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A Benchmark for Room Acoustical Simulation. Concept and Database

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Abstract

Room acoustical simulations are usually evaluated by comparing them to measurements in corresponding physical environments as a benchmark. However, it proved to be challenging to provide a precise representation of the room geometry, the source and receiver characteristics, and the absorption and scattering coefficients to be re-modeled in the simulation. We aim to overcome these shortcomings by providing a database that can serve as a Benchmark for Room Acoustical Simulations (BRAS) and which is expandable and permanently available to researchers and developers of simulation software. The database includes a selection of reference scenes such as “single reflection”, or “diffraction around an infinite wedge” which isolate specific acoustic phenomena. This article introduces the concept of the BRAS along with the description of the currently contained acoustic scenes and discusses the implication of measurement errors. The acquisition of impulse responses for omnidirectional and binaural receivers, the identification of the boundary conditions, and the data structure is detailed in the database itself. The BRAS is publicly available[1]. The free license under which it is provided allows for future extensions such as additional scenes or improved data due to advanced measurement techniques.

Keywords: room acoustic simulation, benchmark, diffraction, scattering

1 Introduction

Room acoustical simulation enables the numerical calculation of sound propagation in enclosed and open spaces. Corresponding algorithms are either based on the assumptions of geometrical acoustics (GA), considering sound to propagate as rays, or on numerical solution of the wave equation, applying different techniques such as finite-difference methods (FDM), the finite element method (FEM), or the boundary element method (BEM) [1]. Due to the high computational effort, the latter are, however, mainly applied for low frequencies and relatively small rooms so far.

Room acoustical simulations have a broad field of application including the acoustical reconstruction of historic venues [2, 3], the design of new concert halls [4], classrooms, open offices or train stations and stadiums [5], the planning of urban areas [6], the creation of complex game audio scenarios [7], the investigation of particular room acoustic phenomena [8, 9] or the experimental study of the impact of room acoustics on speech perception [10] and musical performance [11], to name just a few recent examples. Many of these applications make use of the possibility of listening through the virtual ears of a dummy head or head-and-torso simulator – a process which was coined auralization [12]. At the same time, there is no undivided confidence in the accuracy of room acoustical simulations, when it comes, for example, to the design of new performance venues for music and speech, where acoustic scale models are still an important alternative with specific advantages [13]. The multitude of applications and the importance of acoustical simulation thus necessitates a comprehensive evaluation of the corresponding algorithms, especially if considering that all of them have underlying simplifying assumptions or a limited frequency range of operation (for an overview see [14]).

This technical note illuminates different evaluation strategies for room acoustical simulation along with their specific advantages, disadvantages and challenges (Section 2). It is followed by an introduction of the acoustic scenes (Section 3.1), the acquisition of the database (Section 3.2), and a brief overview of the database organization (Section 3.3). Section 3.4 details how the BRAS can be extended by third parties, while the implication of measurement uncertain-

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[1] `https://dx.doi.org/10.14279/depositonce-6726.3`

ties are discussed in the concluding Section 4. More details, such as the exact source and receiver positions, details about the related measurements, the data formats/structure, and pictures of the scenes and the included acoustic materials are contained in the database itself [dataset][15].

2 Background

Evaluations of room acoustical simulation algorithms were carried out in the three international Round Robins on room acoustical computer simulation, termed RR-I to RR-III in the following [16, 17, 18, 19]. In these Round Robins, different information was provided to the participants at different phases. In phase I of RR-I and RR-II, the participants had to estimate the geometry and the boundary conditions themselves from architectural plans and written information ("3 mm carpet"); in phase II the data was harmonized based on a common 3D model and boundary conditions estimated by room acoustical measurements. In RR-III, absorption and scattering coefficients for one wall and the ceiling of the room were measured in the reverberation room, and taken from tabulated data otherwise.

In an approach to establish a more controlled environment, the Bell Labs Box was created as a small, empty, shoebox room with a single diffracting wedge [20]. A more complex scene was realized more recently by furnishing an empty small room to enable laboratory impedance measurements of all involved objects and materials [21].

Another Round Robin used a simplified analytical reference scene to assess the simulation of double sloped energy decay in coupled rooms at 1 kHz [22]. As a reference, a statistical model for the energy decay in coupled rooms was parameterized based on scale model measurements. To focus solely on the simulation of the energy decay, the participants were instructed to adjust the simulated reverberation times of the two rooms in an uncoupled configuration.

Moreover, two databases with analytically defined test scenarios were established that are intended for cross-validation of wave based simulation algorithms, and provide mathematical scene descriptions without measured or analytical references [23, 24][2][25][3].

