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Auralization of Airborne Sound Transmission and Framework for Sound Insulation Filter Rendering

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Summary
In this study we purpose a framework for auralization of airborne sound transmission in complex buildings and develop the corresponding sound insulation filters for the evaluation of performance of building elements in terms of noise and comfort. This paper describes the implementation of airborne sound transmission based on ISO: 12354 Part-1 (2017) and comprehends the calculation procedures for sound insulation metrics. The filters are designed to predict the sound transmission between dwellings by partitions and by flanking structures in order to estimate the transfer functions between the sources and receivers. An example building is taken as a test case that consists of different type of elements and their constructions. The results for auralization of example building are presented for different source and receiver configurations in coupled rooms.

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1. Introduction

In past few decades research has been done on sound insulation and prediction of insulation metrics. The recent trends in auralization of sound insulations in building acoustics are growing and researcher are seeking its potential usage in virtual reality (VR) systems to realize the perception and evaluation of noise and comfort. This way, studies on sound perception can be performed in a more ecologically valid approach. The most modern VR-systems occasionally incorporate the essential role of sound transmission through coupled rooms separated by portals (i.e. doors, windows, partitioning etc.) and acoustical characteristics of structural elements that explain the response of these spaces and influence the auralization process [1]. Recent developments in building acoustics have played an important role in virtual reality technologies as a powerful tool for numerous potential usages. These developments encompass different research areas such as; architecture design processes and auralization of virtual spaces.
A significant work is available on sound generation and its propagation in room acoustics. In addition to sound propagation, sound transmission is an integral part of the auralization chain and its presence cannot be overlooked. Perdition of sound insulation for building elements is as important for perceptual evaluation as the sound propagation. For this purpose efficient methods for predicting sound insulation metrics and filter rendering techniques are required. These methods should base on the knowledge of sound insulation metrics to compute transfer functions between source and receiver that might be located at different positions [2].
In this paper, the main focus is on construction of building acoustic filters based on standard sound insulation metrics. Subsequently, these filters are used to calculate airborne sound transmission paths form source to receiver placed in coupled rooms of building volumes. In this way an auralization framework is possible to analyse the performance of building elements and to evaluate the noise and comfort levels for building structures in an authentic manners in real-time.

2. Background and Related Work

Most of the auralization processes for architectural environments involve three stages; sound generation, its propagation and sound transmission through building elements. Recent up-to-date auralization models commonly use Geometrical Acoustics (GA) and hybrid methods [2] that describe the propagation of sound in enclosed spaces. The “BASTIAN” [3] software calculates airborne and impact sound transmission between

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coupled rooms, and airborne sound transmission from the exterior. This software is for the airborne part based on databases and ISO: 12354 Part: 1. On the other hand, the real-time room acoustics simulation software “RAVEN” [5] developed by ITA, RWTH University Aachen, Germany relies on the knowledge of room acoustical simulation techniques and enables a physically accurate auralization of sound propagation in complex rooms, including important wave effects such as sound scattering [3]. However, the dynamic placement of source and receiver in different coupled building elements (e.g. rooms) is needed to be addressed in real time and interactive manners.

Auralization of complex building structures requires geometric data management and computation of sound transmission paths (direct as well as flanking paths) originating from any source to the receiver through air in various situations. The data management for complex geometries can be addressed through dynamic scene decomposition into acoustically separated volumes [5].

For an authentic and real-time auralization of complex building to a listener (i.e. at some place within the building volume), a high-tech model is required to be designed for sound insulation rendering by means of estimating sound transmission paths through structural elements and prediction of standardizes insulation parameters. Efficient techniques are needed for designing filter networks based on insulation metrics and filter rendering strategies to compute transfer functions between source and receivers located in adjacent as well as remotely coupled rooms.

3. Methodology

To achieve an auralization of a virtual architectural scene, the prerequisite are: estimation of sound transmission paths through building structures, modelling coupled rooms, scene representation and insulation filters rendering. In a complex building the user typically face a multitude of sounds not only originating from sound sources inside the user’s room, but also from sound sources located in adjacent rooms. Sound sources generate airborne sounds on the structural elements in the form of waves (e.g. bending waves). These waves propagate throughout the building elements and their energies mostly flow through low sound insulations elements creating several types of sound transmission paths [2]. These transmission paths face different sound propagation phenomena; such as, reflections from surfaces and diffractions from joints and edges of the portals. In turn, each element reacts to its excitation by airborne sound waves which propagate to a receiver and excite other elements, respectively [6].

