DOI: 10.61782/fa.2023.0568

forumacusticum 2023

NUMERICAL SIMULATION AND ANALYSIS OF SURFACE SCATTERING - PART 1

Anne Heimes[1*] **Lili Pan**[2] **Michael Vorländer**[1]
[1] Institute for Hearing Technology and Acoustics, RWTH Aachen University, Aachen, Germany
[2] State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, China

ABSTRACT

Absorption and scattering coefficients of surfaces are crucial for simulations in room acoustics and outdoor sound propagation. Because of the poor availability of data, scattering coefficients are among the most uncertain quantities in the simulation chain. In this work, we use an established free-field measurement approach and introduce this for a numerical framework to determine the scattering pattern. It is based on the open-source software Mesh2HRTF, which uses the fast multipole boundary element method, FM-BEM. Furthermore, the characteristics of scattering patterns of references surfaces, such as sine and rectangular shapes, and of specifically designed shapes of building facades are presented.

Keywords: *scattering, numerical simulation, auralization.*

1. INTRODUCTION

Acoustic scattering from surfaces is crucial for acoustic simulations of rooms and urban spaces. Sound propagation in simulations is usually calculated by geometric methods using random incident scattering coefficients [1]. The scattering coefficient describes the ratio of the scattered energy to the total reflected energy from a surface, as shown in Fig. 1. Due to the small amount of available data that can be used in simulations, the integration of the scattering coefficient in the design of real-world applications is a major challenge.

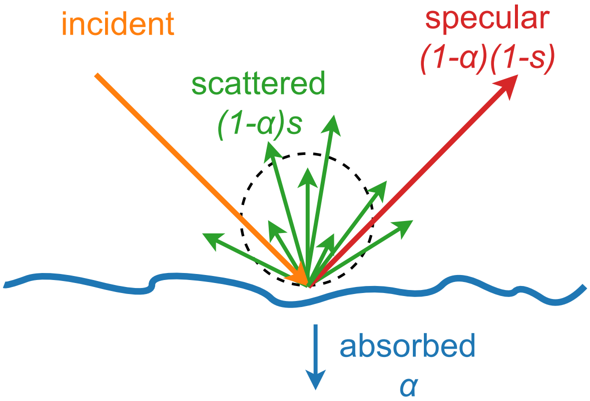

Figure 1. Energy reflected from a corrugated surface into a scattered (green) and specular (red) portion. The total reflected energy is defined as $(1-\alpha)$, the scattered energy as $(1-\alpha)s$ and specularly reflected energy as $(1-\alpha)(1-s)$, where α denotes the random incidence absorption coefficient and s the random-incidence scattering coefficient. [2]

The random scattering coefficient can be determined in a standardized way in a reverberation room according to ISO 17497-1 [1]. In addition, a free-field approach according to Mommertz [3] is available.

Since the scattering databases are rare, a scattering coefficient database of several facades or classical diffusors should be established, therefore many reflection patterns have to be determined. One approach is to simulate the

---

[*] ***Corresponding author***: *ahe@akustik.rwth-aachen.de.*

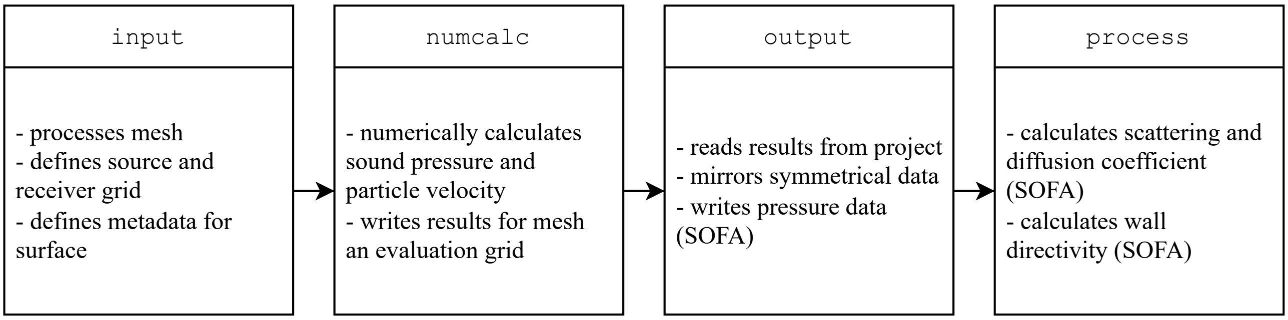

Figure 2. Overview of processing steps in Mesh2Scattering.

scattered sound pressure from the sample surface. This requires an easy-to-use, open and stable numerical toolbox, to ensure that others can easily extend the database.

