Faculty of **Engineering Sciences**

DOCUMENTATION

Visualization of a Noise Barrier for Educational Purposes

A project of Junge DEGA

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Symbol

D_e	**insertion loss:** $[D_\mathrm{e}] = \mathrm{dB}$
D_z	**barrier attenuation:** $[D_\mathrm{z}] = \mathrm{dB}$
L_p	**sound pressure level:** $[L_\mathrm{p}] = \mathrm{dB}$
N	**Fresnel number:** $[N]$ = *dimensionless parameter*
Z	**wall impedance:** $[Z] = \frac{\mathrm{N\,s}}{\mathrm{m}^3}$
α	**absorption coefficient:** $[\alpha]$ = *dimensionless parameter with* $0 \leq \alpha \leq 1$
c	**speed of sound in the fluid:** $[c] = \frac{\mathrm{m}}{\mathrm{s}}$
δ	**path-length difference:** $[\delta] = \mathrm{m}$
f	**frequency:** $[f] = \mathrm{Hz}$
λ	**wavelength:** $[\lambda] = \mathrm{m}$
p	**pressure:** $[p] = \mathrm{Pa}$
ρ_0	**equilibrium density of the fluid:** $[\rho_0] = \frac{\mathrm{kg}}{\mathrm{m}^3}$

Preface

The COMSOL app library of the Technical University of Munich is a collection of applications for simulating acoustic phenomena. They are used in the teaching of acoustics to visually represent fundamental vibrational aspects and provide learners with a visual understanding.

In the current project of the Junge DEGA, new apps are being developed under the leadership of the Technical University of Munich. The finite element method (FEM) simulation developed within this framework by the Mittweida University of Applied Sciences demonstrates the effect of a sound screen on sound propagation. The two-dimensional calculation illustrates the refraction and diffraction of sound waves at the edge of the screen. The geometry of the screen is freely adjustable, and a measurement point for evaluation can be freely moved. Furthermore, absorption coefficients of the wall and the ground can be freely adjusted to approximate the influence of different materials. All of this is supported by a theoretical calculation of barrier attenuation, aiming to integrate simulation and calculation according to DIN (German Institute for Standardization) standards.

The model was created using the Acoustics Module. The final publication is available on the COMSOL® Server of the Technical University of Munich, providing public access. To ensure uniformity within the library, the transition to an app was carried out using a template with the Application Builder.

1 Educational objective

In urban environments, noise pollution has become a significant concern, adversely affecting the quality of life for residents. A report by the EEA reveals that “a considerable number of people are still exposed to high noise levels” (European Environment Agency, 2020, p. 86) and “it is likely that noise outside urban areas will increase by 2030, in particular for road and rail traffic, due to an increase in the number of road and rail vehicles carrying passengers and freight.” (European Environment Agency, 2020, p. 86) In this context, it is not surprising that new methods for shaping acoustic environments are being developed, such as the Soundscape concept, which has found its place within the DIN landscape (Deutsches Institut für Normung e.V., 2018a). However, even in such broader approaches, conventional noise mitigation measures remain an integral part of the approach (Estorff and Lippert, 2023, S. 1–4).

Sound screens, also known as noise barriers or acoustic barriers, have gained popularity as effective measures to minimize noise emissions from roads, railways, and industrial facilities. These barriers are designed to block, absorb, or diffract sound waves, thus reducing the noise levels experienced by nearby communities.

In the field of acoustics education, it is particularly challenging to visually explain the non-visible sound waves. While audibilizing acoustic phenomena can be a helpful teaching tool, it is not always practicable or as versatile as a visual simulation.

In collaboration with the Junge DEGA, the Technical University of Munich has established a COMSOL® app library for a wide range of acoustic and vibration-related applications. It offers numerous simulation apps that can be used to enhance learning by using practical simulations in educational contexts.

