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A framework for characterizing sound field diffusion based on scattering coefficient and absorption coefficient of walls

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ABSTRACT

This paper describes the development of a theoretical framework for quantitatively characterizing sound field diffusion based on scattering coefficient and absorption coefficient of walls. The concepts of equivalent scattering area, equivalent scatter reflection area, average scattering coefficient and average scatter reflection coefficient are introduced in order to express all walls' capability of scatter in a room. Using these concepts and the mean free path, scatter-to-absorption ratio, mean scatter time and diffusion time are defined in order to evaluate degree of diffusion of a space. Furthermore the time variation of specular and scattered components in a room impulse response is formulated. The verification of these characterization methods was performed with computer simulations based on the sound ray tracing method. The results supported that the ideas presented are basically valid.

INTRODUCTION

Regarding room acoustic design, the scattering capabilities of wall surface is as important a design factor as absorption of walls, particularly with regards to the ensuing diffusion of the sound field inside the space. Therefore, various methods of evaluating the wall surface diffusion have been proposed [1-7]. However, a theoretical framework that relates the wall surface diffusion to diffusion of the sound field has not been systematized, while there is a theory regarding the relationship between surface absorption and reverberation time. The main purpose of this study is to clarify the causal relationship between the scattering coefficients of walls [2-5] and physical properties of the sound field. This paper focuses especially on how to express the diffusion of a sound field with the scattering coefficient used as the parameter.

It is well known that there exists general statements on diffuse sound fields from various aspects, such as spatial distribution and flow direction of acoustic energy, spatial correlation etc [8-16]. This paper treats mainly the following concept as the diffusion of sound field. Usually a wall diffusely scatters only a certain fraction of the incident sound whereas the remaining part of it is reflected into specular directions. In each reflection some specular sound energy is converted into non-specular energy, whereas the reverse process, the conversion of diffuse energy into specular energy, never occurs. As a result, this conversion contributes to sound field diffusion. Based on this concept Kuttruff [17] has investigated the conversion of specular energy into diffuse energy during subsequent reflections in equal time intervals. Kuttruff used the scattering coefficient of each reflection in his discussion. Although he might have considered this scattering coefficient as an average value of all walls' coefficients, he did not give a specific definition to the average scattering coefficient. And the method of calculating the average scattering coefficient has not been clarified in his works.

When one evaluates sound field diffusion by using the concept of conversion of specular energy to diffuse energy, if the sound field in a room consists of perfectly diffusing walls the sound field reaches a perfect diffusion state immediately after only one reflection because all the reflected sound is diffuse energy. However, in fact perfect diffusion of the sound field might not be able to be achieved only by one reflection. Even if the room consists of perfectly diffusing walls, several reflections are presumably needed in order to approach perfect diffusion. Therefore in this paper, following concept is introduced in addition to the concept of conversion of specular energy into diffuse energy. After sound energy is scattered and becomes diffuse energy, the energy is repeatedly scattered in certain time intervals until absorbed. The sound field diffusion is progressed by repeated scattering and shorter intervals contribute more to the diffusion.

Therefore this paper describes the development of a theoretical framework for characterizing sound field diffusion based on the concepts stated above. The author proposes the concepts of equivalent scattering area and average scattering coefficient to express diffusion of a sound field [18]. Sound field diffusion is consequently influenced not only by scattering coefficients but also by absorption coefficients. Next the effect of both scattering coefficient and sound absorption coefficient is formulated. Furthermore some evaluation indexes on sound field diffusion are proposed. Finally computer simulations are done in order to verify these formulations and the indexes.

