Abstract

The aim of this thesis is to determine the effect an inclination of a noise barrier has on the reflected noise produced by road traffic. The height distribution of the reflected noise is expected to decrease with an increasing angle of inclination. A theoretical study based on mirror sources and trigonometry explains the relation between the barrier inclination and the height of the reflected noise. The theoretical model is complemented with a scale model measurement and a simulation performed in Odeon. Acoustic hard surfaces and totally absorbent surfaces are used during the theoretical model, scale model measurement and the simulation. The results of the scale model measurement and the simulation supports the behavior of the theoretical model and displays an angle of inclination where the behavior is reversed and at which the height of the pressure is increased with further the increase of the inclination angle.
Acknowledgement

I would like to thank Peter Malm at Tyréns AB for the opportunity to conduct the thesis during the spring of 2011 and to my supervisor techn Dr Karl Bolin at the Department of Aeronautical and Vehicle engineering at KTH, Royal Institute of Technology.

I would also want to thank to the employees of Tyréns AB Acoustic department for helping me with various problems. Special thanks to Martin Höjer for helping me during the scale model measurement and special thanks to Philip Zalyaletdinov and Filip Stenlund for answering my questions and helping me during the simulation.

Stockholm, June 2011-06-09

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1. Introduction

Traffic noise exists at and around every road and railway track around the world. These noises are amongst the largest contribution of environmental noise present in contemporary society. Almost 25% of the European population is exposed to transportation noise over 65dBA in their home [1]; this is more than the guideline values determined by EC [2].

Noise effect humans in numerous negative ways, from direct disorders like hearing impairment but also disorders that builds up by overtime exposure like hypertension, ischemic heart disease, stroke and sleeping disorders [3]. The social costs of traffic noise in the EU are over 40 billion euros per year [1]. Passenger cars, trucks and other conventional transportation vehicles are the major contributors of noise [3,4].

One of the most common ways to limit and decrease the exposure of noise produced by traffic is by blocking the propagation path between the source and the receiver. Various structures fulfill the criteria of blocking the propagation path but the most commonly used are noise barriers and earth berms. Earth berms are a very old method of shielding housing areas from the effects of nature; they often consist of stones and dirt. Noise barriers have a wide range of design shapes (masonry wall, steel structures, transparent shields, etc.) but are generally vertical structures built along the road with one side that faces the noise-source (traffic) and one that faces the structure that is in need of noise protection. What effect a noise barrier has on the propagation path of the traffic noise has been well documented [5] and the problems are known. One of the most researched subjects of noise barriers are the topside of the structure [6]. The topside of the barrier is where the diffraction and scattering that effects the surrounding environment occurs and where most investigation has been conducted to make more efficient barriers. The diffraction that occurs on barriers allows noise to effect the shield side [5,6]. The height of the barrier is determined by texture and roughness of the road, speed limit, level of expected noise reduction and the surrounding environment. The disadvantages that a noise barrier introduces are often of the esthetic impact of the surrounding environment but also the cost of building and maintaining the barrier. In some cases it is more appropriate to build the barrier with an inclination angle, this can due to for example; remove unwanted light reflections that would disturb the handlers of the cars. The effect a barrier with an inclination angle has on the noise propagating paths has been modestly investigated and primarily on how the noise shielding is affected of the degree of inclination. It is known that by giving the barrier an inclination you theoretically move the barrier closer to the source, a proven way of increasing the efficiency of the barrier.

However, the effect of the barrier inclination on the reflected noise has so far been overseen. The reflected noise from a barrier effects the opposite side thus increasing the noise produced from the road. The reflected noise will propagate above/over the barrier on the opposite side of the barrier it reflects on. The behavior of this effect is determined by several factors (surface structure of the wall, type of traffic, heights/distances of barrier/source). The outgoing angle of reflection from the barrier is directly related to the inclination angle of the barrier. In modern calculation and simulation software that handles environment noise by traffic these reflections are modeled as if the noise barrier vertical. Thus not including the effects an inclination of the barrier has on the reflected noise.
1.1 Aim

The aim of this thesis is to determine the result an inclination of a noise barrier has on the reflected noise. This work originated as a request by Tyréns for a correction table for noise barriers with inclinations in environmental noise mapping programs. An investigation based on mirror sources and trigonometry will try to explain the effect inclination has on the reflections from the source compared to a vertical barrier. The theoretical investigation will be compared to simulations performed in Odeon on noise barriers with same inclination angles (0-25 deg from vertical barriers in integer steps). Both the theoretical investigation and the Odeon simulation will be compared to a scale model measurement of a barrier with the same inclination angles. If there is a difference in height distribution of the reflected noise between the vertical barriers and barriers with an inclination a correction table for environmental noise mapping software be created to increase the accuracy on the sound distribution caused by the noise barriers with inclinations.

1.2 Limitations

The theoretical investigation of the reflected noise will be undertaken as a two dimensional near field problem with no material data or atmospheric data. The barrier scale model will consist of only totally reflective surfaces, acoustic phenomena such as scattering and diffraction will not be included. The simulation and the scale model measurement will treat a single source of traffic but with numerous different inclination angles.

These simplifications will influence accuracy in frequency spectrum and pressure distribution, but will give a qualitative guideline on the effect of barrier inclination on reflected noise.
2. Background

2.1 Traffic Noise

Traffic noise is generated by vehicles (passenger vehicles, trucks, vans etc.). Magnitude and frequency of the noise can vary greatly depending on vehicle type. Noise from passenger cars and light vehicles occur mainly from the tire-roadway interaction and are therefore located near the ground. The noise from heavy trucks is produced by a combination of noise from tires, engine, and exhaust, resulting in a noise source that is approximately 2.5 meters above the ground. There are several other factors that affect the traffic noise radiation other than the source noise from the vehicles. Distances, terrain and ground configuration of the surrounding environment do have a significant impact on the radiation of noise from a road.

A rough estimation is that an increase in speed from 50 to 70 km/h roughly increases the generated noise with 4 dB [7]. The frequency spectra and the level of traffic noise are highly dependent on the type of traffic and on the vehicle speed. Typical frequency spectra of passenger cars and light vehicles are displayed in Figure 1.

![Frequency spectrum for passenger cars and light vehicles](image)

*Figure 1: Frequency spectrum of passenger cars and light transport vehicles at a few different speeds, the highest noise level produced by passenger cars is at 1000-2000 Hz. This noise is a product of the interaction between tire and road surface [8].*

Frequency spectra of vehicles classified as medium trucks and heavier traffic can be found in the Appendix 1.
2.2 Noise Barriers

If the noise radiation from traffic cannot be limited by design of the road or by modifying the surrounding terrain, a good option for reducing the noise radiation is through noise barriers. The fundamental requirement that a noise barrier has to satisfy is that it has to be completely acoustically dense and block the line between noise source and receiver. The length or distance of the barrier is also an important factor. The difference between a barrier that completely shields the line of sight between a housing area and the source can be large. If the shielding only covers 90 degrees of the visibility only generate roughly 3 dB decrease whereas a case with that has completely shielded visibility generates a reduction of 10 dB [7].

