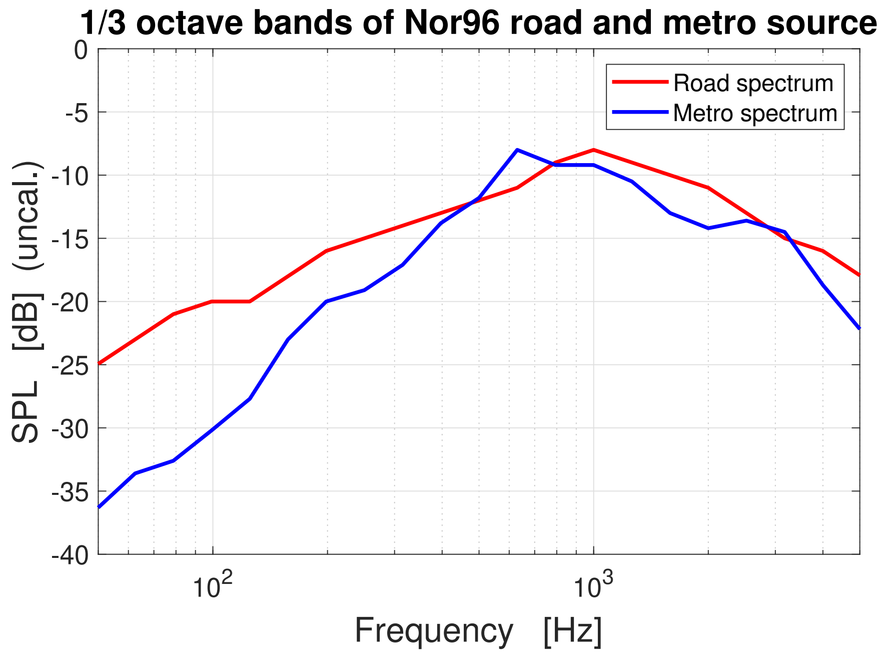



**Figure 3.9:** Spectrum of road and metro sound signal, normalized to have a sum of 0 dB.

A picture from CadnaA showing a birds eye view of the balcony, point source and line sources is shown in Figure 3.10. As can be seen in Figure 3.10, the ground consist of different regions with absorption factors chosen in accordance to ISO 9613-2 [15]. The region marked "soft terrain" represents grassy ground and porous gravel under the metro line, and has an absorption factor of 1. The region marked "hard terrain" represents areas of concrete and tamped ground at the construction site, and has an absorption factor of 0 in accordance to ISO 9613-2.


**Figure 3.10:** Birds eye view of position of balcony in relation to point source, road line source and metro line source in CadnaA simulation. The picture is purely illustrative, as the road source and metro source in the simulations are replaced with line sources, to make calculations based on the industry method of Nor96.

The number of reflections is set to 8. Scattering is not accounted for in Nor96 and is therefore not considered. The meteorological conditions have been set to no wind, a humidity of 50% (40% is not available) and a temperature of 15 degrees.

A matrix of receivers is placed 0.5 meters from the facade at the balcony, with no more than 0.5 meters distance from one another, in order to emulate the sweep 0.5 meters from the facade during measurements. The matrix has 10 columns and 5 rows, so that the sound level over a total of 50 receiver positions are calculated. Each receiver calculates the octave band values and the A-weighed sum of sound pressure level according to the Nordic Prediction Method for industrial noise. The SPL is converted into sound pressure in Excel, where the sound pressure across all receiver positions is averaged to calculate the average octave bands and A-weighed sum of sound pressure level across the balcony facade. The averaged SPL is then imported into Matlab for plotting.

Due to the fact that Nor96 does not account for reflections caused by horizontal planes, an alternative way of replicating the effect of the ceiling should be considered for accurate results. The chosen approach for this thesis is to define a mirror source, symmetrically placed around the height of the ceiling directly above where the original source is located. This makes it possible to estimate the effect of the roof, as illustrated in Figure 3.11.

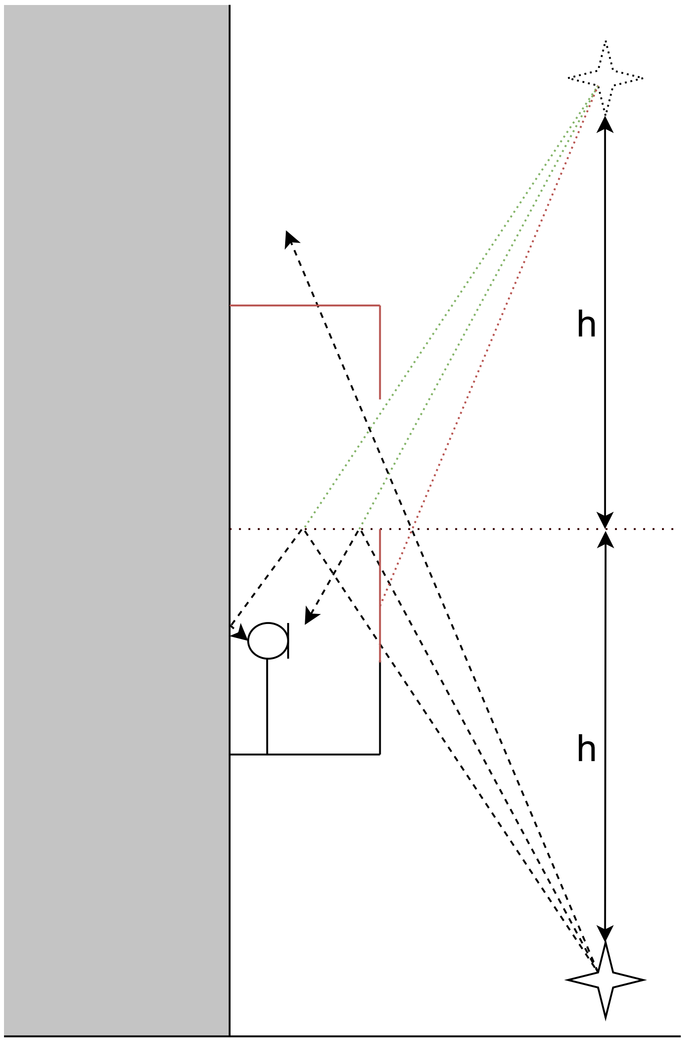



**Figure 3.11:** Illustration of how the effect of the roof can be emulated with an equivalent mirror source. The lines in red signify surfaces only present when the mirror source is active. These surfaces prevent rays generated by the ground source that would not reach the ceiling from getting accounted for when calculating the contribution of the mirror source.

The strength of the mirror source is chosen in such a way that the sound pressure level along the height of the facade where the ceiling would be located is the same for the mirror source as for the ground source. It was found that a mirror source correction of +1 dB for the point source, +0.5 dB for the road line source and -3 dB of the metro line source resulted in the same level at the facade as the ground source.

To estimate the effect of an absorbing ceiling, the octave band values calculated by the unaltered mirror source is modified according to the absorption coefficients in Table 3.1 applied on Equation 2.4. To make sure that only rays that would hit the roof gets accounted for by the mirror source, an absorbing wall and a mirrored balcony is also put up around the balcony to eliminate the contribution of rays that would not be reflected. These surfaces is marked with a red line in Figure 3.11 and is only present when the contribution of the mirror source is calculated. A picture from CadnaA of the mirror source and absorbing wall around the balcony is shown in Figure 3.12.

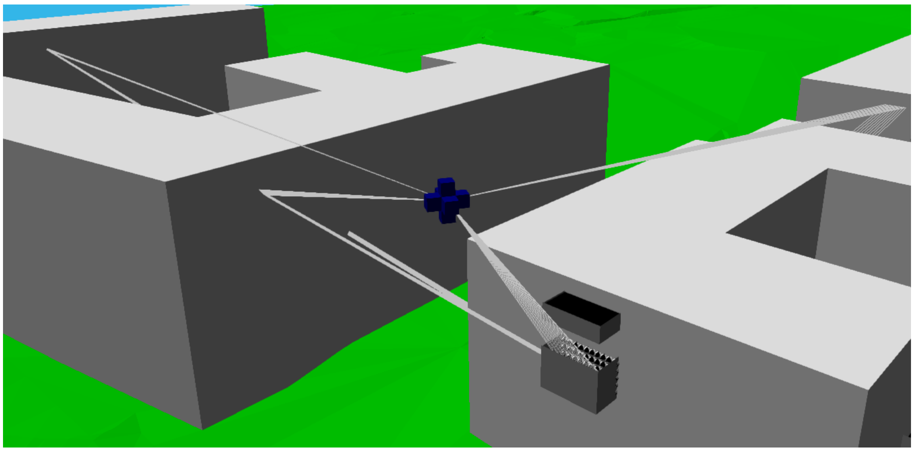


**Figure 3.12:** Screenshot from CadnaA that shows the mirror source and the additional absorbing wall around the balcony, as well as the mirror balcony above the original balcony. The circles along the facade indicate the receiver positions. The rays of up to 1 reflection from the source hitting the lowest row of receivers is shown.

As can be seen in Figure 3.12, some of the rays travel straight through buildings and barriers. This is not an error, but rather a illustrative simplification, as CadnaA calculates the contribution of the rays considering the additional diffraction path over the objects according to Nor96. As can also be seen in the picture, no reflection happens at horizontal surfaces. This also includes the ground, that is instead accounted for by a decibel correction based on the absorption factor underneath the source and receiver.

Given that absorbing walls and the mirror balcony need to be in place for the mirror source to calculate the contribution of the roof properly, the source and the mirror source can not be calculated simultaneously. In order to account for both contributions, the sound pressures are added on top of each other after the calculations are done.

### 3.2.3 Catt Acoustics simulation

Catt Acoustics is designed as a room acoustics program. Despite this, there are no issues using it for calculation of outdoor scenarios. In order for the program to work like intended, however, the simulation needs to be done inside a defined room. Therefore, an anechoic room is used as the outer boundaries. This effectively mimics free field conditions in the area around the building facade. The outer boundary room is 50 × 50 × 50 meters large.

Catt does not allow sound mappings (ie. extraction of the SPL values across a surface) for vertical planes. As the vertical building facade is the main area of interest in this thesis, the building and ground have been flipped 90 degrees so that a sound mapping of the facade behind the balcony can be made. However, for the convenience of the reader the regular coordinates of $\mathbf{x} = (x, y, z)$ will be used for describing the position of the different elements in a practically identical, non-flipped case.

Surface scattering and edge scattering is enabled. The scattering coefficients are chosen in accordance to the recommendations of the Catt Acoustics Manual [31]. The scattering is the same for all surfaces and is shown in Table 3.2.

| **Scattering coefficient s** | | | | | |
|---|---|---|---|---|---|
| 125 Hz | 250 Hz | 500 Hz | 1000 Hz | 2000 Hz | 4000 Hz |
| 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 |

**Table 3.2:** Scattering coefficients for all surfaces used in Catt simulation.

The diffraction settings are set to account for direct diffraction, diffraction followed by surface reflection and surface reflection followed by diffraction. Diffraction into diffraction is not accounted for, because of simulation time challenges.

The number of threads (rays) from a source is set to 12 million, as suggested by the program. Air absorption is enabeled, the temperature is set to 15 degrees, humidity is set to 40% and the density of air is set to 1.2 $\text{kg/m}^3$

A picture showing the Catt Acoustics simulation scenario is shown in Figure 3.13. The sources are colored in red, while the receiver is colored in blue. For simulations of a point source, only the source in the centre, labeled A0 in Figure 3.13, is used. The line source simulations accounts for the sound from the other sources as well. A facade with a balcony is placed along the x-axis, at y = 10. The facade is 40 meters wide and 20 meters tall.