PROBABILISTIC INTERPRETATION OF SOUND ABSORPTION AND SCATTERING COEFFICIENT ON WALLS

Let us consider sound absorption coefficient α and scattering coefficient β as shown in Fig. 1 as parameters for expressing the reflective property of a surface. Both the sound absorption coefficient and scattering coefficient are assumed here as random incident values unless otherwise noted. The sound absorption coefficient, which is defined as the ratio of absorbed sound energy to incident sound energy, can also be construed as the probability that the incident sound energy is absorbed. In the same way, the scattering coefficient can be construed as the probability that reflected sound energy is scattered. Both the probability that sound energy is reflected and the probability of a scatter reflection have values ranging between 0 and 1. Note that the scattering coefficient is the probability that sound energy is scatter reflected, given that it is reflected and not absorbed. The probability that an incident sound is scatter reflected is $(1-\alpha)\beta$, which is the product of the reflection coefficient $(1-\alpha)$ and scattering coefficient β. The probability that an incident sound is specularly reflected can be described as $(1-\alpha)(1-\beta)$;therefore, the following equation results:

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

Now, let us define the ratio of scatter reflected energy to incident sound energy, i.e. the probability that an incident sound is scatter reflected $(1-\alpha)\beta$, as scatter reflection coefficient γ, which is different from the scattering coefficient. In the same way we also define the specular reflection coefficient, μ, which is the probability that an incident sound is specularly reflected $(1-\alpha)(1-\beta)$.

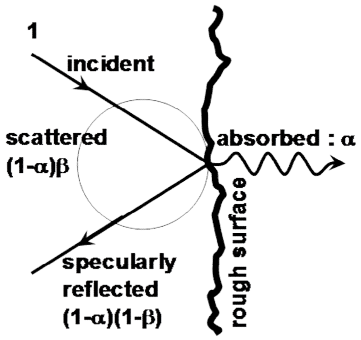

Figure 1. Sound absorption and scattering on a wall

RELATIONSHIP BETWEEN SCATTERING COEFFICIENTS OF WALLS AND DIFFUSION IN A SOUND FIELD

In this section, diffusion of the sound field without considering surface absorption is discussed.

Equivalent scattering area and average scattering coefficient

Equivalent scattering area B is defined by the following equation, which describes all the walls' capability of scattering.

$$B = \sum \beta_i S_i \tag{2}$$

where S_i and β_i is the surface area and scattering coefficient of the i[th] wall respectively.

Scattering coefficient β_i is construed as the probability that reflected energy is scattered on wall i. To describe the average probability of scattering at each reflection in a whole room consisting of several walls, the average scattering coefficient is defined here.

$$\overline{\beta} = \frac{B}{S} = \frac{\sum \beta_i S_i}{\sum S_i} \tag{3}$$

where S is the total surface area of a room.

Scattering frequency and mean scatter time

As for the mean free path d, which describes the distance interval between reflections as sound waves propagate in a room, the inverse $1/d$ is construed as the average reflection frequency per 1 m of propagation. Thus, $\overline{\beta}/d$ is the average frequency that scattering occurs per unit distance. Meanwhile, d can be described as $4V/S$ with room volume V and total surface area S [19-20]. The average scattering frequency, F_s, is defined here by the following relational equation.

$$F_s = \frac{\overline{\beta}}{d} = \frac{S\overline{\beta}}{4V} = \frac{B}{4V} \tag{4}$$

Sound energy is scattered over and over again. The shorter intervals of these repetitions contribute more to sound field diffusion. In other words, higher F_s contributes more to the diffusion. The inverse of F_s represents the mean scattering free path which is the mean distance from the point where scattering once occurs to the point where the next scattering occurs. Through these discussions mean scatter time, MST, can be defined as below.

$$MST = \frac{1}{F_s c} \tag{5}$$

where c is the speed of sound.

Let us consider sound particles as small energy packets which travel with the speed c in all directions of a room. Each particle is scattered in certain time intervals. MST represents an ensemble average of the time intervals of all the particles. The following relational equation is obtained when Eq. (4) is substituted into Eq. (5).

$$MST = \frac{4V}{S\overline{\beta}c} = \frac{4V}{Bc} \tag{6}$$

The F_s and MST are able to be used as measures of degree of diffusion in the space.

