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Effects of Unspecified Experimental Conditions in ISO 17497-1 on the Scattering Coefficients Measured in a Scale Model

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Summary
This study extends the authors' previous investigation on the measurement of random-incidence scattering coefficients in a reverberation room [Acta Acustica United with Acustica 94 (2008) 769-773]. The present study further investigates the effects of some unspecified experimental conditions in ISO 17497-1 on the measured scattering coefficients; these conditions include the sample diameter, the addition of an edge strip around the sample perimeter, the air gap below the turntable, and the absorption of the test sample. The results of scale-model measurements indicate that the sample diameter, air gap below the turntable, and absorption of the test sample have significant effects on the measured scattering coefficient, particularly for values obtained in the mid- and high-frequency bands. The edge effect is minimized by using an edge strip around the sample perimeter; the edge strip has a considerable influence on the scattering coefficients in the highest frequency bands.

PACS no. 43.55.-n

1. Introduction

The ISO 17497-1 standard [1] refers to the technique used for measuring the random-incidence scattering coefficient in a reverberation room. The concept of the proposed ISO measurement technique involves the recording of a series of impulse responses for a circular test sample placed at different angle positions on a centrally rotating base plate. Synchronous averaging of these impulse responses yields a virtual impulse response which relates only to the specular component of the reflected energy. The reverberation time should be obtained from the impulse response measurements under four different conditions (Table I). The scattering coefficient can be calculated from the differences in reverberation time. The measurement should be performed in one-third-octave bands with centre frequencies ranging from 100 Hz to 5000 Hz in either a full-scale or a reduced-scale reverberation room.

$$s = \frac{\alpha_{\text{spec}} - \alpha_s}{1 - \alpha_s}, \tag{1}$$

$$\alpha_s = 55.3\frac{V}{S}\left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1}\right) - \frac{4V}{S}\left(m_2 - m_1\right), \tag{2}$$

$$\alpha_{\text{spec}} = 55.3\frac{V}{S}\left(\frac{1}{c_4 T_4} - \frac{1}{c_3 T_3}\right) - \frac{4V}{S}\left(m_4 - m_3\right), \tag{3}$$

where T_n is the reverberation time obtained for the measurement condition in Table II, and c_n and m_n are the speed of sound in air (m/s) and the energy attenuation coefficient of air (m^{-1}) during the measurement of T_n, respectively.

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Table I. Measurement conditions for four different reverberation times.

Reverberation time	Test sample	Turntable
T_1	Not present	Not rotating
T_2	Present	Not rotating
T_3	Not present	Rotating
T_4	Present	Rotating

Table II. Specifications given in ISO 17497-1. N denotes the scale factor, V the Reverberation room volume, d the base plate diameter, e the minimum distance to the walls of the room, h the structural depth of the test sample, α_s the absorption coefficient of the test sample and n the number of coherent averages. The number of source and microphone positions was two and three, respectively, obeying the minumum number requested by ISO.

Parameter	ISO standard	1/5 scale model
V	$V \geq 200/N^3$	$V = 2.4\,\text{m}^3$
d	$d \geq 1/N \cdot 3\,\text{m}$	$d \geq 0.6$ m
e	$e \geq 1/N \cdot 1\,\text{m}$	$e \geq 0.2\,\text{m}$
h	$h \leq d/16$	$h \leq 0.04\,\text{m}$
α_s	$\alpha_s \leq 0.50$	$\alpha_s \leq 0.50$
n	$60 \leq n \leq 120$	$n = 72$

With respect to the test arrangement in the reverberation room, the standard specifies the minimum volume of the room and the minimum absorption in an empty room.

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Table III. Major differences in the measurement conditions between the authors' previous study [5] and present study.

Measurement conditions	Previous study	Present study
Diffusivity of the sound field in the reverberation room	No diffusers installed	Thirteen diffusers installed
Repeatability test	No repetition	Repetition (three times)
Compensation for air absorption	Numerical method	Nitrogen
Sample rotation technique	Manual stepwise measurements	Continuous measurements
Test cases for each parameter (reduced-scale)	Sample diameter 0.64 m, 0.84 m Air gap below the turntable 50 mm, 222 mm	Refer to Table IV
Materials for the base plate	15 mm thick varnished MDF	15 mm thick acryl panel

Furthermore, the shape and dimensions of the base plate as well as the turntable should be within specified ranges (refer to Table III for the specifications given in the ISO method).