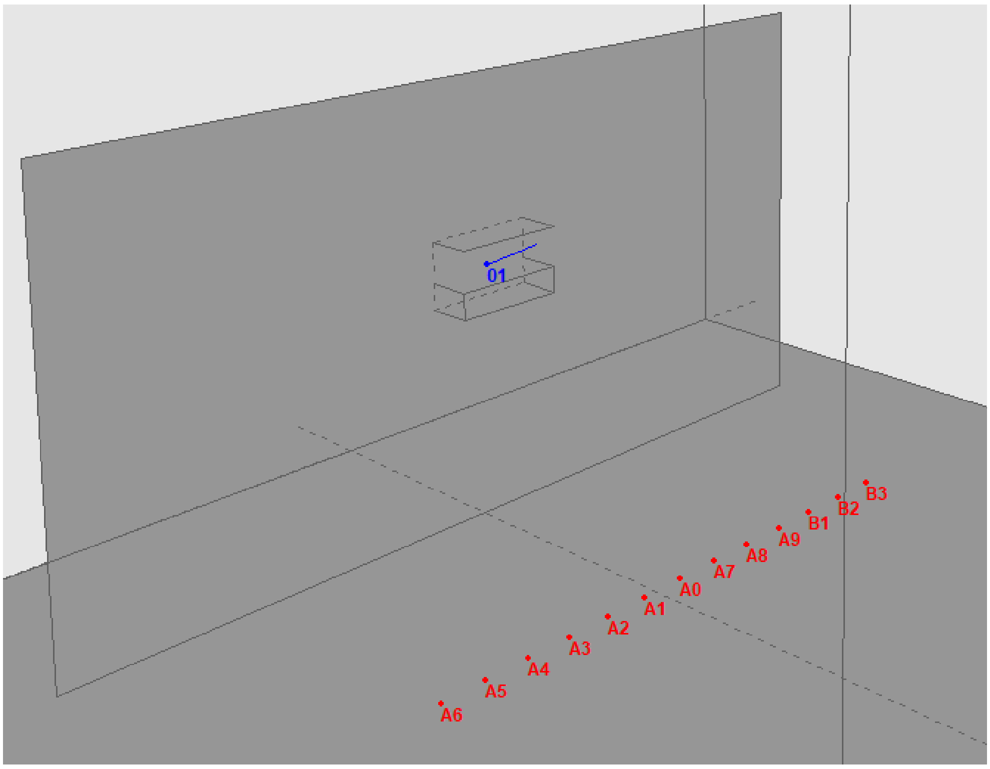



**Figure 3.13:** Screenshot of the facade, balcony, receiver location and line source position in Catt Acoustics.

### Point source

When evaluating the effect of a single point source, the source is positioned 1 meter above ground 10 meters in y-direction from the balcony parapet, at $\mathbf{x} = (0, 22, 1)$. The source is of directivity type "OMNI.SD0" (omnidirectional), pointing towards the middle of the balcony and has a flat frequency spectrum. Rather than measuring the SPL at the receiver location shown in Figure 3.13, the sound pressure from the point source is measured in 3 different heights and 4 different x-positions across the area of the facade behind the balcony, for a total of 12 measurement positions. The receivers are placed at 1 meter distance from one another and have 0.5 meters distance to the facade wall as well as at least 0.5 meters distance to any other adjacent surface. Each receiver gives SPL values in octave bands, as well as an A-weigthed sum of SPL. The sound pressure level of each octave band and the A-weighed sum is retrieved and converted to sound pressure in Excel. Then, the sound pressure calculated across the facade is averaged and converted into single octave band values and a single A-weighed sum.

Finally, post-processing and plotting is done in Matlab.

#### Line source

In addition to the single source scenario, a scenario of a line source has been simulated. The line source consists of a line of 13 point sources positioned 1 meter above ground with 2 meters distance between each other, as shown in Figure 3.13. The sources are incoherent, are of directivity type "OMNI.SD0" (omnidirectional) and the aim position is at the middle of the balcony. The line of sources is placed parallel to the building facade ten meters from the balcony front parapet, with the centre of the line at the centre of the front parapet.

For simulations of line sources, the sound levels have only been calculated at a single receiver position in the middle of the facade, due to simulation time challenges. This have the advantage of allowing to easily save the impulse response from the calculation, which permits more in-depth post processing to be made. The receiver is located at $\mathbf{x} = (0, 10.5, 11.5)$, so that it is in the middle of the balcony, 0.5 meter from the facade. The receiver is omnidirectional and is facing towards $\mathbf{x} = (0, 11.5, 12)$, in other words towards the gap between the front of the balcony parapet and ceiling.

In order to import the data from each source contribution to the receiver, a Matlab script is used. The impulse generated from each source is imported to the script. The script summarize the sound pressure contribution from each source, applies frequency weighting equivalent to the "Road" in Figure 3.9, and calculates summarized octave band values and the A-weighted sum of sound pressure level.

## 3.3 Estimating insertion loss of balcony without ceiling using 517.521

NS-EN ISO 12354-3 [13] is a Norwegian standard for calculating sound insulation against outdoor noise. Appendix C of the standard describes the expected effect of a balcony with absorbing ceiling. According to the standard, the sound reduction caused by the balcony compared to having no balcony is determined by the absorption coefficient of the ceiling and of the height of the line of sight from the source to the facade, as shown in Figure 3.14.

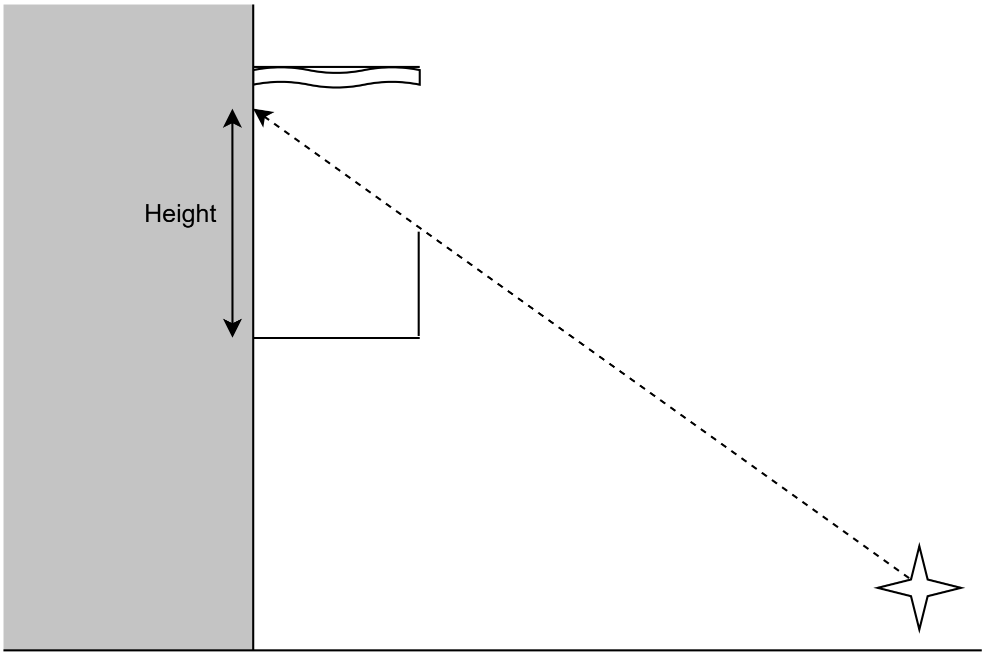



**Figure 3.14:** Illustration of the height of the line of sight.

The line of sight for the balconies in 2nd and 4th floor have been calculated according to the dimensions of Figure 3.4.

## 3.4 Estimating SPL reduction of balcony with absorbing ceiling using ISO 12354-3

Guideline 517.521 of *Byggforskserien* [12] can be used for calculating the insertion loss of barriers. As the parapet, when closed, essentially is a barrier, the guideline can be used to calculate the screening effect of a closed parapet balcony. However, as the ceiling plays an important role for the sound level at balconies, the calculation model is likely accurate only for balconies without ceilings.

The parameters used for calculation is shown in Figure 3.15.

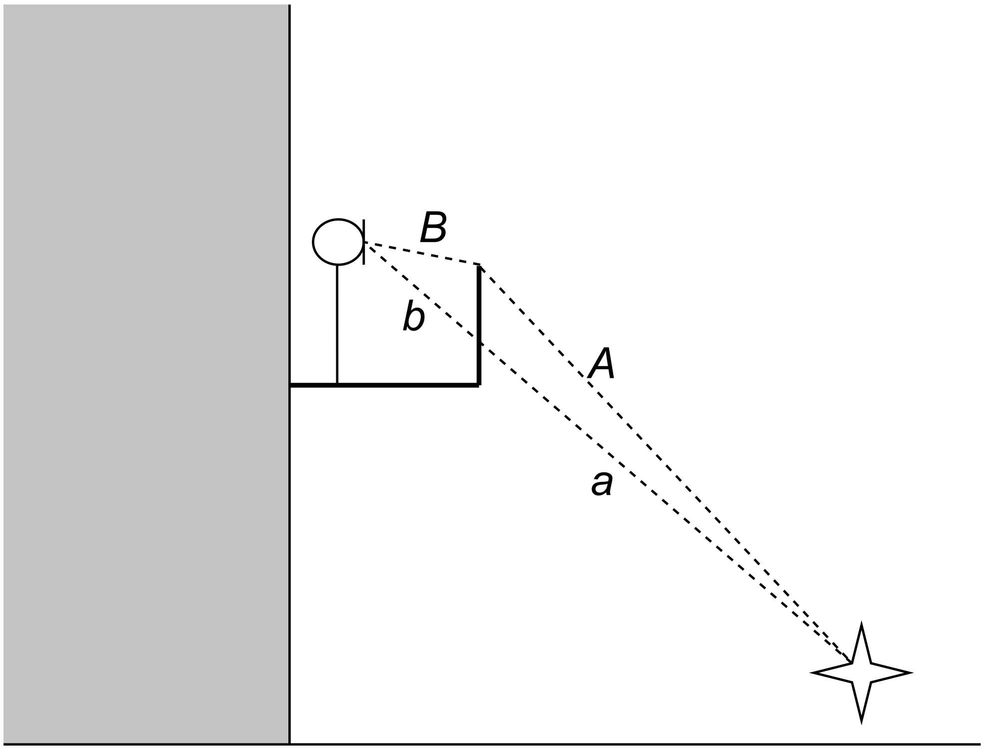



**Figure 3.15:** Illustration of the path length of the direct path and the diffracted path.

The guideline gives an insertion loss for different octave bands with a formula based on the detour, here called Δ, and frequency. Δ is given by

$$\Delta = A + B - a - b \tag{3.1}$$

The parameters $A$, $B$, $a$ and $b$ have been chosen to match the distances from the loudspeaker to the microphone at the facade of the 6th floor balcony in Figure 3.4.

# Chapter 4

# Results

First, the results of the measurements at the balconies is presented, with an emphasis on relative sound level reduction. Then, the results from the estimates of SPL reduction at the balcony facade by Catt and Nor96 is shown and comparisons to the applicable measurements is made. Additionally, the deviation between the two simulation methods across all simulation variants and a comparison of SPL distribution across the facade is presented. Finally, the estimates using guideline 517.521 and ISO 12354-3 is shown and compared to the measurements.

## 4.1 Measured SPL reduction at balcony facade compared to outside of parapet

The A-weighted, calibrated sound pressure levels measured at the 2nd, 4th and 6th floor of a point source and line source is shown in Figure 4.1. The sound level of the absorbing ceiling have been adjusted according to the difference of the sound level between the measured level outside the parapet on the different measurement dates. The line source curve is based on averaged data from bypassing metros.

As seen in Figure 4.1, the line source shows a higher SPL reduction in the 4th floor than the 6th floor. This may be explained by differences in the measurement method, as the microphone measuring the line source in the 4th floor was taped to the parapet, instead being positioned above the parapet 2 meters from the facade. According to NS-ISO 1996-2 [32], measurements done at a rigid surface should have a correction of +6 dB to get to free field conditions, while measurements done at between 0.5 and 2 meters from a rigid surface may need a correction of up to +3 dB to get free field conditions. Subtracting +3 dB correction on the 4th floor measurement outside the parapet, due to the microphone being taped to a surface rather than to be positioned above the parapet 2 meters from the facade, may give a more accurate comparison. This correction will be applied for all future comparisons and plots.

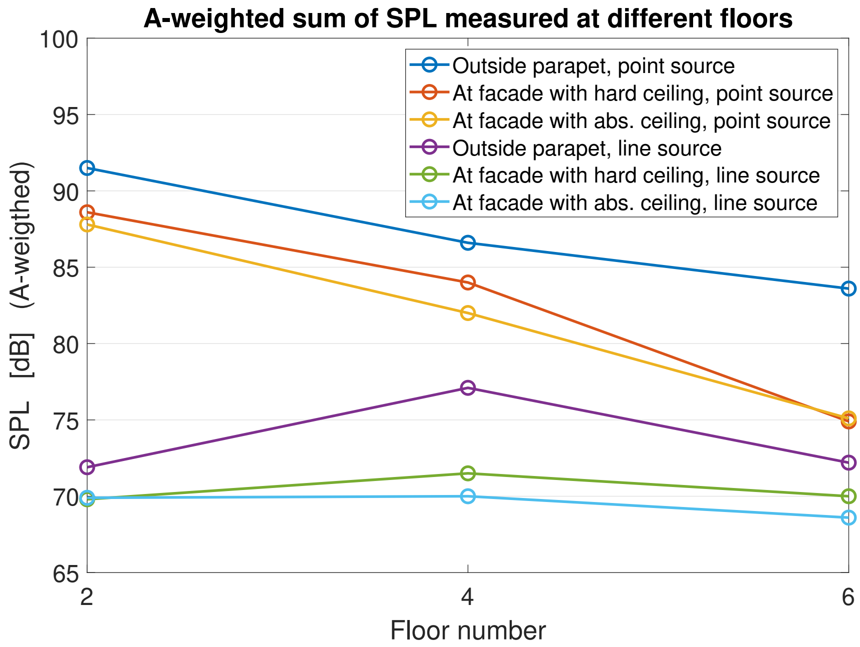



**Figure 4.1:** The A-weighted, calibrated sound pressure levels measured at different floors.

For future comparisons, the balcony in the 4th floor will be used when considering a balcony with hard or absorbing ceiling, while the balcony in 6th floor will be used when considering a balcony with no ceiling. In Figure 4.1, the A-weighted SPL reduction of the 4th floor balcony compared the SPL outside the parapet in the case of a point source is 2.9 dB for a hard ceiling and 4.6 dB for an absorbing ceiling. The 6th floor balcony with reduced ceiling has a sound reduction of about 8.5 dB when exposed to a point source at the facade compared to outside the parapet.

