Numerical simulation of the sound reflection effects of noise barriers in near and far field

D. Lutgendorf

F. de Roo

F. van der Eerden

P. Jean
Centre Scientifique et Technique du Bâtiment, Saint-Martin-d'Héres, France.

D. Ecotière
LRPC, Strasbourg, France.

G. Dutilleux
LRPC, Strasbourg, France.

Summary
This paper deals with the first stages of the development of a new test method for evaluating the reflectivity performance of noise barriers. The reflectivity performance describes the increase in sound level at a receiver due to the presence of the noise barrier. First the current test method for sound reflectivity is simulated with three different numerical simulation models (time and frequency domain). It is shown that a good insight can be obtained in the reflection patterns and the measurement process. The Reflection Index (RI, comparable to the reflection coefficient) in the near-field is dependent on geometry and level of absorption of the material on the barrier. Preliminary results are presented for Reflection Indices in the far field for several types of barrier. From these results the effect of the shape of the barrier can be distinguished. Further research will involve the matching of simulated RIs with measured RIs and the extrapolation from RIs in the near field to RIs in the far field.

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1. Introduction

In the EU FP7 project QUIESST a new test method for sound reflectivity of noise barriers is being developed. This new test method may replace the so-called Adrienne method which is published in CEN Technical Specification 1793-5 [1]. It will be based on an integration of the measurement of reflection effects in a near-field test set-up and the computation of the reflection effect in the far-field. Finally this will lead to a performance indicator for the reflectivity of noise barriers in the far-field.

The development of this far field performance indicator can be subdivided in several essential steps:

1. Accurate simulation of the reflected sound field in the near field in order to be able to match simulation results with the measured results;
2. Tuning simulations with measurement data to determine the general level of absorption;
3. Extrapolation of the near field ‘tuned’ data to effects in the far-field with a numerical simulation method;
4. Development of a simplified engineering method to perform the above extrapolation;
5. Validation of both methods against measured data in near and far field.

This paper will focus on step one and will give an outlook at further research.
2. Description of Adrienne measurements

The current near field measurement method for sound reflection is described in CEN/TS 1793-5 [1]. Nine different source-receiver pairs, at angles equally spaced over an arc from 50° (receiver position 1) till 130° (receiver position 9), are evaluated in a rotated set-up with one loudspeaker, see Figure 1. Time impulse responses are obtained at each position, containing a direct component and reflected components. A special time window is used to filter out the unwanted reflections from the ground from the total signal. After time windowing a signal subtraction method is used to eliminate the direct sound component from the total signal. The Reflection Index (RI) is the ratio between the reflected sound power and the free field sound power. This index is similar to the sound reflection coefficient. The final RI is an average of the RI’s of all nine receivers. The CEN1793-5 standard prescribes analyses in the 100 to 5kHz octave bands, dependent on the receiver position, and a sample rate of 43kHz.

3. Simulation of Adrienne measurements

The most important requirements for the simulation model are its ability to model the non-flat shape of the barriers and its capability of modeling the acoustic impedance of materials most commonly used in noise barriers. In order to perform the same steps as described in the CEN1793-5 standard it is essential that the simulation model can simulate impulse responses of the incident and reflected sound waves with a high time resolution.

To investigate the suitability of different simulation models for near field reflectivity simulations of barriers, three partners of the Quiest consortium (CSTB, LRPC and TNO) have performed simulations of the Adrienne method. Two time-domain models and one frequency domain model were used.

3.1. Test cases

Three different types of complex barrier geometries have been studied (see Figure 2):
- Inclined flat barrier under 14° tilt;
- Saw-tooth: each tooth 30cm high and 30cm deep.
- Step: steps 10cm deep and 30cm high (18° tilt).

A flat vertical barrier is modeled as reference. All types of barriers were simulated with a rigid surface and with a Delany and Bazley impedance with a flow resistivity of 10 and 30 kPa.s/m². This lies in the range of flow resistivity’s of mineral wool types. The layer of absorptive material had a thickness of 0.10m. In addition to the ‘Delany and Bazley’ material, an imaginary absorptive material with a fixed absorption coefficient $\alpha_{\text{fixed}}$ of 0.2, 0.3 and 0.85 in the whole frequency range is modeled. The height of the barrier was 4m which is the minimum required height in the CEN1793-5 standard. The ground was modeled in all cases as a rigid flat surface.

3.2. Frequency domain model

The frequency domain model used in this study is the Boundary Element Method (BEM), see [2] for a description. For the simulation a frequency resolution $\Delta f$ of 10Hz is used. The total simulated time then becomes 0.1s which is enough to include all relevant information of the reflection pattern. A complex impedance can be assigned to the barrier elements to model the material of the barrier.

