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Citation for the original published paper (version of record):

Müller, L., Kropp, W., Forssén, J. (2022). Measurement, Simulation and Auralization of Indoor Road Traffic Noise. *Fortschritte der Akustik*, 2022

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# Measurement, Simulation and Auralization of Indoor Road Traffic Noise

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## Introduction

Building new houses in urban areas is often hindered by the presence of road traffic noise. Thereby, it is especially difficult to achieve sufficient façade sound insulation at low frequencies. Current regulations are mostly based on A-weighted levels and hence not only disregard low frequencies but also omit other factors that might influence the amount of disturbance such as time structure, traffic distance, proportion of heavy vehicles, driving speed and background noise. This motivates the need for experiments evaluating the human response to indoor traffic noise in a controlled virtual environment. Thereby, one challenge is to include the incidence angle dependent transfer paths through the façade in the auralization.

The method presented in this paper utilises wave field synthesis in order to reproduce the sound field caused by moving sound sources on the outside of a window in a, specifically for this purpose designed, living room lab. In order to evaluate the auralization, a physical model of the source position dependent transfer path from a moving outdoor sound source through a window to an indoor receiver position was developed.

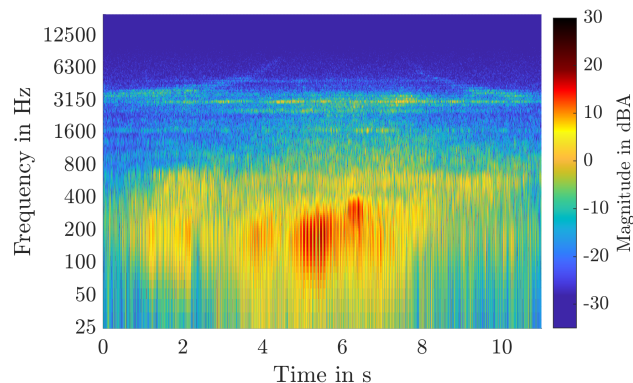
## Measurements



**Figure 1:** Indoor road traffic noise measurement setup.

In order to evaluate the requirements for an auralization method in situ measurements were performed in a 30 m<sup>3</sup> office with approximately 20 m distance to road and a 2.5 m<sup>2</sup> triple glazed window as shown in Figure 1. Calibrated recordings were conducted with a high sensitivity diffuse field microphone, an artificial head, a 32-channel spherical microphone array, a 16-channel equatorial array [1] as well as a stereo microphone arrangement. This wide range of recording techniques allows a comparison of possible reproduction methods based on these measurements, although only the single microphone recordings are used in the following.

Figure 2 shows an A-weighted single channel indoor recording of a heavy truck passage at 50 km/h in time



**Figure 2:** A-weighted spectrogram of 50 km/h heavy vehicle passage recording.

frequency domain. Thereby, it is clearly visible that the low frequencies dominate and that the spectral composition varies over the duration of the passage. Looking closely at the 3 kHz region one can observe a narrow band peak that changes in frequency with the position of the vehicle. This corresponds to the coincidence frequency of the window which depends on the incidence angle of the outdoor pressure wave [2]. In the case where the vehicle passes the window, i.e. at  $t = 6$  s, the coincidence frequency increases rapidly as the wavefront approaches at perpendicular incidence. Depending on the window thickness and material properties this effect typically occurs at relatively high frequencies hence it might not be considered as relevant for the investigation of low frequency traffic sound. However, in this specific measurement scenario it is clearly audible and hence should also be considered in the auralization. This means that, for a perceptually accurate auralization of indoor road traffic noise, the propagation through the window and façade should be modelled as source position dependent and not just as a static filter based on the diffuse field façade reduction.

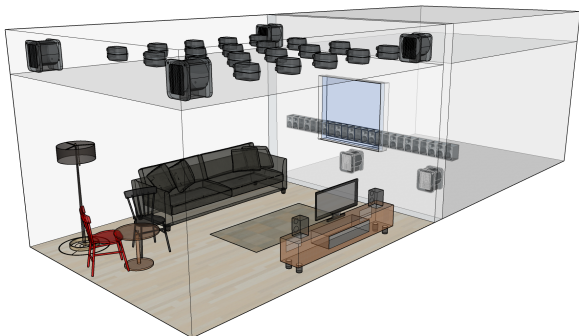
## Auralization

In order to conduct sensitive listening experiments e.g. regarding the effect of indoor traffic noise on cognitive performance the auralization and reproduction method should be sufficiently accurate. Ideally, participants should be placed in a natural environment and hear stimuli that are perceptually indistinguishable from a real life scenario. Thereby, one question that arises and will be investigated in the following is how much the outdoor source position influences the spatial distribution of the indoor sound field. This determines if a spatial reproduction of the indoor sound field is actually required.