The examples demonstrate that any evaluation of room acoustical simulation software has to define a strategy how to provide a suitable reference for the simulation, and how to control the uncertainties related to this reference.

A first source of uncertainty is the geometric model of the acoustic scene. In most geometric room acoustical simulation software it turned out to be favorable to dispense with the representation of small surface structures below 0.5 m [1, p. 176]. For wave-based simulations, on the other hand, a precise model is desirable, and even for algorithms based on ray tracing, the exact threshold of resolution may depend on the way scattering and diffraction is treated. For both approaches, the desired resolution may also depend on the considered frequency band. Therefore, the way a primary acoustic structure is modified and possibly simplified for simulations should, according to the authors, be considered as part of the simulation itself. This is true for the meshing methods for finite element simulations as well as for the geometric simplification for ray simulations. It should not be anticipated by manipulating the reference data in a way that would necessarily favour certain algorithms and certain frequencies over others. Therefore, the BRAS provides exact scene geometries for the reference scenes.

A second source of uncertainty are the boundary conditions. In RR-I to RR-III and in similar investigations [26, 27], the lack of valid boundary conditions data was identified as one of the most important factors why room acoustical simulations differ from measured results. Complex large rooms such as concert venues or lecture halls are important use cases for room acoustical simulations. However, a comprehensive specification of absorption and scattering for all boundaries is practically impossible in these cases, because neither can all different surfaces with their different types of installation be measured in the laboratory, nor are any (standardized) full-range measurement techniques available to determine them in situ. Fitting the input parameters according to measurements of the reverberation time, on the other hand, may be a pragmatic solution for many problems in room acoustics planning. As a procedure for the evaluation of room acoustical simulation algorithms, however, it would contain an element of circular reasoning. If both the premises (the boundary conditions) and the success of the simulation are determined by the same measurement (of room acoustical parameters), the test will always tend to confirm the quality of the simulation algorithm. For these reasons, the boundary conditions provided within the BRAS were directly measured in situ for the reference scenes.

A third source of uncertainty is the behavior of the sources and receivers which are an integral part of the acoustic transfer function. In RR-I to RR-III, the reference measurements were done with industry-standard dodecahedron loudspeakers, whereas for the simulations, perfect omnidirectional sources were assumed. It was shown, however, that the non-ideal directivity of standard dodecahedron loudspeakers, even if they are compatible with the requirements according to ISO 3382, can be observed even at late parts of measured RIRs [28], and causes a measurement uncertainty above the JND for different room acoustical parameters and frequencies above

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[2] `http://news-sv.aij.or.jp/kankyo/s26/AIJ-BPCA/A0-1F/index.html` (Accessed: Mar. 2020)

[3] `https://eaa-bench.mec.tuwien.ac.at/main/` (Accessed: Mar. 2020)

#	Name	RIR	BRIR
RS1	single reflection (infinite plate)	3/3	1/1
RS2	single reflection & diffraction (finite plate)	6/5	–
RS3	multiple reflection (parallel finite plates)	1/1	1/1
RS4	single reflection (reflector array)	6/6	–
RS5	diffraction (infinite wedge)	4/4	1/1
RS6	diffraction (finite body)	3/3	–
RS7	multiple diffraction (seat dip effect)	2/4	–

Table 1: Scenes contained in the BRAS. Columns RIR and BRIR give the number of source/receiver positions used for measuring impulse responses with omnidirectional (RIR) and binaural (BRIR) receivers.

Figure 1: The seven reference scenes included in the BRAS. Numbers refer to Table 1.

500 Hz [29]. To allow for an accurate analysis, measured directivities are provided in high spatial resolution for all sound sources and the binaural receiver used in the BRAS.

3 Database

In its initial form, the BRAS contains a collection of 7 acoustical reference scenes, each of which highlights certain acoustical phenomena and certain spatial configurations. This allows the evaluation of numerical simulations for specific acoustic phenomena such as specular or scattering reflection and diffraction in configurations relevant to room acoustics (scenes RS1–7). For these scenes, the required input data (geometry, boundary conditions) is given with an accuracy of state-of-the-art data acquisition methods.

The database contain impulse responses for omnidirectional and binaural receivers, so that the quality of the corresponding simulations can later be evaluated against the measurements.

3.1 Acoustic Scenes

An overview of the scenes contained in the BRAS along with the number of contained source and receiver positions is given in Tab. 1 and Fig. 1. A more detailed description is given in the documentation [dataset][15]. Scenes RS1 and 5 – 7 were set up at the hemi anechoic chamber and the reverberation chamber at RWTH Aachen University. Scenes RS2 – 4 were set up in the anechoic chamber at TU Berlin.

