'Temporal diffusion'을 활용한 확산음장 평가
Evaluation of the Scattered Sound Field using Temporal Diffusion

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Key Words : Scattering coefficient, Temporal diffusion, Autocorrelation function (ACF)

ABSTRACT

It has been considered that scattered sounds have a positive effect on a hearing impression of a sound filed. This study investigates the degree and the quality of a scattered sound field by using the acoustical parameters and autocorrelation function (ACF) of impulse responses. The acoustical parameters and fine structure of the ACF of an impulse response were used for the evaluation of the scattered sound field. The relationship between the scattering coefficient of surfaces with various hemisphere diffuser configurations and the acoustical parameters and ACF parameters of impulse responses was investigated.

1. Introduction

Sound diffusion by a wall structure is one of the main concerns with respect to the sound quality of concert halls. When the side wall and the reflector do not have sufficient diffusion, "acoustic glare" is perceived by listeners as a negative quality of the hall(1). Tone coloration is also observed as perceptual effects of a single reflection(2). This "distortion" can be explained as comb-filter effects due to interference between the direct sound and the reflection. Flutter echo also have a negative effect on the acoustic quality of a hall. Scattering surfaces prevent coloration which is caused by a strong reflection and flutter echo which is caused by multiple reflections. Also, the diffusion of a sound field affects the characteristics of the nature of the reverberation process. The effect of a scattering wall surface on diffusion in the laboratory can be assessed by determining the scattering coefficient. The procedures for making and evaluating them are set forth in ISO 17497-1(3). However, there is a need to develop measurement and evaluation methods for determining the performance of scattering wall surfaces in actual halls.

Based on the impulse response sound energy ratios, like C_x, have been applied to quantify and predict the acoustical quality of concert halls. C_{50} is useful and C_{80} is commonly used in music related analysis. A more detailed analysis of this part can be achieved by plotting C_x for each 5 ms up to 200 ms. This procedure called early-late energy ratio (ELR) is proposed by Marshall(4). Jeon et al.(5) made systematical investigations to find the optimum diffuser design for a concert hall by using the hemisphere and box-type diffusers. Fujii et al.(6) investigated the effect of an array of circular columns in front of the side walls and the stage walls as diffusers on the acoustical parameters of halls. They made measurements at all seats in two halls having similar floor plans, with and without columns. They found that an array of columns weakens the strong specular reflections from the sidewalls by scattered reflections. In a previous study, Jeon et al.(7) investigated the effect of the diffuser on the sidewalls close to the orchestra pit, on the side walls, and on the soffit of the side balcony using a 1:10 scale model. They found that the effect of the diffusers on the Δt_1 was observed in the far seat positions from the stage and the effect on the IACC was observed at the frontal and side seating positions near the source. Because conventional objective acoustical parameters cannot describe the texture and transient process, Hidaka developed new objective parameters by investigating the fine structure of the impulse responses(8-10). Investigation of the fine structure of impulse responses enables the characterization of the nature of the sequence of early reflections and reverberation.

The autocorrelation function (ACF) of an impulse response is utilized to detect strong reflections which cause coloration and periodical reflections which causes flutter echo. The ACF describes the degree of coherence between the initial part of an impulse response and any other part t later, while the scattering coefficient considers the absorption by the diffuser. In a diffused sound field, the reflections are distributed irregularly in the time domain. The ACF is a suitable measure to investigate the degree of regularity/irregularity. The ACF is used for an objective measure. Kuttruff suggested to use the ACF of a room and proposed the parameter "temporal diffusion" which is defined as the ratio of the amplitude of the second maximum peak (at $\tau \neq 0$) to the maximum peak at the origin ($\tau = 0$)(11). The pulse response of a room can be described by:

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$$h(t)=\sum_k a_k\delta(t-t_k) \tag{1}$$

