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Measurement uncertainty of sound absorption coefficient measured in a 1:8 scale reverberation room

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Abstract The measurements of sound absorption coefficient in a scaled reverberation room are mainly used for the purpose of choosing the materials for acoustic scale models. Another application of scale model measurements of sound absorption coefficient is testing multiple variants and modifications of special acoustic elements, once their scale equivalents are found. Regardless of the purpose of the sound absorption measurement, the measurement accuracy should be known, and therefore it is necessary to determine the measurement uncertainty budget. The measurement procedure is based on the one described in the ISO 354 standard, which means that the measurement of sound absorption coefficient is an indirect type of measurement, and the final measurement uncertainty depends on the uncertainties of all the measured input values. The paper describes an approach to determining measurement uncertainty of sound absorption coefficient measured in a 1:8 reverberation room with the propagation of distributions using the Monte Carlo method. The sensitivity analysis of the final uncertainty is also analyzed with regard to all the measured input values, such as the reverberation time, relative air humidity, air temperature, and the size of the sample. The obtained results show that the measurement uncertainty of the sound absorption coefficient measured in a 1:8 scale reverberation room is comparable to the measurement uncertainty of full-scale measurements and does not change significantly depending on the measurement conditions.

Keywords: Monte Carlo simulations, similitude, acoustic measurements.

1. Introduction

Knowing the sound-absorbing properties of materials used for acoustic scale models is essential for the accurate reproduction of acoustic conditions of the designed rooms. The materials used in the models must present the same acoustic properties in a shifted frequency range as their full-scale equivalents used in real-life applications [1,2]. One of the most important acoustic parameters of materials is their sound absorption coefficient α_s [3], measured in a reverberation room, as described in ISO 354 standard [4]. Because of the substantial sound absorption by air in high frequencies, the measurement of the sound absorption coefficient of materials for scale models cannot be performed in a regular reverberation room. According to the similitude theory, all measurement conditions should be scaled down, including the size of the reverberation room, which is usually made at the same scale as the final model. Scaling geometrical dimensions is relatively easy, and the required measurement frequency range can be ensured by using special electroacoustic equipment, such as ¼'' or 1/8" microphones, audio interfaces with a high sample rate, and dedicated sound sources [5]. The only issue is the sound absorption by air in high frequencies, too large to fulfill the scaled requirement of ISO 354 standard. This can be fixed by drying the air inside the reverberation room or using nitrogen instead of air [1,2,6]; however, it was shown that for this particular type of measurement, such procedures are unnecessary, and the measurements can be performed in room conditions without changing the measurement results [7]. The study described in [7] concerned the influence of measurement conditions on the resulting sound absorption coefficient, but it did not address the matter of measurement uncertainty, which may vary with different measurement conditions, especially relative air humidity values. The measurement uncertainty of the sound absorption coefficient measurements performed at scale is generally not addressed in the literature. The standard itself only brings up the measurement uncertainty of the reverberation times, while the measurement uncertainties of the remaining measured input values are neglected.

In this paper, three matters concerning the measurement uncertainty for scale measurements of sound absorption coefficient are discussed. First, the measurement uncertainty of the sound absorption coefficient measurement performed in a 1:8 scale reverberation room is discussed, in relation to changing relative air humidity. A thorough uncertainty budget for this type of measurement is assessed with the use of the Monte Carlo method. Then, the same method is used for testing the sensitivity of the measurement results to particular measured input values. In the end, the measurement uncertainty after the renovation of the measurement setup is verified and compared with the previously obtained results.

2. Measurement of sound absorption coefficient in a 1:8 scale reverberation room

The measurement of sound absorption coefficient α_s in a 1:8 scale reverberation room is performed based on the method described in ISO 354 standard . For each 1/3-octave frequency band within the range of 800-40000 (100-5000 Hz x 8) the sound absorption coefficient is determined using the following formula:

$$\alpha_s = \frac{A_T}{S} = \frac{1}{S}(A_2 - A_1) = \frac{1}{S}(55.3V\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4V(m_2 - m_1))\,, \tag{1}$$

