SOUND FIELD VISUALIZATION USING THE FINITE-DIFFERENCE TIME-DOMAIN METHOD AND MEASURED SPATIAL ROOM IMPULSE RESPONSES

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1 INTRODUCTION

Visualization is an intuitive way to observe and analyse the phenomena related to the propagation of sound. It is evident that human hearing is highly capable of discriminating different aspects from an acoustic signal. The ability to discriminate is not necessarily enough to identify causality, that is answering the question: what aspect in the audio signal path, being a device or a room, contributes to the perceived difference in sound? Extracting information from a signal and visualizing it is a valuable tool for recognizing causality in cases where direct comparison between conditions via listening is not possible.

A simple and widely used visualization method for room impulse responses is the time or frequency domain visualization, where pressure, magnitude, or phase are shown with respect to time, or frequency. Another common approach is to show the magnitude response in short, possibly overlapping, time windows. This approach is commonly referred to as a *spectrogram*.

In addition to time and frequency-domain characteristics of sound, the direction of arrival of the energy also plays a significant role concerning the perceived spatial image.[4,10] Using estimates for the direction of arrival it is possible to speculate how different parts of the room geometry contribute to the time-domain response, and consequently how the properties of the room affect the spatial impression. Several different methods have been proposed to visualize the directional characteristics of the arriving energy using image sources[17], direction vectors[1,2], or temporal integration of the directional data.[8,11]. The correspondence of the directional analysis to the room geometry can be investigated using measurement data as a starting point, and visualizing the energy in a geometric room model using techniques from computer graphics such as ray casting and texture mapping.[15]

The visualization of the result of acoustic simulation is commonly built-in in simulation software. In geometric methods, the ray paths can be visualized to obtain information on the contribution of each reflective surface of the room. Wave-based methods such as *finite element method* (FEM) can be used to visualize the wave phenomena, such as edge diffraction, in for example loudspeaker enclosures.[6] The *finite-difference time-domain* method (FDTD) has been popular for the visualization of soundfield in enclosed spaces due to the direct availability of the direct time-domain responses.[13,18] Several software packages for FDTD simulation and visualization of general room geometries have been released.[5,12,14]

Although both, visualizations of measured and simulated data, have been previously used in the analysis of room acoustics, the combination of the two has not been proposed to the present authors' knowledge. In this work, an approach to concurrently visualize the progression of a sound field using FDTD simulation, and measured data is proposed. The objective for such an approach is to gain more insight on how different parts of the room geometry contribute to the measured time-domain response. An interactive *graphical user interface* (GUI) is developed to inspect more thoroughly how the soundfield evolves in the time-domain, and to verify possible inaccuracies in the geometric model. The visualiztaion scheme is demonstrated with two example cases.

2 METHODS

In the following, the methods used in the proposed approach are described. First, the details of the measurement setup are reviewed, second, the simulation methods used are presented, and lastly, the interface used to control the visualization is given an overview.

2.1 Mesurement and analysis

The measurement setup consisted of loudspeakers of types Genelec 1029A and 1032A, a microphone of type G.R.A.S. 50 VI, and a laptop computer. Measurements were made using the logarithmic sine sweep method[3] with a 13 s long sweep signal. The microphone array contains six microphone capsules, located at the positions $[-d, 0, 0]$, $[d, 0, 0]$, $[0, -d, 0]$, $[0, d, 0]$, $[0, 0, -d]$, $[0, 0, d]$ with respect to the center of the probe, d being the fixed distance determined by a spacer, and the three values indicating the Cartesian coordinates respectively.

Measurement data was analysed using the *spatial decomposition method* (SDM).[16] The method processes the microphone array responses in short time windows, in which the *time difference of arrival* (TDOA) of the arriving energy is estimated between each microphone pair of the array. The direction of arrival is then estimated using a least squares fit for a plane-wave propagation model from the TDOA estimates of each microphone combination and the theoretical time difference between each microphone pair determined by the dimensions of the microphone array, and the speed of sound. As the localization method assumes that the arriving wave at each time moment is a plane-wave, a single wavefront direction is estimated for each analyzed time window. The estimated direction of arrival and the magnitude measured with the microphone capsule that is closest to the source in the used array are used in the visualization for each time moment.

