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A computer simulation model for room sound field considering diffuse reflection*

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Abstract—A multiple random ray-tracing model was developed for predicting the distribution of sound pressure levels in an enclosed space of any shape. This model considered two diffuse factors of a room: diffuse reflection due to room surfaces and scattering due to objects. The surface diffusion was treated by two different methods on the basis of probability analysis, and the scattering was simulated by a multiple random ray-tracing process. Thus the sound pressure level distribution in a diffuse sound filed can be calculated more precisely.

Keywords: diffuse reflection, room sound filed, computer simulation.

1 Introduction

Since first paper published in 1958, computer simulation technique for room acoustics has developed a lot. It plays a very important role in the research of sound propagation, in the prediction of room acoustical property, as well as in the practice of noise control and acoustical design. Especially since 1980's, some new models have been proposed for more precisely simulating sound fields to realize auralization. At present, there are two main methods for describing sound propagation in an enclosed space, namely, ray-tracing model and image source model. But usually these models only consider specular reflection on room surfaces, so their discrepancy from real conditions is considerable. Hodgson (Hodgson, 1991) has made some comparisons between computer prediction and measurements in an empty scale-model room, various empty factories and gymnasia. Consistent deviations between predictions and experiments were found. For improving the prediction, he proposed that there should be 10%-40% diffuse reflections on the surfaces of the scale-model room, and 60%-90% diffuse reflections in the empty factories. It can be seen that diffuse reflection is a very important phenomenon and can not be ommited. Recently, some new models considering diffusion have been proposed. One of them describes sound reflection process as that a part of incident sound energy is reflected secularly, and the remainder diffusely. The diffuse reflection is assumed to follow a stochastic process(Kuttruff, 1980). Another model assumes that diffuse sound is radiated from diffuse image sources which are located in a range(Dalenback, 1992; Borish, 1984). There are also some methods that combine both ray-tracing and image source model, such as early part image source and late part-tracing model(Heinz, 1993), early part hybrid method and late part ray-tracing(Naylor, 1992).

On the other hand, in most workshops or offices, there are many machines, equipments and furniture, so that sound propagation becomes more complicated. Not only the sound waves are reflected and absorbed by the wall surfaces, but also they are scattered by the objects in them. Sound propagation is then shown as a multiple scattering process. Kuttruff (Kuttruff, 1991) indicated two methods of increasing the diffuseness of a room. They are diffuse reflection on surfaces and scattering among objects. This means that the effect of scattering on the propagation

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of sound is also very important. Hodgson(Hodgson, 1994) has also discussed the importance of these two factors. To describe the multiple scattering of noise in urban area, Leschnik(Leschnik, 1980) developed a random ray-tracing model. This model only considered the scattering due to randomly distributed objects, but did not include the reflection and absorption on boundaries. In this paper, a 3-D(3 dimensional) random ray-tracing model and computer simulation technique are developed to describe sound propagation in enclosed spaces, considering both diffuse factors: diffuse reflection on room surfaces and scattering among objects. The surface diffusion is treated by using two different methods, and the scattering is simulated as a randomly scattering process.

2 Diffuse reflection on room surface

For describing a diffusing surface, a diffusion factor d is used to account for the fraction of incident energy to be diffused. The relation between absorbed, diffused and secularly reflected energy on the surface is then:

$$\alpha + d(1-\alpha) + (1-d)(1-\alpha) = 1, \tag{1}$$

where α is the absorption coefficient.

For a partly diffuse reflection, a random number γ between(0, 1) is first generated. If $\gamma \leqslant d$, the ray will be reflected diffusely, and if $\gamma > d$, the ray will be reflected specularly.

For the specularly reflected ray, the reflection angle is equal to the incident angle. If the incident direction is described as directional angle(α_0, β_0, γ_0), the reflection angle is then given by:

$$\begin{cases} \cos\alpha_1 = \cos\alpha_0 - 2\cos\theta\cos\alpha_n \\ \cos\beta_1 = \cos\beta_0 - 2\cos\theta\cos\beta_n \\ \cos\gamma_1 = \cos\gamma_0 - 2\cos\theta\cos\gamma_n, \end{cases} \tag{2}$$

where θ is the included angle between the incident ray and the normal line of the surface, which can be determined as

$$\cos\theta = \cos\theta_0\cos\alpha_n + \cos\beta_0\cos\beta_n + \cos\gamma_0\cos\gamma_n, \tag{3}$$

where(α_n, β_n, γ_n) are the directional angles of the normal line of the surface.

For the part of diffuse reflection, we use following two simulation methods.

2.1 Uniform diffuse reflection

In this method, reflected rays are assumed to be radiated uniformly. In other words, for a given reflected ray, its reflection angle is randomly decided. Its probability of being reflected to any direction follows an uniform distribution(Fig. 1).