There are several numerical methods for solving the Helmholtz equation, such as the finite element method (FEM), boundary element method (BEM) for the frequency domain, or finite difference time domain (FDTD) for the time domain. These methods differ in their efficiency for certain problems. In our case, BEM would be the most efficient because the sound is scattered from a surface. Many BEM toolboxes are available, such as commercial software like COMSOL and FastBEM. Open software is also available such as Mesh2HRTF [4], AcouSTO [5], Bempp [6] and OpenBEM [7].

This paper presents Mesh2scattering, a numerical toolbox for determining the scattered sound pressure of different surfaces. The toolbox is based on Mesh2HRTF, therefore we use the same terminology as in [4]. It covers the whole process from the mesh to the scattering pattern to the random scattering coefficients or diffusion coefficients [8]. In the following, the workflow with Mesh2scattering is discussed in detail. Furthermore, the toolbox is validated with standard surfaces such as sinusoidal and rectangular surfaces and their analytical solution [9, 10]. At last, a case study with a facade surface is presented.

2. MESH2SCATTERING

Mesh2scattering is based on Mesh2HRTF, but is optimized to simulate scattered sound pressure from geometrical surfaces and calculate their scattering and diffusion coefficients. The structure is based on Mesh2HRTF, as shown in Fig. 2. Unlike Mesh2HRTF, Mesh2scattering is a pure Python package [1] and does not include a MATLAB API or Blender dependencies. Like Mesh2HRTF, it is fully unit-tested and documented.

2.1 Mesh2scattering.input

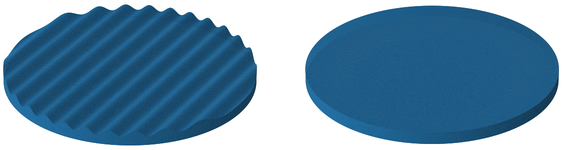

Figure 3. Input mesh or geometry of mesh2scattering, with the surface sample (left) and the reference flat sample (right).

This module converts the input meshes and surface metadata into a `numcalc` project that can be simulated. Fig. 3 shows the two input meshes, with the sample under investigation on the left and a reference sample with the same dimensions but with a flat surface on the right. This reference is required for the scattering coefficient calculation after Mommertz [3]. The reference mesh can also be created within mesh2scattering based on the sample mesh or geometry.

The mesh should have a maximum mesh size of $d_{mesh} < \lambda_{air}/6$ [11]. If no mesh but only geometry is given, a mesh can be generated by `input` module.

For post-processing, various metadata such as

- Surface properties (e.g. structural wavelength,

---

[1] `https://pypi.org/project/mesh2scattering`

peak-to-peak height, diameter, scale and symmetry properties),

- Simulation parameters (e.g. speed of sound and medium density), and
- source and receiver positions, (incl. area weights)

must be defined. These metadata are used to setup the mesh2scattering project and to define parameters for the post-processing. Tey are stored in the root directory as `parameters.json` for each mesh2scattering project. The folder structure is shown below:

```
project name
├─ sample ...  numcalc project.
│  ├─ EvaluationGrids
│  ├─ NumCalc
│  └─ ObjectMeshes
├─ reference ...  numcalc project.
│  └─ ...
└─ parameters.json
```

The sample folder contains the `numcalc` project according to [4] to determine the scattered sound pressure from the sample mesh, analogously the reference folder.

Compared to `Mesh2HRTF.Mesh2input`, Blender is no longer needed, so everything is done directly in Python.

2.2 Mesh2scattering.numcalc

This part is based on the `Mesh2HRTF.NumCalc` module with only minor changes. `Mesh2HRTF.NumCalc` and `numcalc` consist of two parts, first the numerical core itself and some tools to run the simulations in parallel from Python. The numerical core uses the boundary element method coupled with the multi-level fast multipole method [12]. Since we are only interested in the scattered sound pressure field, the numerical core has been adapted so that the direct sound is no longer included by default. The numerical core evaluates the sound pressure and the particle velocity on the boundary and on the evaluation grid.

