

Quality assessment of room acoustic simulation tools by comparing binaural measurements and simulations in an optimized test scenario

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Summary

Latest room acoustic (RA) simulation tools use the powerful combination of geometrical acoustics (GA) for higher frequencies with the finite-element-method (FE) for the lower end. This hybrid approach has the potential to provide a highly accurate agreement between measured and simulated results, even for small spaces where wave effects play an important role at lower frequencies. However, inevitable uncertainties in the characterization of the complex acoustic behavior of real-world sources and room materials make a perfect perceptual match between simulated and measured auralizations almost unachievable in an ordinary room. In order to still benchmark the quality of a room acoustic simulation tool based on a comparison with measured results, a suitable test room is therefore required.

In this study we therefore use a reverberation chamber room with controlled acoustic boundary and source conditions to compare measured and simulated monaural and binaural room impulse responses (RIR), both objectively and by subjective listening test. All simulations are conducted using state-of-the-art FE and GA simulation tools developed at ITA of RWTH Aachen University. The binaural measurements were done using the ITA artificial head.

The best possible elimination of any inaccuracies caused by geometry simplifications, source or material uncertainties or the use of different HRTFs, enables an unbiased quality assessment of the simulation algorithms themselves. Thus the suggested benchmark test provides a measure of how close a simulation can converge to the actual measurement in an ideal case.

PACS no. 43.55.Ka, 43.55.Br

1. Introduction

Several geometrical acoustics based software packages (e.g. ODEON, CATT, EASE) are nowadays commercially available and widely used by acoustic consultants as an accepted design-aid in the planning of concert halls and theatres as well as in the layout of sound installations in buildings and public areas. In addition to these classical RA simulation tools, recent studies [1] show the potential of numerical wave-based tools (e.g. FEM, BEM) to realistically predict the modal characteristics of the low frequency sound field in small rooms. Consequently, a combination of state-of-the-art wave and ray based RA simulation algorithms offers means to realistically model the sound field in the whole audible frequency range for a wide range of room sizes.

However, despite the wide spread application of room acoustic simulation software and the high

requirements for accuracy when applied in the design process of a real room, surprisingly few studies exist, that evaluate the accuracy of the applied algorithms on the basis of a detailed comparison with measured impulse responses in an according real room. While this is presumably in equal parts due to (a) the immense complexity of real rooms and (b) the limited resolution of the human auditory system, the complexity of state-of-the-art hybrid simulation tools that combine highly developed ray tracing, image source and possibly even wave based methods make a measurement based validation of the whole simulation system crucial.

In the course of this study we therefore use a simple, controlled test room similar to Tsingos et al. [2] to evaluate the accuracy of a combined wave and ray based room acoustic simulation algorithm that has been developed at ITA of RWTH Aachen University. The test room has a well defined, simple geometry and all acoustically relevant objects (source, receiver, absorbing

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panels, scatterers) have been chosen carefully and characterized to the best possible extent. Furthermore the measurement setup allows for a gradual increase in complexity as well as a separation of certain aspects of the simulation algorithm, e.g. the scattering algorithm can be evaluated by comparing the simulation accuracy with and without scattering wall present in the room.

2. The combined wave- and ray-based room acoustic simulation tool

2.1 Hybrid geometrical acoustics tool RAVEN

The GA tool RAVEN [3] combines an image source method for the realistic representation of early specular reflections with a stochastic ray-tracing approach to model the diffuse, scattered reflections in the late part of the room impulse response. Sound sources are modeled by inclusion of their directivity and free field sensitivity. By further accounting for the angle of incidence of each sound ray hitting a receiver and making use of head related transfer functions (HRTF) the software allows to generate binaural RIRs including interaural time and level differences.

2.2 FE solver WAVE

On the other hand the FE solver WAVE provides means to numerically solve the Helmholtz wave equation at a given frequency in an arbitrarily shaped enclosed space with given velocity and admittance boundary conditions. In order to limit computation times to reasonable values, we chose a mesh fineness that allows FE calculations up to a frequency of 340Hz which roughly corresponds to the Schroeder frequency in the considered room. Binaural FE results are obtained by including a dummy-head into the FE-model.