A straightforward method to reproduce indoor road traffic noise would be to use recordings made with an arti-

ficial head or microphone array for a headphone based reproduction. However, these in situ recordings do not allow to change parameters such as pass-by distance or vehicle speed which would be necessary for a useful listening experiment. While it is, to the authors' best knowledge, unclear whether or not a participant's awareness of the sound reproduction method actually influences the behaviour in a listening experiment, one can argue that wearing headphones might be perceived as unnatural and makes it harder for a participant to get immersed into the virtual scene. This similarly applies to loudspeaker based ambisonics approaches where the participant would be placed in the center of a loudspeaker array in an anechoic environment.

Instead, a hybrid approach was chosen by converting a transmission suite into a so called living room lab as shown in Figure 3. Thereby, the receiving room was furnished to match the look and feel of an average living room. A double wall with a standard window separates the living room from a second sending room which contains a linear loudspeaker array placed close to the separating wall. The fundamental idea is to use wave field synthesis in order to recreate the sound field caused by a moving outdoor sound source on the outside of the window of the living room. A correct pressure on the outside of the window should then lead to a realistic sound field in the entire living room. By hiding the window behind an acoustically transparent curtain the participants can not see the loudspeakers and hence have the sensation of sitting in an ordinary living room being exposed to real road traffic noise.



**Figure 3:** Sketch of living room lab (left room) and sending room (right room) with loudspeaker setup. The additional speakers in the ceiling were not used for this project.

### Wave Field Synthesis

Wave Field Synthesis (WFS) is utilised in order to create the sound field of a virtual moving outdoor source in front of the window between the sending room and the living room lab. Therefore, a linear loudspeaker array consisting of 24 studio loudspeakers and 2 subwoofers is placed along the separating wall as shown in Figure 3. The loudspeakers are controlled in phase and amplitude in a way that the incoming sound field from an outdoor point source is projected to the outdoor surface plane of the window. This was implemented by using conventional driving functions for a linear loudspeaker array as described in [3]. Thereby, the circumstance that

the loudspeaker contour is one-dimensional rather than two-dimensional causes artifacts both in amplitude and spectral balance which were compensated by including a pre-filter according to [4].

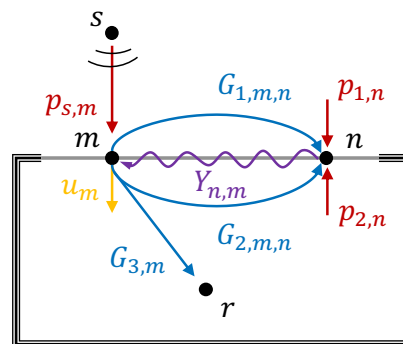
The movement of the outdoor sound source was implemented using the concept of moving Green's functions. This means that the source movement is discretized according to the sampling frequency. For each of these discrete source positions, time delays and weights for each speaker were calculated according to [3] and applied to the corresponding sample of the source signal [5].

As source signal, 38-channel semi-anechoic truck recordings were used. Thereby, the source directivity was implemented by cross-fading between different microphone positions depending on the source position. Additionally, air attenuation was included for each discrete source position according to ISO 9613-1 and a ground reflection was added using the image source method assuming a rough concrete ground. The image sources were treated as separate source positions in the WFS.

### Physical Model

The lack of a ground truth makes it difficult to validate the presented auralization method. In theory, a listening experiment in which participants compare the WFS auralizations to real passages could be conducted. However, in practice it is not possible to have real vehicles driving by the lab. Using the acquired in situ binaural recordings as reference is also not reasonable since their source signals are unknown and they were made in a different room and with another window. It would also be possible to perceptually evaluate the accuracy of individual aspects like the perception of distance, vehicle type or speed. However, these parameters would still not validate the overall plausibility of the auralization.

Therefore, a reference was created by developing a physical model of the entire transmission path assuming that the sound is only transmitted through the window. This allows to simulate the indoor pressure caused by a moving outdoor sound source and numerically compare it to the simulated results of the WFS.



**Figure 4:** Physical model of outdoor sound source  $s$  radiating through a window to an indoor receiver position  $r$ .