2.2 Simulation

The basic principle of the FDTD method is to iteratively solve discretized wave equation in time-domain. The linear wave equation is given:

$$\frac{\partial^2 p}{\partial t^2} = c^2 (\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2}), \tag{1}$$

where p is acoustic pressure and c is the speed of sound. By substituting the partial derivatives with second order accurate difference operators in time domain

$$\delta_t^2 = \frac{p_{i,j,k}^{n+1} - 2p_{i,j,k}^{n} + p_{i,j,k}^{n-1}}{\Delta t^2}, \tag{2}$$

and in spatial domain

$$\delta_x^2 = \frac{p_{i+1,j,k}^{n} - 2p_{i,j,k}^{n} + p_{i-1,j,k}^{n}}{\Delta x^2}, \tag{3}$$

where Δt and Δx the temporal and spatial discretization steps respectively, and the indices i, j, and k denote the discrete locations in the simulation domain ($x = i\Delta x$, $y = j\Delta x$, and $z = k\Delta x$). An explicit update equation in air can then be derived:

$$p^{n+1}_{i,j,k} = \lambda^2 \left(p_{i+1,j,k} + p_{i-1,j,k} + p_{i,j+1,k} + p_{i,j-1,k} + p_{i,j,k+1} + p_{i,j,k-1}\right) + 2(1-3\lambda^2)p^n_{i,j,k} - p^{n-1}_{i,j,k}, \quad (4)$$

where $\lambda = \left(c\frac{\Delta t}{\Delta x}\right)$ is the Courant number. This simple update equation is commonly referred to as the *standard rectilinear* (SRL) scheme. Here we compute the simulation results with a parallel implementation of the SRL scheme.[12]

The FDTD visualizations were video compositions of captured slices from the simulation domain. The captured pressure data is presented in a logarithmic scale using the sign of the linear pressure to indicate the color of each data point (green = positive, blue = negative). The specular reflection paths are solved up to 2nd order using a beam tracer library in the presented visualization cases.[7]

2.3 Interface

The visualization is controlled via a GUI that is implemented using an open source "creative coding" framework *Openframeworks*.[9] The geometric model, source and receiver setup and the measured room impulse responses processed with the directional analysis are loaded into the system. The *energy time curve* (ETC) of the impulse response measured with the capsule closest to the source is visualized as a simple waveform at the bottom of the window. The estimated direction of the arriving energy is visualized as a vector beginning from the receiver position and having a length and hue indicating the magnitude of the energy.