In recent years, numerous studies have attempted to investigate the practical aspects of the diffuse field method based on ISO 17497-1 for measuring the scattering coefficient [2, 3, 4, 5]. Some of these aspects have already been investigated and reported in previous studies [3, 4, 5, 6], but further investigation and verification of the results of these earlier studies is a worthwhile objective. The authors' previous study [5] was a preliminary investigation of the effects of the sample diameter, air gap below the turntable, and absorption of the sample on the measured scattering coefficients.

However, from the viewpoint of obtaining reliable results, some problems remain unsolved with respect to the measurement setup and experimental procedure: these problems include the diffusivity of the sound field in the reverberation room, the repeatability of the test method, the compensation for air absorption, the technique used for rotating the sample, and the limited number of test cases. Some improvements in the measurement conditions were made to obtain reliable measurement results.

Table III compares the major changes in the measurement conditions between the authors' previous and present studies. Excessive air absorption leads to a lower reverberation time, which may result in high measurement errors, particularly for values in the high-frequency bands. The influence of air absorption seems obvious even in the large-scale model, i.e. the 1/2 scale model; unreliable scattering coefficients were obtained at high frequencies [7]. The problem of air absorption in a scale model could be solved by substituting air with nitrogen and by applying a numerical method. A numerical method was utilized for the compensation of air absorption in previous research, but this method was not successful on account of the low signal-to-noise ratio in the high-frequency bands from 15 kHz to 25 kHz (corresponding full-scale frequency bands from 3 kHz to 5 kHz); very low scattering coefficients were obtained. The authors' previous study involved manual stepwise measurements for one complete rotation of the turntable; these measurements required longer measuring times than continuous measurements. It was found that long measuring times result in high scattering coefficients for the base plate at high frequencies [4]. Only two cases for each parameter were tested; further studies with more test cases are required to verify the reliability of the results. For the above reasons, the present research attempted to solve the unsolved problems in the authors' previous study [5] from the viewpoint of practical application of the diffuse field method for measuring the scattering coefficient on the basis of ISO 17497-1. Various experimental conditions for obtaining repeatable scattering coefficients were investigated and the results were discussed.

2. Previous research

In Gomes's study [3], the practical problems related to the measurements of the scattering coefficient were investigated in a 1/5 scale model of the reverberation room. The major issues encountered in his study were the number of averages; the phenomenon of air absorption (particularly at high frequencies); the time variations in the reverberation room; the size, shape, and positioning of the sample; and the precision of the results. The results obtained from the scale-model measurements were also compared with the full-scale results obtained from several different laboratories. Vorländer *et al.* [4] investigated some practical aspects for measuring the scattering coefficient in both full-scale and model-scale reverberation rooms and compared the results of full-scale and model-scale measurements to determine the uncertainties of the measurement method. The results revealed small differences between the results of the full-scale and the reduced-scale measurements that were caused by variations in certain aspects of the mounting method, such as the connection or sealing between the sample and the base plate. In addition, the sample rotation technique, air absorption, and time variances in the full-scale reverberation room were factors that influenced the measured scattering coefficients. Vorländer *et al.*'s results [4] suggest that full-scale measurements could be successfully performed if these practical problems were solved.

Although Gomes [3] and Vorländer *et al.* [4] verified the diffuse field method for measuring the scattering coefficient on the basis of ISO 17497-1 [1], several issues remain unresolved with respect to the practical application of this method; these include the sample area, edge strip

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effect, absorption of the sample, mounting method, and air absorption at high frequencies. Mommertz [3, p.38] proposed the absolute error of the measurement of the scattering coefficient as

$$\Delta s = \frac{\Delta T}{T}\frac{1}{1-\alpha}\left[\frac{2A_1}{S_{\text{sample}}}(2-\delta)+\delta+2\alpha(1-\delta)\right], \quad (4)$$

where α is the absorption coefficient, δ the scattering coefficient, S_{sample} the sample area, A_1 the equivalent absorption area of the sample and $\Delta T/T$ the relative error for the reverberation time. According to this equation, the sample area should be as large as possible to obtain reliable measurement results, but this can lead to a higher absorption area. On the basis of the recommendations in ISO 354 [8] and Mommertz's proposal, Gomes [3] suggested that the sample area should ideally be as large as possible within the limits

$$0.25V^{2/3} \le S \le 0.30V^{2/3}, \quad (5)$$

where V is the volume of the room. ISO 17497-1 specifies that the minimum sample diameter should be $N^{-1} \cdot 3\,\text{m}$ (N: scale factor).