Figure 4 shows the general setup of this physical model. Assuming an outdoor monopole sound source  $s$  the pressure radiation from the sound source to an arbitrary

point on the window  $m$  can be described as monopole radiation. This pressure  $p_{s,m}$  excites the window to vibrate with a certain surface normal velocity  $u_m$  which then leads to sound radiation. The radiation from any point  $m$  on the window to another point  $n$  can be described by a Green's function. On the outside of the window, this Green's function,  $G_{1,m,n}$ , can be determined assuming a monopole on a hard wall. Inside the room, the Green's function  $G_{2,m,n}$  can be obtained by using a modal superposition approach for a rectangular room defining  $m$  as source position and  $n$  as receiver position [2, 4.4.2]. The radiation from a vibrating window point  $m$  to a receiving position in the room  $r$ ,  $G_{3,m}$ , can be calculated in the same way. Finally, exciting the window at one point  $m$  will lead to structure-born sound transmission to an other point  $n$  described by the transfer mobility  $Y_{m,n}$ . Assuming bending waves on a single layer window one can approximate this mobility with the analytical solution for a simply supported plate based on the Euler-Bernoulli theory.

Within this model, three equations can be set up. Firstly, the outdoor pressure on a point  $n$  on the window,  $p_{1,n}$ , equals two times the source pressure plus the sum of the outdoor air-borne contribution of all vibrating points of the window.

$$p_{1,n} = 2 \cdot p_{s,n} + \sum_m u_m \cdot G_{1,m,n} \quad (1)$$

Secondly, the indoor pressure on a point  $n$  on the window,  $p_{2,n}$ , equals the sum of the contribution of all vibrating points on the window.

$$p_{2,n} = \sum_m u_m \cdot G_{2,m,n} \quad (2)$$

Finally, the surface normal velocity of one vibrating point equals the sum of the difference between indoor and outdoor pressure times the corresponding transfer mobility.

$$u_m = \sum_n Y_{n,m} \cdot (p_{1,n} - p_{2,n}) \quad (3)$$

These three equations yield a linear equation system that can be solved for the surface normal velocity of each point of the vibrating window  $u_m$  using matrix inversion. The pressure  $p_r$  at a receiving position in the room  $r$  can then be calculated as

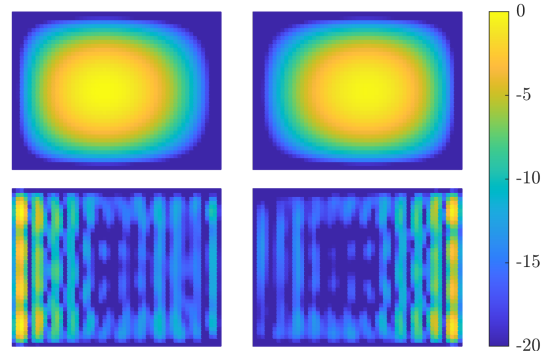
$$p_r = \sum_m u_m \cdot G_{3,m} \quad (4)$$

The size of the equation system depends on the discretization of the window surface which was limited to 6 points per wavelength for the highest frequency of interest.

## Results

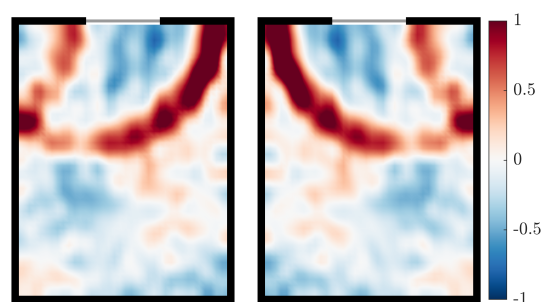
In the following, the results from the previously introduced physical model are analyzed regarding the influence of the outdoor source position on the spatial distribution of the indoor sound field as well as compared to simulated WFS results.

### Spatial Sound Field Distribution



**Figure 5:** Normalized velocity level on 1 cm thick single layer glass window at 10 Hz (top) and 1000 Hz (bottom) for outdoor source with horizontal incidence angle  $\theta = 80^\circ$  (left) and  $\theta = -80^\circ$  (right) relative to surface normal vector.

Figure 5 shows the normalized surface normal velocity level on the window at 10 Hz (top) and 1000 Hz (bottom) for an outdoor sound source placed to the left and right of the window calculated with the model. Thereby it can be observed that, for low frequencies, as expected the entire window moves like a piston and the outdoor source position barely affects the vibrational behaviour of the plate. For high frequencies on the other hand it is clearly visible that the outdoor source position affects the vibration of the window: if the outdoor source is to the left, the left side of the window vibrates with a higher velocity. This indicates a dependence of the window indoor sound radiation on the outdoor source position.

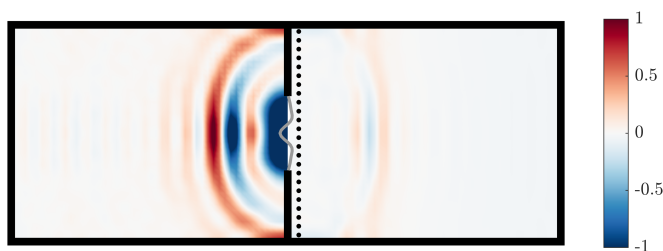


**Figure 6:** Normalized pressure of simulated indoor sound field for an outdoor sound source with horizontal incidence angle  $\theta = 80^\circ$  (left) and  $\theta = -80^\circ$  (right) relative to window surface normal vector emitting a broadband impulse at  $t = 5$  ms after arrival at window.

