Generalizing the reflection model by the use of a particle tracing method

Jean-François Dindart[*]
`dindart@labri.u-bordeaux.fr`

Catherine Sémidor[†]
`catherine.semidor@bordeaux.archi.fr`

Abstract

Splitting the reflection phenomenon in a specular and a diffuse one, current acoustic quality prediction methods can't deal with real materials. In this paper, we describe the implementation of a particle tracing method that can deal with a general model of reflection, the bidirectional reflectance distribution function. Furthermore, being based on the Monte-Carlo methods, this method is not sensitive to combinatorial explosion. The flexibility of the particle tracing method make it a good test bed for comparisons and evaluations of source or reflection models.

1 Introduction

The classical methods (mirror image source and ray tracing) of computerized acoustic prediction only account for specular behaviour of materials. The lack of diffusion was first resolved with artificial late reverberation but gave unnatural sound auralization. New methods that can deal with diffusion were developed. Many of these methods are extensions of the classical ones with a radiosity part ([DKS94]). Almost all of them approximate the reflective behaviour of real materials as a linear combination of a specular and a diffuse behaviours, both independent. This approach, though capitalizing the confidence gained on the classical models, is not totally satisfactory.

These extended methods inherit some of the well-known limitations of the classical methods. Among these limitations, the restriction of geometry is probably the most important. Furthermore, it is difficult to evaluate their relative strengths and weaknesses although they are based on the same approach. It seems also not very likely, given the lack of separation between their computing and reflection models, that they can be extended to more general models of reflection.

We propose to replace these extended methods with a particle tracing method. This method, relying on the Monte-Carlo methods [Fis96], is general enough to deal with complex source and reflection models and takes care of complex geometrical primitives. Furthermore, the generality and flexibility of this method make it a natural test bed for comparisons and evaluations of the numerous source and reflection models currently used.

Section 2 presents the particle tracing method. Sections 3 and 4 describes two parts of this method, the emission and reflection stages. Preliminary results are given in section 5 and section 6 concludes.

2 Particle tracing

This section describe a method to compute a reflectogram given a source, a receptor and a closed environment made of walls. For this method, the medium is supposed non participating. The receptor must be a surface or a volume since particles are used. It will be a sphere with a fixed radius. These assumptions can be relaxed, but this will not be addressed in this paper. To simplify the explanations, the wavelength dependence will be left implicit and only one source will be supposed.

A reflectogram can be considered as the result of the passage through the receptor of a great number of phonons. A straightforward method to compute the reflectogram is:

> Propagate a great number of phonons in the environment and keep track of their passage through the receptor.

Before being propagated, a phonon must first be emitted by a source which fixes its initial location and direction of propagation. After its emission, the phonon travels in a straight line until it hits a wall. According to the reflective properties of the wall, the phonon can then be absorbed or reflected into a new direction (the direction of reflection). If the phonon is absorbed, a new phonon is emitted by the source and propagated in the environment. If the phonon is reflected, it continues its paths along the direction of reflection until it

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[*] LaBRI, Université Bordeaux I.

[†] ERIAC, Ecole d'architecture et de paysage de Bordeaux.

1. **Emission**
    - (a) Probabilistically determine the octave band of the particle according to the power spectrum of the source,
    - (b) fix the initial linear energy density of the particle according to the source power and the number of particles,
    - (c) probabilistically determine the initial location and direction of propagation of the particle according to the emissive properties of the surface of the source.
2. **Propagation** : Find the first wall on the path of the particle.
3. **Reception** : If the particle goes through the receptor, increase the energy density in the volume of the receptor according to the linear energy density of the particle and the length of the path of the particle in the receptor. This increase will be added to the time interval containing the arrival time of the particle in the receptor.
4. **Reflection**
    - (a) reduce the particle's linear energy density according to the absorptive properties of the wall,
    - (b) if the particle's linear energy density remains significant
        - probabilistically determine a reflected direction of propagation according to the reflective properties of the wall,
        - goto stage **Propagation**.
    - (c) else,
        - goto stage **Emission**.

Figure 1: Particle tracing algorithm.

hits a wall. The phonon is propagated this way until absorbed. When a phonon goes through the receptor, the volume energy density in the receptor increases during this passage. The reflectogram is derived from all these increases. Since they are very numerous, it would require a huge amount of memory to track each one. The time scale is discretized and each contribution is deposited in the time slot corresponding to the time arrival of the phonon in the receptor.

The path of a phonon begins with an emission, continues with a series of reflections and ends with an absorption. The basic principle of particle tracing is to model these events (and the physical properties these events depend on) with probabilistic methods.

The method previously defined can be implemented as is, but it will then give poor results. Two problems need to be addressed before a practical algorithm based on this method can be designed. First, a phonon carries so little energy that a very large number of them have to be propagated to distribute the energy of a source. Second, in a complex environment, many phonons will be absorbed before reaching the receptor, wasting much computation time.

A solution to these problems is to bundle some phonons into a meta-phonon: the particle. The number of particles required will be far less than the equivalent number of phonons. Replacing phonons with particles also reduces the computation time wasted. When a particle hits a wall, its energy is reduced according to the absorptive properties of the wall. The particle is absorbed only if its energy can then be considered negligible. In the other case, the particle is reflected back into the environment. The energy of a particle is considered negligible if it falls under a given threshold. Another view of this scheme is to consider that, if α is the probability of absorption of a given wall, $100 \times \alpha$ percent of the phonons bundled in a particle are absorbed. Because of the bias introduced by the thresholding, a russian roulette[Fis96] must be used to avoid it.

An algorithm based on this method is given in figure 1. The propagation and reception stages of this algorithm rely on classical methods of ray-tracing. Since much work have been done on these methods, we will not describe these stages here. A very good introduction to the ray-tracing methods can be found in [Gla89]. The two other stages, emission and reflection, are described in the next two sections.