Kreutner [6] carried out measurements of circular and square samples with the same surface roughness and obtained slightly different results. Although he proposed a correction factor for measuring square samples, it remains unclear whether this factor can be applied independently of the sample area or the edge height. Gomes [3] performed further investigations for different sample shapes, such as circular and square samples, and proposed alternative solutions to minimize the edge effect due to sample geometries, i.e. the height of the edges. As per Gomes's findings [3], the scattering coefficients for two test samples, i.e. hemispherical and sinusoidal samples, showed significant differences when square samples including edges were used. This implies that the edge effect occurs with square samples including edges, and it results in unreliable scattering coefficients. Therefore, the standard recommends that a circular sample shape be used. An alternative method in which the square sample is mounted on a square recess can also be applied if it is impossible to construct circular samples. More comprehensive information on the correction for the edge effect can be found elsewhere [3, 4, 7].

Because excessively high absorption coefficients may lead to unreliable results in scattering coefficient measurements, the ISO standard specifies that the absorption coefficient of the sample should not exceed 0.5. In this context, it is difficult to measure the scattering coefficient of quadratic residue type Schroeder diffusers since these diffusers have high absorption coefficients on account of the interference of sound waves between the gaps [9, 10].

In full-scale measurements, a smaller air gap below the turntable decreases the turntable diffraction at high frequencies [4]. In the scale-model measurements [5], two air gaps of 50 mm and 222 mm (reduced-scale) were utilized, and a lower scattering coefficient was obtained in the frequency bands from 630 Hz to 2.5 kHz when the smaller air gap (50 mm) was used. Few scale-model measurement studies have reported such a result. Further, there is a variety of turntables available from different manufacturers.

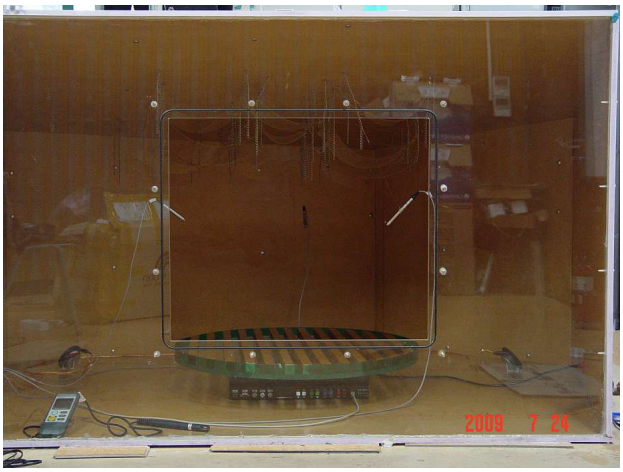


Figure 1. One-fifth-scale model of the reverberation room.

3. Measurements

3.1. Scale-model setup

In the present study, a 1/5 scale model (Figure 1) of the reverberation room was used for the measurement; the volume of the scale model was 2.4 m^3. The scale model was built using 15 mm thick varnished medium density fibreboard (MDF) panels. The base plate was made of a 15 mm thick acryl panel. Prior to the measurements, the diffusivity of the sound field in the reverberation room was tested in accordance with ISO 354 [8]. A total of 13 diffusers (1.5 mm thick acryl) of different sizes with areas ranging from approximately 0.8 m^2 to 3.0 m^2 were installed on the ceiling of the reverberation room; these diffusers correspond to a total surface area of 20 m^2 (full-scale). The results indicated that the measurements in the corresponding full-scale frequency bands from 100 Hz to 5 kHz were reliable. All the scale-model setups satisfied the specifications provided in ISO 17497-1 [1] (Table II).