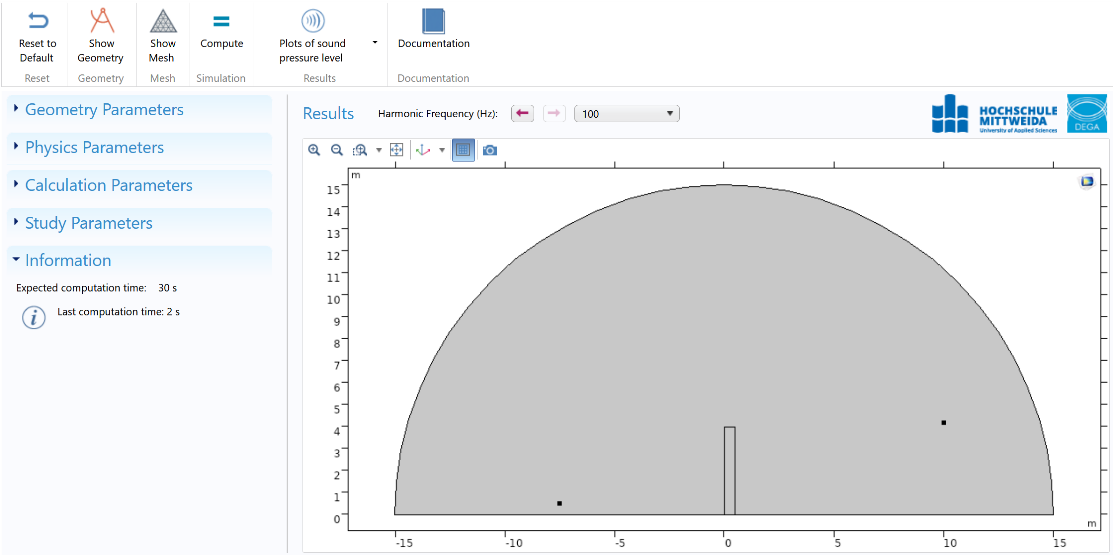
One of these apps, called *Sound Screen*, is part of this library and demonstrates the effects of a sound screen or noise barrier. It illustrates the frequency-dependent sound reducing effects, diffraction phenomena at the edge, as well as the impact of wall and floor absorption. For simplicity and focus on essential aspects, the simulation is reduced to a two-dimensional representation.
Additionally, formulas used in theoretical approaches were incorporated to display the calculated values directly alongside the simulation.

2 Using the app

The selected view displayed in figure 2.1 shows a cross-section of a sound screen or noise barrier, revealing the arrangement of elements. On the left side, a point source is positioned at a height of 0,5 m, emitting sound waves. The sound screen or barrier is placed in the center of the computational domain. Finally, on the right side, a movable measurement point is shown, enabling observation and analysis of the sound's behavior. The lower boundary symbolizes the ground, while the curvature transitions into a perfectly matched layer, allowing for a seamless representation of free sound propagation despite the simulation boundary.

2.1 General layout

The application window is divided into three sections: the menu bar on top, the settings tab on the left, and the results window.



Harmonic Frequency (Hz): 100

Expected computation time: 30 s

Last computation time: 2 s

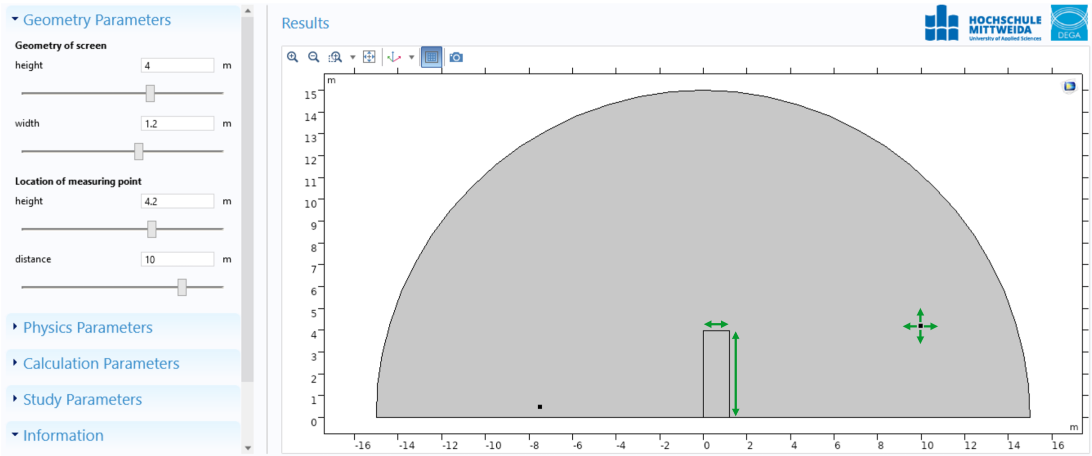
Figure 2.1: Overview

The menu bar allows switching the shown contents in the results window between geometry, mesh, point plot, and sound propagation plot. Furthermore, calculations can be initiated and the documentation can be accessed from here.