Time variation of the specular reflection component and scattered component

The probability that a sound wave is not scattered after a certain number of reflections is described as

$$P_m = \left(1-\overline{\beta}\right)^m \tag{7}$$

where m is the average number of reflections. When $m=ct/d$ is substituted into Eq. (7) the probability that a sound wave has not been scattered for time t after it was emitted, $P_s(t)$, is described as

$$P_s(t) = \left(1-\overline{\beta}\right)^{\frac{ct}{d}} = \exp\left[\frac{\ln\left(1-\overline{\beta}\right)}{d}ct\right] \tag{8}$$

Eq. (8) is in the same form as the Eyring's reverberation theory shown below.

$$P_a(t) = \exp\left[\frac{\ln\left(1-\overline{\alpha}\right)}{d}ct\right] \tag{9}$$

where $\overline{\alpha}$ is the average absorption coefficient.

As stated previously, the following two parameters play important roles in describing the scattering property of a whole room: average scattering coefficient $\overline{\beta}$ and the mean free path d, which determines the incident probability on walls. The interpretation of Eq. (8) is the decay of the ratio of specularly reflected energy to total energy of reflected sound. It can be understood that the speed of conversion of specular sound energy into scattered energy is faster if this decay is faster. Note that Eq. (8) means the decay of the ratio but not the energy decay. This is different from the reverberation decay due to absorption.

Diffusion time

Eyring's formula of the reverberation time is described as

$$T = \frac{0.163\times V}{S\left\{-\ln\left(1-\overline{\alpha}\right)\right\}} \tag{10}$$

Here the diffusion time, DT, can be defined like the reverberation time. The diffusion time is defined as the time when the ratio of specularly reflected energy to total reflected energy becomes -60dB.

$$DT = \frac{0.163\times V}{S\left\{-\ln\left(1-\overline{\beta}\right)\right\}} \tag{11}$$

The DT as well as MST is able to be used as a measure of degree of diffusion in the space. It means that the speed of conversion of specular sound energy into scattered energy is faster if these measures are shorter. Note that the DT is not decay time from a steady state but decay time in a situation where an impulse sound source is used. The reason is because a specular component and a scattered component already coexist in the steady state before beginning of the decay.

EFFECTS OF SOUND ABSORPTION ON SOUND FIELD DIFFUSION

Because there is always a certain amount of absorption in real sound fields, the influence of the absorption should be included in this framework for characterizing sound field diffusion. Therefore, the next sections discuss the effect of both scattering coefficient and absorption coefficient on the sound field diffusion.

Equivalent scatter reflection area and average scatter reflection coefficient

First, equivalent scatter reflection area, G and equivalent specular reflection area, C, are defined below.

$$G = \sum \gamma_i S_i \tag{12}$$

$$C = \sum \mu_i S_i \tag{13}$$

where γ_i and μ_i is the scatter reflection coefficient and the specular reflection coefficient of the ith wall respectively.

The average scatter reflection coefficient $\overline{\gamma}$ and the average specular reflection coefficient are defined.

$$\overline{\gamma} = \frac{G}{S} = \frac{\sum \gamma_i S_i}{\sum S_i} \tag{14}$$

$$\overline{\mu} = \frac{C}{S} = \frac{\sum \mu_i S_i}{\sum S_i} \tag{15}$$

According to the definition, the relationships S = A + G + C and $\overline{\alpha} + \overline{\gamma} + \overline{\mu} = 1$ are obtained. Eq.(14) means that the average scatter reflection coefficient may not always be the same between two different rooms that may have the same average scattering coefficient and average absorption coefficient. That is, the relation of $\overline{\gamma} = \left(1-\overline{\alpha}\right)\overline{\beta}$ is not always valid. This relation is valid as far as sound absorption and scattering are independent of each other. The same is equally true of the specular reflection coefficient, $\overline{\mu}$.

Equivalent scatter reflection area G describes the walls' capability of scatter when considering the sound absorption. It indicates that the smaller the average absorption coefficient, the larger the scattering capability G. And the average scatter reflection coefficient $\overline{\gamma}$ describes the scattering probability based on incident energy. That is to say, the larger the average sound absorption coefficient, the smaller the average scatter reflection coefficient, $\overline{\gamma}$, even if the sound field has the same average scattering coefficient $\overline{\beta}$. In addition, walls with larger surfaces and a smaller absorption coefficient contribute more to sound field diffusion.

