# Case studies in measurement of random incidence scattering coefficients

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Summary

In this work measurements of random-incidence scattering coefficients in three laboratories are compared. The sample geometry is sinusoidal. These surfaces are geometrically identical, but they were constructed in different scales. So far, measurements of this kind were performed only in scale models. Using turntables in real sample size was hardly considered possible. One result of general importance is that measurements are indeed possible in real-scale reverberation rooms with turntables of 3 m diameter. There are only small differences between the real-scale and model-scale results. Some variations of the standard procedure were tested and the uncertainties identified: mounting of the sample, connection or sealing between sample and base plate, way of rotating the sample, air absorption and time variances. The results presented can be regarded as guidelines for application of ISO/DIS 17497-1.

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## 1. Introduction

Acoustic properties of surfaces are an important prerequisite for calculation or, at least, estimation of sound propagation in various applications. The task of determination of the reflection of sound waves in outdoor noise propagation or in underwater acoustics, the complexity of reflections in room acoustics or ultrasonic waves reflected from cracks in a tested material give an impression of the need for a reliable database of surface properties or other discontinuities.

The most important surface property is the acoustic impedance, $Z = p/v$, with $p$ sound pressure and $v$ particle velocity. Any change in boundary conditions, basically changes in material will lead to an impedance-caused reflection of sound waves. The surface impedance and the corresponding reflection are usually related to a finite or infinite flat surface. This problem is among the very basic problems in acoustics, and it is analytically solved for various kinds of waves and impedances.

Another question, however, is the influence of the *shape* of the surface, independently of the surface impedance, and the corresponding effect on the reflection of sound. The complete answer, of course, would involve a consideration of the impedance and the shape of the reflecting surface. In many applications in acoustics these two parameters are interpreted separately, one being a descriptor for sound absorption as an energy relationship, and the other for sound scattering as a spatial relationship (see section 2). Accordingly measurement methods for determination of impedance, absorption and scattering were developed and standardised ([1, 2, 3]), particularly for use in room acoustics.

The importance of the use of a scattering coefficient in room-acoustical computer simulations is already known [4, 5, 6]. With this coefficient, effects of diffuse reflections are taken into account. It is important, however, not to mix up the meaning of the "diffusion coefficient" in contrast to the "scattering coefficient". Both coefficients are related to diffuse characteristics of a reflection, but they have different definitions. The diffusion coefficient is related to the surface scattering uniformity in a free field environment [7, 8, 9].

This contribution aims at clarification of factors causing uncertainties and proposal of measurement parameters giving more robust results in the measurement of the random - incidence scattering coefficient.

## 2. Principle of the measurement and results

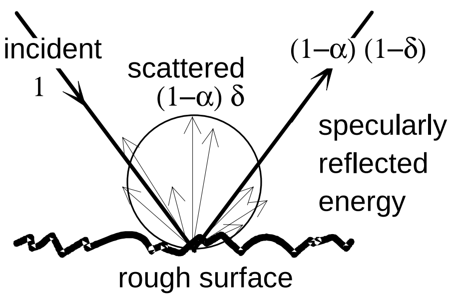


**Figure 1.** Energy components of scattered sound.

The scattering coefficient is defined as a ratio between the scattered energy to the total reflected energy [10] (Figure 1). This definition agrees very well with the model of diffuse reflections nowadays used in ray tracing programs (see [11]). The International Organisation for Standardisation (ISO) was mandated to develop and publish a standard for measuring the random-incidence scattering coefficient with a correlation technique (in diffuse field). The principle of the measuring technique takes advantage of the fact that an impulse response, measured over a diffuser in the same place but in different orientations, presents differences in amplitude and phase in its late part. As impulse responses measured for different orientations of the diffuser are averaged, the late non correlated parts will cancel each other, resulting in an impulse response ("specular impulse response") whose decay time is smaller, when compared to a single measurement (Figure 2). As the name says, this impulse response contains only information about the specular component of the reflections.

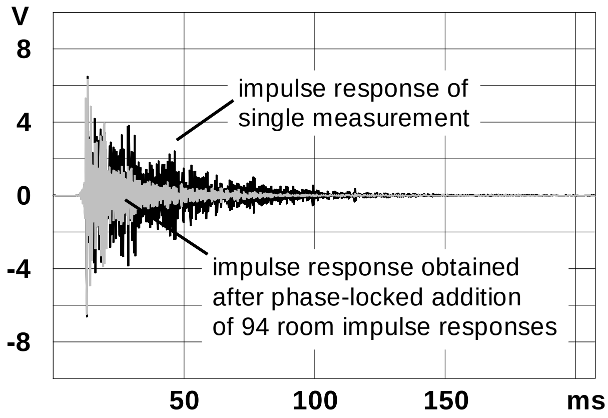


**Figure 2.** Impulse responses measured in a scale model reverberation chamber.

From these impulse responses plus reference measurements performed with a reference flat surface, it is possible to calculate the absorption coefficient ($\alpha$) and the "specular absorption coefficient"($a$).

$$1-a=(1-\alpha)(1-\delta) \quad (1)$$

From this, one determines the scattering coefficient through the following relation:

$$\delta=\frac{a-\alpha}{1-\alpha} \quad (2)$$

In the reverberation room $\alpha$ is determined by using the well-known method according to ISO 354 [2], i.e. from measurements of the reverberation time first without ($T_1$) and later with ($T_2$) the sample present. In a similar way the "specular absorption coefficient" ($a$) is determined from the "specular impulse response", obtained by using a base plate of a turntable and phase-locked averaging of several impulse responses at different orientations of the turntable. This procedure gives the reverberation times after a complete rotation of the base plate alone ($T_3$, "empty room") and of the sample placed on the base plate ($T_4$, "fitted room").

Although the method is already well developed, some aspects are still to be better investigated. In this work effects related to the sample geometry are reported. At first, sinusoidal surfaces were constructed. These surfaces are geometrically identical, but they were constructed in different scales.

The following table gives an impression of the degrees of freedom in the measurement and of the possible sources of errors.

| Parameter | To consider: |
|---|---|
| Sample area | Scale factor with corresponding frequency factor |
| Scale factor | Air attenuation with uncertainties in the correction term |
| Sample shape | Squared or circular base plate, invariant against rotation |
| Sample size / wavelength | Edge effect increasing apparent absorption and scattering |
| Practical operation | Time variances producing artefacts in decay curves |

**Table 1.** Possible variations in a measurement according to ISO 17497-1 [3].

2.1. The sample

As a reference test surface we choose a sinusoidally shaped surface (Figure 3). This choice was only made for practical reasons. It is obvious that the reflection of sound waves on a surface of this shape will be strongly angle-dependent and that this surface is not applicable for random diffusion purpose. In this study it only serves as a reference for comparison purposes.

