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Improved Methods for Calculating Room Impulse Responses with EASE 4.2 AURA

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ABSTRACT

Based on the original implementation of CAESAR as the room acoustic module in EASE called AURA we outline the latest developments in improving the calculation methods and performance. These include particularly the revised diffuse rain algorithm which represents an enhancement to standard ray tracing simulations and significantly increases convergence in coupled rooms with only few sources. A new ray-triangle intersection algorithm, based on a 3D grid scheme, provides significant performance improvement for ray tracing. Also, from a user point of view the number of particles that has to be specified for such stochastic simulations is often not well defined. We present a solution that derives a suggested particle number and length from the mean free path properties of the room and the desired detection rate at the receiver. Furthermore, we emphasize the need for treating large line arrays and loudspeaker columns in a manner adequate for the boundary conditions involved and the frequency range of interest. For this purpose multiple so-called virtual center points are defined in AURA in order to describe the distribution of several representative particle sources over the length of the array. Case studies and results for the above new and extended computation methods are provided and discussed.

1. INTRODUCTION

Over the last decades room acoustic prediction software packages (CATT, Odeon, CAESAR / EASE AURA, [1]) have become increasingly popular. Compared to physical scale models a computer model takes a much shorter time to set up and provides greater flexibility with respect to geometry changes as well. However, there are still two general problems associated with this approach. On one hand, a full-length room acoustic simulation for a mid-size space requires some calculation time, usually several hours on modern PCs. On the other hand, historically coming from a strong numerical and scientific background, room acoustic simulations provide many parameters to adjust, which in turn means many degrees of freedom for the user.

In this work we present some principle improvements to these shortcomings and how they have been implemented in the latest version of AURA, the room acoustic module of EASE. In sum, better control of simulation parameters and shorter calculation times provide the user with a more intuitive and interactive access to computer modeling of room acoustics.

2. AURA OVERVIEW

Based on CAESAR [2-4], the AURA algorithm [5, 6] calculates the transfer function of a room for a given receiver point using the active sound sources. For this purpose a hybrid model is employed that uses an exact image source model for early specular reflections and an energy-based ray tracing model for late and scattered reflections. The transition between the two models is determined by a fixed reflection order. The ray tracing model utilizes a probabilistic particle approach and can therefore be understood as a Monte-Carlo model. At first, the sound source emits a particle in a randomly selected direction with a given energy. The particle is then traced through the room until it either hits a boundary or a receiver or its time of flight reaches the user-defined cut-off time. When the particle hits a boundary it is attenuated according to the surface material and its direction is adjusted according to the reflection law. An essential assumption of this Monte-Carlo approach is that attenuation due to air or surface reflections is taken into account as a reduction of particle energy while the propagation loss over distance is indirectly covered by the reduced detection probability for individual particles with increasing distance and fixed receiver sizes.

Per receiver and simulated frequency a so-called echogram is created which contains energy bins linearly spaced in time. When a receiver is hit, the energy of the detected particle is added to the bin corresponding to the time of flight. Also, as a separate step, the contributions from the image source model are included. The particle model includes scattering in a probabilistic way. Whenever a particle hits a surface, the material absorption part is subtracted from its energy. Then, a random number is generated and depending on the scattering factor the particle is either reflected geometrically or it is scattered under a random angle based on a Lambert distribution. After that the particle is traced until it hits a receiver or a wall again.

3. CHOICE OF PARAMETERS

In the following we show how to estimate the needed number of particles based on a desired detection rate at the receiver and on the assumption that all particle paths are distributed approximately homogeneously throughout the space.

Let the volume of the room be V and the overall number of particles N. The detection volume of the receiver should be V_{Rec} and the number of particles in it be N_{Rec}. We now assume that the particle density is constant in space and time yielding:

$$\frac{N}{V} = \frac{N_{\mathrm{Re}c}}{V_{\mathrm{Re}c}} \tag{1}$$

The average number of particles in the receiver volume N_{Rec} is determined by the product of the mean duration of stay t_{Rec} of a particle in the volume and the rate K at which particles enter. Assuming constant density over time that rate is equivalent to the rate at which particles exit. To determine the number of needed particles we have to define the rate K as well as the duration of stay t_{Rec}.

We now propose that the detection rate is a figure chosen by the user, it controls indirectly the quality / convergence of the ray tracing process. The higher it is the lower is the error due to the discretization in this Monte Carlo model. The time t_{Rec} is given by the speed c of the travelling particle as well as by the mean path length s_{Rec} of the particle through the receiver volume. Thus we find:

$$N = \frac{V}{V_{\mathrm{Re}c}} \times \frac{s_{\mathrm{Re}c}}{c} \times K \tag{2}$$

In a rough approximation we may set $s_{Rec}^3 = V_{Rec}$ so that we find finally

$$N \approx \frac{V}{c \times V_{\mathrm{Re}c}^{2/3}} \times K \tag{3}$$

This is the sought amount of particles N that have to be sent out to achieve a detection rate K at the receiver. In EASE AURA five different settings can be selected by the user as a default, namely approximate detection rates K from *very low* (K = 1/ms) to *very high* (K = 256/ms).

