euronoise 2021
25th to 27th of October
Madeira, Portugal - online

Challenges in interactive sound insulation auralization

Michael Vorländer

Institute for Hearing Technology and Acoustics, RWTH Aachen University, Germany
{mvo@akustik.rwth-aachen.de)

Abstract
Auralization of airborne sound insulation is a tool which was introduced 20 years ago, and it is now available in offline and real-time implementations. The basis is typically the ISO 12354-1 standard. "Real-time" in this respect means that the resulting audio output is ready immediately after having set or changed the conditions for direct and flanking paths. This ensures a smooth design and optimization process for checking compliance with requirements, for example. When it comes to interactive scenarios, however, more aspects become important, since interaction is also related to dynamic situations of moving sources and moving listeners. Such interactive scenes can be used in research on sound perception in buildings where the user can freely move, particularly turn the head and perceive cues of sound localization. This paper summarizes state-of-the-art in sound insulation auralization and gives special focus on application in interactive virtual reality environment for sound perception research.

Keywords: Sound transmission, simulation, auralization, virtual acoustic environments.

1 Introduction

Calculation schemes for prediction of airborne sound insulation of buildings from the performance of building elements are very well established in ISO 12354-1 and -3 [1, 2]. With proper signal processing elements, the standardized prediction approach can be extended towards auralization. Software for simulation and auralization is available since many years as well in research versions [3-4] as in commercial software [5-7]. Some implementations can perform in "real time". Real-time in this respect means that the result is available immediately after having set or changed the input data for direct and flanking paths. This ensures a rapid design and optimization process for checking compliance with requirements, for example.
When it comes to interactive auralization, however, more features of real-time processing must be included. Spatial perception and dynamic systems updates related to the actual listener's position and orientation are required, thus ensuring a realistic and smooth perception of the 3D auditory event. With this, a new dimension of sound perception experiments can be achieved which differs from the usual approach of listening to sound demonstrations and answering questionnaires in static settings.
Recently, an open-source framework which provides the opportunity to create interactive virtual sound insulation auralization was presented [8]. It was also shown in [9] that test results obtained in the virtual environment are in concordance with those in real rooms. In this paper, the framework is briefly described, and the opportunities and challenges and limitations are discussed.

2 Fundamentals of sound insulation auralization

A useful basis for auralization is the standardized sound level difference, D_{nT}, with L_S and L_R for the levels in source room and receiving room, respectively. With reference to reverberation time in the receiving room, T_R, and standardization to $T_0 = 0.5$ s, as expressed in a term of 3 dB, the equation can be expressed as

$$L_{\mathrm{R}} = L_{\mathrm{S}} - D_{\mathrm{nT}} + 10\log T_{\mathrm{R}} + 3 \quad . \tag{1}$$

Similarly to direct sound transmission, the energy flow via flanking paths can be included by using

$$R_{ij} = -10\log \tau_{ij} = 10\log\frac{P_i}{P_j} \quad , \tag{2}$$

with P_{i} and P_{j} denoting the sound power incident on the element i in the source room and radiated by the element j in the receiving room, respectively.

The specific transmission coefficients obtained by separated measurement conditions or calculations have to be combined into a resulting sound transmission coefficient τ'. The fundamental equations of the transmission model appropriate for sound insulation in buildings were developed by Gerretsen [10]. For the complete set of equations it is referred to ISO 12354-1 and -3. For auralization, these equations must be applied in filter design for audio signal processing. For fundamentals of this step, it is referred to [3] or [11].