3.3. Time domain models

Two time domain models are used:
- Transmission Line Matrix (TLM) based on the Huygen’s principle, see [3].
- FDTD or ‘Euler model’ based on the Euler equations, see [4].
An example of the intricate interference pattern of a sound wave after reflecting at a barrier is illustrated in Figure 3.

The time step for Euler is determined by the CFL number (Courant–Friedrichs–Lewy condition) which ensures that the time step in the model is smaller than the time it takes the sound to travel to the adjacent grid point. In other words; the simulation speed should be a factor CFL smaller than the sound speed.

\[
CFL = \frac{c \cdot \Delta t}{\Delta y}
\]

\[
v_{\text{sim}} = \frac{\Delta y}{\Delta t} = \frac{1}{CFL} \cdot c
\]

with \(c\) the sound speed in meter per seconds, grid spacing \(\Delta y\) in meters and time resolution \(\Delta t\) in seconds. For rigid surfaces a CFL of \(1/\sqrt{2}\) is used to ensure a stable solution; with the absorptive material used in this study a CFL of \(1/3\) is necessary to ensure a stable and convergent solution. The grid spacing (the same in both directions) affects the maximum reliable frequency; each wavelength must be described by a certain number \((n)\) of grid points, to get accurate results:

\[
f_{\text{max}} = \frac{c}{(\Delta y \cdot n)}
\]

The used simulation parameters are summarized in Table 1.

<table>
<thead>
<tr>
<th>parameter</th>
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<tr>
<td>EULER</td>
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<td>BEM</td>
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<td>(T) [ms]</td>
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<td>20</td>
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<td>100</td>
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<td>(\Delta y) [mm]</td>
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<td>15</td>
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<td>25 (absorption)</td>
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<td>16.42</td>
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<tr>
<td>(f_{\text{max}}) [Hz]</td>
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<tr>
<td>4000 (rigid)</td>
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<td>1380</td>
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<td>5000</td>
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</table>

As TLM and Euler are time domain models and impedances are generally described in the frequency domain, a problem arises when complex impedances must be assigned to the barrier. A transformation method by Heutschi [5] is used which approximates the complex impedance by a polynomial. This second order polynomial can easily be transformed to the time domain. However, this method is still limited to the smooth Delany and Bazley impedance model because it can be described by a second order.

4. Results

The different results of simulating the Adrienne measurements are described.

4.1. Impulse responses and windowing

In the standard measurement method a special time window (described in CEN/TS1793-5 [1]) is used to filter out the unwanted contributions from the signal. As TLM and Euler both return a time signal the time window can directly be implemented as shown in Figure 5. With BEM an inverse Fast Fourier Transform (IFFT) must be applied before the time window can be used. One example of an impulse response obtained from BEM simulations is depicted in Figure 4. It clearly shows the direct and reflected components, followed by later reflections.

These late reflections (for example from the ground) are cut out by the time window. An
example of this made with the Euler model is shown in Figure 5.

After time windowing the direct component is removed from the signal by subtracting the impulse response from a free field simulation. Essential is that the signals are correctly aligned and described with a high time resolution.

Figure 5. Time windowing of impulse response from Euler simulation. In dashed black the time window, in red the reflected component inside the window, in blue the ground reflection just outside the window.

4.2. Reflection Index

Results of RI for source-receiver pairs at angles 80˚ (#4), 90˚ (#5) and 100˚ (#6) are shown for a flat, saw-tooth and step type rigid barrier in Figure 6.

For the flat rigid barrier an RI of 1 is expected. An RI >1 would implicate that the reflected sound power is larger than the incident sound power on the barrier. This local increase in sound power is due to interference of multiple reflections from the complex shape of the barrier. Because the receivers are positioned in front of different sections of the surface profile, they receive a different pattern of multiple reflections and therefore show differences in RI. The results of simulations of a flat vertical barrier with $a_{6x}$ return for all models the expected complement $RI=1-\alpha_{6x}$.

The averaged RI over nine receivers, computed by all three models, are compared in Figure 7 for a flat barrier and in Figure 8 for a steps type barrier.

Figure 7. Averaged RI over all nine source-receiver pairs for a flat barrier

Figure 8. Averaged RI for a step barrier over all nine source-receiver pairs.
The results for the flat rigid barrier are not the expected RI of 1. This is due to a ground reflection which is partly included in the time window of the impulse response of the lowest source-receiver pair. This issue underlies a limitation of the actual definition of Adrienne method and will be addressed during the development of an updated measurement method in Work package 3 of the Quiest project.

