Recent topics in acoustic scattering coefficient determination for wall surfaces

Tetsuya Sakuma (sakuma@k.u-tokyo.ac.jp)
Hyojin Lee
Graduate School of Frontier Sciences
The University of Tokyo
5-15 Kashiwanoha, Kashiwa, Chiba 277-8563, Japan

ABSTRACT

Three recent topics in acoustic scattering coefficient determination for wall surfaces are briefly presented: 1) validation of the reverberation room method of ISO 17497-1, 2) a new method of measuring normal-incidence coefficients, and 3) alternative determination by numerical simulation. First, the ISO method is reconsidered regarding unclear requirements of two approaches with stepwise and continuous rotation. It is theoretically and experimentally verified that the stepwise approach has a minimum number of angular steps, whereas the continuous approach has a minimum revolution period if using MLS signals, however if using swept sine signals, in the same way as the stepwise approach. Furthermore, the minimum requirements increase as the sample's scattering coefficient is higher, and unexpectedly, as the room's absorption area is smaller. Second, a new laboratory method is introduced for measuring normal-incidence coefficients, which would be useful to evaluate suppression of flutter echoes. The measurement is done in a rectangular room where installing highly absorbent materials on all vertical walls, and a test sample on the floor. In the one-dimensional field, normal-incidence coefficients of the sample can be determined by measuring the change in reverberation time with and without it. Third, as the alternative to measurement, numerical determination of scattering coefficients is demonstrated, and further practical applications are discussed.

1 INTRODUCTION

Since surface scattering plays a significant role in determining acoustic quality of rooms, its applications have been seen in a variety of architectural spaces. Up to now, the scattering coefficient, defined as the ratio of non-specularly reflected to total reflected energy, has been widely used for geometrical room acoustics simulation.

In 2004, a reverberation room method for measuring random-incidence scattering coefficients was standardized by ISO 17497-1 [1], based on the original work [2]. Although the following works investigated the effects of sample geometry, mounting, room condition and time variance [3-5], unclear points still remain in the special scheme employing stepwise or continuous rotation of a test sample. To guarantee the accuracy of the ISO method, Section 2 reconsiders requirements of the sample rotation in relation with test signal and room condition.

As a new attempt, a laboratory method is being developed for measuring normal-incidence scattering coefficients, which would be useful to evaluate suppression of flutter echoes between parallel walls. In Section 3, the principle of the method and some experimental examples are briefly presented with future prospects.
As the alternative to the above measurements, numerical determination is very promising for surface acoustic design. In Section 4, a BEM-based method in the free field determination [6] and numerical examples are presented, and further practical applications are discussed.

2 REVERBERATION ROOM METHOD OF ISO 17497-1

2.1 Two Approaches of Sample Rotation

ISO 17497-1 specifies the continuous approach using a multiple of a periodic pseudo-random signal such as the maximum-length sequence (MLS), where the revolution speed is not limited, although giving a revolution period of 60 seconds for 12 signals as an example. In this approach, the specularly reflected component is extracted through the two processes, cross-correlation for each signal period and coherent averaging of impulse responses over one revolution period. Obviously a certain upper limit exists in revolution speed, but it is not unclear, including whether it depends on the number of signals or the signal period.

The standard alternatively specifies that for the stepwise approach the number of coherent averages should be in the range from 60 to 120, and 72 averages is preferred corresponding to angular intervals of 5 degrees. This limitation is based on the early study [2], but has not yet been completely verified. It is obvious that an insufficient number of averages leads to some underestimation of scattering coefficient, thus the minimum number is of significance.

Another continuous approach using a multiple of a swept sine (SS) is relatively popular [3, 5]. Confusingly, this approach is almost equivalent to the stepwise approach, because not based on the correlation technique but on the time modulation technique. The specularly reflected component is extracted by coherent averaging, thus it is expected that the number of signals can be limited, corresponding to the number of angular steps in the stepwise approach.

