A laboratory method for measuring normal-incidence scattering coefficients of architectural surfaces

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Abstract: Regarding scattering coefficient that represents acoustic scattering capability of architectural surfaces, a reverberation room method for measuring random-incidence values has been standardized in ISO 17497-1, whereas any method has not yet fully established for incidence-angle-dependent values. In this paper, a laboratory measurement method is proposed for normal-incidence scattering coefficients, which will be useful for room acoustics design, particularly assessment of flutter echoes. The measurement is performed in a rectangular room where highly absorbent materials are installed on all sidewalls, and a test sample is mounted on the entire floor. In the quasi-one-dimensional sound field between the floor and ceiling, normal-incidence scattering coefficients of the sample are estimated by measuring the changes of reverberation times with and without the sample. In order to establish the proposed method, the measurement procedure and the test arrangement are examined in 1/4-scale experiments, and finally, it is validated in comparison with theoretical and numerical results.

Keywords: Diffuser, Scattering, Normal incidence, Reverberation time

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1. INTRODUCTION

With an understanding about the significant role of surface scattering in architectural acoustics, concerted researches on measuring, calculating and characterizing its properties have been undertaken in the last two decades [1]. As one of the indices to evaluate reflection characteristics of surfaces, the scattering coefficient, which is defined as the ratio of non-specularly reflected energy to total reflected energy [2,3], is now widely utilized to improve the prediction accuracy of current geometrical room modeling programs, such as ODEON [4], CATT-Acoustic [5] and so on.

For measuring the scattering coefficients, two methods in the free field and in the reverberation room were originally proposed by Vorländer and Mommertz [2]. In practice, the reverberation room method has been standardized by ISO 17497-1 [6], because of its powerful process for the direct determination of random-incidence scattering coefficients. Recently, appropriate measurement conditions were almost established [7,8], especially in the sample rotation scheme with stepwise or continuous measurement [9]. Based on the ISO method, several researches are being undertaken to characterize the random-incidence values of various diffusers [10–12].

Similar to normal-incidence absorption coefficient, it should be noted that normal-incidence scattering coefficient can be particularly useful to assess the suppression of flutter echoes between parallel walls [13], and also is required for theoretical estimation of reverberation time in rectangular rooms [14]. Recently, Rindel proposed an in-situ measurement method for the normal-incidence values, and then, Schmich and Brousse tested the method through numerical simulation and experiment [15]. The theoretical principle is based on the measurement of one-dimensional reverberation times between an existing surface and a mobile panel installed in parallel. The normal-incidence scattering coefficients of the test surface are estimated from the two reverberation times for itself in situ and for a rigid flat reference surface in a laboratory. However, due to the small area and the open edges of the mobile panel, the measurement method is not yet fully reliable, and still under development for the present.

In this paper, an improved laboratory method is proposed for determining normal-incidence scattering coefficients in a rectangular room, where a quasi-one-
dimensional sound field is generated between the floor and ceiling by installing highly absorptive sidewalls. In the same way as the above in-situ method, the normal-incidence values of a test sample mounted on the entire floor are estimated by measuring the changes of reverberation times with and without the sample. In order to establish the proposed method, 1/4-scale experiments are performed to examine the two points: the measurement procedure for energy decay evaluation to determine one-dimensional reverberation times, and the test arrangement, such as the dimensions of the room and the size and orientation of the sample. Furthermore, the validity of the measurement method is discussed in comparison with theoretical results for infinite surfaces [16], and numerical results for finite samples in the free field [17–19].

2. PRINCIPLE OF THE LABORATORY MEASUREMENT METHOD

2.1. Condition of Sound Field

The theoretical principle of measuring normal-incidence scattering coefficients in the proposed laboratory method is the same as in the in-situ method [15], that is, the scattering coefficients are determined by the changes of reverberation times with and without a test sample in a one-dimensional sound field. However, the conditions of sound fields are considerably different between the two methods as illustrated in Figs. 1 and 2. In addition, according to the mirror image principle and Babinet’s principle, sound propagation models from image sources corresponding to specular reflections in the two methods are depicted in Fig. 3.