The dimension and design of noise barriers is very flexible as long as they fulfill the fundamental requirements. There are several companies that produce and sell noise barriers but it is not uncommon that the barriers are specifically modeled depending on a purpose they are meant to fulfill. The only guideline present in the dimensioning of the barrier is the distance between the source and the barrier [7]. These distances are based on the speed of the road; an example of these distances can be seen in Table 1.

<table>
<thead>
<tr>
<th>Speed of Traffic [km/h]</th>
<th>Distance between barrier and source [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>70</td>
<td>7</td>
</tr>
<tr>
<td>90</td>
<td>9</td>
</tr>
<tr>
<td>110</td>
<td>11</td>
</tr>
</tbody>
</table>

*Table 1: The recommended distance due to traffic safety concerns between source and barriers at different speeds of traffic.*

2.2.1 Noise barriers with inclinations.

The most common barriers that are used are vertical barriers but noise barriers can be built with an angle of inclination.

These angles are usually ten degrees from the vertical inclination. Barriers with inclinations have to fulfill the same fundamental criteria as the vertical barriers and there are no special criteria on the case with barriers with an inclination. The inclination can be both towards and away from the source. There are several reasons for erecting a barrier with an inclination, from aesthetic reasons or to solve practical problems such as to remove unwanted light reflections caused by the combination of the headlights of the vehicles and reflective barriers. These barriers are often erected on bridges where a transparent barrier is sought after.
2.3 Theoretical Model

A two-dimensional model of a noise barrier will be constructed in an attempt to describe the relation between the inclination angle and the distribution of the reflected noise. The model will consist of a (barrier, ground, semi-directive monopole) source and a fictional measurement area. The fictional measurement area is located behind the source from the barrier. This is displayed in Figure 2. An attempt to include the frequency spectra of the source will also be performed, due to differences in frequency between different kinds of traffic and velocities can easily be observed in figure 1. The design parameters of the model can be observed in figure 2 and are height of the source (z), height of the barrier (q), distance between the source and the barrier (x), distance between the desired measurement area and the barrier (y), the angle of inclination of the barrier and frequency spectrum of the source.

Figure 2: The figure shows the noise barrier to the left, the source term denoted as Ds and the fictional measurement “wall” to the right. In this figure all sources are located in the source point to a show more realistically how the reflections are transpiring. The blue line represents the reflection that only occurs by barrier, the green line represents the reflections that are a result of the ground to barrier reflections and the red line represents the reflections that are a result of the barrier to ground reflections. The distance between the barrier and the source is denoted as X, the distance between the barrier to measurement area is denoted Y, height of source is denoted Z and height of the barrier is denoted as Q.

2.3.1 Assumptions

There are some simplifications in the theoretical model, the ground and barrier is treated as acoustically hard surfaces hence the sound will be totally reflected at every surface. Acoustic effects such as scattering and diffraction will not be included. The surrounding media will not affect the propagation of the noise. Refraction caused by atmospheric phenomena such as wind and temperature will not be taken into consideration. The model will also only allow two reflections for each noise ray, thus neglecting some of the more complex propagation paths; an example of these is displayed in Figure 3. The justification of these simplifications is that this investigation is an early attempt to find basic relations between the inclination angle and the reflected noise.
Figure 3: The figure displays the base part of a noise barrier with an inclination. The arrow represents an incoming ray. If the noise barrier inclination is too large, a collection of reflection noise rays from several reflection orders will occur at the foot of the barrier.

### 2.3.2 Reflections and Mirror sources

Each ray will follow the basic rules of reflections [9]. For each reflection that occurs in the model, a mirror source will be created. The model structure will only permit three kinds of reflection; hence only three mirror sources will exist. This is displayed in Figure 4. One source represents the reflection that only occurs on the barrier, one that represents the reflections from the ground to the barrier and one represents the reflections from the barrier by the ground. The contribution of each source will be calculated separately and then summed, this is explained more accurately in the chapter 2.3.3 Pressure Distribution.

Figure 4: Vertical Case; The mirror sources that are treated in the theoretical mode, Ms_1 (blue) are the source that represents the reflections that only occur on the barrier. Ms_2 (green) represent the source that is responsible for the ground to barrier reflections and Ms_3 (red) the barrier to ground reflections.
2.3.2.1 Mirror source and reflection summation.

In the vertical barrier case displayed in Figure 4, the reflection with the highest resulting altitude at the measurement area is produced by the mirror source Ms_2; this is due to that all the reflections produced are only determined by the geometrical values. Hence, with the height and distance to the barrier, in the vertical case, Ms_2 will produce the highest reflection. In the barrier case with an inclination, displayed in Figure 5, the highest reflections are depending on the amount of inclination. The amount of inclination affects the height of the reflections produced by mirror source Ms_1 and Ms_2 negative, whereas mirror source Ms_3 highest reflection increases with an increased amount of inclination towards the source.

2.3.3 Pressure distribution

One way to calculate the pressure distribution of the mirror sources is to regard them as point sources [10]. In the theoretical model the mirror sources are regarded as free field. The complex pressure amplitude of a free field monopole can be calculated with equation (2.1). When the mirror source locations in relation to the measurement points have been determined, i.e. when the height and distances between the mirror sources and the measurement area is known, the pressure distribution can be calculated.

\[ p_{free} = S \frac{\exp(ikR_1)}{R_1} \]  \hspace{1cm} (2.1)

\[ R_1 = \sqrt{x^2 + (z - z_s)^2} \]  \hspace{1cm} (2.2)
Where

\( p_{\text{free}} \) Pressure amplitude of the free field
\( S \) Radiation constant
\( k \) Wave number
\( R_1 \) Distance from the source, determined by the height of the mirror source \( (z_s) \) and the height of the receiver \( (z) \) and the distance between them \( (x) \), see Figure 6.

For each reflection, hence for each mirror source an additional term will be added to as such:

\[
p_x = S \frac{\exp(ikR_1)}{R_1} + QS \frac{\exp(ikR_2)}{R_2}
\]

\( R_2 = \sqrt{x^2 + (z + z_s)^2} \)  

Where

\( p_x \) Pressure amplitude at the receiver
\( Q \) Spherical-wave reflection coefficient
\( R_2 \) Distance from the source determined by the heights \( (z) \) and the distance \( (x) \) for/from each source.