The ACF of the room defined by Kuttruff can be expressed by the formula:

$$\Phi(t)=\int_{-\infty}^{+\infty}h(\tau)h(\tau+t)d\tau=\int_{-\infty}^{+\infty}h(-\tau)h(t-\tau)d\tau \tag{2}$$

Substituting Eq. (1) into Eq. (2) we can express the ACF by the following relation:

$$\begin{aligned}\Phi(t)&=\delta(t)\sum_k {a_k}^2+\sum_{k\neq l}\sum a_k a_l\delta(t+t_k-t_l)\\&=\Phi_1(t)+\Phi_2(t).\end{aligned} \tag{3}$$

The temporal diffusion is defined by $\Delta=\Phi_1(0)/\mathrm{Max}(\Phi_2)$. If the temporal diffusion is greater than a certain value, then coloration is perceived subjectively. Bilsen developed Kuttruff's theory and used the ACF of the room to evaluate coloration, echo, or flutter echo(12). Later, Srodecki investigated the ACF of the impulse responses of several auditoriums with different shapes to evaluate the quality of the reverberation decay(13). He compared the temporal diffusion and the reverberation time and found that ACF enables the characterization of the nature of the reverberation process.

This study investigates the effect of different configurations of hemisphere diffusers by using acoustical parameters and the ACF calculated from the impulse responses. The impulse responses were measured in a 1:10 scale model reverberation chamber to determine the scattering coefficient. The acoustical parameters (total energy, early-late energy ratio, EDT and T30) and temporal diffusion extracted from the ACF were analyzed to clarify the characteristics of the diffused sound field.

2. Measurements for the Scattering Coefficient in Reverberation Chamber

The impulse responses to obtain the scattering coefficient were measured in a 1:10 scale model reverberation chamber according to the procedure determined in ISO 17497-1(3). The diffusers were distributed on a circular panel with a diameter of 0.42 m. Two loudspeakers were located at the upper corners of the chamber. 1/8" microphone was used as a receiver. Six impulse responses (2 source positions and 3 receiver positions) were measured for each configuration. To measure the impulse responses, the MLS was used as a sound signal. Firstly, the effect of the hemisphere diffuser height on the scattering coefficient was investigated. The diffuser height was at eight levels: 7.5, 10, 12.5, 15, 17.5, 20, 22.5 and 25 mm. The surface coverage for each diffuser height was constant at 70%. Figure 1 shows the hemisphere diffusers with different heights and the scattering coefficient as a function of the diffuser height. The scattering coefficient was the average of the values at 500 to 3150 Hz in the real scale. The scattering coefficient increases as the diffuser height is increased up to 20 mm. Secondly, the effect of surface coverage on the scattering coefficient was investigated. The surface coverage was at five levels: 14, 28, 43, 57 and 71%. The diffuser height for each surface coverage was 20 mm. Figure 2 shows the arrangement of the hemisphere diffusers and the scattering coefficient as a function of the diffuser height. The scattering coefficient indicates the maximum at the surface coverage of 57%.

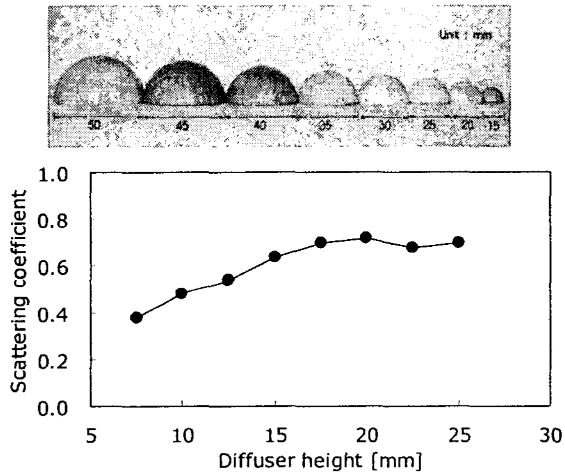

Fig. 1. Scattering coefficient as a function of the diffuser height.