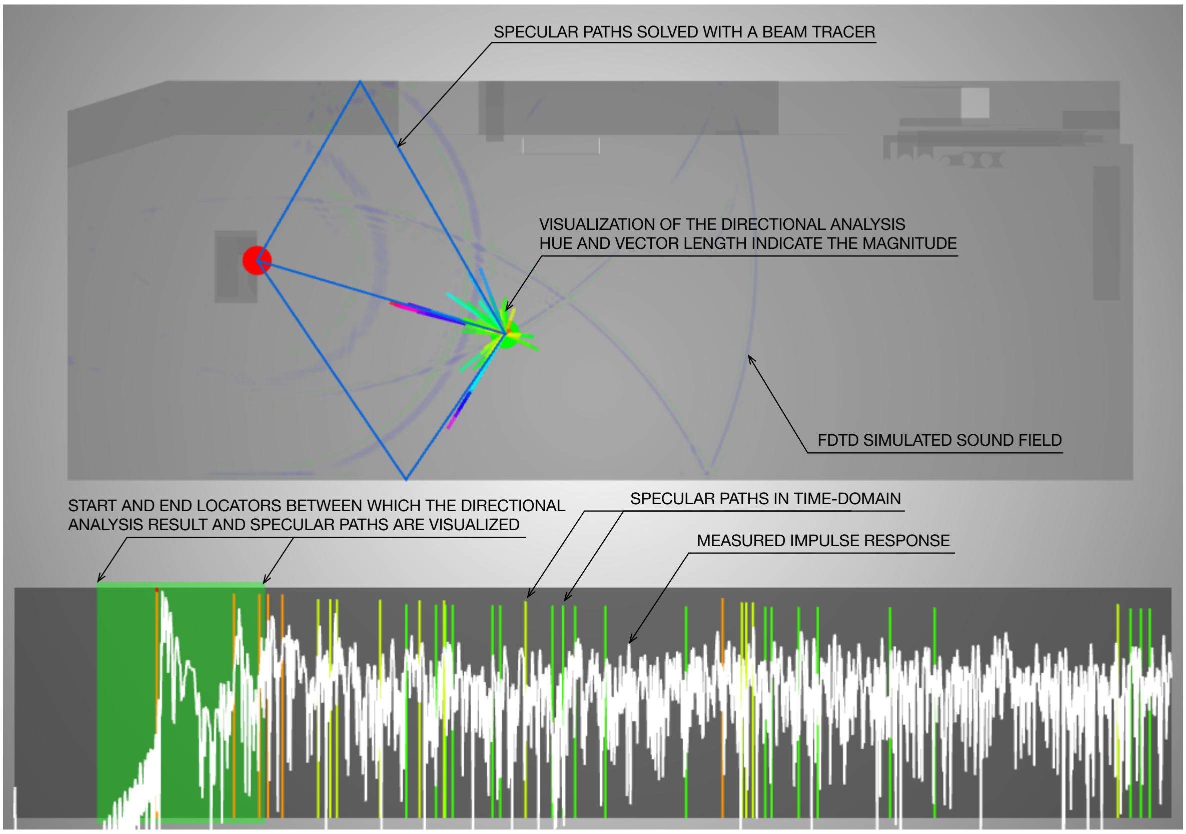


Figure 1 Overview of the visualization scheme.

The time window where the result of the directional analysis is visualized is controlled with GUI locators indicating the start time and the end time. All estimated directions and their respective magnitudes at this time window are visualized. The specular reflection paths are solved using the beam tracer, and visualized according whether the specular paths arrive at the receiver position in the time window determined by the locators.

The captured slice of FDTD simulation domain is mapped on a texture in a corresponding location inside the geometry. The video is played back in synch with the end locator.

3 RESULTS

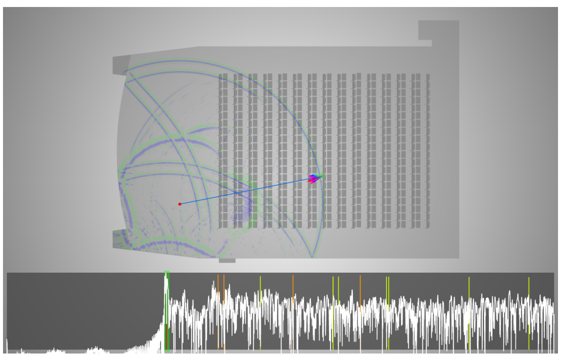
In the following, results of the two example spaces are presented. For each case captured images of the visualization scheme are presented at the time moments indicating direct sound and different early reflections in order to illustrate the functionality of the approach.

3.1 Lecture hall

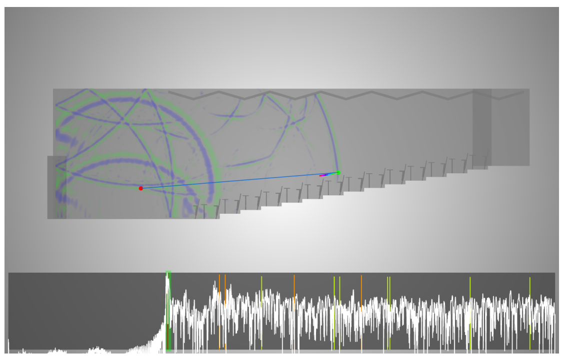
First presented case is a lecturehall with 300 seats, and an approximate volume, and surface area of 1700m^3, and 1400 m^2, respectively. The seating is moderately inclined, and a large, zigzag shaped ceiling element has been installed above the seating. The Genelec 1029A loudspeaker, and a 50mm spacer of the microphone array was used in the measurement. Sampling freuquency was set to 96 kHz. The directional analysis uses a measurement position in the 8th row. The measured response is filtered with an octave band filter with a center frequency of 1 kHz before the directional analysis. The combined visualizations are presented in Figures 2a, 2b, 3a and 3b. The ETC is illustrated from 0 to 100 ms. The window in which the results of the directional analysis are visualized is 1 ms.

