# Computer Simulation Techniques for Acoustical Design of Rooms

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Abstract: After decades of development room acoustical computer models have matured. Hybrid methods combine the best features from image source models and ray tracing methods and have lead to significantly reduced calculation times. Due to the wave nature of sound it has been necessary to simulate scattering effects in the models. Today's room acoustical computer models have several advantages compared to scale models. They have become reliable and efficient design tools for acoustic consultants, and the results of a simulation can be presented not only for the eyes but also for the ears with new techniques for auralisation.

## 1. INTRODUCTION

In acoustics as in many other areas of physics a basic question is whether the phenomena should be described by particles or by waves. A wave model for sound propagation leads to more or less efficient methods for solving the wave equation, like the Finite Element Method (FEM) and the Boundary Element Method (BEM). Wave models are characterized by creating very accurate results at single frequencies, in fact too accurate to be useful in relation to architectural environments, where results in octave bands are usually preferred. Another problem is that the number of natural modes in a room increases approximately with the third power of the frequency, which means that for practical use wave models are typically restricted to low frequencies and small rooms, so these methods are not considered in the following.

Another possibility is to describe the sound propagation by sound particles moving around along sound rays. Such a geometrical model is well suited for sound at high frequencies and the study of interference with large, complicated structures. For the simulation of sound in large rooms there are two classical geometrical methods, namely the Ray Tracing Method and the Image Source Method. For both methods it is a problem that the wavelength or the frequency of the sound is not inherent in the model. This means that the geometrical models tend to create high order reflections which are much more precise than would be possible with a real sound wave. So, the pure geometrical models should be limited to relatively low order reflections and some kind of statistical approach should be introduced in order to model higher order reflections. One way of introducing the wave nature of sound into geometrical models is by assigning a scattering coefficient to each surface. In this way the reflection from a surface can be modified from a pure specular behaviour into a more or less diffuse behaviour, which has proven to be essential for the development of computer models that can create reliable results.

## 2. SIMULATION OF SOUND IN ROOMS

### 2.1 The Ray Tracing Method

The Ray Tracing Method uses a large number of particles, which are emitted in various directions from a source point. The particles are traced around the room losing energy at each reflection according to the absorption coefficient of the surface. When a particle hits a surface it is reflected, which means that a new direction of propagation is determined according to Snell's law as known from geometrical optics. This is called a specular reflection. In order to obtain a calculation result related to a specific receiver position it is necessary either to define an area or a volume around the receiver in order to catch the particles when travelling by, or the sound rays may be considered the axis of a wedge or pyramid. In any case there is a risk of collecting false reflections and that some possible reflection paths are not found. There is a reasonably high probability that a ray will discover a surface with the area $A$ after having travelled the time $t$ if the area of the wave front per ray is not larger than $A/2$. This leads to the minimum number of rays $N$

$$N \geq \frac{8\pi c^2}{A} t^2 \tag{1}$$

where $c$ is the speed of sound in air. According to this equation a very large number of rays is necessary for a typical room. As an example a surface area of 10 m² and a propagation time up to only 600 ms lead to around 100,000 rays as a minimum.

The development of room acoustical ray tracing models started some thirty years ago but the first models were mainly meant to give plots for visual inspection of the distribution of reflections [1]. The method was further developed [2], and in order to calculate a point response the rays were transferred into circular cones with special density functions, which should compensate for the overlap between neighbouring cones [3]. However, it was not possible to obtain a reasonable accuracy with this technique. Recently, ray tracing models have been developed that use triangular pyramids instead of circular cones [4], and this may be a way to overcome the problem of overlapping cones.

### 2.2 The Image Source Method

The Image Source Method is based on the principle that a specular reflection can be constructed geometrically by mirroring the source in the plane of the reflecting surface. In a rectangular box shaped room it is very simple to construct all image sources up to a certain order of reflection, and from this it can be deduced that if the volume of the room is $V$, the approximate number of image sources within a radius of $ct$ is

$$N_{ref} = \frac{4\pi c^3}{3V} t^3 \quad (2)$$

This is an estimate of the number of reflections that will arrive at a receiver up to the time $t$ after sound emission, and statistically this equation holds for any room geometry. In a typical auditorium there is often a higher density of early reflections, but this will be compensated by fewer late reflections, so on average the number of reflections increases with time in the third power according to (2).