For a line source the difference is 3.1 dB for a hard ceiling and 4.2 dB for an absorbing ceiling, after corrections due to the microphone being taped to the parapet. The balcony without a ceiling results in a sound reduction by the line source of 3.6 dB for an absorbing ceiling and 2.2 dB for a hard ceiling.

The octave band sound reduction of the sound level at the facade compared to the sound level outside the parapet for a hard ceiling balcony and absorbing ceiling balcony is shown in Figure 4.2 for a point source and 4.3 for a line source. For full 1/3 octave band values of all the measurements in all floors, see Appendix C.

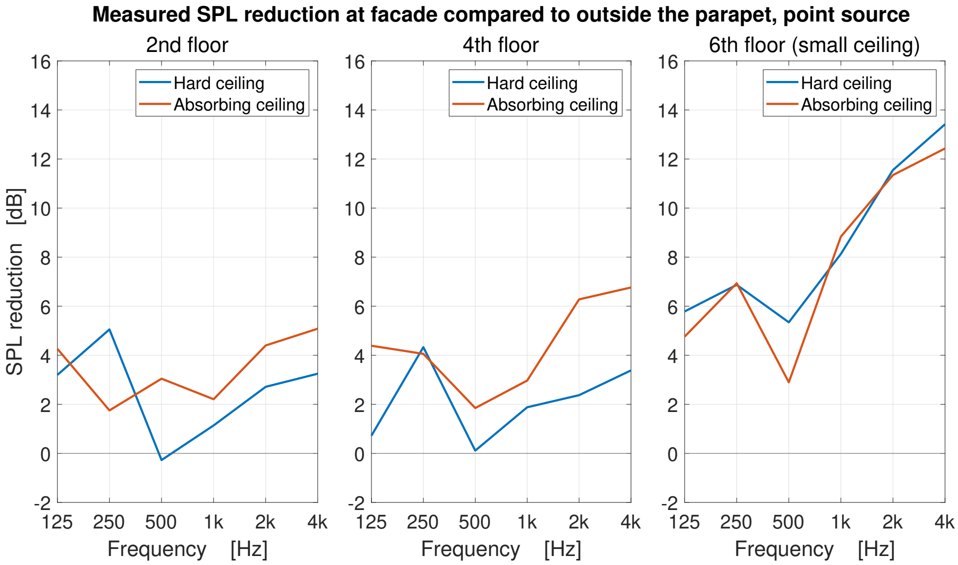



**Figure 4.2:** The octave band sound pressure reduction at the balcony facade compared to outside the parapet, measured at different floors when exposed to point source.

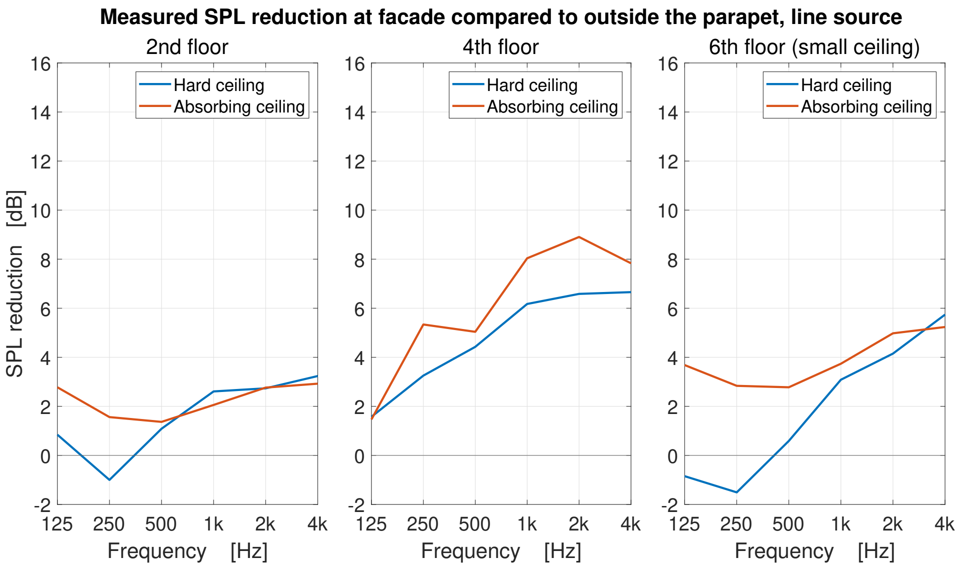



**Figure 4.3:** The octave band sound pressure reduction at the balcony facade compared to outside the parapet, measured at different floors when recording during metro passages.

## 4.2 Estimated SPL reduction at facade

### 4.2.1 Catt acoustics calculation

For post-processing of the line source signal, the spectrum of impulse responses calculated by the receiver in Catt acoustics shows the unweighted frequency response. In order to get accurate octave band values the spectrum is smoothed, as shown in Figure 4.4. The octave bands levels estimated from the smoothed curve of the spectrum is then applied A-weighing, as well as the spectrum weighing of a road line source that was shown in Figure 3.9. The smoothed line covers the frequency range from 100 to 5000 Hz, which allows extraction of the octave bands within this region.

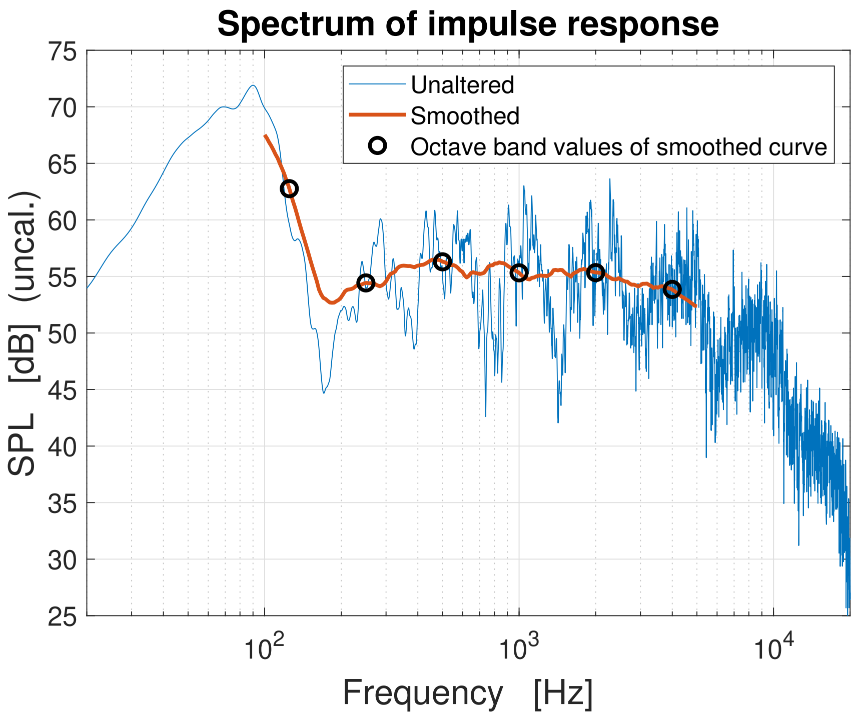



**Figure 4.4:** Spectrum of impulse response of hard surfaced balcony measured in Catt Acoustics[1]. The blue line shows the unaltered spectrum, the orange line shows a smoothed line of the unaltered spectrum, and the black dots are the octave band values measured along the smoothed spectrum line.

### 4.2.2 Nor96 calculation

Using the mirror source method to include the effect of the roof, the individual contribution of the ceiling reflection and the direct or diffracted waves from the

[1]The smoothed curve is made using a function provided by Peter Svensson.

ground source is easily comparable. Such a comparison is shown for a hard surface balcony in Figure 4.5.

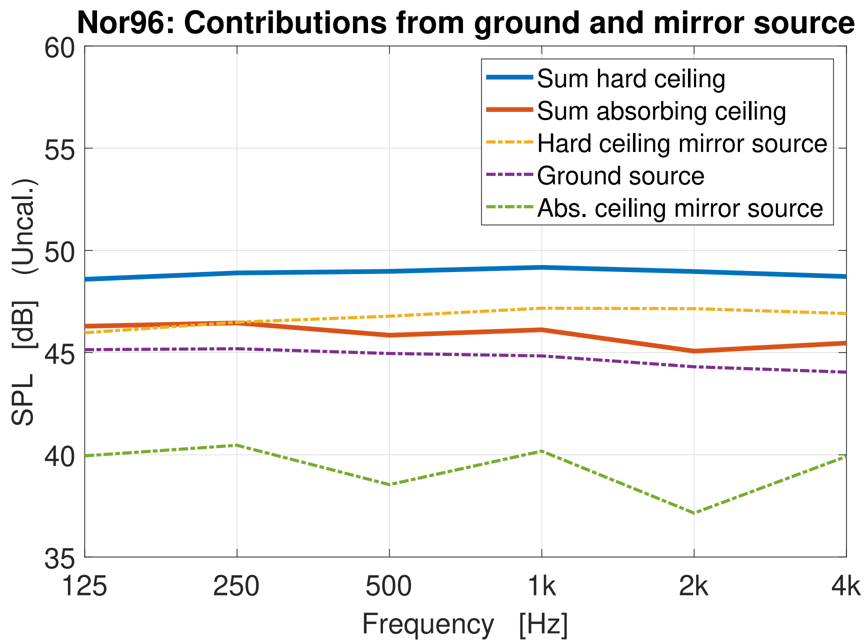



**Figure 4.5:** The average SPL generated at the facade behind the balcony for a point source in Nor96, with contribution from the ground source and the mirror sources for hard and absorbing ceiling being shown.

### 4.2.3 A-weighed SPL reduction

The A-weigthed sound level generated by a point source calculated across the facade in Catt and using the Nor96 prediction method is compared. The comparison of the sound reduction of the various balcony variants listed in Figure 3.8, in comparison to any similar measurements, is shown in Figure 4.6. Because the focus of the thesis revolves around the relative sound level reduction of the balcony, the measured and calculated SPL have been normalized to 75 dB for the facade with no balcony, and the remaining values have been adjusted accordingly. As the measurements were conducted at different dates, in order to account for meteorological variations, the sound level were measured outside the balcony parapet on both occasions and normalized to 75 dB. For the balcony with no ceiling, data from the measurements done at the 6th floor balcony is used, while for balcony with hard surfaces and absorbing ceiling, data from measurements done at the 4th floor balcony is used.

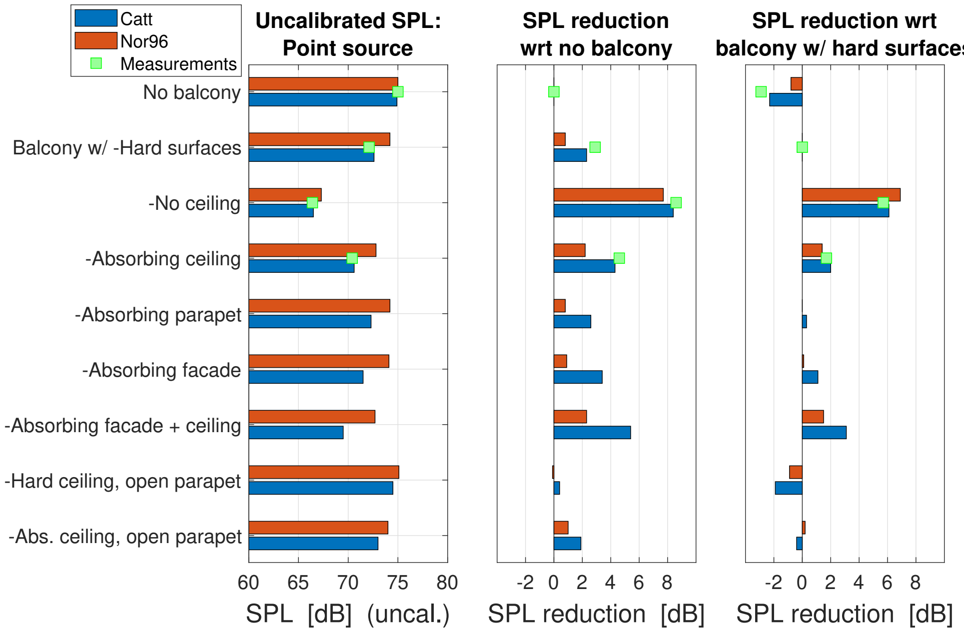



**Figure 4.6:** Comparison of the sound level generated by a point source across the facade of a balcony between Catt acoustics (blue) and Nor96 (orange) and what is measured with a microphone sweeping across the facade (green). Left: Average calculated A-weighted sound pressure levels across the facade, adjusted to 75 dB for no balcony. Middle: Relative sound pressure level reduction of different variants with respect to having no balcony. Right: Relative sound pressure level reduction of different variants with respect to having a closed parapet balcony with only hard surfaces. For example, row 3 in the plot to the right shows the SPL reduction of having a hard surfaced balcony with no ceiling compared to having a balcony with hard walls and ceiling.