where A_T is the equivalent sound absorption area of the sample under test [m^2], S is the sample area [m^2], A is the equivalent sound absorption area of the reverberation room [m^2], V is the volume of the reverberation room [m^3], T is the reverberation time (s), and c is the sound sped in air [m/s]. The subscripts 1 and 2 refer to the measurements taken in an empty reverberation room, and the reverberation room with the sample inside, respectively. The symbols m_1 and m_2 denote power attenuation coefficients, determined as per ISO 354 and ISO 9613 [4,8].
The parameter m is defined as:

$$\begin{aligned} m = \frac{8.686f^2}{10\log(e)}\Bigg(\Bigg[1.84\cdot 10^{-11}\cdot\left(\frac{p_a}{p_r}\right)^{-1}\cdot\left(\frac{T}{T_0}\right)^{\frac{1}{2}}\Bigg] + \left(\frac{T}{T_0}\right)^{\frac{-5}{2}} \\ \cdot\Bigg\{0.01275\left[exp\left(\frac{-2239.1}{T}\right)\right]\left[f_{rO} + \left(\frac{f^2}{f_{rO}}\right)\right]^{-1} \\ + 0.1068\left[exp\left(\frac{-3352.0}{T}\right)\right]\left[f_{rN} + \left(\frac{f^2}{f_{rN}}\right)\right]^{-1}\Bigg\}\Bigg), \end{aligned} \tag{2}$$

where f – frequency [Hz], T – temperature [K], $f_{rO} = \frac{\mathrm{p_a}}{\mathrm{p_r}}(24 + 40400\cdot 10^4\cdot h\cdot\frac{0.02+h}{0.391+h})$ Hz, $f_{rN} = \frac{\mathrm{p_a}}{\mathrm{p_r}}\cdot\left(\frac{T}{T_0}\right)^{-1/2}\cdot\left(9 + 280\mathrm{h}\cdot\exp\left\{-4{,}170\left[\left(\frac{T}{T_0}\right)^{-1/3} - 1\right]\right\}\right)$ Hz, p_a – atmospheric pressure [kPa], h – molar concentration of water vapor (%), $p_r = 101.325$ kPa, $T_0 = 293.15$ K.

2.1. Measurement setup

The measurements of the sound absorption coefficient were taken in the scaled reverberation room, which is a 1:8-scale equivalent of the reverberation room of the Department of Mechanics and Vibroacoustics AGH. The walls of the room and additional diffraction panels are made of acrylic glass, to ensure minimal sound absorption. The walls are 22 mm thick and therefore present high air-borne insulation properties. The setup was also equipped with an air-drying system using silica gel and nitrogen. Electroacoustic equipment comprised of a high-voltage spark source, two ¼'' microphones B&K type 4934, M-Audio Firewire 1814 sound device, and a NEXUS conditioner. The data on air temperature and relative humidity was recorded with Aosong AM2302 sensors. The measurement setup is shown in Fig. 1a). The equipment of the reverberation chamber has recently been refurbished, and the measurements of sound absorption coefficients were repeated and compared to the previous analysis. First of all, the air drying system was eliminated, and the spark source was replaced with a two-way omnidirectional sound source [5] with a CREST CPX 3800 amplifier (Fig. 1b); the microphones were replaced by GRAS 46BE ¼'' microphones and GRAS 12 AL power modules. Data acquisition is now realized by Focusrite Scarlett 12i20 sound device and the hytherograph was replaced by Xiaomi Mi Temperature And Humidity Monitor 2.

a) b)

