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Isotropy and Diffuseness in Room Acoustics: Paper ICA2016-777

Non diffuse sound field in the reverberation room

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Abstract

The measurement method for diffuse field sound absorption (ISO 354) is troubled with low reproducibility, far worse than can be accepted in respect to design of spaces, control of quality and legal security. These differences are expected to be caused by insufficient diffusion in the reverberation room. Already geometrical modelling of sound in a reverberation chamber shows how the result of the absorption measurement depends on the scattering of reflections on walls and ceiling. Measurements in the chamber show the increase in absorption by adding diffusing materials on the walls. Attempts have been made to describe the diffusivity of the sound field based on the variation of the recorded sound decays. Suggestions will be given to increase the measured sound absorption, but also a method will be presented using a reference absorber to overcome the issue of different diffuse field properties in different reverberation rooms.

Keywords: Sound absorption

Non diffuse sound field in the reverberation room

1 Introduction

The reverberation room method is the widely used method for the determination of the random incidence absorption coefficient of materials. It is standardized in ISO 354 [1] and several national standards (e.g. [2]). The method is based on the relation between volume, absorption and sound decay. The results are used to calculate single number values such as αw[3] or reduction of reflections by traffic screens [4]. The obtained absorption coefficients are a.o. used to predict the decay in rooms, select products and to specify the material property in building contracts.

There are however some drawbacks: The value depends on the size of the material and the sound field in the room. Values over 1.0 are found as well as large differences in absorption coefficient measured in different reverberation rooms. The results are insufficiently accurate for the applications mentioned. Several round robin investigations have shown the large spread [5],[6],[7] and the latest version of ISO 354 in 2003 [1] has not improved that sufficiently [8]. It was found that the calculated Reproducibility limit according to [9] R=2,8σr of a 10 cm rockwool sample is about 0,2 for frequencies from 400 Hz and higher and 0,15 for the αw single number value.

To illustrate the influence of the sound field on the sound absorption absorption measurements in one laboratory are shown in figure 1 and 2. Figure 1 shows the measured sound absorption of the same 10 cm rockwool sample in three condition of the sound diffusion of the room: no diffusors, normal panel diffusors including 2 wall diffusors and spherical segment diffusors attached to two walls and the ceiling of the reverberation chamber (“volume diffusors”).

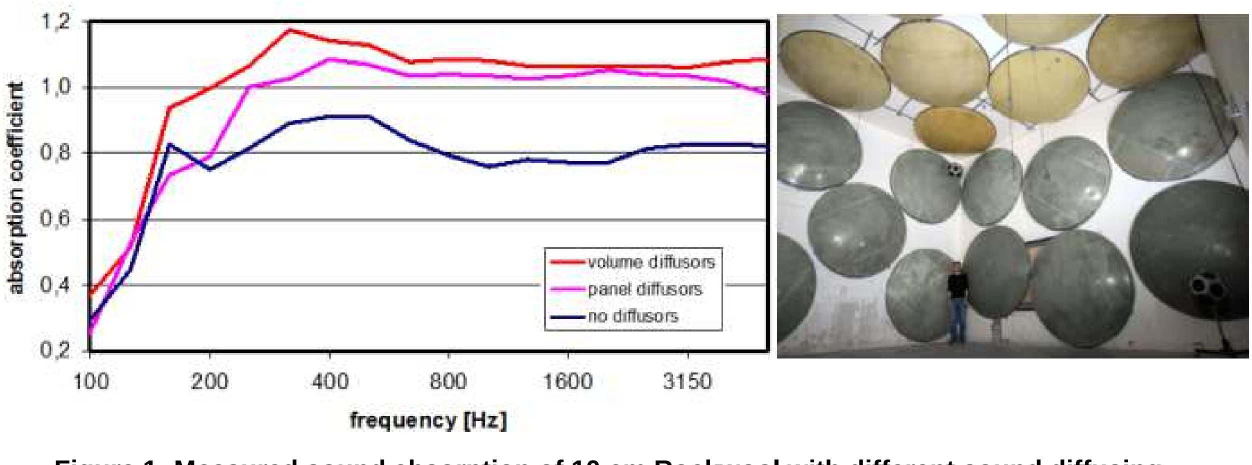

Figure 1: Measured sound absorption of 10 cm Rockwool with different sound diffusing configurations. The spherical segment diffusors (“volume diffusors”) are shown in the right.