The in-situ method supposes to generate a quasi-one-dimensional field between an open rigid wall and a thin rectangular panel installed in parallel. However, some defects arise due to the open sound field around the panel. Regarding an on-site sample, its area is not limited, and therefore, scattered sound energy somewhat returns from the outside area not faced to the panel. Moreover, diffracted sound waves also arrive from the edges of the panel due to multiple diffraction for image sources. Especially using a small panel, these unnecessary components can strongly affect the energy decay of the quasi-one-dimensional field, thus spoiling the accuracy of determining the scattering coefficient.

On the other hand, the laboratory method supposes a quasi-one-dimensional sound field generated between a rigid floor and a rigid ceiling, by installing highly absorptive sidewalls in a rectangular room. Reverberation times are measured in the two conditions without and with a test sample that is mounted on the whole surface of the floor. In the rectangular room, propagation from far image sources is similar to that in a lined rectangular duct, where no destructive wave occurs on the interfaces of image spaces. Therefore, energy attenuation is proportional to the propagation distance, and greatly weakens at higher frequencies if the width and the depth of the room are greater than the wavelength [20]. As a consequence, a more preferable
quasi-one-dimensional field will be achieved with relatively gentle energy decay in the laboratory method.

### 2.2. Determination of Scattering Coefficient

According to the reverberation theory for rectangular rooms with specular and diffuse reflections [14], one of the one-dimensional specular components with the slowest decay remains in the late decay, if the decay is slower than the three-dimensional diffuse component. In the room for the laboratory method, it is likely that the three-dimensional component is rapidly decayed, and the one-dimensional component between the floor and ceiling remains in the late decay. In the quasi-one-dimensional field, normal incidence is dominated for the sample surface due to alternate specular reflections in the vertical direction. Based on the reverberation theory for one-dimensional field [14], the reverberation times without and with a sample are expressed by

\[
T_1 = \frac{6 \ln(10) L_z/c_1}{-\ln(1 - \alpha_{0,n}) + (m_w + m_t)L_z}, \quad (1)
\]

\[
T_2 = \frac{6 \ln(10) L_z/c_2}{-\ln\sqrt{(1 - \alpha_{0,n})(1 - \alpha_n)(1 - s_n)) + (m_w + m_t)L_z}}, \quad (2)
\]

where \( L_z \) is the distance between the floor and ceiling, \( \alpha_{0,n} \) and \( \alpha_n \) are the normal-incidence absorption coefficients of the floor and ceiling and the sample, \( s_n \) is the normal-incidence scattering coefficient of the sample, \( m_w \) is the energy attenuation coefficient due to sidewall absorption, \( c_i \) are the speed of sound, and \( m_t \) are the energy attenuation coefficients of air on the \( i \)-th condition. Note that \( m_w \) depends on not only the absorption coefficient of the sidewalls, but also the width and the depth of the floor, and the frequency.

Consequently, the normal-incidence scattering coefficient of the sample is derived from the above two equations as follows:

\[
s_n = 1 - \frac{1 - \alpha_{0,n}}{1 - \alpha_n} \exp \left[ 12 \ln(10) L_z \left( \frac{1}{c_1 T_1} - \frac{1}{c_2 T_2} \right) - 2L_z (m_1 - m_2) \right], \quad (3)
\]

which is apparently independent of the absorption property of the sidewalls. However, high absorptive sidewalls are necessary for suppressing all components except the one-dimensional specular component. Furthermore, the dimensions of the rectangular room will have limitations in order that the scattered energy from the sample is sufficiently absorbed.