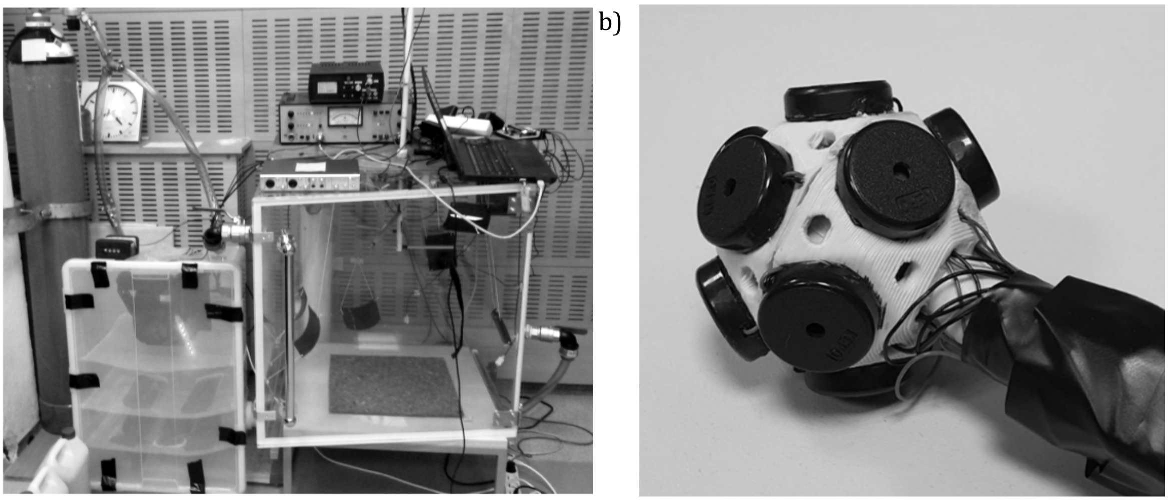


Figure 1. Measurement setup, a) 1:8 scale reverberation room with air-drying system and electroacoustic equipment before the renovation, b) new omnidirectional sound source [5].

3. Determination of the uncertainty of the sound absorption coefficient measurement

According to the ISO 354 standard, the overall measurement uncertainty of sound absorption coefficient is influenced by two effects. The first one is the uncertainty of the measured reverberation time of the empty reverberation room and the reverberation room with a sample inside. The second factor is the reproducibility limits, dependent on the complete measurement setup, which is still being investigated.

Published studies show that knowing the measurement uncertainties of the reverberation times is not sufficient for an accurate estimation of the measurement uncertainty of the sound absorption coefficient α_s. Other factors, such as the measurement uncertainty of the surface area of the sample are also important [9], and with increasing frequency, the measurement uncertainty of atmospheric conditions plays a more significant role [10]. To be able to include all the measurement uncertainties in the final measurement uncertainty budget, in the case of indirect measurement procedures, the *Guide to the expression of uncertainty in measurement* [11] recommends using the law of propagation of uncertainty. If $y = f(x_1, x_2, \dots x_n)$ is an arbitrary function of independent variables $x_1, x_2, \dots x_n$, then the general relation describing the propagation of the measurement uncertainties of these variables is given by:

$$u_f = \sqrt{\sum_{i=1}^{n} \left[\left(\frac{\partial f}{\partial x_i} \right) \cdot u(x_i) \right]^2}, \tag{3}$$

where u_f is the combined standard uncertainty of the final measurement value, and $u(x_i)$ are the measurement uncertainties of the measured input values $x_1, x_2, \dots, x_n$.

To be able to use the law of propagation of uncertainty as described above, the measured values must not be correlated. If they are, the correlation between the measured values must be taken into account. In the case of sound absorption coefficient measurement, it was noted that the reverberation time of the reverberation room with the sample inside may be correlated with the reverberation time of the empty reverberation room [12], which complicates the calculations. What is more, determining the differentials for the atmospheric conditions, i.e. air temperature and relative air humidity is complicated, knowing how they are involved in the parameter m (Eq. 2).

Another approach for determining measurement uncertainty is the propagation of distributions using the Monte Carlo method, introduced as a supplement to the *Guide to the expression of uncertainty in measurement* in 2008 [13]. The use of the propagation of distributions is advised when calculating the derivatives over the measured values is difficult, and the mathematical model of the measured value is complicated. The only condition for using the Monte Carlo method is that the parameters of the statistical distributions describing the measured input values must be known. These parameters can be determined based on the measurement data or the accuracy of the measurement equipment. The measurement data can be usually assumed of a normal distribution; however, if the number of measurement results is less than 30, Student's t distribution is normally applied, with $n - 1$ degrees of freedom, where n is the number of measurements. In this research, Student's t distribution was used for generating the values of the reverberation times T_1 and T_2. For the values of relative air humidity, air temperature, and the size of the measurement sample, uniform distributions were applied. If the error bound of a given measuring instrument is equal to $\Delta\varepsilon$, it should be assumed that the measured values may equally possibly be any value within the interval $\pm\Delta\varepsilon$, and the measured input value is of a uniform distribution of the width $2\Delta\varepsilon$. Once the distributions of the measurement values are known, N-element samples of “measurement values” must be drawn, and the calculations of the final result must be repeated N times (in this case: the values of sound absorption coefficient α_s). The bigger the number N, the more accurate the simulation is. Practically, it is assumed that $N = 10^6$ ensures sufficient accuracy [13]. Once we have 10^6 values of the final parameter (sound absorption coefficient α_s) in non-decreasing order, the P% coverage interval can be determined. When $P = 95\%$, a half of the coverage interval can be considered expanded uncertainty with $k = 2$.

