Objective evaluation of scattered sound field: Theory and methodology of diffuser design
확산음장의 물리적 평가 – 확산체 설계이론과 방법론–

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ABSTRACT

The effect of a scattering wall surfaces on sound diffusion can be assessed by determining the scattering and diffusion coefficients in the laboratory. However, the sound field in a concert hall including scattered reflections is different from the laboratory measurement condition. Therefore, there is a need for objective investigation of diffusion in real sound fields. In this paper, possible acoustical parameters of in-situ measurements are discussed.

1. Introduction

Sound diffusion by a wall structure is one of the main factors affecting the sound quality of concert halls. In recent years, coefficients have been developed to characterize the scattering or diffuse reflections caused by surfaces in rooms. These coefficients have been developed to meet the needs of geometric room acoustic modelers, diffuser manufacturers, and room designers. The methods can be classified either as free or diffuse field. Diffuse field methods have the advantage of quickly obtaining a random-incidence scattering coefficient (ISO 17497-1) while free field measurements for a diffusion coefficient (AES-4id-2001 and ISO 17497-2 draft) are often more laborious to carry out.

The sound field in a concert hall including scattered reflections is different from the laboratory measurement condition. Therefore, there is a need to develop measurement and evaluation methods for determining the performance of the scattering characteristics of wall surfaces in concert halls in terms of the subjective perception of the diffused sound field. Ando [1] found that subjective diffuseness decreases as IACC increases, being independent with the frequencies between 250 Hz and 4 kHz. As an objective index for indicating the degree of diffusion in sound fields, $IACC_{L3}$ was used to indicate the effectiveness of the irregularities on the walls and ceilings of concert hall in creating the acoustical quality of concert hall [2].

More generally, conventional acoustical parameters obtained from the room impulse responses have been used to evaluate the scattered sound field. Suzumura *et al.* [3] compared the sound fields with and without an array of circular columns in front of the side walls and the stage walls as diffusers in a 1:10 scale model of a concert hall. They found that columns in front of the side walls decrease IACC at seats close to these columns. In addition, Δt_1, which is defined by the delay time of the reflection with maximum amplitude in relation to the direct sound, is increased by the columns. Fujii *et al.* [4] investigated the effect of circular column 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. Chiles and Barron [5] conducted measurements with and without diffuser panels in a 1:25 scale model of a rectangular hall. They showed that the diffusers slightly reduce the scatter of reverberation time and that the decay curve with diffusers is more linear with less deviation from the best-fit line. Jeon et al. [6] investigated the effect of hemisphere diffusers on the sidewalls close to the orchestra pit, on the side walls, and on the soffit of the side balcony in a 1:10 scale model of a multipurpose hall. They found that diffusers increase Δt_1 and decrease the sound pressure level and RT. They also showed that the diffuser increase subjective preference.

This paper discusses about the coefficients which are obtained from laboratory measurements first, and then, the possible acoustical parameters for in-situ measurements are discussed.

2. Laboratory measurements

2.1 Scattering coefficient

ISO/TC 43/SC2/WG25 suggested a measurement method for obtaining a random-incidence (three dimensional, 3D) scattering coefficient of surfaces in a

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diffuse field and the ISO 17497-1 has been standardized based on the Mommertz and Vorländer technique [7,8]. The scattering coefficient describes the ability of a surface to move energy away from the specular angles.

Jeon *et al*. [9] made systematic investigations to determine the optimum diffuser design for a concert hall by using hemisphere and cube diffusers. The scattering coefficients of different sizes and surface coverage of wooden hemispheres and cubes were measured in a scale model reverberation chamber. The results show that hemispheres with a height of more than 15 cm have the highest average (500-3150 Hz) scattering coefficient. It was also found that the scattering coefficient becomes higher when the diffuser density reaches about 50% for hemispheres and 30% for cubes. Figure 1 shows the extension of the above study about the hemisphere diffusers. The coverage density was fixed at 71%, therefore the total surface for each diffuser was constant. As shown in Fig. 1(b), lower frequency range is affected by the diffusers as the diffuser height is increased. The absorption coefficient (obtained the reverberation times for scattering coefficient which is different from ISO 354 method) at above 400 Hz increased up to 0.4 (Fig. 1c). The scattering coefficient averaged for 500-3150 Hz increased as the diffuser height is increased up to 200 mm while the absorption coefficient decreased as the diffuser height increased (Fig. 1d). The size of the hemisphere diffuser which gives the highest scattering coefficient is 20 cm in the height in the real scale (40 cm in the diameter).

