An experimental study on the effect of diffusers on the sound absorption measurement

Qiaoxi Zhu

University of Technology Sydney, Sydney, Australia

ABSTRACT

Limited reproducibility of absorption coefficients measured in different laboratories has been observed in the recent inter-laboratory test. This measurement uncertainty can result from the room acoustic design variance amongst laboratories and the material selection for qualification tests. Sound absorption measurements were performed in the reverberation room at the University of Technology Sydney, with test sample sizes and materials under different room acoustic conditions by installing different numbers of diffusers. With the measured data, initial work was made to decompose the sound absorption components based on the geometric feature of the test specimen, which is potential to assist the assessment of the diffuseness of the test facility and the optimization of diffuser installation.

1 INTRODUCTION

One challenge in the reverberation room method for sound absorption measurement is the variability of the measured absorption coefficient of the same sample in different laboratories (Halliwell, 1983). This measurement uncertainty is related to the degrees of sound-field diffuseness in the reverberation room, which can be affected by the interior treatment or the acoustics colouration in testing laboratories (Sabine, 1931). The sound field in a reverberation room might not be diffuse, especially when measuring highly absorptive specimens. With highly reflecting walls and ceiling but highly absorptive sample on the floor, some horizontal propagation paths never interact with the absorbent on the floor and so decay slowly, while paths with strong vertical components decay much more rapidly when they reflect from the floor. However, a diffuse field requires balanced horizontal and vertical components. Thus, diffusers are used to redirect the sound paths and improve diffuseness in the reverberation room, such as surface diffusers, volume diffusers or rotating elements (Cox & d'Antonio, 2016). However, with diffusers installed, the acoustical behaviour in the room is much more complicated. Care should be taken to install diffusers properly (Davy, 2018).

In some standards, there is a procedure to guide the use of diffusers. For example, in Annex A of ISO 354-2003, a procedure is introduced to achieve acceptable diffusivity by using fixed diffusers. The idea is to check the change of the mean value of the sound absorption coefficients from 500 Hz to 5000 Hz with the number of diffusers until it approaches a maximum for a standard test specimen that has a sound absorption coefficient greater than 0.9 over the frequency range from 500 Hz to 4000 Hz (ISO 354: 2003, 2003). Various parameters have been used to assist the assessment of the sound field diffuseness, such as the cut-off-frequency, number of modes, spatial uniformity of reverberant sound field, curvature of energy decay curves, accuracy of measured reverberation time and absorption coefficient (Hasan & Hodgson, 2016). Even with this highly controlled environment in a reverberation room created and commissioned based on the standard, significant deviations in measured quantities have been found in many round-robin tests (Chiara Scrosati et al., 2020; Vercammen, 2010).

Recently, a more dedicated isotropy indicator has been investigated to understand the sound field diffuseness during the sound absorption measurement (Mélanie Nolan, Berzborn, & Fernandez-Grande, 2020; Melanie Nolan, Fernandez-Grande, Brunskog, & Jeong, 2018). This approach requires a large number of sound field measurements, using wave-domain sound field decomposition to determine the sound field components from different directions and calculate an isotropy indicator to evaluate diffuseness. It has been further developed for measuring angle-dependent sound absorption coefficients. However, its large measurement burden makes it not cost-friendly for ISO 354 measurement or test facility commissioning, when the expected test result is only a single random-incident sound absorption coefficient. Based on the sound field decomposition concept, developing an engineering level diffuseness indicator with much fewer measurements could be of interest.

A new reverberation room has been built at the Centre for Audio, Acoustics and Vibration in the University of Technology Sydney (UTS), with its critical parameters reported in (Qiu, Zhu, Wang, & Zhong, 2019). The room volume is approximately 232 m^3, and the dimensions are shown in Figure 1. The ratio between its height and the square root of its floor area is 1.09, slightly larger than one. Sound absorption measurements were performed in this newly built laboratory with varying numbers of diffusers, and varying test sample sizes and materials, to understand how the room geometry and interiors affect the sound absorption test.