An omnidirectional source is used in the simulation with a source signal consisting of a single period of a smooth source function $4\sin^3(\pi f_c t)\cos(\pi f_c t)$ with a fundemantal frequency f_c = 1 kHz, and t being time. The temporal sampling frequency used in the simulation was 42 kHz that resulted in voxel edge dimensions of 14 mm

The alignment between the beam tracer, directional analysis and the simulated sound field is generally good for the early part of the response. An expected variation between the beam tracer result and the two other visualizations can be seen from Figure 3b. In the figure the predicted specular reflection from the ceiling element does not correspond well with the directional analysis nor the FDTD simulated sound field. This is due to the nature of the used geometric prediction method that neglects wave phenomena, and therefore the direction of a reflection from a surfaces containing distinct edges may be mispredicted.

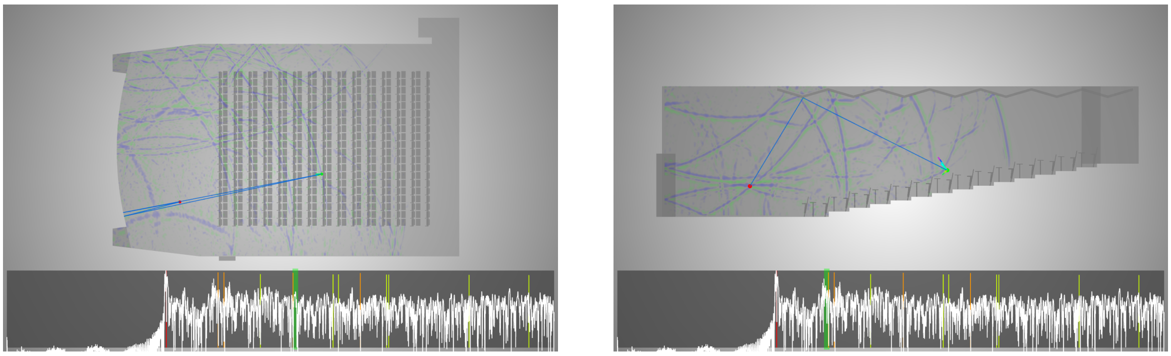


(a) The top view of the lecture hall



(b) The side view of the lecture hall

Figure 2 Soundfield at the time instance when the direct sound arrives at the receiver position. It can be seen that the alignment between the beam tracer result, the simulated soundfield and the directional analysis is very good.



(a) The top view of the lecture hall

(b) The side view of the lecture hall

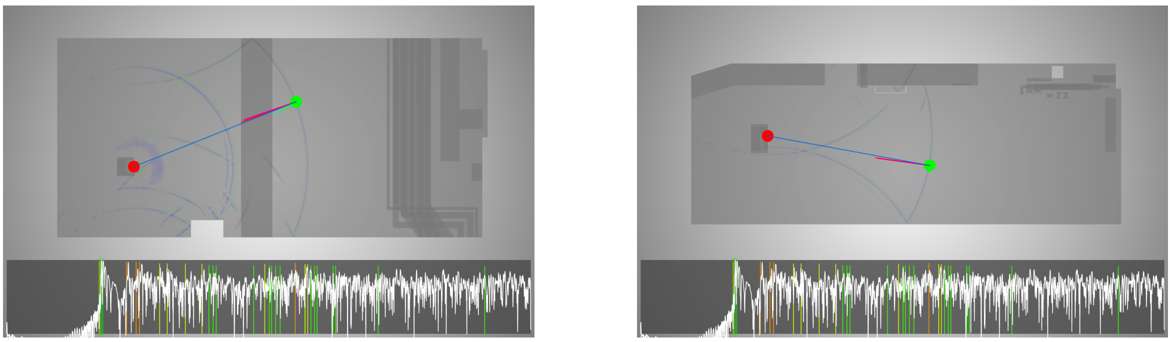
Figure 3 Soundfields at time instances when different first order reflections arrive at the receiver position. In (a), the back wall reflection from a curved surface is prediced with two specular paths with the beam tracer due focusing. The correspondance of the predicted sound field and the directional analysis is good. In (b) the direction of the ceiling reflection that is predicted by the beam tracer is noticeably different than the directional analysis. The directional analysis shows a good correspondence with the soundfield predicted with FDTD.

3.2 Warehouse room

Second example is a small warehouse room with an approximate volume, and surface area of 63 m^3, and 133 m^2 respectively. The room has solid walls and only little structural detail. The Genelec 1032A loudspeaker, and a 25mm spacer of the microphone array was used in the measurement. Sampling freuquency was set to 192 kHz. The source in the simulation was a point source that was place on the surface of a geometric model of the loudspeaker used in the measurement. The impulse responses were band-pass filtered before the directional analysis with an octaveband filter with a center frequency of 4 kHz. The combined visualizations are presented in Figures 4a, 4b, 5a and 5b. The ETC is illustrated from 0 to 50 ms. The time window where the directional analysis is visualized is 0.5 ms.

