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Combined wave and ray based room acoustic simulations of audio systems in car passenger compartments, Part II: Comparison of simulations and measurements

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ABSTRACT

The present series of papers summarizes the results of a three-year research project on the realistic simulation of sound fields in car passenger compartments using a combined Finite Element (FE) and Geometrical Acoustics (GA) approach. The simulations are conducted for the whole audible frequency range with the loudspeakers of the car audio system as the sound sources. The challenges faced during the project relate to fundamental questions regarding the realistic sound field simulation in small enclosures with strong modal and diffraction effects. While Part I of this series of papers focusses on the determination of the boundary and source conditions for the simulation model of the car compartment, the present paper, denoted here as Part II, presents extensive objective and subjective comparisons of the corresponding room acoustic measurement and simulation results.

By applying the FE method to the low frequency part of the room transfer function (RTF) the study aims at the quantification of potential objective and subjective benefits with regard to the simulation quality in small rooms, when compared to a purely geometrical acoustics approach. The main challenges and limitations in the simulation domain are due to the very small volume, the difficult to determine source and boundary conditions and the considerable diffraction effects (especially at the seats) in the car passenger compartments. In order to keep the complexity of the FE simulations at a manageable level, all boundary conditions were described by acoustic surface impedances and no fluid-structural coupling was considered in the FE simulation model.

While the results of the study reveal that an overall good agreement regarding the energy distribution in time and frequency domain is generally possible even in such complex enclosures, the results also clearly show the limitations of the impedance boundary approach in the FE domain as well as the strong sensitivity of the simulation results with regard to the uncertainty in the boundary and source conditions in both simulation domains. It can thus be concluded, that possible fields of application of the FE extension in room acoustic simulations lie in the prediction of the modally dominated low frequency part of the RTF of well defined rooms and in the prediction of sound fields that are strongly affected by near-field or diffraction effects as in the car passenger compartment. However, due to the considerable problems in the determination of realistic boundary conditions for the FE model, improved measurement techniques are urgently needed to further improve the overall simulation quality.

1. Introduction

The full simulation and auralization of the sound field in an arbitrarily shaped room including all aspects of sound generation, room transfer paths, sound reception and also sound reproduction still remains an extremely difficult task encompassing various fields of acoustics. These fields span from the fundamentals of sound propagation in enclosed spaces and the deduced simulation algorithms to the determination of suitable source, boundary and receiver characteristics and finally also to psychoacoustic aspects related to the identification of the major perceptual characteristics of sound fields in rooms. In this context, classical GA simulation methods have nowadays become accepted and highly developed tools for acoustic practitioners and researchers for the prediction of the acoustic characteristics of large rooms like concert halls, theatres or open-space offices. However, when it comes to small rooms, geometrically based methods are generally flawed due to the inherent negligence of important low frequency wave effects, such as standing waves, diffraction and interference.

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While substantial theoretical contributions in small room acoustics have already been made in the 1940s and 1950s [1,2] the prediction of modally dominated sound fields was, at that time, generally restricted to analytical solutions for rather simple geometries and boundary conditions. Despite the fact that suitable formulations for the numerical solution of the Helmholtz wave equation in complex geometry were already published in the late 1960s [3,4], it was not until the 1990s that the rapidly increasing computational power allowed an efficient application of numerical wave based methods such as the Finite Element (FE) or Boundary Element (BE) method to room acoustic problems. Early work on the coupling of low frequency and high frequency models has been pioneered by Kleiner and Granier [5,6] in the mid-nineties who reported unsatisfactory results from their combination methods. The applied combination techniques appear to have been mainly flawed by the restricted frequency range for the numerical FEM simulation. More recent contributions were for example made by Bansal et al. [7] and Summers et al. [8]. Nowadays, it is generally possible to simulate up to frequencies considerably above the Schroeder frequency using FEM or BEM on a standard PC in reasonable computation times. Consequently, the extension of established classical GA tools by wave-based numerical simulations opens the door to the realistic full bandwidth simulation of a whole new range of acoustically interesting small spaces, like reverberation rooms, recording studios or car passenger compartments and first promising results have been published lately [9–12].[1]