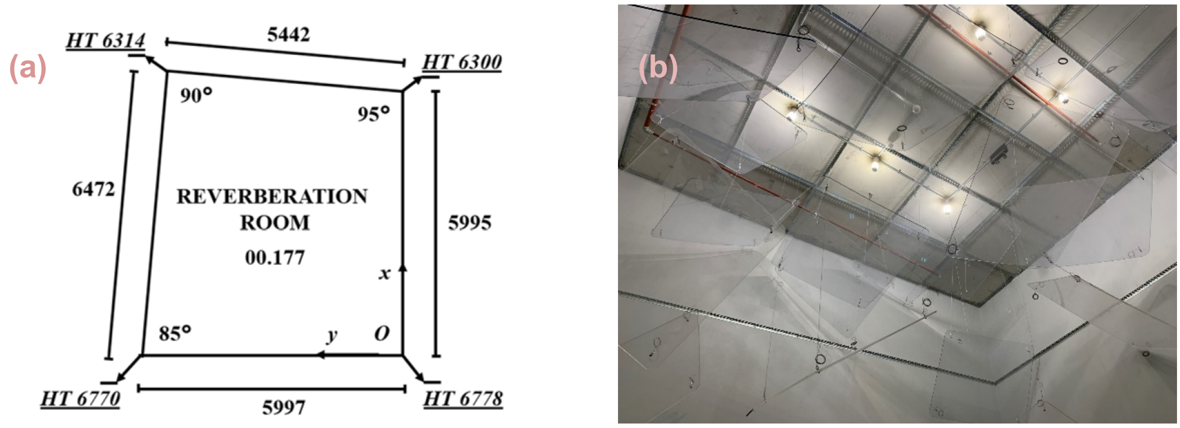

Figure 1: Geometry of the UTS reverberation room. (a) Dimensions, where HT means the height of the wall from floor level, with the default units being millimetre. (b) Suspended diffusers in the reverberation room.

2 METHOD

2.1 Reverberation room method for sound absorption measurement

The room's reverberation time is measured without and with the test specimen and denoted as T_1 and T_2, respectively. The equivalent sound absorption area of the empty room A_1 and that of the reverberation room containing a test specimen A_2 are calculated as

$$A_1 = \frac{55.3V}{cT_1} - 4Vm_1 \tag{1}$$

$$A_2 = \frac{55.3V}{cT_2} - 4Vm_2 \tag{2}$$

where V is the volume of the empty reverberation room, c is the speed of sound, and m_1 and m_2 are the sound attenuation coefficient when measuring the empty room and room with the specimen, respectively. The equivalent sound absorption area of the test specimen is

$$A_{\mathrm{T}} = A_2 - A_1 \tag{3}$$

and the sound absorption coefficient of a plane absorber with an area of S is

$$\alpha_s = A_{\mathrm{T}}/S = \frac{55.3V}{cS}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) + \frac{4V}{S}(m_1 - m_2) \tag{4}$$

However, these formulas are derived under the statistical analysis of room acoustics and based on the assumption of a diffuse field, where sound paths are ideally homogeneous and isotropic (Bies, Hansen, & Howard, 2017). Various investigations have been made to check the sound field diffuseness in a reverberation room through simulation or experimental measurements (Wang, Zhong, Qiu, & Burnett, 2020). However, it's not easy to perform accurate simulation or extensive measurement of the decaying sound field in a reverberation room.

Instead of investigating the detailed sound field, this paper attempts to directly check the matching between the sound absorption formula and the test room from the statistical sense using a few measurements. Since most reverberation rooms are rectangular-like, rather than dome-like, due to construction limitations, the first thing is to check whether the horizontal and vertical components are balanced when measuring a planar specimen of highly absorptive homogeneous material.

2.2 Decomposition of the sound absorption components under diffuse field

For a planar specimen of highly absorptive homogeneous material, which is common in reverberation room commissioning, the equivalent sound absorption area can be divided into three parts considering its geometry and the edge effect (e.g. scattering from the boundary material),

$$A_{\mathrm{T}} = A_{\mathrm{upper}} + A_{\mathrm{edge}} + A_{\mathrm{conner}} = \alpha_{\mathrm{upper}} \times S_{\mathrm{upper}} + \alpha_{\mathrm{edge}} \times S_{\mathrm{edge}} + \beta_{\mathrm{conner}} \tag{5}$$

where S_{upper} and S_{edge} represent the areas of the upper (main) surface and the edges, and α_{upper}, α_{edge} and β_{conner} are the coefficients indicating the sound absorption per unit of the three parts, respectively. If the sound field is sufficiently diffuse (ideally homogeneous and isotropic), the measured sound absorption will be independent of the size of the test specimen. That is, α_{upper}, α_{edge} and β_{conner} should be consistent for varying S_{upper} and S_{edge} from measurements under a diffuse field. Therefore, by testing the same specimen of at least four different sizes, the above formula can be fitted with the measured A_T values with corresponding S_{upper} and S_{edge}, resulting in estimated α_{upper}, α_{edge} and β_{conner}. It can be implemented through MATLAB fit function with the linear polynomial model. Then the decomposition of the sound absorption components can be obtained as $\alpha_{upper} \times S_{upper}$ and $\alpha_{edge} \times S_{edge}$ for the sound absorption through the upper surface and the edges, respectively.