In the settings tab on the left the parameters for the simulation can be changed as shown below.

2.2 Geometry

The geometry parameter settings enable adjustments to the height and width of the sound screen, as well as the location of the measurement point. This can be achieved using the sliders or by directly entering the value into the designated field.



Geometry of screen

height 4 m

width 1.2 m

Location of measuring point

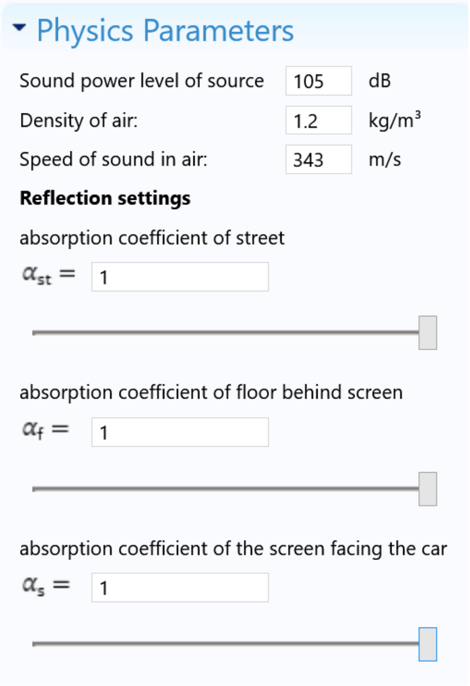
height 4.2 m

distance 10 m

Figure 2.2: Geometry settings

2.3 Physics

The physics parameters permit adjustments to the sound power level of the point source, air properties such as density and speed of sound, as well as the absorption coefficient of various surfaces. The initial slider adjusts the absorption coefficient α of the lane, which is the floor on the left of the screen. The second slider controls the α of the floor to the right, and the third slider regulates the value for the left side of the screen, which faces the point source or vehicle.[1]



Sound power level of source 105 dB

Density of air: 1.2 kg/m^3

Speed of sound in air: 343 m/s

Reflection settings

absorption coefficient of street

$\alpha_{st} =$ 1

absorption coefficient of floor behind screen

$\alpha_f =$ 1

absorption coefficient of the screen facing the car

$\alpha_s =$ 1

Figure 2.3: Physics parameters

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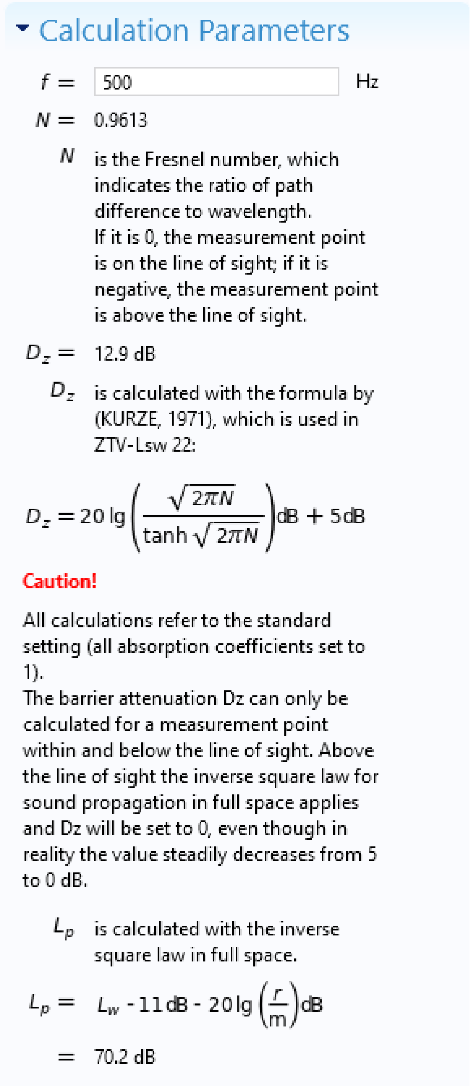
[1] Please be aware that while a sound absorption coefficient of 1 is necessary for the computation of D_z used in the calculations, it can introduce inaccuracies to the simulation in this configuration. Further details can be found in chapter 3.