Scattering frequency, mean scatter time and scatter-to-absorption ratio

Scattering frequency, F_s, is obtained by using the average scatter reflection coefficient.

$$F_s = \frac{\bar{\gamma}}{d} \tag{16}$$

And *MST* is obtained as the next equation by using relation of Eq.(5).

$$MST = \frac{4V}{S\gamma c} = \frac{4V}{Gc} \tag{17}$$

At the same time, the absorption frequency, F_a, that absorption occurs per unit distance is defined below.

$$F_a = \frac{\bar{\alpha}}{d} \tag{18}$$

A ratio of F_s to F_a is defined as the scatter-to-absorption ratio, *SAR*.

$$SAR = \frac{F_s}{F_a} = \frac{\bar{\gamma}}{\bar{\alpha}} \tag{19}$$

And *MST* and Sabine's reverberation time, T_{sabine}, are linked in the next equation.

$$SAR = \frac{T_{Sabine}}{13.8 \times MST} \tag{20}$$

The *SAR* has important meanings for the diffusion of sound fields when considering absorption. One of the meanings is an average number of times that a single sound particle is scattered until absorbed, n_s. The $d/\bar{\gamma}$ represents the mean scattering free path, d_s. And the $d/\bar{\alpha}$ represents the ensemble-averaged distance that a single sound particle propagates until absorbed, d_a. Therefore the n_s can be obtained as the *SAR*.

$$n_s = \frac{d_a}{d_s} = \frac{\bar{\gamma}}{\bar{\alpha}} \tag{21}$$

Sound energy density *E*, which contains a direct sound, can be written as the next equation.

$$E \propto \sum_{m=0}^{\infty} \left(1-\bar{\alpha}\right)^m = \frac{1}{\bar{\alpha}} \tag{22}$$

Non-scattered energy density E_n, which contains a direct sound, and scattered energy density, E_s, can be written as below respectively.

$$E_n \propto \sum_{m=0}^{\infty} \bar{\mu}^m = \frac{1}{\left(1-\bar{\mu}\right)} \tag{23}$$

$$E_s \propto E - E_n = \frac{1-\bar{\mu}-\bar{\alpha}}{\bar{\alpha}\left(1-\bar{\mu}\right)} = \frac{\bar{\gamma}}{\bar{\alpha}\left(1-\bar{\mu}\right)} \tag{24}$$

Therefore the ratio of the scattered component to non-scattered component is also calculated as the *SAR*.

$$\frac{E_s}{E_n} = \frac{\bar{\gamma}}{\bar{\alpha}} \tag{25}$$

Decay of specular reflection energy

The decay of the specularly reflected energy, $P_{\text{spec}}(t)$, is described by using the average specular reflection coefficient, $\bar{\mu}$.

$$P_{spec}(t) = \exp\left[\frac{\ln \bar{\mu}}{d} ct\right] \tag{26}$$

This quantity indicates the time variation of probability that sound energy has not been absorbed and scattered.

In addition, the time variation of the scattered sound energy $P_d(t)$ is the remainder of the subtraction where specular reflection energy $P_{spec}(t)$ is subtracted from total reflection energy $P_a(t)$ as shown below.

$$\begin{aligned} P_d(t) &= P_a(t) - P_{spec}(t) \\ &= \exp\left[\frac{\ln\left(1-\bar{\alpha}\right)}{d} ct\right] - \exp\left[\frac{\ln \bar{\mu}}{d} ct\right] \end{aligned} \tag{27}$$

In addition the decay time of the specularly reflected energy, T_{spec}, can be obtained from Eq. (26). The T_{spec} is defined as the time when the specularly reflected energy becomes -60dB.

$$T_{spec} = \frac{0.163 \times V}{S\left(-\ln \bar{\mu}\right)} \tag{28}$$

There is the following relation between *T*, *DT* and T_{spec}.

$$DT = \frac{T \cdot T_{spec}}{T - T_{spec}} \tag{29}$$

When Eq.(29) is used, it is necessary that the sound absorption and scattering coefficients are independent of each other and that the relation of $\bar{\mu} = \left(1-\bar{\alpha}\right)\left(1-\bar{\beta}\right)$ is valid.

