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A STUDY OF VARIOUS BARRIERS IN ENCLOSED SOUND FIELD BY USING THE COMPUTER PROGRAM—SOFIS

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In the study of the behaviors of barriers in an enclosed field, one should take into account such phenomena as sound energy reflection, absorption, scattering and diffraction. Therefore, the study is much more difficult than that in free field. In this paper, sound barriers are classified into four kinds according to their size, number and shape. Each kind of barriers is modelled by a corresponding method based on a computer program—SOFIS. The program combines the ray-tracing technique and statistical method. The impulse response and some acoustical parameters such as sound pressure level at different positions can be calculated by the program, no matter there are a certain kind of barriers in the field or the field is empty. The ray-tracing program and the algorithms for various barriers are validated by the comparison between measurement and prediction of the reverberation room and the anechoic room of the Northwestern Polytechnic University.

1. INTRODUCTION

With the development of computer industry and signal processing technique, it is possible today to simulate enclosed sound field by digital methods. This technique can be used in the field of industry noise control, auditorium acoustic design, virtual reality, and so on. Geometrical models are often used at the frequency where the wavelength of sound is considerably smaller than any large-scale inhomogeneities. So far, the two famous models for the calculation of transient sound propagation in rooms on computer are the ray-tracing model (RTM) [1] and the image–source model (ISM) [2]. A number of references have investigated these methods and their feasibility has been verified [1–5]. In recent years, several developed algorithms [6–8] have been brought forward in order to improve the precision and efficiency of calculation. Most of them are used for empty rooms. However, in the study of real workshops, we have to deal with the effect of various kinds of barriers. Furthermore, acoustic barriers are often used for noise control, hence they should be an integral part of any computer prediction model. But up to now the behaviors of barriers in enclosed fields have not been fully investigated.

Because the behaviors of barriers are dependent on their shape, number and size, different methods should be used. In this paper, we mainly discuss four kinds of barriers: (1) partial screens; (2) insulative walls; (3) a small number of irregular barriers; and (4) a large number of disorderly placed barriers. In order to simulate these barriers, we developed an improved geometrical model SOFIS by using Visual C ++ and OpenGL, which can calculate the impulse response and some acoustical parameters at defined positions.

The methods based on wave acoustics, such as FEM, are only practical for small room or the situation of low frequency. Moreover, dealing of barriers will need much more computation power. So, this kind of method is unpractical for the research of various barriers in large enclosures. Among those geometric methods, the image source method is only efficient in simulating simple empty rooms and it is unpractical for the rooms with arbitrary shape and various barriers. But the ray-tracing method can deal with arbitrary rooms and the algorithm is relatively simple to design, so SOFIS is developed based on the ray-tracing method. In simulating sound scattering and diffusion at walls or barriers, the statistical method is also used.

2. CALCULATING IMPULSE RESPONSE BY SOFIS

In an enclosure, the sound source, the receiver and their environment including the walls, barriers and media build up a linear system. The signal emitted by the source can be regarded as the input $x(t)$ of the system, and the output $y(t)$ is the signal received by the receiver. So, the relationship between them is

$$y(t) = \int_{-\infty}^{+\infty} x(t-\tau)h(\tau)\,\mathrm{d}\tau. \tag{1}$$

In the above equation, $h(t)$ is the impulse response (IR) which concludes most information of the system. In the study of the sound distribution in enclosures, we usually obtain the energy impulse response in the first place. Then some parameters can be calculated based on it.

In SOFIS, we calculate IR at a receiver by setting up a model according to the following procedure. One assumes that the source emits a certain amount of energy, carried by a finite number of rays. When a ray strikes a wall of the enclosure, it is reflected according to the law of specular reflection or in a random direction. The energy in the diffusion part is equal to the product of the energy in the incident ray and a factor $(1-\alpha)d$, where α is the sound absorption coefficient, and d is the diffusion coefficient of the wall. The two indexes are assumed as independent of the incidence angle. The energy in the specular part is the product of the energy in the incident ray and a factor $(1-d)(1-\alpha)$. The reflected ray is re-reflected at the next collision and the process is continued until the energy content of the ray falls below a predetermined threshold value, which is equal to the product of the initial ray energy and the total ray numbers. The computer records the energy and the arriving time of each ray that has arrived at the receiver, from which the energy impulse response can be computed. Using the same process, we can predict the energy distribution at any position in the enclosed field.