2.4 Calculations

For the specified measurement point, the calculation parameters supplement the simulation with a calculated approach. The user may freely specify the frequency f , for which the barrier attenuation D_z is to be calculated, with an intermediate step through the Fresnel number N . It should be noted that these calculations apply solely to the standard scenario, in which all adjustable absorption coefficients α are set to 1. The D_z is only provided when the measurement point is at or below the line of sight to the sound source. Additionally, the projected sound pressure level L_p for full-space propagation is computed for further estimation, keeping in mind that all α need to be set to 1 for all calculations.



Calculation Parameters

$f =$ 500 Hz

$N =$ 0.9613

N is the Fresnel number, which indicates the ratio of path difference to wavelength.
If it is 0, the measurement point is on the line of sight; if it is negative, the measurement point is above the line of sight.

$D_z =$ 12.9 dB

D_z is calculated with the formula by (KURZE, 1971), which is used in ZTV-Lsw 22:

$$D_z = 20\,\mathrm{lg}\left(\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}}\right)\mathrm{dB} + 5\mathrm{dB}$$

Caution!

All calculations refer to the standard setting (all absorption coefficients set to 1).
The barrier attenuation Dz can only be calculated for a measurement point within and below the line of sight. Above the line of sight the inverse square law for sound propagation in full space applies and Dz will be set to 0, even though in reality the value steadily decreases from 5 to 0 dB.

L_p is calculated with the inverse square law in full space.

$$L_p = L_w - 11\,\mathrm{dB} - 20\,\mathrm{lg}\left(\frac{r}{\mathrm{m}}\right)\mathrm{dB}$$

$= 70.2$ dB

Figure 2.4: Calculation parameters

2.5 Solutions

There are two distinct computational methods for using the application with different objectives. One method involves the frequency domain, while the other is presented in the form of a Cartesian plot. Both methods are explained in the following sections.

2.5.1 Frequency domain

In COMSOL®, a frequency domain refers to a specific mode of analysis used to study the behavior of physical systems in the frequency or spectral domain. In this context, the frequency domain analysis involves examining how a system responds to varying sinusoidal excitation frequencies, as opposed to the time domain analysis that focuses on the system's response over time.

COMSOL® allows users to model and simulate various physical phenomena using the frequency domain analysis approach. It is particularly useful for systems that display significant frequency-dependent behavior, such as the acoustic propagation in this application.

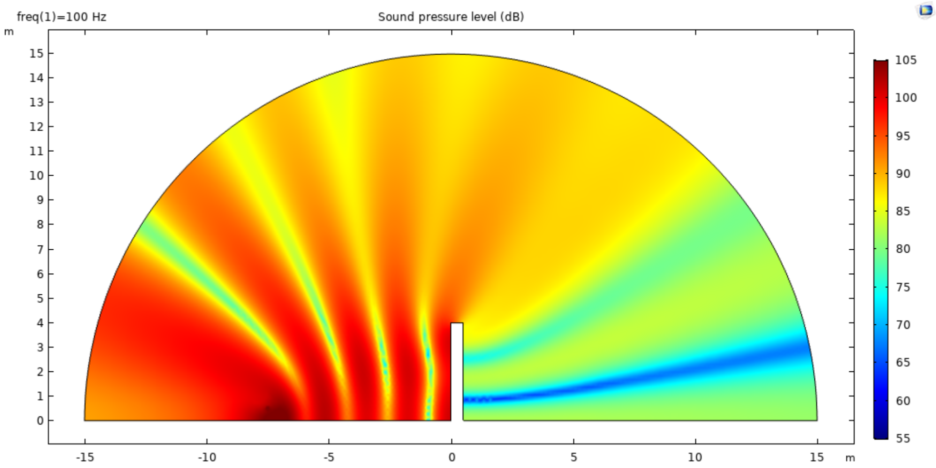


Figure 2.5: Results of an example calculation in the frequency domain

Figure 2.5 presents the outcomes of the frequency domain computation. The striped pattern illustrates the reflections coming from both the street and wall. This pattern can be interpreted as an interaction of sound waves interfering with each other. These interferences are responsible for the diffraction observed at the edge of the noise barrier.

2.5.2 Point graph

The Sound Screen Application includes the point graph shown in figure 2.6 to depict the sound pressure level at a specific measurement point that has already been set in the geometry settings (section 2.2) across a pre-defined frequency range.