Discussion on indexes of sound field diffusion

This section discusses the meanings of the indexes proposed for evaluating sound field diffusion in this paper.

In a steady state sound field, sound energy is scattered repeatedly at time intervals of *MST* on average, and the average number of scattering occurrences until absorbed is *SAR*. That is, shorter *MST* and larger *SAR* mean higher degrees of diffusion. In addition, according to the *MST* a smaller room and a larger equivalent scatter area achieve higher degrees of diffusion. Diffusion treatments on reflective and large walls contribute more to the sound field diffusion. A free field such as in an anechoic chamber is far from a perfect diffusion state because theoretically the *SAR* is zero and the *MST* is infinity.

The time variation of the specular and scattered components in a room impulse response can be calculated by Eq.(26) and Eq.(27). If T_{spec} can be measured by some sort of method, *DT* can be obtained from Eq.(29). The *DT* can evaluate the speed of conversion of specular sound energy into scattered energy. Therefore a shorter *DT* means a higher degree of diffusion. A larger average scattering coefficient causes shorter *DT*. Because the *DT* does not contain the effect of sound absorption, the *DT* can detect only the effect of scattering.

VERIFICATION OF THE FRAMEWORK FOR CHARACTERIZING SOUND FIELD DIFFUSION

In this section, the theoretical equations presented in this paper and results of computer simulations are compared in order to verify the framework for characterizing sound field diffusion proposed in this paper.

Simulation method

The method of computer simulations was the combination of the sound ray tracing method and the Monte Carlo method. First, many sound particles were emitted simultaneously from a point sound source. This corresponds to the emission of a pulse from a sound source, and the number of sound particles corresponds to the sound power of the pulse. A hundred thousand sound particles were generated in this simulation. The direction of propagation of the sound particles from the point sound source was determined stochastically with uniform random numbers on the spherical surface. Then the propagation of sound particles was calculated by 0.1 m steps each. The calculation had been performed for 1 second in this simulation.

When sound particles were reflected from the walls, each sound particle was stochastically determined to be absorbed, scattered, or specularly reflected by the Monte Carlo method. Specifically, uniform random numbers between 0 and 1 were generated, and if the number was between 0 to α, sound absorption occurred, while if the number was equal to or more than α, reflection occurred. In the case of reflection, uniform random numbers between 0 and 1 were generated, and if the number was between 0 to β, scatter reflection occurred, while if the number was equal to or more than β, specular reflection occurred. In the case of scatter reflection, the reflection direction was stochastically given in accordance with Lambert's cosine law. In the case where sound particles were absorbed, the calculations for the absorbed sound particles were aborted at that time. The total number of sound particles is gradually decreased with time. This describes the energy decay that is due to absorption.

In every calculation step, the following were recorded for each sound particle: position, whether it was absorbed or not; propagation distance until it was absorbed; number of specular reflections; and number of scattered reflections. By using these data, the proposed indexes and the time variation of the ratio of specular reflection component to scattered component can be calculated.

Conditions

Investigations were performed by using seven types of rooms, five cubic rooms (20m×20m×20m) and two rectangular rooms (20m×40m×10m). The sound source is located at the center of the rooms. Each room has a different condition of the sound absorption coefficient and the scattering coefficient. These are summarized in Table 1. Note that all six walls have the same sound absorption coefficient and scattering coefficient except Rooms 4 and 5. In Rooms 4 and 5, the pattern of absorption coefficients is the same, and the average absorption coefficient is 0.25. Though these two sound fields have the same average scattering coefficient of 0.25, the scattering coefficient of each wall is different. Room4 is where the reflective walls have a greater scattering coefficient, and Room5 is the opposite of Room4. The average scatter reflection coefficients calculated are different: 0.25 for Room4 and 0.125 for Room5.