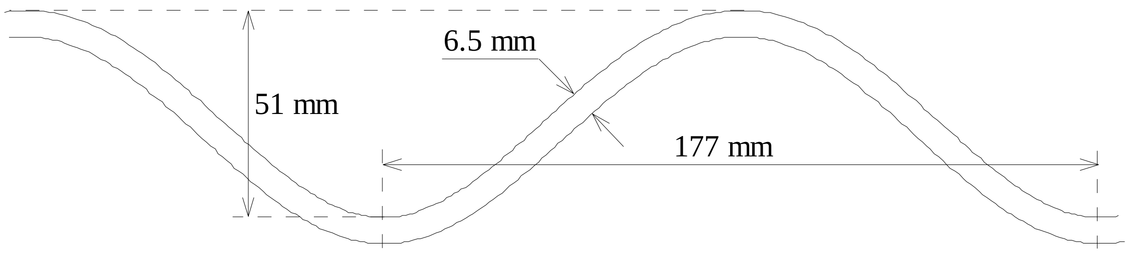


**Figure 3.** Dimensions of the test sample: structural wavelength $\Lambda$ = 177 mm, structural height = 51 mm.

2.2. Real-scale set-ups

Real-scale measurements have been made in 2 different reverberation rooms, using 2 different measurement techniques and using 2 distinct samples, which lead to 8 sets of scattering coefficients.

*2.2.1. The two reverberation rooms*

The reverberation room of the K.U.Leuven (KUL RR) has a volume of 197 m³. A turntable circular base plate is used, consisting of a 21 mm thick multi-layered wood plate over an air gap of 65 mm. This plate is supported by small wheels. For rotation the table is driven by an electro-motor using a belt over the whole edge of the circular plate.

The reverberation room of the University of Liege (ULg RR) has a volume of 190 m³. Its turntable is made of agglomerated wood (20 mm thick, air gap 240 mm) with a hard finishing layer. The plate parts are mounted on a steel frame, which is centrally supported on a bearing and which is centrally driven by a step motor. To minimise the influence of the rotation-variant reflections of this supporting structure, concrete blocks were used to close off the gap space below the rotating plate (Figure 4).

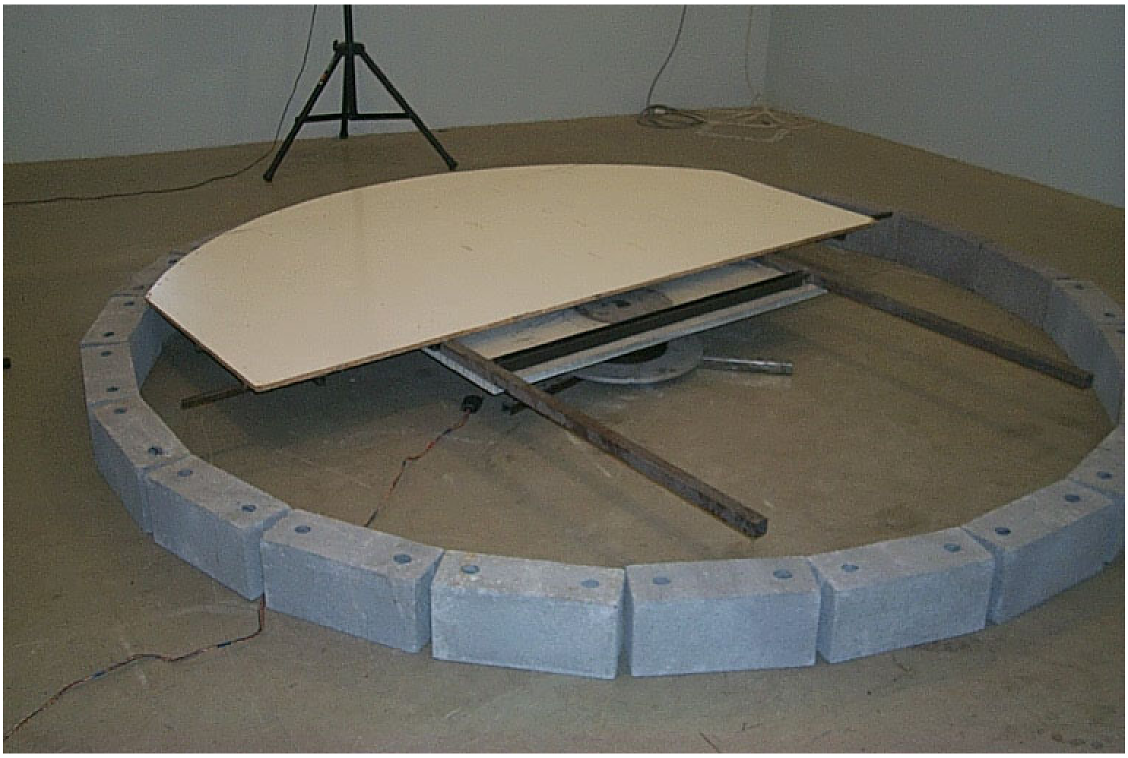

**Figure 4**. Centrally supported turntable at ULg. Air gap below the table closed by a ring of concrete blocks (height 24 cm). Supporting frame, central support and axis (motor is below).

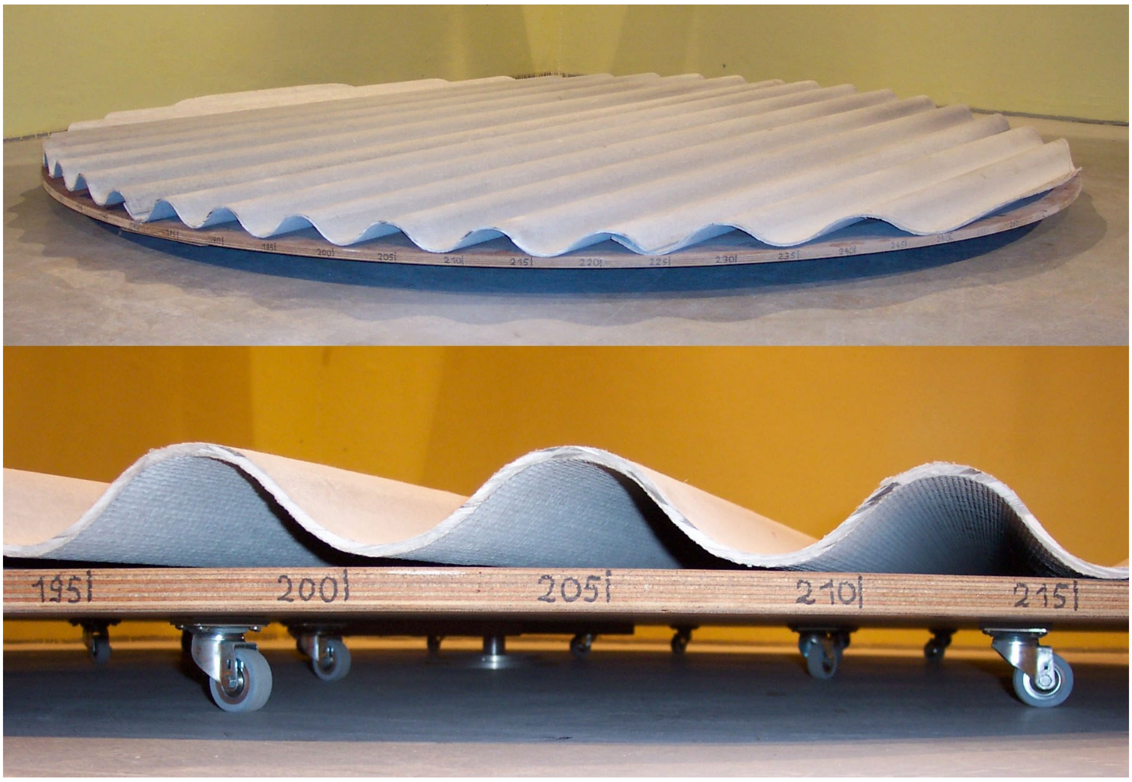


**Figure 5**. Sample placed on turntable (KUL) .

Both circular turntables have a diameter of 3 m, which is the minimum recommended by the ISO publication [3]. No diffuser panels were installed in either of the rooms.

