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Optimization of noise barrier reflection properties

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ABSTRACT

Noise barriers are a common tool to mitigate roadway and railway noise. They are characterized by extrinsic parameters, e.g., the insertion loss, and by intrinsic parameters, i.e., the sound insulation index as defined in EN 1793-6 [1] and the sound reflection index as defined in EN 1793-5 [2] . The reflection index mainly depends on the surface structure of a noise barrier's front side and on the acoustic absorption properties of the materials in use. In this study, a noise barrier was optimized to achieve a maximal $\mathrm{DL_{RI}}$, which is the attenuation of the reflected sound in dB, weighted with the road traffic noise spectrum EN 1793-3[3]. For the optimization, an analytical model similar to the transfer matrix method was used. Its small computational effort allowed to test many different geometries and absorber parameters. The best performing setup was verified with the finite element method (FEM) which was implemented in the open source software FEniCS [4]. Finally, a prototype of the optimized noise barrier was built and measured according to EN 1793-5 [2]. Results of the analytical calculation, the FEM simulation, and the measurement were compared.

Keywords: Noise Barriers, Sound Reflection, Optimization
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1. INTRODUCTION

Noise barriers are important measures against traffic noise. Their intrinsic properties can be assessed with in-situ measurement methods, e.g., sound reflection [2] or sound insulation [1]. A good mathematical model of acoustic barrier properties, allows a cost efficient product optimization in its development phase.

In this study a noise barrier, consisting of aluminum cassette elements, was optimized regarding its sound reflection properties, i.e., the so called $\mathrm{DL_{RI}}$ as described in EN 1793-5 [2].

An analytical mathematical method was derived, to create a high performing model for the optimization process. Various parameters of the noise barrier were varied and their associated $\mathrm{DL_{RI}}$ ratings calculated. Because of inaccuracies of the analytical model, primarily for high frequencies, the resulting optimal parameter configuration was verified with a FEM simulation. To reduce the computational effort, only a periodic cutout of the noise barrier, containing a unit cell of the front plate perforations, was simulated.

A new noise barrier prototype was built, according to the result of the optimization process and FEM verification. Finally, the $\mathrm{DL_{RI}}$ of the noise-barrier prototype was determined.

2. METHODS

2.1 Measurement

First the in-situ measurement method described in [2] was used to determine the sound reflection of a noise barrier. The measurement setup is shown in Fig. 1. A loud-speaker is placed in front of a noise barrier, with a three-times-three microphone grid in between. An impulse response is recorded, containing a direct and a reflected sound component. Subtraction of a free-field impulse response, allows the separation of the direct and the reflected components. Additional time windowing allows the removal of ground reflections from the impulse responses. With the following equation a third-octave band spectrum of the reflection

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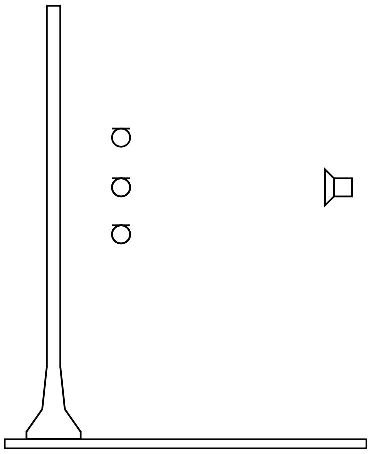

Figure 1 – Measurement Setup

index can then be calculated from the recorded and processed impulse responses.

$$\mathrm{RI}_j = \frac{1}{n_j}\sum_{k=1}^{n_j}\left[\frac{\int_{\Delta f_j} |F[h_{r,k}(t)\cdot w_{r,k}(t)]|^2 \mathrm{d}f}{\int_{\Delta f_j} |F[h_{i,k}(t)\cdot w_{i,k}(t)]|^2 \mathrm{d}f}\cdot C_{\mathrm{geo,k}}\cdot C_{\mathrm{dir,k}}(\Delta f_j)\cdot C_{\mathrm{gain,k}}(\Delta f_g)\right] \tag{1}$$

$F[...]$	...	fourier transform
w_r, w_i	...	time windows
h_r, h_i	...	reflected and incident impulse responses
Δf_j	...	one-third octave band
$C_{\mathrm{geo,k}}$	...	correction for propagation characteristic
$C_{\mathrm{dir,k}}(\Delta f_j)$	...	correction for loud-speaker directivity
$C_{\mathrm{gain,k}}(\Delta f_g)$	...	correction for gain adjustment

The RI is the ratio of the incident and reflected sound intensity, therefore its values are between zero and one. From the spectrum of the reflection index RI_i, a single number rating can be calculated by summation and weighting with the standardized traffic noise spectrum L_i [3].

$$\mathrm{DL}_{\mathrm{RI}} = -10\cdot\log_{10}\frac{\sum_i \mathrm{RI}_i\cdot 10^{0.1L_i}}{\sum_i 10^{0.1L_i}} \tag{2}$$

The $\mathrm{DL}_{\mathrm{RI}}$ represents the noise-barriers effectiveness for road noise in form of a single number rating, meaning that high $\mathrm{DL}_{\mathrm{RI}}$-values represent a low sound reflection, while low values represent high sound reflection.

