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COMPUTER SIMULATION MODEL FOR ROOM DIFFUSE SOUND FIELD

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Abstract: With the development of computer simulation technique for room acoustics, diffuse reflection is considered more and more important. In this paper, some models are developed by considering two diffuse factors in a room-diffuse reflection due to room surfaces and scattering due to objects. The surface diffusion is treated by two different methods on the basis of probability analysis or Energy Conservation Law, and the scattering among objects is simulated as a multiple random ray-tracing process. Thus the sound pressure level distribution in a diffuse sound field can be calculated more precisely and easily. Agreement between the computer simulation results and measurements shows the accuracy of the mathematical and physical model and the applicability of the computer simulation methods. These models can be used in noise control engineering, as well as in the practice of acoustical design.

Key words: diffuse reflection, room sound field, computer simulation
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INTRODUCTION

With the development of computer simulation technique for room acoustics, new models have been proposed for more precisely simulating sound fields to realize auralization. The computer has played a very important role in the research on sound propagation, in the prediction of room acoustical property, as well as in the practice of noise control and acoustical design. 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(1991) compared computer predictions and measurements in an empty scale-model room, and in various empty factories and gymnasia, and found deviations between predictions and experiments. 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 that can not be disregarded. Some new models considering diffusion have been proposed recently. One of them describes sound reflection as a process wherein a part of incident sound energy is reflected specularly, and the remainder diffusely. The diffuse reflection is assumed to follow a stochastic process (Kuttruff et al, 1980). Another model assumes that diffuse sound is radiated from diffuse image sources located in an extended range (Dalenback, 1992, Borish, 1984). There are also some methods that combine both ray-tracing and image source models, such as early part image source and late part ray-tracing model (Heinz, 1993), early part hybrid method and late part ray-tracing (Naylor, 1992), etc.

Sound propagation is more complicated in workshops or offices having many machines, equipment and furniture, as the sound waves are not only reflected and absorbed by the wall surfaces, but are also scattered by the objects in them. Sound propagation is then shown as a multiple scattering process. Kuttruff (1991) proposed two factors for increasing the diffuseness of a room: the diffuse reflection on the surfaces and the scattering among objects. This means that the effect of scatterers on sound propagation is also very important. Hodgson (1994) also discussed the importance of these two factors. Leschnik (1980) developed a random ray-tracing model to describe the multiple scattering of noise in urban area. This model only considered the scattering due to randomly distributed objects, but did not include the reflection and absorption on boundaries.

In this work, some computer simulation models were developed to describe sound propagation in enclosed spaces, by considering the diffuse reflection on room surfaces and the scattering among objects. The surface diffusion is treated by two different methods, and the scattering is simulated as a randomly scattering process.

DIFFUSE REFLECTION ON ROOM SURFACES

In general, reflection on room surfaces can be treated as partial diffuse reflection. This means that a part of the reflected energy is reflected specularly and the remainder diffusely. 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 specularly reflected energy on the surface is then:

$$\alpha + d(1-\alpha) + (1-d)(1-\alpha) = 1 \qquad (1)$$

where α is the absorption coefficient.

In computer simulation, a random number r between $(0,1)$ is first generated. If $r \leqslant d$, the ray will be reflected diffusely, and if $r > d$, 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 by directional angles $(\alpha_0, \beta_0, \gamma_0)$, the reflection direction can be decided from:

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

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

$$\cos\theta = \cos\alpha_0\cos\alpha_n + \cos\beta_0\cos\beta_n + \cos\gamma_0\cos\gamma_n \qquad (3)$$

where $(\alpha_n, \beta_n, \gamma_n)$ are the directional angles of the normal line of the surface.

For the diffuse reflection, we use following two simulation methods:

1. **Diffuse reflection according to Lambert Law based on probability analysis**

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

$$I_\theta = I_0 \times \cos\theta \qquad (4)$$

where I_0 denotes the reflection intensity along the surface normal line, and I_θ is the intensity along θ direction, see Fig. 1.

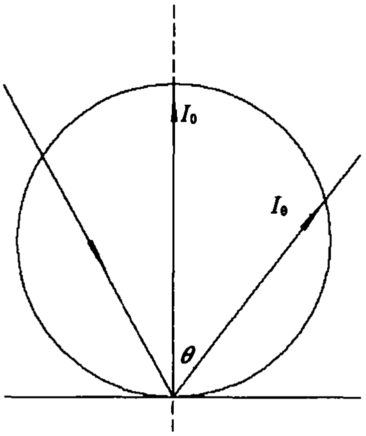

Fig. 1 Diffuse reflection according to Lambert Law

It can be seen that along the direction of the normal line, the reflection intensity is the strongest, and that the bigger the angle θ, the smaller is the reflection intensity. For a given incident ray, the probability distribution of its reflection direction is not uniform. It would be reflected most probably along the normal line, and as the reflection angle deviated, the probability of being reflected along this angle would be decreased. On the basis of the above analysis, we develop a new simulation method. If the highest probability that a ray is reflected along the surface normal line is P_0, the probability that a ray is reflected along angle θ_i is given by:

$$P_{\theta_i} = P_0\cos\theta_i \qquad (5)$$

The total probability along all reflection directions should be unity. If we divide the range $\left[0, \frac{\pi}{2}\right]$ into M parts, the reflection angle θ_i may also be described as Eq. (6).