### 4.2.4 Frequency dependent SPL reduction

A comparison between the measured and, using Nor96 and Catt acoustics, calculated sound reduction achieved by inserting a hard surfaced balcony to a facade without a balcony. A comparison between the measured and calculated effect of replacing a hard ceiling in a hard surfaced balcony with an absorbing ceiling is shown in Figure 4.8.

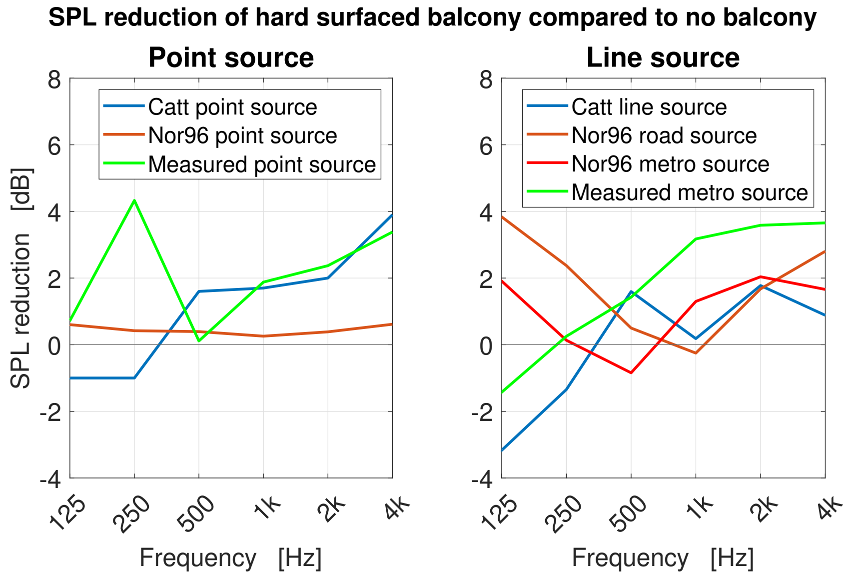



**Figure 4.7:** The SPL reduction in octave bands of having a facade with a hard surfaced balcony compared to a with no balcony.

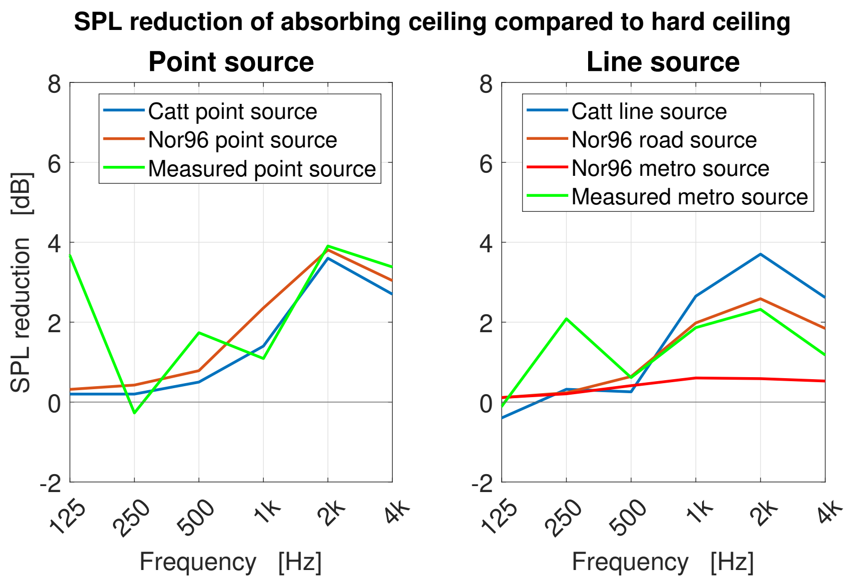



**Figure 4.8:** The SPL reduction in octave bands of having a balcony with absorbing ceiling compared to a balcony with only hard surfaces.

The frequency dependent deviation between the two prediction methods is shown in Figure 4.9. The deviation shows the difference in SPL of balcony with hard surfaces compared to all other variants, as in the right plot of Figure 4.6.

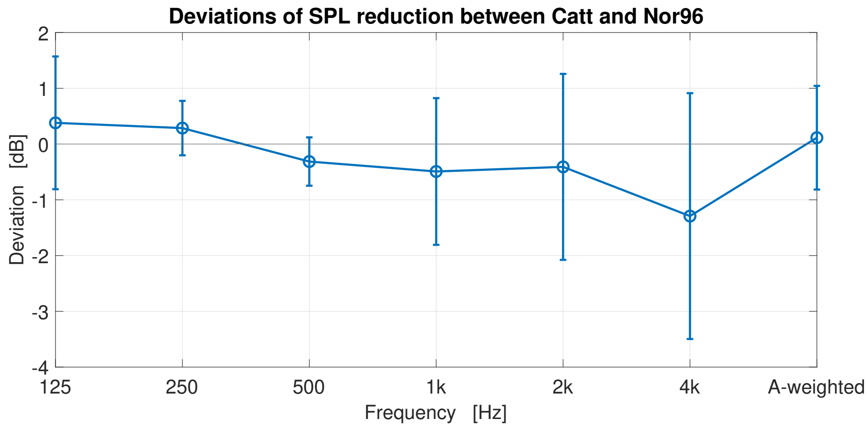



**Figure 4.9:** The frequency dependent deviation between the SPL reduction of Catt acoustics and Nor96. The SPL reduction is averaged across all the calculated variants of each octave band compared to the SPL of a balcony with hard surfaces, like the right side of Figure 4.6 (excluding the top two rows). Positive values means Catt calculates a higher SPL reduction than what Nor96 does.

### 4.2.5 SPL at different parts of facade

In Figure 4.10 the sound level calculated with a balcony with hard surfaces as a function of height and width of the facade is shown. The figure is made by importing the sound pressure levels of different receivers along the facade to a Matlab script that plots the color map of the data. As the focus is on relative sound levels, the sound level of both plots have been normalized to have a maximum value of 80 dB and the remaining values have been adjusted accordingly.

In Figure 4.11 the SPL reduction of replacing a hard ceiling with an absorbing ceiling for a balcony with hard surfaces is shown, as a function of height and width of the facade behind the balcony, in both Catt and CadnaA.

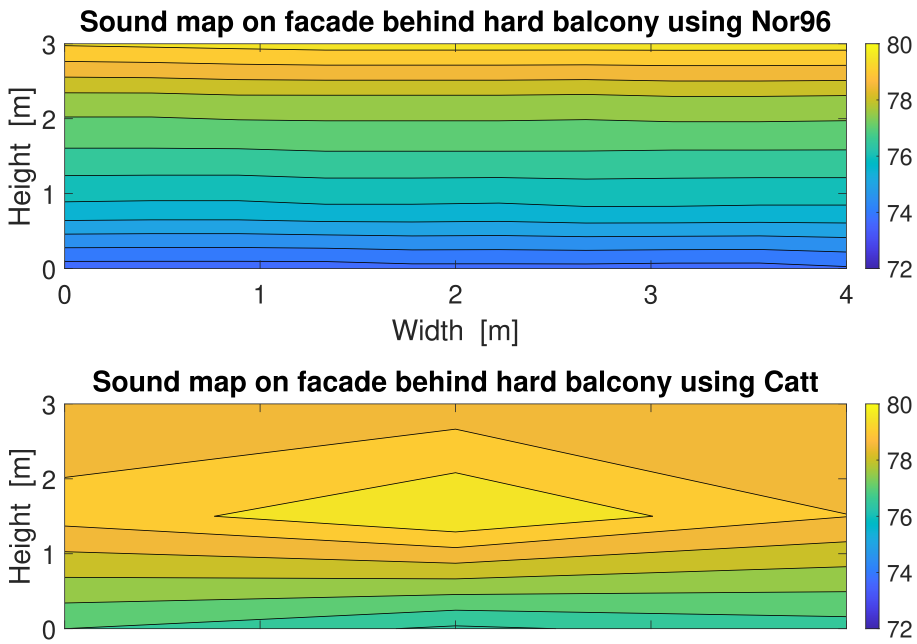



**Figure 4.10:** The SPL at different parts of the facade behind a hard surfaced balcony using Nor96 (top) and Catt (bottom).

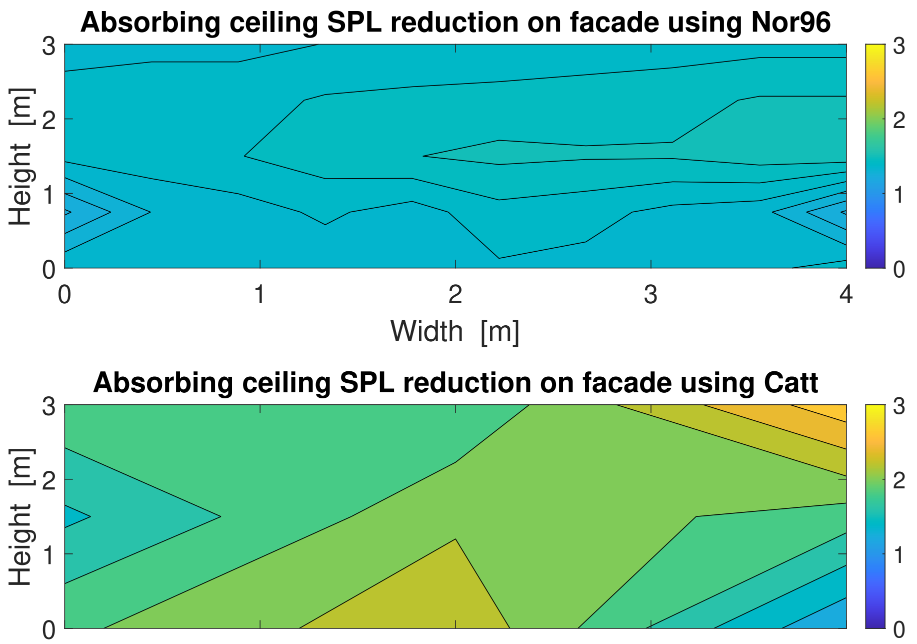



**Figure 4.11:** The SPL reduction of adding an absorbing ceiling at different parts of the facade behind a balcony using Nor96 (top) and Catt (bottom)

## 4.3 Estimated insertion loss of balcony without ceiling using 517.521

Inserting $A = 19.6$, $B = 1.5$, $a = 18.2$ and $b = 2.5$, the detour for the diffracted wave was found to be 0.4 meters compared to that of the direct wave using the method described in guideline 517.521, outlined in Section 3.3. The estimated 1/3 octave band values behind the parapet, compared to the measured values outside the parapet and at the facade in 6th floor, is shown in Figure 4.12. The figure uses the data from the measurements outside the parapet as an estimate of the sound level without a parapet/barrier.

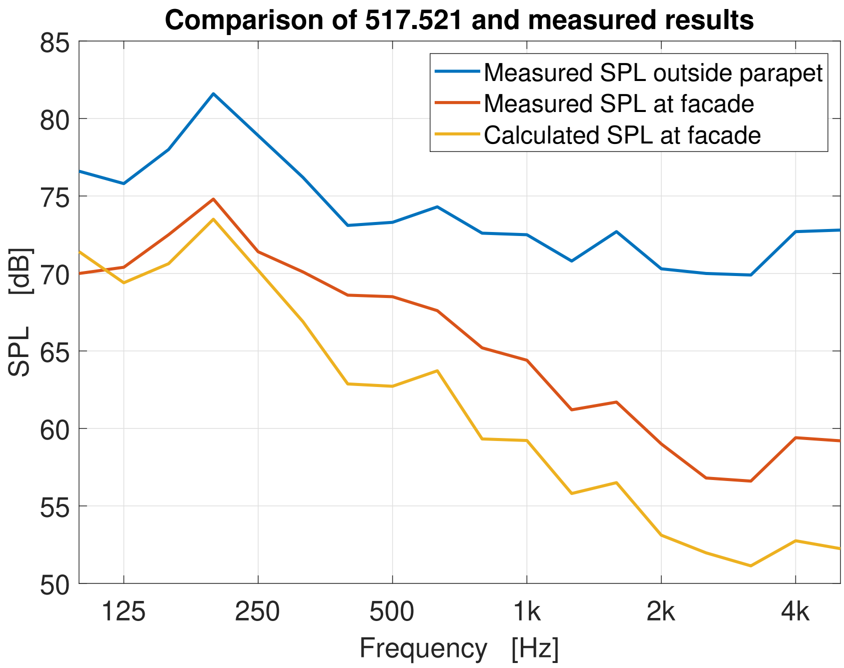



**Figure 4.12:** The estimated 1/3 octave band values of SPL at the facade using guideline 517.521 compared to the measured sound level at the facade and outside the parapet of the 6th floor balcony.

