Uncertainty of impedance tube sound absorption measurements of a spiral-tube-shaped 3-D printed acoustic metamaterial

Original
Uncertainty of impedance tube sound absorption measurements of a spiral-tube-shaped 3-D printed acoustic metamaterial / Prato, Andrea; Schiavi, Alessandro; Pandolfi, Tommaso; Corona, Davide; Fasana, Alessandro. - (2021). (Intervento presentato al convegno 27th International Congress on Sound and Vibration, ICSV 2021).

27th International Congress on Sound and Vibration
The annual congress of the International Institute of Acoustics and Vibration (IIAV)
11-16 July, 2021
ICSV27

Annual Congress of the International Institute of Acoustics and Vibration (IIAV)

UNCERTAINTY OF IMPEDANCE TUBE SOUND ABSORPTION MEASUREMENTS OF A SPIRAL-TUBE-SHAPED 3-D PRINTED ACOUSTIC METAMATERIAL

Andrea Prato
INRiM – National Institute of Metrological Research, Turin, Italy
email: a.prato@inrim.it

Alessandro Schiavi
INRiM – National Institute of Metrological Research, Turin, Italy
e-mail: a.schiavi@inrim.it

Tommaso Pandolfi
Politecnico di Torino, Turin, Italy
e-mail: tommasomaria.pandolfi@studenti.polito.it

Davide Corona
INRiM – National Institute of Metrological Research, Turin, Italy
email: d.corona@inrim.it

Alessandro Fasana
Politecnico di Torino, Turin, Italy
e-mail: alessandro.fasana@polito.it

In recent years, the increasing development of acoustic metamaterials allowed to obtain a wide range of solutions for specific practical applications for sound absorption and insulation, in particular at low frequency. Their acoustical properties are usually simulated and most of the measurements are reported without the associated uncertainty. In this work, the reproducibility of sound absorption measurements of a spiral-tube-shaped 3-D printed acoustic metamaterial in two impedance tubes with diameters of 30 mm and 50 mm is evaluated. The acoustic metamaterial is an ultra-thin narrow-band sound absorbing panel based on coplanar spiral tubes. Measurements on a single sample in five different mounting conditions show compatible results, whereas reproducibility among three different samples, nominally equal, is low, compared to traditional porous materials. Moreover, discrepancies between theoretical and experimental resonance frequencies are in the order of 40%-50%, in terms of relative deviation. Such analysis allows understanding the intrinsic variability of these materials and the naturally occurring inhomogeneity in 3-D printing and realization processes which might have a huge impact on the acoustic performance of the designed prototypes.

Keywords: metamaterials, uncertainty, impedance tube, sound absorption

1. Introduction

In the last ten years, the number of articles about acoustic metamaterials exponentially increased, making it a trending topic among the acousticians' community. Around 4700 articles were published in 2019 and its number is expected to increase in 2020. Most of them report new solutions devised for widely different applications especially for sound absorption, by exploiting their innovative characteristics. While conventional absorbers use viscous dissipation and heat conduction at the fluid-solid interface, yielding porous media and micro-perforated panels as effectual sound absorbers, acoustic metamaterials are composed of decorated membrane resonators, degenerate resonators, hybrid resonators, and coiled Helmholtz resonators, realizing sound absorbers with subwavelength-scale structures [1].

Most of the papers report specific designs and solutions based on analytic calculations or on software simulations [2,3], but few ones are based on actual measurements. From these ones, the most are performed with non-standard methods using self-made experimental setups [4,5] and only few ones report reliable results based on standard methods, e.g. impedance tube method [6,7]. Furthermore, the associated uncertainties, mainly due to repeatability or reproducibility, is, in most of cases, not reported or completely disregarded. Given such context, a metrological approach for the evaluation of the performances of acoustic metamaterials is becoming increasingly necessary and highly recommended in order to provide reliable results. In this paper, starting from an acoustic metamaterial found in literature, reproducibility of sound absorption measurements of 3-D printed polylactic acid (PLA) samples in two impedance tubes (30 mm and 50 mm diameters) is described and reported.

2. Spiral-tube-based acoustic metamaterial

The acoustic metamaterial used for the evaluation of reproducibility of standardized sound absorption measurements in impedance tube is an ultra-thin sound absorbing panel based on coplanar spiral tubes, specifically designed for low-frequency sound absorption [8]. Unlike classic sound absorbing materials, whose performance strictly depends on their thickness, with a minimum of one-quarter wavelength to reach full sound absorption, this ultra-thin sound absorbing panels absorb sound energy with a thickness around one percent of the wavelength. This is achieved by bending and coiling up quarter-wavelength sound damping tubes into 2D coplanar ones, and embedding them into a matrix to form a sound absorbing panel. A schematic view of the reference acoustic metamaterial is depicted in Fig. 1. The inner tubes are coiled up for space-saving purposes, with their axes twisted into spiral lines. The adapting pore on the front covering board allows the sound waves to propagate inside the inner tubes. The tube sits inside a circular disk and is covered by a front layer (containing an adapting pore) and a back terminal layer. From theory [8], sound absorption α of the rigid panel with embedded hollow tubes be determined by Eq. (1),