2.2 Analytical Model

A noise barrier consisting of aluminum cassette elements, which contain absorbing materials, can be roughly modeled as a one-dimensional layered system. In each layer consisting of air or absorbing material, a superposition of an incoming and an outgoing plane sound wave is assumed. At the interfaces between the different layers, certain interface conditions must be met by the sound waves. Additionally, certain boundary conditions at the borders of the layered system must be satisfied. These constraints allow the construction of a linear system of equations, to calculate the amplitudes of the plane waves for every layer. The reflection index can then be calculated from the amplitude ratio in the outermost layer.

The following equation describes the sound pressure of the assumed plane waves in a layer of air.

$$p(x) = A\mathrm{e}^{\mathrm{i}kx} + B\mathrm{e}^{-\mathrm{i}kx} \tag{3}$$

The associated particle velocity is

$$v(x) = -\frac{1}{\rho c}(A\mathrm{e}^{\mathrm{i}kx} - B\mathrm{e}^{-\mathrm{i}kx}). \tag{4}$$

In absorbing materials the wave number k is replaced with the complex wave number k_a which introduces damping [5].

$$k_a = k\sqrt{\kappa - \mathrm{i}\frac{\Xi\sigma}{\omega\rho}} \tag{5}$$

It depends on the following absorber parameters.

κ	...	tortuosity [1]
σ	...	porosity [1]
Ξ	...	specific flow resistivity [$\mathrm{Pa\,s\,m^{-2}}$]

Therefore the sound pressure in a porous absorber can be written as

$$p(x) = A\mathrm{e}^{\mathrm{i}k_a x} + B\mathrm{e}^{-\mathrm{i}k_a x}. \tag{6}$$

The associated particle velocity is

$$v(x) = -\frac{\sigma}{\rho c}\frac{k}{k_a}\left(A\mathrm{e}^{\mathrm{i}k_a x} + B\mathrm{e}^{-\mathrm{i}k_a x}\right). \tag{7}$$

At the layer interfaces continuity of the sound pressure and the particle velocity is assumed with the exception of the back plate and the perforated front of the barrier. These are modeled with the impedance of oscillating masses. Therefore the sound pressure on the left and the right side (p_l, p_r) of the oscillating masses can be written as

$$p_l - p_r = m\mathrm{i}\omega v. \tag{8}$$

The particle velocity v is equal on both sides, for an incompressible mass. For the back-plate the mass m is the mass per unit area of aluminum, while for the perforated front it is the mass of air in the perforations.

$$m'' = \frac{\rho\left(W + b\frac{5}{3}\right)}{\sigma_L} \tag{9}$$

ρ	...	density of air [$\mathrm{kg\,m^{-3}}$]
W	...	thickness of the plate [m]
b	...	radius of the perforations [m]
σ_L	...	perforation ratio [1]

Eq. 8 can be used as a boundary condition if the ratio $\frac{p}{v}$ can be written as $\frac{\rho}{c}$, which represents free field sound propagation.

Finally, a linear system of equations for the amplitudes A, B of all plane waves can be constructed from the boundary and interface conditions. The spectrum of the reflection index can now be calculated from the amplitude ratio in the outermost layer, where an incoming wave, to excite the system, is introduced.

$$\mathrm{RI}(f) = \frac{B(f)}{A(f)} \tag{10}$$

2.3 FEM Model

The analytical model is a very efficient calculation method, which is important for the optimization process. For high frequencies, where the perforated front plate of the noise barrier becomes dominant (Fig. 2), this purely one-dimensional model becomes inaccurate. Therefore a validation of the optimized solution, generated with the analytical model, was necessary.

For this purpose a finite-element simulation, with the open source software FEniCS [4] was performed. To reduce the computational effort only a cutout of the noise barrier, containing a unit cell of the front-plate perforations was simulated with periodic boundary conditions. In contrast to the one-dimensional analytical model, the FEM simulation allows the incorporation of periodic three-dimensional structures, like the front-plate perforations. In Fig. 2 it can be seen, that the FEM simulation produces more accurate results for high frequencies, where the front-plate perforations become dominant, compared to the analytical model.