2.3 Mesh2scattering.output

This module reads the scattered sound pressure results from the mesh2scattering project. It then applies symmetry properties to the sample pressure based on the metadata. For now, rotational symmetry and plane symmetry is supported. The data is then saved as Spatially Oriented Format for Acoustics (SOFA) [13] files and added to the project folder as follows

```
project name
├─ sample
├─ reference
├─ sample.pressure.sofa
└─ reference.pressure.sofa
```

In this way the sound pressure data can also be imported into other software, as SOFA is an open file format.

2.4 Mesh2scattering.process

This module processes the scattered sound pressure data from `output`. It contains

- scattering coefficient calculation [3],
- diffusion coefficient calculation [8],
- random incident scattering and diffusion coefficients, and
- directivity calculation [14]
- angular sectoring for directivity [14].

All results are saved in SOFA format in the project root directory.

3. VALIDATION

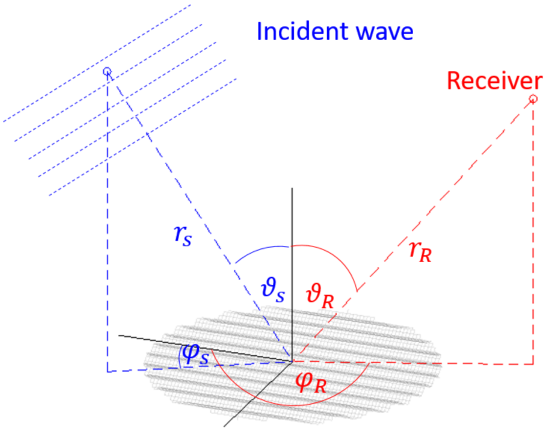

Figure 4. Geometry of the incident wave and the reflected wave vectors.

The simulation is validated against the analytical reference. A sinusoidal surface and a rectangular surface were used to validate the simulation. Both analytical solutions are known from Embrechts [9, 10].

The free-field scattering coefficient calculation [3] requires free-field measurements of the scattered sound pressure or reflection pattern as shown in the Fig. 4. Two reflection patterns must be measured

- $p_0(\vartheta_S, \varphi_S, \vartheta_R, \varphi_R)$, the reflection pattern of an equally sized flat surface, and
- $p_1(\vartheta_S, \varphi_S, \vartheta_R, \varphi_R)$, the reflection pattern of the test sample,

where p_0 serves as a reference measurement to determine the total specular reflectance. Then, the scattering coefficient for each incident plane wave direction is determined according to

$$s(\vartheta_S, \varphi_S) = 1 - \frac{|\sum \underline{p}_1(\vartheta_R, \varphi_R) \cdot \underline{p}_0^*(\vartheta_R, \varphi_R) \cdot w|^2}{\sum |\underline{p}_1(\vartheta_R, \varphi_R)|^2 \cdot w \cdot \sum |\underline{p}_0(\vartheta_R, \varphi_R)|^2 \cdot w} \qquad (1)$$

where w is an area weighting factor resulting from the integration over the receiver half sphere.

For the validation, a sinusoidal and a rectangular surface with a structural wavelength of $\Lambda = 70.8$ mm and a peak-to-peak height of $H = 20.4$ mm were chosen. The angle of incidence of the sound source was set to $\vartheta_S = [15, 30, 45, 60, 75]^\circ$ and $\varphi_S = 90^\circ$ at a distance of $r_S = 10$ m from the center of the sample. The receiver array was set to a 47th order Gaussian distribution at a distance of $r_R = 5$ m. The frequency input was fixed to a 24th-octave band from $0.125 < \Lambda/\lambda < 2$, which corresponds to $500 \text{ Hz} < f < 10 \text{ kHz}$. All defined measures are according to Fig. 4. In this way, the distances correspond to the far-field definition of the diffusion coefficient standard [8].

3.1 Results

Fig. 5 and Fig. 6 directly contrast the analytical solution and the numerical simulation. Overall, a good agreement between the results can be observed. As expected, the simulated scattering coefficient increases before the analytical one due to the edge effect of the finite samples in the simulation. This effect is even higher for more flat sound incidence (i.e. larger θ), because the edge effect becomes more dominant.