Although the reverberation is already quite diffuse in itself (non parallel walls, tilted ceiling), there is a significant difference between the situations without diffusors and with the panel diffusors.

The probable reason for this is the increased diffusion of the horizontal sound field. This is also illustrated in figure 2. In this case the sample is located at three different positions in the room: the normal middle position, the corner position that is (traditionally) used for measurement of chairs and the wall position that is often used for measuring curtains.

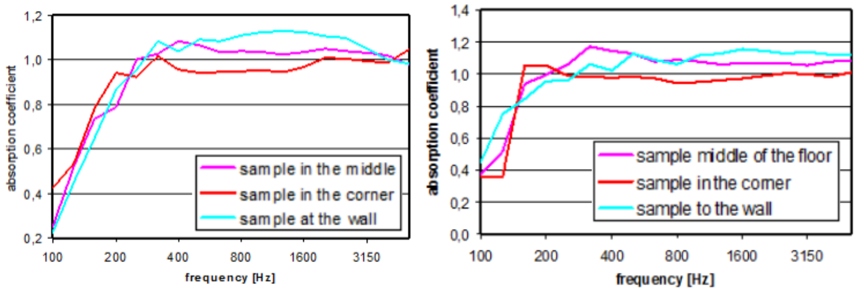

Figure 2: Measured sound absorption of 10 cm Rockwool at three positions in the reverberation room. Left: with normal panel diffusors, right: with volume diffusors.

The results show that the corner position gives reduced absorption at middle and high frequencies. Especially with the panel diffusors, the wall position has significantly higher sound absorption, showing that there is a horizontal sound field dominating the decay rate. The use of the volume diffusors attached to the wall do reduce the difference to some extent, but still there are differences between the positions. From these data it can be concluded, that it is hardly possible to create perfect diffuse sound field conditions in a reverberation room. To reduce the spread between laboratories but also between different positions in the same room additional measures have to be taken. An obvious option is to apply a reference material: A standardised absorber that can be used by laboratories to calibrate the position in the room that is used for the measurement.

In [8] the 10 cm rockwool sample was used to correct the results of two other samples. If a laboratory had e.g. 5% lower value for the 10 cm rockwool than the average result, the results of the other two samples was corrected 5% upward. It was found that the Reproducibility limit R of the other samples reduced significantly by using this correction. That means that laboratories that have e.g. relatively low absorption with the 10 cm Rockwool, they also have relatively low absorption with the other samples.

Introducing a reference absorber would be a significant improvement of the method of measuring sound absorption in the reverberation room according to ISO 354.

In this paper we will discuss such a reference absorber to overcome the limitations of the diffuseness of the reverberation chamber: in respect to requirements, design and sound absorption value.

2 Requirements to a reference absorber

Every laboratory should have this reference material for the calibration procedure, but also for yearly verification according to ISO 17025 procedures. So the material should be easy to handle and store, without damage to the material. The sound absorption of this material should be identical for all laboratories, so it should be well defined, stable, available now and in the future, it should not depend on mechanical behaviour (as for e.g. with panel absorbers) and it should preferably be homogeneous. Nevertheless it can be expected that there will be always small differences between samples. If not at production than may be over the years due to aging, dust collection etc. It is important that small changes in the material properties do not lead to significant changes in sound absorption. To illustrate this the sensitivity s was calculated:

$$s = \frac{\Delta\alpha}{\Delta x} \tag{1}$$

with: $\Delta\alpha$ change in absorption
Δx change in input parameter

Figure 3 shows the sensitivity s for two different input parameters: the thickness of the material and the air flow resistivity. The calculations have been done with the calculation model described further on in this paper.