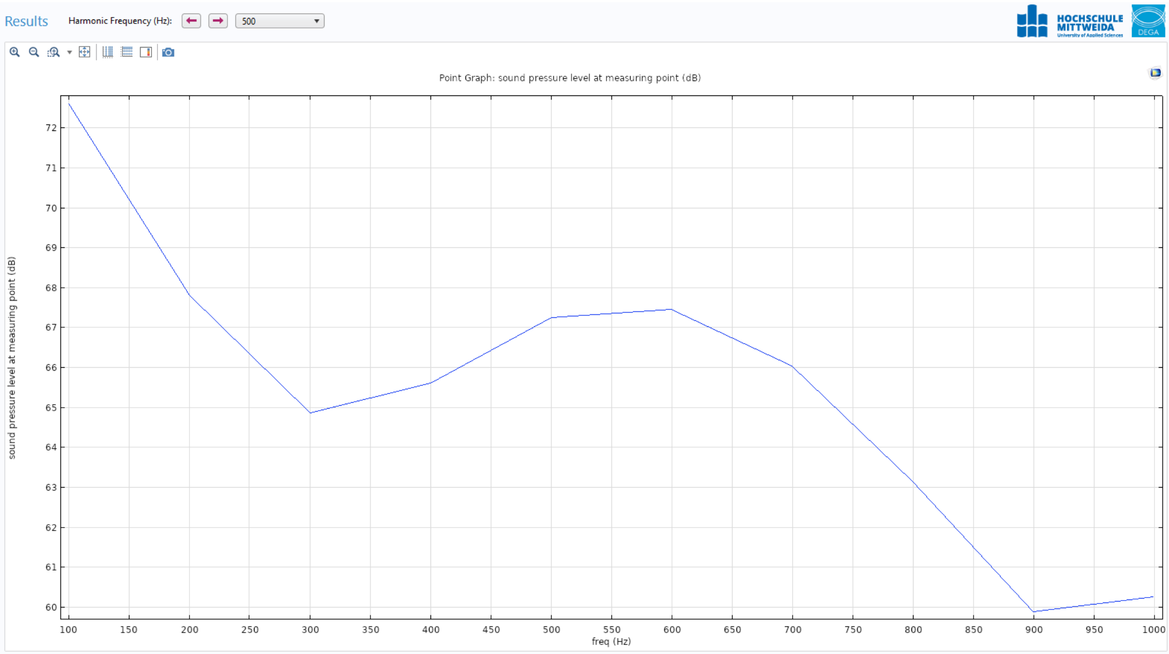

Harmonic Frequency (Hz): 500

Figure 2.6: Point graph for frequency range from 100 Hz to 500 Hz

The analysis of the sound pressure level graph across the frequency range yields valuable insights into the acoustic conditions of the screen at a designated measurement point. Where increases occur in the point graph (e.g. 600 Hz), the sound barrier does not act as effectively as it does at other frequencies (e.g. 300 Hz or 900 Hz). Outside of the teaching environment it is important for understanding the impact of different geometries and materials comprehending noise exposure in diverse environments.

3 Problems and limitations

The chapter below explains the limitations present in the soundscreen simulation and indicates areas requiring potential improvements in future phases.

3.1 Boundaries

No PML was applied to the straight interface at the bottom, resulting in unintended reflections being observable.

This decision was motivated by the objective to tailor the app to acoustics education, where the sound absorption coefficient is frequently used as a parameter. It is of crucial importance for the effectiveness of a noise barrier, as it determines how much sound energy is absorbed by the wall. Materials with higher absorption coefficients are capable of absorbing a greater amount of incident sound energy, leading to more effective noise reduction. They should be directly adjustable here in the application as well to provide straightforward teaching. However, in the current version of COMSOL® being utilized, this capability is only provided for exterior boundaries and is consequently applicable only when no PMLs is placed beneath the floor.
In this particular simulation, therefore, the decision was made to pass the implementation of PMLs up in favor of user-friendliness.

3.2 Transmission

Another limitation of this application concerns the calculation method for D_z described in section 2.4, in which sound transmission through the screen is not factored in. While sound absorption is considered by treating one side of the wall as an exterior boundary, sound transmission is currently not taken into account. As Maekawa pointed out, it is more crucial to focus on diffraction effects rather than sound transmission. However, it is worth noting that considering sound transmission might lead to different results. Therefore, an assessment of the screen material is necessary. If the screen's transmission loss is not significantly greater than the calculated reduction in diffracted sound, the contribution of transmitted energy to the sound level at the receiving point should be calculated. (Maekawa, 1968, p. 172)

4 Physical background

A FEM is utilised to execute the application, which is going to be further eludicated, as well as the location and physics of the sound source, screen and measurement point.

