PROCEEDINGS of the
24th International Congress on Acoustics

October 24 to 28, 2022 in Gyeongju, Korea

ABS-0296

Enabling Interactive Virtual Reality for Room Acoustics in Enclosed Spaced Using Reduced Basis Methods

Hermes SAMPEDRO LLOPIS[1,2]; Cheol-Ho JEONG[2]; Allan Peter ENGSIG-KARUP[2]; Finnur PIND[3]; Pierre CHIGOT[4]; Erling NILSSON[4]; Erik SIKSTRÖM[5]; Jesper BO ANDERSEN[1]

[1] Rambøll, Denmark

[2] Acoustic Technology, Department of Electrical and Photonics Engineering, Technical University of Denmark, Denmark

[3] Treble Technologies, Iceland

[4] Saint-Gobain Ecophon, Sweden

[5] Virsabi, Denmark

ABSTRACT

New technologies allow the rational use of room acoustic simulations in many innovative applications, e.g., Metaverse and virtual reality, which open new horizons for holistic and immersive user experiences in various fields, e.g., building design, video games and multimodal perception. Numerical methods can be used to simulate acoustic wave propagation in rooms for this purpose. These methods can be highly accurate but computationally expensive. Moreover, it is common for engineering applications to perform multiple simulations to identify desired acoustic conditions using different materials, which increases the total computational cost. Computational reduction is achieved by using reduced basis methods (RBM) for parametrized boundary conditions, where the computational burden is reduced by solving the problem in a low-dimensional subspace. Moreover, we combine the simulations with a geometrical acoustics method for the high frequencies above 1 kHz. We present a new concept model of a virtual reality 3D meeting room with interactive acoustic conditions, where the low frequency part of the spectrum is computed using RBM, achieving speedups by a factor of 400 without introducing audible differences. It is constructed for different material parameters on the room surfaces, such as the flow resistivity of the porous material. This concept prototype proves the potential of RBM in building design and interactive virtual auditory displays.

Keywords: Virtual reality, room acoustics simulations, numerical methods.

1. INTRODUCTION

Virtual reality (VR) and Metaverse continue to evolve with higher fidelity in visual rendering, improved realism, and physical accuracy by tapping into accelerated computing. Many new sounds-related applications continue to emerge. Nowadays, architects and building designers are gaining interest on this technology for building design applications and building digital twins, where it is possible to test and optimize the indoor climate quality during the design phase, making more pleasant environment yet more sustainable use of building materials including absorbers. The future acoustic simulation will also require such demands and applications. There are two different conventional methods to perform room acoustic simulations. The geometrical acoustics (GA) methods [1] are approximate mainly to achieve manageable computational cost, but fail to simulate the right wave nature of sound causing a certain level of degradation in the accuracy of the simulations. Numerical discretization methods, on the other hand, solve partial differential equations (PDEs), which include all the wave phenomena, such as diffraction and interference at low frequencies. Some examples of

[1] hsllo@dtu.dk

those methods are the finite element method (FEM) [2], spectral element method (SEM) [3] and the finite difference method (FDTD) [4]. These methods can be substantially more accurate than GA, especially at low frequencies, but the computational cost increases dramatically when increasing the size of the domain and the frequency. Thus, acceleration is needed for practical applications, which can be achieved by reducing the number of degrees of freedom of the system to be solved. A previous study presented a reduced basis method (RBM) [5] for room acoustic simulations where the presented reduced order models (ROM) achieve an acceleration of two to three orders of magnitude for single runs in a *1 m* cube domain [6].

The present work is to create a 3D virtual reality mockup of an actual meeting room located at Rambøll's Head Office in Copenhagen. Both, visuals and acoustic stimuli are merged together in a virtual reality environment to provide a fully immersive virtual experience. A pre-computation approach is used, where all the acoustic simulations are computed in advance. We perform room acoustic simulations using a hybrid method that combines SEM at low frequencies, and a ray-based geometrical acoustics method for high frequencies. SEM in the Laplace domain is exploited for low frequencies, which allows high-order accuracy, geometrical flexibility, stable reduced order modelling, and transient response reconstruction, which are essential for simulating large rooms and high frequencies [6]. The goal is to create a VR mockup that uses reduced order SEM (RB-SEM) for low frequencies that parameterize a porous boundary condition in the room at two fixed receiver positions in the room. A real-time binaural synthesis for enabling head movement, similar to the approach presented in previous study [7] is included, providing a full immersive experience.

