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## Sample rotational symmetry in the random-incidence scattering coefficient measurement

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### Abstract

It is well known that samples with rotational symmetry present an underestimated scattering coefficient when measured through the reverberant chamber method. The ISO 17497-1 even states that symmetric samples should have its center displaced from turntable's center for the measurement. However, it hasn't been discussed if sample isotropy may underestimate the measured coefficient as well. Analysing previous measurement results, this seems to be the case. To investigate the matter, the case of surfaces composed by distributed hemispheres was chosen for study. A method for calculating a sample's symmetry function was developed and is presented. It shows an increase of isotropy as more elements are introduced or the smaller the elements are (in other words, the more "noisy" the surface is). Measurements were made in order to further study the phenomenon. It seems, indeed, that sample isotropy causes an underestimation of scattering coefficients, although more measurements are recommended. Also, it was noticed that even in the case of the studied samples, which have not a strict edge, there are edge effects at play. It can be explained by the greater influence elements further away from the center have on the sound field during the turntable rotation, accentuated by the higher circumference-area ratio the smaller the sample. Accordingly, the sample edge strip, when present, also results in lower measured scattering coefficients. Since there is no strict sample edge, this could be an artifact created by the strip. These effects are discussed alongside other phenomena that affects sample representativeness - a key concept in understanding how the measurement method interprets the sample.

**Keywords:** acoustics, sample representativeness, edge effect, isotropy, autocorrelation.

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### 1. INTRODUCTION

It is well known that samples with rotational symmetry present an underestimated scattering coefficient when measured through the reverberant chamber method. The ISO standard [1] even states that symmetric samples should have its center displaced from turntable's center for the measurement. Following previous researches [2–4]<sup>1</sup>, it was noticed that a similar

effect could have been so far overlooked. This effect is an underestimation of the scattering coefficient due to sample isotropy, that is, the sample presents high degree of rotational symmetry, but not in a discrete manner - the latter meaning a (perfect) symmetry at every, for example, 90°.

Since any surface with a rotational axis may have a calculated degree of rotational symmetry (i.e. any sample in this case), this can be seen as a fundamental matter. This also leads to the thought that symmetry plays some part in the measurement of any sample with significant isotropy or that has a symmetry of order higher than one (i.e. while revolving, it will present

<sup>1</sup>Works [2] and [3] are discussed in section 2.4. In [4], it is simply that numerical simulation was performed for the symmetric sample, but not for the ones declared as random or asymmetric - although this can be justified with another work by Sakuma and Kosaka, which is also discussed.



itself geometrically identical at least once before a complete revolution). In this paper, focus is on the isotropic samples, specially samples composed by hemispheres.

Sample isotropy, should it be of importance, affects sample representativeness - that is, how well the sample represents the real, sampled surface. Therefore, a discussion on the topic, oriented to the matters at hand, is presented in section 2. This discussion also includes edge effect and the use of an edge strip. The application of a symmetry metric on the samples of interest is presented in section 3. Also, measurements and their results are discussed in section 4. Figures, data and codes are provided in a Git repository<sup>2</sup>.

## 2. THEORETICAL BACKGROUND AND DISCUSSIONS

In section 2.1, the measurement procedure of the random-incidence scattering coefficient according to ISO 17497 [1] is summarised. Sample representativeness is discussed in section 2.2. Specific discussions regarding edge effects and sample isotropy are presented in sections 2.3 and 2.4, respectively.

### 2.1 Random-Incidence Scattering Coefficient and Its Measurement

The random-incidence sound scattering coefficient is defined as the energy that is reflected in a non-specular manner by a surface in relation to the total reflected energy. It is calculated by:

$$s = \frac{\alpha_{\text{spec}} - \alpha_s}{1 - \alpha_s} = 1 - \frac{1 - \alpha_{\text{spec}}}{1 - \alpha_s} \quad (\cdot) \quad (1)$$

in which  $\alpha_s$  is the absorption coefficient and  $\alpha_{\text{spec}}$  is the apparent specular absorption coefficient, representing the combination of absorbed and scattered (non-specular) energies.

For the coefficient measurement, the sample is placed on a turntable in a reverberation chamber. The coefficient is calculated based on

reverberation times for four different scenarios differing on sample's presence and turntable's rotation, as shown in Table 1.

| Step  | Sample      | Turntable    |
|-------|-------------|--------------|
| $T_1$ | not present | not rotating |
| $T_2$ | present     | not rotating |
| $T_3$ | not present | rotating     |
| $T_4$ | present     | rotating     |

**Table 1:** The four steps for the scattering coefficient measurement.

The  $\alpha_s$  and  $\alpha_{\text{spec}}$  coefficients are calculated equivalently as absorption coefficients:

$$\alpha_{s,\text{spec}} = \frac{A_{2,4} - A_{1,3}}{S} \quad (\cdot) \quad (2)$$

in which  $S$  is the sample surface area and  $A_i$  is the equivalent absorption area corresponding to measurement step as in Table 1. It is calculated as:

$$A_i = \frac{24 \ln(10) V}{\bar{T}_i \bar{c}_i} \quad (\text{m}^2) \quad (3)$$

in which  $V$  is the room volume,  $\bar{c}_i$  is the average speed of sound and  $\bar{T}_i$  corresponds to the average reverberation time. Both indexes are in respect to Table 1 and the averages are through different positions of source and receiver.

With Equations 2 and 3 written in these forms, the reverberation time must already account for air absorption, for each source-receiver position  $p$ , in the form:

$$T_{i,p} = \frac{-60 \text{ dB}}{d - (\alpha \times c)} \quad (\text{s}) \quad (4)$$

in which  $d$  is the decay rate (dB/s) and  $\alpha$  is the air sound pressure attenuation coefficient (dB/m).