Figure 2 shows another investigation in terms of the coverage density. The height of hemisphere diffuser was fixed at 200 mm, therefore the total surface increased as the coverage density was increased. As shown in Fig. 2(b), the scattering coefficients (obtained by the same procedure as above) above 400 Hz increase when the surface coverage varies from 14 to 57%. The frequency range affected by the surface coverage was not changed because the size of the diffusers was fixed. The absorption coefficient increased as the coverage density was increased (Fig. 2c). The scattering coefficient averaged for 500-3150 Hz increased as the surface coverage is increased up to 57% (Fig. 2d) but too many diffusers is not effective in increasing the scattering coefficient. The 71% surface coverage showed almost the same value as that of 57%, thus, the 57% surface coverage shows better performance than that of 71% in terms of diffusing reflected energy.

2.2 Diffusion coefficient

The AES SC-04-02 standard committee has introduced a method of measuring the (two dimensional, 2D) diffusion coefficient in a free field based on the Cox and D'Antonio technique [10], and has been published in AES-4id-2001 and the draft of ISO17497-2 is being discussed. The definition takes account of how the reflected early energy is distributed.

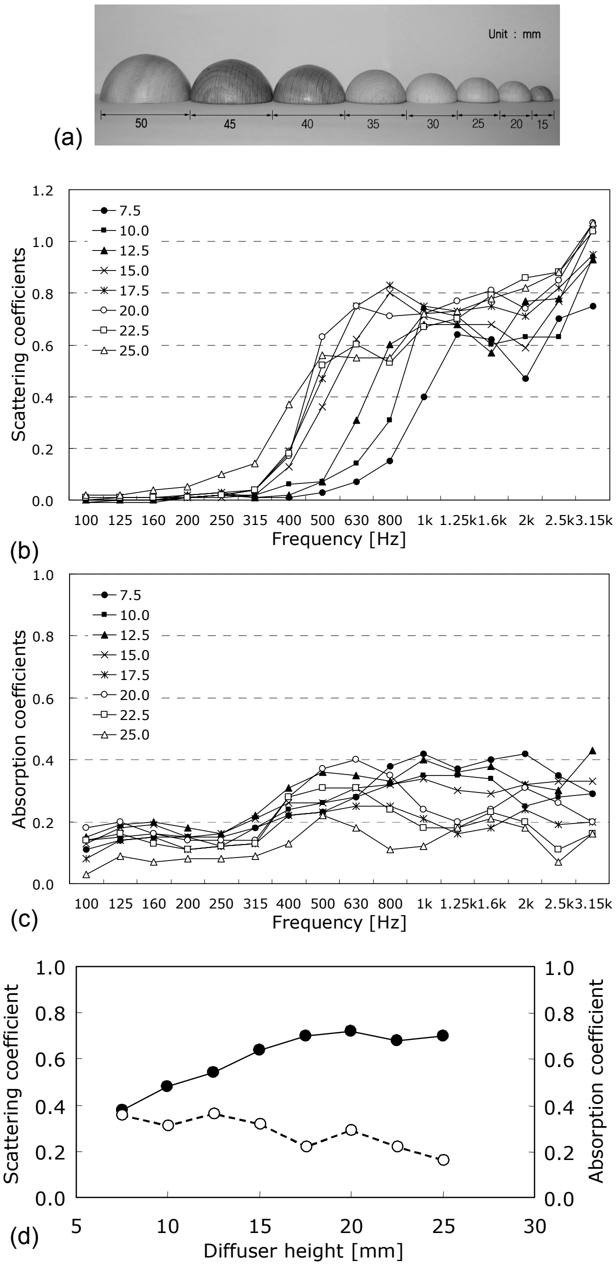

Fig. 1. Diffusers with different structural height (a), scattering (b) and absorption coefficients (c), and scattering and absorption coefficients averaged for 500-3150 Hz (d).

Both scattering and diffusion coefficients are useful to describe the characteristics of the diffusive surface. The definition of the scattering coefficient is useful for the geometric room acoustic models which have separate algorithms for specular and scatter components. The diffusion coefficient is a measure of the uniformity of the reflected sound and is useful to describe the early sound field where the impulse response is dominated by a few isolated reflections.