The calculated sum of A-weighted SPL when the barrier is present using 517.521 is 70.8 dB, compared to the measured sound level outside the parapet of 83.6 dB. This means that the calculated insertion loss using 571.521 is 12.8 dB, while the measured SPL difference between the facade and outside of the parapet was 8.5 dB.

## 4.4 Estimated SPL reduction of balcony with absorbing ceiling using ISO 12354-3

The line of sight height explained in Section **??** of the balcony in the 2nd floor was found to be 2.3 meters. According to Appendix C of NS-EN ISO 12354-3, this gives an SPL reduction compared to no balcony of 2 dB for for ceiling absorption $\alpha \leq 0.3$, 3 dB for $\alpha = 0.6$, and 4 dB for $\alpha \geq 0.9$.

In the 4th floor the line of sight was found to be 3.3 meters. According to Appendix C of NS-EN ISO 12354-3, this gives an SPL reduction compared to no balcony of 0 dB for $\alpha \leq 0.3$, 2 dB for $\alpha = 0.6$, and 4 dB for $\alpha \geq 0.9$.

Figure 4.13 show the estimated SPL reduction using linear interpolation between the sound reduction for different absorption factors in Appendix C of NS-EN ISO 12354-3 and the absorption factor of semullit described in Table 3.1, compared to the measured SPL difference.

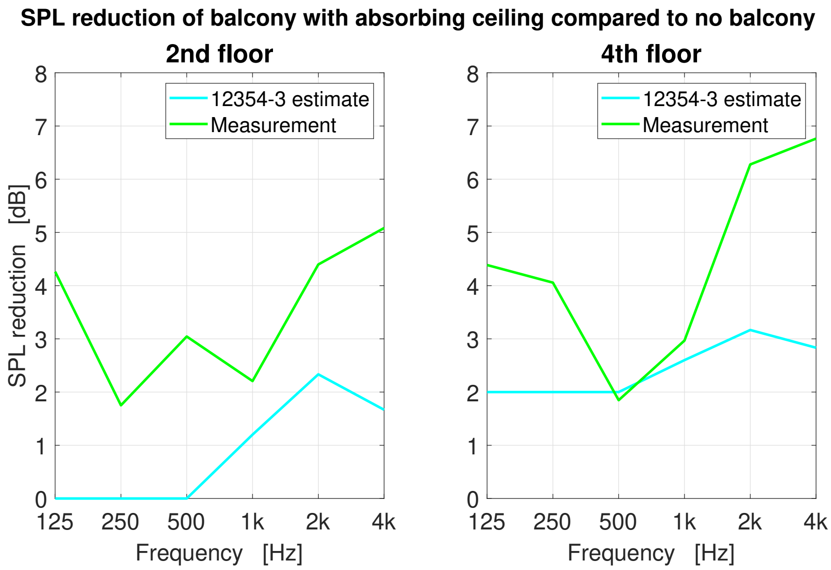



**Figure 4.13:** The measured and estimated SPL reduction for an balcony with absorbing ceiling, compared to no balcony. The estimate is made using linear interpolation between the values of Appendix C in ISO 12354-3.

# Chapter 5

# Discussion

## 5.1 Measured SPL at different floors

The plot of the measurements in Figure 4.2 and Figure 4.3 show that the sound reduction increases with frequency at every floor for both source types. This can be explained by waves of high frequency diffracting less effectively around the parapet of the balcony. This is particularly evident for the point source plot at the 6th floor, which have a slightly higher parapet and also reduced ceiling, resulting in strong SPL reduction for 2k-4k Hz.

It also seems like the difference at the 6th floor between the hard ceiling and absorbing ceiling in Figure 4.2 is very small for the point source, which is to be expected as the ceiling only covers half the balcony. However, the same result is not seen for the 6th floor line source in Figure 4.3, which is surprising. One possible reason is that the sound from the metro hits the balcony at a lower incident angle than what the loudspeaker source does, thereby making the ceiling more noticeable from the source and increasing the effect of ceiling absorption. There could also be some differences in the sound level outside the parapet between the two measurement dates, which is a cause of uncertainty that will be discussed in depth in Section 5.3.1.

## 5.2 Comparison of results

### 5.2.1 SPL reduction compared to no balcony

#### A-weighted SPL reduction

When investigating the improvement caused by inserting a balcony with hard surfaces compared to no balcony shown in the middle column of Figure 4.6, it seems that the calculated screening effect is smaller in Nor96 than in Catt and the measurements. The deviation is varying from 1-3 dB. The correlation between the measurements and Catt seems quite good, with less than 1 dB deviation at all the compared cases.

For the calculations of a balcony with an open parapet, the difference between the two estimation methods is slightly smaller, less than 1 dB. It therefore seems that Catt calculates a greater shielding effect of the parapet than what Nor96 does.

**Frequency dependent SPL reduction**

As seen in Figure 4.7, the point source measurements have a good octave band correlation with the estimate of Catt acoustics, except from the lowest octave bands, where Catt seemingly underestimates the screening effect. Nor96 have a good correlation to the measurements at low frequencies, aside from the spike at 250 Hz, but underestimates the screening for higher frequencies. The spike in SPL reduction measured from the point source at 250 Hz seems out of place, and may be due to variations in background noise, as the screening effect of the parapet should be lower for low frequencies due to diffraction. This is also supported by comparing the measured SPL reduction of the point source to the line source, where no such spike occurs at 250 Hz.

The line source estimates in Figure 4.7 shows a good correlation between Catt simulations and measurements for low frequencies. For higher frequencies, however, the measurements show a greater SPL reduction. The estimates made by Nor96 surprisingly calculates higher SPL reduction for lower frequencies than the measurements. The reason for this is not easy to comprehend, as the parapet should have less effect, thus leading to less sound reduction, for low frequencies.

Comparing the estimate from NS-EN ISO 12354-3 with the measured results in Figure 4.13, it can be seen that NS-EN ISO 12354-3 underestimates the SPL reduction compared to what was measured. However, it may be considered a conservative estimate of the smallest expected effect of a balcony with absorbing ceiling, as the standard is meant to be applicable for all balconies. Due to variations in shape, size and surroundings, some balconies may not reduce as much sound as the ones measured in this thesis, thus increasing the sound level at the facade.

### 5.2.2 Effect of balcony without ceiling

The balcony without ceiling gives the by far highest SPL reduction for both the measurements and the estimates by Catt and Nor96, as seen in Figure 4.6. Despite the good agreement of the three results, however, the comparison is not perfect. Firstly, the elevation of the measured balcony without ceiling is greater than the 4th floor balcony, which will give a higher diffraction angle, thus increasing the expected SPL reduction. Secondly, the parapet height of the measured balcony is greater than in the simulations, which again will increase the expected SPL reduction of the measurements. Third, the measured balcony does have a half-ceiling, which likely will reduce the SPL reduction to some degree, although the effect is unclear as the ceiling of the balcony is not in direct sight of the point source. So in sum, there are two factors in the measurements which relative to the simulations should increase the SPL reduction and one factor that should decrease the SPL reduction. However, increased elevation and parapet height may be fairly common attributes for most real-world balconies without ceilings. Considering the metro measurements, the SPL reduction was far less than for the measurements and estimates of the point source, which as discussed in Section 5.1 could be due to the lower incident angle of the sound. It may therefore seem that in most real world situations 8-9 dB attenuation may be a bit too much. However, one could also argue that a "real" no ceiling balcony (without the half-ceiling) can probably reduce the sound with more than 3.6 dB, which was the measured metro SPL reduction with absorbing ceiling in the 6th floor.

Comparing the estimate from guideline 517.521 of the SPL reduction of a balcony without a ceiling in Figure 4.12, it seems like 517.521 overestimates the insertion loss of the parapet compared to the measurements done. This is especially true for high frequencies. The reason for this could be surface scattering at the facade, which would decrease the sound reduction for high frequencies. Since the 517.521 guideline does consider the facade, any effect it has on the sound reduction is ignored. Furthermore, it should be noted that the comparison is not perfectly accurate, as the measurements without a barrier is done outside the parapet, which is closer to the source. Thereby, the calculated detour is effectively higher than it should have been, which may be another explanation of why 517.521 calculates a sound reduction that is larger than the measurement. On the other hand, the facade correction is not accounted for in the estimates done by the guideline, which should increase the measured sound level inside the balcony more than outside the parapet.

### 5.2.3 Effect of absorbing materials

#### A-weighted SPL reduction

Considering the effect of different areas of absorbing material for a balcony shown to the right column in Figure 4.6, it seems like the estimated effect in Catt and Nor96 and the measured effect has a good correlation. The deviation between the three results is 2 dB or less for all variants, which is barely noticeable for human hearing. Catt estimates a higher reduction for the majority of the variants compared to Nor96, and interestingly enough Nor96 calculates very little effect of absorbing facade and absorbing parapet, compared to the hard surfaced balcony.

The Catt simulations gives a good agreement with the measurements for absorbing ceiling, and can therefore be used as a indication of the SPL reduction of other variants, such as absorbing parapet and facade. The simulation of absorbing facade and ceiling gives a SPL reduction of 3 dB compared to a hard surfaced balcony, which is 1 dB more than having absorbing panels in the ceiling only. These estimates does however have their limitations in practical implementation. The parapet is for instance usually made of glass, and covering it with absorbing panels would likely subdue the architectural expression. The same can be said for the balcony facade, which typically consist largely of glass due to windows and balcony door. In addition to this, the facade in Catt is made of hard concrete, while the measured balcony had a facade of glass and wood. Because glass and wood have higher absorption factor than concrete [28], the installation of absorbing panels at the facade would likely be less effective in the real world balconies compared to what was calculated in Catt.

In general, the effect of absorbing material seems a bit low in both the measurements and the simulations, compared to what is found of earlier research in Section 1.2. For example, the field measurements by May [10] found an attenuation of 4-5 dB by treating the ceiling with absorbing material, compared to the attenuation of 1-2 dB that has been found in this thesis. It is possible that using a material of higher absorption factor, or choosing a better installation approach, could yield better results. In Figure 5.1 the absorption coefficient $\alpha$ expected for installing the ceiling absorbent directly on the concrete (which is what was done for the balconies measured) compared to placing a 50 mm thick layer of mineral wool between the concrete and the absorbent is shown. At the expense of 5 cm of ceiling height and the cost of additional material, the sound reduction could likely be improved by another 2-4 dB, which could be what makes the difference in fulfilling the indoor sound requirements in noise exposed dwellings. Doing so would likely give better SPL reduction for absorbing materials at other surfaces also.

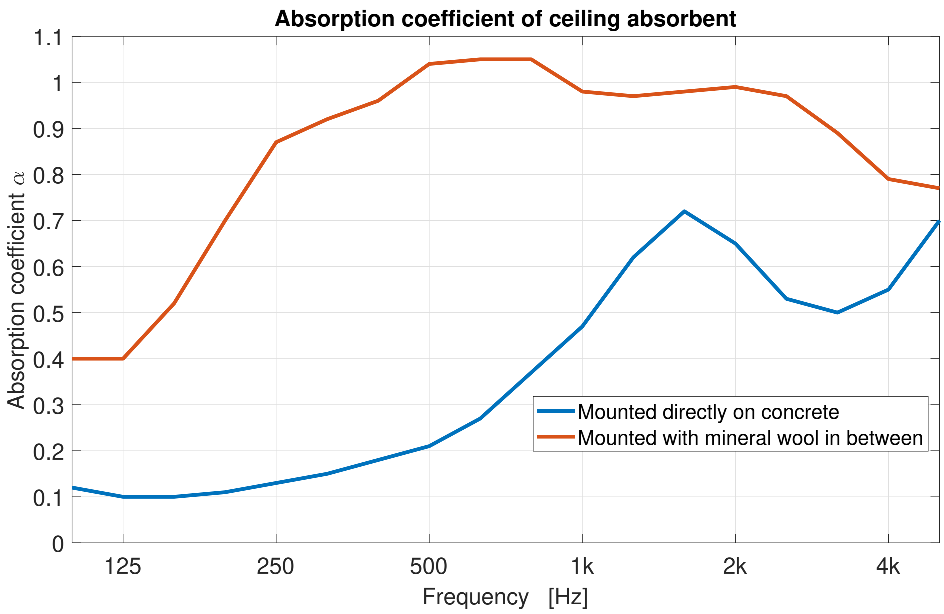



**Figure 5.1:** The absorption factor of the installed configuration compared to the absorption factor of a configuration with mineral wool between the ceiling absorbent and the concrete. The graph is made based on information found at the producers website, troldtekt.com.