Also, the base plate scattering coefficient is calculated in a similar way as the other absorption coefficients:

<sup>2</sup><https://gitlab.com/Phxuibs/fia-2020-22-sample-symmetry.git>.

$$s_{\text{base}} = \frac{A_3 - A_1}{S} \quad (\cdot) \quad (5)$$

It is noticed then that the scattering coefficient is measured in an indirect manner. Steps  $T_1$  and  $T_2$  consider the absorption calculation ( $\alpha_s$ ). Steps  $T_3$  and  $T_4$  suppress scattered energies, accounting them also as absorption. The scattered energy suppression is obtained by superposing impulse responses measured for different orientations by rotating the turntable in steps  $T_3$  and  $T_4$ . The later - reverberant - parts of the impulse responses are incoherent and therefore tend to cancel out, leaving only the early - specular - part.

For a totally symmetric sample (i.e. it is equivalent at any orientation) there is no scattered energy suppression. Therefore, the standard [1] points to a minimum sample displacement from the center of the turntable. It is also noticed that a sample that needs this displacement needs also to be scaled down in order to maintain the originally desired geometrical properties for measurements [6]. Unfortunately, it is not known how displacements may affect the results in relation to a true value.

## 2.2 Sample Representativeness

Sample representativeness is the quality of a sample to represent a real surface for the purpose of properties measurement<sup>3</sup>. For example, one may ask “for a periodic surface, how many periods are necessary to well represent a real surface?”. For a sinusoidal surface, 11 periods seem enough according to Gomes et. al. [7] - similar results were also obtained by Kosaka and Sakuma [8, 9].

For the experiment in [7], the authors built three sinusoidal samples, each on a different scale. Since area was not scaled accordingly, smaller scales samples presented more periods - in other words, more periods could be added without altering the amplitude over period length

<sup>3</sup>It may as well be seen as how the measurement method interprets the sample, which is the important part after all. Also, the measured coefficient is the available feedback on how good the surface sampling is.

ratio ( $A/\Lambda$ ). The results were then plotted in a relative scale: sample period length per sound wavelength ( $\Lambda/\lambda$ ). They can be seen in Figure 1.

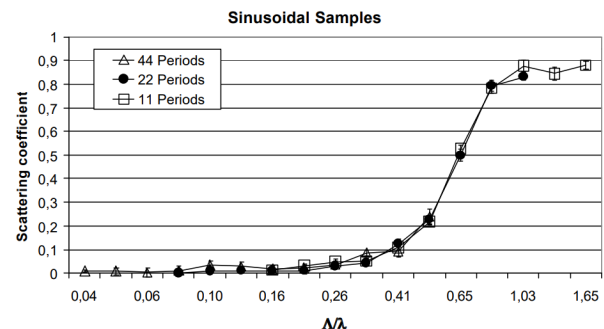


**Figure 1:** Scattering coefficients for sinusoidal samples built in different scales ([7]).

Since the surface dimensional relations are the same, only changing in scale, it is expected that the samples have the same representativeness. The results will then be the same - only shifted through the more traditional frequency axis. Also, the curves will superpose each other in the common ranges in the relative axis<sup>4</sup>. As can be seen in Figure 1, they do. Also, since the samples are from different scales, their ranges are different in this relative axis. The sample with the shortest period is the furthest to the left; the one with the largest period is the furthest to the right.

If the samples have different representativeness, the results do not superpose in the common range. In the work of Gomes et al., it happened when comparing results from another periodic profile (square battens) with six and 12 periods. So, clearly, six periods are not enough to a good representativeness. This type of relative analysis may also be used to compare results from different laboratories, specially when the reverberant chambers have different scales - and so probably do the samples [10].

As discussed in [6], since a proportional change in both amplitude and period length of a sinusoidal profile results only in a change of scale, this procedure is necessary only for practical purposes - for example, a real sized specimen would result in few periods for a

<sup>4</sup>Note that representativeness does not need to be high or “correct” for this to happen, only the same.



good representativeness, being then scaled down for measurements. Therefore, the “amplitude over period length” ratio is sufficient to fully characterize a sinusoidal surface (assumed it has good representativeness). With hemispheres of same size randomly distributed over a flat surface, “area coverage” (also called coverage density) is also sufficient: it relates element size, quantity and total area altogether. Area coverage is simply the ratio between the area occupied by the hemispheres and the total area<sup>5</sup>.

In this way, samples that differ only in the radius  $r$  of the hemispheres they are composed by, having the same area coverage, will present similar scattering coefficients for a common range in the relative axis  $r/\lambda$  - if the samples present same representativeness. In the case of a sinusoidal profile, a period length too large would result in few, not representative, number of periods. In the case of distributed hemispheres, if the hemispheres are too large, sample area must be increased; otherwise, there will be too few elements for a good representativeness. A critical number, or this hypothesis overall, has never been tested.

The sample’s edge may alter representativeness, affecting the measured coefficients (it is discussed in section 2.3). Samples of distributed hemispheres do not present an strict edge [2, 3], as opposed to samples of a sinusoidal profile [7], for example. Nevertheless, the edges are misrepresented since the elements that would be placed on the border are either moved inside the perimeter or removed completely.

To conclude this section, a brief comment in [6] (p. 104) is extended: there are many phenomena that may occur during a scattering coefficient measurement. Not all of them have been openly discussed, quantified or maybe even discovered. So it is important to remember that different effects may be at play; some of them will act in the same direction, others in opposite manners, being possible that, regarding statistical significance, they even out.

## 2.3 Edge Effect

The scattering coefficient was defined to characterise an infinite, borderless surface. With the ISO [1] measurement method, edge effects can be, at best, minimised. Gomes et al. showed that elevated samples that are not circular may present an overestimated scattering coefficient due to edge effects. The elevation or actual edge is the important property, as a square arrangement does not necessarily presents the edge effect - as is the case for randomly distributed hemispheres [11] (p. 64–67)<sup>6</sup>. Then, even a circularly shaped sample probably presents an edge effect if it has a clearly defined border (as is the case of a circularly sawed square wave or sine wave, for example), although the effects are minimised.

In order to minimise the effect of an elevated square base when this shape would be unavoidable, Gomes et al. showed that the sample should be flush mounted on a circular base. On one hand, this mounting hides the edges that wouldn’t exist in the real scenario; on the other, it creates internal reflections that are also an artifact. Also, if the depression is too deep, it could lessen the sound incidence isotropy on the surface, the smaller the sample. So, ideally, the depression depth should be the same as the sample (maximum) height.

