Measurement of Perforated Panels at a Scaled Measurement Setup

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Abstract

In the paper, the authors present an ongoing research on the absorption and measurement uncertainty of perforated panels made at different scales. Knowing the similarity criteria describing the relation between a full-size perforated panel and its scaled equivalent, it is possible to conduct the measurements of the elements of significantly reduced size – with an area not exceeding 0.2 m^2. This procedure notably decreases the costs resulting from the production, transportation and storing the measurement samples. At the same time, the obtained values of sound absorption coefficient measured for the samples at 1:8 scale will characterize their full-size equivalents of geometry changed according to the derived similarity criteria. The paper discusses the possibilities of measurement of scaled samples.

Keywords: scale modelling, law of similarity, dimensional analysis, orifice, miniaturisation

1. Introduction

The methodology of sound absorption measurements is mainly based on the laboratory tests of full-size elements [1, 2]. However, only a limited number of institutions have required technical rooms, so the costs of such a measurement are usually high. An interesting alternative to the laboratory sound absorption coefficient measurements may be provided by so-called model tests, which require measurement samples made at scale. Creating models according to the required similarity criteria, may considerably decrease the costs of both making the samples and having them measured.

In acoustics, scale model tests are mainly used for the analysis of room acoustics phenomena [3, 4], transmission of sounds through the building partitions [5, 6] and sound absorption by materials and systems [7, 8]. Despite such a broad range of application, so far there has been no method which would allow scaling perforated panels and keeping their sound absorbing properties unchanged in the shifted frequency range. Therefore, the aim of the carried research is to propose such a methodology and in the following paper the possibilities of measuring the samples at a scaled measurement setup are discussed, together with the measurement uncertainty.

2. Subject of the research

The subjects of the research were acoustic perforated panels made at scales 1:4 and 1:8 in relation to their full-scale equivalent. The scales were chosen so as to enable the verification of the obtained results by measurement in a reverberation chamber made at 1:8 scale in relation to the full-scale test room of the Department of Mechanics and Vibroacoustics AGH in Cracow.

The measurement samples were made according to the similarity criteria derived by the authors [9], excluding the criterion regarding air viscosity. The following dimensions were scaled: thickness of the panel t_p, radius of the orifice r, distance between the centres of the orifices D, and distance between the panel and reflective surface d, according to the following relations, where f is the frequency, and c_0 is the speed of sound.

$$\Pi_{t_p} = \frac{t_p f}{c_0} \tag{1}$$

$$\Pi_r = \frac{rf}{c_0} \tag{2}$$

$$\Pi_d = \frac{df}{c_0} \tag{3}$$

$$\Pi_D = \frac{Df}{c_0} \tag{4}$$

Table 1 sets together the parameters describing the studied full-size panel and its scaled equivalents.

Table 1. Parameters of a full-size panel and its scaled equivalents used for the verification measurements

parameter	1:1 scale	1:4 scale	1:8 scale
scale factor	1	4	8
thickness of the panel	12.0 mm	3.0 mm	1.5 mm
radius of the orifice	4.0 mm	1.0 mm	0.5 mm
dimensions	-	400 x 450 mm	400 x 450 mm
perforation rate	12.56%	12.56%	12.56%
distance from the reflective surface	100.0 mm	25.0 mm	12.5 mm
measurement frequency range	100 – 5 000 Hz	400 – 20 000 Hz	800 – 40 000 Hz

3. The measurement of sound absorption coefficient at a scaled measurement setup

3.1. *Measurement procedure*

The methodology for sound absorption coefficient measurements in a reverberation chamber made at 1:8 scale is based on the method described by the standard PN-EN ISO 354 [1]. Analogously to the methodology of sound absorption coefficient at the full-size measurement environment, the values of reverberation time T20 must be measured in two configurations: in an empty chamber and in a chamber with the sample under study. The standard recommends taking the measurements in at least 12 spatially independent combinations of sound source and microphone for each configuration. Based on the measured reverberation times it is possible to calculate equivalent sound absorption area of a tested sample, and then – sound absorption coefficient, using equation below:

$$\alpha = \frac{55.3V}{S}\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - \frac{1}{S}4V(m_2 - m_1), \tag{5}$$

where V is the volume of the chamber, S is the area of the tested sample, c, T, m are: sound speed in air, reverberation time in a chamber and intensity attenuation coefficient, respectively, and indexes 1 and 2 denote the configuration of the measurement: without and with the sample. The results should be given in 1/3-octave frequency bands, in the range of 800-40 000 Hz.