2.1 Sound insulation filter design

Starting with the input data of sound insulation in frequency bands, which are obtained by from prediction or measurement, we can create auralization filters. The resulting receiving room level, L_{R}, is

$$L_R = L_S + 10\log\tau' + 10\log\frac{6TS}{V} = L_S + 10\log\tau_{nT} + 10\log\frac{T}{0.5\ s} \tag{3}$$

with V denoting the receiving room volume in m^3 and S the partitions walls surface in m^2. If we now introduce the sound pressure signals, p_{S} and p_{R}, in the source room and the receiving room, respectively, we re-arrange equation (3) into

$$p_{\mathrm{R}}^2 = p_{\mathrm{S}}^2\,\frac{\tau_{nT}\,T}{0.5\ s} \tag{4}$$

$$p_{\mathrm{R}}(\omega) = p_{\mathrm{S}}(\omega)\cdot F_{\mathrm{total}}(\omega) = p_{\mathrm{S}}(\omega)\sum_{i=1}^{N} F_{\tau,i}(\omega)\, e^{-j\omega\Delta\tau_i}\, F_{rev,i}(\omega)\,, \tag{5}$$

with $F_{\tau,\mathrm{i}}$ denoting interpolated filters which are obtained from the energy transfer spectra of the paths involved. $\Delta\tau_{\mathrm{i}}$ are delays corresponding to the geometric situation of the walls and the observation point. $F_{\mathrm{rev,i}}$ is the reverberation excited by each of the sound transmitting elements in the receiving room. The absolute sound pressure level in the receiving room is correct if the input sound pressure signal in the source room is calibrated with reference to $2\cdot 10^{-5}$ Pa. Note that $p_{\mathrm{S}}(\omega)$ is nothing but the complex spectrum of the recorded source signal. The equation can hence be expressed in the time domain by

$$p_{\mathrm{R}}(t) = p_{\mathrm{S}}(t) * f_{\mathrm{total}}(t)\,, \tag{6}$$

with $f_{\mathrm{total}}(t)$ denoting the ”sound transmission impulse response”.

2.2 Sound insulation convolution

Except for the phases, the total set of transfer functions is represented quite accurately, as long as the frequency interpolation and extrapolation does not smoothen the exact physical behaviour too much. This situation is absolutely acceptable since phases in reverberant sound fields cannot be recognised by human hearing. This does not apply, however, to the discrimination of direct sound and the first (early) reflections related to the direction of sound incidence and the spatial aspects of the early part of the impulse response. Those phases are well covered by $\Delta\tau_{\mathrm{i}}$ in equation (5).

After all, the source audio signal (recorded or synthesized) is convolved with the filter, which are also spatialized by using binaural filters (head-related transfer functions, HRTF) corresponding to the geometric situation in the receiving room, as illustrated in figure 1.