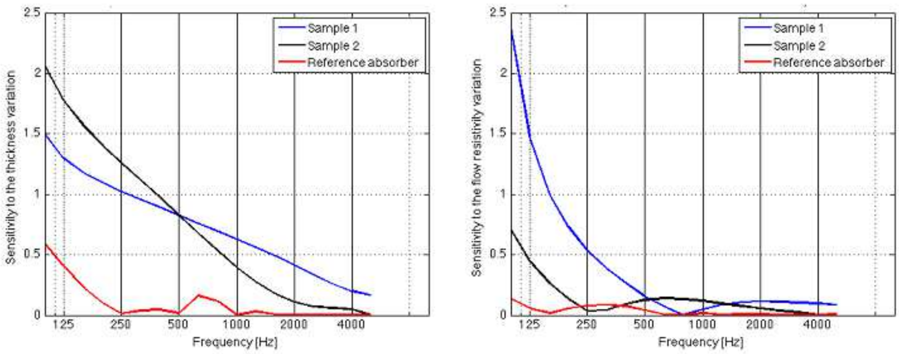

Figure 3: Calculated sensitivity of the sound absorption for variation of an input parameter, glasswool air flow resistivity 12,9 Pa·s·m^{-2} with three thicknesses. Left: for thickness variation, right: for air flow resistivity variation.

The results show that a material with sound absorption properties around α=1 has very low sensitivity for variation of properties. So in terms of sound absorption it is recommended that it should have a very high sound absorption, preferably around α=1 for the full frequency range.

3 Design of the reference absorber

The first step in the design of the reference absorber is made with the use of theoretical prediction of the random incidence sound absorption of different materials. The used theoretical model is summarized here. The complex characteristic impedance Z_c and propagation constant k_t of the material are estimated based on the empirical Delany/Bazley/Miki model [10]:

$$Z_c = Z_0\left(1 + 0.07\left(\frac{f}{r}\right)^{-0.632} - j0.107\left(\frac{f}{r}\right)^{-0.632}\right) \tag{2}$$

$$k_t = \frac{\omega}{c}\left(1 + 0.109\left(\frac{f}{r}\right)^{-0.618} - j0.160\left(\frac{f}{r}\right)^{-0.618}\right)$$

with f frequency [s^{-1}]
r air flow resistivity [Pa·s·m^{-2}]

The surface impedance $Z(f,\theta_i)$ of a material with thickness d on an air gap with impedance $Z_{x=d}$ can be described as function of the frequency and incidence angle θ_i :

$$Z(f,\theta_i) = Z_c \frac{k_o}{k_t}\left(\frac{-jZ_{x=d}\cot(k_x d) + Z_c \frac{k_o}{k_x}}{Z_{x=d} - jZ_c \frac{k_o}{k_x}\cot(k_x d)}\right) \tag{3}$$

With k_o is the characteristic impedance of air ($k_o = \rho c$) and the propagation constant k_x in normal direction in the material:

$$k_x = \sqrt{k_t^2 - k_o^2 \sin^2(\theta_i)} \tag{4}$$

and the surface impedance of the air gap:

$$Z_{x=d} = -jZ_o \frac{k_o}{k_t}\cot(k_o d_o \cos\theta_i) \tag{5}$$

For normal incidence $(\theta_i = 0)$ the sound absorption can be calculated and compared to results obtained from the interferometer:

$$\alpha_\perp = 1 - \left|\frac{Z'(f)-1}{Z'(f)+1}\right|^2 = \frac{4\,\mathrm{Re}(Z'(f))}{|Z'(f)|^2 + 2\,\mathrm{Re}(Z'(f)) + 1} \tag{6}$$

with: $Z'(f) = Z(f)/\rho_o c_o$

The angle dependent sound absorption can be calculated from:

$$\alpha(\theta) = \frac{4\,\mathrm{Re}(Z'(f))\cos\theta_i}{|Z'(f)|^2\cos^2\theta_i + 2\,\mathrm{Re}(Z'(f))\cos\theta_i + 1} \tag{7}$$

The random incidence sound absorption follows from (Paris' formula):

$$\alpha_{rand} = \int_0^{\pi/2} \alpha(\theta_i)\sin(2\theta_i)\,d\theta_i \tag{8}$$

It is important to consider that this random incidence is not related to the size of the sound absorbing object. This is also indicated as an "infinite" absorber. The random incidence sound absorption is calculated for different air flow resistivities and thicknesses, see figure 4. This shows that at low thickness a higher air flow resistivity is required than for higher thickness of the material. A maximum sound absorption can be obtained for air flow resistivity around 6-12 kPa·s·m^{-2} and high thickness. With 200 mm of thickness at low frequencies an absorption around α=1 does not seem feasible.