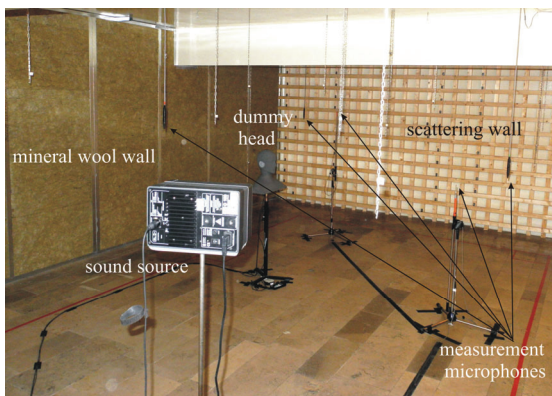


Figure 1: Test room with variable acoustics elements and source and receivers.

2.3 Combination of results from both domains

The simulation results of both domains are merged in the frequency domain, by a simple cross-fade using Butterworth filters of order 16. Listening tests have shown that no audible artifacts are produced by using this method. A more detailed description of the principles and features of both simulation tools as well as on the combination of the results can be found in [4].

3. The controlled test room

The test environment is set up in the reverberation chamber at ITA of RWTH Aachen. Figure 1 shows a picture of the real room and the according GA model and FE Mesh with the source loudspeaker, the measurement microphones and the ITA dummy head. As variable acoustics elements we used a stud lining wall with 50mm Rockwool Sonorock plates and a well defined scattering wall consisting of a regular configuration of vertically and horizontally arranged square-cut wooden beams with an edge length of 6cm. Three test scenarios were defined for simulation and measurement which all used the same dummy head, microphones and loudspeaker in the exact same positions.

- a) Empty reverberation room
- b) Reverberation room with mineral wool wall
- c) Reverb. room with mineral wool and scattering wall

The geometry of the room and the positions and orientations of the sound source and the receivers were carefully measured and used for the creation of the simulation models. The following subsections give a detailed description of the techniques and methods applied for the determination of the simulation input data.

3.1 Determination of material properties

In our simulation model the room boundaries are characterized by their acoustic absorption and scattering coefficients in the GA domain and their acoustic surface impedances in FE domain. Our goal was to determine best-possible a-priori material data and then in a second step adjust this data in our simulations for a best possible fit with the measured RTFs. We therefore conducted various measurements to determine the material properties of the hard reflective reverberation chamber walls, the mineral wool absorber and the scattering wall.

1) The used mineral wool mats consisted of Rockwool Sonorock material with an average density of 40 kg/m^3 and an average thickness of 48mm. The flow resistivity was measured for two different samples according to ISO 9053:1991. Additionally we measured the normal incidence impedance and absorption coefficient for four different samples in the Kundt's Tube according to ISO 10534-2:1998. The final data used for the simulations was then obtained from the empirical Komatsu model [5], where we calibrated the flow resistivity (starting from the measured values) to get a best possible fit with the Kundt's tube results and then calculated diffuse incidence impedance and absorption values with the obtained parameterization². The scattering of the absorber wall was set to a frequency constant value of 0.1.