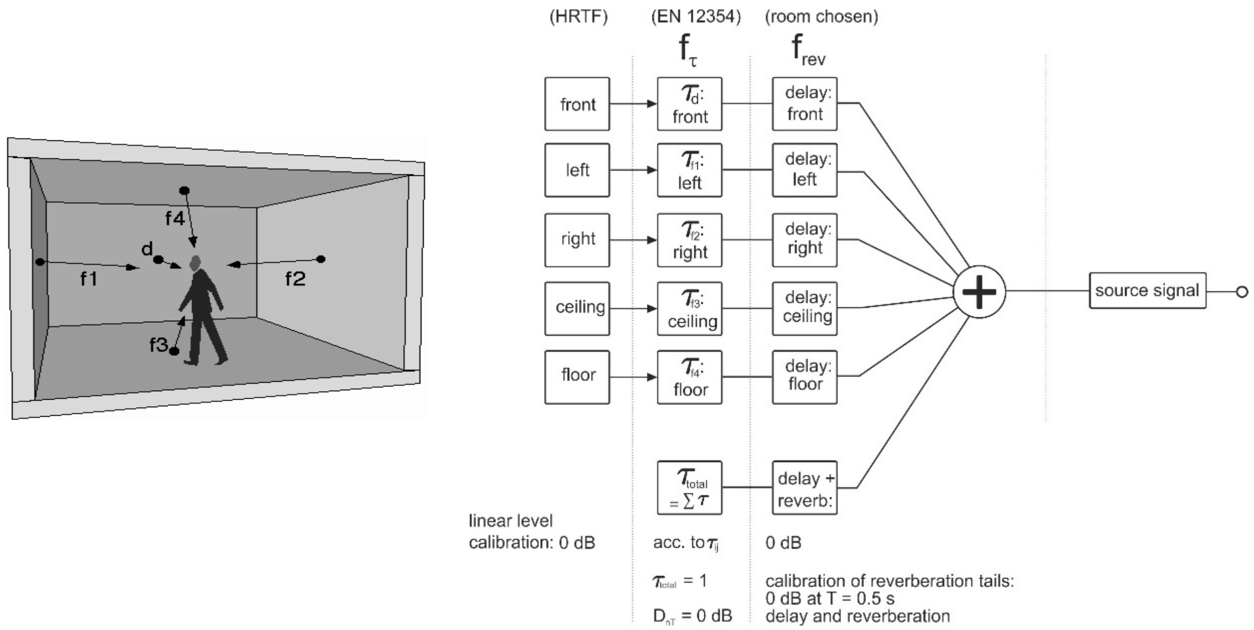

Figure 1 – Left: Geometric situation. Right: Flow chart of airborne sound auralization (after [11]).

3 Extended approach in the open-source framework

In a recently finished project, an interface between psychoacoustic research and building acoustics (airborne sound insulation) in built environments was developed. It forms an integrated solution for auditory-visual virtual reality environments and extension of the software tools for a real-time building acoustics simulator for open data and open access." (link www.virtualbuildingacoustics.org).

In the course of this work, an extended sound insulation prediction model was developed which goes beyond the standard conditions of ideal diffuse sound fields in the rooms. Room impulse responses were modelled in more detail for the direct and reverberant parts and their energies and onsets [12, 13]. The sound transmission coefficients for the walls are distributed on a surface grid of "patches" instead of using energy concentration in the centre point of the wall. With this, angle-dependent irradiation on the walls can be calculated and further processed. For the radiation walls in the receiving room, distributed equivalent source points were used. For building façades, basic models for angle-dependent sound transmission coefficients were implemented as follows: 1.) the reverberation of both source and receiving rooms is an important acoustical parameter which are taken into account depending on the room characteristics (e.g. room geometries, walls' absorptions etc.), source directivities and the spatial variation of sound field inside rooms, 2.) the sound insulation filters from source to receiving rooms are calculated for extended walls by using concept of segmenting individual building element into a multitude of secondary sound sources with non-uniform energy distribution, and 3.) the room impulse responses (RIRs) are synthesized from one-third octave band values of the reverberation times of source and the receiving rooms with more appropriate time structures of direct and reverberant sound. It is now discussed how these extensions lead to improvements and to new challenges, too.

3.1 Simulation with distributed secondary sources

At first, considering the building elements in a grid of patches was introduced in order to include a direct sound excitation by directional irradiation of the walls, hence also taking into account directional sound sources. This was achieved in the energy domain properly but without phase relation of the structural waves in the walls. The phase of the sound incidence on the wall patches, however, is covered by the relative propagation delays between the source and the wall patches. This means, that for forced transmission the total response coincides with the cosine of the incidence angle as concerns the energy but the phase is set to zero. This way, the wall acts as a single vibrating element also on the other side, where the secondary sources radiate in the receiving room. For resonant transmission, above the critical frequency, the phase coincides with the actual bending wave phase. The patches can then radiate in the receiving room according to their relative running phases like in a bending wave pattern. Whether or not this is perceptually relevant in auralization could be elaborated more in further refinements and tests of the model.
The extended sound insulation model was validated by reproducing the results of level differences D_{nT} in a comparison with ISO standard data in a kind of virtual measurement. In two selected cases, the results of sound transmission into the receiving room based on diffuse sound field assumptions were compared with those obtained from the auralization. Under conditions, which match the measurement standards of sound insulation testing, the results of the auralization differed by on average 0.6 dB and 0.3 dB for outdoor and indoor source positions, respectively. It was also shown that for non-standard settings the source directivity and position have an influence on the transmitted energy to the receiving room. This fact was even more obvious in the case of sound transmission through building façades.