The advantage of the image source method is that it is very accurate, but if the room is not a simple rectangular box there is a problem. With $n$ surfaces there will be $n$ possible image sources of first order and each of these can create $(n - 1)$ second order image sources. Up to the reflection order $i$ the number of possible image sources $N_{sou}$ will be

$$N_{sou} = 1 + \frac{n}{(n - 2)}[(n-1)^i - 1] \approx (n-1)^i. \quad (3)$$

As an example we consider a 1,500 m$^3$ room modelled by 30 surfaces. The mean free path will be around 16 m which means that in order to calculate reflections up to 600 ms a reflection order of $i = 13$ is needed. Thus equation (3) shows that the number of possible image sources is approximately $N_{sou} = 29^{13} \approx 10^{19}$. The calculations explode because of the exponential increase with reflection order. If a specific receiver position is considered it turns out that most of the image sources do not contribute reflections, so most of the calculation efforts will be in vain. From equation (2) it appears that less than 2500 of the $10^{19}$ image sources are valid for a specific receiver. For this reason image source models are only used for simple rectangular rooms or in such cases where low order reflections are sufficient, e.g. for design of loudspeaker systems in non-reverberant enclosures [5, 6].

### 2.3 The Hybrid Methods

The disadvantages of the two classical methods have led to development of hybrid models, which combine the best features of both methods [7, 8, 9]. The idea is that an efficient way to find image sources having high probabilities of being valid is to trace rays from the source and note the surfaces they hit. The reflection sequences thus generated are then tested as to whether they give a contribution at the chosen receiver position. This is called a visibility test and it can be performed as a tracing back from the receiver towards the image source. This leads to a sequence of reflections which must be the reverse of the sequence of reflecting walls creating the image source. Once 'backtracing' has found an image to be valid, then the level of the corresponding reflection is simply the product of the energy reflection coefficients of the walls involved and the level of the source in the relevant direction of radiation. The arrival time of the reflection is given by the distance to the image source.

It is, of course, common for more than one ray to follow the same sequence of surfaces, and discover the same potentially valid images. It is necessary to ensure that each valid image is only accepted once, otherwise duplicate reflections would appear in the reflectogram and cause errors. Therefore it is necessary to keep track of the early reflection images found, by building an 'image tree'.

For a given image source to be discovered, it is necessary for at least one ray to follow the sequence which defines it. The finite number of rays used places an upper limit on the length of accurate reflectogram obtainable. Thereafter, some other method has to be used to generate a reverberation tail. This part of the task is the focus of much effort, and numerous approaches have been suggested, usually based on statistical properties of the room's geometry and absorption. One method, which has proven to be efficient, is the 'secondary source' method used in the ODEON program [9]. This method is outlined in the following.

After the transition from early to late reflections, the rays are treated as transporters of energy rather than explorers of the geometry. Each time a ray hits a surface, a secondary source is generated at the collision point. The energy of the secondary source is the total energy of the primary source divided by the number of rays and multiplied by the reflection coefficients of the surfaces involved in the ray's history up to that point. Each secondary source is considered to radiate into a hemisphere as an elemental area radiator. Thus the intensity is proportional to the cosine of the angle between the surface normal and the vector from the secondary source to the receiver. The intensity of the reflection at the receiver also falls according to the inverse square law, with the secondary source position as the origin. The time of arrival of a reflection is determined by the sum of the path lengths from the primary source to the secondary source via intermediate reflecting surfaces and the distance from the secondary source to the receiver. As for the early reflections a visibility test is made to ensure that a secondary source only contributes a reflection if it is visible from the receiver. Thus the late reflections are specific to a certain receiver position and it is possible to take shielding and convex room shapes into account.

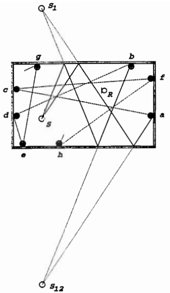


Figure 1. Principle of a hybrid model. Two sound rays create image sources for early reflections and secondary sources on the walls for late reflections.