The BRAS contains seven reference scenes. Scene RS1 features a single reflection on a quasi infinite rigid (1a), absorbing (1b), and scattering (1c) surface for different angles of sound incidence. A reflection and diffraction on rigid and absorbing finite plates of two sizes was measured in RS2. Impulse responses were acquired for different angles of sound incidence, and receiver positions in front of and behind the plate. Despite its geometric simplicity, this scene is challenging due to diffraction and sound transmission around and through the plate, which has to be modeled either with extended geometrical or wave based methods. Scenes RS3 – 7 aim at recreating simplified versions of relevant room acoustical scenarios: The reflection between parallel plates (RS3) evokes a flutter echo that is often problematic in larger venues. Reflector arrays (RS4) are frequently used in concert halls to direct early reflections to the audience area. Diffraction around wedges and bodies (RS5 & 6) is relevant in noise mapping and urban acoustics, and diffraction on a repeated structure caused by grazing sound incidence (RS7) occurs in audience areas and is well known for causing the seat-dip effect.

3.2 Acquisition

All measurements and scene setups were supervised and processed by the three primary authors. To assure consistency across the data of different scenes, a standardized protocol, identical equipment, as well as identical measurement and post-processing scripts were used that only differed with respect to the length of the sine sweeps and final impulse responses, which were both adjusted to the level of reverberation and background noise. All acoustic measurements were conducted with a sampling rate of 44.1 kHz, and all impulse responses were obtained by swept sine measurements and spectral deconvolution [30]. A detailed description of the measurements is beyond the scope of this article and is contained in the documentation of the database itself [dataset][15]. In the following, a brief overview that outlines the content of the BRAS along with the accuracy of the measurements is given.

Scene geometries. The objects of the reference scenes were constructed using medium density fibre board. Sources, receivers and objects were positioned in the scenes using cross-line lasers, a laser distance meter, and a laser angle measurer. The positioning accuracy was cross-checked by means of an acoustic time of flight analysis between pairs of sources and receivers. This analysis showed an accuracy of 2.3 cm (1.6 cm on averavge) for scenes RS1, RS5–7, and CR1–4 and an accuracy of 5.5 cm (3.4 cm on average) for the remaining scenes. The increased uncertainty in these case stems from the wire-woven floor of the fully anechoic chamber where the measurements were conducted.

Boundary conditions. Boundary conditions for 28 materials are contained in the BRAS by means of 3rd octave absorption and scattering values. For the reference scenes RS1–7, normal incidence absorption was determined between 100 Hz and 4 kHz according to ISO 10534-2 [31] and angle dependent values were measured between 300 Hz and 15 kHz according to Mommertz [32] using the setup of RS1.

Directivities. Full-spherical directivities of the loudspeaker used in the BRAS were measured in a hemi anechoic chamber with a resolution of $2° \times 2°$ in azimuth and elevation. For this purpose the speaker was placed on a turntable that controled the azimuth at a height of 2 m above the ground. The elevation was controlled by an arm that was equipped with a G.R.A.S. 40AF free-field microphone at a distance of 2 m. Repeated measurements showed a good reproducibility with mean absolute deviations of 0.5 dB. The measurements were interpolated to a $1° \times 1°$ sampling grid using spherical harmonics. An analysis of the data before and after the spherical harmonics processing showed absolute deviations below 0.4 dB for frequencies below and and 1 dB for frequencies above 10 kHz. While the used half inch microphones are supposed to be modeled as omnidirectional in the simulations, the directivity for multiple head-above-torso orientations of the binaural receiver was taken from the FABIAN HRTF database [33].

Impulse responses. Impulse responses were measured for selected positions of a small active two way speaker, a half inch class I measurement microphone, and a binaural receiver. For the binaural receiver, binaural impulse responses were obtained for head-above-torso orientations between ±44°.

3.3 Availability

The BRAS is available under a Creative Commons share alike license (CC-BY-SA 4.0)[4]. For a detailed description of the structure and data format please refer to the documentation [dataset][15]. To assure accessibility, the content is provided in open, or wide spread file formats wherever possible: The scene geometries are given in SketchUp files, accompanied by overview and detail photos of the scenes. The source and receiver directivities, as well as the scattering and absorption coefficients (initial and fitted estimates) are provided in text files. The measured IRs are given as wav files and SOFA containers [34].