**Frequency dependent SPL reduction**

Comparing to the measured and simulated values in Figure 4.8, it can be seen that the sound reduction is much higher in the measurements for the 125 Hz octave band. This is possibly an error caused by external factors, as the absorption factor of the ceiling is only 0.1 at this octave band. However, at higher frequencies, there is a strong correlation between the measurements and both simulation methods, and the SPL reduction seems to follow the absorption coefficient of semullit in Table 3.1 fairly well.

For the line source in Figure 4.8, the measurements show a spike at 250 Hz that the simulations does not. This is odd, particularly when considering the measurements were done over at least 30 minutes. One explanation may be the possibility of significant variations in the frequency of the background sound levels during the metro passages on the different measurement dates. Another explanation may be that the microphone position deviated slightly on the different measurement dates, causing modal variations, which will be discussed in greater depth in Section 5.3.1. For higher frequencies, the measured SPL reduction of the metro is close to that of the line source Catt and road source in Nor96, but the Nor96 metro source calculates too low a SPL reduction compared to the measurements. This could have something to do with the mirror source implementation of the line source in CadnaA, which will be discussed in Section 5.3.2.

### 5.2.4 Deviation

The deviation of SPL reduction in Figure 4.9 suggests that while Catt calculates higher sound reduction for the lowest frequency, Nor96 gradually calculates higher SPL reduction than Catt as the frequency increases. Moreover, the standard deviation increases with frequency. One possible explanation for the deviations at higher frequencies could be that Catt accounts for scattering, which as defined in Table 3.2 increases with frequency. This will reduce the screening effect of the parapet in Catt for higher frequencies.

It seems strange that Catt calculates a slightly higher A-weighted reduction on average when considering that for most of the octave bands, Nor96 calculates a higher SPL reduction. Moreover, the octave bands at 2kHz and 4 kHz, which is the region human hearing is the most sensitive to, is clearly in favor of Nor96 in terms of SPL reduction. One possible explanation could be differences in the calculation methods between the two. Catt gives the octave bands from 125 Hz to 16 kHz, while Nor96 gives the octave bands from 63 Hz to 8 kHz, which may mean that different octave band regions are considered in the A-weighted sum.

### 5.2.5 Sound level at different parts of facade

Figure 4.10 shows that the sound level is highest in the top of the facade in Nor96, while in Catt the sound level is highest in the middle of the facade. This may suggest that the strength of the mirror source, which is closer to the top of the facade than the bottom, is over-represented compared to that of the ground source. Oddly, there are no significant variations in the horizontal direction in CadnaA, despite the signal being generated for a point source.

Figure 4.11 shows that the SPL reduction of an absorbing ceiling at different points of the facade varies more in Catt than in Nor96. Nor96 seemingly calculates slightly greater screening effect in the middle of the facade, while it is hard to identify any specific pattern in Catt. It should however be noted that the microphone resolution in Catt is lower that that of Nor96, which could impact the results somewhat.

## 5.3 Uncertainties

### 5.3.1 Measurement uncertainties

As the focus of the thesis is the relative sound reduction of different configurations, the uncertainty of the measurements will solely be described in terms of factors that can cause variations between the measurements. In general, the uncertainty is likely higher for the metro source measurements, as these measurements were only done at a single, stationary location for each balcony and could therefore be affected by modal variations to a greater degree.

#### Measurement positions

As shown in Figure 3.4, the distance from the loudspeaker to the microphone position outside the parapet of the balcony of 2nd, 4th and 6th floor is 10.5 m, 14.6 m and 19.7 m, respectively. The respective measured sound levels at these positions are 91.5 dB, 86.6 dB and 83.6 dB. Given that the loudspeaker has a source power level of 100 dB, the expected free field sound level at these positions when accounting for geometrical divergence given Equation 2.1 is respectively 88.6 dB, 85.7 dB and 83.1 dB. Comparing the measured SPL with the expected free field values, the difference compared to the expected free field values is smaller the higher the balcony elevation becomes. It therefore seems like the contribution from facade reflections is higher for lower floors. This could have something to do with the balconies on the facade prevent reflections from reaching the upper floors. On the higher floors, the incident reflection angle get larger, which can cause more sound to get blocked by the balcony ceiling of the lower floors, thus reducing the reflected sound reaching the receiver position.

For the measurements done at the facade, the distance between the microphone and the facade is approximately 0.5 meters. According to NS-ISO 1996-2 [32], measurements done at this distance may need a correction of up to 3 dB to get free field conditions. The measurements done outside the parapet is done at approximately 2.5 meters from the facade and 0.5 meters from the parapet. In an ideal world, measurements would instead have been done 0.5 meters from the same facade at the same position with no balcony present. This would remove the uncertainty caused by reflections from the facade. NS-ISO 1996-2 does not define any correction on measurements done at more than two meters from the facade. However, it also seems unlikely that measurements done at 2.5 meters distance could be considered free field. Moreover, there would probably be some reflections from the parapet, which is made of thick glass.

Another factor to consider is that the measurements done outside the parapet is slightly closer to the source than the measurement position at the facade. This serves to counteract the facade contribution by increasing the sound level. For the balcony at the 4th floor, the difference in distance from the facade position to the source and the parapet distance to the source in Figure 3.4 is 1.3 meters. This is a 9 % increase in distance, which translates to about 0.7 dB additional loss due to geometrical divergence according to Equation 2.1.

The last factor to consider in terms of measurement positions is deviations in placement or locations of microphone sweep. For the sweep measurements the variations in the distance between the microphone and the facade during facade measurements could likely a impact on the measured sound level, however due to the reflection of the ceiling, this may not be as significant as for a plain facade, as discussed in [26]. For the metro measurements, the uncertainty caused by variations in placement is likely greater. The microphone is stationary placed, which makes it more susceptible to modal variations. The balcony can be considered a half-open room, as the parapet does not go all the way up to the ceiling, which makes horizontal modal variations negligible. However, vertical modal variations caused by variations in the microphone height is a possibility, as responses can develop between the floor and the ceiling. This is something that can cause uncertainties at certain frequencies due to standing wave patterns between the floor and the ceiling, which can have significant impact on the sound level when the microphone elevation changes.

#### Meteorological effects

There were some meteorological variations in the conditions of the measurements. However, as the distance from the point and line source to the balcony is relatively short, the uncertainty caused by meteorologic effects is probably negligible.

#### Measurement equipment

The calibration files for recorder #14, that was used for the point source measurements at the first measurement date, shows a measured SPL of 113,9 dB before the measurements and 113,8 after the measurements. For the second measurement date, the same recorder shows calibration levels at 113,5 before the measurements and 113,8 after the measurements. As these deviations are below 0.5 dB, the sound levels are in accordance to ISO 1996-2 [32] reliable, but some deviations due to measurement equipment still can still be a factor for uncertainty.

As different microphones were used for the different positions and floors during metro measurements, this could be a source of uncertainty for the metro measurements. The calibration data for the various microphones vary from 113.4 dB to 114 dB, so the deviations are likely at 0.6 dB or less.

### Source variations

As two different loudspeakers were used, the loudspeaker signals could differ, despite the loudspeakers being of the same type and on paper having identical frequency response. As seen in Figure C.1 in Appendix C, the sound level deviates quite a bit outside the parapet between the two measurement dates. One reason for this, which could be a source of uncertainty, is the change of loudspeaker.

The source signal generated by the metro could deviate a bit from the two measurement situations due to variations in the passage speeds and differences in the conditions of the metros. However, it is believed that as the data used is the average of at least 7 passages, the variations are relatively small. As can be seen in Figure C.2 in Appendix C, the shapes of the frequency responses of the hard surfaced balcony done during the first measurement day is pretty similar to the shapes of the measured level in the balcony with absorbing ceiling during the second measurement day, which indicates that the generated SPL from the source have not changed much frequency-wise. However, as no measurements were done outside the parapet during the first measurement day, there is no direct comparison of the absolute sound levels, which is a cause for uncertainty of the SPL reduction of having a hard surfaced balcony compared to no balcony.

### Background noise

The road behind the metro created a lot of constant noise at the balconies, particularly the ones at the higher floors. Constant noise is not going to affect the sound level difference measured, however the traffic could vary. Also, due to the road being around 100 meters or more away from the balconies, the meteorological differences between the measurement dates could start to play a role at the background sound level. In addition to the road traffic, there were a bit of periodic noise from the construction site itself. The background sound level recorded at the facade was found to be 66 dB 66,6 dB and 65,6 dB on respectively the 2nd, 4th and 6th floor during the first measurement day, while it was found to be 64.8 dB, 64.9 dB and 63 dB on the second measurement day. The absorbing material likely have some impact on the measured background level, since the comparison of background noise was done at the facade rather than outside the parapet.. Recordings were paused during periods of excessively high sounds, but there were likely still background noise affecting the recordings and creating deviations at the background level of different measurements. This is particularly relevant for the point source measurements, as these were not done simultaneously, and were done over shorter amounts of time. However, even for the line source noise from the construction site could cause uncertainty or error in measured SPL reduction, as some of the noise came from higher floors in buildings next to the building where the measurements were done, thus ignoring the effect of the parapet and likely increasing the sound level at the balcony more than outside the parapet.

### 5.3.2 Nor96 uncertainties

#### Number of reflections

When implementing Nor96 in CadnaA, one factor limiting the potential accuracy is the number of reflections the program will take into consideration when performing the calculations. In the simulations eight reflections were used. A reference simulation of 14 reflections were also made to investigate whether increasing the number of reflections would have an impact on the results. While the simulation duration increases exponentially with the number of reflections, the result indicates that the extra reflections have little impact on the results. The deviation between the simulation with 8 reflections and the same simulation but with 14 reflections was found to be approximately $\frac{3}{1000}$ dB. It therefore seems that the number of reflections is high enough to not be a relevant cause of inaccuracies in the simulation.

#### Mirror source

The mirror source implementation in CadnaA of the Nor96 prediction method is not really ideal as it entails a lot of potential errors, which will be discussed in depth in the following paragraphs. Despite this, the results of the simulations show that the effect of the mirror source is consistent to that of the simulated ceiling in Catt. A conclusion may therefore be drawn on average the results of the mirror source can be considered to be somewhat accurate in mimicking the effect of an actual ceiling.

The mirror source implementation used to account for the ceiling of the balcony is not a perfect mirror of the original signal, as it does not account for the effect of the ground. Investigating the sound pressure level at different parts of the facade close to the balcony reveals significant deviations of the contribution of the mirror source compared to the contribution of the ground source. For the point source and road line source, the sound pressure level generated by the mirror source is respectively 1 dB and 0.5 dB lower than that of the ground source. This is likely due to the fact that the ground close to the balcony is reflecting, making the sound pressure level from the ground source amplified. The metro line source has a sound level of the ground source that is 3 dB lower than that of the mirror source. One reason for this could be that the area around the metro is soft, absorbing ground, which will only have an impact on the ground source. Furthermore, the metro lies in a ditch at the bottom of a slope leading up to the construction site where the balcony is located. The slope is steep enough to make certain parts of the metro line source to get blocked off from the direct transmission path to the balcony. This can cause a significant portion of the signal generated by the ground source will get absorbed by the environment, thus lowering the sound pressure level.

Another problem with the mirror source is the risk of unwanted reflections from the surrounding buildings around the balcony. The easiest fix may be to simply have an absorption factor of 1 for all surrounding building elements, but as the balcony is located at a relatively great distance from the nearby buildings it is likely not a great issue.

As there is no ceiling, another issue is that the estimation is not able to calculate the ray path of rays going down to the balcony floor and up to the ceiling again. This limits the amount of relevant reflections of the mirror source simulations. This issue could be partially solved by flipping the model, causing the ceiling to become a wall and one side wall to become the floor, with the unfortunate issue that the other side wall would not have an effect in the calculation method. However, this may not have a great impact compared to not being able to account accurately for the ceiling. As both earlier studies and the results of the estimations and measurements done in this thesis indicate, the ceiling is the most important surface of reflection in balconies, and may therefore be preferable to have in place over the side-wall of the parapet. The disadvantage of such a configuration is that it does not allow to import the model of actual dimensions that were used in the simulations.

#### Floor reflections

Nor96 does not, with exception of the ground, account for reflections of horizontal surfaces. This has the unintended effect that the floor of the balcony in CadnaA is effectively always absorbing. This should in theory increase the SPL reduction of a hard surfaced balcony compared to no balcony, however as was seen in the middle of Figure 4.6, the reduction is greater in Catt and the measurements than Nor96. This suggest that it does not have a major effect on the result, and/or that the effect can be considered corrective in terms of minimizing the difference between the results.