The first version of the ISO 17497-1 in 2004 inhibited the use of an edge strip around the sample, although it adopted the flush mounting method - probably because there was evidence supporting the flush mounting for non circular samples and none for the use of an edge strip in general cases. Nevertheless, further studies were carried out by researches at the Chonbuk National University (Choi, Jeong, Kim, Lee and others) [13–15] and an edge strip became normative [1]. The main argument seems to be that “the scattering coefficients measured for the sample with an edge strip were considerably smaller than those measured for the sample

<sup>5</sup>A ratio between element size and average distance between elements would also suffice, but this last parameter is harder to calculate.

<sup>6</sup>Shtrepi et al. found significant differences in the scattering coefficients between circular and square arrangements. However, they used randomly oriented and distributed cubes and lower area coverages. In this way, the higher number of elements in the circular arrangements could’ve had more influence in the results.

without an edge strip” [15]. However, without a true value for comparison, one cannot know if the lessening is actually too much.

Another observation that seemed missing is that, although the edge strip significantly altered the measured coefficients for different sized samples, it is expected the edge to affect specially smaller ones since the circumference-area ratio is higher. The use of an edge strip adjusted clearly overestimated values for the smaller sample - but some of these values became lower than those of the mid-sized sample. For this one, the scattering coefficient even increased with the used of the edge strip in some frequencies [15]. The circumference-area ratio also suggests that the undesired edge effects are more prominent in smaller samples<sup>7</sup>. Indeed, the measured coefficient for the larger sample was usually lower and the authors pointed out that the measurement uncertainty was lower [15]. With the presented results, it is clear that the work on the use of the edge strip is indeed important and should be further investigated.

## 2.4 Sample Isotropy

In section 2.1, it is mentioned that the standard recognizes that a perfectly symmetric sample will not affect the sound field while revolving and the scattered energy won't be suppressed. But what happens when the sample presents almost total symmetry? In other words, what happens when the sample presents high isotropy?

The first time the idea of sample isotropy having an effect on the measured scattering coefficient was cogitated, was while reading the work of Jeon et al.. They compared the scattering coefficient of randomly distributed hemispheres according to their size. The tendency was that smaller hemispheres present a lower scattering coefficient. They also measured the coefficient for different area coverages - different quantities of hemispheres covering the base plate. It was found that the maximum scattering was achieved around 57 % of area coverage; at 71 %, the

scattering was lower. According to the authors “the scattering coefficients seem to decrease [...] due to lacking surface irregularities”. With this sentence, it wasn't clear if the authors were referring to a surface property indeed, or to the measurement method property.

It became clear that the mention was to a surface property after the continuation of the work with Kim et al.. The authors expanded a lot the work on distributed hemispheres with a broader range of sizes, all also presented with different coverages. The results are easily available through table for analysis.

They are presented graphically in Figures 2 to 5, corresponding to the coverage densities of 14 %, 28 %, 57 % and 71 %. In those,  $R$  and  $r$  are the radii of the sample and hemispheres, respectively, and  $n$  is the number of hemispheres. Since the interest here does not lie in absolute values, but in investigations on deviations of sample representativeness, the Figures present both axes with relative quantities: the abscissa is in hemisphere radius in relation to wavelength; the scattering coefficient is presented in deviations from the highest value in the group, in percentages. It is clear that the increase in area coverage is accompanied by the relative decrease of measured values for the smaller elements.

What is seen in for 28 % is closer to what is expected: curves closely together (except for the sample composed by the largest elements), meaning good agreement between representativeness of the different samples. It probably does not happen in the 14 % coverage scenario due to low quantity of elements and therefore lower representativeness, specially for larger elements. Also, the absolute values for the scattering coefficient are lower, meaning that absolute deviations are relative larger. Nevertheless, there is no clear distinction between curves related to elements' size.

Thinking only on the increase of area coverage due to an increase in the quantity of elements, from results in [5] and also discussions in [16], more isotropic samples may indeed lead to lower scattering coefficients simply because of its definition regarding strictly “non-specularly

<sup>7</sup>Kosaka and Sakuma, studying the scattering coefficient of sinusoidal surfaces with a numerical method, also noticed higher scattering coefficients for smaller samples and attributed this observation to edge effect.