2.1. MODELLING THE SOUND SOURCES

Most ray-tracing procedures only consider an omni-directional point source, which emits sound rays randomly or symmetrically in the enclosure. In SOFIS, not only omni-directional source, but also directional point source, line source and panel source can be simulated.

If the source is omni-directional [9], we choose n circles uniformly on a unit sphere along the Z-axis, then each circle is divided into $m_i(=n^2\sin\theta_i)$ equidistant points. If n is large enough, all points on the unit sphere can be looked as evenly distributed. The direction of each ray can be denoted as that of the vector from the source to a point on the unit sphere (Figure 1). Therefore, an arbitrary ray's direction is equal to the following unit vector:

$$V_{i,j} = (\sin\theta_i\cos\varphi_{i,j}, \sin\theta_i\sin\varphi_{i,j}, \cos\theta_i), \tag{2}$$

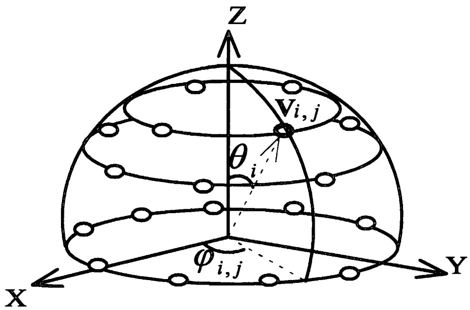

Figure 1. The direction of initial rays.

where θ_i and $\varphi_{i,j}$ of the ray can be calculated as

$$\theta_i = \frac{(2i-1)\pi}{2n}, \quad i = 1, 2, 3, \ldots, n, \tag{3}$$

$$\varphi_{i,j} = \frac{(2j-1)\pi}{2m_i}, \quad j = 1, 2, \ldots, m_i. \tag{4}$$

If E_s is the energy of the source, energy of E_s/N will be assigned to each ray. The total number N of initial rays can be proximately calculated by [10]

$$N \approx \frac{n(n-1)}{2}. \tag{5}$$

To consider the directivity of a simple sound source, we can limit the initial rays in a solid angle (like a bugle) if we know the shape of the loudspeaker, or if the directivity factor is known, we multiply it with the energy taken by the rays.

To simulate a complicated source [10] such as a line source, we divide it into a certain number of point sources, which can be traced simultaneously. The energy at a receiver is the summation of contribution of every point source.

2.2. MODELLING SOUND PROPAGATION IN EMPTY ENCLOSURE

If the enclosure is empty, the wall which meets the following conditions will be collided by a ray:

(1) the ray has a point of intersection with the plane which covers the wall;
(2) the point of intersection is in the ray's direction;
(3) the point of intersection is in the real area of the wall;
(4) the distance between the intersection point and the point it struck at the last time is the nearest one.

According to the above conditions, the real point of intersection of a ray can be found, then its new direction should be computed. Firstly, we generate a random number between 0 and 1 by the computer. If the number is higher than the diffusion coefficient of the wall, the ray will be reflected in a specular direction. No diffuse reflection energy arrives at the receiver. Otherwise, a secondary source is generated at the collision point, which gives its diffuse energy to the receiver. The new ray is emitted in a random direction, which can be calculated by the following equation:

$$\alpha = \sin\theta \sin\varphi, \;\; \beta = \sin\theta \cos\varphi, \;\; \gamma = \cos\theta, \tag{6}$$

where $\theta = \arcsin(r_1)$, $\varphi = 2\pi r_2$, r_1 and r_2 are two independent random numbers in [0, 1].

The distribution of all the rays in the enclosed field can be worked out by repeating the above steps.

2.3. MODELLING THE SOUND RECEIVER

In SOFIS, a changeable sphere receiver is used. We have derived a formula [10] to calculate the minimal radius r_{min} of the sphere:

$$r_{min} = d_{SR}\sqrt{\frac{8}{3N}}, \tag{7}$$

where d_{SR} is the distance from the source to the receiver, N is the total ray number. This equation is similar to that given by Hilmar [11].

3. SIMULATING THE BEHAVIORS OF BARRIERS

In the ray-tracing algorithm, the most time-consuming step is to analyze the relationship between all the rays and boundaries of the space. It is obvious that the existence of barriers will make this step much more complicated. So, the computation efficiency is one of the factors we have to consider when selecting a certain method. The behaviors of barriers are not the same when they have different size, shape or number. That is another reason why we use various methods for simulation. In this paper, we take into consideration the following four possible cases.