Figure 6: The figure above displays the relation between distances, heights and the sources in equation (2.2) and (2.3). On the lower left part of the figure an imaginary mirror source can be observed.
2.4 Scale model measurement

To verify the theoretical model a scale model measurement has been undertaken. The scale measurement was conducted in a semi-anechoic chamber. Since the semi-anechoic chambers environment resemble the assumed surface conditions in the theoretical model. The lengths and height scales that are used in the theoretical model impose the measurements to be conducted on a 1:3 scale.

Along all the edges of the barrier, unwanted diffraction will occur. The barrier model is supposed to mimic an actual noise barrier in all respects so some of these sources are unwanted. The sources on the vertical edges of the barrier are virtually nonexistent in real situations due to the fact that most noise barriers are horizontal long structures. To avoid and limit the contribution of these vertical edge sources the barrier should be as long as possible. Diffraction sources will also exist on the crest of the model, but these are present in a real case as well.

2.4.1 Semi-Anechoic chamber

The measurement will be conducted in a semi-anechoic chamber. A semi-anechoic chambers sound environment is very similar to an actual outdoor sound environment. An outdoor sound environment has hard ground and very limited reflections due to lack of reflective surfaces. Semi-anechoic chambers mimic this environment well due to hard ground and highly absorbent walls and ceiling.

2.4.2 Sound source

Because of the wide frequency spectrum excited by traffic the sound source excites pink noise (noise with uniform sound level over a wide frequency spectrum). To limit the direct sound contribution of the source and focus the measurement on the reflected noise the source should be semi directive and be facing the barrier, thus removing unwanted sound.

2.4.3 Scaling

The measurement will be performed on a 1:3 scale model with typical distances of road and noise barriers for Swedish roads with 70 km/h speed limit [7]. All the heights and distances from the theoretical model are scaled to on third of their actual size. The original distances and their scaled counterparts is displayed in Table 2. The horizontal length of the barrier should be as long as the semi-anechoic room permits.

<table>
<thead>
<tr>
<th>Actual Distance</th>
<th>1:3 - Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between source and barrier [m]:</td>
<td>8</td>
</tr>
<tr>
<td>Distance between measurement area and barrier [m]:</td>
<td>7</td>
</tr>
<tr>
<td>Height of Source [m]:</td>
<td>0.3</td>
</tr>
<tr>
<td>Height of Barrier [m]:</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 2: The table above displays the scaled distances and heights of the scale measurement [7.]
2.4.3.1 Frequency Scaling.

The frequency spectrum is influenced by the scaling as well. Because the distances and heights are scaled to one third of their actual size the frequency content also has to be treated as scaled as 1:3. For example, if noise with frequency content at 3 kHz is exposed on the barrier it will behave as if it was 1 kHz because the distances and lengths of the model are one third of their actual size. The wavelength of equation (2.5) is based on the speed of air \( c \) and the frequency \( f \).

\[
\lambda = \frac{c}{f} \tag{2.5}
\]

The wavelength of a frequency is a measure of distance between repetitions of a shape feature (peaks, nodes etc.). It is this entity factor that is affected by the scaling. Since the distances in the model are scaled, so will also the wavelength of the reflected noise. Thus the measurement must be corrected to represent the exact frequency.
2.5 Simulated model

To be compared with the scale model measurement and to verify the predictions from the theoretical model a simulation of noise barriers will be undertaken in the acoustic prediction software Odeon. The simulation will consider the same geometrical setup as in the theoretical model. The geometrical model used in the simulation is externally built in Google SketchUp. The simulation will be performed on numerous identical noise barriers but with altered angles of inclination.

2.5.1 Geometrical model

The geometrical model used for the simulation is made in Google SketchUp. SketchUp is a 3D-modeling program designed by Google. This program can be used to make 3D-models that can be exported to Odeon for simulation. In SketchUp, parts of the model can be divided into layers or groups. Thus giving the opportunity to apply material data to specific parts of the model. The model will consist of numerous identical barriers divided into different sections; each section will consist of a unique inclination angle on the barrier. The range of inclination angles simulated is derived from the results from the theoretical model.

2.5.2 Odeon

Odeon is an acoustic prediction and auralisation program developed and owned by Alectia, Grontmij Carl Bro, Rambøll and ØDS-Holding A/S. The Odeon software is designed for interior acoustic simulations of buildings. From geometry and surface properties acoustics can be simulated, predicted, illustrated and listened to. Odeon uses image-source method combined with ray tracing. In Odeon material data will be applied to the structures of the model, acoustic parameters like diffusion, scattering etc. will also be included in the simulation to make it as close to the scale measurement as possible.

2.5.2.1 Sound source and Receiver points.

Acoustic predictions in Odeon require sound sources and receivers. Sources can be designed with acoustic parameters like directivity and frequency spectrum. Receivers can be modeled as points or to grids cover entire areas.

In each segment of the barrier model a sound source and several receiver points is placed. The sound sources will consist of semi-monopoles point sources and to remove unwanted direct contribution each source will be directed towards each barrier. Another unwanted contribution can occur in Odeon simulation is that the semi-monopole sources is not ideal (the sound sources are designed as speakers) so even a semi-monopole source has some contribution to the non-directive hemisphere. This contribution can create a ground reflection between the source and the receiver points that is unwanted. To remove this reflection the signal strength of the source will be much larger in the semi-part of the source.
To facilitate a comparison between the results from Odeon at different frequencies with the scale measurement, the sources in the simulated model should excite pink noise, thus allowing the comparison to include frequency, inclination angle and the height of the reflected noise between the simulated model and the scale measurement. To obtain the relationship between the angle of inclination and the height of the reflected noise, several receiver points will be used at different heights and located on the measurement wall located opposite to the barriers.

3. Method

3.1 Theoretical Model

The theoretical model is based on a general case of traffic, an ordinary Swedish highway with a speed limit of 70 km/h. The input parameters of the model are the height of the source, the height of the noise barrier, the inclination angle of the barrier, the base distance between the source and barrier, the distance between the barrier and the measurement area and the frequency spectrum of the source. The heights and distances used in the model are displayed in Table 3. The angle of inclination used is in the range from 0 to 25 degrees of inclination towards the source. The model is implemented in Matlab and the code is available in Appendix 2.

<table>
<thead>
<tr>
<th>Height of source [m]</th>
<th>Height of Barrier [m]</th>
<th>Distance – Barrier to Source [m]</th>
<th>Distance – Barrier to Measurement area [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>2.5</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 3: The table above displays the height and distances used in the theoretical model.

The sources are divided into three categories as seen in Table 4. The source division is based on the number of reflections that occurs in the model with these specific parameters.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Source type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>Mirror source</td>
<td>Source term that represents the noise that is only reflected on the barrier denoted as Ms_1 in Figure 4</td>
</tr>
<tr>
<td>gb</td>
<td>Mirror source</td>
<td>Source term that represents the noise that is reflected first on the ground then on the barrier, denoted as Ms_2 in Figure 4</td>
</tr>
<tr>
<td>bg</td>
<td>Mirror source</td>
<td>Source term that represents the noise that is reflected first on the barrier then on the ground, denoted as Ms_3 in Figure 4</td>
</tr>
</tbody>
</table>

Table 4: The table above describes the different sources that the analytical model consists of.