2. METHODS

2.1 Room acoustic simulations

The acoustic wave propagation can be described by the second order wave equation. In this study, the expression is written in the Laplace transform evaluated at a fixed complex frequency $s = \sigma + i\gamma$

$$s^2 p - c^2 \Delta p = s p_0 + p_{t,0}, \tag{1}$$

where $p(\boldsymbol{x}, s)$ is the sound pressure, $\boldsymbol{x} \in \Omega$ is the position in the domain Ω, t is the time in seconds, $c = 343$ m/s is the speed of the sound and $p_0(\boldsymbol{x}, t)$, $p_{t,0}(\boldsymbol{x}, t)$ corresponds to the initial condition and the derivative at $t = 0$ s. A Gaussian pulse is utilized as initial condition for the sound pressure. The SEM formulation [8, 9] is used to discretize (1),

$$\left(s^2 \boldsymbol{M} + c^2 \boldsymbol{S} + s c^2 \frac{\rho}{Z_s} \boldsymbol{M}_\Gamma\right) \boldsymbol{p} = s \boldsymbol{M} p_0, \tag{2}$$

where $\boldsymbol{M} \in \mathbb{R}^{N \times N}$ is the mass matrix, $\boldsymbol{S} \in \mathbb{R}^{N \times N}$ is the stiffness matrix, N denotes the degree of freedom (DOF) and $Z_s = \frac{p}{v_n}$, is the surface impedance, being $v_n = v \cdot \boldsymbol{n}$ the normal velocity at the boundary Γ and $\boldsymbol{n}$ the outward pointing normal vector of the boundary. For simplicity, (2) can be written as

$$\boldsymbol{K}\boldsymbol{p} = \boldsymbol{q}, \tag{3}$$

where $\boldsymbol{K} = s^2 \boldsymbol{M} + c^2 \boldsymbol{S} + s c^2 \frac{\rho}{Z_s} \boldsymbol{M}_\Gamma$ and $\boldsymbol{q} = s \boldsymbol{M} p_0$.

Frequency-independent boundary conditions are given by assigning a surface impedance value to a wall, Z_s, while frequency-dependent boundary conditions are implemented via the method of auxiliary differential equations (ADE) [10, 11]. The admittance at the boundary is given by $Y(\omega) = \frac{v_{n(\omega)}}{p(\omega)}$, where ω is the angular frequency and can be approximated as a rational function, used to recover the particle velocity expression at the boundary. Finally, the time domain signal is obtained by use of the the Weeks method [12, 13].

2.2 The reduced basis method

The key challenge of the method is to construct a reduced basis that preserves the physical dynamics of the original problem for a required accuracy level. The high-fidelity solutions $p_{FOM}(\boldsymbol{x}, s, \mu)$ of the parametrized problem under variation of the parameter μ in the parameter space $\mathbb{P}$, approximates the solution manifold. The goal is to approximate the solution manifold with a small number of basis functions$\{\phi_i\}_{i=1}^{N_{rb}}$, where N_{rb} is the number of basis functions. The FOM solution can be approximated as an expansion of the reduced basis and coefficients

$$p_{FOM}(\boldsymbol{x}, s, \mu) \approx p_{ROM}(\boldsymbol{x}, s, \mu) = \sum_{i=1}^{N_{rb}} \phi_i(x) a_i(s, \mu). \tag{4}$$