3.1. PARTIAL SCREENS

See Figure 2(a). In this case, barriers are regarded as walls of the enclosure. If the positions of all the barriers and the characteristics such as absorption coefficients of each surface of the barriers are known, all rays can be traced as in empty rooms.

When the screen is large and the frequency of the sound is high, it must be recognized that the sound will diffract over them and create a shadow zone. Some researchers have tried to find a solution for the diffracted field and several algorithms have been given [12]. Giuliana Benedetto's method [13] is more convincing, but is not very convenient in terms of computer time. In this paper, we only consider the first order diffraction approximately and the sound reduction is calculated by the following equation:

$$\Delta L = 10\,\lg\frac{10H^2}{\lambda R}, \tag{8}$$

where ΔL is the sound level reduction, H the height of the screen, λ the wavelength, and R the distance between the sound source and the screen.

The above equation is an abbreviated form of Fehr's equation [14]:

$$\Delta L = 10\,\lg 10\left[\frac{2}{\lambda}R - \left(\sqrt{1 + H^2/R^2} - 1\right) + D\left(\sqrt{1 + H^2/D^2} - 1\right)\right]. \tag{9}$$

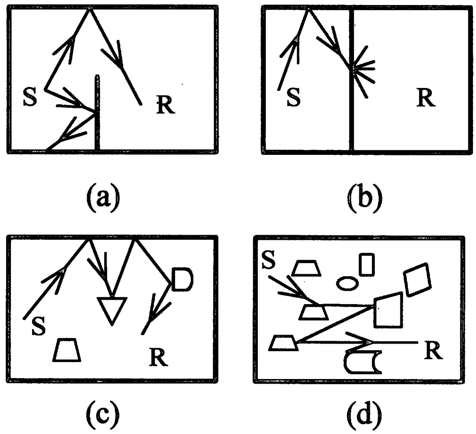

Figure 2. Various barriers: (a) partial screens; (b) insulative wall; (c) a small number of irregular barriers; (d) a large number of irregular barriers.

It emphasizes the inverse wavelength relationship and is only useful as an estimate since the distance is vital to the desired end result.

3.2. INSULATIVE WALLS

When a partial wall becomes large enough, it will separate the enclosure into two small spaces. See Figure 2(b). In this case, the barrier is an insulative wall. There are two possible cases:

Case 1: The receiver and the source are in the same space. In this case, we need not consider the sound propagation in another space. The processing method is the same as that of empty room.

Case 2: The receiver and the source are in different spaces. In this case, we have to consider the effect of the insulative wall. Equivalent sources are used for this case. First we trace the rays in the space in which the source lies and calculate the intensity of a number of receivers very close to the insulative wall. These receivers are regarded as sound sources for another space. They radiate hemispherically with the main axis according to the normal of the wall. The energy of such an equivalent source can be calculated from the area and the insulation coefficient of the wall and the sound intensity at the excitation side:

$$W = IS(1 - t), \tag{10}$$

where W is the sound energy of the equivalent source, I the sound intensity of the excitation side, and t the insulation coefficient of the wall.

3.3. A SMALL NUMBER OF IRREGULAR BARRIERS

See Figure 2(c). Because the number of barriers is small and their positions are known, the propagation of every ray can be exactly traced. In our program, each barrier is substituted by an equivalent object, which has the same volume as it.

If a ray hits a barrier, a new ray will emit from the center of the equivalent object. We define its new direction in a random way. To determine its energy, a random number

r between 0 and 1 is generated by the computer at first. Then it is compared with the absorption coefficient of the barrier. If r is lower than the absorption coefficient, the energy of the ray is regarded as being totally absorbed. On the contrary, its energy is looked as changeless. This simple statistical method is used to describe the absorptive characteristics of the irregular barriers.

If a ray hits a wall, the treatment is like that in the empty room.

3.4. A LARGE NUMBER OF DISORDERLY DISTRIBUTED BARRIERS

See Figure 2(d). This case is very common. For instance, in a workshop, there might be many machines and other sundries. Most of them are placed disorderly and some of them are very complicated in shape. It is difficult to trace each ray exactly in this case. We follow the statistical method recommended by Kuttruff [15, 16].