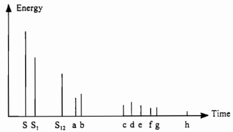


Figure 2. Reflectogram for the receiver R in Figure 1.

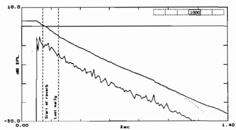


Figure 3. Typical impulse response (energy) and decay curve calculated with a hybrid model.

Figure 1 illustrates in schematic form how the calculation model behaves. In the figure, two neighbouring rays are followed up to the sixth reflection order. The transition order is set to 2, so above this order the rays' reflection directions are chosen at random from a distribution following Lambert's law (see later). The first two reflections are specular, and both rays find the image sources $S_1$ and $S_{12}$. These image sources give rise to one reflection each in the response, since they are visible from the receiver point $R$. In a more complicated room this might not be true for all image sources. The contributions from $S$, $S_1$ and $S_{12}$ arrive at the receiver at times proportional to their distances from the receiver. Above order 2, each ray generates independent secondary sources situated on the reflecting surfaces. In the simple box-shaped room these are all visible from the receiver, and thus they all give contributions to the response. In Figure 2 is displayed the response identifying the contributions from the source, the two image sources and the eight secondary sources.

In a complete calculation the last early reflection (from an image source) will typically arrive after the first late reflection (from a secondary source), so there will be a time interval where the two methods overlap. This is indicated on the calculated energy response curve in Figure 3. Also shown is the reverse-integrated decay curve, which is used for calculation of reverberation time and other room acoustical parameters.

In the hybrid model described above it is a critical point at which reflection order the transition is made from early to late reflections. Since the early reflections are determined more accurately than the late reflections one might think that better results are obtained with the transition order as high as possible. However, for a given number of rays the chance of missing some images increases with reflection order and with the number of small surfaces in the room. This suggests that the number of rays should be as large as possible, limited only by patience and computer capacity. However, there are two things which make this conclusion wrong. Firstly, the probability of an image being visible from the receiver decreases with the size of the surfaces taking part in its generation, so the number of reflections missed due to insufficient rays will be much fewer than the number of potential images missed. Secondly, in real life, reflections from small surfaces are generally much weaker than calculated by the laws of geometrical acoustics, so any such reflections missed by the model are in reality of less significance than the model itself would suggest. Actually, the efforts of an extended calculation may lead to worse results.

Recent experiments with the ODEON program have shown that only 500 to 1000 rays are sufficient to obtain reliable results in a typical auditorium, and an optimum transition order has been found to be two or three. This means that a hybrid model like this can give much better results than either of the pure basic methods, and with much shorter calculation time. However, these good news are closely related to the introduction of diffusion in the model.

## 3. DIFFUSION OF SOUND IN COMPUTER MODELS

The scattering of sound from surfaces can be quantified by a scattering coefficient, which may be defined as follows: The scattering coefficient δ of a surface is the ratio between reflected sound power in non-specular directions and the total reflected sound power. The definition applies for a certain angle of incidence, and the reflected power is supposed to be either specularly reflected or scattered. One weakness of the definition is that it does not say what the directional distribution of the scattered power is; even if $\delta = 1$ the directional distribution could be very uneven.

According to the above definition the scattered power $P_{scat}$ can be expressed as:

$$P_{scat} = \delta P_{refl} = \delta(1-\alpha)P_{inc} \tag{4}$$

where $P_{refl}$ is the total reflected power, $P_{inc}$ is the incident power and $\alpha$ is the absorption coefficient of the surface. The scattering coefficient may take values between 0 and 1, where $\delta = 0$ means purely specular reflection and $\delta = 1$ means that all reflected power is scattered according to some kind of 'ideal' diffusivity.