*2.2.2. The two measurement techniques*

In the K.U.Leuven measurement technique [12], a 16 s logarithmic sweep from 40 Hz to 18 kHz is used. For the measurement of $T_3$ and $T_4$, the turntable is continuously rotating with a total revolution time of 9 min 20 s, during which 35 sweep responses are averaged in real-time. Two loudspeakers and three microphones on fixed positions are used, which lead to six source-receiver combinations, with a total measuring time of approximately 45 minutes for $T_2$ and $T_4$ (or $T_1$ and $T_3$).

The ULg measurement technique [13, 14] uses a 12 s logarithmic sweep from 100 Hz to 22 kHz, followed by 6 s of silence. For the measurement of $T_3$ and $T_4$, the turntable is stepwise rotated in steps of 10°. Time synchronisation is achieved by emitting a burst before the sweep. One loudspeaker and two microphones are used, with a total measuring time of approximately 80 minutes for $T_2$ and $T_4$ (or $T_1$ and $T_3$).

In both measuring techniques all reverberation times are calculated from a linear fit to the logarithmic plot of the backward integrated squared third octave band filtered impulse responses in the range from –5 dB to –20 dB [3].

Both samples are made of fibre cement elements, with an approximate sine-shaped profile. They have the same specifications (Figure 3) but are sawn by different craftsmen to form a 3 m diameter circular shape. They are posed directly on the base plate (Figure 5).

*2.2.3. Preliminary comparison of measurement results*

The results of the measurements made with the K.U.Leuven technique are given in Figure 6. The technique seems to give consistent results, independent of the reverberation room or the sample used.

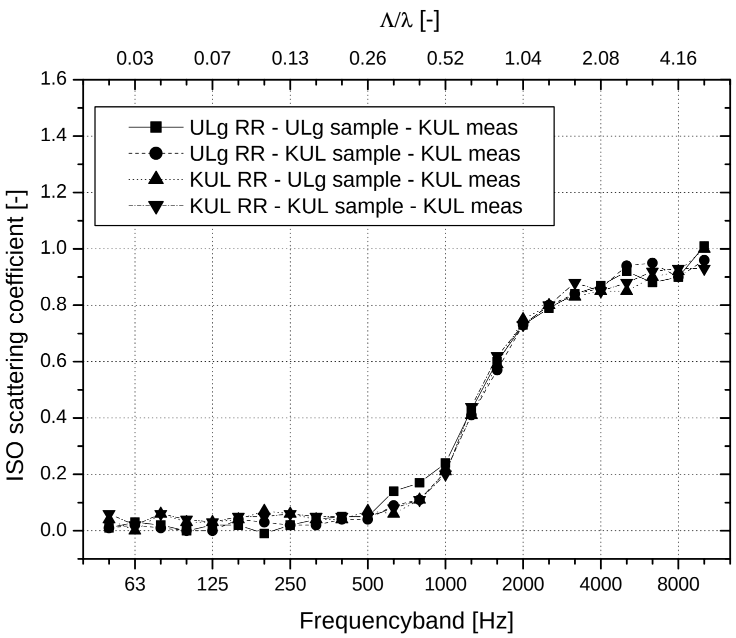


**Figure 6.** Measurement results for the K.U.Leuven measurement technique on both samples in both reverberation rooms.

Measured scattering coefficients using the ULg technique (Figure 7) show a big spread starting at 1500 Hz and exceed unity starting at 4000 Hz. Possible explanations for these phenomena will be given in section 3.2.

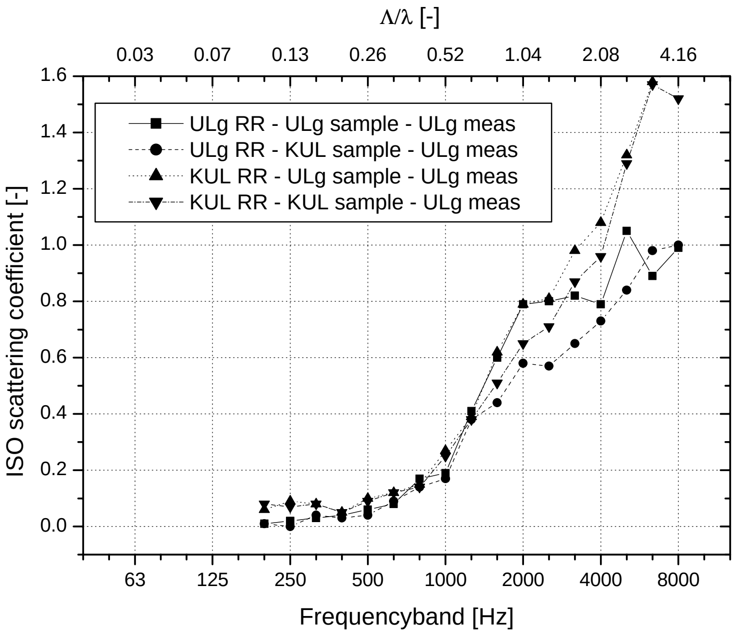


**Figure 7.** Measurement results for the ULg measurement technique on both samples in both reverberation rooms.

2.3. Scale model set-up

Measurements of reduced-scale samples of a surface with profile similar to the one shown in Figure 3 were performed in a scale reverberation room. The repeatability of measured scattering coefficients was checked and considered to be acceptable for (scaled) frequencies up to 12.5 kHz (with standard deviation smaller than 0.03).

*2.3.1 The reduced-scale reverberation room*

The scale model has a volume of approximately 1 $m^3$ and a surface area of approximately 6 $m^2$. Its dimensional relation with the full-scale reverberation chamber at the Institute of Technical Acoustics (ITA) is about 1:5. Three diffuser panels were placed in the scale model aiming to improve sound diffusion at frequencies lower than 1.1 kHz (the Schroeder frequency of the empty chamber). Measurements in the frequency range from 600 Hz to 10 kHz are considered reliable. This corresponds to real-scale frequencies between 80 Hz and 4 kHz. A circular base plate, with a diameter of 0.8 m, is fixed over an automatic turntable and its scattering coefficient is within the limits suggested in ISO 17497-1 [3], being smaller than 0.05 in the frequency range of interest. The scaled reverberation room is shown in Figure 8.