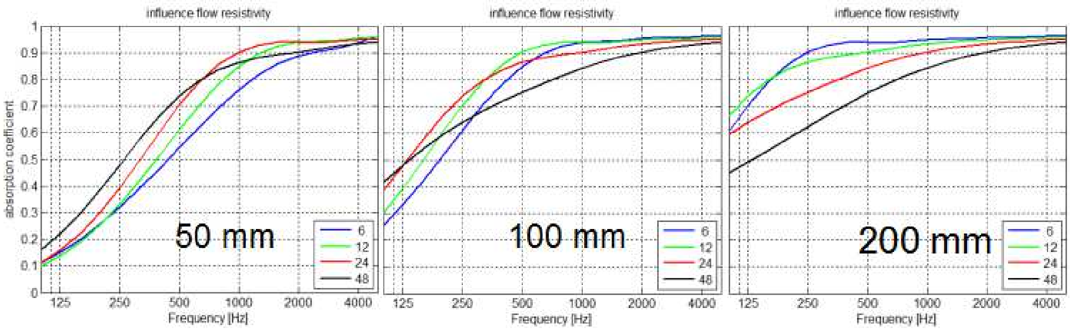

Figure 4: Calculated sound absorption for different air flow resistivity (in kPa·s·m^{-2}) and thickness of the material (in mm)

The material selected was glasswool with specifications in table 1 below [11]:

Table 1: Specifications of the selected material

Product	Industry Modus S	Open porosity	0,99
Finishing	Both sides glass fibre	High frequency limit of the dynamic tortuosity	1,01
Binder content	7,0 ± 0,5 %	Viscous characteristic length	82 µm
Density	26,5 ± 1,5 kg/m^3	Thermal characteristic length	182 µm
Thickness	100 ± 1 mm	Static thermal permeability	31.10^{-10} m^2
Air flow resistivity	12,9 kN.s.m^{-4}		

The material can be applied directly on the floor of the reverberation chamber, but it is also possible to apply an air gap, thus increasing the low frequency absorption. The calculated influence of thickness of this material, both with and without air gap, is shown in figure 5.

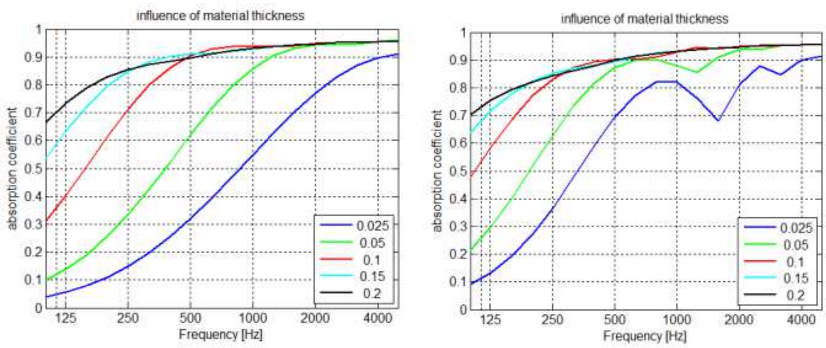

Figure 5: Calculated sound absorption of glasswool with air flow resistivity 12,9 kPa·s·m^{-2} and thickness of the material. Left: with hard backing, right: with an air gap of 100 mm.

Most of the results show a slight increase at quarter wavelength. Especially the material on an air gap shows a decrease at half wavelength. For normal incidence these effects are more clearly visible.

From the calculation results two configurations were selected and tested further: the 200 mm with a hard backing and 100 mm with an air gap of 100 mm. The practical advantage of the latter is the less storage space. The 200 mm consists of two layers of 100 mm. Figure 6 shows the impedance measured in the impedance tube, for pure tones at middle frequencies of third octave bands. In addition to the two selected configurations the 100 mm with hard backing is shown.