We now consider a small wall element $dS$ which is hit by a plane sound wave with the intensity $I_0$ and the angle of incidence $\theta$ relative to the wall normal. The incident power is thus $I_0 dS\cos\theta$. The reflected sound can be regarded as emitted from a small source located on the wall element and the three-dimensional scatter of reflected sound can be described by a directivity $D_{\theta,\phi}$. At a distance $r$ from the wall element the intensity of reflected sound is

$$I_{\theta,\phi} = D_{\theta,\phi}\frac{P_{refl}}{4\pi r^2} = D_{\theta,\phi} I_0 \cos\theta \frac{(1-\alpha)}{4\pi r^2} dS \tag{5}$$

An omnidirectional source on the wall would have the directivity $D_{\theta,\phi} = 2$, but instead ideal diffuse reflections should follow Lambert's cosine law: in any direction $(\theta,\phi)$ the intensity of scattered sound is proportional to $\cos\theta$, i.e. proportional to the projection of the wall area. The incident power on a surface exposed by a diffuse sound field would also obey Lambert's law, so this must be considered the ideal angular distribution.

If the scattered sound power is assumed to be independent of the azimuth angle $\phi$, the angular distribution can be found as a function of the elevation angle $\theta$. For a given $\theta$ the sound power is emitted through a ring with height $rd\theta$ and radius $r\sin\theta$, so that

$$dP_\theta = I_{\theta,\phi} 2\pi r^2 \sin\theta \, d\theta = P_{refl} \tfrac{1}{2} D_{\theta,\phi} \sin\theta \, d\theta \tag{6}$$

which for the Lambert directivity $D_{\theta,\phi} = 4\cos\theta$ leads to

$$dP_\theta = P_{refl} 2\cos\theta \sin\theta \, d\theta = P_{refl} \sin 2\theta \, d\theta \tag{7}$$

Hence, the angular distribution of ideal diffuse reflections is $\sin 2\theta$.

Diffuse reflections can be simulated in computer models by statistical methods [10]. Using random numbers the direction of a diffuse reflection is calculated with a probability function according to Lambert's cosine-law, while the direction of a specular reflection is calculated according to Snell's law. A scattering coefficient between 0 and 1 is then used as a weighting factor in averaging the coordinates of the two directional vectors which correspond to diffuse or specular reflection, respectively.

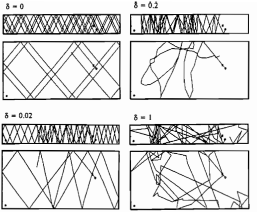


Figure 4. One sound ray in a simple room with different values of the surface scattering coefficient.

An example of ray tracing with different values of the scattering coefficient is shown in Fig. 4. The room is a rectangular box with a relatively low ceiling. All surfaces are assigned the same scattering coefficient. Without scattering, the ray tracing displays a simple geometrical pattern due to specular reflections. A small scattering coefficient of 0.02 changes the late part of the reflection pattern, and a value of 0.20 is sufficient to obtain a diffuse looking result.

By comparison of computer simulations and measured reverberation times in some cases where the absorption coefficient is known, it has been found that the scattering coefficient should normally be set to around 0.1 for large, plane surfaces and to around 0.7 for highly irregular surfaces. Scattering coefficients as low as 0.02 have been found in studies of a reverberation chamber without diffusing elements. The extreme values of 0 and 1 should be avoided in computer simulations. In principle the scattering coefficient varies with the frequencyæscattering due to the finite size of a surface is most pronounced at low frequencies, whereas scattering due to irregularities of the surface occurs at high frequencies. However, today's knowledge about which values of the scattering coefficient are realistic is very limited, and so far it seems sufficient to characterize each surface by only one scattering coefficient, valid for all frequencies.

## 4. ACCURACY AND CALCULATION TIME

Recently an international round robin has been carried out [11] with 16 participants, most of them developers of software for room acoustical simulations. In an 1800 m³ auditorium eight acoustical criteria as defined in [12] were calculated for the 1kHz octave band in the ten combinations of two source positions and five receiver positions. For comparison measurements were made in the same positions by seven different participants. Drawings, photos, material descriptions and absorption coefficients were provided. It came out that only three programs can be assumed to give unquestionably reliable results. The results of these programs differ from the average measurement results by the same order of magnitude as the individual measurement results. So, the reproducibility of the best computer simulations can be said to be as good as a measurement, which is quite satisfactory. However, some of the programs produced 5-6 times higher differences. It is interesting to note, that the three best programs (one of which is the ODEON program) use some kind of diffuse reflections, whereas the results from purely specular models were more outlying. It is also typical that the best programs do neither require extremely long calculation times nor extremely detailed room geometries.