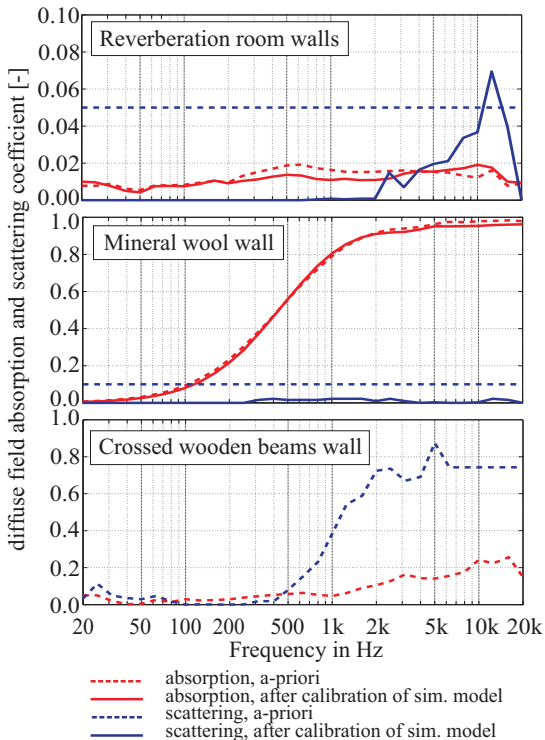


Figure 2: A-priori and calibrated absorption and scattering coefficients of materials in test room.

2) The random-incidence absorption coefficient of the scattering wall was obtained by full scale reverberation chamber measurements following ISO 354:2003 and the scattering coefficient was

² The fitted Komatsu model showed an almost perfect match with measurement results from the Kundt's Tube. This procedure has the advantage of consistent impedance and absorption data for diffuse incidence for the whole audible frequency range.

measured following ISO 17497-1:2004 in a 1:6 scale model reverberation room on a turntable. Since no suitable low frequency impedance measurement technique could be applied to the scattering wall, a frequency dependant real valued surface impedance was calculated from the absorption coefficients (used in FE simulations).

3) The average random-incidence absorption of the reverberation room walls was calculated from the RT in the empty reverberation room. The scattering coefficient was set to a frequency constant value of 0.05 and again a real valued impedance function was calculated from the measured absorption coefficients.

Figure 2 shows the a-priori determined absorption and scattering data for all materials and the data obtained after calibration of the simulation model for a best possible fit with measured RIRs.

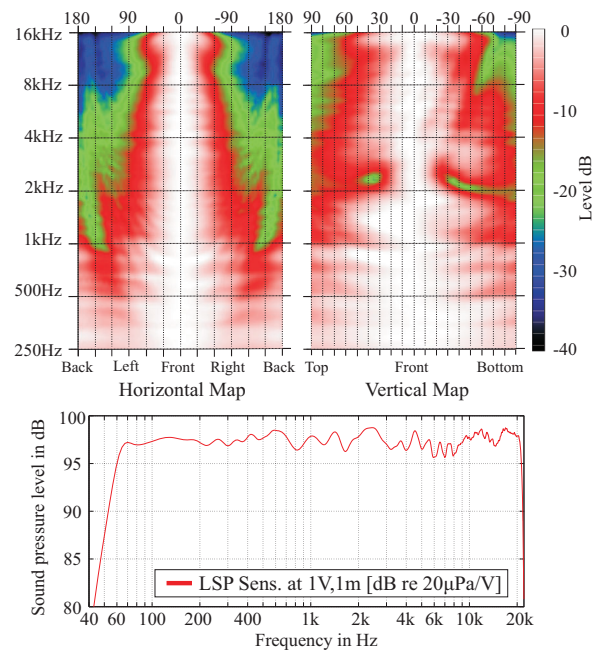


Figure 3: Directivity and free field sensitivity on axis at 1V,1m of used K&H O100 loudspeaker.

3.2 Determination of source characteristics

In the GA simulation domain the sound source is characterized by its free field sensitivity at 1V,1m on axis and its directivity pattern, which were both independently measured at ITA of RWTH Aachen and at IFAA Aachen³ for the K&H O100 Loudspeaker used in this study. The measurements

³ Institut für Akustik und Audiotechnik, www.ifaa-akustik.de

showed a very good agreement. Figure 3 shows the horizontal and vertical directivity maps and the free field sensitivity from the IFAA measurements. The simulation uses 5° resolution, where the image source model uses minimum phase DFT spectra with an FFT degree of 10 and the ray tracer uses third octave band data. The FE simulation used a monopole source which is adequate for the considered loudspeaker up to approx. 400Hz.