$$\theta_i = \frac{\pi}{2} \times \frac{i}{M} (i = 0, 1, 2, \cdots\cdots, M) \qquad (6)$$

$$\text{Since: } \sum_{j=0}^{M} P_{\theta_j} = 1 \qquad (7)$$

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

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

and: $$P_{\theta_i} = \frac{\cos\left(\frac{\pi}{2}\times\frac{i}{M}\right)}{\sum_{j=0}^{M}\cos\left(\frac{\pi}{2}\times\frac{j}{M}\right)} \qquad (10)$$

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

2. Hybrid model of image source method and diffuse surface integration

Chien and Carroll (1980) has suggested a method to describe the diffuse reflection on rough surfaces caused by a single point source. Wu and Kittinger (1995) combined this model with traditional image source model to simulate the sound propagation in urban streets (with densely distributed buildings along two sides), which can be used in the prediction of city transportation noise. Here, we apply this model in an enclosed space, adding the absorption and reflection (both specularly and diffusely) of room surfaces.

In Fig. 2, when the sound waves are totally reflected diffusely, that is $d = 1$, the energy density E_{diff} of diffuse reflection received by receiver R can be obtained through surface integration (Chien et al, 1980):

$$E_{\mathrm{diff}} = \frac{W(1-\alpha)}{2\pi^2 c}\int_s \frac{\cos\theta\cos\theta'\,\mathrm{d}s}{r^2 r'^2} \qquad (11)$$

where W – sound source power;

c – sound velocity;

α – absorption coefficient of surface;

r – distance between element ds and source O;

r' – distance between element ds and receiver R;

θ – incident angle of element ds;

θ' – diffuse reflection angle of element ds.

The sound energy of partial diffuse reflection can be described as:

$$E_{\mathrm{diff}} = \frac{W(1-\alpha)d}{2\pi^2 c}\int_s \frac{\cos\theta\cos\theta'\,\mathrm{d}s}{r^2 r'^2} \qquad (12)$$

where d is the diffuse factor of the surface.

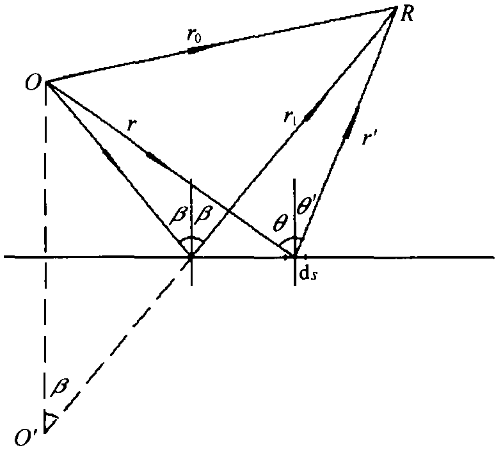

Fig. 2 Sound source and receiver beside a diffuse wall

In this case, the sound energy density at R is:

$$E = \frac{W}{4\pi c r_0^2} + \frac{W}{4\pi c}\frac{(1-\alpha)(1-d)}{r_1^2} + \frac{W(1-\alpha)d}{2\pi^2 c}\int_s \frac{\cos\theta\cos\theta'\,\mathrm{d}s}{r^2 r'^2} \qquad (13)$$

where r_0 – distance between O and R;

r_1 – distance between image source O' and R.

The first, second and third terms of Eq. (13) are the contributions of direct sound, specular reflection and diffuse reflection respectively. The total sound energy density at point R can be obtained by summing the above items from the source and all image sources, which is:

$$E = \frac{W}{4\pi c r_0^2} + \sum_{i=1}^{N}\frac{W}{4\pi c}\frac{(1-\alpha_i)(1-d_i)}{r_{1i}^2} + \sum_{i=1}^{N}\frac{W(1-\alpha_i)d}{2\pi^2 c}\int_{s_i} \frac{\cos\theta_i\cos\theta'_i\,\mathrm{d}s_i}{r_i^2 r_i'^2} \qquad (14)$$

where r_{1i} – distance from the image source of ith wall to R;

r_i – distance from the element of ith wall ds_i to source O;

r'_i – distance from the element of ith wall ds_i to R;

θ_i – incident angle of element ds_i;

θ'_i – diffuse reflection angle of element ds_i ;

N – number of walls of the room.