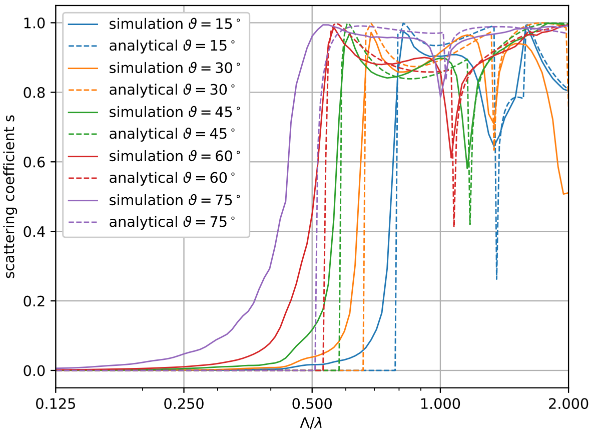

Figure 5. Comparison of analytical and simulated scattering coefficients of a sinusoidal surface for different angles of incidence.

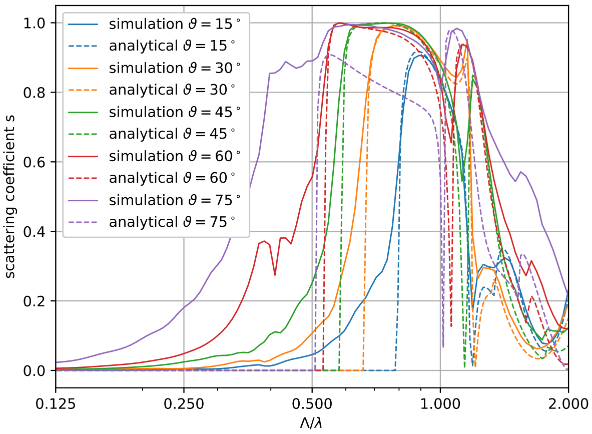

Figure 6. Comparison of analytical and simulated scattering coefficients of a rectangular surface for different angles of incidence.

For the sinusoidal surface in Fig. 5, the scattering coefficient is partly lightly overestimated compared to the analytical solution, especially for rapid scattering coefficient changes over frequency.

Generally, the rectangular surface (Fig. 6) shows slightly less agreement between the simulated and the analytical solution compared to the sinusoidal surface. This might be due to the longer edge of the rectangular surface.

4. CASE STUDY

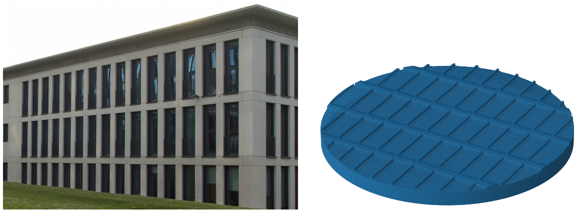

Figure 7. Building facade under investigation (left) and the corresponding sample (right).

As for its intended use, the tool is used to simulate real building facades to determine the random-incidence scattering coefficients for auralization. In this example, we used the facade of the Institute for Hearing Technology and Acoustics (IHTA), Kopernikusstraße 5, Aachen at the RWTH Aachen University. The facade is shown in Fig. 7 (left). It has a real structural wavelength of $\Lambda_{real} = 1.37$ m and a real depth of $H_{real} = 179.12$ mm. To scale the sample to a diameter of $d = 80$ cm with 11 repetitions in one dimension, we chose a scaling factor of 19. This results in a sample structural wavelength of $\Lambda = 72.105$ mm and a sample depth of $H = 9.4274$ mm. Fig. 7 (right) shows the small scale sample of the building facade.

Fig. 8 shows the scattering coefficients for the IHTA facade up to $\frac{\Lambda}{\lambda} = 2$, which corresponds to a real frequency of $f_{max} = 500$ Hz. As expected, the random incident scattering coefficient starts to increase around $\frac{\Lambda}{\lambda} = 0.5$. This scattering coefficient can be used for geometrical acoustic methods to properly account for scattering.

5. CONCLUSION AND OUTLOOK

Mesh2HRTF 1.x is a numerical solver optimized for HRTF simulations. Mesh2scattering was forked from it and completely reused for scattering pattern simulations. In addition, post-processing steps for the calculation of diffusion coefficients, scattering coefficients, random incident coefficients, directivity calculation and angular sectoring are introduced. The goal is to simulate scattering coefficients of surface structures for geometric acoustics.

Furthermore, the simulation was validated by comparing the scattering coefficient for different angles of incidence with the corresponding analytical solutions. With a sinusoidal and a rectangular surface chosen as sample surfaces, an overall good agreement between the simulated and the analytical scattering coefficient solution was shown.