4. Using Monte Carlo method for sensitivity analysis

In regular full-scale measurements of the sound absorption coefficient α_s, the most important factor determining the measurement uncertainty is the uncertainty of the reverberation time measurement, which is independent of frequency [10]. For higher frequency bands, the importance of atmospheric conditions measurement uncertainty increases. Since the measurements performed in a scaled reverberation room are taken for a higher frequency range than usual, it is worth verifying how particular measurement uncertainties impact the final uncertainty of sound absorption coefficient measurement. For this purpose, relative sensitivity coefficients may be used. The relative sensitivity coefficient defines how much the final result changes if the particular measured value is changed by 1% or in other words – by how much percent the final result is misestimated if the given input parameter is misestimated by 1%. The relative sensitivity coefficient is defined as [9, 14]:

$$W_i = \frac{x_i}{y}\frac{\partial f}{\partial x_i} = \frac{x_i}{y}\frac{u_i(y)}{u(x_i)}, \tag{4}$$

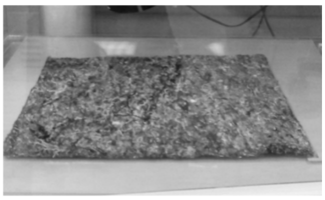
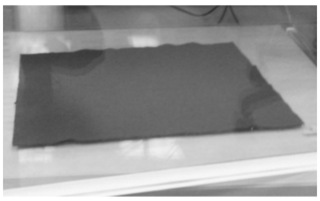
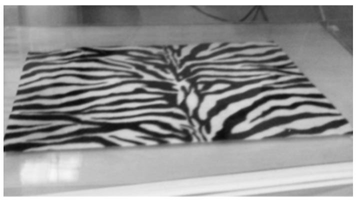
where $u_i(y)$ is the standard measurement uncertainty of the final result caused by the measurement uncertainty of the x_i value only; the remaining symbols are as defined earlier. The standard measurement uncertainty caused by the uncertainty of one measurement input value can be estimated with the Monte Carlo method. The simulations must be repeated for drawing the investigated measurement input value only, and keeping the remaining measurement input values constant. For example, if the sensitivity coefficient for the reverberation time T_1 is to be determined, N values of T_1 are drawn from an appropriate distribution, and the other input parameters remain constant. The remaining calculations of measurement uncertainty are exactly as described in Section 3.

5. Results

5.1. Measurement uncertainty vs relative air humidity

The study was performed for three different textile materials of the same dimensions: 0.4 x 0.45 m. The properties of the materials are listed in Tab. 1

Table 1. Material samples used in the study.

Material	A – Poroso felt	B – cotton woven	C – synthetic textile
Thickness [mm]	5.7	1.4	2
Mass density [kg/m^2]	28	147.3	39.4
picture			

The sound-absorbing properties of the materials were tested for relative air humidity values within 5.2% and 41.8% with a ~2% step. The measurements were taken for 12 individual combinations of sound source and microphone, and each measurement was repeated twice. The results were tested for gross errors with the Grubbs test [14]. The parameters of each measurement data set were used for generating input parameters' distributions. For the reverberation times, Student's t-distributions of $n-1$ degrees of freedom were used. In this case n was equal to 24 (or less, if there were any gross errors deleted). For relative air humidity, air temperature, and the size of the measurement sample, uniform distributions were applied, and their parameters were determined by the accuracy of the measurement instruments. The accuracy of the temperature measurement was 1°C, for relative air humidity it was 2%, and the accuracy of the measurement of the sample dimensions was determined as 1 cm. It was assumed that the accuracy of the dimensions depends not only on the accuracy of the measuring tape but is also a result of hand-cutting the samples, and as a result, a larger margin of error was adopted for the calculations. The results are shown in Fig. 2 as a function of frequency and relative air humidity. As was shown in previous research, the remaining atmospheric conditions (air temperature and pressure) are of negligible importance.