The second important parameter for the calculation is the cut-off time. We derive it based on the reverberation time given by measurement or by the theory of Eyring / Sabine and based on an approximate time of flight for the direct sound and early reflections. Three different settings are available; the length is defined by

$$T = T_0 + \sigma \times RT \tag{4}$$

with RT being the maximum value of the reverberation time in all 1/3rd octave bands. In EASE AURA the *standard length* setting is given by T_0 = 150 ms and σ = 3/4, the *extended length* is defined by T_0 = 300 ms and σ = 1, and the *very extended length* is set to T_0 = 500 ms and σ = 3/2. The last choice is particularly recommended when coupled-room behaviour is expected or the distances between sources and receivers are very large (in average > 100m).

Some examples are displayed in Table 1 for a receiver diameter of 1 m. Empirical tests for different venues showed good correlation of the quality of results when the same setting for the particle number was selected.

Hall	Volume [m³]	Max. RT [s]	Number of Particles (Setting = Low)	Cut-Off Time [s] (Setting)
BB Akademie, Berlin	2 307	2.37	41 000	1.93 (Standard)
Concert Hall, Berlin	14 600	3,07	262 000	3.37 (Long)
Frauenkirche, Dresden	28 517	7,46	512 000	5.75 (Standard)

Table 1: Parameters suggested for EASE AURA calculations based on mean path statistics

4. INTERSECTION ALGORITHMS

For room acoustic models brute-force ray tracing (testing all triangles for intersection) is often impractical, since computation time scales linearly with the number of triangles. Improved performance is obtained by structuring triangle data such that each ray is tested for intersection only with a subset of triangles. Current methods are based on two main strategies: hierarchical bounding volumes (HBV) [7] and space partitioning [8, 9]. In the former case, a hierarchy of simple bounding volumes (such as spheres) is constructed, where a particular volume may include either a number of smaller child-volumes or actual triangles. A ray is tested for intersection starting at the top of the hierarchy, such that a particular child-volume is only tested if the parent was hit. The cost of ray-bounding volume intersection is small, and the resulting computation scaling with the number of triangles is approximately logarithmic. In space partitioning schemes, the physical space where the triangles reside is partitioned into smaller cells or so-called voxels. Rays are followed through adjacent voxels and tested only against triangles pertaining to those voxels. The partitioning may be uniform or more complex, e.g. hierarchical, adaptive, etc. .

Previous studies [10] indicate that no particular ray-tracing acceleration structure is obviously the most efficient, since the total computation cost depends both on algorithm and hardware implementation. Whereas highly refined hierarchical acceleration schemes may require less intersection tests, the associated data structures are non-uniform (i.e. hard to parallelize), involve traversal of non-local data structures and as such are less suitable for cache and vector processing optimisations as available on modern processors and graphics cards. On the other hand, space partitioning methods, in particular those involving simple data structures like uniform grids, are more suitable to efficient implementation on vector processing elements.

We chose to implement a uniform grid ray-tracing algorithm similar to Amanatides and Woo [9]. A 3D uniform grid is assigned to the simulation box and each triangle is associated with every cell having a common interior point with it. The grid spacing in every direction is determined automatically via an empirical formula, which in our tests achieved a performance close to hand-optimisation: the number of cells on each axis is proportional to the square root of the total number of triangles and to the box length along the axis divided by the average box dimension (since in general the triangles form approximately a 2D shell, such a formula matches the average cell dimension to the average triangle dimension). Up to 64 cells per axis are allowed, in order to limit memory requirements. Given a ray specified by an origin and direction vector, a fast grid traversal algorithm computes the next grid cell intersected by the ray. Each triangle associated with this grid cell is then tested for intersection with the ray. No particular optimisation is done to avoid duplicate ray-triangle tests when one triangle spans multiple voxels. Thus a ray-triangle intersection is only considered if it occurs within the boundaries of the current cell. The grid traversal continues until a hit point is found or the ray exits the simulation box.

The software implementation was carefully designed to facilitate vector optimisation on SIMD-capable processors, i.e. to minimize branching and optimise instruction scheduling, in particular it is easily transferable to programmable graphics processing units. We tested the algorithm against the previous EASE ray tracing library which uses a HBV method. Using the Intel C++

optimising compiler on a Pentium4 processor, the grid algorithm applied to realistic test cases with more than 10000 triangles can be up to 5 times faster than the previous method (Fig. 1).