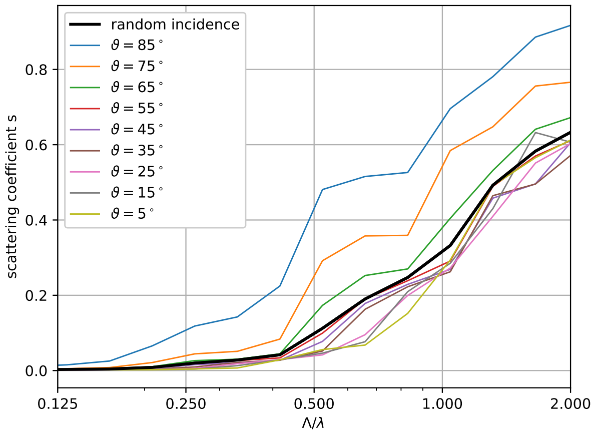

Figure 8. Random incident (**–**) and averaged for incident angles (others) scattering coefficients of the IHTA facade.

Finally, a case study of a building facade was presented. The thus simulated random incident scattering coefficient simulated can be used for more accurate auralization.

Instead of separating the energy into scattered and reflected parts, the reflection pattern as well as the dependency on the angle of incidence should be included. This will be discussed in the complementary study [14].

6. ACKNOWLEDGMENTS

Simulations were performed with computing resources granted by RWTH Aachen University under project rwth1245. This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under the project number Vo 600/48–1.

7. REFERENCES

[1] ISO 17497-1:2004, *Sound-scattering properties of surfaces. Part 1: Measurement of the random-incidence scattering coefficient in a reverberation*

room. Geneva, Switzerland: International Organization for Standards, May 2004.

[2] M. Vorländer and E. Mommertz, “Definition and measurement of random-incidence scattering coefficients,” *Applied Acoustics*, vol. 60, pp. 187–199, June 2000.

[3] E. Mommertz, “Determination of scattering coefficients from the reflection directivity of architectural surfaces,” *Applied Acoustics*, vol. 60, pp. 201–203, June 2000.

[4] F. Brinkmann, W. Kreuzer, J. Thomsen, S. Dombrovskis, K. Pollack, S. Weinzierl, and P. Majdak, “Recent Advances in an Open Software for Numerical HRTF Calculation,” *Journal of the Audio Engineering Society*, vol. in print, 2023.

[5] U. Iemma and V. Marchese, “AcouSt.”

[6] T. Betcke and M. W. Scroggs, “Bempp-cl: A fast Python based just-in-time compiling boundary element library.,” *Journal of Open Source Software*, vol. 6, p. 2879, Mar. 2021.

[7] P. Juhl and V. Cutanda Henriquez, “OpenBEM, Boundary Element Method software,” Apr. 2023.

[8] ISO 17497-2:2012, *Sound-scattering properties of surfaces. Part 2: Measurement of the directional diffusion coefficient in a free field*. Geneva, Switzerland: International Organization for Standards, May 2012.

[9] J. Embrechts, L. D. Geetere, G. Vermeir, M. Vorländer, and T. Sakuma, “Calculation of the random-incidence scattering coefficients of a sine-shaped surface,” *Acta Acustica united with Acustica*, vol. 92, pp. 593 – 603, 2006.

[10] J.-J. Embrechts and A. Billon, “Theoretical Determination of the Random-Incidence Scattering Coefficients of Infinite Rigid Surfaces with a Periodic Rectangular Roughness Profile,” *Acta Acustica united with Acustica*, vol. 97, pp. 607–617, July 2011.

[11] S. Marburg, “Six boundary elements per wavelength: Is that enough?,” *Journal of computational acoustics*, vol. 10, no. 01, pp. 25–51, 2002. Publisher: World Scientific.

[12] H. Ziegelwanger, W. Kreuzer, and P. Majdak, “Mesh2hrtf: Open-source software package for the numerical calculation of head-related transfer functions,” in *The 22 nd International Congress of Sound and Vibration*, (Florence, Italy), Unpublished, 2015.

[13] AES Standards Comitee, “AES69-2022: AES standard for file exchange - Spatial acoustic data file format,” 2022.

[14] L. Pan, A. Heimes, and M. Vorländer, “Numerical simulation and analysis of surface scattering - part 2,” in *10th Convention of the European Acoustics Association*, (Turin, Italy), 2023.