Abstract

The subject of room simulation attracted the attention for the last few decades. Methods for acoustic simulation of rooms have been developed for purposes of analysis, design, and virtual performance. Geometrical-acoustics based methods, the mirror-image method and the ray-tracing method, have been mainly used.

In this paper, the application of diffusion in room acoustics computer models is discussed. The paper specifies the specular-radiant method to calculate the acoustic response of rooms. This method integrates the geometrical and the radiant approaches to predict the sound field in those rooms with boundaries of partially specular reflectivity. Furthermore, the room impulse response is auralised for given sources and receiver positions. Finally, evaluation tests are presented.

1. Introduction

Concert and opera halls or lecture rooms may have good or bad acoustics. In order to judge the acoustical quality of rooms, the sound fields in enclosures have to be studied, and important factors have to be understood. Therefore it is aimed to develop computer models to predict the acoustical properties of a certain room. One has to define the geometry of the room, the acoustics of its boundaries, and the position of the sources, then the impulse response of the room can be calculated at different listening positions.

In room acoustics, a number of physical-based models have been developed to simulate the sound fields in rooms. The wave-theory based models, as the finite element method [1] and the boundary element method [2], may be used to describe the propagation of sound. From a physical point of view the wave theory [3] provides the more accurate description of sound fields in rooms, but its practical application are still limited due to the large numerical calculations required [4][5].

A simplified method for the description of sound propagation in rooms is to use geometrical-acoustics based models, as the mirror-image method and / or the ray-tracing method [6][7][8]. These methods can only provide a partial description of the sound propagation in rooms, as the scattering phenomenon is neglected.

Another method that could be applied to describe the sound propagation in rooms is the radiosity method [9]. It is based on the integral equation for the irradiation strength of the wall [4], where pure diffuse reflections according to Lambert law were assumed. In practical situations, a portion of the energy is diffusely reflected [10][11][12]. A reasonable method for simulating the sound fields in rooms is the specular-radiant model [13]. The method integrates the geometrical and the radiant approaches to simulate rooms with boundaries of partially specular reflectivity.

In this paper, the mirror-image method and the specular-radiant method are discussed. The effects of simulating diffuse reflections on the sound field are presented. The sound field is auralised and subjective tests are used to judge the effects of simulating diffuse reflections in computer models.

2. Simulation of sound fields in rooms

In this section, only two models are discussed: The mirror-image model as an example for geometrical-acoustics based models, and the specular-radiant model as an example for simulating sound diffusion in rooms. The two methods are compared to each other.

2.1. The mirror-image method

It is a geometrical-acoustics based method. It is based on the principle, that the sound rays are reflected specularly. A specular reflection is constructed geometrically by mirroring the source with respect to the plane of the reflecting surface. A visibility test has to be performed to check the validity of the image source to a certain listening position. The distance between the receiver and the image source determines the arrival time of the reflection.

The method allows an exact representation of the sound rays running from the source to the listener after a given number of reflections.

2.2. The specular-radiant method

It integrates the geometrical-acoustics based methods and the radiosity method. In this method, each reflecting surface is patched into a number of elements. Each element has a very small area, ΔA. The specular-radiant method is based on the principle that the energy radiated from one element-area and incident upon another one...
depends on the form factor between the two elements [14]. If a certain amount of energy is radiated from element i and is incident upon element j, the form factor from element i to element j is defined mathematically as:

\[ F_{ij} = \frac{\cos \theta_i \cos \theta_j}{\pi R_{ij}^2} (\Delta A_j) \quad (1) \]

where k is the order of reflection, (\Delta A)_j is the area of the surface element j, \( \theta_i, \theta_j \), and \( R_{ij} \) are shown in figure 1 and figure 2 for k = 0, and k = 1 respectively.

The specular-radiant method could handle any combinations of specular-specular, specular-diffuse, diffuse-specular, and diffuse-diffuse reflections. The method needs a large computational power compared to the mirror-image method. An extra number of mirror-image elements (figure 2), MIE, has to be calculated to handle the specular-diffuse and the diffuse-specular reflections. The value could be mathematically expressed as:

\[ \text{MIE} = (N-1)*m \quad (2) \]

where N is the number of elements/patches of the reflecting boundaries in the room, and m is the number of mirror-images calculated for each element. The value of m depends on the number of reflecting surfaces of the room, and it depends on the order of reflection, k. The mirror-image elements are calculated once, as it does not depend on the listening position, i.e. by moving the listener, the calculation of MIE is not repeated.