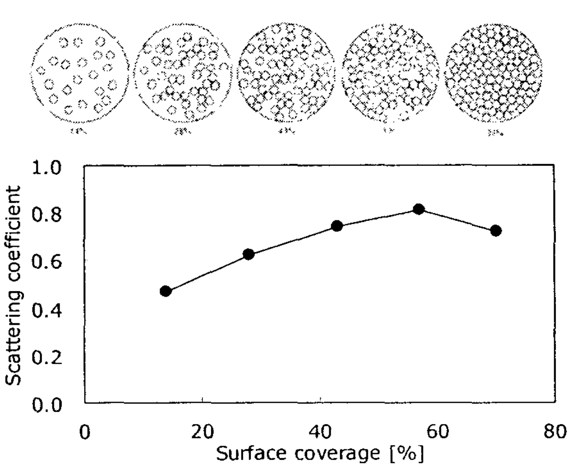

Fig. 2. Scattering coefficient as a function of the surface coverage.

3. Results of Acoustical Parameters

3.1 Total energy

Figure 3a shows the total energy as a function of the diffuser height. The total energy decreases as the frequency is increased. Large dips were found for 22.5 mm of the diffuser height at frequencies investigated. This dips means deficiency of the diffusers because the scattering coefficient is higher than those at other frequencies. As shown in Fig. 3b, the total energy also decreases as the frequency is increased. Also, the total energy decreases as the surface coverage is increased at frequencies investigated. Figures 3a and 3b show that the total energy is independent of frequency.

3.2 Early-late energy ratio (ELR)

As proposed by Marshall(4), the early-late energy ratio (ELR) C_x for each 5 ms up to 200 ms was calculated.

$$C_x = 10\log_{10}\frac{\int_0^x p^2(t)}{\int_x^\infty p^2(t)} \tag{4}$$

Figure 4a shows the ELR as a function of the diffuser height. The ELR increases as the frequency is increased at frequencies investigated. Peaks were observed at 22.5 mm. These peaks were observed up to 70 ms of the integration interval. Figure 4b shows the ELR as a function of the surface coverage. The ELR also increases as the frequency is increased at frequencies investigated. The ELR increases as the surface coverage is increased.

3.3 EDT and reverberation time (T30)

Figures 5a and 5b show the EDT and T30 as a function of the diffuser height. Dips were found for 175 mm of the diffuser height at 500 and 2000 Hz while the EDT and T30 at 1000 Hz increase monotonously as the diffuser height is increased. Figures 5c and 5d show the EDT and T30as a function of the surface coverage. EDT and T30 at 2000 Hz are much shorter than those at 500 and 1000 Hz. Both EDT and T30 decrease as the surface coverage is increased.

3.4 Temporal diffusion

Figure 6a shows the temporal diffusion as a function of the diffuser height. The temporal diffusion was the average of the values at 800 to 1600 Hz in the real scale. The temporal diffusion indicates the maximum at the diffuser height of 20 mm. Figure 6b shows the temporal diffusion as a function of the surface coverage. The temporal diffusion increases as the surface coverage is increased except for the surface coverage of 14%.