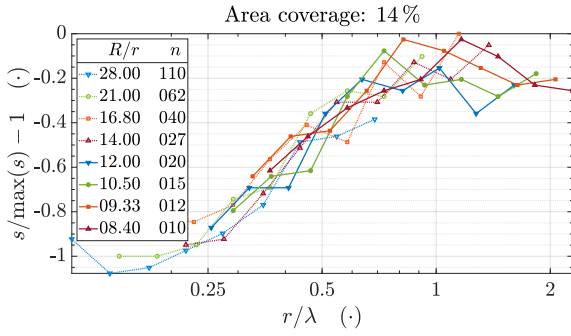


**Figure 2:** Scattering coefficients for distributed hemispheres at 14 % area coverage. Data from [3].

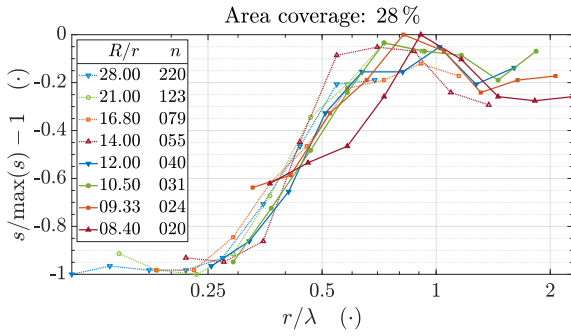


**Figure 3:** Scattering coefficients for distributed hemispheres at 28 % area coverage. Data from [3].

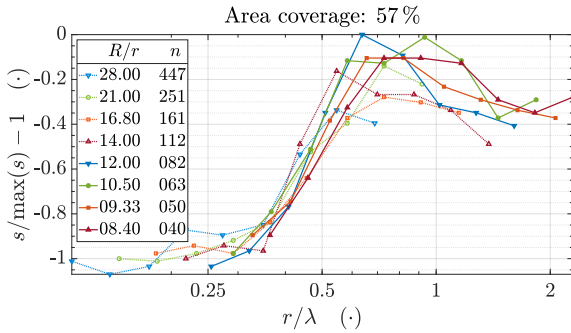


**Figure 4:** Scattering coefficients for distributed hemispheres at 57 % area coverage. Data from [3].

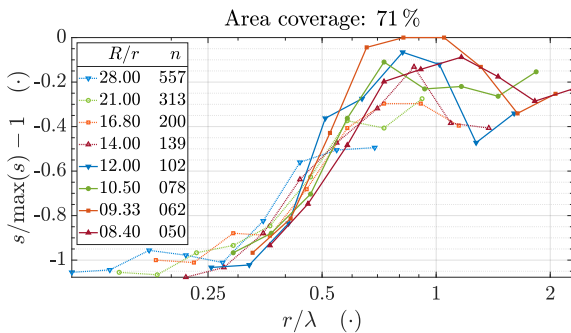


**Figure 5:** Scattering coefficients for distributed hemispheres at 71 % area coverage. Data from [3].

interest<sup>8</sup>. In other words, the effect of isotropy as an artifact due to the measurement procedure may play some part in lowering absolute values of scattering coefficients for higher area coverages, but it is not the only phenomenon causing this result. Therefore, even if the (artifact) isotropy effect is quantified and accounted for, the scattering values for higher coverage densities may be, as a true surface property, lower.

However, as discussed in section 2.2, it is expected that, as long as the quantity of elements is representative, the area coverage is the only property relevant to characterise this type of surface. Therefore, the lower scattering coefficients for smaller elements as presented in Figures 4 and 5 may be, indeed, due to higher isotropy (as an artifact).

An important note is that it is clear that highly angle-dependency leads to high scattering values [16, 17]<sup>9</sup>, but it's not clear that an opposite effect, which is isotropy, necessarily results in undesired artifacts; Sakuma and Kosaka, for a 1D sinusoidal surface, obtained similar results from a measurement and a numerical simulation that considered sample rotation, and these were higher than those calculated using the Mommertz' method. For a 2D sinusoidal surface, both numerical methods presented similar results. For this surface, still using Mommertz' method, the scattering was also similar over most of the frequency range to a pseudo-random surface [9].

### 3. SYMMETRY FUNCTION

A symmetry metric was developed in order to confirm that sample isotropy is indeed higher for smaller hemispheres and is also more accentuated for high coverage densities [6]. This symmetry function, or coefficient, is better explained with an example. It's also useful to look at the sample and functions involved both at a polar coordinate system, which better represents the physical reality, and a rectangular coordinate system, which better presents the functions involved. This last is actually a

<sup>8</sup>See Figures 7 and 8 for the 2 kHz analysis in [5] and section 3.5 in [16].

<sup>9</sup>See section 5.3.3 in [17].

redirection of energy” as the component of

stretched polar plane, not a mapping from the polar plane. A sample example is then present on Figure 6.

The first step to calculate the symmetry coefficient is to have a function that describes the sample. A function  $f[\phi]$  that describes the total area occupied by hemispheres at each slice  $\Delta\phi$  was chosen as the sample's function. For the given example, it's presented on Figure 7.

Then, the symmetry function is the (circular) autocorrelation (or circular convolution) of the sample's function  $f$  normalised by the correlation's highest value<sup>10</sup>:

$$\begin{aligned} S_o[\tau] &= \frac{R_{ff}[\tau]}{\max(R_{ff}[\tau])} \\ &= \frac{R_{ff}[\tau]}{R_{ff}[0]} \\ &= \frac{\sum_{\tau=0}^{2\pi-\Delta\tau} (f[\phi] \cdot f[\phi + \tau])}{\sum (f[\phi] \cdot f[\phi + 0])} \quad (\cdot) \quad (6) \end{aligned}$$

in which  $\cdot$  is the dot product operator,  $\Delta\tau$  is the unitary discrete displacement and  $\tau$  is the angular displacement. It is interesting to notice that this displacement corresponds to an actual sample rotation. Figure 8 presents the calculated symmetry function for the sample function presented in Figure 7.

If  $S_o[\tau] = 1$ , then the sample presents a discrete symmetry at every  $|\tau|$  rotation. In other words, if the surface is rotated a  $\tau$  amount, in any direction and with any reference (starting) angle, it will present itself in the same way as if none rotation was taken. More examples and intuitions are discussed in [6].

### 3.1 Randomly Distributed Hemispheres Sample Generation

For the sample isotropy property investigation, some randomly distributed hemispheres samples were generated. For densities below 50 %, a simple blind approach using MATLAB was sufficient. That is, both an angle and distance from the center were uniformly randomly chosen.

If there was enough room for a hemisphere at those coordinates, it was “placed” there - those coordinates were saved. If not, the coordinates were discarded and another was chosen in the same way.

For samples with density higher than 50 %, they were designed using Adobe Illustrator. The coordinates were acquired using a free online graphical tool<sup>11</sup> from the generated figure. These coordinates could then be read by MATLAB for further processing.

To emphasise the randomness and due to the different design approaches, a color scheme was created for plotting. The plot colors followed from dark blue to light green. In this way, randomly generated samples present mixed up hemispheres of different colors, following the color scheme in the order the coordinates were generated. The handcrafted samples will present the color scheme cycling the sample.

### 3.2 Sample Isotropy

As shown in [6], according to the metric presented in section 3, the sample isotropy indeed increases for higher area coverages and for smaller elements. Figure 9 illustrates this finding. Also, it is shown in [6] that, as suspected, the scaling of a sample does not affects its isotropy, even if empty borders are created in the process (an empty border is, in fact, isotropic, and therefore does not affect the sample isotropy).