For surfaces, we may calculate the numerical result of the above equation. If the ith surface is divided into m elements, then:

$$\int_{s_i} \frac{\cos\theta_i \cos\theta'_i \, ds_i}{r_i^2 r_i'^2} = \sum_{j=1}^{m} \frac{\cos\theta_{ij}\cos\theta'_{ij}\Delta s_{ij}}{r_{ij}^2 r_{ij}'^2} \qquad (15)$$

where θ_{ij} – incident angle of the jth element on ith surface;

θ'_{ij} – diffuse reflection angle of the jth element on ith surface;

r_{ij} – distance from the jth element on ith surface to O;

r'_{ij} – distance from the jth element on ith surface to R;

Δs_{ij} – area of the jth element on the ith surface.

Thus, Eq.(14) can be rewritten as:

$$E = \frac{W}{4\pi c r_0^2} + \sum_{i=1}^{N} \frac{W}{4\pi c}\frac{(1-\alpha_i)(1-d_i)}{r_{1i}^2} + \sum_{i=1}^{N} \frac{W(1-\alpha_i)d}{2\pi^2 c}\sum_{j=1}^{M}\frac{\cos\theta_{ij}\cos\theta'_{ij}\Delta s_{ij}}{r_{ij}^2 r_{ij}'^2} \qquad (16)$$

SCATTERING AMONG OBJECTS

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

$$n = N/V \qquad (17)$$

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

$$n_Q = \frac{1}{4V}\sum_{i=1}^{N} S_i \qquad (18)$$

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

$$\bar{r} = 1/n_Q \qquad (19)$$

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 Leschnik (1980) for the conditions of urban and forest areas, and include the boundary condition of a room in it. Thus, the location of objects follows 3-D Poisson distribution, and the distance R traveled by a ray between two objects is as follows:

$$R = -\ln(r)/n_Q = [-\ln(r)]\bar{r} \qquad (20)$$

where r is a random number between (0, 1). When R is smaller than the distance traveled by the ray from the initial point to a room surface, the ray will hit an object first, and its further propagation direction is independent of its incident direction, and can be determined according to Eq.(21) – (22):

$$\begin{cases} \theta = \arccos r_1 \\ \varphi = 2\pi r_2 \end{cases} \qquad (21)$$

$$\begin{cases} \cos\alpha = \cos\theta\sin\varphi \\ \cos\beta = \sin\theta\sin\varphi \\ \cos\gamma = \cos\varphi \end{cases} \qquad (22)$$

where r_1 and r_2 are two random numbers between 0 and 1.

APPLICATION

We measured the sound fields of two workshops in the Electroacoustic Equipment Plant of Hangzhou, and compared measurements with computer simulation results. (1) Workshop 1: The plan of workshop 1 and measuring points are shown in Fig. 3. There are many machines and furniture in the workshop. The size of the room is 12.0 × 10.4 × 3.3 m^3. (2) Workshop 2: The plan of workshop 2 and measuring points are shown in Fig. 4. The size of the room is 10.5 × 13.7 × 4.3 m^3.

The absorption coefficients of wall surfaces could be obtained from the Architectural Acoustics Handbook, but those of the objects could not be easily obtained. As the materials and the shapes and structures of the machines and furniture influence the absorption coefficient, we assign coefficients of 0.05 – 0.15 to these objects.

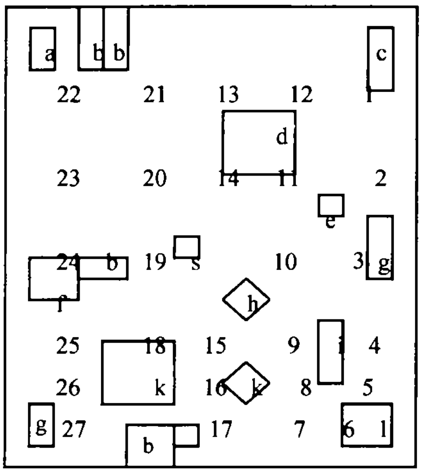

Fig. 3 Plan of Workshop 1 and measuring points
a: air conditioner; b: table; c: cabinet; d: machine tool; e: power box; f: cabinet; g: computer desk; h: numeric control machine tool; i: power box; j: machine tool; k: machine tool; l: printer; s: sound source; 1 – 27: measuring points