3.2. Some unspecified experimental conditions in the scattering coefficient measurements

Table IV presents some unspecified experimental conditions in ISO 17497-1 that were used for further investigation. The first parameter, sample diameter, quantifies the area of the test sample with respect to the volume of the reverberation chamber; three base plate diameters, 0.64 m, 0.74 m, and 0.84 m (reduced-scale), were investigated. Test sample areas ranging from 7.07 m^2 to 13.44 m^2 (full-scale), as given by the ISO standard [1] and Gomes's study [3], were considered. Therefore, the three sample areas studied were in the range 8.04–13.85 m^2 (full-scale). Periodic battens of 11–13 periods were used for different base plate diameters.

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Table IV. Some unspecified experimental conditions in ISO 17497-1.

Parameter	Variation	Previous research
Sample diameter (reduced scale)	0.64 m, 0.74 m, 0.84 m	[2, 3, 5]
Edge effect	Sample with and without an edge strip	[3]
Air gap below the turntable (reduced scale)	105 mm, 125 mm, 145 mm, 165 mm, 185 mm	[4, 5]
Absorption of the test sample (frequency-averaged values)	Unvarnished periodic battens ($\alpha = 0.31$) Varnished periodic battens ($\alpha = 0.09$)	[3] [5]



Figure 2. Samples of the periodic battens (top: sample without an edge strip; bottom: sample with an edge strip).

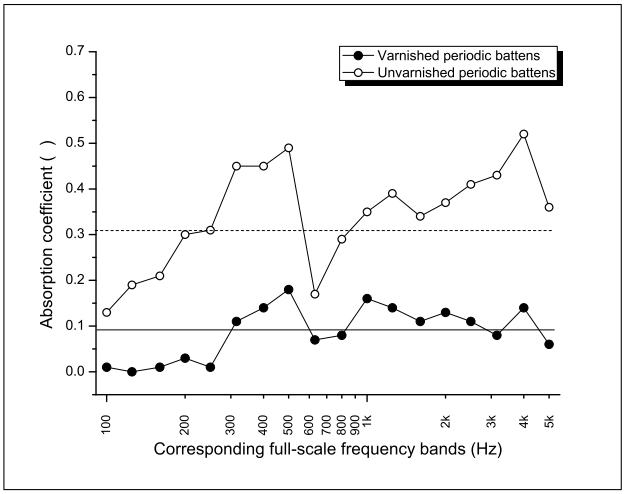


Figure 3. Absorption coefficients of the unvarnished and varnished periodic battens. Solid and dashed lines indicate the frequency-averaged absorption coefficients of the varnished and unvarnished periodic battens, respectively.

The second parameter concerns the problems related to the edge effect of the sample. Samples with and without an edge strip around the sample perimeter were investigated (Figure 2). For the cancellation of the edge effect originating from the exposed sides along the sample perimeter, an edge strip made of rigid and reflective materials was previously used for measuring the random-incidence absorption coefficient [8]. The edge strip used in the study was made of a 3 mm thick acryl panel (reduced-scale).

The third parameter is the air gap below the turntable: five different values of the air gap, 105 mm, 125 mm, 145 mm, 165 mm, and 185 mm (reduced-scale), were investigated. The turntable used in this study has a height of 0.105 m. This parameter would be more critical in the full-scale measurements than in the scale-model measurements because it depends on the type of motor used [4, 5]. Although various types of turntables are commercially available, the effect of the type of turntable on the scale-model measurements has received little attention.

The fourth parameter is the absorption of the test sample. Periodic battens (3 cm × 3 cm) made using MDF were utilized as the test samples. The absorption coefficient was controlled by varnishing the batten surface. The frequency-averaged absorption coefficients of the unvarnished and varnished battens were 0.31 and 0.09, respectively (Figure 3).