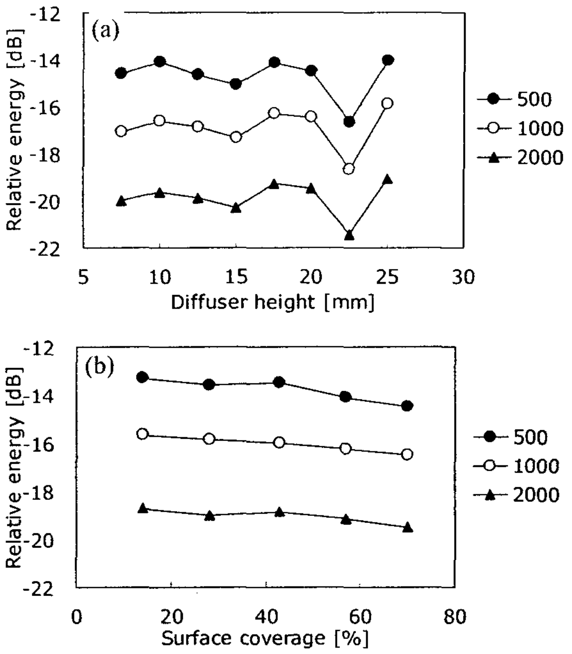

Fig. 3. Total energy as a function of the diffuser height (a), and the surface coverage (b).

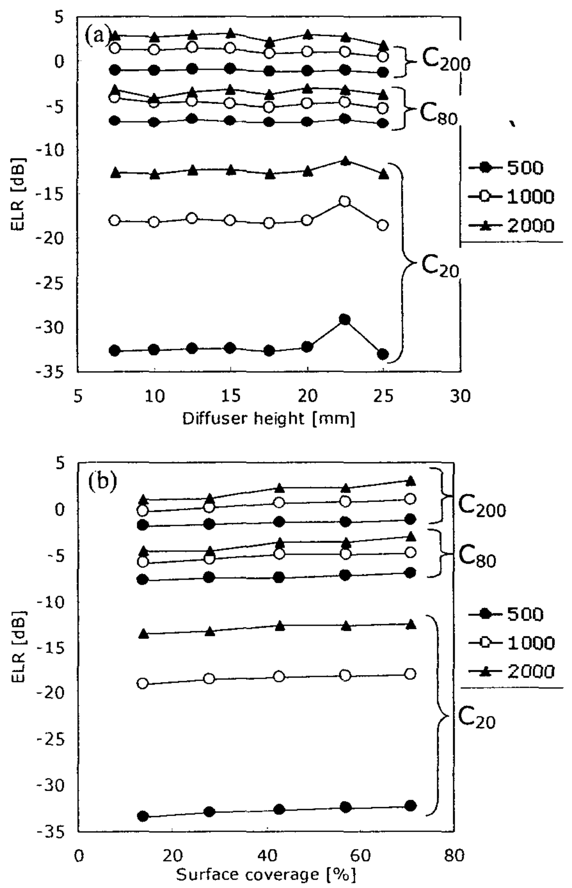

Fig. 4. Early-late energy ratio as a function of the diffuser height (a) and the surface coverage (b).