Based on such a probability analysis, we divide the latitude angle [0, $\pi/2$] into M parts, and the reflection angle can be described as:

$$\theta_i = \frac{\pi}{2} \times \frac{i}{M}, \tag{4}$$

where θ_i is the included angle between the surface normal line and the reflected ray.

If a random number r is generated among (0, 1), and $\frac{i-1}{M} < r < \frac{i}{M}$, the ray should be reflected along θ_i direction, and θ_i can be easily changed to directional angles (α_i, β_i, γ_i).

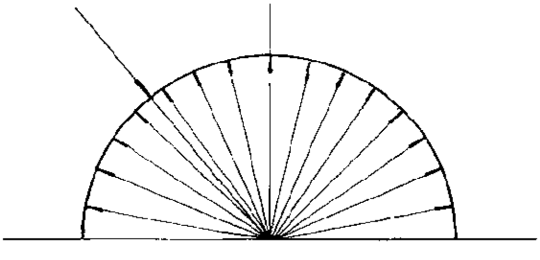

Fig. 1 Uniform diffuse reflection

2.2 Diffuse reflection according to Lambert Law

Using Lambert function to treat diffuse reflection is a common method. It can be described as:

$$I_\theta = I_0 \times \cos\theta, \tag{5}$$

where I_0 denotes the reflection energy along the surface normal line, and I_θ is the reflection energy along θ direction (Fig. 2).

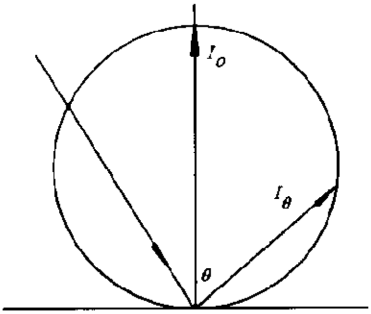

Fig. 2 Diffuse reflection according to Lambert Law

It can be seen from Fig. 2 that along the direction of surface normal line, the reflection energy is the strongest, and the bigger the angle θ is, the smaller the reflection energy is. As to a given incident ray, the probability distribution of its reflection direction is not uniform. It would be reflected most probably along the surface normal line, and as the reflection angle deviated, the probability of being reflection along this angle would be decreased. On the basis of the above analysis, we developed a new simulation method. If the biggest probability is present as p_0 which is happened along the surface normal line, the probability with which a ray is reflected along angle θ_i is given by:

$$P_{\theta_i} = P_0 \cos\theta_i. \tag{6}$$

The total probability along reflection direction should be unit. If we divide the range $[0, \pi/2]$ into M parts, the reflection angle θ_i may also be described as Eq. (4).

$$\text{Since: } \sum_{i=0}^{M} P_{\theta_i} = 1, \tag{7}$$

$$\text{then: } P_0 \times \sum_{j=0}^{M} \cos\left(\frac{\pi}{2} \times \frac{j}{M}\right) = 1, \tag{8}$$

$$P_0 = \frac{1}{\sum_{j=0}^{M} \cos\left(\frac{\pi}{2} \times \frac{j}{M}\right)}, \tag{9}$$

$$\text{and } P_{\theta_i} = \frac{\cos\left(\frac{\pi}{2} \times \frac{i}{M}\right)}{\sum_{j=1}^{M} \cos\left(\frac{\pi}{2} \times \frac{j}{M}\right)}. \tag{10}$$

For a random number r between (0, 1), if, $\sum_{j=0}^{k-1} P_{\theta_j} < r < \sum_{j=0}^{k} P_{\theta_j}$, then θ_k is the reflection angle, and $\theta_k = \frac{\pi}{2} \times \frac{k}{M}$.

3 Scattering among objects

Before a sound ray hits a surface, it may hit a scatter first, such as furniture, machine, etc. The scatterer density n in a room is given by;

$$n = N/V, \tag{11}$$

where N is the number of the scatterers in the room and V is the volume of the room. The surface density of scatters in the room can be determined by:

$$n_Q = \frac{1}{4V}\sum_{i=1}^{N} S_i, \tag{12}$$

where S_i is the surface area of i th scatterer. The mean free length $\bar{\gamma}$ between the scatterers, which is also the distance that a sound ray travels between two arbitrary objects, is given by Leschnik (Leschnik, 1980):

$$\bar{\gamma} = 1/n_Q, \tag{13}$$

In general, the distribution of scatterers in a room is not regular, and the number of scatterers is quite big, so it is very difficult and not necessary to definitely trace the sound ray among these objects. In this paper, we use the model developed by Leschinik (Leschinik, 1980) for the conditions of urban and forest areas, and we add the boundary condition of a room in. Thus, the location of objects obeys a 3-D Poisson distribution and the distance R travelled by a ray between two objects has the form:

$$R = -\ln(r)/n_Q = [-\ln(r)]\bar{\gamma}, \tag{14}$$

where r is a random number between (0, 1). When R is smaller than the distance traveled by the ray from initial point to a room surface, the ray will hit an object first, and its further propagation direction is in dependent of its incident direction, and can be determined according to Eq. (15)-(16):

$$\begin{cases} \theta = \arccos r_1 \\ \varphi = 2\pi r_2 \end{cases}, \tag{15}$$

$$\begin{cases} \cos\alpha = \cos\theta\sin\varphi \\ \cos\beta = \sin\theta\sin\varphi, \\ \cos\gamma = \cos\varphi \end{cases} \tag{16}$$

where γ_1 and γ_2 are the random number between (0, 1).

4 Multiple random scattering model

The sound source may be placed at any position in a room. It gives out large quantity of sound rays along any direction evenly. Computer will trace each ray one by one. If the ray impinges on a scatterer, it will randomly selected a new traveling direction, with a part of energy being absorbed. If the ray meets a wall of the room, it will be reflected specularly or diffusely, with a part of energy being absorbed too. After undertaking multiple reflection, scattering and absorption on rooms surfaces or scatterers, the sound ray will be withdraw from tracing when its energy is smaller than one set value. The next ray is generated in turn. Finally, by summing up the energy spatial distribution of sound energy in the room.

Whenever a sound ray hits a scatterer, or a room surface, a part of sound energy will be absorbed. After N times impinging, its sound energy becomes:

$$E_N = E_0\prod_{i=1}^{N}(1-\alpha_i), \tag{17}$$

where, E_0 is the initial energy a sound ray carries, α_i is the absorption coefficient of an object or a surface. Once the sound energy is smaller than one set value, computer tracing is stopped and next sound ray is generated. Here we used another method to judge if a ray will be absorbed. Each time, computer generates a random number r between (0, 1) and if $r < \alpha_i$, the sound ray is considered to be absorbed. With a large quantity of rays, both methods are equivalent.

The room is divided into many small cubes, by summing up the numbers of sound rays passing through each cube, and adding the sound energy carried by these rays, the sound energy distribution in 3-D space can be obtained. Computer simulation flow chart is shown in Fig. 3.