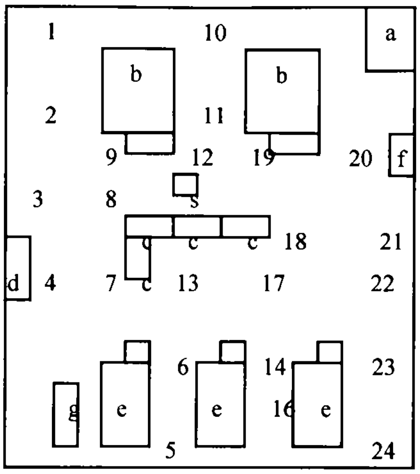

Fig. 4 Plan of Workshop 2 and measuring points
a: paper pile; b: forming machine; c: table; d: cabinet; e: machine tool; f: controlling machine; g: working table; s: sound source; 1 – 24: measuring points

Calculation results are shown in Fig. 5 – Fig. 6, showing that:

1. The calculation results by traditional ray – tracing model deviate by about 3dB ~ 4dB from measurements generally. The maximum deviation was about 5dB. After taking into account the effect of diffuse reflection on room surfaces, the accuracy of the calculation was raised, especially when $d = 0.6 - 0.8$. For Workshop 1, use of the Lambert model based on probability analysis (model 1) showed that when $d = 0.6$ and 0.8, the mean deviations from measurements were 1.81 dB and 1.83 dB respectively, and maximum deviations were 3.2 dB and 3.1 dB. For Workshop 2, when $d = 0.6$ and 0.8, the mean deviations are 1.92dB and 1.87dB, the maximum deviations were 3.3 dB and 3.2 dB. Use of the surface integration model (model 2) showed that the mean and maximum deviations were 1.9 dB and 2.6 dB for Workshop 1; 1.9 dB and 2.7 dB for Workshop 2.

2. When both diffuse reflections on room surfaces and among objects were taken into account (model 3), the calculation results become better. When $d = 0.8$, the mean and maximum deviations were 1.04 dB and 2.6 dB for Workshop1 and 1.45 dB and 2.5 dB for Workshop 2.

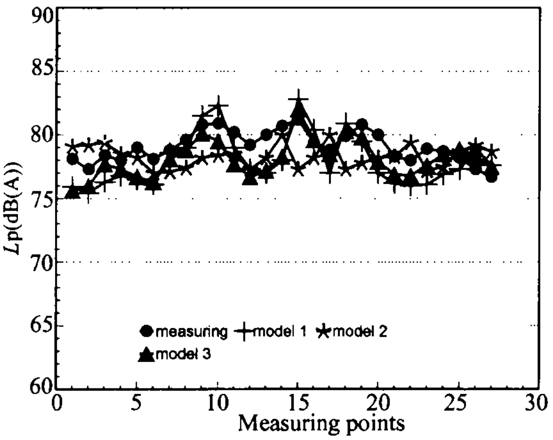

Fig. 5 Calculation results for Workshop 1

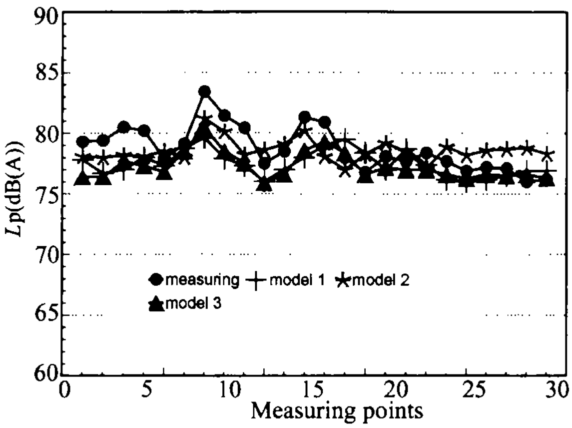

Fig. 6 Calculation results for Workshop 2

CONCLUSIONS

Sound propagation within some rooms such as workshops and offices undergoes a complicated multiple random scattering process. Inside these rooms, sound waves are reflected and absorbed on wall surfaces, and also scattered by obstacles such as machines and furniture. The diffuseness of a room is due to both diffuse reflections on surfaces and scattering among objects. The random acoustic ray-tracing model presented in this paper considers both diffuse factors together, easily and precisely describes the actual sound propagation process. This model can be applied to noise control and acoustical design practice. From the computer simulation results, the following conclusions can be drawn:

1. The traditional ray-tracing model and image source model do not consider any diffuse factors, so they cause considerable deviations of calculation results from measured results.
2. Application of Lambert Law to treat the factor of diffuse reflection on room surfaces can raise the accuracy of calculation.
3. The hybrid method of image source and surface integration also considers the diffuse reflection on room surfaces, and so, can improve the calculation accuracy too. This method is based on the Energy Conservation Law, and its calculation accuracy is influenced by the number of surface elements which is circumscribed by computer capacity.
4. If both diffuse reflections on room surfaces and among objects are considered together, the calculation results match measurements better, which shows the necessity of considering the two diffuse reflection factors in computer simulation. The method presented in this paper is more suitable for simulating those rooms with many scattered objects inside.

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