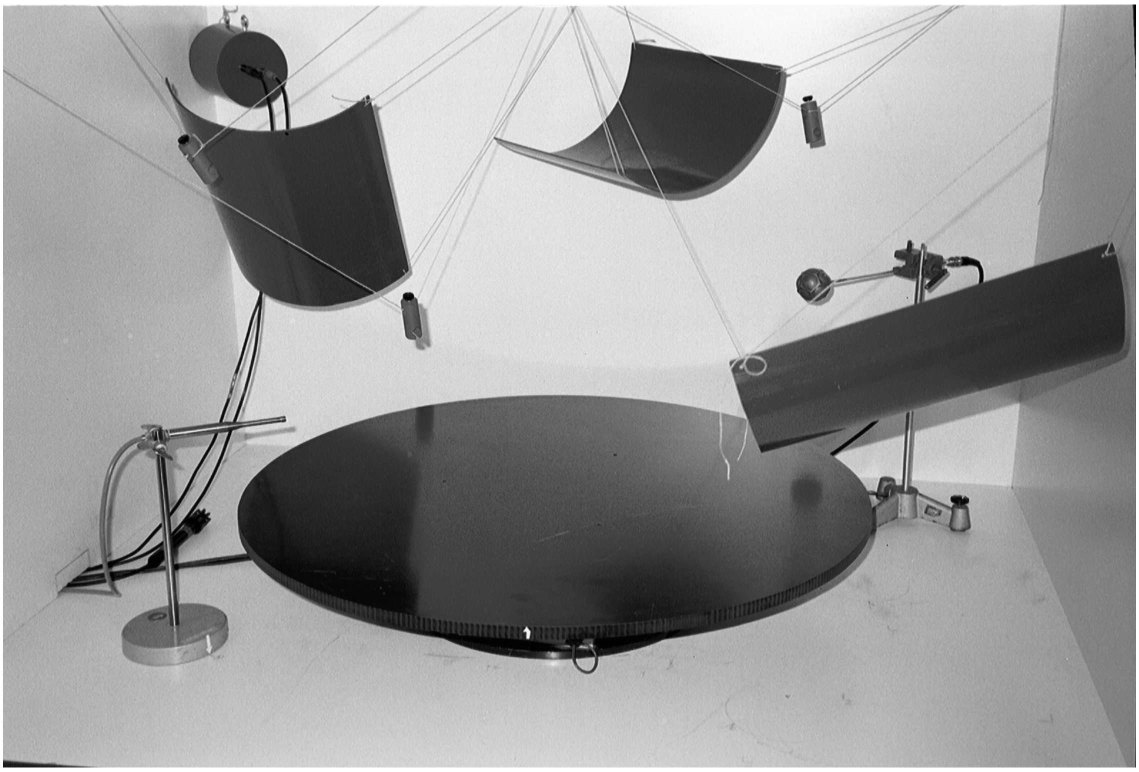

**Figure 8.** Reduced-scale reverberation chamber at ITA.

*2.3.2 The measuring technique*

The measurements in the scale reverberation room were performed using the correlation technique with Maximum-Length Sequence (MLS) as excitation signal. One important requirement was to match the total time of excitation with the period of rotation of the turntable. The MLS were set to order 16 and filtered in the desired frequency band [15]. The reproduction rate of the sequences and the sampling rate of the signal from the microphone were set to 44.1 kHz. With this combination 54 periods had to be sent and averaged, in order to match the 80 s rotation period of the turntable.

Also in this case, the reverberation times were calculated from a linear fit to the logarithmic plot of the backward integrated squared third octave band filtered impulse responses in the range from –5 dB to –25 dB. The reverberation times used for the calculation of the absorption coefficients were averages of measurements performed in five microphone positions, for only one source position. Only one microphone was used and, after closing the door, a waiting time of three minutes (15 min/N according to ISO 17497-1 [3]) was required before starting a measurement, in order to avoid time variations due to air motion or variation of environmental condition during the measurement. The total time required to determine the scattering coefficients was approximately two hours.

*2.3.3 The samples*

Three samples of a surface with profile similar to the one shown in Figure 3 were constructed in three different scales: 1/2.5, 1/5, and 1/10. The main motivation for this was to investigate the influence of the number of periods (present in the sample) into measured scattering coefficients. The samples have 11, 22, and 44 periods of a sinus, respectively, and all of them have a diameter of 0.8 m. The scattering coefficients measured for the samples shown in Figure 9 are displayed in Figure 10. Here they are not represented as a function of frequency, but as a function of the ratio between the structure period and the sound wavelength (Λ/λ). This kind of representation is useful, as one needs to compare results that were measured with samples constructed in different scales.

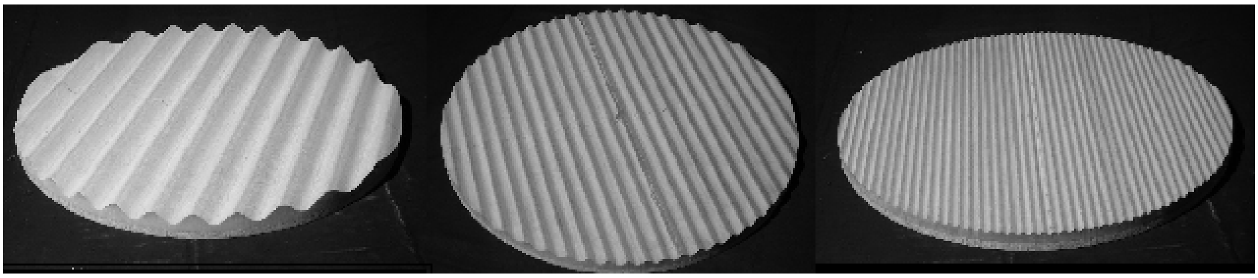

**Figure 9.** Samples of a sinusoidal surface, which profiles are similar to the one shown in Figure 3 (constructed with different scale factors: 1/2.5, 1/5 and 1/10).

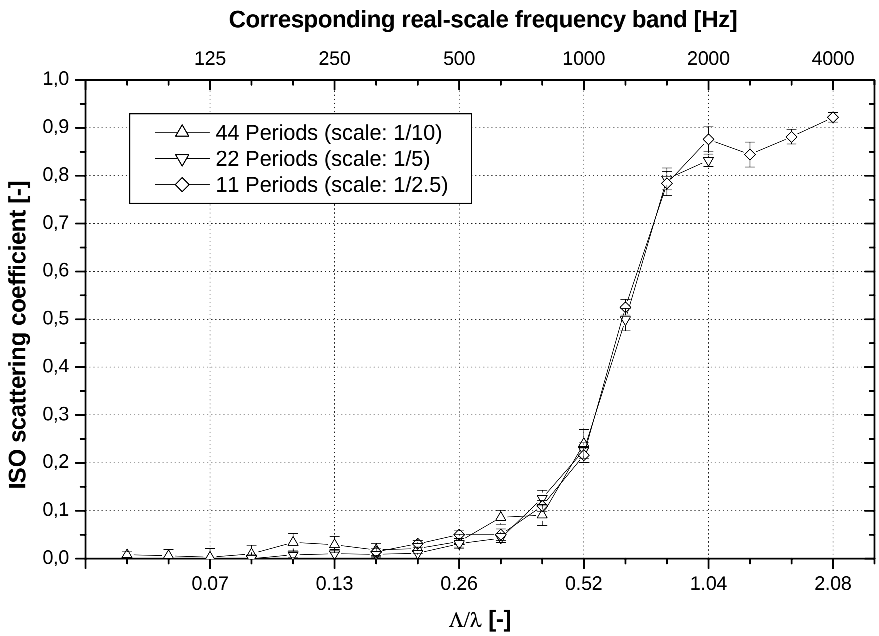


**Figure 10.** Scattering coefficients of a sinusoidal surface, measured on samples constructed in three different scales.