2.3 Check of diffuseness through sound absorption component decomposition

The fitting result of Equation (5) can be used to analyze the diffuseness of the test sound field. Firstly, the goodness-of-fit metrics can be observed, including the sum of squares due to error (SSE), R-squared coefficient of determination (R-Square), degree-of-freedom adjusted coefficient of determination (adjusted R-Square), and root mean squared error (RMSE). A good fit will have SSE and RMSE approaching 0 while R-Square and adjusted R-Square approaching 1. If it fits well, it means that the test sound field is less affected by the sample size; If not, it means that the test sound field varies with the sample size and does not conform to the properties of the diffuse field.

For a good fit, the resulting α_{upper}, α_{edge} can indicate whether the horizontal and vertical sound field components are balanced, as an engineering alternative to assess diffuseness. Assume that S_{upper} is more sensitive to the vertical components and S_{edge} is more sensitive to the horizontal components. We can check whether the fitted coefficients are within a reasonable range. For example, use a general range that $\alpha_{upper} \in [0,1]$ and $\alpha_{edge} \in [-1,1]$, or a narrow range based on the knowledge of the exact test material properties. If the fitted α_{upper} exceeds the given range, the vertical sound field components might overweight the horizontal ones. If the fitted α_{edge} exceeds the given range, the horizontal sound field components might overweight the vertical ones.

3 EXPERIMENT

In the UTS reverberation room, sound absorption measurements were performed with 14, 17, 20 diffusers, respectively. Figure 1(b) shows that the diffusers are transparent perspex panels suspended from the ceiling. Each panel has dimensions 1.50 m × 1.20 m × 0.01 m. Two specimens were tested with different sample areas, as shown in Figure 3. One is a 200 mm thick specimen of glass wool inserted in protecting boxes made from MDF, including six boxes of dimension 1200 x 1200 x 200 mm and three boxes of dimension 1200 x 600 x 200 mm to account for the total specimen area 10.8 m^2. This specimen is detailed in (C Scrosati, Roozen, & Piana, 2019). The other is a 50 mm thick specimen of thermally-bonded polyester fibre, including three pieces of dimension 2400 x 1200 x 50 mm and three pieces of dimension 1200 x 600 x 50 mm for the total specimen area 10.8 m^2.

Figure 2: Six diffusers with relatively lower heights to the floor were removed for the measurement with 14 diffusers.

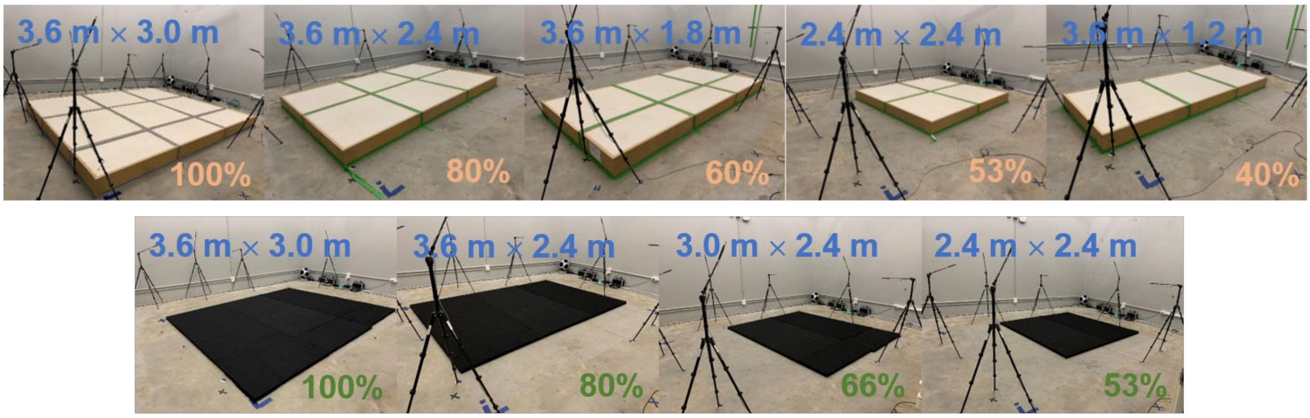

Figure 3: Sound absorption measurement of two highly absorptive specimens with varying sample areas. The 200 mm thick glass wool specimen is shown in the upper row and the 50 mm thick polyester specimen is shown in the lower row. The length and width of each test sample, as well as the percentage ratio between the upper surface area and the total area (10.8 m^2) are marked.