### 5.3.3 Catt Acoustics uncertainties

#### Scattering

Using the scattering coefficients shown in Table 3.2 for all surfaces is likely quite simplified. For example, the facade which in real life consist largely of bricks, likely have a somewhat higher scattering due to the irregular shape of brick facades. Additionally, the other balconies that were located at the facade in the measurements would be a source of scattering. A higher scattering at the facade around the balcony would increase the sound level inside the balcony, thus reducing the effect of the parapet or absorbing ceiling. However, a significant part of the facade, as well as the parapets, consists of glass. Glass would likely would have a lower scattering coefficient than what is given in Table 3.2, as the surface of the glass is very smooth. Therefore the scattering of the facade in Table 3.2 could be considered as a suitable average.

The ceiling consist of either unpainted concrete or of absorbing panels, depending on the situation. These materials probably scatters less than brick and more than glass, which suggest that the values in Table 3.2 may be somewhat accurate. If, however, the real scattering is higher than the values used in the simulations, the result would be that less sound would be reflected specularily and reach the inside of the balcony, resulting in a lower sound level. The opposite is true if the scattering actually is lower: More sound would reach the inside of the balcony, resulting in a higher sound level.

**Line source limitation**

Due to limited simulation time, the amount of point sources in the line source is limited. Ideally, the sources would have been closer spaced and the line would have stretched out over a longer distance, to mimic a true line source more closely. However, tests done with a longer line of sources with the same spacing or with closer spaced point sources indicated little difference in spectrum compared and sound level to the chosen setup.

Another problem with the line source in Catt is that the phase of the sources are not accounted for, as the spectrum for the sum of the sources is generated by averaging the spectrum generated by each source. This may not be an actual issue, however, as the sources are incoherent.

## 5.4 Further work

There are several factors within the sound insulation provided by balconies that could benefit from further investigation. One possibility would be to determine if a relation between the measured reverberation time inside the balcony and its SPL reduction could be drawn. Another subject of interest would be to investigate whether the different values of SPL reduction would vary significantly across the prediction methods and measurements when different floors are considered.

# Chapter 6

# Conclusion

Measurements and estimations using Catt, Nor96, guideline 517.521 and ISO 12354-3 have been used to investigate the sound reducing effect of balconies with and without sound absorbents.

The field measurements show that compared to not having a balcony, placing a hard surfaced balcony can lead to an average sound reduction of around 3 dB across the facade behind the balcony when exposed to a point source or a line source. Furthermore, by placing absorbing material in the ceiling, an additional sound reduction of 1-2 dB, to a total SPL reduction of 4-5 dB compared to no balcony can be achieved. By installing an solution of an absorbent with greater absorption factor this SPL reduction can likely be increased even further.

The estimations on facade SPL reduction show that Catt Acoustics calculates a higher sound reduction than what Nor96 does, both when comparing the sound reduction of a hard surfaced balcony and the reduction when placing absorbing materials at different areas of the balcony. It also seems like the estimates from Catt are more accurate than Nor96 compared to the measurements. The simulations in Nor96 underestimates the sound reduction effect compared to the measurements and is not ideal in this case as the method does not consider reflections at horizontal surfaces. This was attempted solved by creating a mirror source to account for the contribution of the roof, however the results should be considered somewhat unreliable.

Estimations done with the 517.521 guideline shows that the guideline overestimates the sound reduction of a parapet compared to what is measured at the balcony for higher frequencies. However, the measurement scenario is not ideal as the comparative measurement is done outside the parapet, which is a cause of uncertainty. Lastly, estimations made based on Appendix C of ISO 12354-3 shows that the estimate is quite conservative compared to the measurements. The SPL reduction could, however, vary depending on the balcony variant and surroundings, so the estimate may be a decent approximation of the minimum expected SPL reduction.

# Chapter 7

# Acknowledgements

I would like to give thanks to Brekke & Strand for suggesting the thesis, providing equipment to do measurements, software to do simulations of Nor96, providing standards and background information and for offering a desk at their office space to work in with access to help from the employees whenever I needed it. A special thanks goes to my external supervisor, Tore Killengreen, for following up the project, providing useful tips to what to focus on, helping with measurements and giving constructive feedback on the thesis. I would also like to thank Truls Klami for helping to understand CadnaA for the Nor96 estimations and Sigmund Olafsen for helping out with measurements.

Further, I would like to thank NTNU for collaborating with the thesis and providing me access to standards and Catt Acoustics. A special thanks goes to my supervisor, Guillaume Dutilleux, for providing useful suggestions in finding background information, conducting simulations and measurements and writing the thesis. I would also like to thank professor Peter Svensson for helping me understand Catt Acoustics and giving suggestions as to how to present results, and my co-student Henrik Berg for proofreading the thesis and giving useful corrections and suggestions.

Finally, I would like to thank Veidekke for allowing me to conduct measurements on the balconies of their construction site.

# Bibliography


[1] B. Rasmussen, 'Building acoustic regulations in europe – brief history and actual situation,' *Baltic-Nordic Acoustics Meeting*, pp. 4–7, 2018. [Online]. Available: https://events.artegis.com/urlhost/artegis/customers/1571/.lwtemplates/layout/default/events_public/12612/Papers/Keynote_Rasmussen_BNAM2018.pdf.

[2] *68% of the world population projected to live in urban areas by 2050, says UN*, https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html, Accessed: 2020-02-25.

[3] 'Retningslinje for behandling av støy i arealplanlegging (T-1442/2021),' pp. 4–5,

[4] Y. G. Tong, S. K. Tang and M. K. L. Yeung, 'Full scale model investigation on the acoustical protection of a balcony-like façade device (l),' *The Journal of the Acoustical Society of America*, vol. 130, no. 2, pp. 673–676, 2011. [Online]. Available: https://doi.org/10.1121/1.3598430.

[5] S. K. Tang, C. Y. Ho and T. Y. Tso, 'Insertion losses of balconies on a building façade and the underlying wave interactions,' *The Journal of the Acoustical Society of America*, vol. 136, no. 1, pp. 213–225, 2014. [Online]. Available: https://doi.org/10.1121/1.4883379.

[6] S. K. Tang, 'Noise screening effects of balconies on a building facade,' *The Journal of the Acoustical Society of America*, vol. 118, no. 1, pp. 213–221, 2005. [Online]. Available: https://doi.org/10.1121/1.1931887.

[7] H. Hossam El Dien and P. Woloszyn, 'Prediction of the sound field into high-rise building facades due to its balcony ceiling form,' *Applied Acoustics*, vol. 65, no. 4, pp. 431–440, 2004, ISSN: 0003-682X. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003682X03001701.

[8] H. H. El Dien and P. Woloszyn, 'The acoustical influence of balcony depth and parapet form: Experiments and simulations,' *Applied Acoustics*, vol. 66, no. 5, pp. 533–551, 2005, ISSN: 0003-682X. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003682X04001574.

[9] D. Hothersall, K. Horoshenkov and S. Mercy, 'Numerical modelling of the sound field near a tall building with balconies near a road,' *Journal of Sound and Vibration*, vol. 198, no. 4, pp. 507–515, 1996, ISSN: 0022-460X. [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0022460X96905842`.

[10] D. N. May, 'Freeway noise and high-rise balconies,' *The Journal of the Acoustical Society of America*, vol. 65, no. 3, pp. 699–704, 1979. [Online]. Available: `https://doi.org/10.1121/1.382482`.

[11] M. Vorländer, 'Prediction tools in acoustics - can we trust the pc?' *Baltic-Nordic Acoustics Meeting*, 2010. [Online]. Available: `https://www.akutek.info/Papers/MV_Prediction_tools_acoustics.pdf`.

[12] A. Homb and S. Hveem, *Håndbok 47: Isolering mot utendørs støy*. Forskningsveien 3B, Postboks 123 Blindern, 0314 Oslo: Norges Byggforskningin-stitutt, 1999, p. 66.

[13] *NS-EN ISO 12354 -3: Building acoustics - estimation of acoustic performance of buildings from the performance of elements. part 3: Airborne sound insulation against outdoor sound.* 2017.

[14] T. F. W. Embleton, 'Tutorial on sound propagation outdoors,' *The Journal of the Acoustical Society of America*, vol. 100, no. 1, pp. 31–48, 1996. DOI: `10.1121/1.415879`. [Online]. Available: `https://doi.org/10.1121/1.415879`.

[15] *ISO 9613 - 2: Acoustics - sound attenuation during outdoor sound propagation*, 1997.

[16] S. L. Garret, *Understanding Acoustics - An Experimentalist's View of Acoustics and Vibration*. ASA Press/Springer, 2017, p. 552.

[17] P. JEAN, J. DEFRANCE and Y. GABILLET, 'The importance of source type on the assessment of noise barriers,' *Journal of Sound and Vibration*, vol. Volume 226, Issue 2, pp. 201–216, 1999, ISSN: 0022-460X. [Online]. Available: `https://doi.org/10.1006/jsvi.1999.2273`.

[18] H. Kuttruff, *Room acoustics. $5^{th}$ edition.* 2 Park Square, Abingdon, Oxon OX14 4RN: Spoon Press, 2009, p. 20.

[19] H. Kuttruff, *Room acoustics. $5^{th}$ edition.* 2 Park Square, Abingdon, Oxon OX14 4RN: Spoon Press, 2009, p. 32.

[20] *ISO 17497 - 1 - 2: Acoustics - sound scattering*, 2004.

[21] J. Embrechts, 'Determination of the scattering coefficient of random rough diffusing surfaces for room acoustics applications,' *Acta Acustica/Acustica*, 2001.

[22] A. Everest, *The Master Handbook of Acoustics. $4^{th}$ edition.* McGraw-Hill, 2001, pp. 491–493.

[23] A. Everest, *The Master Handbook of Acoustics.* $4^{th}$ *edition.* McGraw-Hill, 2001, pp. 245–256.

[24] *ISO 10847: Acoustics — in-situ determination of insertion loss of outdoor noise barriers of all types*, 1997.

[25] *IEC 61672-1: Electroacoustics - sound level meters - part 1: Specifications*, 2013.

[26] S. Olafsen, D. Bard, M. Strand and T. Espejo, 'Methods of field measurements of facade sound insulation,' *Noise Control Engineering Journal*, vol. 63, pp. 467–477, Sep. 2015. DOI: 10.3397/1/376342.

[27] *NS 8177 -1: Acoustics - measurements of sound pressure level from rail traffic.* 2010.

[28] M. Vorlander, *Auralization - Fundamentals of acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality.* Berlin: Springer-Verlag, 2008, pp. 304–310.

[29] 'Environmental noise from industrial plants general prediction method,' no. 4, 1982.

[30] *ISO 717 - 1: Acoustics - rating of sound insulation in buildings and of building elements. part 1: Airborne sound insulation.* 2020.

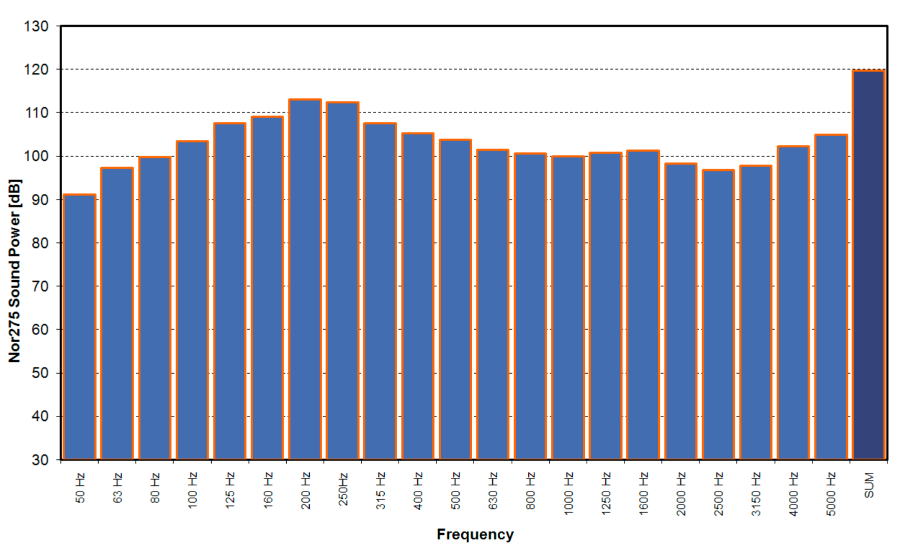
[31] CATT, *CATT-A v9.1e:1. User's manual.* 2019, pp. 124–126.

[32] *NS ISO 1996 - 2: Acoustics - description, measurement and assessment of environmental noise. part 2: Determination of sound pressure levels.* 2017.

# Appendix A

# Loudspeaker characteristics

The frequency response of the loudspeaker is shown in the following picture. Information about serial number and calibration is shown in the following pages. Loudspeaker set 5 was used during the first measurement day, while loudspeaker set 2 was used during the second measurement day.