3.1.1 Linear equation method

The only parameter in equation (2.1) to (2.4) that is changing with the simplifications mentioned earlier is the length between the mirror source and the measurement area. Linear equations are used to determine the distances between the sources and a desired point at the measurement area. Because of these simplifications, these distances can be described as a straight line between two fixed points (the mirror source and the barrier). Linear solution equations are used to determine these distances. To interpret the theoretical model as linear equations, the horizontal distance between the source and the noise barrier and the horizontal distance between the measurement areas to the noise barrier are regarded as y-axis.
The height of the mirror sources and the height of the noise barrier are regarded as x-axis. This is explained by equation (3.1) – (3.2).

\[ y = hx + m \]  
\[ h = \left( \frac{y - y_0}{x - x_0} \right) \]

Where

- \( y \) Y-value of positioning in a Cartesian coordinate system
- \( x \) X-value of positioning in a Cartesian coordinate system
- \( h \) Slope
- \( m \) Offset

With the input parameters two linear equations are calculated for each source expressing the maximum and minimum contribution angle of the source to the measurement area. The source with a linear equation that generates the highest maximum y-axis value at the desired measurement wall which is located at \( x_0 \), determines the height of the measurement area.

3.1.1.1 Inclination correction for linear equation solution.

Correction for the amount of inclination the barrier has is directly influencing the linear equations of the maximum/minimum contribution. The inclination correction influences the desired maximum/minimum points on the barrier, the x-value in terms of height correction and the y-value as a distance correction.

3.1.2 Pressure distribution

The pressure distribution over the measurement area is divided into three different source terms. This is implemented in the code as equation (3.3) which is a modification of (2.3).

\[ p_c = Q_b \frac{\exp(ikR_b)}{R_b} + Q_{gb} \frac{\exp(ikR_{gb})}{R_{gb}} + Q_{bg} \frac{\exp(ikR_{bg})}{R_{bg}} \]

Where

- \( R_b \) Distance between the mirror source that represents the barrier reflections, and the measurement wall
- \( R_{gb} \) Distance between the mirror source that represents the ground by barrier reflections, and the measurement wall
- \( R_{bg} \) Distance between the mirror source that represents the barrier by ground reflections, and the measurement wall
- \( Q_{b,gb,bg} \) Spherical-wave reflection coefficients for each mirror source.
The spherical-wave reflection coefficient (Q) from equation (2.4) is assumed to be 1 since all the surfaces are treated as acoustically hard. The spherical-wave reflection coefficient is a function of four quantities; wave number, distance, reflection angle and normalized ground impedance. The wavenumber (k) includes the frequency information from the input parameters. The reflected noises will also changes in phase. Each reflection yields an 180° change, thus the gb and bg – source terms are unaffected, but the b – term phase information is changed 180°.

3.1.3 Aim and summation of the theoretical model

When then inclination increases, the noise distribution at the measurement area/line is decreases in height. This behavior will continue until a critical angle of inclination where the height of the reflection caused by the bg - source will be higher in relation to the reflections produced by the b - source and gb - source. This inclination angle is going to be referred to as turning angle ($\theta_t$). When the height of the reflected noise is increasing after the turning angle, a pressure point will increase at equal height as the highest reflection. This is due to that the barrier will act as a focus-horn of the reflected noise. With higher degree of inclination, the higher the focus point of the pressure will be located.

The initial outcome on the inclination-height relationship is going to be used as reference values to build the simulated model and the scale measurement.
3.2 Scale model measurement

The measurement was performed in Tyréns semi-anechoic chamber room in Arninge, Stockholm. Barrier models where built in 1:3 scales of the geometrical values from the theoretical model. An added structure was fastened to the backside of the barrier model so it could be given an inclination towards the source. A source box was built to change the directivity of an Omni-directive sound-speaker to semi-directive. Six microphones were used and fastened to customized microphone stand. Photographs from the measurement are available in Appendix 3.

3.2.1 Choice of equipment

The sound source used in the measurement was an Omni-directional speaker made by Martin Höjer from Tyréns. Since the frequency of the reflected noise was of interest, preferably in one third octave bands, a 12 – channel Brue & Kjaer PULSE system was used. The six microphones were Brue & Kjaer type 4189 measurement microphones and the calibrator was a Brue & Kjaer type 4231. The noise source used in the measurements was a Larson Davis SRC20 that produced a pink noise.

3.2.2 Equipment used in the measurement:

Microphones: Bruel & Kjaer type 4189
Sound System Bruel & Kjaer 12-channel PULSE
Calibrator Brue & Kjaer type 4231
Sound speaker Martin Höjer Omni-directional speaker
Noise source Larson Davis SRC20

Specifications on most equipment used are available in the Appendix 3.

3.2.3 Barrier model, Source box and Microphone stand

The Barrier model, Source box and Microphone stand where built by the author and Martin Höjer. The barrier is built with 1,8cm thick MDF-board, with measurements from Table 2 in chapter: 2.4.3 Scale models. The barrier supporting system and the inclination system is made of a 2 cm thick wooden board with additional metal-parts for the inclination system. The source box is built with 2 cm thick wooden board and is filled with mineral wool that acts as acoustic damping.

Microphones were positioned on a thin wooden stick to remove unwanted reflections from the microphone stand. The six microphones were positioned at equal distances from 0.33 cm up to 2 meters. These distances represent a microphone at every meter in a full scale situation. The microphone stand was built from a 5x10x2000cm wooden beam.
3.2.4 Scale model setup

The barrier model was placed in one of the corners of the semi-anechoic room. To get full contribution from the reflected noise to the lowest of the microphones both the source box and the microphone stand was placed with an equal angle facing the barrier. The distances used in the measurement can be found in Table 2 in chapter: 2.4.3 Scale models. The setup of the scale measurement is displayed in Figure 7.

3.2.5 Measurement

All of the microphones were calibrated with 94dB reference level produced by the calibrator before the measurement was conducted. The PULSE system was set to take a mean value over 30 seconds. The sound source was exciting pink noise for 20 seconds before each of the measurements were started.

The inclination angle of the barrier was manually set and corrected before each measurement. The measurement started with vertical barrier and ended with the 25 degrees of inclination case. All of the measurements were performed, analyzed and saved in Bruel & Kjaer PULSE software.