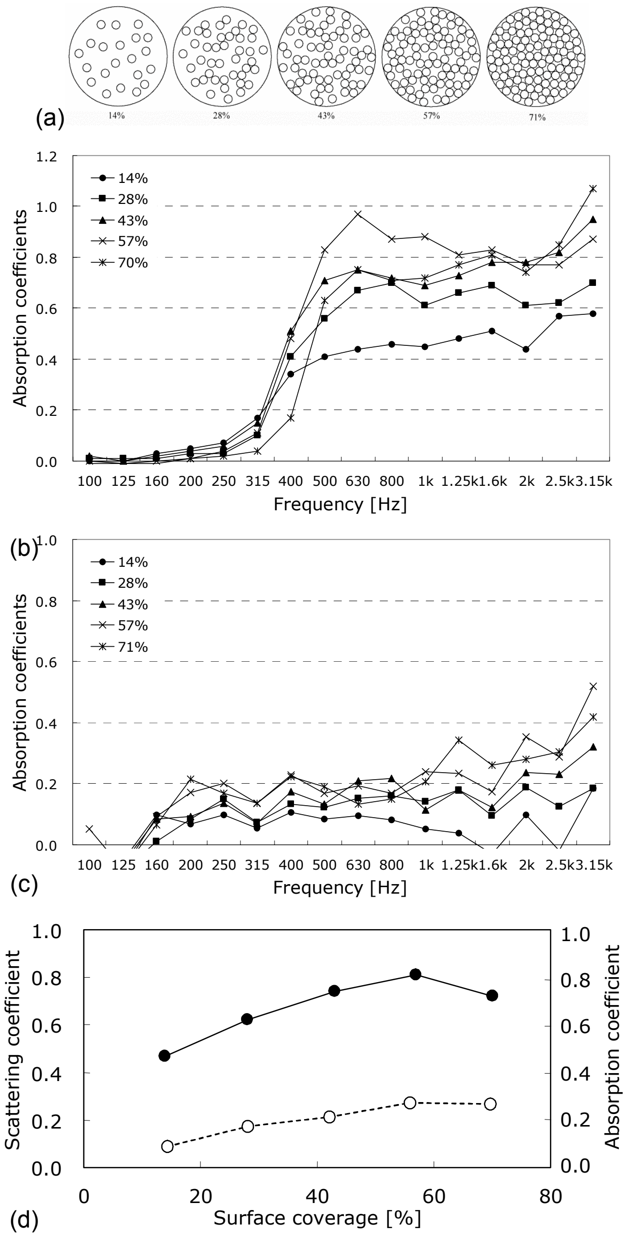

Fig. 2. Diffuser arrangements with different surface coverage (a), scattering (b) and absorption coefficients and (c) scattering and absorption coefficients averaged for 500-3150 Hz (d).

Figure 3 compares the scattering and diffusion coefficients of the same diffusers. The frequencies affected by QRD diffuser are lower than those of Skyline® for both the scattering and diffusion coefficients. The scattering coefficient at below 500 Hz is almost 0 and increased as the frequency increased at above 500 Hz while the diffusion coefficient showed a certain increase at below 250 Hz due to the edge diffraction by the specimen.