## 4. SAMPLES MEASUREMENTS

A physical setup was built in order to verify if the sample representativeness would be indeed the same for scaled samples of randomly distributed hemispheres. The measurements were performed in the chamber built by [Cavalcante and Felchak](#). It has a system for automatised placement of loudspeaker and microphones, leading to higher repeatability and shorter measurement periods [19, 20].

The chamber has a volume of 1.48 m<sup>3</sup>, which leads to an approximate scale factor of 5. The turntable has 790 mm in diameter. The

<sup>10</sup> $\max(R_{ff}[\tau]) = R_{ff}[0]$  is an identity of the autocorrelation function.

<sup>11</sup><https://apps.automeris.io/wpd/>.

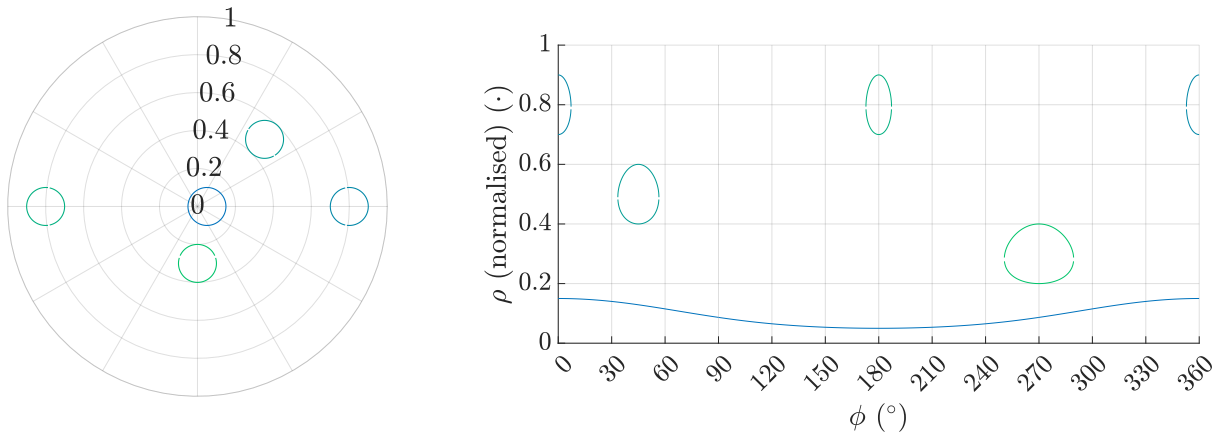


**Figure 6:** Distributed hemispheres sample example (elements' radii are  $R/10$  - a tenth of sample's total radius). The sample is projected on both polar and rectangular (stretched) planes. Also,  $\rho$  is the distance to the center of the sample.

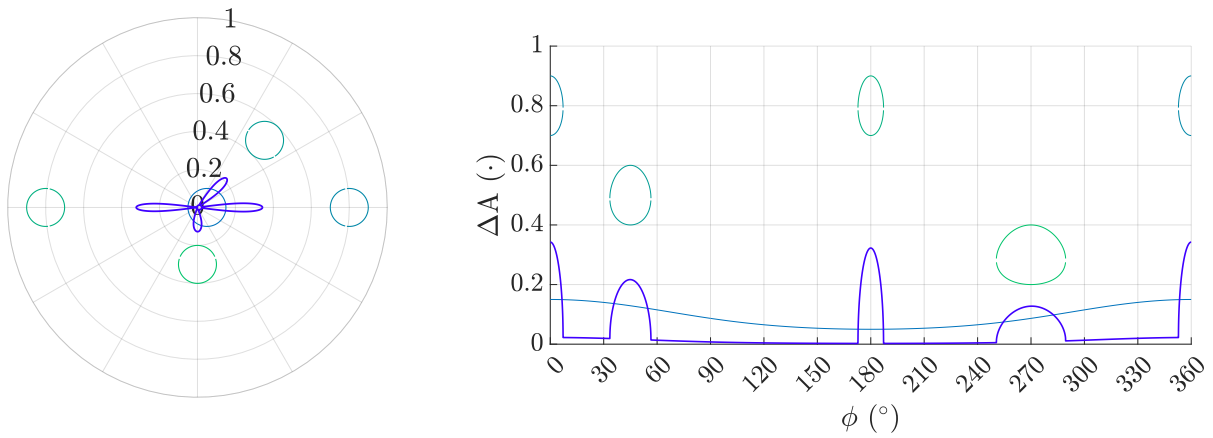


**Figure 7:** In indigo, the sample function - area distribution - for the sample in Figure 6.

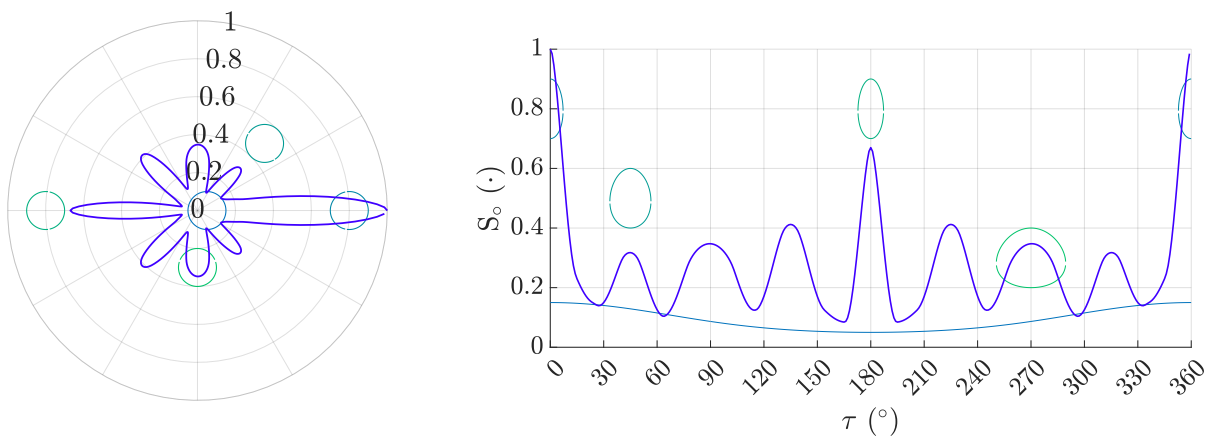


**Figure 8:** In indigo, the symmetry function for the sample in Figure 6 using the sample function presented in Figure 7.