Figure 7: The figure above displays a 3D-model rendering of the semi-anechoic chamber with the scaled model-parts of the measurement. On the upper right side the barrier model can be visible with the inclination support structure behind it. The box on the right side of the rendering represents the source box. The structure on the left side of the source box represents the microphone stand with its six wooden microphone holders.
3.2.6 Aim and summation of the measured model

The aim of the model measurement is to verify the theoretical models calculated turning angle ($\theta_t$). But also display the actual relationship between the height of the pressure peak and the angle of inclination. One of the key question and wanted effect is to see if the barrier will act as a focus horn after the $\theta_t$ thus displaying an increase in pressure at the highest reflected noise on the measurement area.

The frequency of the reflected noise is also of interest. The results from the measured model will be a-weighted. The results of the measured model will be used in a comparison of octave bands between the scale model measurement and the simulated model.
3.3 Simulated model

The geometric model used in the simulation is based on the geometric data used both in the theoretical model and in the scale model measurement. The simulated model consists of 26 segments each containing a noise barrier, all with similar geometric distances but with different inclination of the barrier. The first barrier represents the pure vertical case and then barriers with increasing inclination angle from 1 degree to 25 degrees towards the source. A noise source and six receiver points is positioned in each segment.

3.3.1 SketchUp Model

The model is set up according to the standard width of a Swedish road that has a speed limit of 70 km/h. The geometric data used is the same as in the theoretical model, see Table 2. The height limitation of the model is set to six meters based on the results from the theoretical model. The measurement area in all the segments is expressed as a six meter high wall one meter behind the location of the source. Each of the barrier segments is isolated by walls between the segments. Behind each barrier (looking from the source) a wall is located to enclose each segment.

Figure 8: The figure above shows a segment of the barrier model used in the simulation. Each segment is modeled exactly the same and placed next to each other. On the lower left side of the figure the barrier is visible. The two missing sides are hidden in the figure.

Each section has been divided into three kinds of SketchUp layers; wood, absorbent material and painted concrete. The ground of each segment is divided into painted concrete, the barrier to wood and the remaining parts as absorbents. This division of layers is applied to mimic the environment in the scale measurement. Thus it is set to only investigate how the reflection of the barrier behaves with respect to the barriers inclination angle.
3.3.2 Odeon setup

Scattering and diffraction along the top edge of the barrier are enabled. The simulation is run with a transition order of 10 which means that the 10 first reflections of each ray is treated as mirror sources all reflections above that are calculated with ray-tracing. Each source in every segment is set to emit 10 million rays.

3.3.2.1 Sound source and Receiver points.

For each unique barrier segment, a point-source with semi-directivity is facing the barrier at the same location used in the theoretical measurement, the distances used can be found in Table 3. All the sources excite pink noise.

3.3.3 Aim and summation of the simulated model

The purpose of the simulated model is that it will acts as a bridge between the theoretical model and the scale measurement. The key subject and desired behavior is to notice if the $\theta_t$ from the theoretical model is evident. And if the simulated model yields similar relationships between the pressure distribution and the angle of inclination, as the measurement does. The frequencies of the reflected noise are naturally of interest and will be used in the comparison.
4. Results

The first section of this chapter graphically displays the result from the theoretical model, the scale model measurement and the simulated model. The results are also available as tables in Appendix 4. The second section of this chapter is an analysis of the results from the theoretical model and a comparison of octave bands between the simulated model and the scale measurement.

4.1 Results graphs

4.1.1 Theoretical model

Figure 9: The figure above displays the distribution from the theoretical model. The inclination range is 0 to 25 degrees.
4.1.2 Scale measurement

Figure 10: The figure above displays the results from the scale measurement for the 1 kHz octave bands pressure distribution for different angles of inclination, the inclination range from vertical to 25 degrees. The measurement displayed in the figure is A-weighted and interpolated.

Figure 11: The figure above displays the results from the scale measurement for the 2 kHz octave bands pressure distribution versus the height for different angles of inclination, the inclination range from vertical to 25 degrees. The measurement displayed in the figure is A-weighted and interpolated.
4.1.3 Simulated model

Figure 12: The figure above displays the results from the simulated model for the 1 kHz octave bands pressure distribution versus height for different angles of inclination, the inclination range is from vertical to 25 degrees. The figure displays only positive dB values. The figure is interpolated.

Figure 13: The figure above displays the results from the simulated model for the 2 kHz octave bands pressure distribution versus height for different angles of inclination, the inclination range is from vertical to 25 degrees. The figure displays only positive dB values. The figure is interpolated.
4.2 Analysis and Comparison

In this chapter the results of the theoretical model are evaluated. A comparison between the simulated and the scale model is also evaluated in both the 1000 Hz octave band and the 2000 Hz octave band.

4.2.1 Theoretical Model

First and most noticeable in Figure 9 is the relation between the angle of inclination and height of the reflected noise. As expected the height of the pressure maximum is negatively influenced with an increasing inclination angle until the predicted $\theta_t$. In Figure 9 the $\theta_t$ occurs roughly at an inclination angle of 10 degrees. After the $\theta_t$ the height of the pressure increases. However the theoretical model does not calculate the pressure distribution correctly.

Each angle of inclination should produce an pressure distribution among the mirror sources. Hence the theoretical pressure-focus point produced by the inclination angle at the $\theta_t$ is absent. The focus point produced by the inclination should also be noticeable even with inclination angles inferior to $\theta_t$.

The reason why the theoretical model does not calculate the pressure distribution correctly is because the source terms do not scale in strength with relation to the inclination angle. For each angle of inclination the amount of reflected noise should be distributed exclusively among the mirror sources. This distribution is only determined by the angle of inclination. In the vertical case most of the energy of the reflected noise is distributed to the mirror sources representing the barrier reflections and the ground to barrier reflections. In the vertical case the contribution of the barrier to ground mirror source is almost negligible. With an increasing inclination angle the contribution of the barrier to ground will increase drastically whereas the contribution from the ground to barrier and barrier mirror source will decrease.
4.2.2 Simulated and measured model comparison

A comparison of the simulated and the measured model is performed for two octave bands.

4.2.2.1 Comparison: 1 kHz Octave band

![Graphs showing pressure distribution](image)

Figure 14: The figures above are a comparison between the results of the scale measurement and the simulation. Both figures represent the results in 1 kHz octave band. The left figure shows the results from the scale measurement and the right figure shows the results from the simulated model.

The comparison in Figure 14 shows that $\theta_t$ is observed in both the scale measurement and in the simulated model. In both cases it occurs at an inclination degree of 10. The scale measurements pressure distribution displays the expected pattern; a focus point located at the lower heights for the small angles of inclination. With increasing angle of inclination the focus points starts to increase in above $\theta_t$.