$$\alpha = 1 - |R|^2 = 1 - \left|\frac{Z_{in} - Z_{c0}}{Z_{in} + Z_{c0}}\right|^2 = 1 - \left|\frac{\dfrac{-i\,(\rho/C)^{\frac{1}{2}}\cot(kL)}{N\pi r^2/A} - Z_{c0}}{\dfrac{-i\,(\rho/C)^{\frac{1}{2}}\cot(kL)}{N\pi r^2/A} + Z_{c0}}\right|^2 \tag{1}$$

where R is the reflectance, Z_{in} is the input acoustic impedance of the panel, Z_{c0} is the acoustic impedance of air, ρ is the effective density of the tube, C is the effective compressibility of the tube, k is the wavenumber, L is the tube length, N is the number of tubes inside the panel, r is the radius of the tube and A is the area of the panel.

Full absorption α=1 is reached when the input impedance of the panel Z_{in} and the characteristic impedance of the air Z_{c0} match, i.e. if the radius of the tube r is large enough to consider $(\rho/C)^{1/2}=Z_{c0}$, and when the porosity $\zeta=N\pi r^2/A$ and cot(kL) are equal.

In the reference paper, the panel was designed in order to be suitable into the 60 mm diameter impedance tube, therefore R_0 was equal to 30 mm and the area $A=\pi R_0^2$ of the sample was 2.83×10^{-3} m^2. The length L of the tube (N=1) was set to 205 mm and the theoretical inner radius r of the tube was imposed to 4.85 mm. However, to facilitate the fabrication, a square cross-section of the tube was chosen by the authors of the cited paper [8], with its side determined by $a^2=\pi r^2$, entailing a=8.60 mm, which also corresponds to the inner thickness t_{in}. In this way the effective density ρ and compressibility C of the tube match the acoustic impedance of air Z_{c0} [8] and the porosity is $\zeta=a^2/(\pi R_0^2)=0.026$. With these values, full absorption is reached when $\cot(kL)=\zeta=0.026$, thus at a frequency $f=(c\cdot\cot^{-1}\zeta)/(2\pi L)=411$ Hz, where c is the speed of sound in air. The thickness of the front layer with the adapting pore t_f and the thickness of the closed-back layer t_b was 3.4 mm and 5 mm, respectively, giving a total thickness t_{tot} of the panel of 17 mm.

In the present paper, since measurements are performed in two different impedance tubes with diameters of 30 mm and 50 mm, these parameters are consequently scaled, as well as the expected maximum absorption frequency. Values are reported in Table 1.

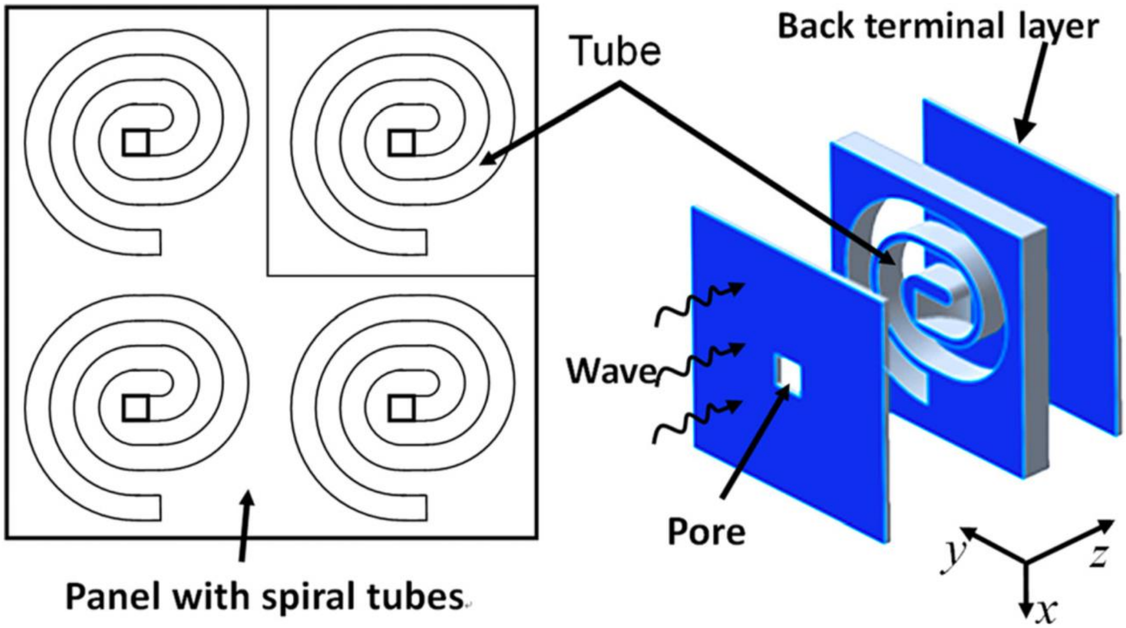

Figure 1: Schematic draw of the sound absorptive panel with spiral tubes [8].