2.2 Theoretical Error Estimation

Assuming air condition is time invariant, the scattering coefficient is determined by

\[
s = \frac{\alpha_{\text{spec}} - \alpha_s}{1 - \alpha_s}, \quad \text{with} \quad \alpha_s = 55.3 \frac{V}{cS} \left( \frac{1}{T_2} - \frac{1}{T_1} \right) \quad \text{and} \quad \alpha_{\text{spec}} = 55.3 \frac{V}{cS} \left( \frac{1}{T_4} - \frac{1}{T_3} \right).
\]

(1)

where \( V \) is the room volume, \( S \) is the sample area, \( T_1, T_2 \) are reverberation times without/with a sample at rest, and \( T_3, T_4 \) are those without/with a sample in rotating. Considering an error in \( T_4 \) due to sample rotation, the related error in scattering coefficient is given by

\[
\Delta s = \frac{\Delta \alpha_{\text{spec}}}{1 - \alpha_s} \approx - \frac{\Delta T_4}{T_4} \alpha_{\text{spec}} + \frac{A_1}{S} \frac{A_1}{1 - \alpha_s}.
\]

(2)

where \( A_1 \) is the absorption area of the room including air absorption.

In the stepwise approach, one measurement is performed when a test sample is fixed at each angular step, where the impulse response can be regarded as a superposition of the specular and the diffuse components. Assuming that the components correspond to the coherent and the incoherent over the whole measurements, synchronized averaging reduces the diffuse energy relative to the specular energy with increasing the number of steps \( N \) (Figure 1 (a)). In the continuous approach, a multiple of measurements is performed with periodic signals in sample rotation. If the cross-correlation technique is used with MLS, the specular energy is localized as the coherent, whereas the diffuse energy is spread over the signal period \( T_S \) as a random noise.
The noise energy is relatively reduced by synchronized averaging, accordingly the measured noise level depends on the revolution period \( T_R = N T_s \) (Figure 1 (b)).

\[
N = \frac{10^\left(\mu - \nu s\right) + 1}{10^\left(\nu s - \nu R/10\right) + \mu} + 1, \quad \text{with} \quad \mu = \frac{\alpha_s + A_i/S}{\alpha_{\text{spec}} + A_i/S} \quad \text{and} \quad \nu = \frac{1 - \frac{\alpha_s}{\alpha_{\text{spec}} + A_i/S}}.
\]

(3)

where \( R \) is the decay level for evaluation of \( T_4 \), fixed at -20 dB in the ISO standard. Figure 2 (a) illustrates the minimum number of steps for \( |\Delta s| \leq 0.05 \). It is seen that more steps are required for a greater scattering coefficient, and unexpectedly, less absorption of the room.

On the other hand, in the continuous approach using MLS, the minimum revolution period can be determined, proportional to the reference reverberation time \( T_0 = 55.3 V/cS \), by [7]

\[
T_R = \frac{1 - \mu}{\alpha_s + A_i/S} \frac{(1 - \nu s) R/60 + \beta (1 - 10^{R/10})}{(1 - 10^{\nu s R/10} + 10^{-6\beta} (1 - 10^{R/10}) T_0}.
\]

(4)
where $\beta = \frac{T_W}{T_4}$ with a truncation time $T_W$. Figure 2 (b) illustrates the minimum revolution period ratio for $|\Delta| \leq 0.05$, in the case with a typical truncation time $T_W = T_1/2$. It is seen that a longer revolution period is also required for a greater scattering coefficient, less absorption of the room, and additionally, the room volume. Note that the minimum ratio considerably depends on the truncation time, thus the accuracy control would be troublesome in this approach.

2.3 Experimental Verification

The continuous approach was tested in 1/4 and 1/1 scale measurements with SS and MLS signals, in a variety of conditions changing the revolution period and the signal period. Figure 3 shows results for a sample (15 battens, 10 cm square at 20 cm pitch in real) in 1/4 scale. In the use of SS, the scattering coefficients are underestimated at high frequencies as the number of signals is less than 30, whereas, as the revolution period is shorter than 81.9 s/rev in the use of MLS. These results support the above theoretical expectations that the minimum number of signals exists for SS, corresponding to the number of steps in the stepwise approach, and the minimum revolution period exists for MLS.

In the 1/4 scale room, $A_1/S$ increases roughly from 0.5 to 2.5 as the frequency goes up due to air absorption. Referring to Fig. 2, it can be stated that air absorption contributes to reducing an underestimation of scattering coefficient at high frequencies. However, the current ISO standard specifies that the room should satisfy that $A_1 \leq 0.30V^{2/3}$, and $A_1/S \leq 1$ as a rule-of-thumb. In real scale measurements, less absorption requires a long revolution period especially in the use of MLS, which can involve another critical problem due to time variance of air condition.