3 The emission stage

Since all particles are emitted by the source, the initial state of any particle depends on the properties of the source. The state of a particle is completely defined by a frequency, a linear energy density, a location and a direction of propagation. The dependence between source properties and state values are:

- the frequency depends on the spectral power of the source,
- the linear energy density depends on the total power and volume of the source and the number of particles that will carry this power,
- the location depends on the geometry and the surface emissive property of the source.
- the direction depends on the directional emissive property of the source.

Stochastic processes based on the source properties are used to evaluate the initial state of a particle[1]. The variance of these processes can be reduced with more particles. A better solution is the use of variance reduction techniques developed in the domain of the Monte-Carlo methods. Among all the variance reduction techniques, the importance sampling is of great interest here. Its principle is to draw more samples in the more important regions of the sampled function (the spectral power for example). It does so by sampling according to a *probability density function* $p(x)$ of similar shape to the sampled function. To draw a sample according to $p(x)$, the cumulative function $P(x)^2$ of the *pdf* is computed and inverted. Given these functions, the importance sampling consists of drawing a uniform sample s and computing $P^{-1}(s)$. When the *pdf* can not be analytically integrated, the probability distribution function $P(x)$ can be computed and tabulated. A complete description of methods needed to sample the initial state of a particle is given in [Pat93].

A study of some variance reduction techniques and their combinations is conducted in [Laf96]. A very detailed presentation of the mathematical framework of the variance reduction techniques is presented in [Fis96].

Sampling frequency, location and direction of propagation independently allow the particle tracing method to deal with many kinds of sources fairly easily.

4 The reflection stage

Current reflection models used in acoustic quality prediction methods can only give crude approximation of real materials. The particle tracing method makes use of a more complete description of the reflection phenomenon: the bidirectional reflectance distribution function, *brdf*. It describes the directional distribution of the reflected sound. A complete and physically sound framework for the *brdf* is presented in [Gla95].

The *brdf* is a mathematical concept that can be implemented with many different assumptions. Depending on these assumptions, the reflection model can be as simple as the ideal diffuse (or lambertian) model, or as accurate as measured data. These models are used to answer two questions in the reflection stage:

- given a particle hit on a wall, will this particle be absorbed or reflected?
- (When a particle is reflected) what will be its new linear energy density and its new direction of propagation?

As with the source model, importance sampling can be used to reduce the variance of the reflection sampling. Due to the limited space, only two very basic *brdf*, and a linear composition of them are presented. More realistic *brdf* models are described in [LW94], [NN96], [LF97] and [Emb98].

4.1 Ideal diffuse model

In the ideal diffuse model, a wall reflects the sound with the same intensity in all directions above it. A reflected direction of propagation can be sampled by uniform sampling of the hemisphere above it. The absorption can be accounted for with the usual absorption coefficient.

4.2 Ideal specular model

In the ideal specular model, a wall reflects sound only in the mirror direction given by the Descartes Snell law. The *brdf* is then a Dirac distribution. Since the mirror direction is unique and totally determined by the incoming direction and the wall normal, no stochastic process is needed here. The absorption can again be accounted for with the usual absorption coefficient.

4.3 Linear combination model

A better but still very limited approximation of a real material can be obtained with a linear combination of ideal diffuse and ideal specular models.

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[1] The initial location of a particle emitted by a point source will, of course, be deterministic.

[2] It is called *probability distribution function.*

The linear combination is defined by two coefficients, the diffuse absorption coefficient, C_d, and the specular absorption coefficient, C_s. These coefficients must be such that $C_d + C_s = 1$.

A simple implementation can consist of dividing an incoming particle into two particles, one spawned by the diffuse reflector and the second spawned by the specular reflector. But this solution, being sensitive to combinatorial explosion, must be avoided. One particle must not divide into particles. Each time a particle is reflected on a wall with a linear combination material, an uniform random sample u is drawn. If u is inferior to C_d then the particle will undergo a diffuse reflection. Otherwise, it will undergo a specular reflection.

5 Preliminary results

We have implemented the particle tracing algorithm in C under Linux. For testing purpose, we implemented the ideal diffuse and ideal specular models. Although failing to represent many reflective behaviour, these models are required for a comparison between the particle tracing method and the classical ones. A well known acoustic prediction software package, epidaure, is used for the comparisons.

The tests were conducted on a “shoe box“ room with uniform absorption. The results for the two models of reflection and the epidaure software and the theoretic results are exposed in figure 2. The particle tracing method results are in good adequation with the theory and epidaure results.

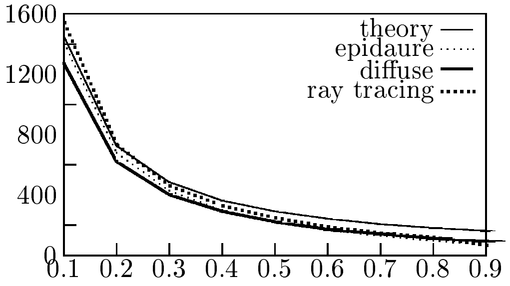

Figure 2: Computed and theoretical $T_r(ms)$ in function of the coefficient of absorption

6 Conclusions and future work

We have presented a particle tracing method which defines a more general framework than the classical methods in acoustic quality prediction. Another interest of particle tracing is the definition of a flexible test bed for source and reflection models. This test bed should simplify evaluations and comparisons of different models. A source model, based on [CS98], and a reflection model, based on [Emb98], will be especially considered. The source model pays special attention to source directivity to which some new acoustic quality criteria are sensitive. The reflection model defines a physically sound model of *brdf* that can be parameterized to approximate measured *brdf* of real materials.

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