3.1 Sound absorption measurement with different numbers of diffusers

Figure 4 shows the result of the sound absorption coefficients measured using the two specimens, respectively, with 14, 17 or 20 diffusers installed. The upper surface area of each sample in this test was 10.8 m^2.

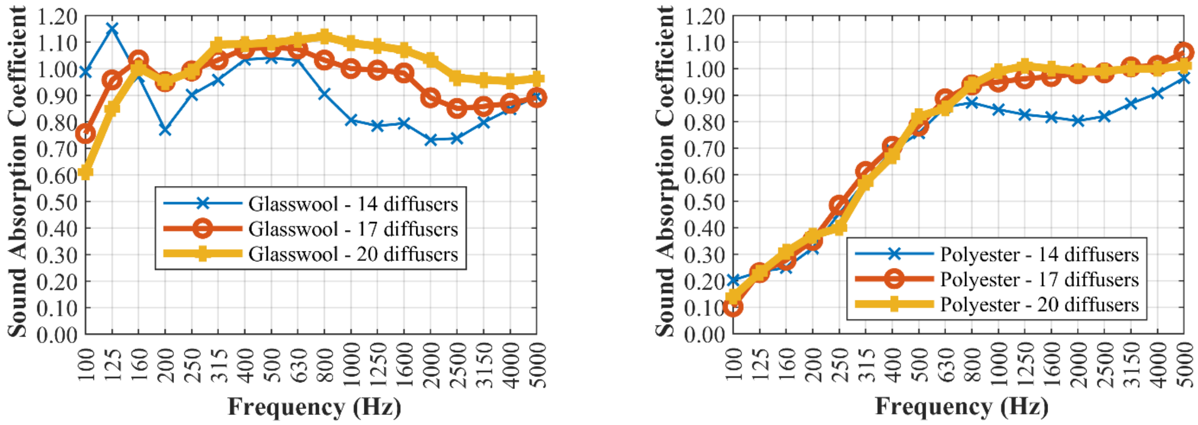

Figure 4: Measured sound absorption coefficients (α_s) of specimens with the upper surface area of 10 m^2, tested with 14, 17 or 20 diffusers, respectively.

3.2 Sound absorption measurement using samples of different areas

Figure 5 shows the result of the sound absorption coefficients measured using the two specimens, respectively, with different upper surface areas. The number of diffusers in this test was 20 for the 200 mm thick glass wool specimen while 14 for the 50 mm thick polyester specimen.

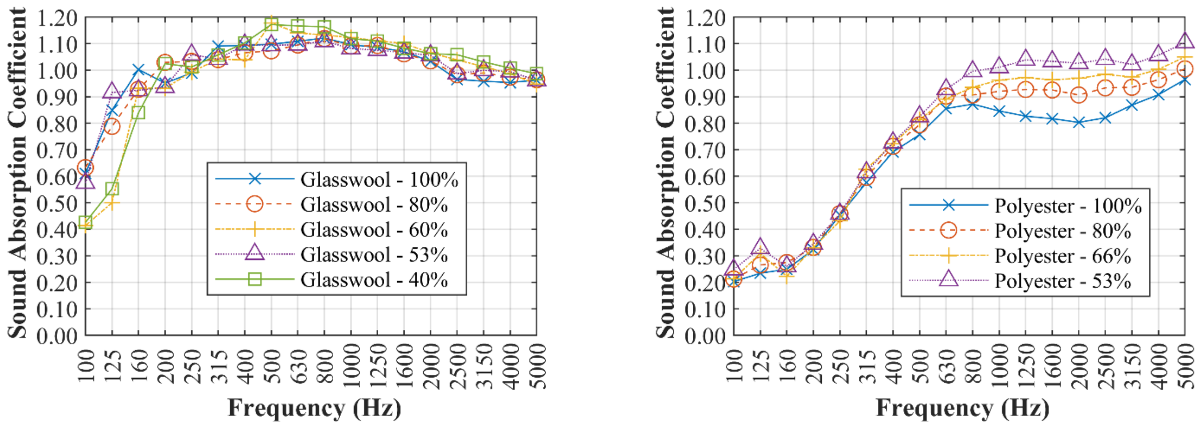

Figure 5: Measured sound absorption coefficients (α_s) of specimens with different sample sizes. The percentage value is the ratio between the upper surface area of each sample and the total area (10.8 m^2).

4 DISCUSSION

As described in Section 2.2, the coefficients of α_{upper}, α_{edge} and β_{conner} in Equation (5) can be obtained by least-squares fitting of the measured sound absorption values for different sample sizes. The following Section 4.1 presents the fitting result of the 200 mm thick glass wool specimen tested with 20 diffusers, and Section 4.2 presents the fitting result of the 50 mm thick polyester tested with 14 diffusers.