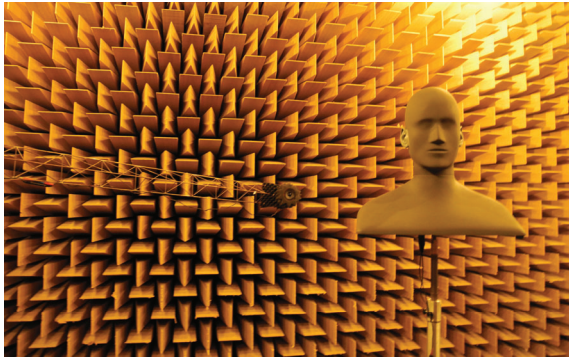


Figure 4: Measurement of HRTF data of ITA dummy head in the anechoic chamber at ITA.

3.3 Determination of receiver characteristics

During the measurements in the reverberation chamber we used four Sennheiser KE-4 microphones for the determination of reverberation times, two reference microphones (1 GRAS ¼” and 1 B&K ¼”) to compare with monaural IRs and the ITA dummy head to compare with binaural simulations. The reference microphones were expected to work as ideal pressure sensors with a flat frequency response for diffuse incidence up to at least 15kHz. The dummy head was included by the use of HRTF data which was carefully measured in 3° resolution in the anechoic chamber of ITA (see Figure 4). The measurements were normalized to the pressure at the center position of the head. The reference measurements were conducted using exactly the same measurement setup and equipment as with the head present in order to equalize the loudspeaker and microphone frequency responses. Due to the non negligible size of the used ½” Schoeps microphones the difference between the pressure and the free field sensitivity of the microphones also had to be accounted for⁴.

⁴ During the reference measurement the pressure at the center of the head is calculated using the free field sensitivity of the used microphone but during the HRTF measurement the

4. Results of measurements and simulations

The evaluation of the measurements and simulation results was focused on three main subjects. Firstly, the reverberation times have been analyzed and used for final optimizations of the input data. Secondly, other important room acoustic parameters were investigated, such as Clarity, Definition and Early Decay Time. In a third step, the binaural measurements using the ITA dummy head were objectively and subjectively compared to simulated binaural impulse responses. In this paper, only results for the empty reverberation chamber and the reverberation chamber with Sonorock absorption material covering one side wall are presented.

4.1 Results for the empty reverberation chamber

The first simulations were run using the calculated and measured a-priori material data and they well reflected the acoustic room characteristics. However, the resulting reverberation times were slightly underestimated. Too high absorption coefficients resulted probably from measurements in the reverberation chamber with suspended diffuser panels, whose surface area and absorption were not accounted for and thus accumulate in the calculated absorption of the chamber walls.

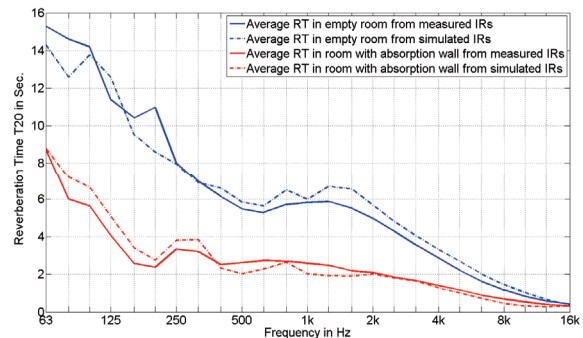


Figure 5. Reverberation times T30 of measured and simulated (GA+FEM) impulse responses for the reverberation chamber, for the empty case and with installed absorber.

pressure at the blocked ear canal entrance (where the microphone sits) needs to be calculated using the pressure sensitivity curve of the microphone. Thus the difference between the pressure and free field sensitivity needs to be accounted for. For the used Schoeps microphones this correction is about 2.5dB at 4kHz and 6dB at 8kHz.