The FOM solutions are collected into a matrix

$$S_N = \left[p_{FOM}(\boldsymbol{x}, s_1, \mu_1); \dots ;p_{FOM}\left(\boldsymbol{x}, s_{N_s}, \mu_{N_\mu}\right)\right], \tag{5}$$

where N_s is the number of complex frequencies and N_μ the number of parameter values. The generation of the basis performed by applying singular value decomposition (SVD) to S_N. The reduced basis is obtained by truncating the basis while keeping the essential information that ensures the desired accuracy of the results. The matrix expression of the reduced system is (add ref)

$$\boldsymbol{K_{ROM}} \boldsymbol{a} = \boldsymbol{q_{ROM}}, \tag{6}$$

Finally, the sound pressure is obtained by

$$\boldsymbol{p_{ROM}} = \boldsymbol{\phi a}. \tag{7}$$

2.3 Hybrid method, binaural rendering and head-rotating feature

Binarual auralization for enabling head movement inside the virtual model is crucial for an immersive/realistic VR experience. It is achieved by calculating multiple impulse responses at the surface of an open virtual sphere around the receiver position [14], to obtain the second order ambisonic channels in a post-processing stage. The impulse responses of both, SEM and GA solutions should be combined into a broadband impulse response. The use of second order ambisonic channels, allows the user to freely move the head in the virtual reality model, using a real-time binaural rendering system presented in previous study [7].

2.4 Simulation setup

The dimensions of the chosen meeting room are *5.58 m* × *2.96 m* × *2.59 m*. The virtual model consists of three different scenarios, where the user is capable to change between three different acoustic conditions. First, the original room is presented, which is made of two gypsum walls, two glass walls, a thin carpet on the floor and an acoustic ceiling. A second case is implemented by adding a set of curtains at the two glass walls. A third case is implemented by adding an extra curtain in one of the gypsum walls. Two standing receiver positions are selected at $(r_x,r_y,r_z,)_1= (1,1.48,1.2)m$ and $(r_x,r_y,r_z,)_2= (3.6,0.5,1.2)m$. The sound source at $(s_x,s_y,s_z,)= (5.5, 1.48,1.2)m$, is placed at one of the gypsum walls, in front of a TV, simulating an online meeting on the room. The estimated range of the reverberation time using Sabine’s formula is 0.2s to 0.6s. Table 1 presets the materials assigned to the different surfaces.

SEM simulations are performed using a polynomial order *P=4,* and using *5* points per wavelength (*PPW*) with an upper frequency of 1.123kHz, corresponding to the 1kHz 1/3 octave band. The degree of freedom (DOF) of the model is 221.805.

The ROM is constructed by parameterizing the flow resistivity of the curtains. FOMs simulations with $\sigma_{mat} = 10.000, 25.000, and\ 45.000$ Nsm^{-4} were used to create the ROM. As an example, a curtain with a new flow resistivity value$\sigma_{mat} = 40.000$ Nsm^{-4} was computed with an acceleration of 400 compared to the FOM. The ROM becomes more valuable when a large number of ROM calculations are required, e.g., during the design stage of a room where many different acoustic materials are tested to find the optimal acoustic condition.

Table 1 – Boundary acoustic parameters

Material	Surface $[m^2]$	*Freq. indep.*	*Freq. dep.*		
		Z_s $[kgs^{-1}m^2]$	d_{mat} $[m]$	σ_{mat} $[Nsm^{-4}]$	d_0 $[m]$
Glass	2x 15.2	20.000	-	-	-
Gypsum	2x 7.67	30.000	-	-	-
Floor	17.4	70.000	-	-	-
Ceiling	17.4	-	0.04	10.000	0.7
Carpet	17.4	-	0.015	20.000	0
Curtain	2x 15.2 (+7.67)	-	0.02	40.000	0.2

2.5 Virtual 3D model

A visual twin model of the room is recreated by capturing visuals of the real environment. Figure 1 shows the rendering of the room, while Figure 2 shows the source and receivers positions. The model is implemented in Unity, where the visual scene is synchronized with a real-time audio processor that reproduces, and process the audio files to provide real-time interaction with the user and head orientation.

The visuals also include the corresponding materials of the three different acoustic scenarios to provide a visual change when switching between the different acoustic conditions.

Figure 1 – Visual recreation of the meeting room.

