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The difficulties of simulating the acoustics of an empty rectangular room with an absorbing ceiling

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ABSTRACT

In this study, simulations of a scale model of an unfurnished rectangular room with an absorbing ceiling using an energy-based geometrical acoustic model and a phased geometrical acoustic model are compared to measurements. This room can represent a typical classroom or office. This comparison concluded that the phased model can capture more details of the sound field, particularly at low frequencies. For accurate predictions, precise surface descriptions are needed for the phased GA method, which are not always available. The main drawback of the phased model is a longer calculation time.

1. Introduction

Many common rooms, e.g. offices and classrooms, are rectangular with absorbing ceilings and low scattering on the surfaces. The sound fields in them are therefore highly non-diffuse, which can increase the need for precision in simulations of their acoustic properties. Many commonly used simulation tools for room acoustics are energy-based geometrical acoustic methods, which means that they neglect the wave nature of the sound propagation and thus phase information in the propagation and on reflections. Tracing the phase can be of particular importance when modeling the acoustics of a room below the Schroeder frequency [1], where the modal overlap is low. The Schroeder frequency generally increases for a decrease in the size of a room, and phase information can therefore be especially important when simulating the acoustics of smaller rooms at low frequencies. It has furthermore been shown that the phase shifts on reflections can be important for surfaces of high absorption [2]. Improving the accuracy of geometrical acoustic simulations by use of pressure-based models with complex-valued and angle-dependent boundary conditions has previously been done in phased beam tracing [2–5], phased ray-tracing [6] and also in the image source method [7–9]. The aim of the present study is to compare measurements of a scale model in two configurations with results from an energy-based simulation model and from a pressure-based simulation model.

The room acoustic simulation tool PARISM [10] (Phased Acoustical Radiosity and the Image Source Method) has been developed in order to be able to model the acoustics of rooms with non-diffuse sound fields and absorbing ceilings. PARISM is, as the name implies, a combination of the image source method (ISM) and acoustical radiosity (AR) that includes phase information in the propagation and on reflections in ISM by pressure-based summation of the reflections. It also includes the angle dependence of the absorbing surface properties in both ISM and in AR. PARISM is an extension of the energy-based CARISM [11] (Combined Acoustical Radiosity-Image Source Method). AR is inherently energy-based, but in PARISM a pressure impulse response is reconstructed. The result of PARISM is thus a pressure impulse response. The basic theory and algorithm of PARISM can be found in previous work by the authors [10,12].

ODEON [13–15] is a well-established room acoustic simulation software that is based on a hybrid model, in which early reflections are found by a combination of ISM and ray tracing, and the late reflections are found by ray tracing. ODEON is energy-based and uses angle-independent diffuse field descriptors of the surface properties, but an approximated angle dependence can be included [16].

It has been shown that it is important to include surface scattering in geometrical room acoustic simulation [17], and reflections are therefore often divided into two parts: a specular reflection and a scattered reflection. Both PARISM and ODEON include scattered reflections, but in quite different ways. It is however assumed that the same descriptor can be used in the two methods to determine the amount of sound energy scattered in a reflection.

The angle dependence of surface properties is in some geometrical methods completely disregarded, in some approximated [14,16], and in some fully included [10]. The angle dependence of absorption properties is important in non-diffuse sound fields, because some angles of incidence are more likely to occur than others. It has been shown that

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the sound field of a rectangular room with an absorbing ceiling and low diffusion can be decomposed into two parts: the non-grazing sound field that has small angles of incidence with the absorbing ceiling and the grazing sound field that has large angles of incidence with the ceiling [18]. A porous absorber ceiling generally absorbs most efficiently at small angles of incidence, whereas the absorption coefficient approaches zero for grazing incidence [19]. The non-grazing sound field therefore decays much faster than the grazing. Including the angle dependence of the sound absorption of an absorbing ceiling can therefore be necessary to obtain acceptable simulation results.

In this study, PARISM simulations and ODEON simulations are compared with measurements to investigate the influence of including full angle dependence and phase information in geometrical acoustic simulations of non-diffuse sound fields. This will illustrate the difficulties in simulating rectangular rooms with absorbing ceilings and low scattering. When simulating real rooms and comparing with measurements, it is often a problem that the surface properties are not known but must be determined by rough measurements, numerical models, or estimated and fitted. This is the case in this study, which thus also illustrates the difficulties when using simulations in practice. The input surface descriptors to the two models are as much the same as possible, but some differences will occur due to the inherent differences in the models.