## 3. Case studies

### 3.1 Scale models

The use of scale models for the measurement of scattering coefficients is attractive, since it allows samples of different types of structures to be constructed and measured more easily. Measuring on scale models allows us more easily to construct a database of scattering coefficients for typical surfaces. Results of investigations carried out with reduced-scale samples are presented in the next sections.

#### *3.1.1 Number of periods*

Periodical structures such as rows of columns, seating areas or special diffusers are frequently present in rooms. If the scattering coefficient of such structures is to be measured, one is led to the question of how many periods should a test specimen contain, in order to obtain a representative value. The measurement procedure is defined to give measurement results representing an infinitely large surface. Effects cause by the finite size like edge effects are considered as systematic measurement errors, similarly to those happening in measurements of absorption coefficients in reverberation rooms (ISO 354). They will be discussed in section 3.1.3. As one intends to compare the effectiveness of sound diffusers, the measurements must be conducted following standard rules.

In the measurement procedure for determination of random-incidence absorption coefficients there is a possibility for measuring single objects. The result is then an equivalent absorption area, rather than an absorption coefficient. One could likewise consider determining an equivalent scattering area rather than a scattering coefficient for single objects. But this definition and an adequate measurement procedure is still to be given in the future.

The samples presented in section 2.3.3 were measured in order to better elucidate the question regarding the number of periods necessary to measure representative values. In this study there was minimal difference between the results obtained for the samples with 11, 22 and 44 periods (as displayed in Figure 10). Almost all differences observed fell within the uncertainty limits of the measurements. A further observation of these results reveals that the difference in the edges of the samples constructed in different scales does not influence the scattering coefficient, suggesting that edge effects of any kind are really small when using circular samples.

While the observation of Figure 10 leads one to the conclusion that the presence of 11 periods in a sample of a periodical structure is already enough to measure a representative scattering coefficient, the observation in results from measurements on rectangular battens [16] was that 6 periods are apparently insufficient. The factors determining the minimum number of periods required remain to be closer investigated.

### *3.1.2 Scale factor*

In order to check the agreement between scattering coefficients of the sinusoidal surface, when performing measurements in real and reduced scale, results obtained for both situations are displayed in Figure 11 against the ratio between structural period and sound wavelength. The comparison is done between averaged scattering coefficients measured for the real-scale sample using the K.U.Leuven measurement technique and mean results obtained with the reduced-scale samples.

Although all the differences in set-up, measuring technique and scale, the real-scale results compare very well with those obtained in the scale reverberation room. The deviations observed can be partly explained by small discrepancies between the profiles of the full and reduced-scale samples and also between their borders. In the full-scale sample there is a gap between the sample and the base plate, while in the reduced-scale samples there is not such a gap.

Furthermore, as can be observed in Figure 10, which shows scattering coefficients measured with samples constructed in different scales, the scale factor does not seem to influence the results as long as the conditions regarding sample size, number of periods and the room volume for the scale factor in question are fulfilled according to the standard ISO 17497-1 [3].

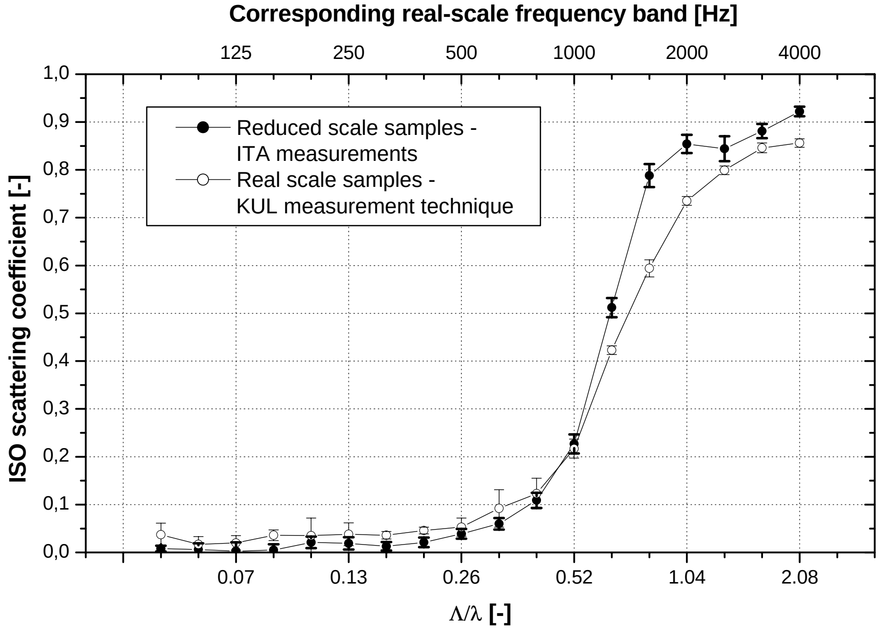


**Figure 11.** Comparison of the scattering coefficients measured by using the K.U.Leuven technique for the real-scale sample and in Aachen for the reduced-scale samples (averaged results).

*3.1.3. Shape of the sample, edge effect*

The ISO standard [3] codifies that a test specimen shall be circular. This guarantees that edge effects have no or only a small influence over the results. It should be mentioned again that the random-incidence scattering coefficient is a quantity corresponding to an infinitely large surface, independently how this surface is bounded and installed in practical application in a hall. It has similar meaning as random-incidence absorption coefficients to be addressed to large areas in rooms. Effects of mounting (flush or elevated), freely hanging panels etc. must be treated separately from what we discuss here: a scattering effect purely from the surface roughness profile.

Accordingly the shape and size of the sample should represent the behavior of an infinite surface as best as possible. To verify this influence of the sample shape, the 1/5 circular sample of the sinusoidal surface was sawn in a square shape (see Figure 12), and the scattering coefficients were measured. As shown in Figure 13, the scattering coefficients measured with the square sample are much larger than those measured with the circular sample. Former studies [16] indicated that the difference between the surface area of the samples does not affect the final result in this particular case, and the additional scattering is attributed to the contributions from the sides of the square sample. The explanation for this fact is straightforward from the principle of the measurement. As one thinks of a disc with finite border height, turning concentric with the axis of rotation of the base plate, it is simple to imagine that the diffraction in the resulting averaged impulse response due to the edges would be the same as those which would exist in a single impulse response, independent from the orientation of the sample. That is, the edges of the disc are “invisible” to the method. The same would not happen with a square plate with the same height, and the diffraction from the borders would be located in the impulse responses in different times, depending on the orientation of the plate.

Some methods for overcoming the measurement errors when using square samples (since it is not always possible to construct circular samples) have been tested but a final, definitive solution is still to be found. The best results were obtained with the squared sample mounted in a square recess, the top plane of the sample placed flush with the base plate [17].

