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# Factors influencing scattering coefficient measurement accuracy in scaled reverberation room

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ABSTRACT

The method described in ISO 17497-1 standard has been worldwide adopted to measure the random-incident scattering coefficient of irregular surfaces either in a full-size reverberation room or in a scale model. In practical measurements, the sound energy propagation and decay at high frequencies (over 10 kHz) are easily affected by small operating errors and by tiny changes in the measurement conditions. It is difficult to obtain the same accuracy of results in the scale model as that in a full-size reverberation room while maintaining the same setup in both tests as suggested in the standard. This study performed a series of experiments in a 1:10 scale reverberation room to investigate the influence of several practical aspects on measurement accuracy. A maximum length sequence diffuser, with a design frequency of 1700 Hz (full-size value), was used as the specimen. All results obtained in the scaled reverberation room were compared to the reference values measured in a full-size reverberation room. Five factors were studied, which included different recording methods (double-channel and eight-channel), number of source positions (one and four), number of receiver positions (one, two, four and eight), turntable rotation conditions (full-turn or half-turn rotation during $T_3$ and $T_4$ measurements), and numbers of averages (24, 36 and 72). The results show that the first three factors above have greater impacts on the measurement accuracy of the scale model experiments than the remaining factors. When the multichannel recording method and four source positions were used in the scaled tests, the measured scattering coefficient values were more reliable, appearing much closer to the reference data over the whole frequency range. Furthermore, applying a half-turn of the turntable (in reference to the measurements of the axisymmetric diffusers) and a 36-impulse coherent average can greatly reduce the test duration without decreasing the measurement accuracy.

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## 1. Introduction

In the acoustics design of modern performance spaces, it is popular to install proper sound diffusing materials or structures on the upper sidewalls, the rear walls or the ceilings, which could help enhance the mixture of sound energies and the uniformity of the sound field and improve the acoustic experience of the audiences and performers [1,2]. In practical projects, it is necessary and important for acoustical engineers to have a good knowledge of the sound scattering characteristics of different diffusive surfaces. In references [3–9], it has been verified that more reliable predictions can be obtained when the sound scattering properties of the surfaces are included in room acoustic prediction formulas and computer simulations. Therefore, it is important to correctly estimate and measure the degree of sound scattering of diffusive surfaces. Among the kinds of estimation methods, the random-incident scattering coefficient ($s$) [10], which represents the percentage of the nonspecular reflected sound in the total reflected sound in front of the diffuser surface, has been widely accepted and most frequently used in research and projects because of its more practical applications in computer simulations such as ODEON, CATT, RAYNOISE, and RAVEN.

Laboratory measurements of the scattering coefficient, which can be made in either a full-sized or scaled reverberation room, has been standardized in ISO 17497-1: 2004 + A1: 2014 [11]. Since the publication of the ISO standard, uncertainties in the measurement method and the way in which they influence the measured results have been studied. To obtain more accurate results, some scholars [12–18] have carried out a series of experiments in a full-scale reverberation room to investigate some aspects of the measurement procedure that are recommended in the standard, such as the shape of the test sample, the rotation of the turntable, and the number of coherent averages. For instance, Geetere and Vermeir [14] found that when the turntable rotated step-by-step

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(manually or automatically), the measured scattering coefficient values of the base plate were much higher than those measured with continuous rotation of the turntable and that a long waiting time after closing the door of reverberation room had little influence on the measurement accuracy. To minimize the edge effect caused by the exposed boundaries of the test sample or the turntable, it is recommended to use some sealing methods, such as edge strips and concrete blocks [13,15,16]. In addition, some unspecified aspects of the standard have also been investigated in prior research [18–23]. Shtrepi et al. [20] studied the influence of microphone height, the scattering properties of the turntable, and the height of the air gap below the base plate on the accuracy of full-size measurements. In a study by Embrechts [15], to improve the accuracy of the phase-locked averaging of the measured impulse responses, a tone burst was sent certain seconds before the emission of a sweep signal so that the direct sound could be clearly identified in the measured impulse responses. With decades of development, at present, the scattering coefficient can be measured in a full-scale reverberation room with reasonable accuracy.