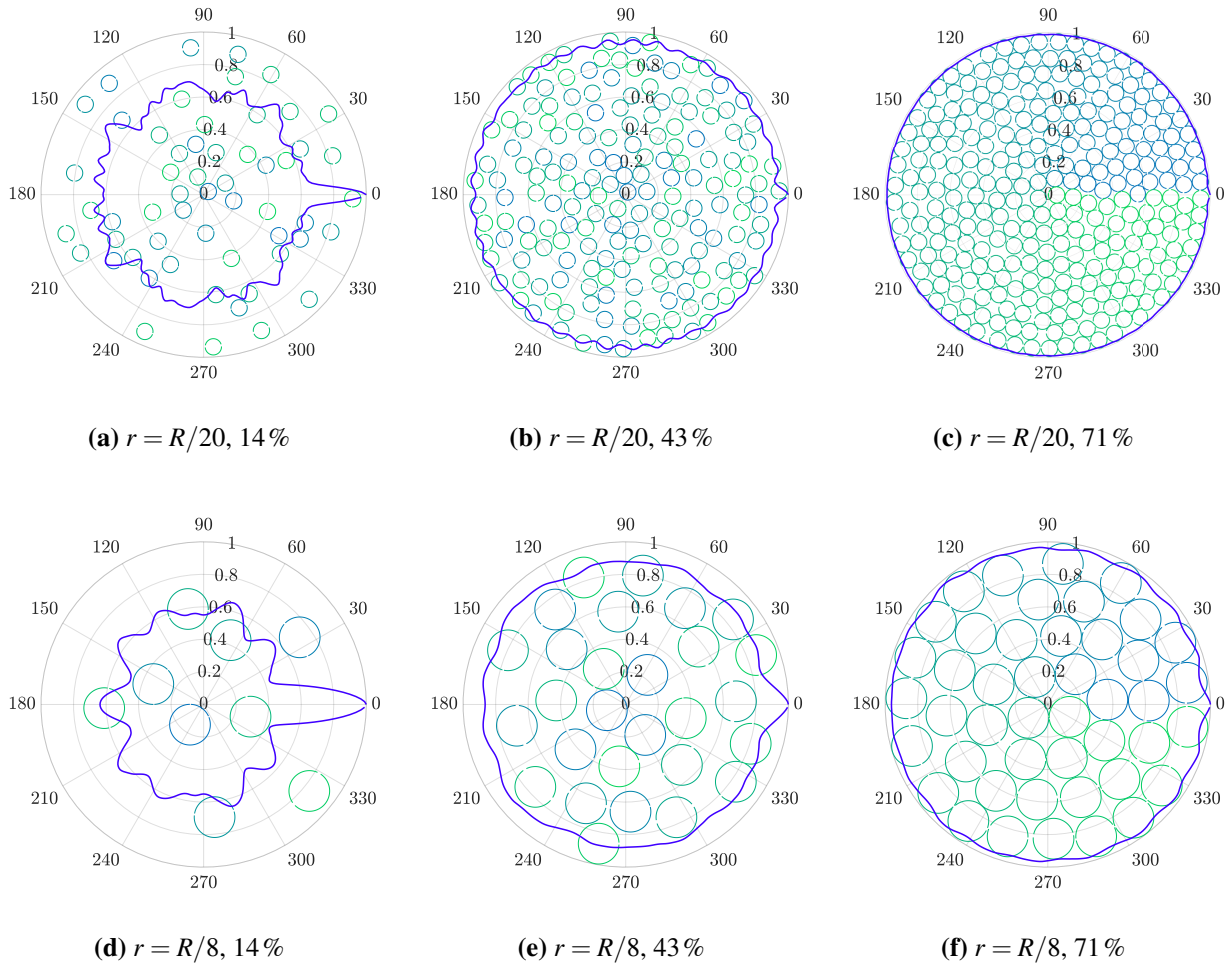


**Figure 9:** In indigo, symmetry functions of samples composed by randomly distributed hemispheres.  $r$  corresponds to the elements' radii,  $R$  corresponds to that of the sample, and the percentage values correspond to the area coverage.

sound source is a 100 mm sided cube with six loudspeakers, built by [Tourinho](#). The two random-incidence microphones are GRAS 46AQ with GRAS 12 AL power supplies. The A/D converter is an RME Hammerfall DSP Multiface II with power amplifier Alesis RA-100.

During all turntable rotations, a set of 72 sweeps was emitted, each followed by a short period of silence to better accommodate the decays of all frequency bands. Each signal (with silence) was approximately 1.37 s long. The ITA toolbox<sup>12</sup> for MATLAB was used to carry the impulse response measurements and reverberation time calculations. For the standard's [1] specificity of the impulse response truncation at  $-30$  dB, an algorithm presented in [6] was utilised. The minimum recommendation of 12 loudspeaker-microphone positions was followed.

In what concerns uncertainty calculations, [Müller-Trapet and Vorländer](#) showed that correlations between variables should be taken into account. A correlation coefficient of 1 should be used between  $T_1$  and  $T_3$  and, between  $T_2$  and  $T_4$ ,  $1 - \alpha_{\text{spec}}$  is a good approximation. All uncertainty equations are then presented in [6] (sec. 2.3.5) and are utilised. Repeatability is accounted in section 4.1.

#### 4.1 Samples

The measured samples were all composed of randomly distributed hemispheres and their characteristics are presented in Table 2. Images of them are present in the Git repository. Attention is brought to the fact that, rounding the turntable radius to 400 mm, sample B can be interpreted as a reduced scale version of sample C - the elements' size is reduced in proportion with sample radius - and therefore

<sup>12</sup><https://git.rwth-aachen.de/ita/toolbox>.



presents, overall, the same isotropy. This is the main reason behind choosing elements with radii 15 mm and 20 mm. Also, the high coverage density of 71 % was chosen to bring evidence to the isotropy matter, as seen in Figures 2 to 5. This high density, together with small sized elements, also avoid an insufficient, non representative, number of elements.