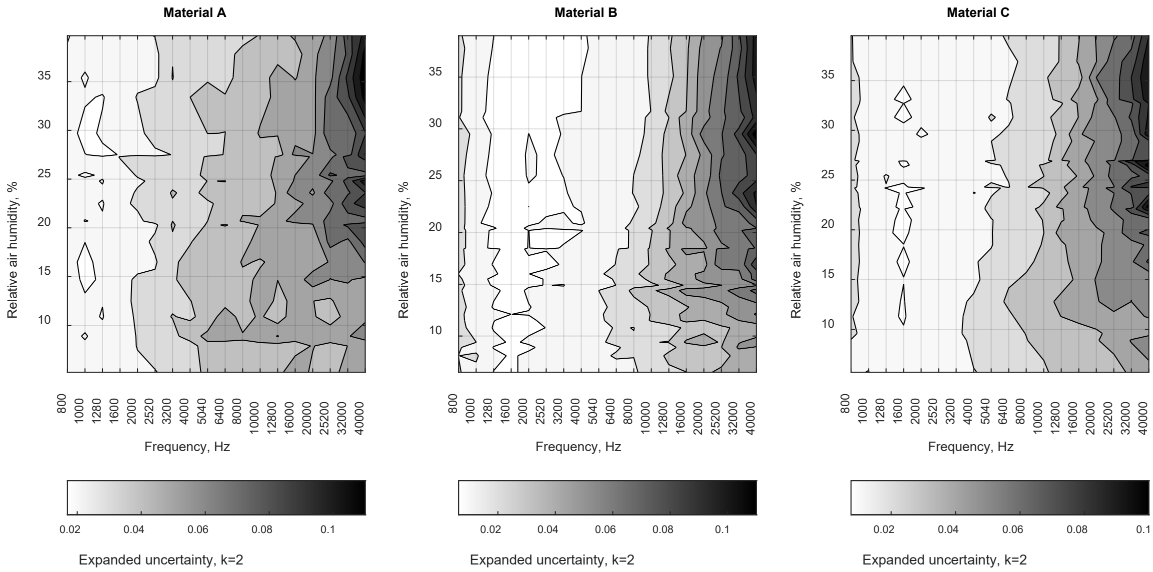


Figure 2. Expanded uncertainty of sound absorption coefficient as a function of frequency and relative air humidity.

Fig. 2 shows that the measurement uncertainty of the sound absorption coefficient measured in a 1:8 scale reverberation room is comparable to the measurement uncertainties determined for full-scale measurements, for corresponding frequency bands [10,12]. The only significant differences are for the highest frequency bands, where the uncertainty of at-scale measurements is higher than for full-scale measurements, especially for higher relative air humidities. For all the tested measurement samples, changing relative air humidity impacts the expanded uncertainty only for the highest frequency bands (above 20 kHz). In the highest frequency band, the difference between the measurement uncertainty determined for the lowest and the highest relative air humidity was 0.047 for material A, 0.054 for material B, and 0.044 for material C. However, when we compare the values of the expanded uncertainty with the values of the sound absorption coefficient across the frequencies, for the highest relative air humidities (Fig. 3), we can see that relative to the sound absorption coefficient, the measurement uncertainty is rather stable (around 10%, excluding the lowest frequency bands).