3.2. *Measurement setup*

Since the measurement of sound absorption coefficient in a scaled reverberation chamber is based on the procedure described in the standard PN-EN ISO 354 [1], the miniaturized measurement room should meet the requirements of this standard, after adjusting the requirements to the scale factor of the chamber.

The design requirements for a 1:8 scale measurement chamber and the parameters of the chamber used for experiments are given in Table 2. In regular room atmospheric conditions, the chamber does not meet the requirement regarding the minimum reverberation time in entire frequency range. However, as it was shown in previous study [10] it is not necessary for the measurement of sound absorption coefficient.

The reverberation chamber used for the measurements is a model of the full-size reverberation chamber of the Department of Mechanics and Vibroacoustics AGH in Cracow. The Schroeder frequency resulting from the dimensions of the chamber is around 320 Hz. This frequency is a limit measurement frequency of the chamber – the measurements are only reliable above 320 Hz. This requirement is met for the measurement samples made at 1:8 and 1:4 scales, whereas the measurement samples made at bigger scale factors (for example 1:2) would require lower measurement frequencies – below the Schroeder frequency of the chamber.

Table 2. Requirements for the design of the reverberation chamber and 1:8 scale and the properties of the chamber used for experiments

	minimum recommended		at the measurement setup	
volume	0.29 m^3		0.35 m^3	
area of the sample under study	0.16-0.19 m^2		0.18 m^2	
reverberation time	frequency	T20	frequency	T20 (room atmospheric conditions)
	1 000 Hz	0.63 s	1 000 Hz	0.99 s
	2 000 Hz	0.63 s	2 000 Hz	0.96 s
	4 000 Hz	0.63 s	4 000 Hz	0.79 s
	8 000 Hz	0.56 s	8 000 Hz	0.56 s
	16 000 Hz	0.44 s	16 000 Hz	0.30 s
	32 000 Hz	0.25 s	32 000 Hz	0.14 s

The walls of the model and the additional reflective elements are made of plexiglass, in order to ensure minimum sound absorption and maximum insulation from the airborne sounds. A high voltage spark source is used at the setup, which generates signals of 400 Hz – 40 kHz; it is possible to register impulse responses of the chamber in this frequency range, which after scaling (scale factor 1:8) corresponds with the frequency range of 50 Hz – 5 kHz. Two ¼-inch free field microphones GRAS 46BE are used for the data acquisition. The microphones are connected to the measurement interface M-AUDIO FireWire 1814, through SV 06A. The acquisition of data regarding air temperature and relative humidity is realized through the thermo-higrometers Aosong AM2302. The measurement setup is shown in Figure 1.

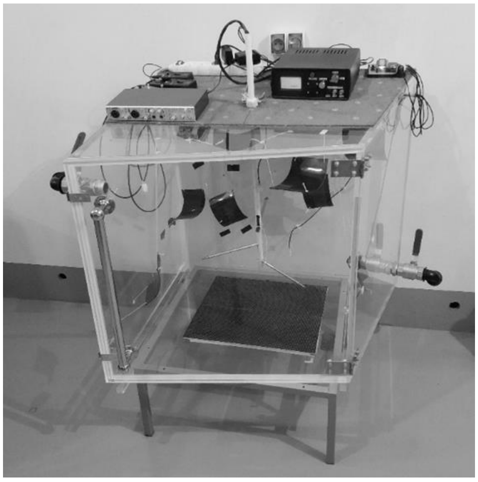

Figure 1. Setup for the measurement of sound absorption coefficient (reverberation chamber at 1:8 scale)