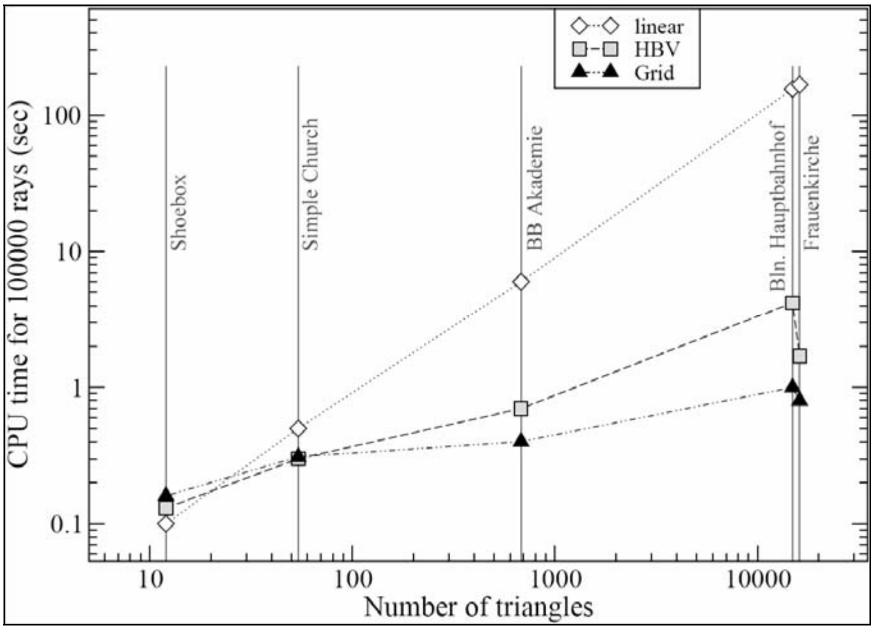

Figure 1: Comparison of algorithm performance vs. number of triangles for typical room acoustic geometries

5. DIFFUSE RAIN

It was described in the overview section how the echogram for a particular receiver location is generated. For the introduced Monte-Carlo model it can be shown [11], that the energy added for each particle must be normalized to the receiver diameter d_{Rec} and the overall particle number N_{Sum}. The resulting echogram normalization factor R_E is:

$$R_E = \frac{16}{N_{Sum} d_{\mathrm{Rec}}^2} \tag{5}$$

As outlined above the scattering is taken into account at the time when a particle is reflected by a wall. In that respect the scattering coefficient defines the probability for a specular reflection or a scattered reflection of the particle. While this method works well in approximately convex rooms, it is less effective for more complex or strongly concave geometries, such as two rooms, which are only coupled through a small connection. This is a common case for halls with a reverberant room connected to them. In such a case it happens, that only few of all particles radiated by the source in the main room may find their way into the more reverberant subspace and many fewer will find their way out again. At that time they will still have to hit a receiver to be detected and to add the effect of the reverberant chamber to the simulation result.

Asymptotically, for very many particles, this is not a problem. However, for small particle numbers the convergence towards the end result is not satisfying since the detection probability in the above cases (like for particles coming back from the reverberant room) is very low. This situation can be improved by using an adapted form of the diffuse rain algorithm originally proposed by R. Heinz [11]. Here, the scattering effect is included differently. Whenever a particle hits a surface, an energy contribution is added to each receivers echogram depending on the energy of the particle and if the receiver is visible from the point of reflection. The sound energy received at the wall is weighted by Lambert's law (angle υ) and attenuated by the distance x between the point of reflection and the receiver (which can be understood as a re-emission from the surface) yielding an overall weighting factor R_S given by:

$$R_S \approx \frac{\cos(\upsilon)}{\pi x^2} \tag{6}$$

Then a random number is generated to decide whether the reflection happens to be geometrically or diffusely. If the latter is the case a subsequent detection by a receiver is forbidden until another wall was hit. This condition ensures full compatibility of the deterministic diffuse rain part with the probabilistic Monte-Carlo model.

The diffuse rain approach redistributes probabilities for low particle numbers while the asymptotic limit is the same as for the original algorithm. Of course, due to the increased number of visibility checks also the calculation time per emitted particle is increased.