3.3. Measurement technique

In the measurements, a 1.34-s logarithmic sweep from 500 Hz to 100 kHz was used; this corresponded to full-scale frequencies from 100 Hz to 20 kHz. The compensation of air absorption in the scale-model was dealt with by substituting air with nitrogen. The relative humidity was approximately 11% throughout each measurement. With respect to concert hall acoustics, a relative humidity ranging from 2% to 5% is preferred in order to compensate for the effect of air absorption at high frequencies in the scale-model measurements [11, 12]. Although the relative humidity used in the study was somewhat higher than that used in concert hall acoustics, it was found to be satis-

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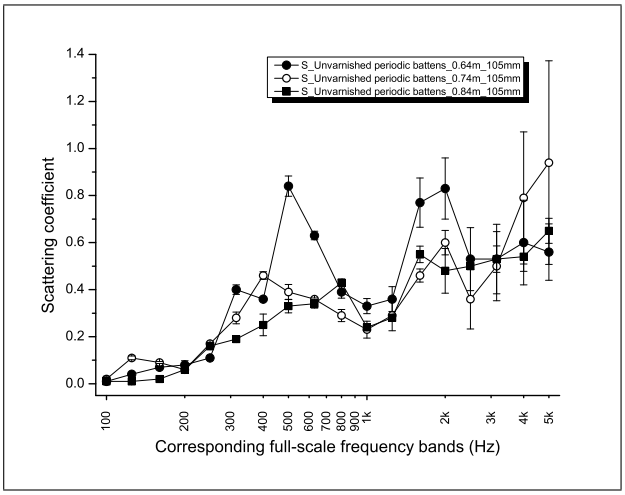


Figure 4. Scattering coefficients of unvarnished periodic battens for three different sample diameters (sample without an edge strip; air gap of 105 mm).

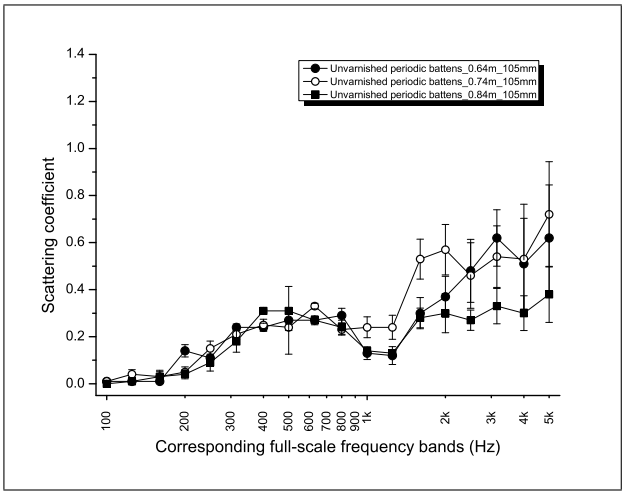


Figure 5. Scattering coefficients of unvarnished periodic battens for three different sample diameters (sample with an edge strip; air gap of 105 mm).

Table V. Measurement equipment used in the study.

Equipment	Model	Manufacturer
Loudspeaker	XT25TG30-04	Vifa
1/2 inch microphone	Type 4191	B&K
Microphone preamplifier	Type 26AK	G.R.A.S
Conditioning amplifier	Type 2829	B&K
A/D board	Lynx L22	Lynx Studio Technol. Inc.
Measurement software (Dirac V.4.1)	Type 7841	B&K
Turntable	LR 360	Linear X Systems

factory for providing reliable results, particularly at high frequencies. An automatic turntable was used to perform continuous measurements; the total measurement duration was equal to the time required for one revolution of the turntable (105.26 s). Table V lists the equipment used in the study. The repeatability of the scattering coefficient measurements was tested. In all, nine measurements were carried out; the standard deviations after nine measurements showed that the measurements had reliable repeatability in the corresponding full-scale frequency bands from 100 Hz to 5 kHz. For this reason, the measurements were repeated three times, and the results were presented as mean scattering coefficients and their corresponding standard deviations.