### 3. MEASUREMENT SETUPS IN A 1/4-SCALE ROOM

#### 3.1. Test Arrangements

Measurements are performed in a 1/4-scale rectangular room that is made of acrylic boards with a thickness of 10 mm, as illustrated in Fig. 4. The absorptive materials installed on the four sidewalls are polyurethane foams with a density of 25 kg/m³ and a thickness of 150 mm. In order to examine the influence of room geometry, four room dimensions are arranged by changing the height and floor area of the rectangular room as specified in Table 1. On the basis of Room I, the room height and the floor area are reduced to half by raising the floor, and by shifting polyurethane foams to the inside, respectively.

For test samples, four types of one-dimensional periodic surface with rectangular and triangular profiles are chosen as illustrated in Fig. 5. The samples are composed of laminated wood with a period of 50 mm, and mounted on the entire floor in the two orthogonal orientations as illustrated in Fig. 6. It is obvious that the samples have capability of scattering mostly in the periodic direction under the normal incidence condition. Thus, there is a possibility that a discrepancy occurs between the measured results in the two orientations due to different side lengths of the samples.

Figure 7 shows random-incidence absorption coefficients of the floor and ceiling, the sidewalls and Sample R1, supplementarily measured according to ISO 354 [21] with frequency converted to real scale. Although the values of the polyurethane foam are over 1 at lower frequency...
bands due to the area effect, it is confirmed that the floor and ceiling are very reflective, and the sidewalls are sufficiently absorptive in all frequency bands. Thus, it is likely that a one-dimensional field will be almost generated in the vertical direction of the room. The random-incidence absorption coefficients of the floor and ceiling, and the samples are below 0.1, but small differences are seen at high frequencies. Since it is difficult to measure the normal-incidence values, those of the samples, the floor and ceiling are assumed to be zero in the following determination of scattering coefficients. In theory, this assumption leads to the error expressed by

\[
\Delta s = \frac{\alpha_n - \alpha_{0,n}}{1 - \alpha_{0,n}} (1 - s_n),
\]

and accordingly, an overestimate of up to 0.1 will be involved in a low scattering coefficient.

### 3.2. Measurement Procedures

As illustrated in Fig. 8, room impulse response measurements are performed using swept sine signals in 6 combinations of 2 sources (dodecahedral loudspeaker) and 3 receivers (omni-directional microphone) in Room I. In other rooms, the sources and receivers are positioned by the same scale ratio of Room I. To suppress undesirable scattering from the loudspeaker, the sources are located near the corners of the floor. In accordance with ISO 354, energy decay curves are obtained by the backward integration method, and then reverberation times are determined by the least squares regression of slope. In the calculation of scattering coefficients, the arithmetic means of reverberation times for 6 measurements are used in 1/3-octave bands. This procedure is referred to the previous study that the arithmetic mean is nearly equivalent to the reverberation time for the total energy in a quasi-one-dimensional field [22].

Figure 9 shows energy decay curves of Room I without a sample, measured in all combinations of sources and receivers. Although the deviations are remarkable among the curves, those overall slopes are relatively similar. Nevertheless, the mean decay curves are not linear, and therefore, reverberation times are varied depending on the evaluation range of decay levels. The evaluation of decay curves for determining scattering coefficients is discussed in the following section.
4. RESULTS AND DISCUSSION

4.1. Determination of Reverberation Time

Figure 10 shows average decay curves of Room I in 1/3-octave bands, measured without and with Sample R1, mounted in the two orientations. For reference, a theoretical curve of power-law decay, \( L = 10 \log_{10} \left( \frac{t_0}{t} \right) \) (\( t > t_0 = L_z / 2c \)), is drawn for an infinite flat room, assuming that two half lines of image sources are laid outside the walls, and a receiving point is located in the center of the room [23]. In the empty condition, the decay curves are remarkably curved between \( -5 \) to \( -25 \) dB, and the early rapid decay seems to be dominated by the power-law decay. On the other hand, the late decay curves become relatively linear and fall away from the theoretical one, which is considered due to sidewall absorption and air attenuation. In the condition with the sample, the slopes become more linear and steep in some frequency bands, and the influence of sample orientation is rather seen in high frequency bands.