For convenience, additional data that serves the evaluation of simulated IRs is also provided. This includes an excerpt of the anechoic recording of W. A. Mozart's string quartet No. 1 (bars 1 – 6, second movement, Reinhold Quartett[5]) for the perceptual evaluation of the binaural impulse responses, as well as compensation filters for common headphone models and FABIAN's inverted diffuse field transfer function provided as part of the FABIAN database [35], which can be used for headphone equalization. The compensation filters were obtained by regulated least mean squares inversion of the headphone impulse responses (HpIRs), averaged after re-positioning between measurements [33].

3.4 Third party extensions

The BRAS will be maintained and extended by the Institute for Technical Acoustics at RWTH Aachen University and the Audio Communication Group at TU Berlin for the foreseeable future. Third party contributions are welcome and should contain the following data:

- A scene description provided as a SketchUp 3D model that includes the geometry, positions, and orientations of all objects, sources and receivers in the scene and the names of the acoustic materials.
- Photographs of the scene showing the overall setup and details.
- Measured impulse responses according to the scene description provided as wav and SOFA files. The unit of the impulse responses shall be Pascal.
- High resolution directivity measurements of the sources and receivers (if not omnidirectional) provided in csv files. Full-spherical directivities shall be measured with a resolution of $2° \times 2°$ or better.
- Descriptions of the acoustic materials provided as 3rd octave absorption and scattering coefficients or complex impedance measurements (csv files).

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[4] `https://dx.doi.org/10.14279/depositonce-6726.3`

[5] `www.reinholdquartett.de`, checked Nov. 2019

- A written documentation of the measurements including
    - a description the scene setup and the positioning accuracy. The positioning accuracy shall be comparable or better than the accuracy of already existing scenes.
    - a detailed list of the used equipment
    - a description of the directivity measurements and the achieved accuracy.
    - a description of the material property measurements and achieved accuracy.

Third party contributions with new scenes can be acquired with equipment previously used in the creation of the BRAS. In this case, the required acoustic sources and receivers will be made available to third parties, which has the advantage that the corresponding directivities are already contained in the database. Alternatively, different equipment could be used in which case directivity data of the used acoustic transducers has to be provided in a resolution and format that is comparable to the data already contained in the BRAS. After submission, the data will be reviewed by the maintainers of the BRAS according to the criteria listed above. If accepted for inclusion, the new data will be added to the BRAS, the third party contributors will be included in the list of authors and will be invited to join the board of reviewers for future contributions.

4 Discussion and Outlook

The Benchmark for Room Acoustical Simulation (BRAS) provides a collection of acoustic reference scenes such as a single reflection on a quasi infinite plate. With information about the primary structure, the boundary conditions, the source and receiver characteristics, and measured transfer functions for different source-to-receiver configurations, it is meant to provide data for evaluating acoustic simulations.

The scenes contain simple structures, for which geometry and boundary conditions can be given with high accuracy, based on laser distance and angle measurements and laboratory measurements of absorption and scattering coefficients. With a precision in the range of millimeters for positioning the objects, average accuracies of 1.6 cm and 3.4 cm for positioning the sources and receivers (depending on the scene), and a valid frequency range from 100-300 Hz to 4-15 kHz (depending on the scene and the materials used) these scenes highlight different acoustical phenomena such as single and multiple, specular and scattering reflection and diffraction, which are relevant for sound propagation in closed spaces, so that room acoustical simulation software can be evaluated with regard to its performance in these phenomena.

Measuring or predicting the surface absorption and scattering properties will remain a challenging task in the practice of room acoustic planning, and it is very likely that measured acoustic references cannot be provided for complex rooms for years to come. While in situ measurement methods are able to provide reliable results for the simple scenes used in the BRAS database [36, 37, 38], the uncertainties increase and the valid low-frequency range decreases when they are used in complex environments [39, 40]. Generating highly controlled benchmark scenes for complex small rooms seems promising [21], but considerable differences between measurements and simulations still remain at least for low frequencies despite great efforts in acquiring complex impedance data. A simplified room representation with partly estimated boundary conditions is thus currently unavoidable for larger complex rooms. Neglecting the phase information alone, however, is unlikely to cause perceivable artifacts with GA simulations under ecological conditions and non-uniform absorption [41].

However, recent tests have also shown that GA-based room acoustic simulation programs reach their limits even in simple scenes where the boundary conditions can be reliably determined, especially when it comes to the treatment of scattering and diffraction [42]. Here, the BRAS database shall provide a basis for evaluation and further development of the underlying algorithms.

The BRAS will be maintained by the related groups at RWTH Aachen and TU Berlin, and is meant to serve the community as a resource to be expanded in the future, for example by adding new scenes or by applying advanced measurement methods for acoustical boundary conditions. These extensions, both by the original authors or other groups, can then be published as new versions of the current database.

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