4. Results and discussion

First, the effect of the sample diameter on the scattering coefficient was investigated. Figure 4 shows the scattering coefficients of the unvarnished periodic battens measured for three sample diameters when a sample without an edge strip was used. The air gap below the turntable was 105 mm. The observed changes in the scattering coefficients of the unvarnished periodic battens as a function of the sample diameter were not systematic. Some of the scattering coefficients were greater than 1.0 in the 4 kHz and 5 kHz octave bands. To minimize the edge effect due to the exposed sides along the sample perimeter, an edge strip was utilized, and the scattering coefficients of the unvarnished periodic battens were measured (Figure 5). Please note that the scattering coefficients of the base plate were measured by placing the edge strip along the base plate perimeter. As shown in Figure 5, the scattering coefficients measured for the sample with an edge strip were considerably smaller than those measured for the sample without an edge strip; the edge effect at high frequencies was also minimized by using the edge strip. Some of the overestimated scattering coefficients in the 500 Hz, 630 Hz, 1.6 kHz and 2 kHz octave bands for the sample diameter of 0.64 m were corrected. The scattering coefficients measured with an edge strip along the sample perimeter as a function of the sample diameter showed a different trend in comparison with those measured without an edge strip. The highest scattering coefficients were obtained at the sample diameter of 0.64 m for the sample without an edge strip, while the sample diameter of 0.74 m showed the highest scattering coefficients for the sample with an edge strip. In previous research [5], the sample diameter of 0.64 m (the air gap below the turntable was 222 mm) showed a lower scattering coefficient in the frequency bands from 400 Hz to 2.5 kHz, but opposite tendencies were observed in the present study. The findings of the present study can possibly be attributed to some improvements in the measurement conditions (Table III).

Analysis of variance (ANOVA) was employed to further verify the differences in the scattering coefficients for the three sample diameters. The scattering coefficients measured for the sample with an edge strip were used for the ANOVA test since the effects of edge scattering were reduced in these measurements. The one-way ANOVA tests whether the means of two or more samples are equal. It assumes that all the samples are drawn from normally dis-

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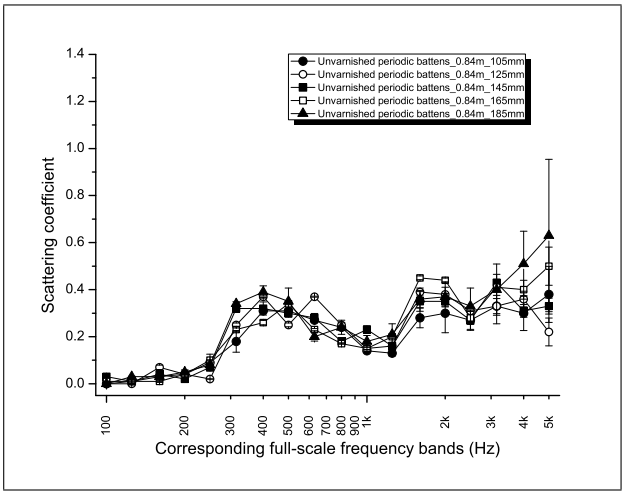


Figure 6. Scattering coefficients of unvarnished periodic battens for five different values of air gap (sample with an edge strip; sample diameter of 0.84 m).

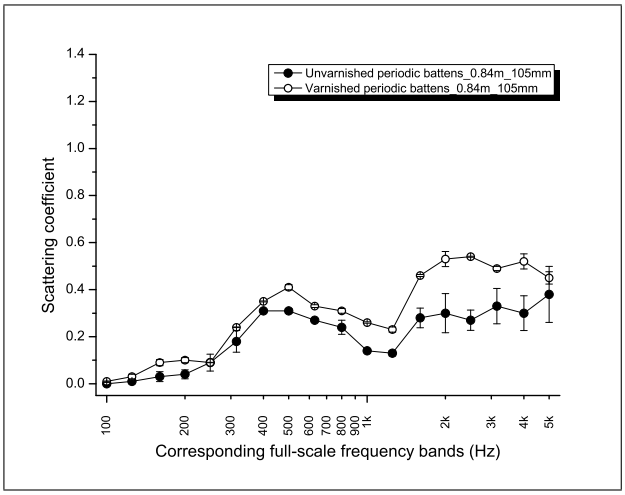


Figure 7. Scattering coefficients of unvarnished and varnished periodic battens (sample with an edge strip; sample diameter of 0.84 m; air gap of 105 mm).