2. Surface properties

For room acoustic simulations, choosing the appropriate acoustic descriptors for the surfaces is important in order to get reliable results. The choice must be based on the room type, simulation method and surface materials. There are several descriptors that can be used, but often the choice is limited by the availability of the descriptors [20]. In geometrical room acoustic simulations, two properties of the surfaces are needed: their absorbing and their scattering characteristics. For the absorbing characteristics in energy-based simulation tools, the absorption coefficient is commonly used because it is the fraction of the energy incident on a surface that is absorbed. The absorption coefficient can be angle-dependent, but in many cases absorption coefficients are determined under assumed diffuse field conditions, e.g. according to ISO 354 [21]. This coefficient can be referred to as the Sabine absorption coefficient because it is calculated from Sabine's equation. Alternatively, a diffuse field absorption coefficient can be estimated from the angle-dependent absorption coefficient by use of Paris' law [22], which states that

$$\alpha_{RI} = \int_0^{\pi/2} \alpha(\theta)\sin(2\theta)d\theta, \tag{1}$$

where $\alpha(\theta)$ is the angle-dependent absorption coefficient, θ is the angle of incidence with the normal of the surface and the result, α_{RI}, is referred to as the random-incidence (RI) absorption coefficient.

Manufacturers of materials generally only supply the Sabine absorption because it is easy to measure and simple to understand for the users. Measurements of the Sabine absorption coefficient can give values that are larger than one, which does not physically make sense for the common definition of the absorption coefficient as used in geometrical acoustic software, because it is not possible that more energy is absorbed than what is incident on the absorber. The assumptions of the determination of the Sabine absorption coefficient are however only valid for an infinite absorber and the finite size of the absorber and diffraction from the edges can thus result in values above one. Thomasson's size correction [23] can be applied to approximate the equivalent infinite RI absorption coefficient. However, the absorption coefficients given by manufacturers are often what can be referred to as practical absorption coefficients for which any values above one are simply truncated to one [24].

Rindel has developed a method for estimating an angle-dependent absorption coefficient from a diffuse field absorption coefficient [16]. This method assumes that the diffuse field absorption coefficient is equal to the absorption coefficient at 60° for local reaction, and from this an angle-dependent absorption coefficient is calculated. It has been shown that the local reaction assumption can be problematic for absorbers with an air gap [25] and that the equivalent incidence angle of a porous absorber in a diffuse sound field is 45° if it is of extended reaction and 55° if it is of local reaction [26]. The approximated angle dependence is thus not complete, but in many practical applications it can be useful if the only available value is a diffuse field absorption coefficient, because an estimated angle dependence is then expected to be better than none.

If the phase shifts on reflections are to be included in the simulations, it is not possible to use the absorption coefficient to describe the absorbing characteristics of the surfaces. Complex-valued descriptors, such as the reflection factor R or the surface impedance Z, must then be used. For plane waves incident on an infinite absorber, the absorption coefficient is related with the reflection factor by $\alpha = 1-|R|^2$. The reflection factor can for plane waves be found from the impedance by

$$R(\theta,f) = \frac{Z(\theta,f)-\rho_0 c_0/\cos\theta}{Z(\theta,f)+\rho_0 c_0/\cos\theta}, \tag{2}$$

where ρ_0 is the density of air and c_0 is the speed of sound in air. In the above equation, it is assumed that the impedance depends on angle of incidence, and materials for which this is the case are said to be of extended reaction. If it instead is assumed that the impedance is angle-independent, such that normal incidence impedance is sufficient for describing its behavior, the material is said to be of local reaction.

The angle-dependent impedance is rarely available, because it can be problematic to measure, especially for high angles of incidence and small samples [27,28]. It can therefore be necessary to use models for the estimation of it. One such model is Miki's model [29] that uses the flow resistivity of a porous absorber to estimate the impedance. The flow resistivity is much more practical to measure than an angle-dependent impedance. Gunnarsdóttir et al. [25] have shown that for a porous absorber with rigid backing, Miki's model produces acceptable results, regardless of whether local or extended reaction is assumed. For a porous absorber with an air gap backing, it was found that Miki's model can also produce acceptable results as long as extended reaction is considered [19]. A misprint has been found in the work by Gunnarsdóttir et al. [25], where the k_0 in Eq. (2) should be k.

The scattering characteristics are most often described by the scattering coefficient, which is the fraction that is non-specularly reflected to the total reflected energy [30]. The scattering coefficient therefore does not contain any information about the angular pattern in which the scattered energy is distributed. The scattering coefficient can be measured under assumed diffuse field conditions following the ISO 17497-1 [31], giving a result that is independent of the angle of incidence, and this value is therefore referred to as the random-incidence scattering coefficient. To include the full distribution patterns of the scattered reflections, bidirectional reflectance distribution functions (BRDF's) [32] must be used, which are dependent on both the angle of incidence and the outgoing angle. The BRDF's are however rarely used in geometrical acoustics because it would complicate the calculations, and for simplicity the random-incidence scattering coefficient is thus the preferred choice. Unlike the random-incidence scattering coefficient, BRDF's are furthermore difficult to measure, and the random-incidence scattering coefficient is therefore also more often available.

The random-incidence scattering coefficient is rarely known for materials that are not designed with the specific purpose of scattering sound and must for many common surfaces be estimated based on experience. For rooms with non-diffuse sound field, scattering has a large influence [33] and setting the correct scattering coefficient can therefore be a crucial factor in obtaining good simulation results.