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Combined wave and ray based room acoustic simulations of audio systems in car passenger compartments, Part I: Boundary and source data

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ABSTRACT

The present series of papers summarizes the results of a three-year research project on the realistic simulation of car audio sound 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.

The paper denoted here as Part I focuses on boundary and source representations in the FE and GA domain and suggests guidelines for a best-possible acquisition of the required data. Since a straight-forward determination of the boundary and source characteristics is mostly hampered by the immense complexity and inhomogeneity of the materials and loudspeaker configurations inside a car compartment, different measurement and calculation methods have been applied to determine the required data and quantify the corresponding uncertainty. The paper clearly points out the strength and weaknesses of the applied methods depending on the considered frequency range and material characteristics. In order to keep the complexity of the FE simulations at a manageable level, all passive boundaries were considered as locally reacting with impedance conditions.

Part II of the study applies the obtained data in combined FE-GA room acoustic simulations and compares the simulated room impulse responses (RIR) with corresponding measurement results. In a final step the observed differences in the RIRs are related to the uncertainty and inherent errors in the boundary and source representation.

1. Introduction

Any kind of room acoustic simulation requires the establishment of a geometric room model and suitable mathematical models for the source radiation, the sound reflections at the room boundaries and the sound reception. Under the assumption of a sufficiently accurate sound propagation model it is the accuracy of these models and their assigned input data that are the leading factors influencing simulation quality and accuracy. Taking into account that contemporary CAD (Computer Aided Design) tools facilitate the design of high quality geometric room models, even more emphasis is put on the need for a realistic representation of the acoustic source, boundary and receiver conditions. In order to thoroughly understand how these factors influence the simulation accuracy a clear cut distinction needs to be drawn between the inherent simplifying assumptions made in these models and the uncertainty in the determination of their required input data [1]. Moreover, it is important to note that the commonly applied source, boundary and receiver models vary considerably depending on the underlying sound field model (e.g. FEM and GA). There is knowledge in literature about the uncertainties of methods for determination of acoustic boundary conditions. But the combination of all these methods and the best choice of the specific method for the boundaries and materials in a car compartment are not trivial tasks and worth to be studied with regard to applicability and uncertainty into the final sound pressure field and auralization.

Fig. 1 gives a quick overview of the required models for geometrical acoustics and the finite element method. While the receiver representation in the FE and GA domain and the final simulation results will be discussed in Part II of the paper [2], the present Part I focuses on the required boundary and source data and presents the results obtained for the materials and loudspeakers used in the considered car passenger compartments. Both for the boundary and source conditions our analysis is structured into three parts,

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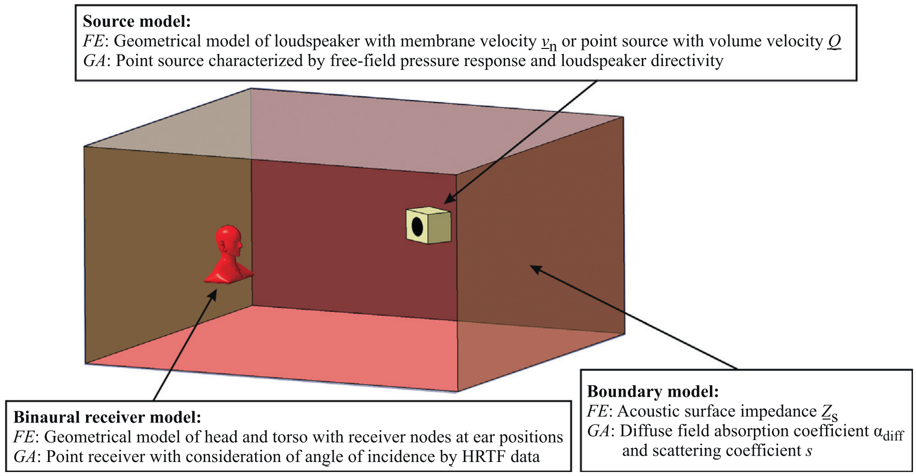

Fig. 1. Overview of source, boundary and receiver models in geometrical and wave based room acoustic simulations.

which deal with the following questions: (1) Which data is required in the FE and GA domain and how does the different input data in both domains relate to each other? (2) Which measurement methods or calculation models exist to determine the required data? (3) What are the conclusions from the results and their uncertainties in the case of the car materials and loudspeakers?