4.1 Sound absorption decomposition under diffuse-like field measurement

As shown in Figure 6, the sound field with 20 diffusers was diffuse-like. Specifically, α_{upper} has values around 1.0 except for the one-third octave band centred at 250 Hz, and the goodness-of-fit metrics SSE and RMSE approach 0 while R-Square and adjusted R-Square approach 1. Figure 7 shows the fitting curve per one-third octave band centred between 100 Hz and 5000 Hz, with the measured curve as a reference.

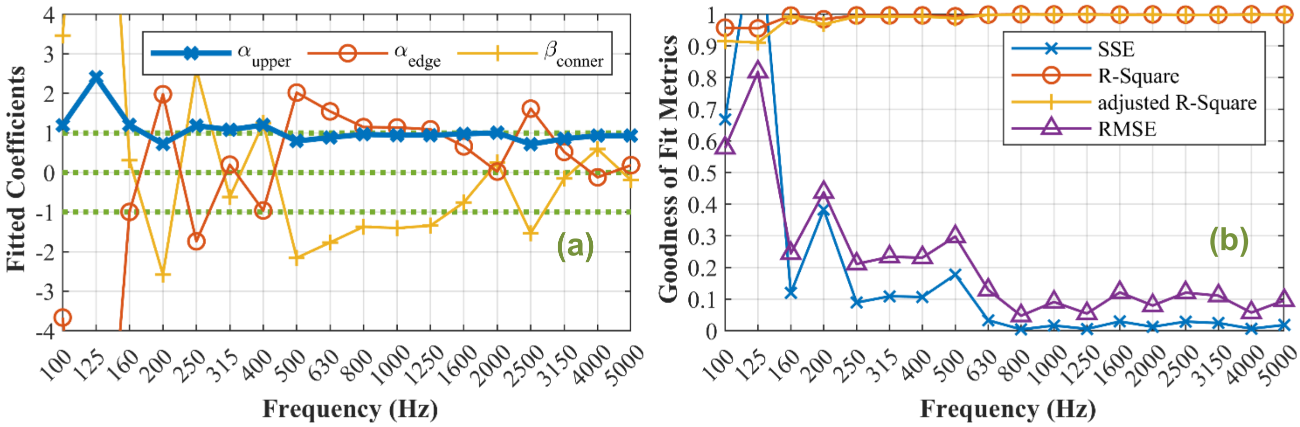

Figure 6: Fitting result of the 200 mm thick glass wool specimen tested with 20 diffusers.