4.1 FEM

The FEM is a numerical technique widely used for solving complex engineering problems across various fields, including acoustics. FEM simulations involve dividing a complex structure or domain into smaller, manageable elements to approximate the behavior of the entire system. It is an essential tool for analyzing acoustic phenomena, as it allows engineers and researchers to study sound propagation, transmission, and radiation in different materials and environments.

4.1.1 Priciples of FEM

The Finite Element Method is characterized by great flexibility. It is based on the concept of discretization, where the continuous problem is transformed into a set of discrete equations for each element. Subsequently, the assembly of these solutions results in the solution for the global structure. The complex problem is decomposed into the consideration of smaller and simpler subproblems. (Betten, 2003)

First the behavior of each element is described by elemental equations, considering factors like material properties, boundary conditions, and geometry. These equations typically involve partial differential equations to model wave propagation or diffusion of sound. The elemental equations are then combined to formulate the global system of equations, which represents the entire domain. In the end numerical methods, such as matrix inversion, iterative solvers, or time-domain methods, are employed to solve the system of equations and obtain the solution for the problem.

4.1.2 FEM in acoustics

Finite Element Method simulations have a wide range of applications in acoustics, some of which are:

Noise Reduction and Control FEM simulations enable engineers to analyze the noise distribution and transmission paths in complex structures, such as automobiles, aircraft, and industrial machinery. By identifying the dominant noise sources and understanding the noise propagation mechanisms, effective noise reduction strategies can be developed.

Room Acoustics In architectural acoustics, they are used to study the acoustic behavior of rooms and auditoriums. This helps in optimizing the room design, including the placement of reflective surfaces, diffusers, and absorptive materials, to achieve desired acoustic characteristics, such as reverberation time and sound field distribution.

Automotive Noise Control FEM simulations were employed by researchers to analyze the noise transmission paths in a vehicle's cabin and optimize the placement of sound insulation materials. This resulted in a significant reduction in interior noise levels and improved passenger comfort.

Sound propagation in fluids Furthermore they are used to show the sound propagation in different fluids like air or water. In this particular project of the Junge DEGA the sound and wave propagation over a noise barrier was analyzed and visually illustrated.

4.1.3 COMSOL Acoustics Module

The physics interfaces include various fluid models that can simulate the way sound travels in complex materials. This includes modeling sound propagation in porous or fibrous materials using the Poroacoustics domain feature, simulating sound transmission in narrow sections with uniform cross-sectional areas using the Narrow Region Acoustics domain feature, and using fluid models to define how sound is absorbed in bulk materials. To limit the computational domain in both time and frequency, there are also perfectly matched layers (PML) available. Furthermore, there are specialized tools for viewing and analyzing results, which make it easier to visualize how sound radiates in different patterns through polar, 2D, and 3D plots. (COMSOL, 2022)

The COMSOL® Acoustics Module utilizes the linearized Euler equations to model and simulate acoustic phenomena in most cases. The linearized Euler equations are a set of partial differential equations that describe the propagation of small perturbations in a fluid, which represents the acoustic wave behavior.

In the linear acoustic approximation, the equations govern the variations in pressure, velocity, and density in the fluid medium due to sound waves. The COMSOL® Acoustics Module enables users to solve these equations numerically to study various acoustic phenomena such as sound propagation, reflection, refraction, diffraction, absorption, and radiation.

There are nine main branches in the COMSOL® Acoustics Module — Pressure Acoustics, Elastic Waves, Acoustic-Structure Interaction, Aeroacoustics, Thermoviscous Acoustics, Ultrasound, Geometrical Acoustics, Pipe Acoustics, and Acoustic Streaming. This Project only uses the Pressure Acoustics Branch described in the following section.

4.1.3.1 Pressure Acoustics

The Pressure Acoustics branch provides interfaces where the acoustic field is characterized by the pressure variable p . Acoustic problems are addressed through the frequency domain interface in the context of the Helmholtz equation solution, conducted in the frequency domain. The Junge DEGA project exclusively utilizes this particular interface for plotting sound pressure levels corresponding to varying frequencies.