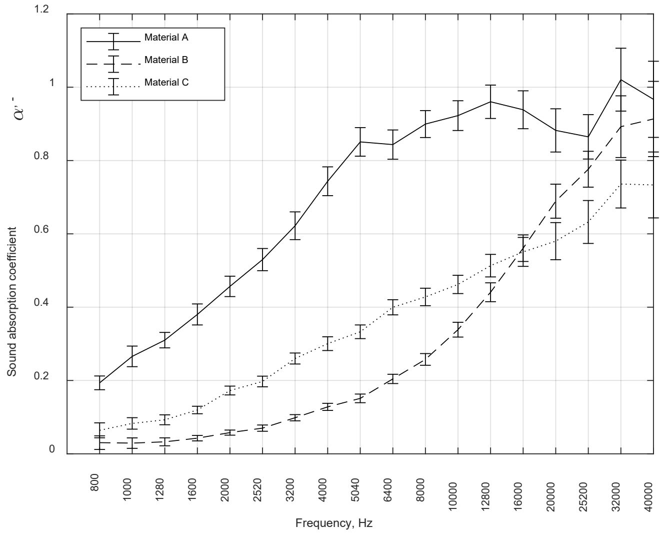


Figure 3. Sound absorption coefficients of the samples under study together with expanded uncertainty.

5.2. Sensitivity analysis

The sensitivity coefficients were calculated for the measurement data obtained for the lowest and the highest relative air humidities, i.e. 5.2% and 39.7% for material A, 6.5% and 41.8% for material B, and 5.7% and 39.5% for material C. The results are shown for material C in 1/1-octave frequency bands since all the analyses presented the same trends.

5

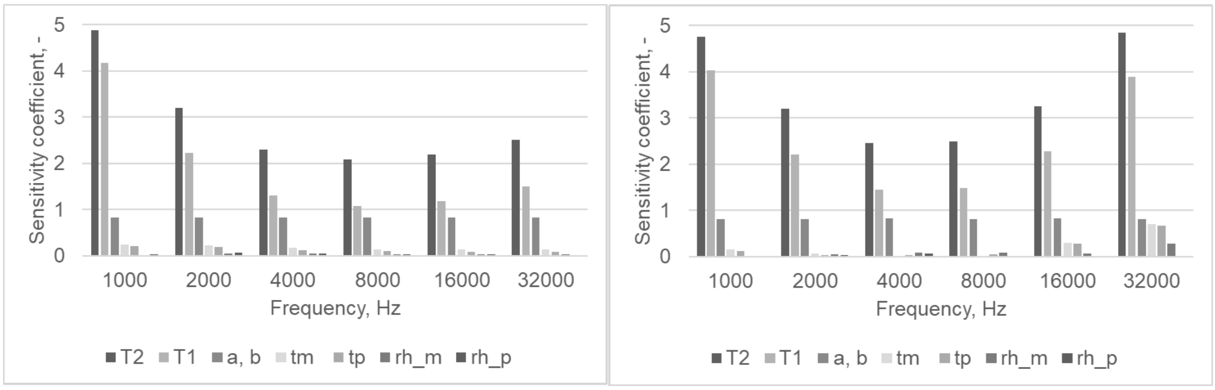


Figure 4. Sensitivity coefficients for all the measurement values, material C, 5.7% RH (left), 39.5% RH (right). T2 – reverberation time with the sample, T1 – reverberation time without the sample, a,b – sample dimensions, tm, rh_m – temperature and relative air humidity with the sample, tp, rh_p – temperature and relative air humidity of the empty reverberation room.

The analysis of the obtained values of sensitivity coefficients shows that no matter the relative air humidity, the most important factor influencing the uncertainty of the sound absorption coefficient measurements is the accuracy of the reverberation time measurements, both for the empty reverberation room and the reverberation room with the sample inside. The reverberation time with the sample inside the reverberation room showed higher values of sensitivity coefficients, which is probably caused by the fact that introducing the measurement sample to the reverberation room disrupts the diffuseness of the sound field. Higher values are observed for lower frequencies, due to the formation of modes inside the reverberation room. In the case of higher relative air humidity, they increase again for the highest frequency bands, which is probably caused by the large absorption of sound by air. The impact of the measurement accuracy of the sample dimensions is below 1 and constant across the frequencies, which is logical since the dimensions of the sample are independent of any other measurement conditions. The importance of the air parameters measurement accuracy increases with increasing frequencies, especially for high relative air humidity values. This observation is consistent with the observations made by the previous authors; however, in the case of this measurement setup, the values of sensitivity coefficients are always below 1, which means that the error of 1% in the measurement of relative air humidity or air temperature results in less than 1% error in the final result of the sound absorption coefficient.