Figure 1 illustrates the several types of sound transmission paths that exist in coupled room scenario, whereas the dominant part of the sound energy is transmitted by direct paths through directly separating structural elements (e.g. walls, doors and windows) and a small portion of sound energy is transmitted through different flanking paths. Using this path separation scheme, the total portion of the sound power can be described in accordance with the standard calculation methods described in [8].

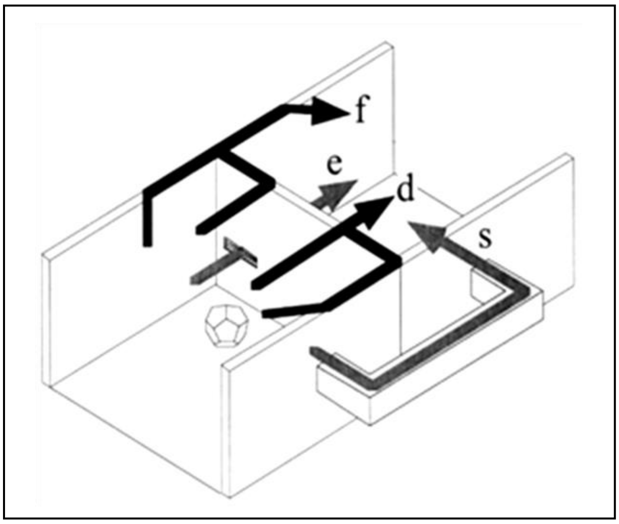

Figure 1. Sound transmission paths in two adjacent rooms including direct (d) and flanking (f) paths up to first-order junctions [3].

4. Computational Framework

In this section an airborne sound insulation rendering framework is described which is based on the knowledge of sound insulation metrics calculated from standard procedures [9]. Based on the computed sound insulation metrics, sound insulation filters are constructed for predicting transmission paths through building structural elements. Figure 2 illustrates the framework for calculation procedures for sound insulation metrics, prediction of transmission paths and construction of sound insulation filters for rendering airborne sound transmission (i.e. direct transmission, flanking transmission).

The basic sound insulation parameters for prediction of performance of individual element are: sound reduction index (***R***), vibration transmission over junctions ($\boldsymbol{K_{ij}}$), sound reduction index improvement of additional layers ($\boldsymbol{\Delta R}$) and normalized flanking level difference ($\boldsymbol{D_n}$). There exist numerous models, however, we adopted ISO: 12354-Part-1 (2017) [9] for calculations of above mentioned insulation metrics.

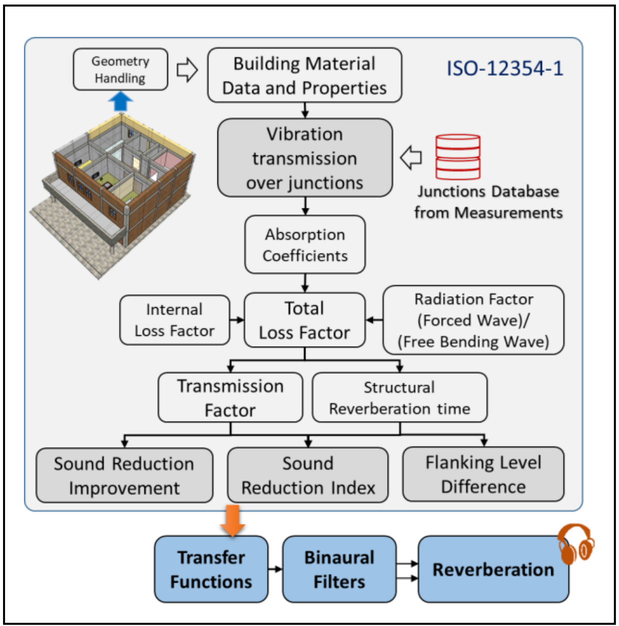

Figure 2. Auralization flow diagram for a building scene.

According to ISO Standard, the total transmission factor is divided into several transmission factors, related to each element in the receiving room and the elements and systems involved in the direct and indirect airborne transmission, as shown by equation 1 and equation 2.

$$R' = -(log\tau') \qquad (1)$$

where,

$$\tau' = \tau_d + \sum_{f=1}^{n} \tau_f + \sum_{e=1}^{m} \tau_e + \sum_{s=1}^{k} \tau_s \qquad (2)$$

Here the terms *'d'* and *'f'* refer to direct sound energy radiation and flanking sound energy radiation, whereas the terms *'e'* and *'s'* refers to portal energy radiations (doors, windows etc.) and indirect airborne energy radiations respectively. Equation 3 and equation 4 show the transmission for separating elements and the flanking elements respectively.