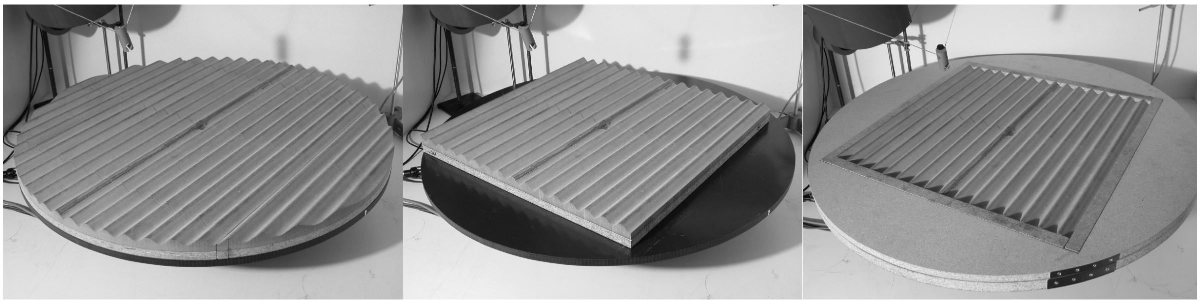

**Figure 12.** Samples of the same 1/5 sinusoidal surface. left: circular, middle: squared, right: squared in a recess.

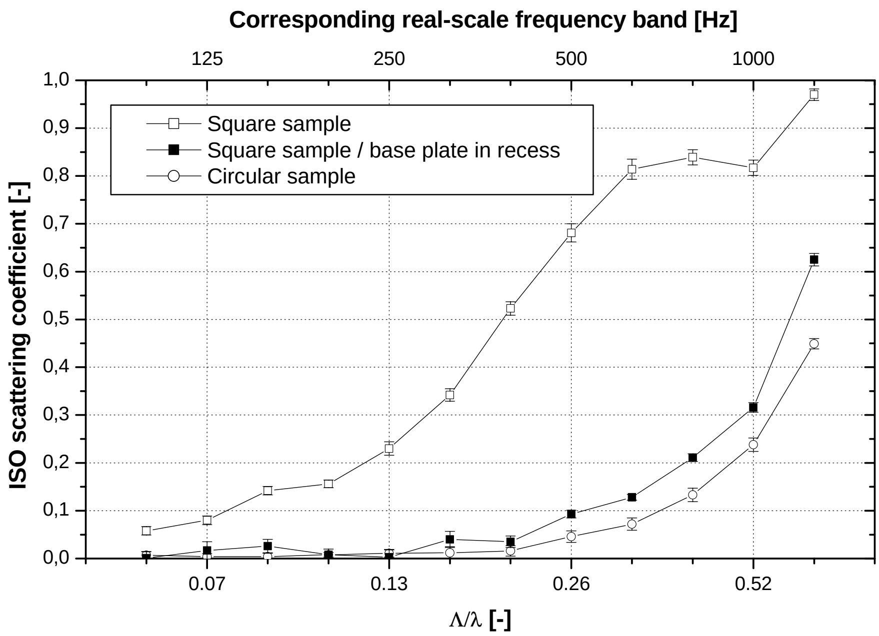


**Figure 13.** Scattering coefficients of a circular and a square test specimen of the same 1/5 sinusoidal surface.

*3.1.4. Air absorption*

A parameter which can affect the precision of the results is the relative humidity, especially when performing measurements in scale models. Considering a 1/5 model, measurements up to the 40 kHz third or octave band must be performed, in order to reach the 8 kHz real-scale frequency band. The excess of air absorption will cause the reverberation time to be lower and, consequently, the scattering coefficient more sensitive to possible measurement errors.

The ISO method for measuring the random-incidence scattering coefficient is often applied in reduced-scale reverberation chambers. In these cases, a simple measurement of the absorption coefficient, i.e., of the room's reverberation time without and with the material sample, will lead to the problem that the order of the measured quantities tends to be in the same range of the resolution of the measuring system. For measuring the scattering coefficient it is expected that this problem becomes even larger. To have an idea of how the air absorption affects the measurement, the equations for the exponential decay presented in [18] can be used.

If a measurement was performed in an environment where air absorption can be considered irrelevant, $T_2$ and $T_4$ could be described by:

$$T_2 \propto 1 \big/ (A_{\mathrm{room}} + \alpha_{\mathrm{sample}} S_{\mathrm{sample}})$$
$$T_4 \propto 1 \big/ (A_{\mathrm{room}} + a_{\mathrm{sample}} S_{\mathrm{sample}}) \quad , \qquad (3)$$

where $A_{\mathrm{room}} = (S_{\mathrm{room}} - S_{\mathrm{sample}})\bar{\alpha}_{\mathrm{room}}$ is the equivalent absorption area of the empty reverberation room and $S_{\mathrm{room}}$ is total surface area of the reverberation room.

In other cases, however, for higher frequencies or relative humidity in the range of 10% to 40% (for frequencies between 10 kHz and 40 kHz, as seen in Makrinenko [19]), these decays should be described according to Andersen [18]:

$$T_2 \propto 1 \big/ (A_{\mathrm{room}} + \alpha_{\mathrm{sample}} S_{\mathrm{sample}} + 4mV)$$
$$T_4 \propto 1 \big/ (A_{\mathrm{room}} + a_{\mathrm{sample}} S_{\mathrm{sample}} + 4mV) \quad , \qquad (4)$$

where $m$ is the air attenuation constant and $V$ the volume of the reverberation room. Assuming a value of 0.16 $\mathrm{m}^{-1}$ for $m$, which corresponds to a relative humidity of 70% at 27 kHz, the schematic envelope of the decay curve (of the specular impulse response, as given by [18]) when considering and when not considering air absorption would be as shown in Figure 14. For this plot, the following values were assumed: $\delta = 1$, $\alpha_{\mathrm{sample}} = 0$, $a_{\mathrm{sample}} = 1$, number of averages = 72, $A_{\mathrm{room}} = S_{\mathrm{sample}} = 0.5\ \mathrm{m}^2$, $m = 0.16\ \mathrm{m}^{-1}$ and $V = 1\ \mathrm{m}^3$,