By defining a grid of receiver points in the room the spatial distribution of the indoor sound field can be evaluated as shown in Figure 6. The left plot shows the first wavefront and first side wall reflection for an outdoor sound source placed on the left of the window and the right plot illustrates the sound field for a source on the right. These time-domain results were obtained by apply-

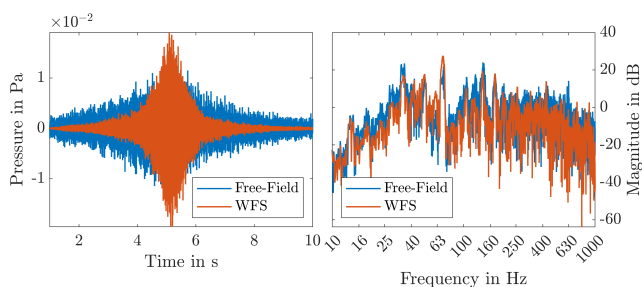
ing an inverse Fourier transform to the frequency-domain results of the model. Here it is clearly visible that the spatial distribution, i.e. the angle of the first wavefront in the room, depends on the outdoor source position. This proves that, from a physical point of view, the correct outdoor source position should be included in an auralization which motivates the presented WFS approach. However, further listening experiments are needed in order to evaluate if these spatial differences are actually perceivable.

## WFS Evaluation



**Figure 7:** Simulated normalized pressure in living room (left) and sending room (right) at  $t = 5$  ms for synthesized 1 kHz low-pass impulse plane wave propagating in window normal direction. The black dots indicate the WFS speakers, the grey line visualizes the surface normal velocity on the window.

In order to evaluate the performance of the WFS, the sending room of the living room lab was added to the physical model by replacing the free-field Green's function  $G_{1,m,n}$  with a modal approach [2, 4.4.2]. By defining the WFS loudspeaker positions as sound sources, the entire lab setup including the two coupled rooms and the window can be simulated. Figure 7 shows an example plot of the sound field in the living room (left) as well as the sending room (right) at  $t = 5$  ms when synthesizing a 1 kHz low-pass filtered impulse as plane wave propagating in normal direction of the window. In this specific case the reflection of the separating wall close to the loudspeakers strongly interferes with the synthesized plane wave which is why the pressure in the sending room at this point in time is weaker than the pressure in the receiving room. Comparing this simulation using the actual WFS speaker signals for a moving source to the simulated indoor pressure for the same continuously moving outdoor source in free-field allows to investigate the influence of the WFS and the sending room reflections on the time and frequency composition of the pressure at single indoor receiver positions.



**Figure 8:** Simulated pressure at single indoor receiver position for heavy vehicle passage comparing a moving outdoor source in free-field and WFS implementation in lab.

Figure 8 compares the spectra and time signals of the pressure obtained by those two different simulations. While the spectra at the selected receiver position are very similar, the time signal comparison reveals that there is a discrepancy between the envelope of the simulated receiver pressure for an outdoor sound source in free-field compared to the same source movement synthesized by the WFS. The reason for these deviations is the limited length of the WFS array which leads to an aperture effect [6]. If the outdoor sound source is located far away at an horizontal angle of  $\theta = 0^\circ$  relative to the normal of the window the array can easily reproduce the resulting plane wave as shown in Figure 7 since it propagates in normal direction of the linear array. For larger horizontal incidence angles on the other hand, the resulting pressure gradient in array normal direction becomes small which leads to a lower amplitude in the WFS. This could possibly be improved by either manually adapting the envelope of the speaker signals depending on the source position or by using a different array geometry like a semicircle. Alternatively, one could use the developed physical model to predict the desired pressure in front of the window as well as the transfer functions from each loudspeaker position to the window for a pressure matching sound field reconstruction approach [7].

## Conclusion

This paper presented a wave field synthesis based auralization approach for indoor road traffic noise. A physical model was developed which proved that the spatial distribution of the indoor sound field is influenced by the outdoor source position. Using this model it was shown that, within certain limitations, the implemented WFS approach is able to reproduce the spectral and spatial characteristics of a moving outdoor sound source but leads to an incorrect envelope of the time signal at an indoor receiver position. Improving the auralization to obtain a correct time structure will be subject of future research.

## Acknowledgements

This project has been funded by Formas – a Swedish research council for sustainable development – under grant agreement FR-2016/0005.

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