By using an iterative simulation algorithm which would slightly adjust the absorption with factors calculated by the Eyring equation, the input data was improved without excessive modifications, as shown in Figure 2. Of course pure geometrically based simulations lack wave effects, so that the fitted parameters are not correct for low frequencies. The modally dominated lower end was therefore simulated using the FEM extension. The combined geometrically (GA) and wave (FEM) based results, with a Butterworth crossover in the frequency domain at 300 Hz, are shown in Figure 5.⁵ It can be seen that the simulated reverberation times are very close to the actual on-site measurement, for low as well as high frequencies. Respective Schroeder Energy Decay Curves are shown in Figure 6. But also other parameters, such as Clarity C50, are predicted with reasonable accuracy, at least for the empty reverberation chamber, a little less accurate for the reverberation chamber with installed absorber, as shown in Figure 7.

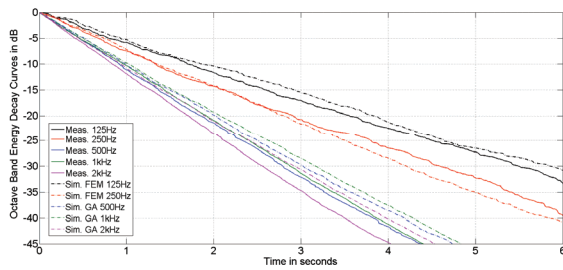


Figure 6. Measured and simulated (GA+FEM) early decay curves for the empty reverberation chamber.

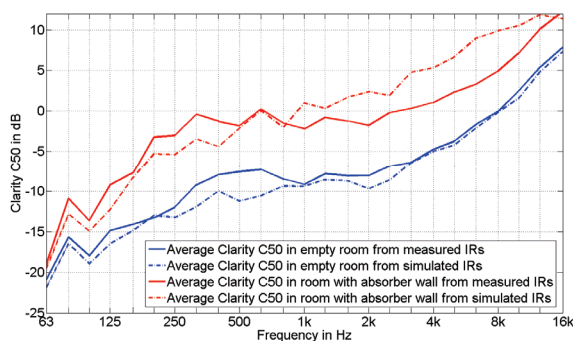


Figure 7. Measured and simulated Clarity C50 for the empty reverberation chamber and for the chamber with installed absorber.

⁵ All frequency content related result plots will begin at 60 Hz, as the amount of energy that is radiated by the used loudspeaker is too low for any evaluations at lower frequencies, as indicated in Figure 3.

The spectral plots in Figure 8 demonstrate the benefit of the FEM low frequency simulation, as the important modal peaks are captured in the simulation, which could not be covered by a geometrically based method. This advantage is clearly experienced in preliminary listening test with random samples. Also the temporal structure of the sound decay shows a good agreement to actual measurements, as shown in the spectrograms in Figure 9 for one ear of the ITA dummy head that was used in the binaural measurements and simulations.

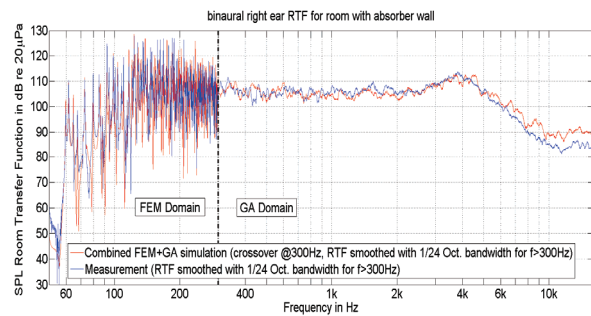


Figure 8. Spectrum of measured and simulated (GA+FEM) binaural impulse responses for the right ear of the ITA dummy head in the reverberation chamber with mineral wool wall.

