Numerical sound field modelling in room acoustics and workshops using sound particles

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Introduction

Sound field modelling in room acoustics has attracted considerable attentions in the last decades. Many mathematical models have been derived to predict the sound field distribution and the sound decay in quasi-cubic rooms, long enclosures, low rooms, etc., including many effects, as the atmospheric attenuation, scattering by wall and diffusion by scattering objects. For rooms with complex shapes, ray-tracing based softwares have been developed and are widely used in room acoustics. On the other hand, the use of sound particles instead of sound rays was also investigated in the past, but has not really been developed. However, this concept seems well adapted to room acoustics simulations, since it allows to model easily most of physical phenomena occurring during the sound propagation in a room [1, 2]. In this paper, we present an example of Monte Carlo simulations, using sound particles, to predict the sound propagation in rectangular enclosures with diffusely reflecting boundaries and fitting objects.

Numerical simulations

Principle

Let us consider N sound particles emitted from a sound source in a complex enclosure (figure 1). A particle is then defined by its position $\mathbf{x}$ and its velocity $\mathbf{v} \equiv (c, \theta, \phi$ in spherical coordinates,whose norm is equal to the sound velocity c. Sound particles propagate along straight lines in the medium, until they hit a wall or fitting objects. At each collision, they are reflected in new directions, according to the reflection laws of the wall and fitting objects. During propagation, sound particles may be also absorbed by walls or due to the atmospheric attenuation. Since sound particles are characterized by a constant energy, the sound energy density is simply proportional to the distribution of sound particles in the medium.

The aim of the numerical model is to follow each sound particle, during its propagation in a rectangular enclosure $\ell \times H \times L$, at each time increment Δt. In order to determine the distribution of sound particles in the enclosure, a rectangular meshing (N_x, N_y, N_z) is realized. The energy density at a receiver, at time $p\Delta t$, is then proportional to the number of sound particles located in the receiver volume $(\ell/N_x) \times (H/N_z) \times (L/N_y)$ at this time. In order to model all physical phenomena (emission, reflection, diffusion and absorption), Monte Carlo simulations are carried out. It consists in generating series of random numbers which are in agreement with the density probability of the physical phenomena to model.

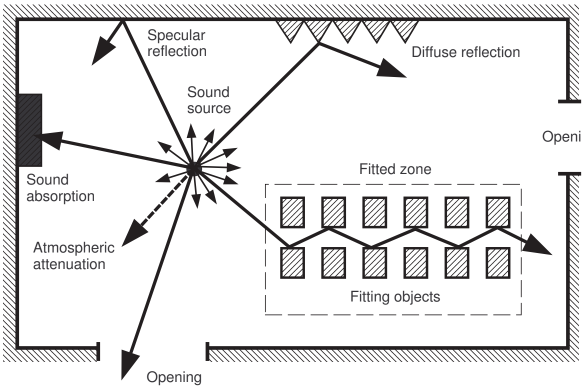

Figure 1: Schematic representation of the propagation of sound particles in a complex enclosure.

By definition, he accuracy of the Monte Carlo simulations increases with the number of sound particles.

Algorithm

Sound source Let us consider an omnidirectional sound source. At time $t = 0$, all sound particles are emitted in all directions with the same probability, around the sound source. In spherical coordinates, the velocity of the particles is then given by generating two random numbers θ and ϕ, respectively between $-\pi$ and π, and $-\pi/2$ and $\pi/2$, in respect with a uniform density distribution.

Boundary condition At boundaries, sound particles may be absorbed (due to the absorption coefficient α of the wall) or reflected in a new direction, according to the reflection law of the wall. This reflection law is representative of the wall irregularities, and can be modelled as a mixing of a specular and a diffuse reflection. The ratio of specular and diffuse reflections is then defined by the accommodation coefficient $d \in [0, 1]$ ($d = 1$ for specular reflection). The reflection law can be noted $R(\mathbf{v}, \mathbf{v}') \equiv R(\theta, \phi; \theta', \phi')$, and represents the probability that a incident sound particle with a velocity $\mathbf{v}$ leaves the boundary after reflection in the direction $\mathbf{v}'$.

In the numerical simulations, a first number $\xi \in [0, 1]$ is generated according to a uniform distribution. If $\xi < \alpha$ the particle is absorbed and disappears from the system. Conversely, for $\xi > \alpha$, the particle is reflected in a new direction. A second random number $\zeta \in [0, 1]$ is then generated. If $\zeta < d$, the particle is reflected in the specular direction. If $\zeta > d$, the particle is reflected in agreement with the reflection law $R(\mathbf{v}, \mathbf{v}')$. According to the analytical expression of the reflection laws, several methods