Date: 2020-02-28

# Instrument Set – BS-HalvkuleSet #5

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-HALVKULESET#5-101 | Amplifier | Nor 280 | 2804290 | 2020-02-12 |
| BS-HALVKULESET#5-201 | Speaker | Nor 275 | 2755230 | 2020-02-12 |

# *Certificate of Calibration*

**Certificate No.:** 53984

| | |
|---|---|
| **Object:** | Hemi-Dodecahedron loudspeaker. |
| **Supplier:** | Norsonic AS |
| **Type:** | Nor275 |
| **Serial number:** | 2755230 |
| **Client:** | Brekke & Strand akustikk as<br>Norge |

**This unit is tested and verified in accordance to the Norsonic production standard set for Nor275 and comply with ISO 140-4 Annex A standard for airborne insulation measurements in field.**

**Instrumentation used for verification traceable to:**

Electrical Parameters: MT, Norway
Acoustical Parameters: PTB, Germany
Environmental Parameters: Justervesenet. Norway

**Adjustments:** None

**Comments:** None

| **Date of verification:** | **Verification interval recommended** |
|---|---|
| 2020-02-12 | 2 year (s) |

**The environmental parameters applicable to this calibration are kept well within limits ensuring negligible deviation on obtained measurement results.**

**Verified by:**
Kent Narvesen

Norsonic AS
Postboks 24
3421 Lierskogen
Org.nr. 929 743 040

Sign. Kent Narvesen

Norsonic AS, P.B 24, 3421 Lierskogen. Visitor address: Gunnersbråtan 2, Tranby, Norway.
Phone +47 32858900 Fax.: +47 32852208. email: info@norsonic.com

# Certificate of Calibration

**Certificate No.:** 53983

**Object:** Power amplifier including noisegenerator.

**Supplier:** Norsonic AS

**Type:** Nor280

**Serial number:** 2804290

**Client:** Brekke & Strand akustikk as
Norge

**This unit is tested and verified in accordance to the Norsonic production standard set for Nor280.**

**Instrumentation used for verification traceable to:**

Electrical Parameters: MT, Norway
Acoustical Parameters: PTB, Germany
Environmental Parameters: Justervesenet. Norway

**Adjustments:** None

**Comments:** None

**Date of verification:** 2020-02-12

**Verification interval recommended** 2 year

**The environmental parameters applicable to this calibration are kept well within limits ensuring negligible deviation on obtained measurement results.**

**Verified by:**
Kent Narvesen

Norsonic AS
Postboks 24
3421 Lierskogen
Org.nr: 929 743 040

Sign. Kent. Narvesen

Norsonic AS, P.B 24, 3421 Lierskogen. Visitor address: Gunnersbråtan 2, Tranby, Norway.
Phone +47 32858900 Fax.: +47 32852208. email: info@norsonic.com

Date: 2021-02-01

# Instrument Set – BS-HalvkuleSet #2

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-HALVKULESET#2-101 | Amplifier | Nor 280 | 2804009 | 2021-01-26 |
| BS-HALVKULESET#2-201 | Speaker | Nor 275 | 2755141 | 2021-01-26 |

# *Certificate of Calibration*

**Certificate No.:** 54218

**Object:** Hemi-Dodecahedron loudspeaker.

**Supplier:** Norsonic AS

**Type:** Nor275

**Serial number:** 2755141

**Client:** Brekke & Strand akustikk as
Norge

**This unit is tested and verified in accordance to the Norsonic production standard set for Nor275 and comply with ISO 140-4 Annex A standard for airborne insulation measurements in field.**

**Instrumentation used for verification traceable to:**

Electrical Parameters: MT, Norway
Acoustical Parameters: PTB, Germany
Environmental Parameters: Justervesenet. Norway

**Adjustments:** None

**Comments:** None

**Date of verification:** 2021-01-26

**Verification interval recommended** 2 year (s)

**The environmental parameters applicable to this calibration are kept well within limits ensuring negligible deviation on obtained measurement results.**

**Verified by:**
Kent Narvesen

Sign.

Norsonic
Norsonic Calibration Laboratory
VAT no.: NO 929 743 040 MVA

Norsonic AS, P.B 24, 3421 Lierskogen. Visitor address: Gunnersbråtan 2, Tranby, Norway.
Phone +47 32858900 Fax.: +47 32852208. email: info@norsonic.com

# *Certificate of Calibration*

**Certificate No.:** 54219

| | |
|---|---|
| **Object:** | Power amplifier including noisegenerator. |
| **Supplier:** | Norsonic AS |
| **Type:** | Nor280 |
| **Serial number:** | 2804009 |
| **Client:** | Brekke & Strand akustikk as<br>Norge |

**This unit is tested and verified in accordance to the Norsonic production standard set for Nor280.**

**Instrumentation used for verification traceable to:**

Electrical Parameters: MT, Norway
Acoustical Parameters: PTB, Germany
Environmental Parameters: Justervesenet. Norway

**Adjustments:** None

**Comments:** None

| **Date of verification:** | **Verification interval recommended** |
|---|---|
| 2021-01-26 | 2 year |

**The environmental parameters applicable to this calibration are kept well within limits ensuring negligible deviation on obtained measurement results.**

**Verified by:**
Kent Narvesen

Sign.

Norsonic
Norsonic Calibration Laboratory
VAT no.: NO 929 743 040 MVA

Norsonic AS, P.B 24, 3421 Lierskogen. Visitor address: Gunnersbråtan 2, Tranby, Norway.
Phone +47 32858900 Fax.: +47 32852208. email: info@norsonic.com

# Appendix B

# Microphone data

The location of each microphone is shown in Table B.1. The serial numbers of all the components of the microphones are shown in the subsequent pictures.

| Date used | Device ID | Location |
|---|---|---|
| 05.06.2021 | 140#14 | All point source measurements for all floors. |
| | 140#5 | All metro measurements at facade for all floors. |
| 15.06.2021 | 140#1 | Metro measurements at facade of 4th floor. |
| | 140#3 | Metro measurements outside parapet of 6th floor. |
| | 140#12 | Metro measurements at facade of 2nd floor. |
| | 140#13 | Metro measurements at facade of 4th floor. |
| | 140#14 | All point source measurements for all floors.<br>Metro measurements at facade of 6th floor. |
| | 140#18 | Metro measurements outside parapet of 2nd floor. |

**Table B.1:** The locations and measurement dates for the microphones.

## Instrument Set – BS-Nor140 #1

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-NOR140#1-101 | Sound Level Meter | Nor 140 | 1404010 | 2021-01-08 |
| BS-NOR140#1-202 | Mic Preamp | Nor1209 | 15541 | 2021-01-08 |
| BS-NOR140#1-301 | Mic | 1225 | 264739 | 2021-01-08 |
| BS-NOR140#1-401 | Calibrator | 1251 | 33028 | 2021-01-07 |

## Instrument Set – BS-Nor140 #3

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-NOR140#3-101 | Sound Level Meter | Nor 140 | 1402882 | 2021-01-26 |
| BS-NOR140#3-201 | Mic Preamp | Nor1206 | 30976 | 2021-01-26 |
| BS-NOR140#3-301 | Mic | 1225 | 264799 | 2021-01-26 |
| BS-NOR140#3-401 | Calibrator | 1251 | 33340 | 2021-01-26 |

## Instrument Set – BS-Nor140 #5

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-NOR140#5-101 | Sound Level Meter | Nor 140 | 1403721 | 2020-09-02 |
| BS-NOR140#5-201 | Mic Preamp | Nor1206 | 31055 | 2020-09-02 |
| BS-NOR140#5-301 | Mic | 1225 | 79581 | 2020-09-02 |
| BS-NOR140#5-401 | Calibrator | 1251 | 33027 | 2020-09-11 |

## Instrument Set – BS-Nor140 #12

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-NOR140#12-101 | Sound Level Meter | Nor 140 | 1406403 | 2019-08-03 |
| BS-NOR140#12-201 | Mic Preamp | Nor1209 | 12044 | 2019-08-03 |
| BS-NOR140#12-301 | Mic | 1225 | 226847 | 2019-08-03 |
| BS-NOR140#12-401 | Calibrator | 1251 | 33915 | 2019-09-11 |

## Instrument Set – BS-Nor140 #13

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-NOR140#13-101 | Sound Level Meter | Nor 140 | 1406404 | 2019-12-16 |
| BS-NOR140#13-201 | Mic Preamp | Nor1209 | 12045 | 2019-12-16 |
| BS-NOR140#13-301 | Mic | 1225 | 226841 | 2019-12-16 |
| BS-NOR140#13-401 | Calibrator | 1251 | 35013 | 2021-02-18 |

## Instrument Set – BS-Nor140 #14

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-NOR140#14-101 | Sound Level Meter | Nor 140 | 1406405 | 2020-09-16 |
| BS-NOR140#14-201 | Mic Preamp | Nor1209 | 12046 | 2020-09-16 |
| BS-NOR140#14-301 | Mic | 1225 | 226857 | 2020-09-16 |
| BS-NOR140#14-401 | Calibrator | 1251 | 35014 | 2020-09-14 |

## Instrument Set – BS-Nor140 #18

| BS ID | CONTAINING: | INSTRUMENT: | SERIAL NUMBER: | LAST CALIBRATION |
|---|---|---|---|---|
| BS-NOR140#18-101 | Sound Level Meter | Nor 140 | 1407588 | 2020-09-14 |
| BS-NOR140#18-201 | Mic Preamp | Nor1209 | 22635 | 2020-09-14 |
| BS-NOR140#18-301 | Mic | Nor1225 | 384561 | 2020-09-14 |
| BS-NOR140#18-401 | Calibrator | Nor1255 | 125525516 | 2020-09-29 |

# Appendix C

# Full measurement data

The sound level measured by in the case of a point source is shown in Figure C.1, while the SPL measured in the case of a line source is shown in Figure C.2.

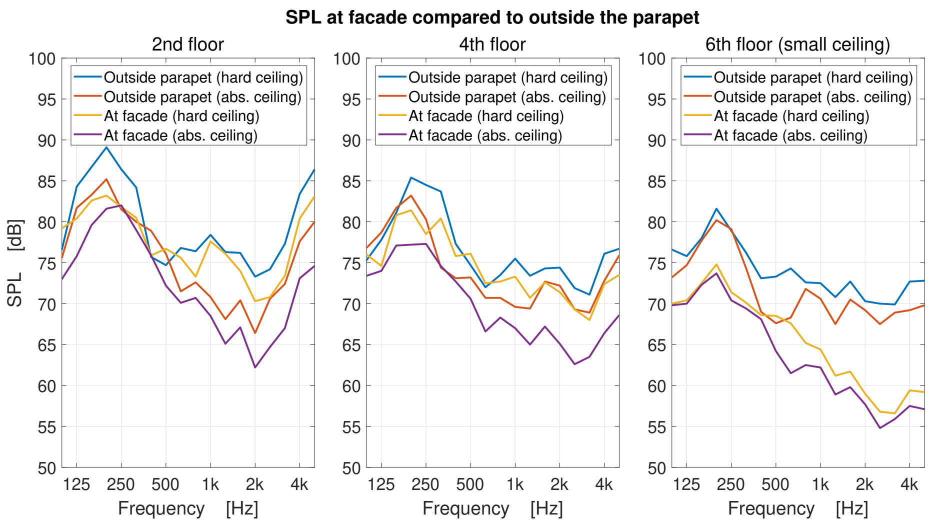



**Figure C.1:** The third octave band sound pressure reduction at the balcony facade compared to outside the parapet, measured at different floors when exposed to point source.

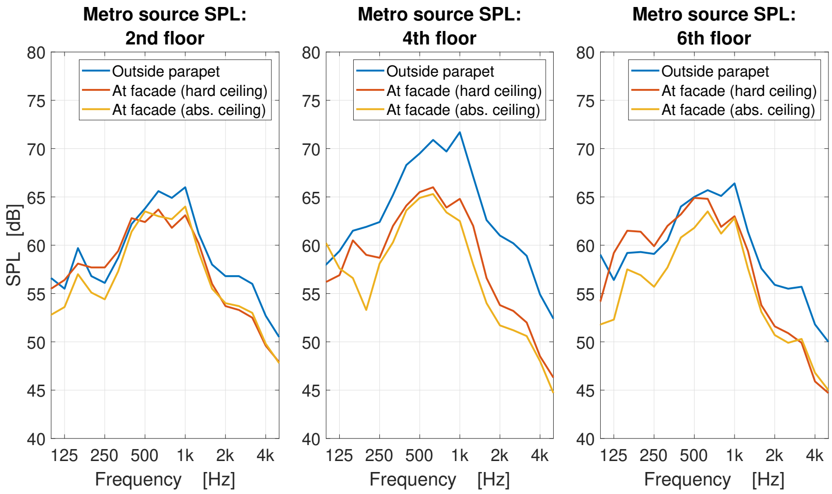



**Figure C.2:** The third octave band sound pressure reduction at the balcony facade compared to outside the parapet, measured at different floors when exposed to line source.

NTNU

Norwegian University of Science and Technology