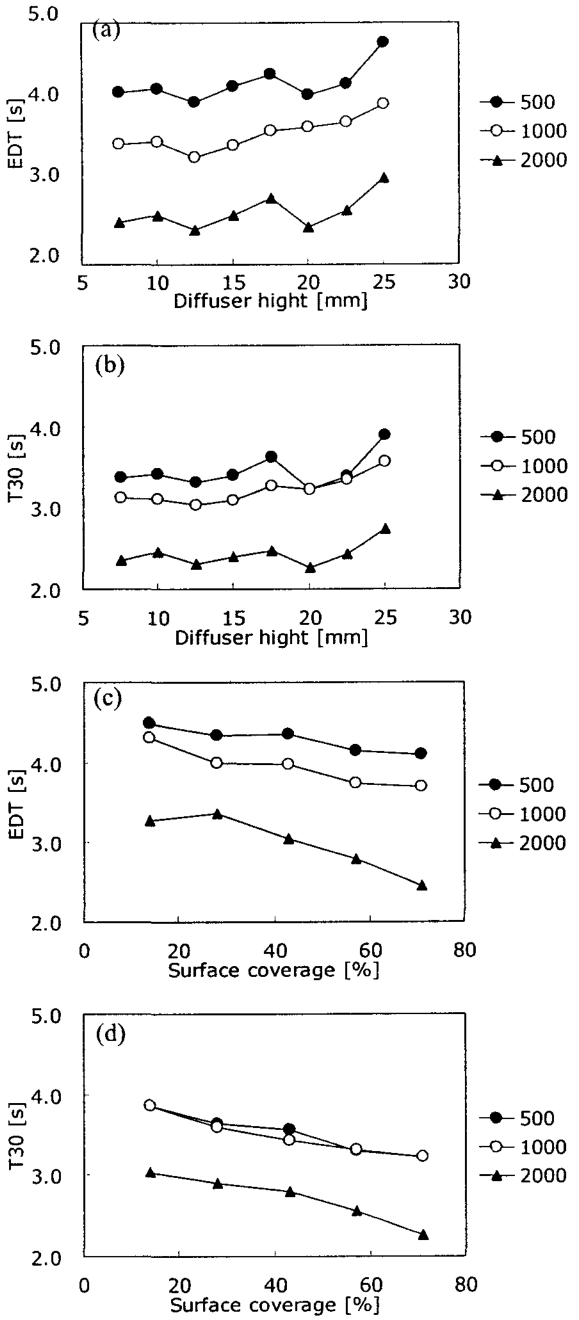

Fig. 5. EDT (a) and T30 (b) as a function of the diffuser height. EDT (c) and T30 (d) as a function of the surface coverage.

4. Conclusions

The impulse response measured for obtaining the scattering coefficient in a scale model reverberation chamber was investigated. The effects of the diffuser height and the surface coverage on the scattering coefficient, acoustical parameters and the ACF of impulse responses were investigated.

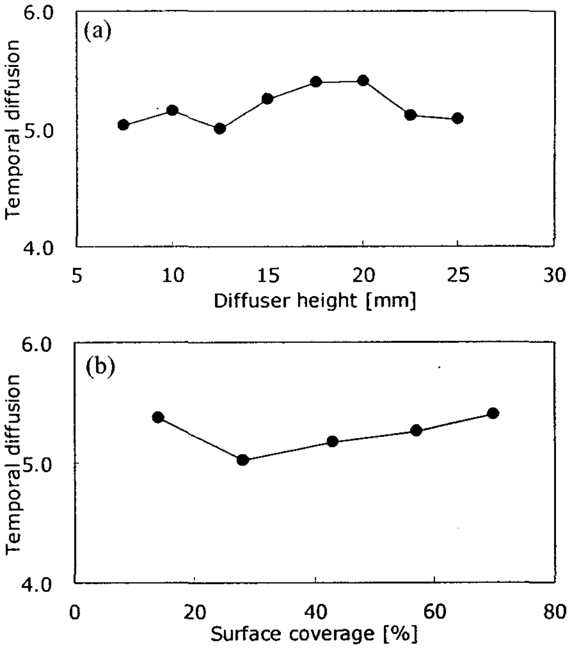

Fig. 6. Temporal diffusion as a function of the diffuser height (a) and surface coverage (b).

- In the measurement for the scattering coefficient, it was found that hemispheres with a height of 20 mm have the highest average (500 to 3150 Hz) scattering coefficient. It was also found that the scattering coefficient becomes higher when the diffuser density reaches 57%.
- In the investigation for the surface coverage, the total energy decreases as the surface coverage becomes larger. This is due to the increase of the surface area of hemisphere diffusers. The results of the total energy and the early-to-late energy ratio showed that when the total energy is small the early-late energy ratio becomes large. This means that the late energy component is absorbed by the diffusers.
- The EDT and T30 at 1000 Hz increase as the diffuser height is increased while there were dips between the diffuser heights of 17.5 and 20 mm at 500 and 2000 Hz.
- The average scattering coefficient (800-1600 Hz) indicates the maximum at the diffuser height of 20 mm. The temporal diffusion increases as the surface coverage is increased except for the surface coverage of 14%.

Parameters investigated in this paper can be possible measures to describe the quantity and the quality of the diffusers. These parameters should be investigated in actual halls as well as in the laboratories.

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