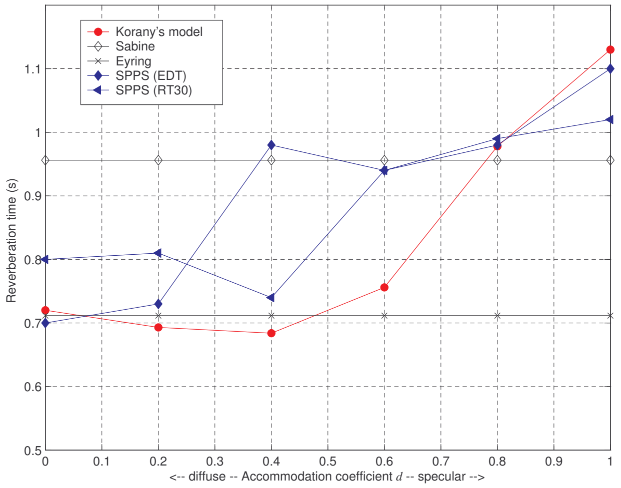

Figure 2: Reverberation times comparisons between SPPS simulations (10^6 particles), Korany's model [4] and the classical theory of reverberation, in an empty low hall ($20 \times 30 \times 10$ m) with a non-uniform wall absorption.

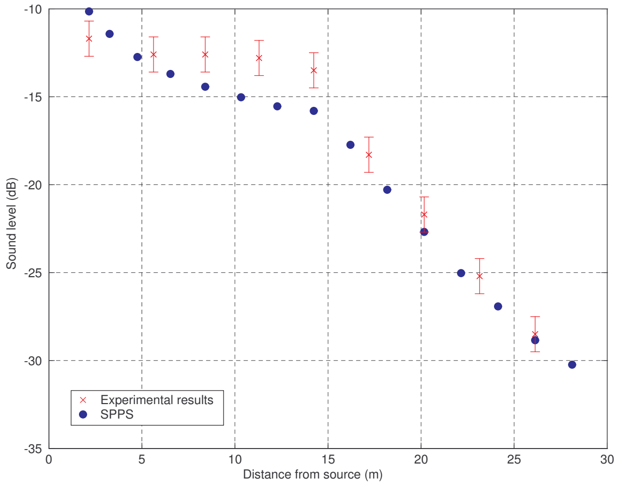

Figure 3: Sound level comparisons between SPPS simulations (750 000 particles) and experimental data [3], in a non-uniform fitted room ($30 \times 8 \times 3.85$ m), with specularly reflecting boundaries and non-uniform wall absorption.

can be used to determine the reflection direction. For an uniform law, two uniform random numbers (θ, ϕ) between $-\pi$ and π, and 0 and $\pi/2$ are sufficient. For simple law, like the Lambert's law, the method of the inverse cumulative distribution function (ICDF) can be used. For complex reflection shapes, the rejection method is the last solution, but increases the computational times in comparison with the others methods.

Diffusion by fitting objects Considering a large number of obstacles in a fitted zone (figure 1), it becomes impossible to describe each collision individually. By using the average absorption coefficient β, the density n, and the average cross section $\bar{q}$ of the fitting objects, it allows to define a mean free path between collisions $\lambda = (n\bar{q})^{-1}$ and a cumulative distribution function $\hat{p}$, and then to use a statistical approach [3].

When a sound particle gets in the fitted zone, a random number R is generated according to the ICDF method,. It represents the distance that the particle must be travelled in order to find an obstacle. When the effective distance of propagation is equal or larger than R, an absorption test is carried out. A uniform random number $\xi \in [0, 1]$ is generated. If $\xi < \beta$, the particle is absorbed. Conversely, for $\xi > \beta$, the particle is reflected in a uniform random direction. Then, the process starts again until the particle leaves the fitted zone or is absorbed.

Atmospheric attenuation During propagation, particles may be absorbed due to atmospheric attenuation. This is introduced in the model by considering the probability $g = \exp -m\, d_0$ that a particle is absorbed during a elementary path $d_0 = c\Delta t$, where m is the atmospheric attenuation coefficient. Then, a each time increment Δt, a random number ε is compared to g. If $\varepsilon > g$, the particle is absorbed. Conversely, the particle propagates in the medium.

Validation and conclusion

The algorithm has been implemented using MATLAB®. The program (SPPS) has been applied to many cases (cubic rooms, long enclosures, etc.), including diffuse reflections and fitting objects. Numerical simulations have been compared to several models, experimental data, as well as, the classical theory of reverberation (CTR) and show a very good agreement. As an example, Figure 2 presents the results for a room with boundaries of partially specular reflectivity. First, the figure shows that the CTR is not appropriate in this cases. Secondly, both results of SPPS and Korany's simulations [4] give a similar evolution. A second example is given at Figure 3, in a fitted workshop, and shows a good agreement with experiments. However, the main restriction lies in the computational times, which drastically increases with the number of particles and sound sources. Moreover, the model is really appropriated to complex enclosures producing sound diffusion. For empty enclosures with specular reflections, image-sources methods require less computational times and give more accurate results.

References

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