tributed populations with equal variance. The p-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true; p-values of < 0.05 are statistically significant, resulting in rejection of the null hypothesis. The one-way ANOVA result indicates that the sample diameter ($p < 0.05$) had a significant effect on the scattering coefficients at low frequencies (125 Hz, 200 Hz, and 400 Hz), intermediate frequencies (630 Hz and 1–1.6 kHz), and high frequencies (2 kHz and 3.15 kHz); the most significant effect was obtained in the 200 Hz, 630 Hz, 1 kHz and 1.6 kHz octave bands ($p < 0.01$). Figures 4 and 5 show that the sample with a diameter of 0.84 m showed smaller standard deviations with regard to the measured scattering coefficient; this suggests that the sample diameter of 0.84 m should be used in order to obtain reliable scattering coefficient measurements. This result is in agreement with the results obtained in previous research [3].

To minimize the edge effect, measurements were carried out for the sample with an edge strip. Figure 6 shows the scattering coefficients of the unvarnished periodic battens measured for five values of air gap below the turntable. In the measurements, the sample diameter was set to 0.84 m. As shown in Figure 6, the scattering coefficients increased with the air gap below the turntable, and larger variations were found for the values at intermediate and high frequencies; this finding was in good agreement with the results of previous research [4, 5]. This suggests that the air gap below the turntable should be maintained at a small value. An alternative for minimizing the turntable diffraction due to the air gap would be to recess the turntable within the floor of the reverberation room. The one-way ANOVA results show that the air gap ($p < 0.05$) has a significant effect on the scattering coefficients at low frequencies (100–160 Hz and 250–400 Hz), intermediate frequencies (500 Hz to 1.6 kHz), and high frequencies (4 kHz); the most significant effect was obtained in the 315 Hz and 630 Hz octave bands ($p < 0.0001$).

The scattering coefficients of the unvarnished and varnished periodic battens were measured to verify the effect of the absorption of the test sample on the scattering coefficients. Figure 7 shows the scattering coefficients of the unvarnished and varnished periodic battens. The sample diameter was 0.84 m, and the air gap below the turntable was 105 mm. As shown in Figure 7, the scattering coefficients of the varnished periodic battens were higher than those of the unvarnished ones; the differences were the greatest at high frequencies from 1.6 kHz to 4 kHz. This result showed an opposite tendency in comparison with the results of the authors' previous research [5]: lower scattering coefficients were obtained for varnished periodic battens in the frequency bands from 250 Hz to 630 Hz. In general, larger standard deviations in the scattering coefficients were observed for the unvarnished periodic battens than for the varnished ones. The repeatability of the measurement results was improved when a more rigid and reflective sample was used. The one-way ANOVA result shows a significant effect of absorption ($p < 0.05$) on scattering coefficients at low frequencies (160 Hz, 200 Hz, and 400 Hz), intermediate frequencies (500 Hz to 1.6 kHz), and high frequencies (2.00–3.15 kHz); the most significant effect was obtained in the 400 Hz and 1 kHz octave bands ($p < 0.0001$).

5. Conclusion

The present study further investigated the effects of some unspecified experimental conditions in the diffuse field method on scattering coefficient measurements obtained on the basis of ISO 17497-1. The results of the present study are summarized as follows:

- The scattering coefficients of the unvarnished periodic battens did not vary systematically with an increase in the sample diameter. Larger sample diameters were associated with smaller standard deviations of the measured scattering coefficient. This suggests that the sample diameter should be as large as possible.

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- The scattering coefficients increased with the air gap below the turntable, and larger variations were found for the values at mid- and high-frequencies. This suggests that the air gap below the turntable should be small.
- Larger standard deviations of the scattering coefficients were observed for the unvarnished periodic battens than for the varnished ones. The repeatability of the measurement results was improved when a more rigid and reflective sample was used.
- The edge effect was minimized by using an edge strip around the test sample perimeter. It was found that the edge strip had a considerable influence on the scattering coefficients in the highest frequency bands. ISO 17497-1 specifies "*do not cover the perimeter with a rigid border of fixed height*." This is likely to be in contrast with the results obtained from the present study.

The results of the present research were limited to the scale-model measurements, and no comparisons with full-scale measurements and theoretical results were carried out. Thus, to verify the findings of this study, full-scale measurements must be performed so that the results of the full-scale and model-scale arrangements obtained under the same experimental conditions can be compared.

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