## 5. ADVANTAGES OF COMPUTER MODELS COMPARED TO SCALE MODELS

It is quite obvious that a computer model is much more flexible than a scale model. It is easy to modify the geometry of a computer model, and the surface materials can be changed just by changing the absorption coefficients. The computer model is fast, typically a new set of results are available a few hours after some changes to the model have been proposed. But the advantages are not restricted to time and costs. The most important advantage is probably that the results can be visualised and analysed much better because a computer model contains more information than a set of measurements done in a scale model with small microphones.

### 5.1 The Reflectogram as a Tool

The reflectogram displays the arrival of early reflections to a receiver. When the early reflections are calculated from detected image sources, it follows that each single reflection can be separated independently of the density of reflections, and in addition to arrival time and energy it is possible to get information about the direction and which surfaces are involved in the reflection path. The latter can be very useful if a particular reflection should be removed or modified.

### 5.2 Display of Reflection Paths

The reflection paths for all early reflections may be visualised in 3D and analysed in detail. During the design of a room it may be interesting to see which surfaces are active in creating the early reflections. Although it is difficult to extract specific results from such a spatial analysis, it can help to understand how a room responds to sound.

### 5.3 Grid Response Displays

With a computer model it is straight forward to calculate the response at a large number of receivers distributed in a grid that covers the audience area. Such calculations are typically done over night, and it is extremely useful for the acoustic designer to see a mapping of the spatial distribution of acoustical parameters. Uneven sound distribution and acoustically weak spots can easily be localized and appropriate countermeasures taken.

### 5.4 Auralisation

In principle it is possible to use impulse responses measured in a scale model for auralisation. However, the quality may suffer seriously due to non-ideal transducers. The transducers are one reason that the computer model is superior for auralisation. Another reason is that the information about each reflection's direction of arrival allows a more sophisticated modelling of the listener's head-related transfer function.

Most of the recent research concerning auralisation has concentrated on the 'correct' approach, whereby each link in the chain from source to receiver may be modelled as an impulse response. See Kleiner et al. [13] for an overview of the technique. However, the convolution technique involved requires either expensive hardware for real-time convolution or long waits for off-line convolution, and often the impulse response is too short to produce a realistic reverberation. An alternative technique for auralisation, which avoids the convolution bottleneck, has recently been proposed [14]. The method is based on an interface between a digital audio mainframe and a room acoustical computer model. This means that auralisation can follow immediately after the room acoustical calculation in a receiving point, and there are no limitations on length of the source signal. The early reflections and the late reverberant reflections are treated by two different techniques. With this technique 40-50 early reflections will usually be sufficient to create a realistic sounding room simulation, and long reverberation time is no problem.

The early reflections are very important for obtaining a realistic auralisation. For presentation through headphones the following three methods are used in order to obtain localization outside the head:

- Interaural time difference. This is the dominant cue for localization of broad band sound in the horizontal plane.
- Interaural intensity difference. The signal to the ear in the direction of the incident reflection is raised up to 6 dB. This is a simplified representation of the reflection effect of the head relative to free field.
- Spectral cues. The spectral peaks and notches due to the outer ear are roughly simulated by filters Although this is known to be the main cue for elevation, the intention at this stage has not been to create a localization for different elevation angles, but rather to avoid the front-back confusion and to improve the out-of-the-head localization.

The auralisation technique offers the possibility to use the ears already during the design process. Several acoustical problems in a room can easily be detected with the ears, whereas they may be difficult to express with a parameter that can be calculated.

## 6. CONCLUSION

Computer techniques for simulation of sound in rooms have improved significantly in recent years, and for the consultant the computer model offers several advantages compared to the scale model. The scattering of sound from surfaces has appeared to be very important in room acoustical simulation technique, and this has created a need for better information about the scattering properties of materials and structures. Although the scattering can be handled by the model, the knowledge about which scattering coefficients to use is very sparse. So, it can be concluded that there is a need for a method to measure the scattering coefficient of surfaces. Until then there remains an inherent piece of guesswork in room acoustical simulations. On the other hand, it is no surprise that the user can influence the quality of a simulation.

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