Figure 11 shows reverberation times and Eyring absorption coefficients (denominator in Eq. (1)) of Room I in the empty condition, which are determined in various decay ranges of 10, 20 and 30 dB, changing the top level from \( -5 \) dB to lower levels. It is seen that the reverberation times tend to be longer for later decay, and correspondingly the absorption coefficients decline and converge to the
lowest values. Above 500 Hz, the absorption coefficients for late decay are almost less than 0.2, and the components of sidewall absorption are relatively constant. On the other hand, the sidewall absorption rises sharply at lower frequencies below 500 Hz. As expected from the general characteristics of a lined duct [20], the critical frequency will be in inverse proportion to the width or depth of a room. Finally, it is inferred that reverberation times had better be determined in a decay range below $C_0/20$ dB, with a lower frequency limit of 630 Hz in this case.

4.2. Determination of Scattering Coefficient

Figure 12 shows normal-incidence scattering coefficients of Sample R1 in the two orientations. The grey solid and dotted lines represent theoretical and numerical results.

![Fig. 12 Normal-incidence scattering coefficients of Sample R1 in the two orientations. The grey solid and dotted lines represent theoretical and numerical results.](image)

In comparison between the two orientations, Orientation Y gives less peak values at 2 and 2.5 kHz, which are rather lower than the numerical results. On the other hand, those in Orientation X fairly correspond with the numerical results. The discrepancy will arise from that scattered energy cannot be fully dispersed into the absorptive sidewalls if the room’s height is not enough relative to the sample’s width. Regarding the room’s ratio of height to width in the periodic direction, Orientations X and Y have 1 and 0.75, respectively. It suggests that the distance between the sample and the opposite surface should be not less than the side length of the sample, which is minutely examined in the next section.

4.3. Influence of Room Dimensions

Figure 13 shows normal-incidence scattering coefficients of Sample R1 (Orientation X) in Rooms I to IV, determined in the decay ranges of 20 dB.

![Fig. 13 Normal-incidence scattering coefficients of Sample R1 (Orientation X) in Rooms I to IV, determined in the decay ranges of 20 dB.](image)
coefficients seem to be more reliable at high frequencies. In particular, considerable underestimation occurs in the measured values, if the aspect ratio is less than 1.

Figure 14 shows normal-incidence scattering coefficients of the four types of sample, mounted in Orientation X in the four rooms, with the evaluation decay range from −20 to −40 dB. On the whole, the measured results in Room III are obviously in the best agreement with the numerical results. It is again observed that greater underestimates occur as the height-to-width ratio decreases, except for Sample T2 that has low scattering coefficients at all frequencies. One of the reasons for the exception may be due to not taking into account absorption coefficients of the sample, which was theoretically estimated by Eq. (4).

Figure 15 shows Eyring absorption coefficients of the four rooms in the empty condition, determined in various decay ranges of 20 dB. As the height-to-width ratio decreases, the absorption coefficients tend to be lower, which seems favorable to generate the one-dimensional specular field at first sight. However, a decrease in the height-to-width ratio also reduces the dispersion of energy scattered from the sample into the sidewalls. If the decay of the diffuse field is slower than the specular one, an underestimate in scattering coefficient can occur, which is more possible for higher scattering coefficients as observed in the above results.

### 4.4. Limitations of Measurement

According to the radiosity theory based on Lambert’s cosine law, the form factor between the floor and ceiling is equivalent to the ratio of return energy onto the opposite surface for each diffuse reflection. This form factor can be explicitly given by [24]

\[
F = \frac{2}{\pi XY} \left[ \ln[(1 + X^2)(1 + Y^2)/(1 + X^2 + Y^2)] + X/1 + Y^2 \tan^{-1}(X/1 + Y^2) + Y/1 + X^2 \tan^{-1}(Y/1 + X^2) - X \tan^{-1} X - Y \tan^{-1} Y \right],
\]

where \(X = L_a/L_c\) and \(Y = L_b/L_c\).