2. Boundary conditions

In the course of this paper the term ‘boundary condition’ refers to all passive boundary surfaces that constitute the inner lining of the car passenger compartment. The acoustic reflection characteristics at these surfaces can generally be described by suitable coupling conditions between the fluid and structure domain, which yield a mutually coupled model, with suitable sound propagation models for all materials involved in the layered boundary configuration. In room acoustic modeling this is however not desired since the model generally only extends over the fluid domain (i.e. the air inside the room) in order to keep the complexity at a manageable level. In the following it will therefore be discussed under which conditions the physical behavior of a boundary wall can be described independent of the incident sound field by its acoustic surface impedance $\underline{Z}_S$.[1]

2.1. Required boundary data

2.1.1. FE domain

In order to better understand the circumstances under which the acoustic surface impedance sufficiently describes the physical behavior of a boundary wall, the problem shall be approached from a more physical point of view. Following Mechel [3, p.23ff] a general type of boundary condition at the boundary of an inviscid fluid media can be formulated by demanding that the sound pressure and the surface normal velocity on each side of the boundary surface have to be continuous. It can be shown [3, p.24] that this statement is equivalent to the postulation of identical surface impedances $\underline{Z}_S = \frac{\underline{p}}{\underline{v}_n}$ at the boundary interface and identical tangential components of the propagation constants in both adjoining media. These equivalent formulations are however rather ‘coupling conditions’ than ‘boundary conditions’, since they are not independent of the type of the sound field in front of the boundary. However, under the assumption that sound propagation behind the boundary is only possible in the perpendicular direction to the boundary surface, the behavior of an acoustic boundary can be described solely by its acoustic surface impedance $\underline{Z}_S$, which is in this case independent of the incident sound field. Such boundaries are called ‘locally reacting’ [3, p.23], since the surface normal velocity $\underline{v}_n$ at a point **x** at the boundary depends only on the sound pressure $\underline{p}$ at the exact same point **x** and is independent of the surrounding pressure distribution [4, p.30]. This is obviously not true for elastic plates since adjacent elements are coupled by their bending stiffness. Moreover, in the case of porous absorber materials this approximation is only admissible if the absolute value of the propagation constant of the porous absorber is much higher than that of air [5].

We are thus aware that an impedance boundary approach in the FE domain neglects possible coupling effects caused by structural vibrations of the car materials. However, these effects are only considered to significantly influence the room sound field in the very low frequency range, where strong modal coupling between fluid and structural waves is expected. Moreover, it should be mentioned that in addition to the immensely increased model complexity, the use of a fully coupled fluid–structure model of the car compartment introduces considerable new challenges and uncertainties with regard to the measurement and evaluation of all relevant material parameters and mounting conditions.

2.1.2. GA domain

In geometrical acoustics simulations the reflection characteristics of the room boundaries are generally modeled by assigning the diffuse-field absorption coefficient α_{diff} and scattering coefficient s to each boundary. In contrast to wave-based frequency domain models the geometrical models typically require these data as frequency band averages (octaves or third-octaves). With regard to the absorption characteristics at the boundary this means that both the phase-shift at the boundary reflection as well as the angle dependence of the reflection coefficient are neglected in typical GA simulations. Although there has been some discussion about the inclusion of the reflection phase and/or the angle dependence of the reflection factor [6–10] it can be concluded that at least for the late part of the impulse response this simplification is generally admissible. This can be explained by the immense reflection overlap in the late part of the IR which makes it impossible to perfectly reconstruct its temporal fine structure anyway. Only in the early part of the IR which is modeled by the image source method (ISM) and at rather low frequencies a benefit might be achievable by considering an angle dependent complex reflection factor [10]. However, in the case of the car passenger compartment with

[1] In the course of this paper the underscore is used to indicate complex numbers.