In conclusion, it is suggested for the amendment of ISO 17497-1 that: i) add a minimum absorption area of the room, ii) for the critical room condition, reexamine the minimum number of steps in the stepwise approach (the current range $60 \leq N \leq 120$ may be appropriate), iii) limit the signal type to time modulated signals such as SS in the continuous approach.

![Figure 3](image-url)  
**Figure 3:** Random-incidence scattering coefficients measured in 1/4 scale with SS (upper) and MLS (lower): (a) fixed signal period, (b) fixed revolution period, (c) fixed number of signals.
3 MEASUREMENT OF NORMAL-INCIDENCE SCATTERING COEFFICIENT

3.1 Principle of Measurement

The principle of measuring normal-incidence scattering coefficient is based on a simple idea that reverberation time of a one-dimensional field is shortened by a diffuse surface [8]. Figure 4 shows a 1/4-scale measurement setup where a one-dimensional field is generated by installing highly absorptive walls in a rectangular room. A test sample is mounted on the rigid floor, and two reverberation times, $T_0$, $T_1$, are measured without/without the sample.

In the one-dimensional field, normal incidence is dominated for the sample surface due to alternate reflections between the floor and ceiling. Based on the reverberation theory for one-dimensional field [9], the normal-incidence scattering coefficient of a sample $s_n$ is given by

$$s_E = \frac{13.8 L_c}{c} \left( \frac{1}{T_1} - \frac{1}{T_0} \right) - (\alpha_{Ez,1} - \alpha_{Ez,0}),$$

with $s_E = -\ln(1 - s_n)$.

(5)

where $L_c$ is the room height, $\alpha_{Ez,0}$, $\alpha_{Ez,1}$ are Eyring average absorption coefficients for the floor and ceiling without/with a sample, as follows:

$$\alpha_{Ez,0} = -\ln(1 - \alpha_{n,0}), \quad \text{and} \quad \alpha_{Ez,1} = -\ln\left(1 - \alpha_{n,0}\right)\left(1 - \alpha_{n,s}\right).$$

(6)

with $\alpha_{n,0}$, $\alpha_{n,s}$, the normal-incidence absorption coefficients of the floor/ceiling and the sample.

3.2 Measurement Setup

The 1/4 scale room is made of acrylic boards, with installing polyurethane foams (25 kg/m3, 150 mm thick) on the four walls. The absorption coefficients of the foam measured in a reverberation room are greater than 1 at all frequency bands. For a typical test room, the area of the sample is set at 4.8 m x 3.6 m, and the room height is at 3.6 m in real scale, however appropriate geometry for the measurement is to be further investigated. Impulse response measurements are done using SS signals in 10 combinations (2 sources, 5 receiving points), and an energy decay curve is obtained in each 1/3 octave band as the arithmetic means of the levels for all combinations. On trial, a sample that has the same periodicity as tested in Section 2.3 is mounted on the floor in the two orthogonal orientations.
3.3 Experimental Examples and Discussion

In averaged decay curves, remarkable curvature was seen especially at high frequency bands regardless of without/with the sample. In detail, the first decay to -10 dB is rapid, while the late decay from -15 dB is slow and relatively constant. Figure 5 shows scattering coefficients for the two sample orientations, determined in a variety of decay ranges. Although the measurements are unreliable below 500 Hz, the results measured in a certain condition roughly agree with the black lines representing numerical results (see Section 4). It is seen that the coefficients determined from the late decay generally decline, and tend to be steady as the decay level range is greater. Additionally, the effect of sample orientation seems not negligible to evaluate high scattering coefficients.

In some measurements for various samples, similar tendencies to the above mentioned were confirmed [10]. Up to now, an appropriate scheme for decay evaluation is not yet clarified, but the laboratory measurement method has a basic possibility to be established. To exclude the first rapid decay, and to keep a sufficient decay range, a range from -15 dB to -35 dB may be reasonable, however, it possibly depends on the geometry of the room, that is, the proportion of the sample area to the distance between two reflective surfaces. The examination on this point is currently in progress.