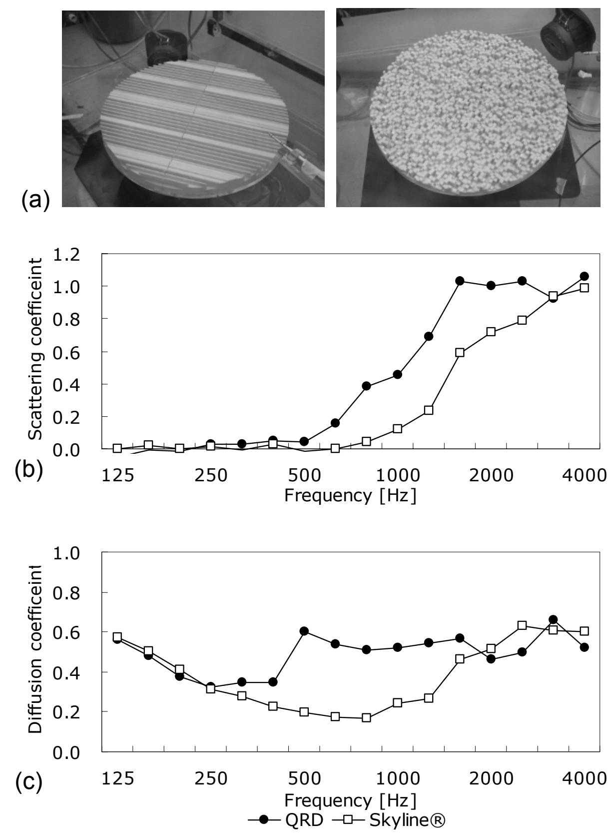

Fig. 3. Comparison of scattering and diffusion coefficients of the same diffusers. (a) QRD (left) and Skyline® (right) diffusers, (b) scattering and (c) diffusion coefficients.

The efficiency of diffusers should be discussed in terms of the directivity and absorption at each frequency. There must be a frequency-dependent compensation from the absorption power of the diffusers in the random incidence case, for example, “scattering coefficient ≈ Diffusion coefficient + 3-D absorption”.

3. In-situ measurements

3.1 Effects of diffusers on sound fields in halls

Scattering surfaces can prevent both tone coloration caused by a strong reflection and flutter echo caused by multiple reflections. Also diffusers are applied to the rear wall of a hall to prevent long-path echoes caused by late arriving reflections with a level significantly above the general reverberance. Those echoes are often heard at the front of badly designed auditoria and on the stage. The echo also comes from a balcony front, soffit or many other multiple reflection paths. Absorption treatment can also be used to prevent echoes; however, diffusers have the advantage of preserving the sound power generated by the sound sources. Diffuser types and locations should be carefully chosen to improve the reverberance, special impression, and clarity (intelligibility) of a sound field. To investigate the effect of diffusers on sound fields in halls, the total sound energy, structure of early reflections and energy decay which can be obtained from fine structures of (the early part of) the impulse response and the conventional acoustical parameters.

Figure 4 shows the effect of diffusers on the sound fields in halls with different shapes. In a shoebox hall, audience receives diffuse reflections instead of specular reflections. In a fan shape hall without diffusers, audience in the main audience area cannot receive the early reflections because the side wall reflects the sound from the stage to the rear of the hall. Diffusers on the side walls in a fan shape hall provide the early reflections toward the audience area by re-direction of the sound. Diffusers provide reflections not only for the audience area but also for the stage area [11].

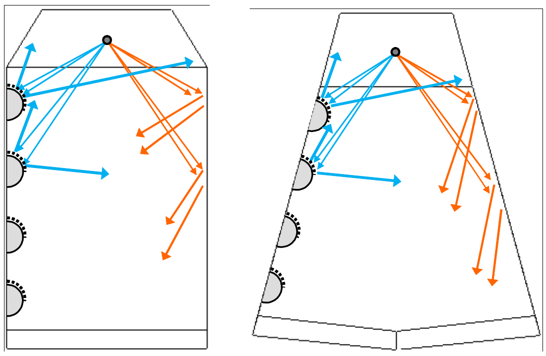

Fig. 4. Sound fields of the audience and stage areas in a shoebox (left) and a fan shape (right) halls affected by diffusers.

3.2 Reflection number

To quantify the effect of diffused surfaces on reflections, the idea of the number of reflections for 20dB decrease relative to the direct sound (Fig. 5) was introduced in addition to the reflection energy. Our previous study [14] showed that the reflection number of the early part (0-80 ms) of the impulse responses increased by the diffusers.

4. Remarks

To determine the effect of diffusers on the sound field of halls with in-situ measurements, the relationship between scattering coefficient with diffusion coefficient and the reflection numbers were introduced. Further measurements will be needed to validate these parameters.

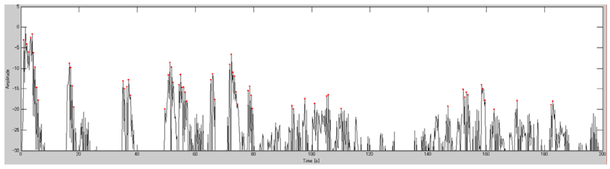

Fig. 5. Idea of the reflection number. First the amplitude of the reflections was normalized relative to the direct sound. Then, the reflection numbers whose amplitude exceeds -20 dB were counted.

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