3.3. *Measurement uncertainty*

For a complete expression of the results of sound absorption coefficient measurements, it is necessary to determine the measurement uncertainty. According to PN-EN ISO 354 standard [1] only two factors comprise the total measurement uncertainty: reverberation time measurement uncertainty and reproducibility limits. However, studies on the measurement uncertainty in full-size measurements indicate that for the accurate assessment of sound absorption coefficient measurement uncertainty, other factors must be considered as well, such as the area of the measurement sample [11] or the atmospheric conditions [12]. The latter is especially important for high frequency bands. Since the measurement in a scale reverberation chamber is shifted towards higher frequencies, the atmospheric conditions should be considered in the total measurement uncertainty. Most commonly, for the determination of measurement uncertainty in case of indirect procedures, the law of uncertainty propagation is used. However, given the correlation of input parameters [13] and complexity of the relation between the output parameter – sound absorption coefficient α and input parameters such as temperature and relative air humidity (involved in the intensity attenuation coefficient m), the authors have chosen Monte Carlo method for the determination of the total measurement uncertainty.

In order to use Monte Carlo method for the determination of measurement uncertainty, the distributions of input parameters used for the determination of an output parameter – in this case sound absorption coefficient α, must be known. They can be estimated using the obtained measurement results or based on the precision of measurement instruments. If the number of measurement results is less than 30, Student's t-distributions of $n-1$ degrees of freedom should be assumed [14]. This type of a distribution was assumed for generating the values of reverberation time T20. For the generation of relative air humidity values, temperature values and specimen size values, uniform distributions were used. If the maximum measurement error defined for an instrument is $\Delta\varepsilon$, it should be assumed that the real value of the measured parameter may be situated at any point of the interval $\pm\Delta\varepsilon$ equally possibly. The distribution of the input value is then a uniform distribution of width $2\Delta\varepsilon$. Having the distributions of input parameters, N values of each input parameter must be generated and the calculations of the output value (in this case – sound absorption coefficient) must be repeated the same number of times. The bigger the N, the more accurate the final result. For practical use it is agreed that $N = 10^6$ gives satisfactory results [15]. Having 10^6 values of sound absorption coefficient in non-decreasing order it is possible to determine an interval which covers P% of the obtained results. In case of a symmetric distribution the limits of the interval are given by the samples y_{max} and y_{min} of the indexed equal to $N\frac{P}{2}$ and $N\left(1-\frac{P}{2}\right)$, respectively. If $P = 95\%$, the value of $0.5(y_{max} - y_{min})$ corresponds to the total measurement uncertainty of the output value.

The measurements of sound absorption coefficient were performed for nine independent combinations of sound source-microphone; it was repeated twice for each combination. The values of reverberation times obtained in the measurements were tested for gross errors, using Grubbs test [16]. The obtained statistics characterizing each measurement data set were used for the generation of the distributions of input parameters. For the reverberation time, Student's t-distributions of 17 degrees of freedom (or less – if some of the values were rejected by Grubbs test) were generated. For the values of relative air humidity, temperature and sample size, uniform distributions were used, and the widths of these distributions were dependent on the measurement instruments. The accuracy of the temperature measurement was 1°C, for relative air humidity it was 2%, and for the size of a sample – 0.5 cm (this was connected not only with the measurement definition, but also inaccurate manufacturing).

4. Results

The results of the sound absorption coefficient measurements of the specimens made at 1:4 and 1:8 scales are presented in the figures below, together with the measurement uncertainty. The samples were additionally verified in a finite element method model, created in COMSOL Multiphysics software. The samples and the models were created using the derived similarity criteria, neglecting the criterion regarding air viscosity. The results obtained in the numerical model were additionally transformed to obtain the statistical sound absorption coefficient to be compared with the measurement results [17]. The consistency between the obtained values is very good – for the sample made at 1:4 scale, root mean square difference between the results of the simulation and measurement is 0.028 for all the tested frequency bands (13.6% of the maximum value), and for the sample at 1:8 scale – 0.031 (11.6% of the maximum value). The curves obtained by measurement are slightly higher for the frequencies above 800 Hz which may be cause by the material properties of the manufactured samples – the simulations assume perfectly smooth and rigid surfaces.