Table 1. The absorption and scattering coefficient conditions of the seven rooms tested in this paper

Room's dimension	20×20×20 (W×L×H)										20×40×10 (W×L×H)			
Room type No.	1		2		3		4		5		6		7	
Wall's attributtions	α	β	α	β	α	β	α	β	α	β	α	β	α	β
Front wall	0.2	0.2	0.2	0.5	0.5	0.5	0.0	0.5	0.0	0.0	0.2	0.2	0.2	0.5
Back wall							0.5	0.0	0.5	0.5				
Left wall							0.0	0.5	0.0	0.0				
Right wall							0.5	0.0	0.5	0.5				
Ceiling							0.0	0.5	0.0	0.0				
Floor							0.5	0.0	0.5	0.5				

Calculation results of the time variation of the specular reflection component and scattered component

Fig. 2 shows the results of the time variation of the specular reflection component and scattered component for each room. Left and right figures are the theoretical solutions and simulation results respectively. The theoretical values were calculated by Eq. (9), Eq. (26) and Eq. (27). Because the theoretical values are probabilities of 0 to 1, the values are multiplied by the total number of sound particles used, one hundred thousand, in order to compare to the results of computer simulations.

The theoretical solutions and simulation results correspond well in all rooms. This means the theoretical framework for characterizing sound diffusion proposed in this paper is basically valid in various conditions of the absorption coefficients, the scattering coefficients and the room shapes. However they are slightly different in the early period. The initial difference is derived from the presence of the time-lag, which corresponds to the distance between the sound source and walls when the scattering of sound waves starts in the simulation.

In all cases the total energy and the specular reflection energy monotonically decrease with time while scattered sound energy increases and then decreases. However, the rate at which the specular reflection and scattered sound components vary seems to be different. Comparing the results of Rooms 1 and 2, the total energy decay is exactly the same because the average sound absorption coefficient is the same. The one with a larger average scattering coefficient increases more steeply in the generation of scattered sounds. The same thing can be said between Rooms 6 and 7. However this is not valid in the cases of Rooms 4 and 5. Although both rooms have the same average absorption coefficient and the same average scattering coefficient, the curves of specular component and scattered component in both rooms are different. These results are caused by differences of the combination of the sound absorption coefficient and scattering coefficient. This indicates that the sound absorption and scattering are not independent each other and that the combination of both should be considered for the sound field diffusion. The equations (12), (13), (14) and (15) can calculate the effect of such combinations.

Thus, if using the theoretical framework for characterizing sound diffusion described in this paper in addition to conventional reverberation theory, further investigation about sound fields can be performed where energy decay is divided into the specular reflection component and the scattered sound component.