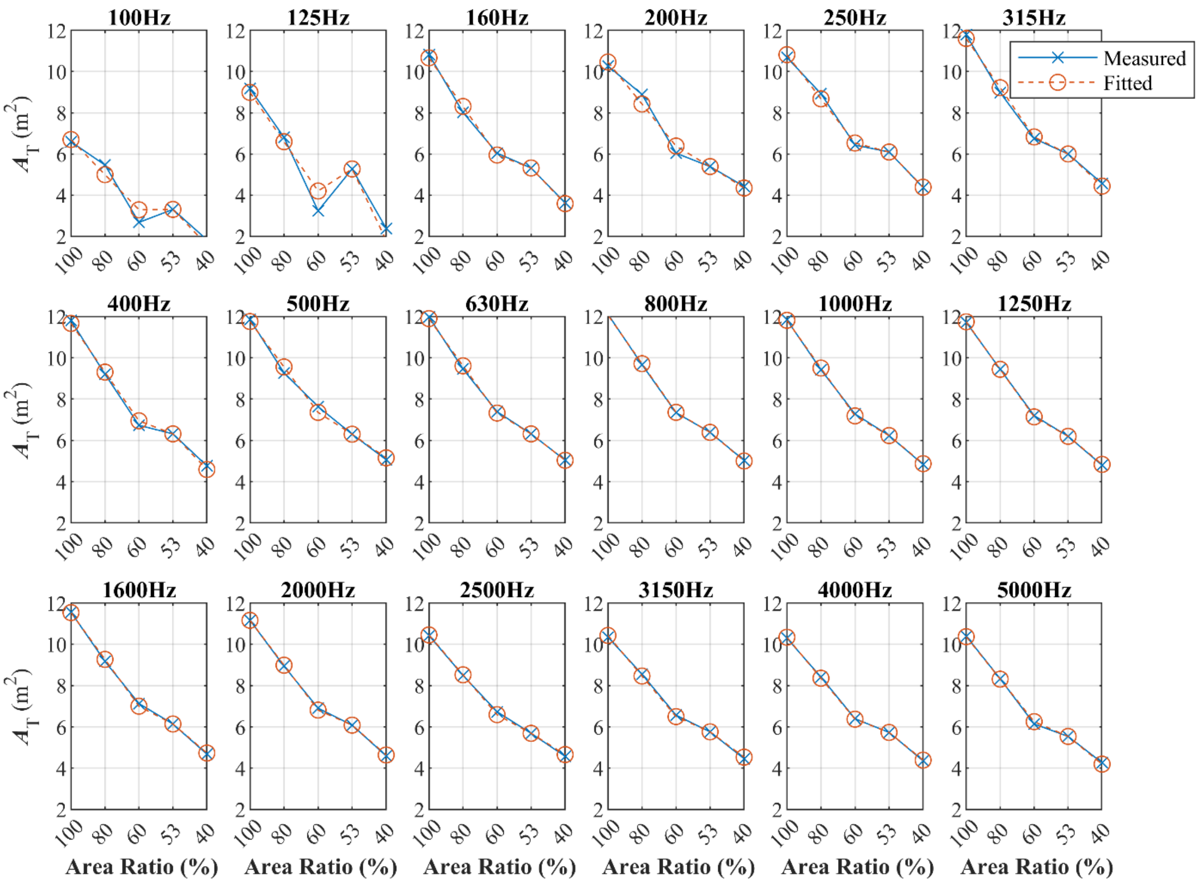

Figure 7: Fitting curves of the 200 mm thick glass wool specimen tested with 20 diffusers.

4.2 Sound absorption decomposition under non-diffuse field measurement

As shown in Figure 8, the sound field with 14 diffusers was non-diffuse when the test specimen was highly absorptive. Specifically, α_{upper} has values lower than except or even negative for most one-third octave bands centred between 100 Hz and 5000 Hz, and α_{edge} has values that are excessively out of range, which indicates the sound field could be dominated by the vertical components. Though the goodness-of-fit metrics look well, they only indicate the sound field was not sensitive to the sample size. Figure 9 shows the fitting curve per one-third octave band, with the measured curve as a reference.

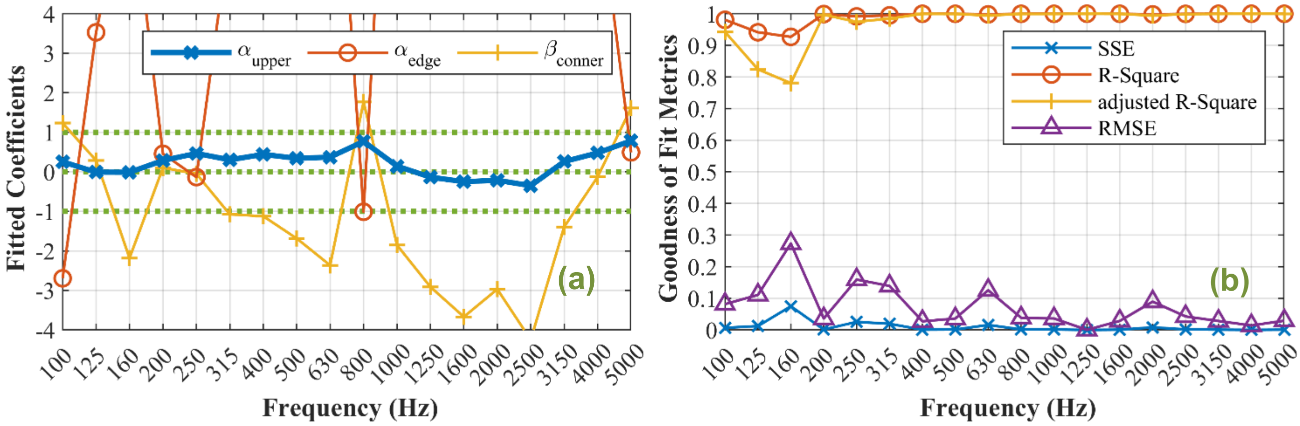

Figure 8: Fitting result of the 50 mm thick polyester specimen tested with 14 diffusers.