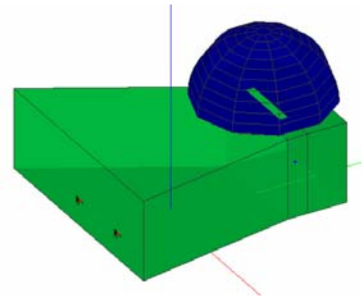

Figure 2: Simple model of two coupled spaces

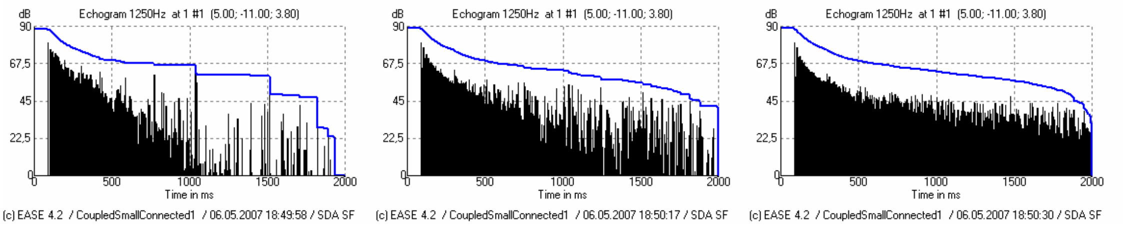

Figure 3: Conventional simulation for 50k, 500k and 5M particles

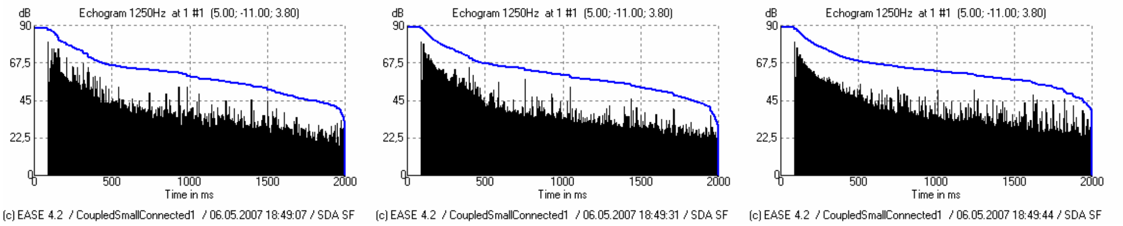

Figure 4: Diffuse Rain simulation for 10k, 100k and 1M particles

For the comparison of calculation performance we have used a very simple model consisting of two coupled spaces, the larger one is the main room with a low reverberation time, the smaller one is an attached cupola with a high reverberation time (Figure 2). Figures 3 and 4 show example echograms calculated for this room. The particle numbers have been chosen so that the calculation times are similar (approx. 3 min, 30 min and 5 hours). It is obvious that the new diffuse rain algorithm adds a much higher particle density towards longer times. This smoothens the energy distribution for low particle numbers / short calculation times significantly. It is also clear that for very large particle numbers both algorithms must converge asymptotically which can be verified in the given example as well.

6. COMPLEX SOUND SOURCES

So far we have not paid much attention to the validity of the point source approximation of the loudspeakers involved in the model. However, nowadays many modern loudspeaker systems, such as line arrays or steered columns, cannot be considered as a single point source for the purpose of modelling. In the framework of EASE such complex sound sources can be described by DLLs or GLLs ([12]). With respect to room-acoustic simulation it needs to be discussed therefore how high-resolution data models for loudspeakers ([13]) should be treated when reflections and scattering have to be computed. Of course, frequency resolutions higher than 1/3rd octave are not practical to consider for the calculation of reflection levels looking at the information available for wall materials today and in the near future. The same holds true for data regarding complex reflection factors that is seldom available. On the other hand, an increased angular resolution will only require more memory for the balloon data, but it does not affect the performance of the ray tracing procedure in general, because the interpolation algorithms for intermediate data points stay essentially the same.

We emphasize that when loudspeaker cabinets are modelled using several point sources there is not much sense in considering each source individually with respect to calculation times and gain in accuracy. But large loudspeaker arrays should not be reduced to a single point source either, because of the errors involved regarding shading and geometrical reflections. Therefore a sensible compromise has to be developed. Here the idea of so-called Virtual Center Points ([12]) is introduced. These points practically represent a group of sources within a loudspeaker cabinet, which are to be combined as a single source of rays for room acoustic calculations. By this means a viable method seems found to limit calculation times needed for particle simulations like in AURA on one side and to keep the modelling accuracy for the sources at the level of the modelling accuracy for the room geometry on the other side.

7. CONCLUSION

We have introduced several improvements to standard room acoustic methods like used in EASE AURA. Of particular concern was a better performance with respect to calculation times and asymptotic convergence as well as a simpler way for the user to understand and adjust calculation parameters. Simplified control parameters utilizing mean path estimates, a faster grid-based intersection computation engine, an improved approach to the simulation of scattering called Diffuse Rain and a practical way of modeling complex sound sources have been recently implemented in EASE AURA. These additions could significantly enhance the performance and usability of the room acoustic program module.

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