$$\tau_d = \tau_{Dd} + \sum_{F=1}^{n} \tau_{Fd} \qquad (3)$$

$$\tau_f = \tau_{Df} + \tau_{Ff} \qquad (4)$$

Here, *Dd* is Direct-Direct Path, *Df* is Direct-Flanking Path, *Fd* is Flanking-Direct Path and *Ff* is Flanking-Flanking Path.
For a linear and time invariant (LTI) system, the total transfer function *'H_{trans}'* between the sound source and the receiver via structural elements is described as follows:

$$H_{trans} = \sum_{x=0}^{X} \sum_{y=0}^{Y} H_{S,x}\, H_{x,y} H_{y,R} \qquad (5)$$

Here, *'$H_{S,x}$'* represents the room transfer function between source and structural element *'x'*, *'$H_{x,y}$'* describes the transfer function for transmission between the structural elements *'x'* and *'y'* of the rooms. This data is calculated from the direct and flanking sound transmission as expressed in equation 1-4. *'$H_{y,R}$'* represents the transfer function between the *'y'* element of the receiver room to the listeners *'R'*. *'H_{trans}'* describes the standardized filter function which is calculated form interpolated transmission coefficients of the respective building elements [8]. Figure 3 illustrate the mathematical procedure involved in the process of computing transfer functions.

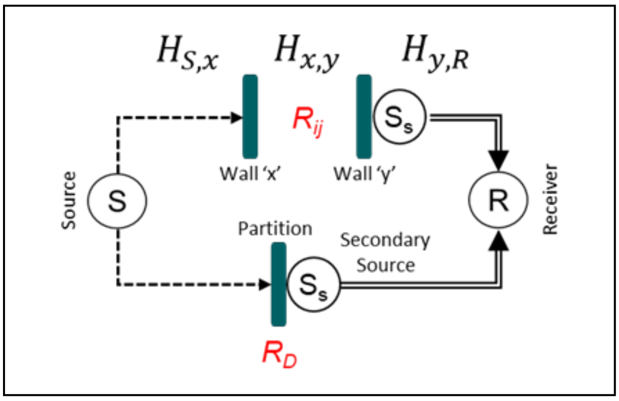

Figure 3. Types of filters for calculating transfer functions.

In this model, the transmission paths from the sound source to the secondary sources are calculated. The binaural HRTF for each direction are included and the total signal is obtained after superposition of the direct and flanking paths. Their contribution to the total reverberation is added to achieve a plausible spatial sound with respect to coloration and level.

5. Implementation (Case Study)

A multi-storey building is constructed in Sketchup software as shown in Figure 4, which consists of typical resident apartment. For the evaluation purpose, coupled rooms are selected. A sound source and a receiver are positioned at the center of each room as per requirements of standard [7]. The ceiling, floor and external walls of the building are considered as concrete blocks. The partitions between rooms 1 and 2, rooms 2 and 3, and rooms 3 and 4 are considered as plaster, autoclaved aerated concrete and calcium respectively.

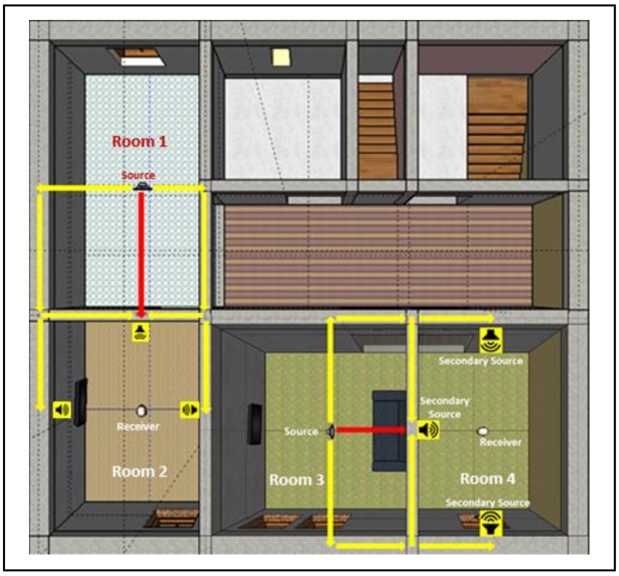

Figure 4. SketchUp model of an example building consists of two pairs of coupled rooms.