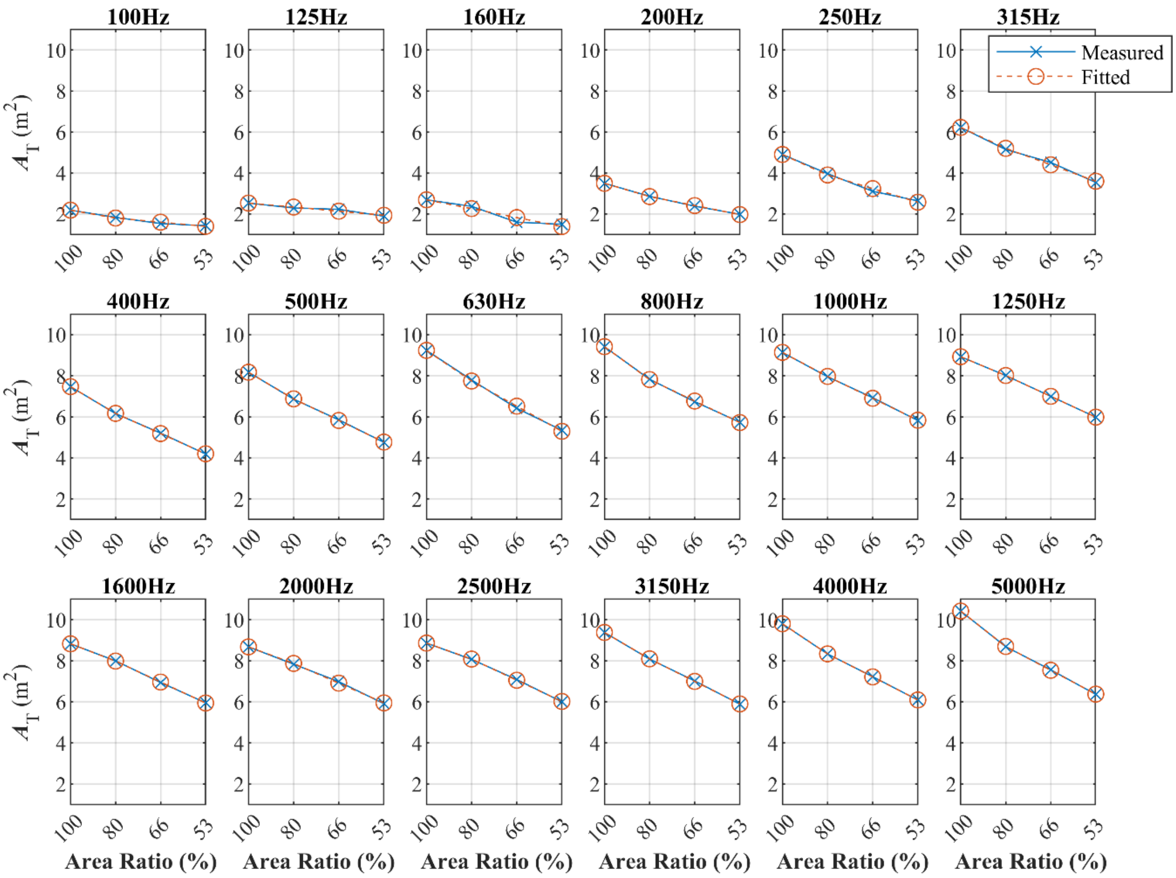

Figure 9: Fitting curves of the 50 mm thick polyester specimen tested with 14 diffusers.

4.3 Required number of measurements for sound absorption decomposition

Figure 10 shows the difference in measuring any four or five samples of different sizes to perform the fitting for the 200 mm thick glass wool specimen tested with 20 diffusers. Since data of five different sample sizes are available, fitting was performed respectively on five options, i.e. using the measurement of samples with all the five different sizes or any four amongst them. Due to the diffuse-like sound field, the results are very close to each other. The deviation excluding the sample with the area ratio of 40% is more outstanding than others. A potential cause is that the sample with the area ratio of 40% has a width to length ratio of 0.33, much smaller than the suggested sample's width to length ratio, i.e. between 0.7 and 1.0 (ISO 354: 2003, 2003). From this observation, measuring four samples with distinct surface areas may be sufficient for implementing the sound absorption decomposition for the specimen of plane absorber with homogeneous materials.