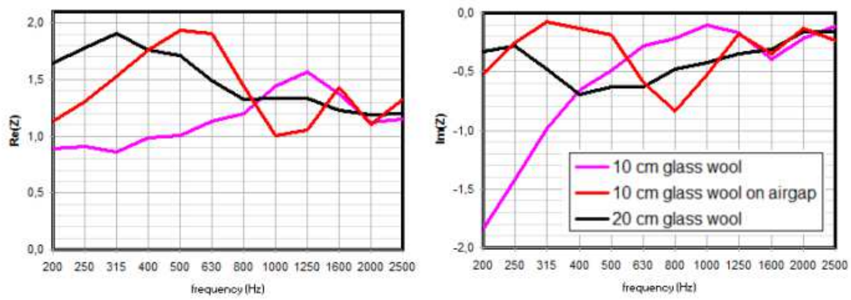

Figure 6: Measured impedance of three different configurations

An absorption of α=1 can (only) be reached for $Re(Z)=1$ and $Im(Z)=0$. It can be seen that for high frequencies the results converge to this value.

The measurement results are not identical to the calculated results. A more detailled analysis showed that a better agreement is achieved by using air flow resistivity of 8,5 kPa·s·m^{-2}.

Next step was a practical configuration of the material in a protective casing. Based on material size 600x1200mm wooden casings were produced for both material thickness. Including the material thickness of 18 mm, the size of the total sample with 15 of such elements is 3180 x 3708 mm, total surface 11,79 m^2. For the measurement with the air gap the casings with the mineral wool were positioned on a bearing system and closed with a frame. The measurement results in the reverberation chamber are shown in figure 7. These results show that the performance of the 200 mm glasswool is very good over the whole frequency range. Especially below 800 Hz the performance of the 200 mm glasswool is better than the 100 mm glasswool on an air gap. However the 200 mm glasswool shows a peak at 125 Hz, that is not explained.

A comparison was made between the 200 mm in the casing and without casing (but with a frame around it); the results are shown in figure 8.

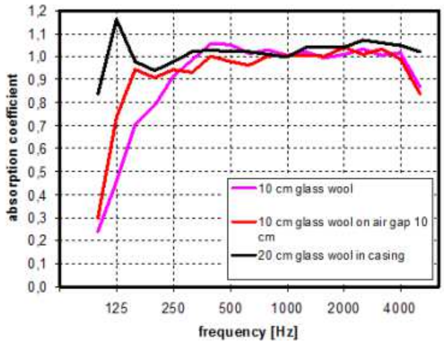

Figure 7: Sound absorption measured in the reverberation chamber with three configurations.

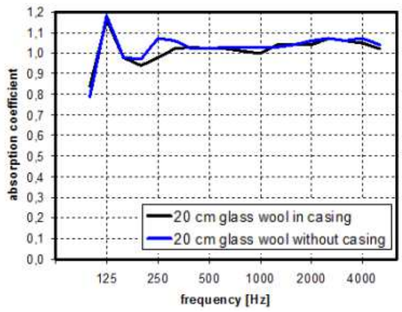

Figure 8: Sound absorption measured in the reverberation chamber of 200 mm glasswool, with and without casing

The results show that the peak at 125 is not caused by the casing. On the other hand a significant influence of the casing is found at third octave band frequencies 250 and 315 Hz. So it is concluded that the best option is to use the 200 mm of glasswool without casing, although there is an irregularities at 125 Hz and an α=1 cannot be expected in the 125 Hz octave band.

4 The sound absorption coefficient of the reference material

The optimum situation would be if the "true" sound absorption of the reference material could be determined on theoretical basis, to be able to calibrate the sound absorption in the laboratory to this value. The difference between the calculated random incidence sound absorption and the sound absorption in the reverberation room is the finite size of the sample. A method using the radiation impedance of a finite size sample is presented in [12] and [13]. This method assumes local reaction, where the sound wave in the material only propagates normal to the surface. For a homogeneous material a wave propagation in the material is to be expected corresponding to Snell's law. The method in [12] can be used also for extended reaction:

$$\alpha(f,\theta_i) = 2\int_0^{\pi/2} \frac{4\,\mathrm{Re}\left(Z'(f,\theta_i)\right)}{\left|Z'(f,\theta_i)+\overline{Z_r}(ke,\theta)\right|^2}\sin\theta d\theta \qquad (9)$$

$$\overline{Z_r}(ke,\theta) = \frac{1}{2\pi}\int_0^{2\pi} Z_r(ke,\theta)d\varphi$$