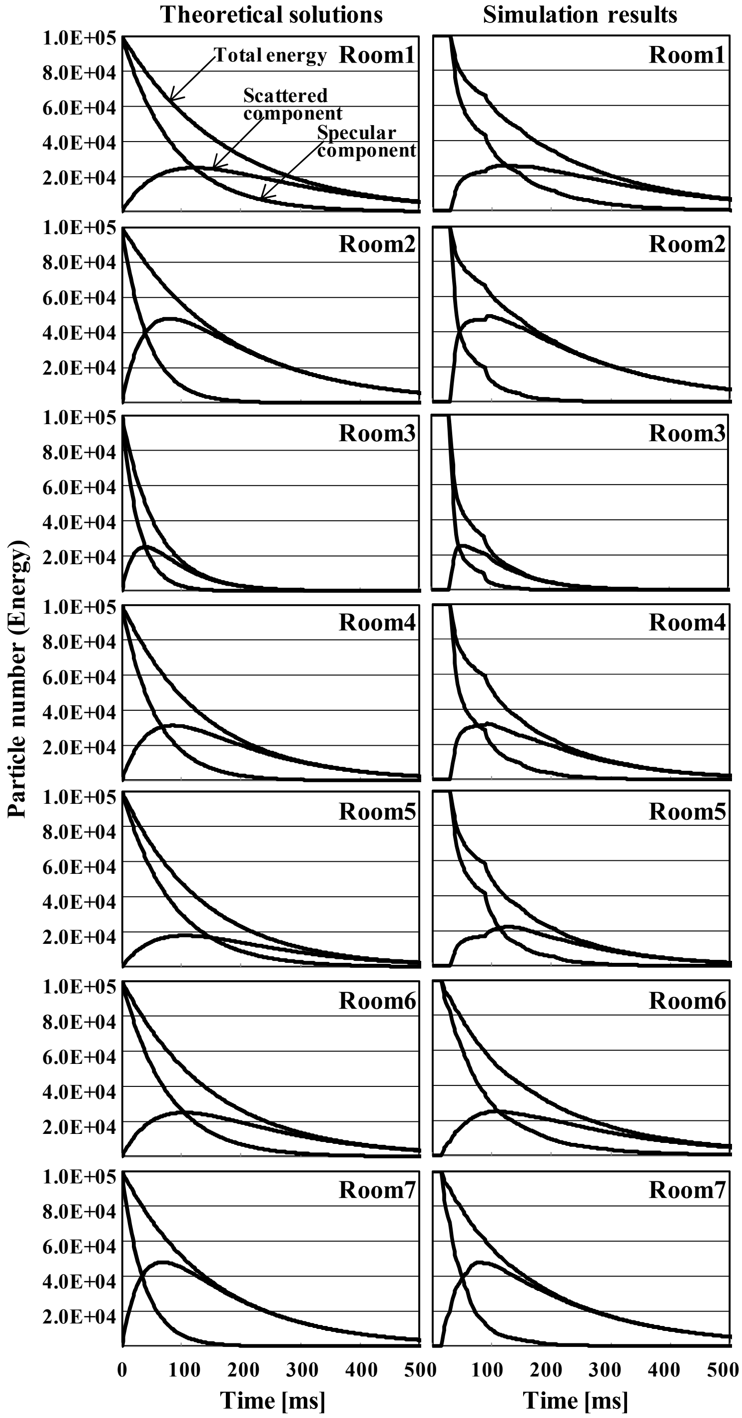

Figure 2. Time variation of the specularly reflected sound energy and the scattered sound energy in the seven rooms tested. (Left: theoretical solutions, Right: simulation results)

Calculation results of the indexes of sound field diffusion

Table 2 shows the theoretical solutions and simulation results of *T*, *DT*, *SAR*, and *MST*. The simulation results were calculated by methods described below. *T and* T_{spec} were derived from decay curves of the computer simulation. And then the *DT* was calculated by using Eq.(29). The *MST* was obtained by the recorded information for all sound particles. The *SAR* was obtained as the average number of times that sound particles are scattered until they are absorbed.

As shown in Table 2 the theoretical solutions and simulation results basically correspond well in all rooms although they are slightly different in Rooms 4 and 5. The differences might be derived from the unevenly-distributed absorption coefficients and scattering coefficients.

In the results of *DT*, it can be seen that the larger scattering coefficients yield shorter *DT* even if the reverberation times, *T*, are same. In particular, the *DT* of Rooms 2 and 3 are the same because the average scattering coefficients are the same, even if the average sound absorption coefficients are different. That is, the *DT* cannot evaluate the effect of sound absorption on the sound field diffusion, only the effect of scattering coefficient. According to *DT*, Rooms 2, 3 and 7 have high degrees of diffusion.

According to *SAR* and *MST*, although the degrees of diffusion in Rooms 2 and 7 are high, that of Room3 is not very high. This is because the average sound absorption coefficient of Room 3 is high. In Rooms 4 and 5, their *SAR* and *MST* are different although the results of the *DT* almost are same. Therefore the effect of the sound absorption, especially the combinations of it and the scattering coefficient, can be evaluated by using *SAR* and *MST*.