In theory, with the same measurement procedure and testing setup, the results measured in a scale model should be the same as those tested in a full-size reverberation room. With the benefits of convenient installation, flexible operation and low costs, scaled measurements are more attractive than full measurements and allow us to more easily construct a database of scattering coefficients for acousticians and engineers. Hence, the accuracy of scaled measurements of the scattering coefficient is as important as that of full-size measurements. However, scaled measurements, especially those for large-scale factors, are more sensitive to tiny changes in environmental conditions and to small measurement errors than full-size measurements. To improve the accuracy of scale model measurements, some scholars [12,13,24–27] studied the influence of some practical aspects in a scale model reverberation room and provided some helpful guidance on scaled measurements. Sakuma and Hyojin [24] suggested that the turntable should rotate by 3° to 6° for each measurement, and the results measured in the full-size and scale model demonstrate that the combination of turntable rotation speed and signal period could influence the measurement accuracy. Vorländer et al. [13] studied the problem of air absorption in scaled measurements and suggested substituting other gases for air to increase scaled measurement accuracy. Jeon [26] tested the scattering coefficient of wooden hemispheres in two different scaled reverberation rooms (with scale factors of 5 and 10). It was found that the effect of air absorption increased with the scale factor and that the mean scattering coefficients obtained in the 1:10 scale chamber showed good agreement with the results obtained in the 1:5 scale chamber when substituting nitrogen for air in the 1:10 scale model. Although this method could weaken the effect of air absorption, it might be hard to popularize due to the demanding measurement apparatuses and techniques required. Other ways to overcome this problem should be investigated in the future, such as maintaining low air humidity or reducing the test duration. In addition, some aspects or factors affecting the scaled measurement accuracy have not been addressed in previous research, such as the recording method. Therefore, more work is needed to investigate and measure the effects of these factors (both specified and unspecified by the ISO standard) on scaled measurement accuracy.

In this study, a series of experiments was performed in a 1:10 scale reverberation room to investigate the effect of some aspects of the ISO standard on scaled measurement accuracy, aiming to provide some helpful guidance for scaled measurements and contribute to a standard revision. A maximum length sequence (MLS) diffuser was taken as the specimen in this paper. Several aspects of the standard were investigated, including the number of source positions and receiver positions, the number of averages (n = 24, 36 and 72), the turntable rotation condition (full revolution and half revolution), and the recording method (double-channel and eight-channel). There are some recommendations given for the first three aspects by the standard, while the last two aspects are not specified in the standard; this paper is the first to study their impacts on the scaled measurement accuracy of scattering coefficient. The results measured in the 1:10 scale chamber were compared with reference results measured in the full-scale reverberation room. Finally, a proper measurement arrangement for the scale reverberation room, together with some suggestions on the measurement procedure and testing setup for scaled reverberation rooms, was recommended.

## 2. Theory

The random-incident scattering coefficient is defined as the ratio of nonspecular reflected sound energy ($E - E_{spec}$) to the total sound energy reflected from a surface ($E$) in a diffuse sound field. According to the measurement method described in ISO 17497-1 [11], the measurement of the random-incident scattering coefficient ($s$) consists of two parts: the measurement of the absorption coefficient $\alpha_s$ and the specular absorption coefficient $\alpha_{spec}$. The relationship (Eq. (6)) between the above three parameters can be easily derived from their definitions (Eqs. (1)–(3)):

$$s = \frac{E - E_{spec}}{E} \tag{1}$$

$$\alpha_{spec} = \frac{E_0 - E_{spec}}{E_0} \tag{2}$$

$$\alpha_s = \frac{E_0 - E}{E_0} \tag{3}$$

Since the measurement process for $\alpha_s$ is detailed in ISO 354 [28], it will not be described in detail here. $\alpha_{spec}$ is defined as the ratio of the nonspecular reflected acoustic energy ($E_0$ - $E_{spec}$) to the total incident sound energy ($E_0$) (Eq. (2)). In the measurement of $\alpha_{spec}$, the key is to extract the specular energy from the reflected pulses, which can be done by phase-lock averaging the room impulse responses obtained from different orientations around the sample. As the specular reflections in these impulses are highly correlated while the scattered sound is not in phase, the scattered sound energy interferes destructively after phase-lock averaging of the impulse responses.

The measurement processes of $\alpha_{spec}$and $\alpha_s$ are similar, both of which need to measure the impulse responses of the reverberation room with and without the sample. The only difference is that the measurement of $\alpha_{spec}$ requires the turntable to rotate in order to obtain impulse responses from different orientations of the sample. From the impulse responses obtained under different conditions (as shown in Table 1), four reverberation times can be calculated. With them, the scattering coefficient can be calculated using Eqs. (4–6):

$$\alpha_s = 55.3\frac{V}{S}\left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1}\right) - \frac{4V}{S}(m_2 - m_1) \tag{4}$$

**Table 1**
Measurement conditions for the four different reverberation times.

| Reverberation time | Sample | Turntable |
|---|---|---|
| $T_1$ | Not present | Not rotating |
| $T_2$ | Present | Not rotating |
| $T_3$ | Not present | Rotating |
| $T_4$ | Present | Rotating |

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