3. The effects of simulating diffusion in computer models

In this section, the effect of simulating diffusion on the sound energy distribution is presented. Two rooms are simulated, each of 11m x 7m x 3m. In the first room, the absorption coefficient of the ceiling is 0.83, whereas that of all other walls is set to 0.2. The reflecting walls of the second room have a uniform absorption coefficient of 0.2. In both rooms, a uniform diffusion coefficient, d, is assigned to all boundaries.

Figures 3, 4 and 5 show that increasing the value of the diffusion coefficient yields to a uniform distribution of the sound energy over a time \( t > 50 \) msec., i.e. a smooth decay curve is obtained for \( d = 0.7 \) as shown in figure 5. Compare also the impulse response shown in figure 6 to that shown in figure 7. The same conclusion
is deduced in case of the second room, by comparing figure 8 to figure 9.
Another factor that may affect the sound energy simulated by means of the specular-radiant method is the order of reflection of the elements, k. Figure 10 shows that for values of $k \geq 2$, the decay curves almost coincides with each other.

*Figure 4:* decay curve in room1, the specular-radiant method is applied, $d = 0.2$

*Figure 5:* decay curve in room1, the specular-radiant method is applied, $d = 0.7$

*Figure 6:* the impulse response of room1, the mirror-image method is applied.

*Figure 7:* the impulse response of room1, the specular-radiant method is applied, $d = 0.7$

*Figure 8:* decay curve in room2, the mirror-image method is applied

*Figure 9:* decay curve in room2, the specular-radiant method is applied, $d = 0.7$

4. Auralisation

In the field of acoustic simulation of rooms, the auralisation technique plays an important role. It offers the possibility to make a room model audible, and so the acoustics of a specific room can be subjectively judged.
In this paper, the sound energy is calculated in octave bands by applying either the mirror-image method or the specular-radiant method. The magnitude of the sound pressure is calculated, and it is modulated with the corresponding single frequency signal. The modulated signals are overlapped to get the impulse response of the room (see figures 6 and 7). The impulse response is convolved with dry speech signals to judge the acoustical quality of the simulated room.

The judgement takes place by colleagues at the Institute of Communication Acoustics at the Ruhr-Universität Bochum. They were asked to judge the room response as stated below.

a. Room1 that is simulated by applying the mirror-image method is compared by hearing to that simulated by applying the specular-radiant method.

b. The comparison stated in a. is repeated for room2.

c. Three simulations for room2 are compared to each other by hearing. The responses are calculated by applying the specular-radiant method. The diffusion coefficient, d, is 0.7, and different values for the order of reflection, k, are used: k = 3, 5, 7.

The result of the survey is summarized as follows:

a. Room1, that is simulated by applying the mirror-image method is perceived as more reverberant.

b. Room2, that is simulated by applying the specular-radiant method is perceived as more reverberant.

c. There was no large difference between the three responses, but the room that is simulated for k = 7 is subjectively judged to be a bit more reverberant than the room simulated for k = 3 or 5.

The results of the survey, that are stated in a, b and c could be clarified by comparing the energy level of any two decay curves over a time t, $T_{30} \leq t \leq T_{60}$, where $T_{30}$ and $T_{60}$ are the time at which the energy level drops to -30 dB and -60 dB respectively. It is noticed that within the specified time range, t, the energy level shown in figure 3 is higher than that shown in figure 5, whereas the energy level shown in figure 9 is higher than that shown in figure 8. It is concluded, that the reverberation perceived by applying the specular-radiant method may be more or less than that perceived by applying the mirror-image method, depending on the distribution of the sound energy over the specified time, t.

5. Conclusions

In this paper, different acoustic models of rooms are discussed. The simulation of sound diffusion in rooms is presented. The paper specifies the specular-radiant method to be applied for acoustic simulation of rooms. The effect of applying sound diffusion in room acoustic computer models is mentioned. Subjective tests have been presented.

6. References