The edge strip covering sample D is made of 5 mm thick acrylic, with a height of 50 mm. It is fixed on the chamber floor, just bordering the flush mounted turntable, in order to avoid any additional scattering during rotations. The guidance discussed in section 2.3 about the recess depth on a flush mounting (or, analogously, edge strip height) was not followed to ease the measurement of other, higher samples.

In what concerns repeatability, sample C, left untouched, was measured twice on different days. Only for the 4000 Hz and 12,500 Hz bands the measurements were out of the confidence interval. At least for the higher frequency bands, part of this is probably due to air absorption. Figure 10 presents the relation between the energy decay rate due to air absorption and the total energy decay rate, which accounts for both air and surface absorptions, for different measurement steps.

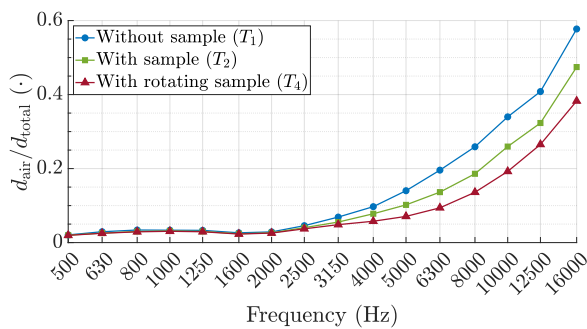


**Figure 10:** Energy decay rate due to air in relation to the total decay rate for sample C.

The ISO [1] limit for equivalent absorption area is respected for the larger samples; however, the same cannot be said for the smaller one. The ratio between equivalent absorption area for  $T_1$  and sample area is presented in Figure 11.

The hemispheres are made of polystyrene. It

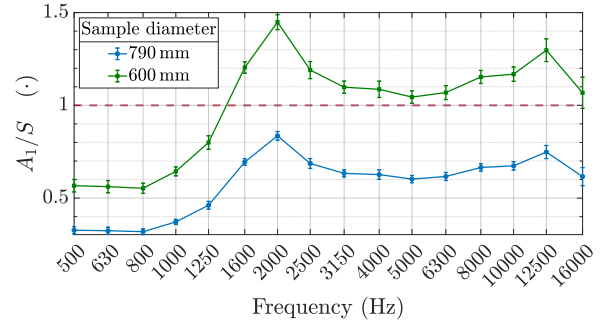


**Figure 11:**  $A_1/S$  ratio with expanded uncertainty. The standard rule-of-thumb-limit is 1 [1].

leads to higher absorption coefficients than usual, but still below the standardized limit. The values are presented in Figure 12.

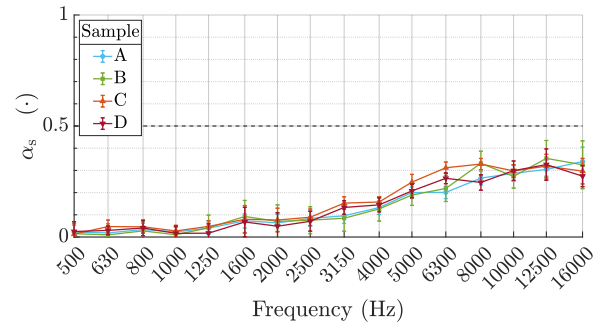


**Figure 12:** Samples' absorption coefficient with expanded uncertainty. The standard limit is 0.5 [1].

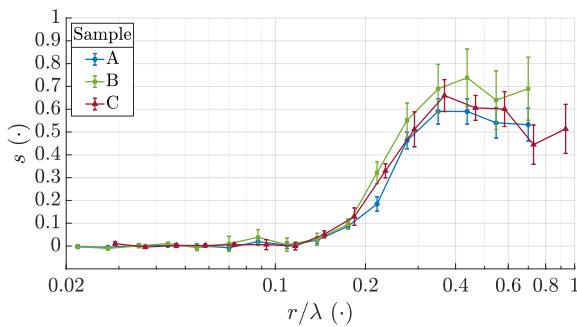
## 4.2 Measurement Results

Figure 13 presents the measured scattering coefficients of samples A, B and C. Due to sample isotropy, lower coefficients are expected for sample A in relation to sample C. Although this overall tendency is observed, the deviation is not significant, probably due to the small difference in the  $R/r$  ratio. The main objective, however, is to compare the results for sample B in relation to the others: this sample is the same as sample A, but less elements due to the smaller area; also, it should have same representativeness as sample C, since it is only a scaled version of it. So, regarding isotropy, similar results are expected to samples B and C, with A presenting lower scattering values. The scattering for sample B, however, is clearly, although not always statistically significant, higher than the others.

This may be explained by three factors:

**Table 2:** Measured samples

| Sample | $r$ (mm) | $R/r$ | $R$ (mm) | Quantity | Coverage (%) | Edge Strip |
|--------|----------|-------|----------|----------|--------------|------------|
| A      | 15       | 26.3  | 395      | 491      | 71           | no         |
| B      | 15       | 20.0  | 300      | 284      | 71           | no         |
| C      | 20       | 19.72 | 395      | 276      | 71           | no         |
| D      | 20       | 19.72 | 395      | 276      | 71           | yes        |


**Figure 13:** Scattering coefficients with expanded uncertainty for samples A, B and C.

1. the ratio  $A_1/S$  is higher than the maximum allowed by the standard [1]. However, it didn't affect the random-incidence absorption coefficient measurement, as shown in Figure 12;
2. eccentricity on turntable rotation and/or on the sample placement; and,
3. higher circumference-area ratio, as discussed in section 2.3, affects sample representativeness.

Following measurement error theory, a perfectly centered sample placement or axis of rotation is impossible. Although an error of 5 mm would be high considering craftsmanship, it would correspond to less than 2 % of a 300 mm sample radius. As cited in section 2.1, the effects of eccentricity are not fully known. One may guess that any eccentricity would affect more the results the smaller the sample since the relative linear displacement would be larger. However, the object being measured is virtually an area and what affects the sound field is the displacement of a volume, so what is the most relevant quantity, then?