3.2 Angle-dependent sound incidence

For irradiation of façade elements, the patches serve as energy collectors and transmitters in the same way as for indoor case. Outdoors, however, the irradiation on the façade is dominated by direct sound from specific incident angles. Although the scenario of the reference angle of 45° incidence as defined for façade sound insulation poses a well-established compromise, it is unclear how the sound transmission of noise from of a car pass-by, for example, must be modelled with specific subsequent incidence angles during the pass-by and how this affects the auditory perception.

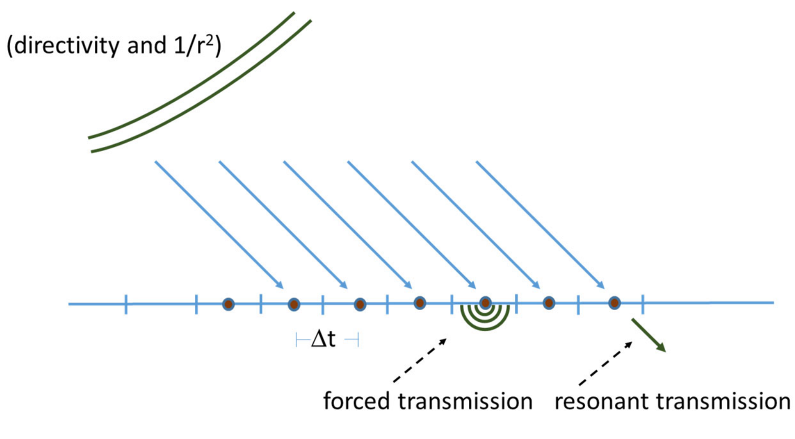

Figure 2 – Excitation of a grid of patches building façade with oblique incidence and radiation from secondary sources

The model is illustrated in Fig. 2. Oblique-angle sound irradiation to the patches results in relative delay, Δt, sound transmission characteristics according to the building element and material model, and radiation by the grid of secondary sounds. Depending on the frequency range, forced or resonant transmission must be treated for the secondary sound individually as concerns timing and sound power. The main challenge in this part is

to implement an appropriate sound transmission model for construction elements, which can be solved for oblique angles. Furthermore, a challenge is to extrapolate the angle-dependent transmission from standard measurement results in sound transmission laboratories (diffuse field) or in-situ (45^{o} incidence) with appropriate physical assumptions on the underlying type of construction.
Although the sound insulation model is rather detailed in terms of structural-acoustics input data, the claim of the model is not to predict all kinds of existing building elements. In any case, measured sound transmission coefficients from test facilities may serve as input, so that existing (real) building situations can be simulated and compared with measurements. As the model and its open source software is open for any kind of input data, improvements and extensions for more construction types can be implemented easily.

3.3 Extrapolation to low frequencies

The results of sound insulation data are usually measured or predicted in one-third octave bands between 100 Hz and 3150 Hz, or in the extended range between 50 Hz and 5000 Hz. It is clear that the frequency range below 100 Hz may play a significant role for the effective sound insulation. This might become even more important since low frequency sound sources are increasingly relevant in residential buildings (TV and Hifi equipment). It is a challenge to extrapolate sound insulation data such as standardized sound level differences of flanking data towards lower frequencies. With physical models of the wall, model assumption can be developed, such as single-layer or double layer, depending on the resonance frequency or critical (bending wave) frequency. This may be feasible with sufficient knowledge of the actual construction type.
The main challenge, however, is modal behavior in the building element and in the rooms. The connection between the building element and the surrounding elements, usually a junction, is a very critical part in predictions ISO 12354. The associated modal pattern depending on the size and boundary condition leads to specific modal effects in the sound transmission coefficient. The modal response of the room (below the Schroeder frequency) contributes with further unpredictable effects in the auralization model.
This means that in the end, it cannot be expected that the resulting auralization is authentic for the building situation under investigation, at least not until wave-based components are added into the framework. But it is clear that the auralization can be interpreted as one possible case of modal responses. This way, it can serve as plausible solution and basis for comparisons within the framework.