Building up on the findings of these previous publications, the project, which was carried out in collaboration with a partner in the automotive industry, aimed at the generation of realistic binaural auralizations of the sound field generated by the loudspeakers of the car audio system inside the passenger compartment. The general challenges faced in the project were of course very similar to those described in the simulation study of the recording studio presented in [9,15]. However, as will be shown in the following, the car passenger compartment constitutes a far more difficult simulation environment than the recording studio control room. This has various reasons. Firstly, a car passenger compartment is obviously not designed with the primary intent of exceptionally good acoustics (in contrast to a recording studio). While this is in itself no problem for the simulation, it conveys the problem that relatively few or none a priori information exists on the acoustic characteristics of the boundary materials and sound sources in the car. Even worse, in contrast to the materials used in the studio (e.g. the homogeneously layered absorbers) the car materials are mostly not accessible to a straightforward determination of their acoustic characteristics, due to curved shapes and highly inhomogeneous material structures. Secondly, the geometrical acoustics simulation faces obvious limitations caused by (a) the various diffraction edges at the front seats and head rests, (b) the high geometrical detail and complex, curved shape of many boundary surfaces and (c) the close vicinity of sound source and receiver to each other as well as to surrounding boundaries (cf. limitations of the image source method (ISM) and the stochastic ray tracing (SRT) in [16]). Finally, the inclusion of a binaural receiver model in the FE and GA domain, also introduces open questions, since due to the very small volume of the car compartment it is a priori not clear in how far the presence of one or several occupants influences the room acoustics in the car.

All investigations presented in this study are based on simulations and measurements of two different car models of the same manufacturer. While the sound sources, i.e. the loudspeakers in the car compartments, have been investigated individually for both car models, the material data has been obtained on the basis of laboratory measurements of sample materials and in situ measurements which were only obtained for one of the car models. However, since the used materials in both car models are very similar, it appears reasonable to use the obtained boundary data also for the simulations of the other car model. Detailed information on the determination of all boundary and source conditions is given in Part I of this series of papers [17].

An outline of the present paper is given as follows. To start with, Section 2 briefly summarizes the used simulation methods and tools and specifies the general settings for the simulation setup in both domains. Next, Section 3 describes how the simulation models for the FE and GA simulations have been obtained from detailed CAD models of the car compartments. Section 4 then briefly describes the definition of the different boundary regions and summarizes the difficulties of the used determination methods for all boundary and source data. Based on this input data, Section 5 presents selected room acoustic simulations for the two car passenger compartments and compares the results with the corresponding measurements obtained in the real compartments. While the discussion in Section 5 is primarily based on the obtained transfer functions and reverberation times, the results are also discussed on the basis of a subjective comparison of monaural and binaural auralizations of the simulations and measurements. Finally, Section 6 concludes the paper and suggests guidelines for the simulation of sound fields in car passenger compartments with regard to the FE and GA domain.

It should finally be mentioned that for the sake of brevity we do not report all results that were obtained in the course of the project. Instead, the focus is put on the presentation and discussion of selected, representative results that illustrate the potentials and limitations of the applied methodology in all steps of the simulation process.

2. Simulation methods, tools and settings

The applied combined simulation approach uses a frequency-domain FE method to calculate the modally dominated low frequency part of the RTF and a time-domain GA-based algorithm for the high frequency part of the RTF. In particular, the software *LMS Virtual Lab Rev 9-SL3* was used for the FE simulations. The GA simulations were run using the hybrid tool *RAVEN* which is currently developed at *ITA of RWTH Aachen University*. The term 'hybrid' means in this case that the simulation algorithm combines an image source method for the calculation of the early order reflections with a stochastic ray tracing approach for the late part of the impulse response. Extensive details on the implemented algorithms are given by Schröder [18].

The simulation results from both methods are finally combined in the frequency domain by a cross-fade filter, i.e. a lowpass filter for the FE results and a high pass filter for the GA results with $f_{\mathrm{cutoff,\ LP}} = f_{\mathrm{cutoff,\ HP}}$. Taking into account that the FE and GA simulation results generally show an incoherent phase relationship in the cross-fade frequency range, Butterworth filters with 3*dB* attenuation at the cut-off frequency were used. Since using ordinary Butterworth filters causes a frequency dependent latency in the

[1] Although intermediate results of the project have already been presented at international conferences in 2009 and 2010 [11,13,14], it has to be emphasized that the present paper gives a conclusive summary of the project results including completely new simulation results. All simulations have been re-run for the following three main reasons; (a) the GA simulation tool *RAVEN* has undergone continuous, far reaching modifications and improvements in the course of the project; (b) our continuous efforts regarding the determination of better boundary and source data have lead to inevitable adjustments of the used simulation input data, which make it difficult to compare the results obtained at different stages throughout the project both in the FE and GA domain and (c) the FE frequency range has been extended up to 3 Hz for selected simulations. The presented new results are thus obtained on the basis of consistent simulation input data using the latest *RAVEN* version (as of October 2011) and an extended FE frequency range.