![Diagram showing scattering coefficients for different decay ranges: (a) 24 periods, (b) 18 periods.](image)

**Figure 5:** Normal-incidence scattering coefficients for two sample orientations, determined in different ranges of decay levels: 10 dB (upper), 20 dB (middle), and 30 dB (lower).
4 NUMERICAL DETERMINATION OF SCATTERING COEFFICIENTS

4.1 Numerical Model of the Free Field Method

A free field method to determine directional scattering coefficients was proposed by Mommertz [6], where the coefficient is given by the correlation between two reflection directivities for a sample and for a flat reference plate. Because reflection directivities are required, this method is very laborious for measurement, but suitable for numerical simulation using the boundary element method (BEM) [11].

In the numerical model, it is considered that a plane wave impinges on a surface in the free field, assuming that a sample and a reference plate with an equal area are perfectly reflective and have negligible thickness. It was verified that the outline shape hardly affects scattering coefficients of the surface [11], accordingly a square of 3 m, equal to the diameter in ISO 17497-1, may be recommendable for easy mesh generation.

Applying BEM in the normal derivative form to each incidence condition (\(N\) directions), the linear system is expressed by

\[
A[p_1, p_2, \ldots, p_N] = [d_1, d_2, \ldots, d_N], \quad \text{with} \quad A_{ij} = \iint_{\Gamma_i} \frac{\partial^2 G(r, r_q)}{\partial n_i \partial n_q} dS_q, \quad d_j = \frac{\partial}{\partial n} \exp(-j k_l \cdot r). \tag{7}
\]

where \(p_j\) is the sound pressure difference between the two sides of \(j\)-th element, and \(k_l\) is the wave number vector for \(l\)-th incidence condition. Solving the above system, the sound pressure differences for all elements are given, and in the post processing, reflection directivities can be calculated for each incidence condition. Finally, according to Mommertz’s definition, the directional scattering coefficient for each incidence condition is given by

\[
s(\theta, \varphi) = 1 - \frac{|\sum_{i=1}^{N} p_{0i} \cdot p_{i*}|^2}{\sum_{i=1}^{N} |p_{0i}|^2 \sum_{i=1}^{N} |p_{i*}|^2}. \tag{8}
\]

where \(p_{0i}, p_{i*}\) are the sound pressure reflected to \(i\)-th direction for the reference plate and for the sample. According to Paris’ formula, a random-incidence scattering coefficient can be also obtained by statistical averaging of directional coefficients, although it is not completely the same as the coefficient measured by the reverberation room method [12].

4.2 Numerical Examples and Discussion

Figure 6 illustrates three types of samples with periodic surfaces. For such samples, scattering coefficients can be calculated up to 4 kHz by a latest workstation with about 100 GB of memory. Figure 7 (a) shows random/normal-incidence scattering coefficients of the samples, calculated from directional coefficients as illustrated in Figure 7 (b). Numerical simulation can provide detailed characteristics of not only scattering coefficient but also diffusion coefficient [13], and it would be very promising as the alternative to the above measurements.

As an attempt, numerical simulation was applied to maximize the average scattering coefficient of periodic surfaces, where the optimal ratios of height to period were respectively found for the above three types of surfaces in random- and normal-incidence conditions [14]. Further applications to practical surface design will be expected, such as control of incidence angle dependence for first reflections in concert halls, fast calculation for one-dimensional surface structures and so on.
Figure 6: Geometry of three types of samples with periodic surfaces.

(a) Random/normal-incidence                          (b) Incidence angle dependence

Figure 7: Scattering coefficients calculated for three types with $L = 20$ cm and $h = 6$ cm.

5 CONCLUSIONS

Three recent topics in acoustic scattering coefficient determination for wall surfaces were briefly presented: 1) validation of the reverberation room method of ISO 17497-1, 2) a new method of measuring normal-incidence scattering coefficients, and 3) alternative determination by numerical simulation. Regarding the current ISO standard, issues on the sample rotation were pointed out, and requirements of the stepwise and the continuous approaches were suggested for the amendment. The new laboratory method for normal incidence is still under development, where some unclear points remain in test arrangement and evaluation of decay curves. On the other hand, numerical determination of scattering coefficients is almost for practical use in the full frequency range, and further applications to surface design are expected from now on.
REFERENCES