3.4 Open-source framework

The framework "Virtual Building Acoustics was published in open source format with documentation under the link http://virtualbuildingacoustics.org. The source code in C# and it provides interfaces to the game engine developers' platform "Unity" in the form of plugin. The required connections for real-time acoustic filtering and audio reproduction to the VA software (http://virtualacoustics.org) are added to the corresponding GIT repository at https://git.rwth-aachen.de/ita. The source code documentation is linked under http://developer.virtualbuildingacoustics.org.
The VBA website home page describes and introduces the project highlights. The documentation website under the following link, http://documentation.virtualbuildingacoustics.org is a complete description of how to build an audiovisual building acoustics project. In addition to the documentation, three example scenes are included: open-plan office with adjacent conference room, classroom with façade to a busy street, adjacent music rehearsal rooms in a music school.

4 Conclusion and outlook

The contribution of this work was the development of a universal research platform to interface building acoustics of virtual architectural environments and audio-visual virtual reality systems. The framework provides real-time performance and interactivity. This opens opportunities for innovative experiments on noise

effects in the built environment. Challenges are mainly lack of models for angle-dependent sound transmission, and filter design at low-frequencies.
The auralization models can also be based on experimental results from test results in sound insulation laboratories. This way, the real-time auralization model is open for improvements in theory and experiment of building elements. The outdoor sound propagation package in VBA includes acoustic simulation of urban sound propagation models which are helpful in many research and urban planning areas and might also be useful in early designing stages of such environments. These simulation models contribute to characterization of acoustic properties of these environments, especially for auralization of noise and evaluation of its effects in an ecologically valid but still reproducible manner.

Acknowledgements

The author likes to thank Imran Muhammad for implementation and testing of open-source framework. HEAD Genuit Foundation is acknowledged for supporting the project under the funding P-17/4-W and P-20/01-W.

References

[1] ISO 12354-1: Building acoustics: estimation of acoustic performance of buildings from the performance of elements - Part 1: airborne sound insulation between rooms. International Organization for Standardization, Geneva (2017).

[2] ISO 12354-3: Building acoustics: estimation of acoustic performance of buildings from the performance of elements - Part 3: airborne sound insulation against outdoor sound. International Organization for Standardization, Geneva (2017).

[3] Vorländer, M.; Thaden, R. Auralization of airborne sound insulation in buildings. Acustica 86(1), 2000, pp 70-76.

[4] Rodríguez-Molares, A. A new method for auralization of airborne sound insulation. Applied Acoustics, 74(1), 2013, 116-121.

[5] http://www.cstb.fr/dae/en/nos-produits/logiciels.html

[6] https://www.datakustik.com/products/bastian/bastian/

[7] https://www.soundofnumbers.net/

[8] Imran, M.; Heimes, A.; Vorländer, M. Interactive Real-time Auralization of Airborne Sound Insulation in Buildings. Acta Acustica 5, 2021, p. 19. https://doi.org/10.1051/aacus/2021013

[9] Imran M.; Vorländer, M.; Schlittmeier, S.J. Audio-video virtual reality environments in building acoustics: An exemplary study reproducing performance results and subjective ratings of a laboratory listening experiment. J. Acoust. Soc. Am. 146 (3), EL310, 2019, https://doi.org/10.1121/1.5126598

[10] Schlittmeier, S.J.; Hellbrück, J.; Thaden, R.; Vorländer, M. The impact of background speech varying in intelligibility: Effects on cognitive performance and perceived disturbance. Ergonomics 51(5), 2008, pp 719-736.

[11] M. Vorländer: *Auralization: fundamentals of acoustics, modelling, simulation, algorithms and acoustic virtual reality*. 2nd edition. Springer Nature, Switzerland, 2020

[12] Barron, M.; Lee, L.J. Energy relations in concert auditoriums. I. J. Acoust. Soc. Am. 84(2), 1988, pp 618-628.

[13] Vorländer, M. Revised Relation between the Sound Power and the Average Sound Pressure Level in Rooms. Acustica 81, 1995, pp 332-343.