Conversely, the remaining eight branches cater to distinct problem-solving requirements and do not find applicability within the noise barrier context. For example, transient systems are handled by the Pressure Acoustics Transient interface, which employs the classical wave equation for solutions. Incorporation of nonlinear effects is possible through the Nonlinear Acoustics (Westervelt) feature, while the Boundary Mode Acoustics interface is instrumental in studying propagating modes in waveguides and ducts. The Boundary Element interface efficiently addresses extensive radiation and scattering problems by solving the Helmholtz equation via the BEM method. (COMSOL, 2022)

The Pressure Acoustics branch affords a wide array of boundary conditions encompassing sound-reflective walls, distinct impedances, tunable absorption coefficients, and provisions for various source types such as point sources or cylindrical wave propagation. The repertoire further encompasses radiation, symmetry, periodic, and port conditions, apt for modeling open boundaries. Impedance conditions span models for different components of the human ear, human skin, simple RCL circuit models, and more. (COMSOL, 2022)

Within this application, the adjustable absorption coefficient α serves as a boundary condition replicating different materials of both the sound barrier and the road surface.

The Sound Screen application employs air as the relevant fluid for simulating sound propagation over a noise barrier. The integration of a PML emulates an unbounded environment. Without this, the upper curved boundary would reflect sound back to the ground, which fails to reflect the behavior in real-world scenarios.

4.2 Sound screen

As mentioned in the Educational objective, ensuring a quiet environment for citizens gets more important in the future. To see how the sound screen is affecting sound waves and thus affecting the acoustical environment, this application was programmed for young engineers and students in the acoustic field.

4.2.1 Positionings

The positioning and dimensions of the point sound source, the screen, and the measurement point significantly influence the simulation results. The default settings are aligned with DIN-compliant scenarios.

4.2.1.1 Point sound source representing a car on a lane

In the process of sound immission calculation, each lane is partitioned into small sections, which are considered as point sound sources situated at an elevation of 0,5 m above the lane's central axis (Müller and Möser, 2004, p. 478). This approach aligns with the specifications outlined in DIN 18005 (Deutsches Institut für Normung e.V., 2023, p. 8), which similarly dissects larger sources into point sources. In our particular simulation, a standard separation distance of 7,5 m between the lane and the noise barrier is employed.

4.2.1.2 Measurement point representing a sound immission point

The measurement point is initially configured at a default position, situated 10 m horizontally and 4,2 m in height. It is adjustable, facilitating the assessment of various scenarios in an educational context, while the default setup simulates a sound immission point, similar to one used in front of a window on an upper floor. The significant immission points according to TA Lärm (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2017) are located 0,5 m beyond the central axis of the open window in the room that is both most affected by noise and protected, as specified in DIN 4109 (Deutsches Institut für Normung e.V., 2018b).

4.2.2 Simulation parameters

The simulation outcomes are notably contingent on the nature of the surroundings. Both the characteristics of the point sound source and the properties of the air and surfaces play a role in shaping sound propagation.

4.2.2.1 Sound power level of source

The sound pressure level of the point source serves as a fundamental parameter that directly influences the overall sound pressure level within the simulated environment. The sound pressure level must be sufficiently high to allow a significant portion of it to propagate to the sound barrier, enabling the observation of the barrier's effect.

4.2.2.2 Characteristics of the fluid

For the choice of the propagation medium, air was selected. Air's properties can be more precisely characterized by two key parameters: its density ρ_0 and the speed of sound c.

These parameters play a pivotal role in acoustic phenomena. What makes them especially significant is the direct interdependence between c, wavelength λ, and frequency f encapsulated by the equation $c = \lambda \cdot f$. This equation signifies that any modification of c inevitably induces corresponding changes in both λ and f. (Sinambari and Sentpali, 2020, pp. 19ff)

In practical terms, this interrelationship means that alterations in any one of these parameters can have cascading effects throughout the simulation results. Therefore, understanding and controlling the density and speed of sound of the chosen medium is vital in ensuring the accuracy and reliability of the simulation outcomes.

4.2.2.3 Absorption coefficients

The absorption coefficient α is a quantifiable parameter that indicates the degree of sound energy absorption by the material of the wall. This coefficient reflects the material's ability to absorb sound waves rather than reflecting or transmitting them.

In comparison to wall impedance Z, the calculation and application of the absorption coefficient are often simpler in practice. Wall impedance requires a deeper analysis of the wall's acoustic properties, including sound reflection, transmission, and absorption at the boundaries. This analysis can be complex and demands a detailed understanding of material properties as well as wall geometry.