5.3. Comparison between the results before and after the renovation of the measurement setup

After it was shown that the results of the sound absorption coefficient measurements do not depend on the atmospheric conditions, the measurement setup was refurbished, as described in Section 2.1. The instrumentation was replaced by simpler and more reliable equipment, and the air-drying system was removed. In order to verify whether the new instrumentation and measurement conditions do not aggravate the measurement uncertainty, the measurements of the sound absorption coefficient were repeated. The results of the measurements taken for Material C are shown in Fig. 5. The measurement conditions were: 39.5% relative air humidity and 24.3°C for the measurement before the renovation, and 65% relative air humidity and 22.6°C for the measurement after the renovation. The second measurement sample was cut from a different part of the material bale after a period of time, therefore the differences between the measured sound absorption coefficients can be observed. The values of the measurement uncertainties are comparable, even though the measurement conditions differ.

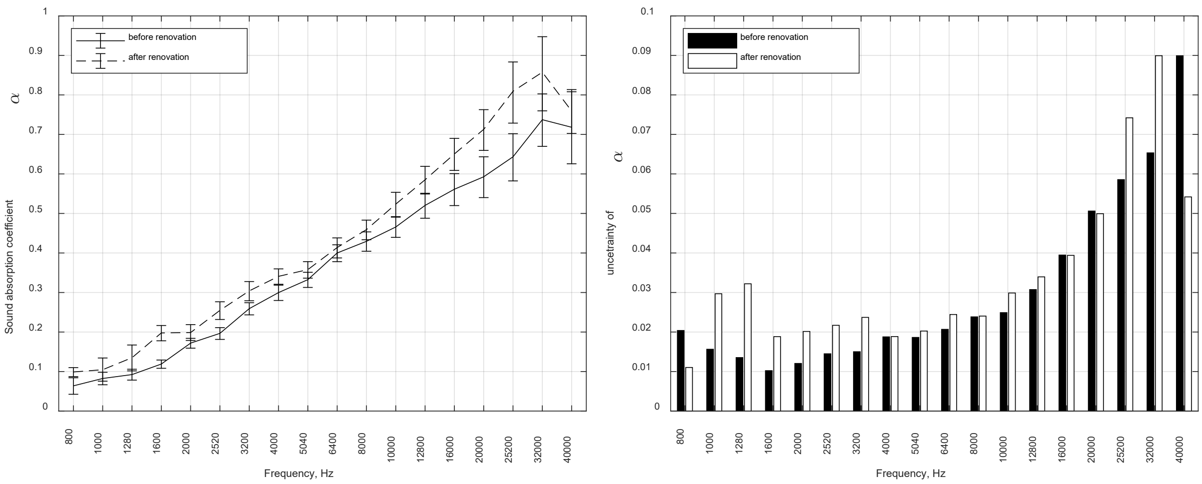


Figure 5. Sound absorption coefficient measured before and after the renovation of the measurement setup (left); comparison of the measurement uncertainties before and after the renovation of the measurement setup(right).

5. Conclusions

In this paper, a study on determining measurement uncertainty of sound absorption coefficient measurement in a 1:8 scale reverberation room was described. The possibilities for determining measurement uncertainty were described, and the propagation of distributions using the Monte Carlo method was chosen and described in detail. First, a thorough uncertainty budget was prepared, including the impact of all the measurement values on the final results. It was shown that the measurement uncertainty of the sound absorption coefficient measured in a 1:8 scale reverberation room is comparable with the measurement uncertainty of the full-scale measurements. Then, the influence of the relative air humidity on the measurement uncertainty was verified. It was shown that the influence of the air parameters measurement accuracy on the final measurement uncertainty increases for the highest frequency bands only, and still, the sensitivity coefficients remain below 1 in the whole frequency range. In the end, the measurement uncertainties from before and after the renovation of the measurement setup were compared. It was shown that the changes made to the measurement setup and measurement conditions had no significant impact on the final measurement uncertainty.

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Additional information

The author declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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