Firstly, we calculate the mean free path between obstacles according to the following equation:

$$\bar{L} = \frac{4V}{\bar{S}}, \tag{11}$$

where $\bar{L}$ is the mean free path, V is the total volume of the barriers and the enclosed field. $\bar{S} = \sum_{k-1}^{N} S_k$, S_k is the area of the kth obstacle.

The scattering process can be described by a three-dimensional Poisson process [17], so the free path between barriers after a period of time can be estimated by generating a random number between [0, 1].

$$D = -\bar{L}\ln(r), \tag{12}$$

where D is the free path between barriers, and $r \in [0, 1]$ is a random number.

Before we decide whether a ray has collided with a barrier or a wall of the enclosure, we calculate the shortest distance d_{min} between the ray and the walls in its propagation direction. If $d_{min} > D$, the ray is regarded as having collided with a barrier and the reflected ray can be created in a random way, else it is considered have collided with a wall, and the method of computing reflected ray is the same as that used for empty rooms.

4. COMPUTATION AND DISCUSSION

Firstly, the impulse response of the defined receiver can be modelled and then the sound pressure level can be calculated by the following equation:

$$SPL = 10\,\lg\left(\int_0^{\infty} \rho c I(t)\,\mathrm{d}t/4\times 10^{-10}\right), \tag{13}$$

where SPL is the sound pressure level, ρc is the impedance of the air, and $I(t)$ is the energy decay curve (sound intensity versus time), which can be obtained from the discrete energy impulse response by interpolation.

To validate the program SOFIS, the reverberation room and the anechoic room in our university have been both predicted and measured. The size of the reverberation room is $5{\cdot}75\times 3{\cdot}22\times 4{\cdot}92\ \mathrm{m}^3$, with a loudspeaker, located at (0·6, 0·6. 1·4). The sound power level is 79·6 dB. All the walls were constructed of cement and the absorption coefficient of each wall is taken to be 0·08 when the frequency is 1 kHz. The size of the anechoic room is $3{\cdot}2\times 5{\cdot}6\times 3{\cdot}8\ \mathrm{m}^3$. The model of these two adjacent rooms is shown in Figure 3.

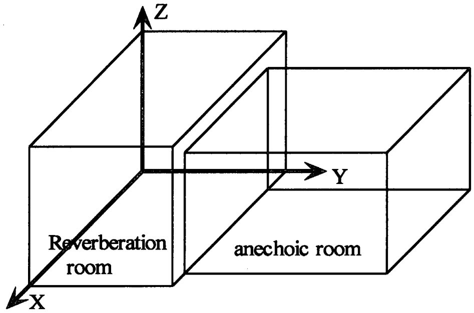

Figure 3. Model of the reverberation room and the anechoic room.

TABLE 1

Predicted and measured results

	Receivers				
	A	B	C	D	E
Co-ordinates	(3, 1·6, 1·2)	(3·8, 2, 1·2)	(4, 1·5, 1·2)	(4, 0·6, 1·2)	(4·6, 1·2, 1·2)
Predicted SPL (dB)	77·2	76·8	74·7	74·4	74·3
Measured SPL (dB)	76·1	75·5	74·3	73·6	73·9

4.1. SCREEN

A thin screen was put in the reverberation room, at the position $X = 3{\cdot}4$m and it is paralleled with the axis Y. The area of the screen is $1{\cdot}75 \times 1{\cdot}45\,\mathrm{m}^2$ and one side of it is a glaze, on which the ray's energy will be totally reflected, and the absorption coefficient of another side is 0·21 (1 kHz). The predicted and measured SPLs of five receivers are shown in Table 1. As can be seen from Table 1, the error between measurement and prediction is about 1·0 dB. This shows that the algorithm for screen modelling is correct.

In order to find the effect of the height of the screen, different screens with the same surface area were used, and the measurement and prediction processes were repeated. Figure 4 shows the predicted SPLs at the same receivers when the height of the screen h is different. It can be found that the height of the screen has little effect on the SPL at receivers A and B. But at receivers C, D and E, the higher the screen is, the lower the SPLs are. This demonstrates that the program can also be used to optimize the screen design for the work of noise control.