Assuming that the sidewalls are perfectly absorptive, the reverberation time of the diffuse field is given by

\[
T_d = \frac{6 \ln(10) L_d/c_2}{-\ln[F(1 - \alpha_{0,d})(1 - \alpha_d)] + m_2 L_d},
\]

where \(L_d\) is the mean free path between the floor and ceiling, which is somewhat greater than \(L_c\), \(\alpha_{0,d}\) and \(\alpha_d\) are the absorption coefficients of the ceiling and the sample under the diffuse incidence. To satisfy the condition that the decay of the specular field is slower than the diffuse one, \(T_2 > T_d\), the following relation is required from Eqs. (2) and (6):

\[
s_n < s_{n,max} = 1 - (1 + 2m_n L_c)F^{2L_c/L_d} < 1 - F^2.
\]

Accordingly, the maximum measurable scattering coefficient \(s_{n,max}\) can be roughly estimated from the room dimensions. Table 2 shows the form factors, the ratios of mean free path to room height calculated numerically, and the maximum scattering coefficients estimated with
a typical Eyring absorption coefficient of the sidewalls, $m_aL_z = 0.2$ (refer to the high frequency range in Fig. 15), for the above four rooms. This estimation seems to be roughly in agreement with the underestimates in Figs. 13 and 14. In a typical case of a cubic room, $F \approx 0.20$ and $L_d/L_z \approx 1.13$, which results in a maximum scattering coefficient of 0.92. Nevertheless, it should be recalled that the sidewalls’ attenuation coefficient for the specular field $m_a$ increases as the form factor is smaller, thus spoiling the measurement.

5. CONCLUSIONS

For determining normal-incidence scattering coefficients of architectural surfaces, a laboratory measurement method was newly proposed, which is performed in a quasi-one-dimensional sound field in a rectangular room with highly absorbent sidewalls. A test sample is mounted on the entire rigid floor, and the normal-incidence scattering coefficient is estimated from the reduction in reverberation time with the sample. As the first stage, 1/4-scale measurements were performed to validate the proposed method, and more specifically, to examine the influences of the measurement procedure and the test arrangement in comparison with theoretical and numerical results.

Regarding the measurement procedure for energy decay evaluation, the following tendencies are generally demonstrated:

- Determination of reverberation times from later decay is appropriate for estimating the scattering coefficients of the test sample.
- The decay range of 20 dB from $-20$ to $-40$ dB may be empirically reasonable to exclude the first rapid decay and to keep a sufficient decay range.

It is confirmed that the results measured in the above condition fairly agree with the numerical results for different types of samples in the mid and high frequency range. However, it is noted that a considerable overestimate can be involved in a low scattering coefficient if the absorption coefficient of the sample is not taken into account.

On the test arrangement, the following findings were clarified for ensuring the accuracy of the measurement:

- A sample with one-dimensional periodicity should be arranged as its short side to be in the periodic direction, if the sample is not square.
- The distance between the test sample and the opposite surface, which is the height of the room in the present configuration, should be greater than the side length of the sample, but guaranteed up to 1.5 times for the present.
- In general, a square area would be favorable for the test sample, excluding the influence of sample orientation.

Supposing that the surface roughness of a test sample is less than 20 cm, and the measurement frequency range is limited to be above 500 Hz, the sample area should be around 2.65 m square in accordance with ISO 17497-1, thus requiring a height of about 3 to 4 m for the test room. This requirement for room dimensions seems to be fairly realistic in real scale, for instance, easily built inside a rectangular test room specified in ISO 10140-5 [25] for measuring sound insulation of building elements.

After all, the proposed laboratory method is fairly advantageous to the in-situ method for the accuracy of determination, and will be practical for assessing the capability of suppressing flutter echoes of various architectural surfaces. Besides, an extended method of measuring scattering coefficients in two-dimensional sound field is proposed in [26].

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