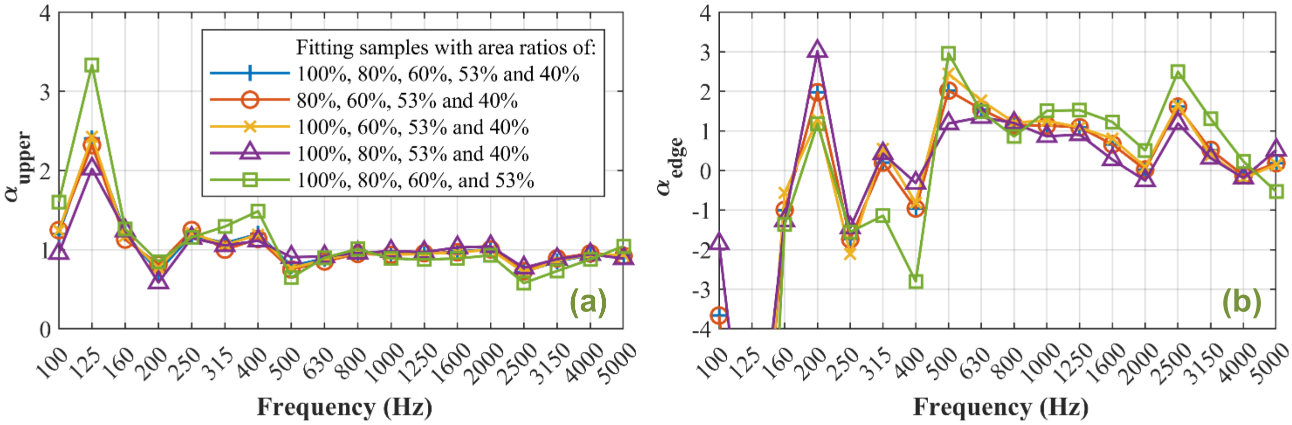

Figure 10: Fitting coefficients (a) α_{upper} and (b) α_{edge} of the 200 mm thick glass wool specimen tested with 20 diffusers, from the measurement of samples with all the five different areas or any four amongst them.

5 CONCLUSIONS

This paper reported the sound absorption coefficients measured with different conditions of diffusers, different sample materials and different sample sizes. With the measurement data, initial work was carried out on decomposing the sound absorption components based on the geometric feature of the test specimen. Furthermore, primarily investigation was made on an alternative way to assess the diffuseness of the test facility and assist the optimization of diffuser installation.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the contribution of the materials suppliers, especially the DENORMS Round Robin test organisers, and the UTS Tech Lab technical support team in installing test samples and diffusers for extensive sound absorption measurements.

REFERENCES

Bies, D. A., Hansen, C. H. and Howard, C. Q. (2017). *Engineering noise control*: CRC Press.
Cox, T. and d'Antonio, P. (2016). *Acoustic absorbers and diffusers: theory, design and application*: CRC Press.
Davy, J. (2018). Does diffusivity affect the spatial variance of reverberation time? *Proceedings of the 25th International Congress on Sound and Vibration* (ICSV25), Hiroshima, Japan.
Halliwell, R. (1983). Inter-laboratory variability of sound absorption measurement. *The Journal of the Acoustical Society of America,* vol. 73(3), pp. 880-886.
Hasan, M. and Hodgson, M. (2016). Effectiveness of reverberation room design: Room size and shape and effect on measurement accuracy. *Proceedings of the 22nd International Congress on Acoustics*, Buenos Aires, Argentina.
Nolan, M., Berzborn, M. and Fernandez-Grande, E. (2020). Isotropy in decaying reverberant sound fields. *The Journal of the Acoustical Society of America*, vol. 148(2), pp. 1077-1088.
Nolan, M., Fernandez-Grande, E., Brunskog, J. and Jeong, C.-H. (2018). A wavenumber approach to quantifying the isotropy of the sound field in reverberant spaces. *The Journal of the Acoustical Society of America*, vol. 143(4), pp. 2514-2526.
Qiu, X., Zhu, Q., Wang, S. and Zhong, J. (2019). A case study on the new reverberation room built in University of Technology Sydney. *Proceedings of the 23rd International Congress on Acoustics*, Aacheh, Germany.

Sabine, P. E. (1931). A critical study of the precision of measurement of absorption coefficients by reverberation methods. *The Journal of the Acoustical Society of America,* vol. 3(1A), pp. 139-154.
Scrosati, C., et al. (2020). Towards more reliable measurements of sound absorption coefficient in reverberation rooms: An Inter-Laboratory Test. *Applied Acoustics,* vol. 165, pp. 107298.
Scrosati, C., Roozen, N. B. and Piana, E. (2019). Principles at the basis of the DENORMS Round Robin Test on the low frequency sound absorption measurements in reverberation rooms and impedance tube. *Proceedings of the 26th International Congress on Sound and Vibration* (ICSV26), Montreal, Canada.
Vercammen, M. (2010). Improving the accuracy of sound absorption measurement according to ISO 354. *Proceedings of the International Symposium on Room Acoustics*, Melbourne, Australia.
Wang, S., Zhong, J., Qiu, X. and Burnett, I. (2020). A note on using panel diffusers to improve sound field diffusivity in reverberation rooms below 100 Hz. *Applied Acoustics,* vol. 169, pp. 107471.