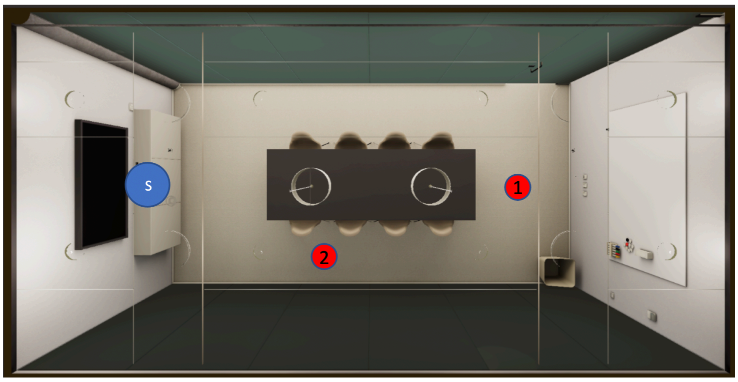

Figure 2 – Source and receiver positions in the meeting room. S denotes the source, while 1 and 2 denote receiver locations.

3. CONCLUSIONS

This work presents an actual meeting room located at Rambøll, Denmark in a virtual reality mockup of which three acoustic (and corresponding visual) conditions are changed on the fly. The main novelty of this work is the use of RB-SEM for a real 3D room case to compute a new acoustic condition at low frequencies, enabling a speedup of 400. Admittedly, not all the frequencies are simulated using SEM to make the simulation time manageable. We have hybridized with a geometrical acoustics at high frequencies. Head rotation inside the virtual model is allowed and implemented via the 2nd order ambisonics. This is an on-going attempt towards an immersive VR-based building design and renovation process using ROM.

ACKNOWLEDGEMENTS

We are grateful for the financial support from the Danish Sound Cluster that allowed for setting up a collaborative innovation project among partners from Technical university of Denmark, Rambøll, Ecophon, Virsabi, and Treble Technologies.

REFERENCES

1. L. Savioja and U. P. Svensson. Overview of geometrical room acoustic modeling techniques. J. Acoust. Soc Am. 2015; 138(2): 708–730.
2. Craggs. A finite element method for free vibration of air in ducts and rooms with absorbing walls. J. Sound Vib. 1994; 73(4): 568–576.
3. F. Pind, A. P. Engsig-Karup, C. H. Jeong, J. S. Hesthaven, M. S. Mejling, and J. S. Andersen. Time domain room acoustic simulations using the spectral element method. J. Acoust. Soc. Am. 2019; 145(6): 3299–3310.
4. D. Botteldooren. Finite-difference time-domain simulation of low-frequency room acoustic problems. J. Acoust. Soc. Am. 1995; 98(6): 3302–3308.
5. J. S. Hesthaven, G. Rozza, and B. Stamm. Certified Reduced Basis Methods for Parametrized Partial Differential Equations. Springer; 2016.
6. H. Sampedro Llopis, A.P. Engsig-Karup, C-H. Jeong, F. Pind, J. S. Hesthaven. Reduced basis methods for numerical room acoustic simulations with parametrized boundaries. J. Acoust. Soc. Am. 2022; 152 (851).
7. H. Sampedro Llopis, F. Pind, C-H. Jeong. Development of an auditory virtual reality system based on pre-computed B-format impulse responses for building design evaluation. Building and Environment. 2020; 169: 106553.
8. J. S. Hesthaven and T. Warburton. Nodal Discontinuous Galerkin Methods—Algorithms. Springer, New York; 2008.
9. H. Xu, C. Cantwell, C. Monteserin, C. Eskilsson, A. P. Engsig-Karup, and S. Sherwin.

Spectral/hp element methods: Recent developments, applications, and perspectives. J. of Hydrod. 2018; 30(1): 1–22.
10. B. Cotté, P. Blanc-Benon, C. Bogey, and F. Poisson. Time-domain impedance boundary conditions for simulations of outdoor sound propagation. AIAA Journal. 2009; 47(10).
11. R. Troian, D. Dragna, C. Bailly, and M.-A. Galland. Broadband liner impedance eduction for multimodal acoustic propagation in the presence of a mean flow. J. Sound Vib. 2017; 392: 200–216.
12. W. T. Weeks. Numerical inversion of laplace transform using Laguerre functions. J.Assc. Comp. Mach. 1966; 13(3):419–429.
13. C. Bigoni and J. S. Hesthaven. Simulation-based anomaly detection and damage local ization: an application to structural health monitoring. Comput. Math. Appl. Mech. En. 2020; 63: 12896.
14. R. Boaz. Fundamentals of spherical array processing. Springer Topics in Signal Processing. 2015 (8): pp.1-193.