When absorption is added the RI’s are, especially for higher frequencies, much lower than 1 which would be expected. The difference between the two types of barriers is smaller when absorption is present.

Although the general trends of the results agree, also some differences can be distinguished, especially between BEM and the Euler model. The exact shape of the impulse responses from each model is different, due to BEM needing an IFFT whereas Euler directly uses a time signal. This causes them to react differently on the presence of the unwanted ground effect inside the window during the post-processing steps of time-windowing and signal subtraction.

5. Outlook on further research

Previous sections show that with simulations a good insight can be obtained in the results for reflectivity of complex shaped barriers in the near field. The final aim of this research is finding a far field indicator describing the reflectivity of noise barriers in the far-field. As an input for this extrapolation from near to far field, the known geometry of the barrier and the measured RI at each receiver location in the near field will be available. The extrapolation model (first numerical model then engineering method) will provide the RI in the far field. This approach is visualized in Figure 9.

5.1. Far field effects - RI\text{farfield}

A number of indicative far field analyses are done with BEM. Receivers are located at 100 meter from the foot of the barrier and at heights of 1.5, 5, 10 and 20 meter. The source is located at ground level at 5m from the barrier. The RI\text{farfield} is defined as (in 1/3 octave bands) [6]:

\[
RI_{\text{farfield}} = 1 - \alpha_{eq} = \frac{\sum |P_{\text{barrier}}|^2}{\sum |P_{\text{ref}}|^2} \tag{3}
\]

with \(P_{\text{barrier}}\) and \(P_{\text{ref}}\) the reflected complex pressures from respectively the barrier of interest and the flat vertical rigid reference barrier. The \(\alpha_{eq}\) is the equivalent absorption coefficient to be applied to the reference barrier in order to get a similar reflection pattern as the complex barrier.

Results are shown for a receiver height of 5m for a barrier with porous concrete (modeled with Hamet impedance model [7] with parameters \(\sigma=20\) kPa.s/m\(^2\), \(d=0.10\)m, structure factor of 2 and porosity of 0.25) and mineral wool (modeled with a combined Delany&Bazley and Hamet impedance model with parameters \(\sigma=35\) kPa.s/m\(^2\), \(d=0.10\)m, structure factor of 8 and porosity of 0.9), see Figure 10.

\[
\alpha_{eq} = \frac{\sum P_{\text{barrier}}^2}{\sum P_{\text{ref}}^2} \tag{4}
\]

Figure 10. \(\alpha_{eq}\) in octave frequency bands for barriers with porous concrete at receiver at range=100m and 5m height.

The apparent absorption due to the shape of the barrier can easily be distinguished in the figure by comparing the \(\alpha_{eq}\) of a complex barrier with the \(\alpha_{eq}\) of a flat barrier made from the same material:

\[
\alpha_{\text{shape}} = \alpha_{\text{complex barrier}} - \alpha_{\text{flat barrier}} \tag{4}
\]
As can be seen in Figure 11, the stepsB type barrier performs similar to the inclined barrier for all materials (having a similar tilt angle) until 500Hz which corresponds to a wavelength value that is closely linked to the surface profile dimensions; the effect of the tilt of the barrier is dominating over the profile of the surface. Besides that the with more absorption the shape effect of these barriers decrease with more absorption.

The shape effects of the rigid seesaw approaches the expected results of a vertical flat rigid barrier ($\alpha_{eq}=0$ or RI=1). Adding absorption increases the positive effect of the shape on the reflectivity of the barrier.

From the presented barriers the shape effect of the inclined barrier has the highest positive value.

![Image](image-url)

Figure 11. $\alpha_{shape}$ in octave frequency bands of several barrier types with different materials at 100 meter and at a height of 5 meters.

6. Conclusions

The simulations have demonstrated that it is possible to model the sound reflected by noise barriers in near field in an accurate way. This enables the simulation of the post-processing steps of the current Adrienne method. The simulation models can be used in the development of the new method.

The time domain models show especially a very good insight in the interference patterns and measurement process. Modeling impedances in BEM is very easy whereas the time-domain models have difficulty due to the necessary transformation to the time-domain. With all models a large range of barrier designs can be handled.

The preliminary far field results show that the shape of the barrier can have a very positive effect on the effective reflectivity of the barrier in the far field. Further research will focus on matching the measurements with simulations and the further development of the extrapolation step from near to far field.

Acknowledgement

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References