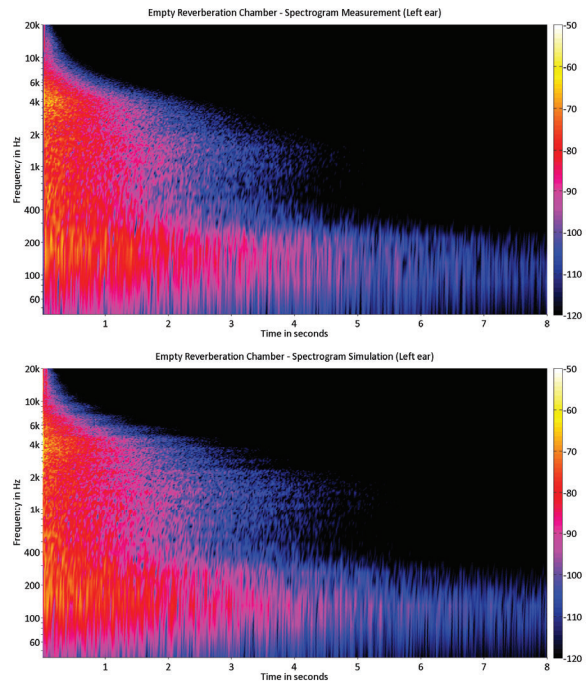


Figure 9. Spectrograms of measured (top) and simulated (GA+FEM, bottom) binaural impulse responses for the left ear of the ITA dummy head in the empty reverberation chamber.

4.1 Results for the reverberation chamber with installed absorber

After installing the Sonorock absorber which covered one complete side wall, the simulation became a little bit more demanding. The unusual and non-Sabinean room configuration puts a big emphasis on the sound field representation, especially with high importance of the spatial characteristics of the sound decay. The energy and spectrum of sound waves become highly dependent on the direction of incidence, even for late reflections.

It also turned out that due to the concentrated absorption on one wall, the applied scattering coefficient has direct influence on parameters such as the reverberation times. This could be used for fine-tuning of the so far guessed scattering coefficients in each frequency band by matching the reverberation times in different scenarios (with and without absorber) to the actual reverberation times from the according measurements. The resulting scattering coefficients are shown in Figure 2 and they seem to be reasonable for the plain and glossy walls of the reverberation chamber.

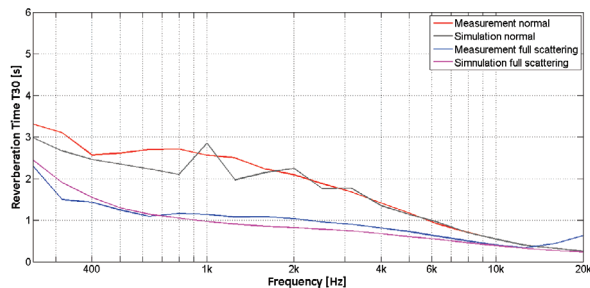


Figure 10. Measured and simulated reverberation times T30 for the reverberation chamber with installed absorber for the normal configuration and diffuse configuration with suspended panels and full scattering for all materials.

An additional validation of absorption parameters and simulation algorithm is achieved by comparing the results under the assumption of a diffuse sound field again. Therefore, the reverberation chamber was additionally equipped with suspended diffuser panels and the according simulation was run using the former absorption coefficients, but with 100% scattering applied to all surfaces. Results from this comparison are shown in Figure 10 and they prove that the applied absorption input data as well as the simulation algorithm yield reasonable results.

Figure 5 depicts the simulated reverberation times T30 for the case study with installed absorber. The a-priori data for the absorbing material leads to a fairly good prediction of the reverberation time with just a slight underestimation of T30, and thus the initial input data is not further modified, as shown in Figure 2.

5. Conclusions

The presented method proposes the evaluation of room acoustic simulation algorithms by applying them in a controlled test environment. The correct input data for simulations is usually a crucial point and source of uncertainties. To avoid ambiguities in the identification of weak points of a simulation, the input data has been gathered in detailed and independent measurements and calculations. This has put the focus on the actual simulation algorithms themselves. The results showed that the presented simulation tool which combines FEM and GA based techniques provides reliable results and bears comparison with real world measurements.

This conclusion could be verified in preliminary listening tests, which indicated a very promising agreement between auralizations with measured and with simulated binaural impulse responses using the presented software.

Further results will be published in the near future.

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