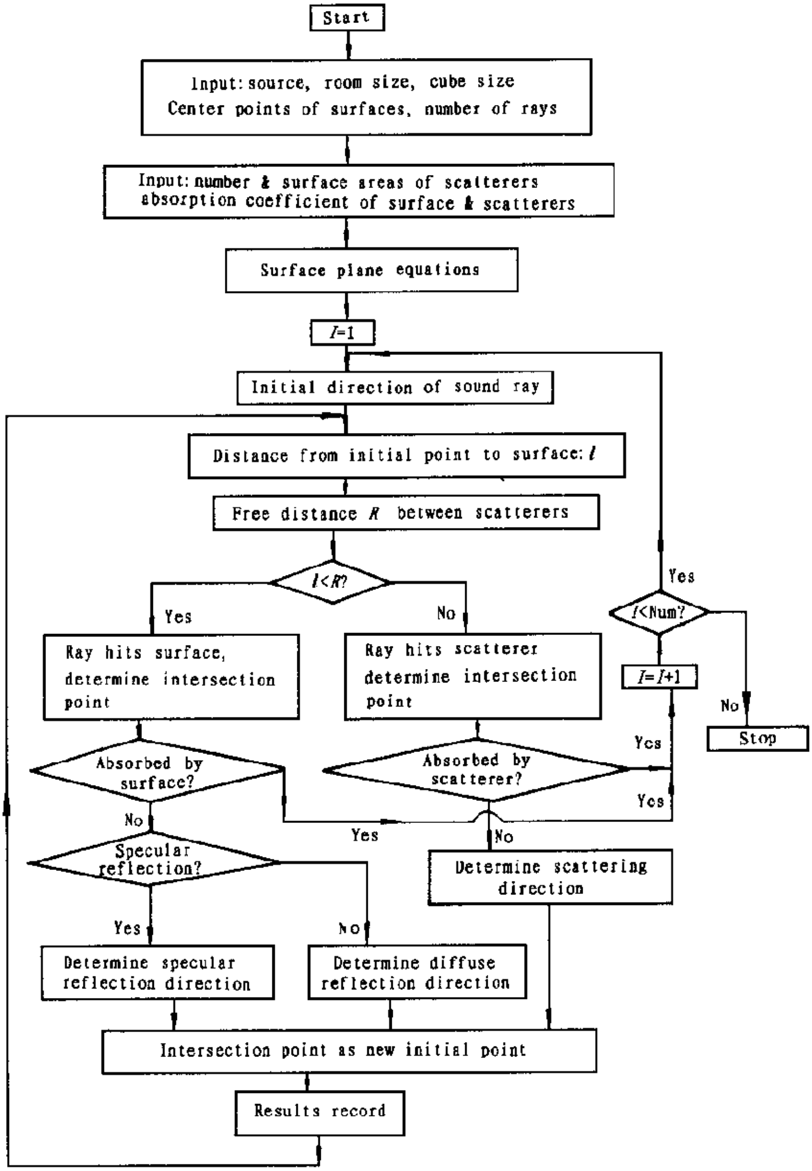

Fig. 3 Flow chart of computer simulation

5 Application

We measured the sound fields of two workshops in Electroacoustic Equipment Plant of Hangzhou, and compared measurements with computer simulation results.

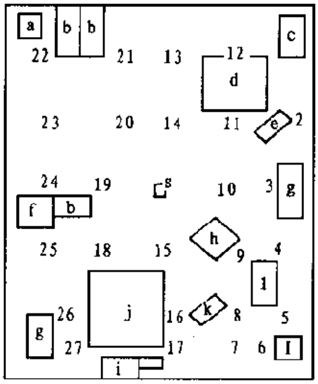

Fig. 4 Plane of workshop 1 and measuring points

a: air conditioner; b: table; c: cabinet; d: machine tool; e: power box; f: cabinet; g: computer desk; h: numeric control machine tool; i: pulse power supply; j: numeric control precision machine tool; k: machine tool; l: printer; s: sound source; 1-27: measuring points

5.1 Workshop 1

The plane of workshop 1 and measuring points are shown in Fig. 4. There are many machines and furniture in the workshop. The size of the room is $12.0 \times 10.4 \times 3.3$ m^3. For calculation, the absorption coefficients of wall surfaces are checked from Architectural Acoustics Handbook according to their materials and constructions, while that of the objects can not be easily obtained, because not only the materials of the machines and furniture, but also their shapes and structures will influence the absorption coefficient. Thus, we assign the coefficients of 0.05-0.15 to these objects. The calculation results showed that the differences are quite small.

The sound field distributions of workshop 1 are calculated by the method of random diffuse reflection and diffuse reflection model according to Lambert Law. It is found that the calculated results mached the measuring results quite well while $d = 0.6$—0.8. For random diffuse reflection, when $d = 0.8$, the mean and maximum deviation from measurement are 0.73 and 2.6 dB; when $d = 0.6$, the mean and maximum deviation from measurement are 1.04 and 2.5 dB. For diffuse reflection according to Lambert Law, when $d = 0.8$, the mean and maximum deviation from measurement are 0.73 and 1.8 dB; when $d = 0.6$, the mean and maximum deviaiton from measurement are 1.02 and 2.2 dB. It can be seen that, the calculation results with big d match the measurements quite well. The results of Lambert diffusion method is a little bit good than the other method, but the difference is so small that we may consider both methods are equally feasible for calculating the sound in fields of such room like workshop with rough walls and many objects in it.

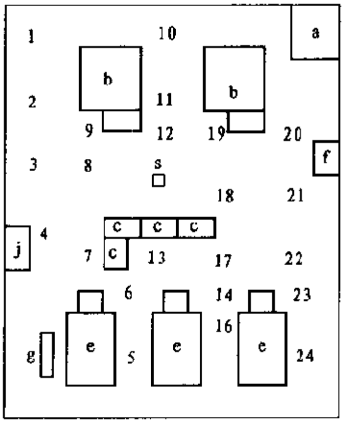

Fig. 5 Plane of workshop 2 and measuring points

a: paper pile; b: forming machine; c: table; d: cabinet; e: machine tool; f: controlling machine; g: working table; s: sound source; 1-24: measuring point

5.2 Workshop 2

The plane of workshop 2 and measuring points are shown in Fig. 5. The size of the room is $10.5 \times 13.7 \times 4.3$ m^3.

The comparison of measurements and calculation results of workshop 2 with the method of random diffuse reflection, and the results calculated by using the diffuse reflection model according to Lambert Law showed that the mean deviations of calculating results from measurements are within 3dB. The same conclusion applies to workshop 1 as well.

6 Conclusions

Sound propagation in some rooms such as workshops and offices follows a complicated multiple random scattering process. In these rooms, sound waves are not only submitted to be reflected and absorbed on wall surfaces, but also to be scattered by obstacles such as machines and furniture. The diffuseness of the room is caused by both diffuse reflection on room surfaces and scattering among objects. The 3-D random acoustic ray-tracing model present in this paper considers both diffuse factors together. It will describe the actual sound propagation process more precisely and easily. This model can be applied to noise control and acoustical design practice.

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