The pressure distribution pattern that the simulated model illustrates is directly related to the Odeon setup. Although the simulated model displays a probable relationship between the $\theta_t$, inclination angle and height of the pressure it does not calculate the pressure distribution correctly. The receivers in the model only yield values if the receiver is struck by a ray of reflected noise, the contribution of the receiver points that are not struck have negative levels.
4.2.2.2 Comparison: 2 kHz Octave band

Figure 15: The figures above are a comparison between the results of the scale measurement and the simulation. Both figures represent the results in the 2 kHz octave band. The left figure is the results from the scale measurement and the right figure is the results from the simulated model.

The 2 kHz octave band comparison in Figure 15 reveals that the \( \theta_t \) is perceptible in both the scale measurement and in the simulated model. The scale measurements focus point is located at three meters for the initial angles of inclination, thereafter is lowered by the increase of inclination. The focus point after \( \theta_t \) is divided into two points. One smaller that increases with the increasing of angle of inclination as expected at the \( \theta_t \) but there is also an additional focus point present that increases in height at an inclination angle of 15 degrees.

As in the previous comparison, Fig 14, the pressure distribution pattern that the simulated model illustrates is a direct result of the Odeon setup. The simulated model displays the expected pattern of \( \theta_t \).
5. Discussion

Although the theoretical model does not calculate the pressure distribution correctly, it still predicts the maximum height of reflected sound with reasonable accuracy. With present input parameters, the theoretical model can be used to calculate an approximate \( \theta \). The comparison at 1 kHz between the scale model measurement and the simulated model confirms the desired pressure distribution to the inclination angle, thus it can be assumed that this relationship is mainly based on the geometric relations between heights and distances. In the 2 kHz octave band comparison the scale model measurement presents a different behavior, with two pressure focus points; this can be a result of measurement error or an unknown phenomena. The 2 kHz case still displays that there is a height shift of the reflected noise pressure distribution for different angles of inclinations.

The reliability of the scale model measurement and the simulated model can also be taken into consideration. The scale model of the barrier model had a limitation in width caused by the size of the semi-anechoic chamber. An ordinary noise barrier is in practice a long horizontal structure. On all the edges of the barrier model (occurring mostly on the topside of actual noise barriers) diffraction source exists. This phenomenon could influence the pressure distribution but is probably not the cause of the strange behavior in the 2 kHz measurement. The simulated model results could be improved for more precise results of the pressure distribution and the results produced in this thesis are influenced by the authors confined knowledge of the software. But the results produced still display the desired behavior in the relationship between the pressure distribution at height and the angle of inclination.

Nevertheless, the knowledge of the effect the inclination has on the reflected noise in combination with the free design opportunities that noise barriers have enables the use of inclinations not only to remove unwanted light reflections but also to influence the noise radiation of traffic. An inclination can be used as an extra added feature to decrease the noise radiation. Because of the changes in height of the reflected noise as a result of the inclination this can be taken into consideration when planning the use of inclinations of noise barriers. A vertical barrier yields reflected noise at much higher altitude but at lower pressure compared to an inclined barrier that generates reflections at lower height but at increased pressure. This information can be useful in the staging processes of planning new housing areas near traffic that uses noise barriers. Another aspect that an inclination introduces is that more of the reflected noise interacts with the barrier and the ground. For each reflection that occurs energy is lost and with consideration of modern acoustic asphalt and barriers with absorbent material this could be used to reduce the noise radiation further.
5.1 Future work

5.1.1 Pressure distribution

To improve the pressure distribution of the theoretical model several steps could be taken.

- Include the scaling in strength for the mirror sources relatively to the angle of inclination of the barrier.
- Improved accuracy of the pressure calculations by including acoustic data such as damping and scattering for each component in the theoretical models as well as atmospheric data for the environment.

5.1.2 Scale model measurement

Additional parameters could be introduced to the scale model measurement for more precise and deeper results.

- If microphones would be used positioned on both sides of the barrier the effect the inclination have on the diffracted noise that propagates over the barrier could be included.
- A wider barrier scale model would reduce the influence of diffraction sources along the edges of the model.
- If more microphones used would result in more precise information on the pressure distribution of the reflected noise.

5.1.3 Simulated model

The simulations made in Odeon could be improved for more precise results regarding the pressure distribution. If the sources used would be modified to represent traffic both in strength and frequency much more exact results would be produced. If additional receiver points where used in the simulated more precise results could be produced regarding the pressure at height distribution.

6. Conclusions

The aim of this thesis was to determine the result an inclination of a noise barriers has on the reflected noise. This work originated as a request by Tyréns for a correction table for environmental noise mapping programs for noise barriers with inclinations. The correction table for environmental noise mapping programs has not been completed, but the thesis theoretical approach to the relationship between the reflected noise and the inclination angle of noise barriers has been verified and justified to a plausible degree by the scale model measurement and the simulated barrier models. A noise barrier blocks the propagation path of noise but the produced reflections effect the noise radiation on the opposite side of the road. This thesis results indicate that an inclination angle on the noise barrier has a prominent effect on the pressure distribution of the reflected noise and with further studies this effect could hopefully be used to decrease the noise radiation of roads.
Reference

[1] Infras (2004): External costs of transport (accidents, environmental and congestion costs) in Western Europe - University of Karlsruhe and Infras/IWW


Appendix

Appendix 1

Figure 16: The figure above displays the frequency spectrum for medium trucks for different speeds.

Figure 17: The figure above displays the frequency spectrum for heavy trucks for different speeds.
Appendix 2
clc
clear all
close all

for angle = 0:25
disp(sprintf('Calculating angle %d',angle))
% ------------ Input Parameters ---------------%
L1 = 7; %Distance between barrier and source [m];
L2 = 8; %Distance between barrier and measurement area [m];
H1 = 0.30; %Height of source [m];
H2 = 2.5; %Height of barrier [m];
V = angle; %Angle of tilt [degree];
f_min = 900; %Minimum Frequency [Hz]
f_max = 1500; %Maximum Frequency [Hz]
tol = 100; %Tolerance [nr]

% ----- Position of source and barrier and wavenumber calculation-----%
% x1, x2 = Source position
x1 = L1;
y1 = H1;
% x1, x2 = Barrier top position
x2 = 0;
y2 = H2;
% Converting angle of tilt from degrees to radians %
V1 = (V*(pi/180));
pref = (2*(10^-5));
% --------------Correction for tilt-------------- %
% Barrier location correction for tilt %
x2 = x2 + (tan(V1)*H2);
% Barrier correction for tilt %
c_b_corr = sqrt((L1^2)+((H2-H1)^2));
A_b_corr = acos((L1)/(c_b_corr));
A_b_corr = (A_b_corr-V1);
Y2_b_new = (tan(A_b_corr)*(L1))+H1;
% Ground->Barrier correction for tilt %
c_gb_corr = sqrt((L1^2)+((H1+H2)^2));
A_gb_corr = acos((L1)/(c_gb_corr));
A_gb_corr = (A_gb_corr-V1);
Y2_gb_new = (tan(A_gb_corr)*(L1))-H1;
% Barrier->Ground correction for tilt %
c_bg_corr = sqrt((L1^2)+(H1^2));
A_bg_corr = acos((L1)/(c_bg_corr));
A_bg_corr = (A_bg_corr+V1);
Y2_bg_new = (tan(A_bg_corr)*(L1));
% Create frequency range, size tol
f = linspace(f_min,f_max,tol);
k = (2*pi*f)./c;