The input data for the model comes from standard material properties and geometrical information from where we computed the sound reduction indices *'R_{ij}'* and the level differences *'$D_{n,e}$'* for each element. Hence the transfer functions for each flanking path are computed. The radiating walls of the receiver room are modelled as point sources that are located in the center of each wall. The real sound radiation from a wall surface differs from the radiation of a point source at the wall surface but it was shone in previous work [8] that the differences are hardly audible. From the geometric data of the receiving room and the position of the listener, the distances and directions of the point sources can be calculated relative to the listener. In receiving rooms, the direct sound radiated from the walls can be considered as five independent point sources, therefore, the sound spectra of these sources are frequency shaped by the sound reduction indices *'R_{ij}'* of the respective paths. Figure 4 shows the secondary sources for the respective walls in the receiving rooms.

6. Results

From the one-third octave band data for sound transmission coefficients of each element the transfer functions for direct and each flanking path is obtained. From these transfer functions the spectra of each secondary source in the receiving room are is calculated using equation 3 and equation 4.

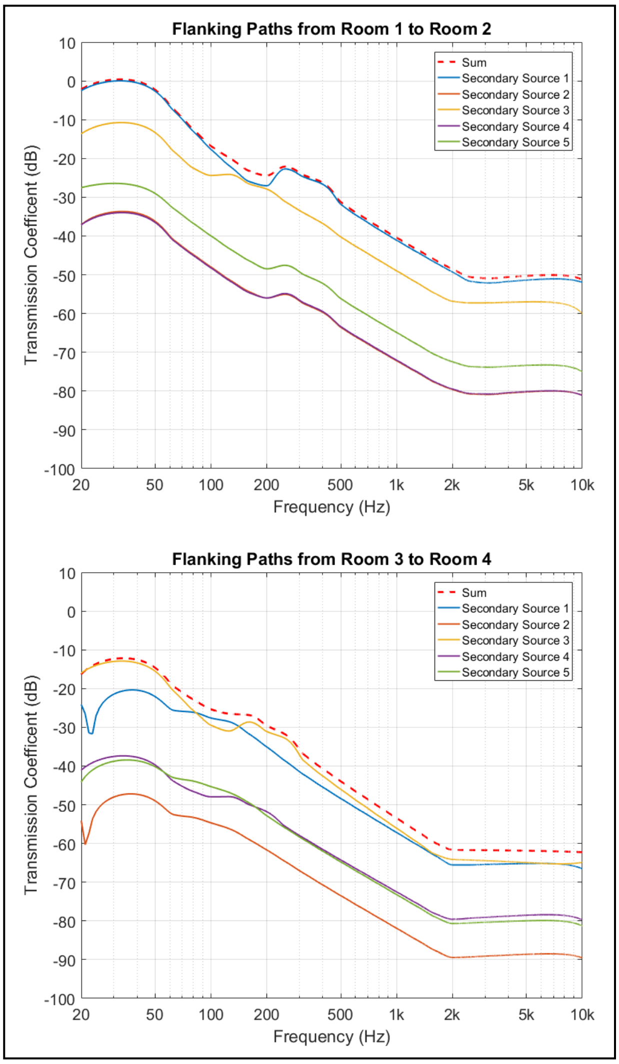

Figure 5. Interpolated spectra of summation for all paths of each secondary source.

The transfer functions for each receiving room's element (secondary sources) are show in Figure 5. These spectra represent acoustic filters for the transmission of sound from the source room to the receiving room. The input data, normally, are present only for frequencies between 50 Hz and 5 kHz so an appropriate handling for the frequencies below and above these values must be applied. The direction of the sources relative to the listener are considered by applying the head related transfer functions between the points of radiation on the walls and the listener.

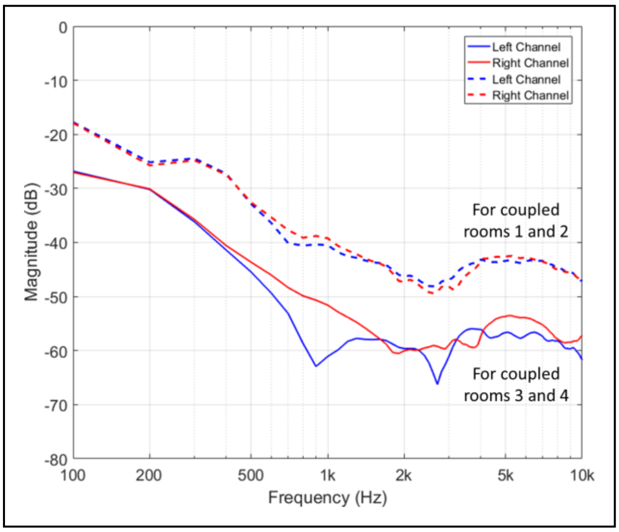

Figure 6. Addition of all spectra for binaural transfer function from source to receiver after including HRTF signals to the interpolated spectra of secondary sources.