The source signal for the simulation was a single period of a source function $4\sin^3(\pi f_c t)\cos(\pi f_c t)$ with a fundamental frequency f_c = 4 kHz. The temporal sampling frequency used in the simulation was 140 kHz that resulted in voxel edge dimensions of 4.3 mm.

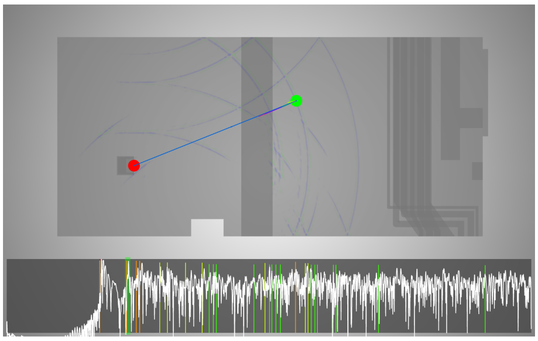
A good alignment between the beam tracer, the directional analysis and the predicted sound field can be observed in the presented time windows.



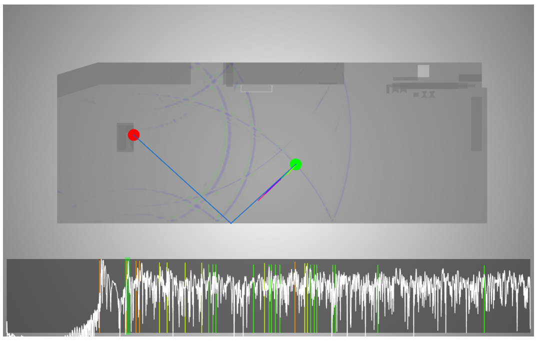
(a) The top view of the warehouse room.

(b) The side view of the warehouse room.

Figure 4 Soundfield at the time instance when the direct sound arrives at the receiver position.



(a) The top view of the warehouse room.



(b) The side view of the warehouse room.

Figure 5 Soundfield at the time instance when an early reflection arrives at the receiver position. The reflection is a first order reflection from the floor.

3.3 Considerations with the geometric model

The accuracy of the geometric model is an important factor of the visualization as the simulated sound field is completely determined by the model. Equally important factor is the accurate documentation of the measurement positions. These two factors may be overwhelmingly hard to accomplish with large spaces, complex geometries and limited time. Therefore an acquisition and inspection of an existing geometric model, and careful planning of the measurement setup is highly advantageous. Even with a carefully constructed model and simulation setup, misalignments especially with the microphone array position and orientation are hard to overcome.

The accuracy that is needed to evaluate the early reflections in an auditorium or performance space is not speculated here although the proposed interactive visualization is shown to be a helpful tool for pinpointing possible misalignments between the measurement and simulation.

4 CONCLUSIONS

A method for visualizing soundfields using the FDTD method and the directional analysis of measured room impulse responses was introduced. It was found that with an accurate room model the simulated soundfield corresponds to the measured data in the early part of the response that is one of the key features to determine the characteristic sound of a space. The result indicate that in order to achieve more accurate predicition of the early reflections, a wave-based simulation method can lead to better result in terms of time-domain scattering. It should be noted that not only the geometric methods, but also directional analysis of measurements and FDTD method have their own shortcomings, and therefore using multiple methods in the analysis may give more detailed information on the effect of room structure to the time-domain response.

Future work includes the developement of more specific tools to the visualization environment, such as frequency domain analysis of responses, and possibility to introduce additional elements to the room model and compare the changes to existing measured and simulated responses. The approach to compare measurements and simulations using an interactive application as presented may be highly advantageous for objective comparisons between room models.

5 ACKNOWLEDGEMENTS

The research leading to these results received funding from the Academy of Finland, Project No. 265824. The calculations presented above were performed using computer resources within the Aalto

University School of Science "Science-IT" project. The authors are grateful to Prof. Lauri Savioja, Dr. Sakari Tervo, Dr. Jonathan Botts, and Mr. Sebastian Prepelita for their valuable comments, which helped to improve the quality of this paper.

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