The radiation impedance $\overline{Z}_r(ke,\theta)$ is an average for azimuth angles φ from 0 to 2π. The radiation impedance can be calculated by four double integration [12]. The radiation impedance depends on the angle of incidence (referring to the normal), the frequency and the characteristic size of the sample (for a square the e is the length or the width). For different ke and θ the radiation impedance is given in [13] in table form. For very large sample size the radiation impedance converges to $1/\cos\theta$ and the resulting angle dependent sound absorption is identical to (7). To reduce uncertainties it would be good to use the measured values from the interferometer (for normal incidence) to calculate the sound absorption at oblique incidence. For a material with hard backing the impedance is given by:

$$Z'(f,\theta_i) = -j\frac{Z_c}{Z_0}\frac{k_t}{k_x}\cot(k_x d) \tag{10}$$

This can be separated in a variation by the angle and the value at normal incidence:

$$Z'(f,\theta_i) = \frac{k_t}{k_x}\frac{\cot(k_x d)}{\cot(k_t d)}Z'(f,0) \tag{11}$$

The first part can be calculated, based on the air flow resistivity according to (2b) and (4) and the impedance at normal incidence $Z'(f,0)$ can be measured in the interferometer.

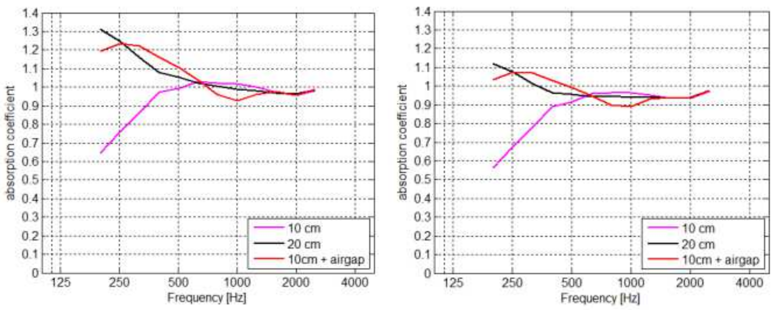

Figure 9: Calculated sound absorption for a finite sample of 3,18x3,2 m, based on the measured impedance in the impedance tube, an air resistivity of 8,5 kPa·s·m^{-2} and formula (11). Left: full integration, right: limited integration for 0<q<78°.

Figure 9 shows the calculated sound absorption for a finite sample (“diffuse field”) based on the measured impedance in the impedance tube, assumption of an air resistivity of 8,5 kPa·s·m^{-2} and formula (11).The result shows that the calculated sound absorption is significantly higher than the measured one in the low frequency region (below 500 Hz). By comparison with an alternative method, the modal decomposition method, it is suggested in [14] that an improvement can be made by avoiding grazing modes, this is done by limiting the integration angle to 78°. The result in figure 9, as well as [14] show that, although the difference is smaller, there is still a distinct difference between calculated and measured values at low frequencies.

It is concluded that at this moment the calculation of the sound absorption of a finite sample from the calculated or measured material properties has some inaccuracies and shows unrealistic results. At this moment this makes it not possible to define the "true" absorption coefficient based on these theoretical considerations.

5 Conclusions

Research has been performed to overcome the non perfect diffuse field conditions in the reverberation room, by application and optimisation of a reference sound absorber. It was found that 200 mm of mineral wool shows good sound absorption characteristics for almost the whole frequency range, however with a peak at 125 Hz. A practical solution to protect the reference material with a wooden casing showed negative influence on the sound absorption and has to be abandoned. At this moment it seems not possible to calculate the "true" sound absorption for a finite sample at perfect diffuse field conditions. That means that the reference values for the reference materials have to be "stated" values, e.g. based on measurements in several laboratories.

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