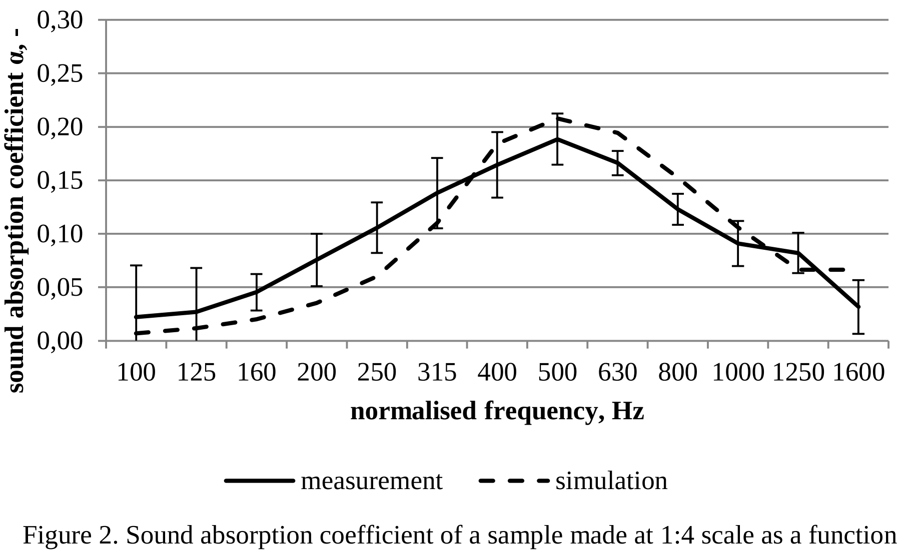

Figure 2. Sound absorption coefficient of a sample made at 1:4 scale as a function of frequency, obtained by measurement and in a numerical simulation (after necessary mathematical transformation)

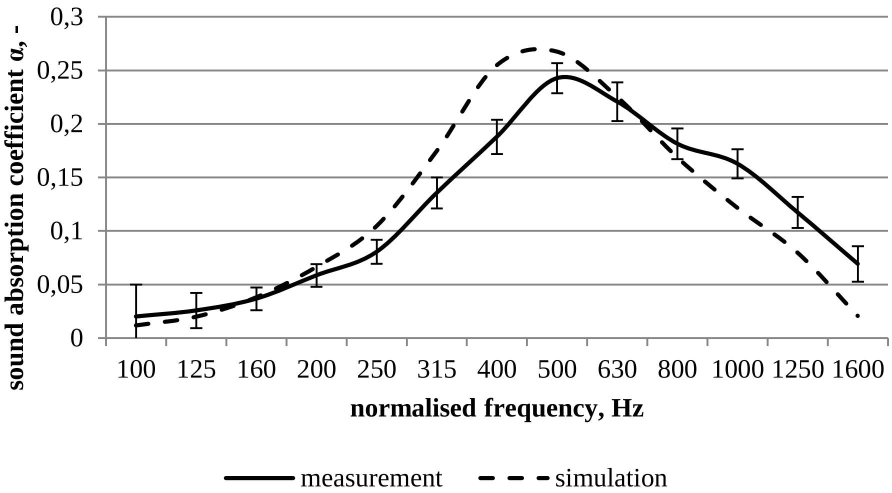

Figure 3. Sound absorption coefficient of a sample made at 1:8 scale as a function of frequency, obtained by measurement and in a numerical simulation (after necessary mathematical transformation)

5. Conclusions

In the paper, the authors present the verification of the previously proposed similarity criteria derived for perforated panels. The verification was performed by measurements; two samples were tested: a sample made at 1:4 scale and a sample made at 1:8 scale in relation to their full-size equivalent. The measurements, performed in a 1:8 scale reverberation chamber, show very good consistency with the numerical simulations. Also, the uncertainty of the measurement of sound absorption coefficient of scaled perforated panels was discussed. The values of uncertainty correspond to the full-size measurements, which proves that scale model measurements can be used for the verification of designed solutions without any aggravation of the measurement accuracy.

Acknowledgments

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