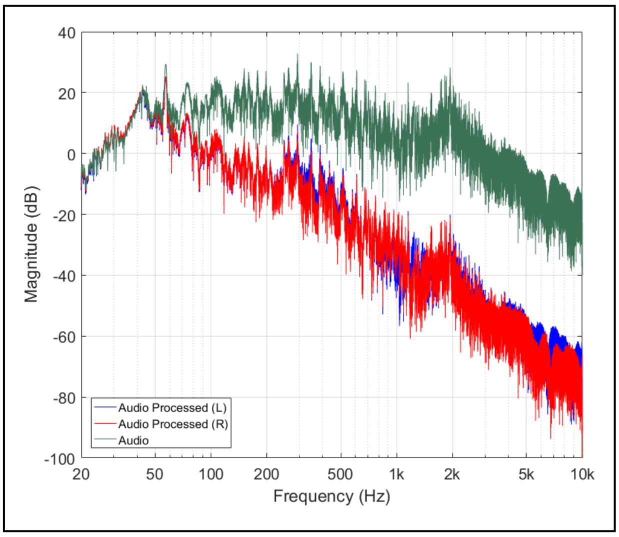

Figure 7. Frequency domain representation of source room 1 (green) and receiver room 2 binaural (red and blue) audio signals.

Afterwards the direct sounds are added to form the direct sound cluster of the impulse response direct. The result are shown in Figure 6. In the receiving room, a reverberant sound field is excited by the transmitted direct sounds. As a simplification, only one reverberation process for all five point sources is considered. An example sound source is convolved with the final transfer function between the source and receiver for both cases and the resultant sound and original sound spectra are shown in Figures 7-8. Figure 7 shows that the sound insulation is low at low frequencies for the coupled rooms 1 and 2 as compared to that of coupled rooms 3 and 4.

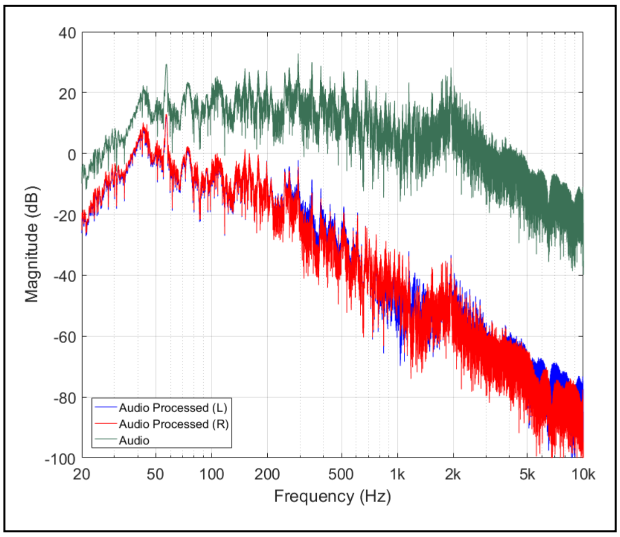

Figure 8. Frequency domain representation of source room 3 (green) and receiver room 4 binaural (red and blue) audio signals.

7. Performance

A Core i7 PC with 16 GB random access memory is used for implementing the framework. In terms of computations, the sound transmission paths calculation part is taking most of the processing time for calculating the transfer functions between source and receiver. The computational cost for these transfer functions is 70-80 millisecond for all secondary sources. This calculation is required only one time as offline process to initialize the virtual building scene for a fixed geometry and building elements and as long as the source and receiver stay the same coupled room, therefore, is not effecting real-time process for auralization. The convolution process for HRTFs and insulation filters requires five times operation and each operation requires 25-30 millisecond computational time.

8. Summary and Outlook

Airborne sound insulation is implemented for auralization of virtual buildings structures. This paper described the calculation for sound insulation metrics based on ISO 12354, Part-1 and the development of sound insulation filters. An example building was processed and the results for

different coupled-room pairs are shown. It was shown that the coupled rooms 1 and 2 are poorly insulated at lower frequencies, whereas, the couple rooms 3 and 4 and better insulated at both lower and high frequencies.
Furthermore, it is intended to improve the framework by integrating room acoustics filter in addition to sound insulation filters by including the room acoustical characteristics of both source and receiver rooms by using room acoustical simulation. The real-time filter rendering approaches will be developed for complete auralization of multi-coupled rooms in virtual reality. This will be the basis for novel sound perception tests where test subjects can be invited to perform any task of daily life of work or learning under conditions of usual behavior and movement, while the building acoustic scenario and the sounds presented are only used as moderating factors. This way it is intended to create more realistic tests than simply asking for "annoyance" in questionnaires.

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