% Create frequency range, size tol
f = linspace(f_min,f_max,tol);
k = (2*pi*f)./c;
% Linear eq. approx

% Ground->Barrier source

\[ k_{1\text{\_top}} = \frac{(Y_{2\text{\_gb\_new}} - (-y_1))}{(x_2 - (-x_1))}; \]
\[ m_{1\text{\_top}} = Y_{2\text{\_gb\_new}}; \]
\[ g_{b\text{\_top}} = (k_{1\text{\_top}} \cdot L_2) + m_{1\text{\_top}} + H_1; \]
\[ k_{1\text{\_bot}} = \frac{(y_1 - 0)}{(x_1 - 0)}; \]
\[ m_{1\text{\_bot}} = 0; \]
\[ g_{b\text{\_bot}} = (k_{1\text{\_bot}} \cdot L_2) + m_{1\text{\_bot}}; \]

% Barrier source

\[ k_{2\text{\_top}} = \frac{(Y_{2\text{\_b\_new}} - y_1)}{(x_2 - (-x_1))}; \]
\[ m_{2\text{\_top}} = Y_{2\text{\_b\_new}}; \]
\[ b_{\text{\_top}} = (k_{2\text{\_top}} \cdot L_2) + m_{2\text{\_top}}; \]
\[ k_{2\text{\_bot}} = \frac{(0 - y_1)}{(L_2 - x_1)}; \]
\[ m_{2\text{\_bot}} = y_1 - (k_{2\text{\_bot}} \cdot x_1); \]
\[ b_{\text{\_bot}} = (k_{2\text{\_bot}} \cdot L_2) + m_{2\text{\_bot}}; \]

% Barrier->Ground source

\[ k_{4\text{\_top}} = \frac{(Y_{2\text{\_bg\_new}} - 0)}{(x_1 - 0)}; \]
\[ m_{4\text{\_top}} = Y_{2\text{\_bg\_new}}; \]
\[ b_{\text{\_top}} = (k_{4\text{\_top}} \cdot L_2) + m_{4\text{\_top}} - H_1; \]
\[ k_{4\text{\_bot}} = \frac{(0 - y_1)}{(L_2 - x_1)}; \]
\[ m_{4\text{\_bot}} = y_1 - (k_{4\text{\_bot}} \cdot x_1); \]
\[ b_{\text{\_bot}} = (k_{4\text{\_bot}} \cdot L_2) + m_{4\text{\_bot}}; \]

% Diffraction source

if \[ b_{\text{\_top}}(\text{end}) > g_{b\text{\_top}}(\text{end}) \]
\[ d_{\text{\_top}} = b_{\text{\_top}}; \]
else
\[ d_{\text{\_top}} = g_{b\text{\_top}}; \]
end

\[ k_{3\text{\_bot}} = \frac{(0 - y_1)}{(L_2 - x_1)}; \]
\[ m_{3\text{\_bot}} = y_1 - (k_{3\text{\_bot}} \cdot x_1); \]
\[ d_{\text{\_bot}} = (k_{3\text{\_bot}} \cdot L_2) + m_{3\text{\_bot}}; \]

% Creating the min_max of each source

bg_min_max = [bg_bot bg_top];
gb_min_max = [gb_bot gb_top];
b_min_max = [b_bot b_top];
d_min_max = [d_bot d_top];

% Setting up location of sources & target area and add masking

% Target area at x = L_2 y = 0->d_max (in tol steps)

if \[ g_{b\text{\_min\_max}(2)} > b_{\text{\_min\_max}(2)} \]
\[ T = [L_2 \cdot \text{ones}(\text{tol},1) \ \text{linspace}(0, g_{b\text{\_min\_max}(2)}, \text{tol})']; \]
else
\[ T = [L_2 \cdot \text{ones}(\text{tol},1) \ \text{linspace}(0, b_{\text{\_min\_max}(2)}, \text{tol})']; \]
end

% Location of sources in size of target

d = repmat([L1 H1],[tol 1]);
gb = repmat([-L1 -H1],[tol 1]);
bg = repmat([-L1 -H1],[tol 1]);
b = repmat([-L1 H1],[tol 1]);

% Only allow direct contribution of the sources

d_mask = (d_min_max(1)<=T(:,2)) & (T(:,2)<=d_min_max(2));
gb_mask = (gb_min_max(1)<=T(:,2)) & (T(:,2)<=gb_min_max(2));
bg_mask = (bg_min_max(1)<=T(:,2)) & (T(:,2)<=bg_min_max(2));
b_mask = (b_min_max(1)<=T(:,2)) & (T(:,2)<=b_min_max(2));

% Prepare for plotting

% Calculate distances from all sources to targets (Pythagoras on columns)

delta_d_T = sqrt((T(:,1)-d(:,1)).^2 + (T(:,2)-d(:,2)).^2);
delta_gb_T = sqrt((T(:,1)-gb(:,1)).^2 + (T(:,2)-gb(:,2)).^2);
delta_bg_T = sqrt((T(:,1)-bg(:,1)).^2 + (T(:,2)-bg(:,2)).^2);
delta_b_T = sqrt((T(:,1)-b(:,1)).^2 + (T(:,2)-b(:,2)).^2);
% --- Repeat deltas tol number of times in col direction (nr. frequencies to calc. for) --- %
delta_d_T = repmat(delta_d_T,[1 tol]);
delta_gb_T = repmat(delta_gb_T,[1 tol]);
delta_bg_T = repmat(delta_bg_T,[1 tol]);
delta_b_T = repmat(delta_b_T,[1 tol]);
% --- Each frequency needs the same masking --- %
d_mask = repmat(d_mask,[1 tol]);
gb_mask = repmat(gb_mask,[1 tol]);
bg_mask = repmat(bg_mask,[1 tol]);
b_mask = repmat(b_mask,[1 tol]);
% --- Repeat for frequency (row direction)--- %
k = repmat(k,[tol 1]);
% --- Pressure calculation matrix (row = height) (cols = frequency) --- %
p = gb_mask.*(exp(sqrt(-1).*k.*delta_gb_T)./delta_gb_T) +
... bg_mask.*(exp(sqrt(-1).*k.*delta_bg_T)./delta_bg_T) +
... b_mask.*(exp(sqrt(-1).*k.*delta_b_T+pi))./delta_b_T +
... d_mask.*(exp(sqrt(-1).*k.*delta_d_T))./delta_d_T);
P = 10*log10(p/pref);
% --- Create plotting area x f_min->f_max, y = d_min->d_max --- %
if gb_min_max(2)>bg_min_max(2)
[X Y] = meshgrid(linspace(f_min,f_max,tol),linspace(0,gb_min_max(2),tol));
PH_E(:,:,angle+1) = [mean((abs(P)),2) linspace(0,gb_min_max(2),tol)'];
else
[X Y] = meshgrid(linspace(f_min,f_max,tol),linspace(0,bg_min_max(2),tol));
PH_E(:,:,angle+1) = [mean((abs(P)),2) linspace(0,bg_min_max(2),tol)'];
end;
end
% ------------------ Plotters ---------------------------- %
for idx = 0:25
X = squeeze(PH_E(:,1,idx+1));
Z = squeeze(linspace(PH_E(1,2,idx+1),PH_E(end,2,idx+1),tol)');
Y = idx*ones(100,1);
XX = [XX,X];YY = [YY,Y];ZZ = [ZZ,Z];
plot3(X,Y,Z,'k'),grid on, hold on
end
plot3(squeeze(PH_E(end,1,1:26)),0:25,squeeze(PH_E(end,2,1:26)),'or'),grid on, hold on
grid on
axis square
camproj perspective
view(63,14)
set(gca,'YTick',[0:2:25])
figure
surf(XX,YY,ZZ,XX)
grid on
axis square
camproj perspective
view(63,14)
set(gca,'YTick',[0:2:25])
Figure 18: The pictures above is from the scale model measurement and is of the barrier model and its barrier supporting system.
Figure 19: The pictures above is from the scale model measurement and is of the noise source and the source box.