4.2. INSULATIVE WALL

We considered the insulative wall between the reverberation room and the anechoic room. Six receivers were put at both sides of the insulative wall and were near the wall surface. Receivers in the reverberation room are labelled 1, 2 and 3. Those at the other side are labelled 4, 5 and 6. At 1 kHz, the transmission coefficient of the wall is 0·42 and this has been implemented in our computer model. Figure 5 shows the predicted and measured results.

It can be found that the predicted average insertion loss of the wall is 19·2 dB. It is about 3 dB lower than the experimental result. The surfaces of the anechoic room being thought as

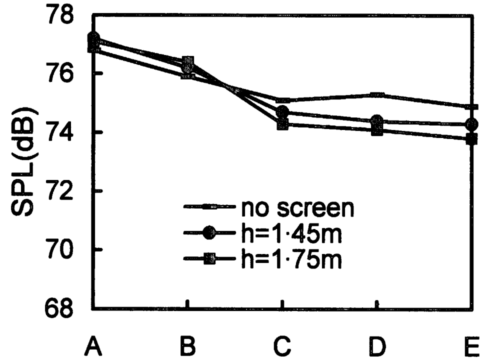

Figure 4. The effect of height of the screen.

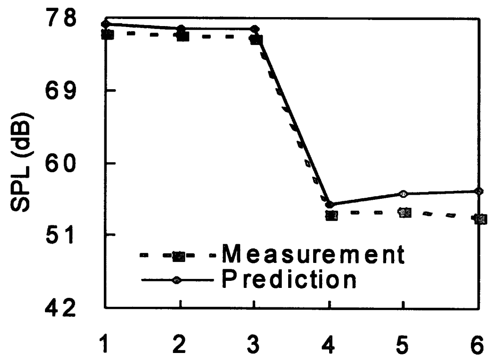

Figure 5. Effect of the insulative wall.

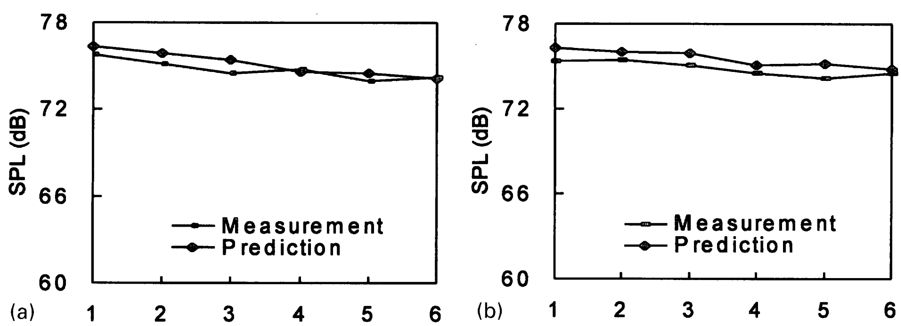

Figure 6. SPLs at six receivers: (a) five barriers; (b) 16 barriers.

totally absorptive might be a cause of error. Though the equivalent source method can only supply approximate results, it still can be used as the reference in noise control work.

4.3. A NUMBER OF IRREGULAR BARRIERS

A number of small irregular objects were put in the reverberation room. The average surface area of them is about $1{\cdot}2\ m^2$. Two cases have been considered. First, we put five chairs in the reverberation room. The predicted and measured results are shown in Figure 6(a). Then, eleven other irregular objects were added into the room. The results in this case are shown in Figure 6(b).

We can find that the difference between the results obtained from measurement and prediction in both cases are < 2 dB. It can also be found that the differences among various receivers decrease with the increase of barrier number. This is reasonable because the irregular sound barriers can add the diffused reflections within the reverberation room. Therefore, more sound barriers will mean a more even sound distribution. The above results have shown that our model is applicable for the situation of a number of irregular sound barriers.

5. CONCLUSIONS

This paper has described the principle and the algorithm of a computer program, SOFIS. Various barriers have been studied based on this program. The comparison between prediction and measurement in a reverberation room and an anechoic room has shown that the algorithms described in this paper can correctly model the behaviors of various barriers.

For irregular sound barriers the statistical method was proved to be very accurate. However, the computation time will increase with the increase of barrier number. In the case of screen, it can be seen that the higher the screen is, the more the sound loss generated. This can be used to design the sound screen in noise control work. For another kind of barrier, the insulative wall, only the effect of the exciting side on the receiving side has been considered, thus the results are approximate and mainly used as a reference.

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