Table 2. Theoretical solutions and simulation results of the proposed indexes for sound field diffusion

Room type		1	2	3	4	5	6	7
Theoretical solutions	*T* [s]	2.4	2.4	0.8	1.9	1.9	2.1	2.1
	DT [s]	2.4	0.8	0.8	1.9	1.9	2.1	0.7
	SAR	0.80	2.00	0.50	1.00	0.50	0.80	2.00
	MST [s]	0.25	0.10	0.16	0.16	0.31	0.21	0.08
Simulation results	*T* [s]	2.6	2.6	0.9	1.8	1.7	2.3	2.3
	DT [s]	2.4	0.8	0.7	1.5	1.7	2.1	0.7
	SAR (n_s)	0.80	2.01	0.50	0.87	0.50	0.80	2.01
	MST [s]	0.24	0.10	0.15	0.16	0.27	0.21	0.09

CONCLUSIONS

A theoretical framework for characterizing sound field diffusion based on scattering coefficient and absorption coefficient of walls was developed. This method was developed by using two concepts concerning the diffusion of sound field. The one is the conversion of specularly reflected energy to diffuse energy and the other one is the frequency of repeating scatter.

First a basic framework for understanding diffusion of sound field without absorption was discussed in section 3. One of the important things in this framework is to distinguish the walls' capability of scatter and the degree of diffusion of the space. The equivalent scattering area, *B*, and the average scattering coefficient, $\overline{\beta}$, were defined for the former. And the mean scatter time, *MST*, and the diffusion time, *DT*, were defined for the latter. This theoretical framework related the walls' capability of scatter to the degree of diffusion of the space.

In section 4, the effect of both scattering coefficient and absorption coefficient on the sound field diffusion was discussed. One of the most important points was that the two are not independent of each other. Based on this, a theoretical framework for understanding sound field diffusion considering the sound absorption was developed. The equivalent scatter reflection area, *G*, and the average scatter reflection coefficient, $\overline{\gamma}$, were defined for the walls' capability of scatter when considering the sound absorption. And the mean scatter time, *MST*, was redefined to include effects of the sound absorption. Furthermore the scatter-to-absorption ratio, *SAR*, also was defined. The *SAR* has important meanings for the diffusion of sound field that has absorption. The *SAR* represents the average number of times that a single sound particle is scattered until absorbed and the ratio of the scattered energy component to non-scattered component. In a steady state sound field, sound energy is scattered repeatedly at time intervals of *MST* on average. Shorter *MST* and larger *SAR* mean higher degrees of diffusion.

The time variation of specular and scattered components in a room impulse response also was investigated. According to the results, even if rooms have the same average absorption coefficient and the same average scattering coefficient, the time variations of the specular and scattered components are different when the combinations of the surface sound absorption coefficients and scattering coefficients are different.

In section 5, the framework for characterizing sound field diffusion proposed in this paper was verified by the computer simulation. It was shown that the theoretical solutions and the simulation results corresponded well and that this method also could calculate the mutual effects of the sound absorption and scattering by room surfaces. Therefore these results supported that the theoretical framework is basically valid.

The ideas presented in this paper may be applied to the handling of scattered sound in room acoustic computer simulation based on the geometrical acoustics. However, the significance of this theoretical framework is not only to the above. Because the method for measuring the scattering coefficient has already been defined by an ISO standard, it is possible to prepare a database of the coefficients gradually. Therefore one can design the degree of sound field diffusion by applying the equations in this paper. In the design of diffusion, the average scattering coefficient and the average scatter reflection coefficient are important parameters and the

DT, *SAR* and *MST* can be used as evaluation indexes for the sound field diffusion. *SAR* and *MST* are especially important, because each real room space includes its own amount of absorption.

The *DT, SAR* and *MST* are important concepts, but there is not a method for measuring these in real space at this stage. The development of the measurement method of these is needed. The verification of this theoretical framework for characterizing sound field diffusion stated in this paper was performed with computer simulations based on the sound ray tracing method. Further verification should be performed with a simulation of wave acoustics and actual measurements.

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