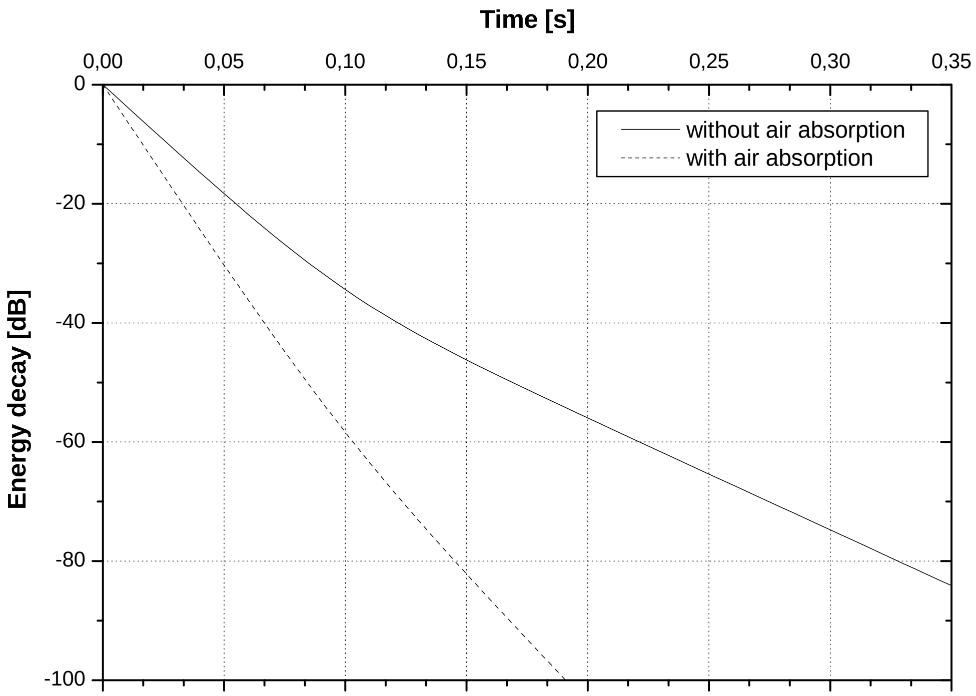


**Figure 14.** Decay curve $E(t)$ of the specular impulse response used in determination of $T_4$ when considering and not considering air absorption.

Because of air absorption, $T_2$ and $T_4$ may become very similar, and it is more difficult to distinguish one decay from another. In this case, the transition from one decay to another lasts longer and some errors could exist due to this situation. Actually, reverberation time measured in the scaled reverberation chamber at 27 kHz, for example, are much smaller than what can be seen in Figure 14, in the order of 0.1 s. In this situation, the difference between $T_4$ and $T_2$ may lie in the range of 0.01 s, what tends to produce excessively high measurement errors.

The problem of air absorption in scale models is surely not new and there are ways to overcome it [20], for example, substituting the air by another gas. The use of Nitrogen is very common. A practical investigation was not done for this work, but the problem should be further investigated.

3.2 Real-scale case studies

Numerous experiments have been carried out in both reverberation rooms in order to study the influence of several measurement parameters. For this study also, other test samples have been used. First, different measurement signals for obtaining the impulse responses are compared. We compared MLS signals, linear and logarithmic sweeps. The best signal to noise ratios were obtained using logarithmic sweeps. This confirmed the conclusion of Stan et al. in [13] for applications in quiet unoccupied rooms. Also in the case of continuous rotation, best signal to noise ratios were obtained using logarithmic sweeps. As a consequence, logarithmic sweeps have been used for the further analysis.

*3.2.1. Manual or automatic turntable, stepwise measurements or continuous measurements*

Three measurement procedures are possible for rotating the turntable: manually rotating over $\Delta\theta$ by entering the room, motorised rotating over $\Delta\theta$ or motorised continuous rotating. Using these three procedures, the scattering coefficient of the K.U.Leuven base plate has been measured for one fixed source-receiver combination, according to the ISO draft [3].

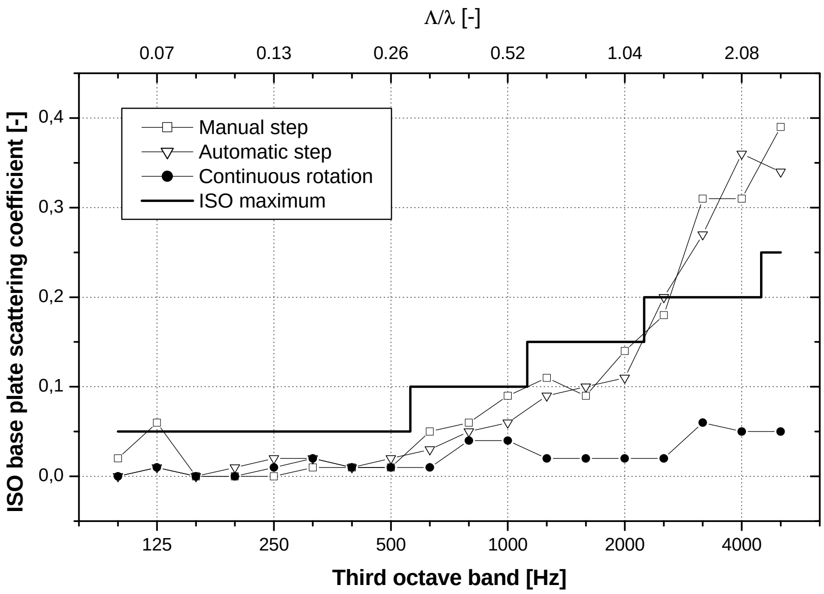


**Figure 15.** The scattering coefficient of the K.U.Leuven base plate, measured following three different procedures.

As can be seen in Figure 15, lowest values are obtained using continuous measurements. The values for the stepwise measurements exceed the maximum values specified in the ISO draft [3] at high frequencies. For the measurement of $T_3$, we choose $\Delta\theta$ equal to 5°, which means 72 measurements (see also section 3.2.3) and a total measuring time of more than 1 hour for one complete rotation in the case of the motorised stepwise measurements. Manual stepwise measurements take almost 2 hours for one complete rotation of the turntable. On the other hand, the continuous measurement took 9 minutes to complete. Too long measuring times lead to overestimated scattering coefficients at higher frequencies. We can conclude from this that manual rotation of the turntable is not recommended (this will be reinforced by the analysis in section 3.2.2). Stepwise measurements are possible, but in this case the total measuring time for one complete rotation must be reduced as much as possible (see also sections 3.2.2 and 3.2.4). Nevertheless, continuous measurements are to be preferred over stepwise measurements.

*3.2.2 Time variances*

When measuring in small scale models, effects of time variances may still be solved by waiting for steady-state conditions. Real-scale measurements of scattering coefficients, however, can take a long time (in our cases 45 minutes and 80 minutes, respectively). During this time, small steady changes in air temperature or humidity can affect measurement reliability, especially at high frequencies and low relative humidity. These effects can be considered to play on a longer time. However, opening the door of the reverberation room may cause more sudden temperature and/or humidity changes and certainly initiates air movements which influence the measurement quality. As written above, the signals used here were logarithmic sweeps. With this choice the smallest possible time variance effect is expected. With MLS signals these effects would be larger [21].

To study this (short time) effect, the average of 6 impulse responses was measured for a stationary turntable but for different time intervals between measurements with and without door openings [14]. The reverberation times as obtained from these averaged impulse responses were normalised to the reverberation time calculated from one impulse response and are plotted in Figure 16. A small change in reverberation time can be seen due to temperature and humidity drifts when the door stays closed. However, when opening and closing the door between the measurements, the late parts of the impulse responses are more incoherent and result in a lower reverberation time after averaging.