Figure 20: The pictures above is from the scale model measurement and displays the entire setup for the scale model measurement. The barrier model has an inclination angle in the picture to the left.
Specifications of equipment used during the scale measurement

Larson Davis SRC20

Specifications

Frequency Characteristics
- Sine Wave: 0.01 Hz to 25 kHz
- Pink Noise: 20 Hz to 20 kHz
- White Noise: 1 Hz to 20 kHz
- High Sine: 250 Hz to 120 kHz

Sine Wave Spectral Purity
Harmonic Distortion
- 1 Hz to 10 kHz: 80 dB
- 10 kHz to 25 kHz: 65 dB

Output Characteristics
- Sine Wave Amplitude:
  - 40-120 dBµV (100 µV to 1 Vrms)
  - Sine Wave Accuracy (at 1 kHz):
    \[ \pm 0.02 \text{ dB (max)} \]
  - Sine Wave Flatness (relative to 1 kHz):
    - < 10 kHz: \[ \pm 0.1 \text{ dB (max)} \]
    - 10 kHz to 18 kHz: \[ \pm 0.2 \text{ dB (max)} \]
    - 20 kHz to 25 kHz: \[ \pm 0.5 \text{ dB (max)} \]
  - High Sine Flatness (rel. to 1kHz using computer command):
    - 1 kHz to 10 kHz: \[ 0.0 \text{ dB \pm 0.1 dB} \]
    - 12.5 kHz to 0.02 dB ±0.1 dB
    - 15.75 kHz: \[ 0.04 \text{ dB ±0.1 dB} \]
    - 20 kHz: \[ 0.06 \text{ dB ±0.1 dB} \]
    - 25 kHz: \[ 0.13 \text{ dB ±0.2 dB} \]
    - 31.5 kHz: \[ 0.15 \text{ dB ±0.3 dB} \]
    - 40 kHz: \[ 0.20 \text{ dB ±0.4 dB} \]
    - 50 kHz: \[ 0.41 \text{ dB ±0.6 dB} \]
    - 63 kHz: \[ 0.65 \text{ dB ±0.8 dB} \]
    - 79.4 kHz: \[ 1.02 \text{ dB ±1.0 dB} \]
    - 100 kHz: \[ 1.56 \text{ dB ±1.5 dB} \]
    - 130 kHz: \[ 2.30 \text{ dB ±2.0 dB} \]
  - High Sine Frequency Resolution: 250 Hz
  - High Sine Amplitude Accuracy at 1 kHz: \[ \pm 0.1 \text{ dB} \]
  - High Sine Amplitude Resolution: 0.01 dB
  - Pink Noise Output Level (set at 120 dB):
    - 0.04 to 0.05 Vrms (0.0470 Volts ±(0.4 dBV) Typical)
  - White Noise Output Level (set at 120 dB):
    - 0.25 to 0.28 Volts (0.27 Volts ±(1.3 dBV) Typical)
  - Output Impedance: 50 ohms
  - Connector: 3NC Female

Frequency Sweep
- Type: Linear or logarithmic
- Direction: Up or down
- Start/Stop Frequency (direction changes at zero crossing): 0.01 Hz to 35 kHz
- Times: 1 ms to 25,000 seconds
- Rates: 0.001 to 20 decades/second

Specifications are subject to change without notice.

Please contact your local Larson Davis representative or reach us directly for more information.


### Table 5: The figure above displays the results from the simulated model for 1 kHz octave bands pressure distribution at the height for different inclination angles from vertical to 25 degrees. The measurement displayed in the figure is a-weighted.

<table>
<thead>
<tr>
<th>Angle</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
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<td>44.1</td>
<td>41.3</td>
<td>36.9</td>
<td>33.6</td>
<td>32.3</td>
</tr>
<tr>
<td></td>
<td>45.9</td>
<td>42.8</td>
<td>40.6</td>
<td>36.0</td>
<td>33.7</td>
<td>32.4</td>
</tr>
<tr>
<td></td>
<td>45.7</td>
<td>41.8</td>
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</tr>
<tr>
<td></td>
<td>42.9</td>
<td>42.4</td>
<td>38.6</td>
<td>36.0</td>
<td>33.8</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>41.6</td>
<td>43.0</td>
<td>38.6</td>
<td>35.9</td>
<td>33.8</td>
<td>32.6</td>
</tr>
<tr>
<td></td>
<td>42.6</td>
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<td>45.5</td>
<td>41.6</td>
<td>37.3</td>
<td>34.8</td>
</tr>
<tr>
<td></td>
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<td>46.3</td>
<td>46.2</td>
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Table 6: The figure above displays the results from the simulated model for 1 kHz octave bands pressure distribution at the height for different inclination angles from vertical to 25 degrees. The measurement displayed in the figure is dBA.


Appendix 5

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Table 7: The figure above displays the results from the simulated model for 1 kHz octave bands pressure distribution at the height for different inclination angles from vertical to 25 degrees. The measurement displayed in the figure is dBA.
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Table 8: The figure above displays the results from the simulated model for 1 kHz octave bands pressure distribution at the height for different inclination angles from vertical to 25 degrees. The measurement displayed in the figure is a-weighted.