Conversely, the effect regarding the circumference-area ratio seems aside these

ponderings. Specially in a sample composed by randomly oriented and distributed elements, the physical impact the sample rotation has on the sound field is higher at the border than at the center, seeing that the effective displacement of elements near the border is higher than those near the center. This phenomenon may be interpreted as another type of edge effect - since there is not a strict edge. For samples that are more angle dependant, like 1D surfaces, this type of edge effect is probably lessened; that is, aside from the edge effect discussed in section 2.3, different sample regions contribute more equally to the impact on the sound field while rotating. This deduction comes from discussions from Cox and D'Antonio (sec. 5.3.3), comments by Sakuma and Kosaka<sup>13</sup> and results from Jeon et al.. The authors obtained higher scattering coefficients for ordered cubes than for randomly distributed ones [2]. Also, as discussed in [6], effects that involve the samples' areas will probably be higher in reduced scale chambers, since the relation of the sample's area to the chamber volume is higher. However, it is important to remember that, as discussed in section 2.4, lower scattering values for low angle-dependant samples may be indeed partially expected simply due to the coefficient definition.

Finally, isotropy may explain the lower scattering coefficients for smaller elements in Figures 4 and 5, and also the expected lower values for sample A in relation to sample C, as discussed. It can also explain the lower values of A in relation to B. However, it can't explain the higher values of B in relation to C. Edge effect (circumference-area ratio), as noticed by Kosaka and Sakuma due to differences in samples' diameters, may explain both. The differences between A and B,

<sup>13</sup>See section "Effect of averaging processes".



and B and C, are simply because of the difference in diameters. The difference due to the use of smaller elements (A and C) is that because the sample with smaller elements may be interpreted as a larger, extended version of the sample with larger elements. That is, a sample like C being scaled down to become B and then extended to become A, so A is an extended version of C.

Although this analysis makes sense, [Kosaka and Sakuma](#) analysed sinusoidal samples. [Gomes et al.](#) also did, but the results of samples with 11, 22 and 44 periods were very close from each other (see Figure 1). So this idea of “extending a surface with change of scale” resulting in lower scattering coefficient due to edge effect seems to only make sense when there’s a significant increase in isotropy. So edge effect may explain the higher measured scattering for sample B, but the lower values of scattering due to element size are, indeed, probably due to isotropy (as well as part of the decrease for higher area coverages, presented in section 2.4). As discussed in section 2.2, many effects are at play and therefore the scattering values may also be the result of a mix of both phenomena.

Lastly, Figure 14 presents the results for samples C and D, the only difference between them being the addition of an edge strip. As can be seen, the strip addition resulted in significant lower measured scattering, even with a sample that has not a strict edge. As discussed over the results in Figure 13, an edge effect may exist nevertheless. However, it remains to be known if the lower scattering coefficients result only from attenuating undesired edge effects or if the blocking of high polar (high  $\theta$  in spherical coordinates) sound incidence and reflection leads to lower than desired measured coefficients. As discussed, in this type of sample, the bordering elements are, after all, the most influential.

## 5. CONCLUSION

This paper brought to light two phenomena that seemed untouched, at least explicitly:

1. sample isotropy resulting in lower scattering coefficients as a measurement artifact; and,
2. the edge strip may attenuate edge effects,

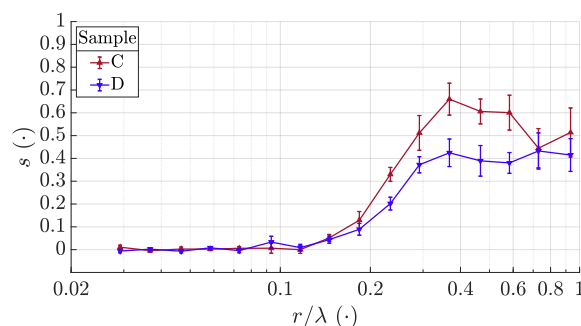


**Figure 14:** Scattering coefficients with expanded uncertainty for samples C and D.

but it may also result in lower than desired scattering values by affecting the sound incidence on the sample.

Although there are not definite conclusions on the matters, hopefully this work brings some ideas and tools to help solve them, as:

1. higher sample circumference-area ratio leads to higher edge’s influence and affects sample representativeness;
2. for distributed elements samples, elements near the border are more influential than those near the center;
3. therefore, there seems to be, indeed, an edge effect on samples that have not a strict edge;
4. isotropy increases for higher coverage densities and for smaller elements; and,
5. change of scale is a powerful tool. Samples composed by different sized elements may be interpreted as an extended or shrank version of the other depending on the proportion of elements sizes and samples’ areas.

Also, attention was brought to sample representativeness, in the sense that, with its various involved phenomena, it is a key factor on sound scattering measurement. It is the governing factor in causing deviations in the results of samples A to D. In the current case, it is either in the form of sample isotropy or different types of edge effect. To attenuate the latter, large samples are preferred over small ones. Regarding isotropy, in the case

of distributed elements, large elements should be used as long as there is a representative quantity of them - a value that has not yet been determined. By looking at Figure 3, a quantity between 24 and 31 elements seems enough - at least for hemispheres with an area coverage of 28 %.

It is important to remember that other factors, external to the sample, may also interfere. Examples are eccentricity on sample rotation or placement, low degree of diffusion in the chamber [23] and microphone height [8, 9, 12].

To better consolidate these ideas, some recommendations for future works are pointed out:

1. study on how turntable and sample placement eccentricity affect the measured scattering coefficient of different sized samples;
2. application of numerical methods both on the isotropy and edge strip matters for distributed elements samples;
3. measure samples with larger elements than those composing samples A to D to further verify the role of sample isotropy on the measured scattering coefficient. Also, continue the work with lower area coverages for further comparison with the work by Kim et al.; and,
4. regarding the edge strip matter, measurements specially of smaller samples of distributed elements with a strip are recommended for further comparison.

## 6. ACKNOWLEDGMENTS

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