Conversely, the absorption coefficient can be determined through empirical measurements by directing sound waves onto the material and measuring the reflected and absorbed energy. This enables a more practical assessment of sound absorption properties of materials and their suitability for noise control.

Therefore, the absorption coefficient is also preferred in this application to characterize the performance of noise barriers and to evaluate materials based on their ability to absorb sound energy. It is evident in simulations that the absorption coefficient of the wall, as well as that of the ground, directly influences the outcome. Furthermore the absorption coefficient is more comprehensible for students who are encountering concepts related to acoustics and material parameters for the first time.

4.2.3 Calculation parameters

In addition to the simulation results, the app incorporates computational approaches. The values for the barrier attenuation D_z and insertion loss D_e are frequency-dependent parameters that rely on the previously mentioned quantities.

4.2.3.1 Fresnel number

The Fresnel number N is a metric that expresses the relationship between the path-length difference δ and wavelength λ. It is essential for accounting for the frequency dependence of both D_e and D_z.

The path difference in this context refers to the disparity between the distance that the direct sound would travel from the transmitter to the receiver without obstruction and the shortest distance it can take over the sound screen. The Fresnel number helps predict how waves will bend and spread as they encounter the screen's edge, influencing the overall sound distribution and pattern. According to (Kurze and Anderson, 1971, p. 36) it is calculated through

$$N = \frac{2\delta}{\lambda}. \tag{4.1}$$

4.2.3.2 Barrier attenuation

The barrier attenuation D_z refers to the reduction in sound energy or intensity, which in this case is caused by an acoustic barrier. It's a measure of how effectively the screen can reduce the transmission of sound waves from one side to the other. The higher the barrier attenuation the more effectively it reduces the sound energy, resulting in lower noise levels.

As shown in (Kurze and Anderson, 1971, S. 42) and further described in (Hübelt and Schulze, 2007, pp. 19-21), the barrier attenuation is calculated through

$$D_\mathrm{z} = 20\,\lg\left(\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}}\right)\,\mathrm{dB} + 5\,\mathrm{dB} \tag{4.2}$$

resulting in a frequency-dependent value, as it directly depends on the Fresnel number shown in equation 4.1.

4.2.3.3 Insertion loss

Insertion loss D_e refers to the reduction in signal strength or power when a device, component, or material is inserted into a system. It's often used to describe the attenuation of a signal as it passes through a medium or device, such as in acoustics or electronics. In acoustics, insertion loss measures the reduction in sound level caused by an acoustic barrier or other sound-blocking measures. In electronics, insertion loss can describe the decrease in signal strength when a component is added to a circuit, such as a filter or attenuator.

The application of the Mittweida University of Applied Sciences for simulating a sound screen is now developed and is accessible in the app library of the Technical University Munich under apps.vib.ed.tum.de

Glossary

BEM (*Boundry Element Method*) Numerical technique for solving partial differential equations by focusing on discretizing the problem only on its boundary.

COMSOL® Software company, that develops and provides the simulation software called *COMSOL® Multiphysics*. Users utilize it to create numerical models based on partial differential equations, which describe the behavior of physical systems. Specific calculations such as sound waves and acoustic phenomena require additional toolboxes like the acoustic toolbox.

DEGA Deutsche Gesellschaft für Akustik (*German Acoustical Society*). Scientific association and professional society in Germany, that focuses on the study and application of acoustics.

EEA *(European Environment Agency)*. Agency of the European Union (EU) responsible for collecting and analyzing environmental data, producing reports on Europe's environment, and providing support for EU environmental policies and decision-making. It plays a central role in promoting environmental sustainability within the EU.

FEM (*Finite Element Method*) Numerical technique used to solve complex engineering problems by dividing them into smaller, more manageable elements.

Junge DEGA (*young DEGA*) Youth division and subgroup within DEGA that specifically adresses young members and students, who are interested in the field of acoustics. It provides a platform for young acousticians to network, exchange knowledge, and engage in activities related to acoustics.

PML (*Perfectly Matched Layer*) A specialized technique in FEM simulations, used to simulate wave propagation with minimal reflections at the model boundaries. By incorporating anisotropic absorbing materials and tailored impedance profiles, PML attenuates outgoing waves, enhancing accuracy by minimizing artificial boundary effects.

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