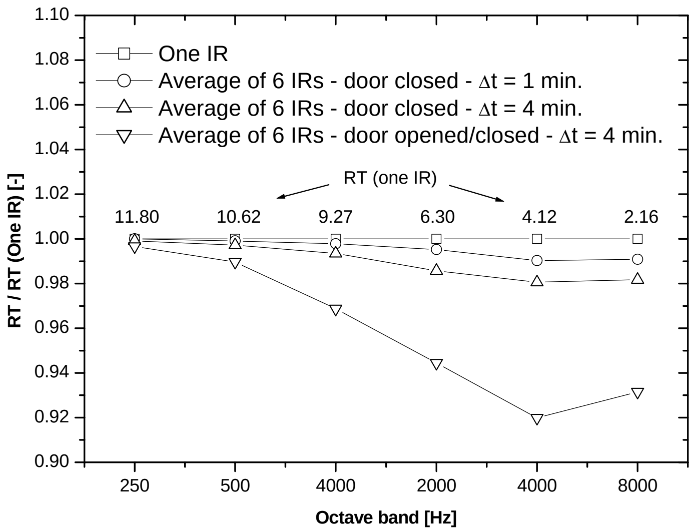


**Figure 16.** Normalised reverberation times for different waiting times with and without opening the door of the reverberation room.

The draft standard [3] recommends a waiting time of 15/*N* minutes after closing the door, in order to let the room stabilise. *N* is the scale factor of the measurement set-up. The standard does not distinguish between the case of opening the door for moving the turntable or the case of opening the door for changing source or microphone positions. In the first case, this would lead to very impractical real-scale measuring times of more than one day. Obviously the influence of this waiting time has not been studied. However, for changing source or microphone position, we found no differences in the measured scattering coefficient when respecting this waiting time or not [12].

Temperature and humidity drifts (long time effects) are compensated for in the draft standard [3] by taking into account the speed of sound and air absorption in the calculation of the scattering coefficients. Nevertheless one must avoid these effects to occur within one complete rotation of the turntable. Therefore, temperature and humidity must be monitored during measurement. We recommend to restrict the maximum allowable temperature and relative humidity change to 0.1 °C and 1% respectively.

*3.2.3 Number of averages*

When evaluating reverberation times from decay curves over a fixed range (e.g. from –5 dB to –20 dB), larger scattering coefficients require to average over a larger number of impulse responses in order to have a correct measurement of the relevant part of the decay curves [10]. As a rather safe guideline, the draft standard [3] recommends a minimum of 60 averages. For stepwise measurements, this can cause measurement times to become too large to ensure stable room conditions during one complete rotation of the turntable. So it is preferred to reduce total measurement time rather than to increase the number of averages. As a global rule, measurement times of more than one hour should be avoided. A higher turntable speed and an optimal sweep signal length will help to realise this goal.

In the case of continuous measurements, a larger number of averages can easily be made. Here, a high turntable speed and a short sweep length are also recommended. However, to avoid impulse response time aliasing influencing the estimated reverberation time, the sweep length must be longer than half the longest expected reverberation time.

*3.2.4 Unavoidable practical problems*

A first practical problem is that the base plate has a minimum diameter of 3 meters. In both reverberation rooms, it was not possible to build this rotating plate in only one piece. Two (or more) pieces have to be assembled inside the room, in such a way that the resulting gaps or slits between them are reduced as far as possible, as this could create scattering at high frequencies. A turntable supported by wheels is preferred to a centrally supported table because a supporting frame construction is not necessary and the air gap below the table is smaller, which both decrease turntable diffraction. Moreover we can reduce the need for an additional enclosing of the cavity due to a lower cavity height.

In practice not all kinds of diffusers are suitable for real-scale measurements. The diffuser panels must be light enough not to bend the base plate and have to be such that they can be sawn into a circular shape. It must also be noticed that, with this technique, single plane scattering cannot be measured, since random incidence is assumed.

The motor used to rotate the turntable should be as silent as possible, in order to avoid an influence on the slope of the decay curve (Schroeder curve) in the range –5 to –20 dB in all third octave bands considered, according to the standard draft [3].

The edge effect as studied in section 3.1.3 has not been studied in real-scale measurements. Also the question of whether or not filling the air space between the sample and the base plate remains open and needs to be studied more extensively.

As a last item, care should be taken not to wait a long time between two impulse response measurements. Indeed, some variations have been occasionally observed in the temporal behaviour of the loudspeakers voice coil, depending on the rate of signal emissions, and resulting in slight differences in reverberation time measurements. In this respect, continuous rotating methods still present an advantage over stepwise rotating ones.

## 4. Summary and conclusions

This contribution aims at identifying uncertainties and at proposal of measurement parameters giving more robust results in the measurement of the random-incidence scattering coefficient. Although the method is already well developed and soon standardised in ISO/DIS 17497-1, some aspects are still to be better investigated. In this work practical aspects related to both real-scale and model-scale are reported.

So far, only very few large-room results of random-incidence scattering coefficients were published. In this study measurements were performed to compare the results of real-scale and model-scale arrangements of the same sinusoidal profile. The standard draft ISO/DIS 17497-1 provides a sufficient basis for testing corrugated surfaces The real-scale results agree quite well with results from scale model measurements. Differences in the results could be explained in little variations of the mounting method and of the measurement procedure. The following sources of uncertainties were identified:

- mounting of the sample, connection or sealing between sample and base plate
- way of rotating the sample
- air absorption
- time variances

The experiences with the measurement method showed that an installation of large turntables involved a number of practical problems, but these could be solved. Real-scale measurements of random incidence scattering coefficients are very sensitive to reverberation room conditions. Special attention must be drawn to temperature and relative humidity stability. Most reliable scattering coefficients are obtained using short measuring times, preferably using motorised continuous rotation measurements. Using stepwise measurements, base plate scattering coefficients exceed the maximum values specified in the ISO draft at high frequencies. For real-scale measurements the draft standard recommends a waiting time of 15 minutes after closing the door, in order to let the room stabilise. However, for changing source or microphone position, we found no differences in the measured scattering coefficient when respecting this waiting time or not. Furthermore, a high turntable speed and logarithmic sweeps with a short sweep length are recommended. Using MLS signals, however, might lead to the necessity of longer waiting times, such as recommended in the standard.

There were only small differences between the results obtained for the samples with 11, 22 and 44 periods, provided, the elementary guidelines for performance of model-scale measurements are followed. This demands particularly special attention to air absorption. A further concern of this work regarded the shape of the sample and the influence of the borders on the measurement results. It has been shown that non-circular samples give reliable scattering coefficients only if they are mounted in a recess of the base plate, to minimize the effect of the rotation-variant reflections at their edges.

It would also be interesting to compare these measurement results with the results of the random-incidence scattering coefficients derived by numerical computations. Several methods can be tried for that purpose, from BEM (at low frequencies) to Kirchhoff approximation theory (at high frequencies). Simulations are presently carried out by the authors of this paper in order to obtain reliable results for sinusoidal surfaces.

Also interesting would be to consider which uncertainty may be allowed for random-incidence scattering coefficients. It is assumed that the best concert halls take benefit not only from the basic room shape but also from the corrugations of the walls. Random-incidence scattering is responsible for energy mixing, energy extraction from geometrical paths and for filling gaps in the impulse response. The question is how accurately scattering coefficients must be determined for application in room acoustical computer simulations in order to achieve a good correspondence with audible effects of scattering [22]. It can be expected that the accuracy of scattering coefficients needed is not too high, but this should be subject to further research.

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