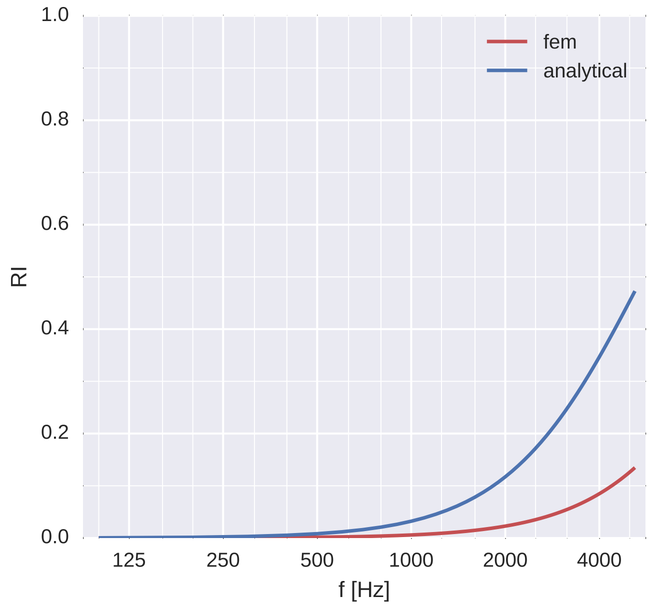

Figure 2 – Comparison of the reflection index of a perforated plate with a hole ratio of 30 %

3. OPTIMIZATION OF SOUND REFLECTION PROPERTIES

The analytical model described in the previous section was used to optimize the arrangement and type of absorbing materials inside of a noise barrier consisting of aluminum cassette elements. The key quantity, which had to be maximized, was the DL_{RI}. The input parameters for the optimization were the layer thicknesses (a1 to a5 Fig. 3) and the absorber properties (flow resistivity Ξ, tortuosity κ), while the total thickness of the system was held constant Eq. 11. To reduce the number of free parameters only a system with not more than two absorbing layers was considered. Also, the porosity σ of the absorbing materials was not varied, because of its small influence on the reflection index. The small computational effort of the analytical model allowed the calculation of the DL_{RI} for over five million different absorber arrangements. Fig. 4 shows a subset of the generated DL_{RI} data, generated in the optimization process.

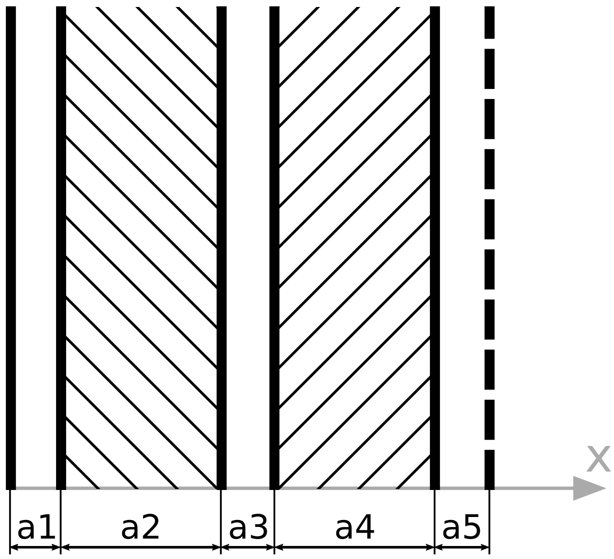

Figure 3 – Noise barrier cross section to be optimized

$$a1 + a2 + a3 + a4 + a5 = 12\,\text{cm} \tag{11}$$

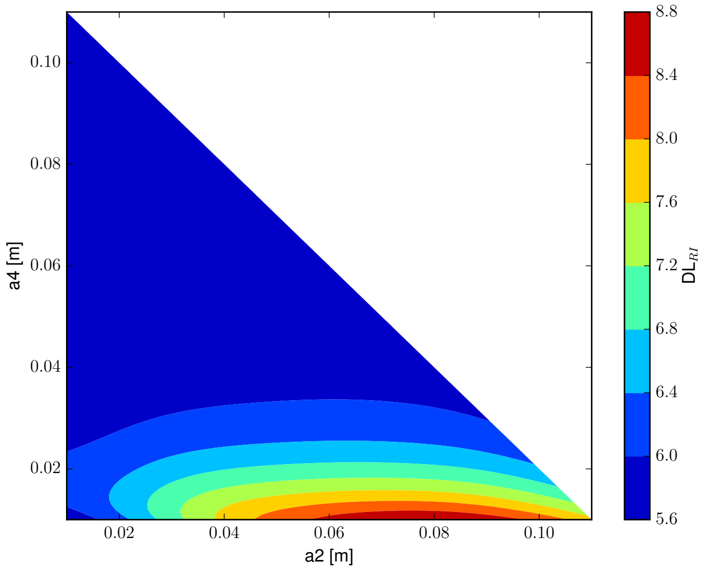

Figure 4 – Subset of the DL_{RI} data for constant absorber parameters ($a1 = a5 = 0$ and $a2 + a4 \leq 11\,\text{cm}$)

4. CONCLUSION

In this study the inner structure of a noise barrier was optimized in regard to the reflection properties. The aim was to maximize the DL_{RI} of a noise barrier with a given outer geometry. For this purpose a simple analytical model was created to achieve a high computation speed. This allowed the investigation of over five million absorber configurations.

In addition a FEM simulation of the optimal absorber configuration was performed, to compensate inaccuracies of the analytical model for high frequencies.

Based on these simulations, a new noise-barrier prototype was built. A validation measurement of the prototype revealed a DL_{RI} above 8, which represents a relevant improvement compared to the noise barriers currently available on the market.

A more detailed description of the methods used in this paper is currently under review in the scientific journal "Applied Acoustics".

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