Table 1: Geometrical characteristics of the acoustic metamaterial

Sample ID	R_0 / mm	L / mm	a / mm	t_{in} / mm	t_f / mm	t_b / mm	f_0 / Hz
Reference 60 mm sample [8]	30	205	8.6	8.6	3.4	5	411
50 mm sample	25	169	7.1	7.1	2.8	4.1	500
30 mm sample	15	100	4.2	4.2	1.7	2.5	839

3. The 3-D printed samples

The samples of the acoustic metamaterial are realized with a Makerbot Replicator 2 3-D printer, which is a medium-high quality machine on the market. The declared resolution is 0.1 mm. The material used for the realization of the acoustic metamaterial is polylactic acid (PLA). This material is of interest in terms of sustainability, has a density of 1.210-1.430 g·cm^{-3} and a melting temperature of 150-160 °C. In

Fig. 2 the 3-D printer (left) and a PLA filament bundle (right) used for the production of the samples are shown.

Figure 2: The 3-D printer (left) and a PLA filament bundle (right) used for the realization of the samples.

Three samples were realized for each diameter (30 mm and 50 mm), respectively, as shown in Fig. 3 (left). Each sample was printed in two steps since it is not possible to achieve the whole sample at once. The main core with the front cover and the inner tube (Fig. 3, right) is realized at first, and subsequently the back layer. The two pieces were glued by means of a fluid adhesive (Loctite®). Coupling of the two pieces is guaranteed by printing two small centring spurs on the inner core and two coincident small blind holes on the back layer.

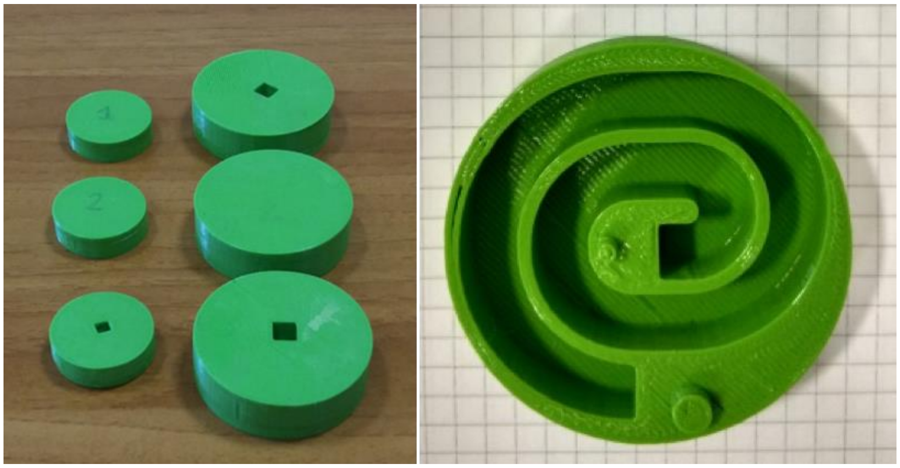

Figure 3: The three samples with diameters of 30 mm and 50 mm (left) and the inner part of a sample with the embedded spiral tube and centring spurs (right).

4. Impedance tube measurements

Sound absorption measurements are performed in the impedance tube in accordance with ISO 10534-2 [9] (two-microphone technique) at INRiM laboratory. The two impedance tubes of 30 mm and 50 mm diameter each (Figure 4), are equipped with two ¼’’ microphones (Brüel & Kjær 4136) and with a white noise source which generates a flat spectrum in the 100-5000 Hz frequency range. The 30 mm tube (length of 45 cm and microphone spacing of 16 mm) allows measuring with high accuracy in the frequency range of 400-6300 Hz and the 50 mm tube (length of 52 cm and microphone spacing of 26 mm) in the frequency range of 100-3150 Hz. The frequency resolution was set to 0.5 Hz. The possible gaps among the sample perimeter and the tubes' inner surfaces have been sealed by covering the sample border with technical petroleum jelly. In this way, the size of the voids between the tested material and the sample holder is reduced in order to minimize circumferential effects. Temperature and atmospheric pressure are measured with properly calibrated transducers. In both 30 mm and 50 mm impedance tubes, measurements are performed and repeated five times on a single sample by removing, rotating and fixing it each time into the tube, in order to evaluate the reproducibility of a single sample in different mounting conditions. Subsequently, measurements are performed on the other two samples in order to evaluate the reproducibility among three samples, nominally equal.

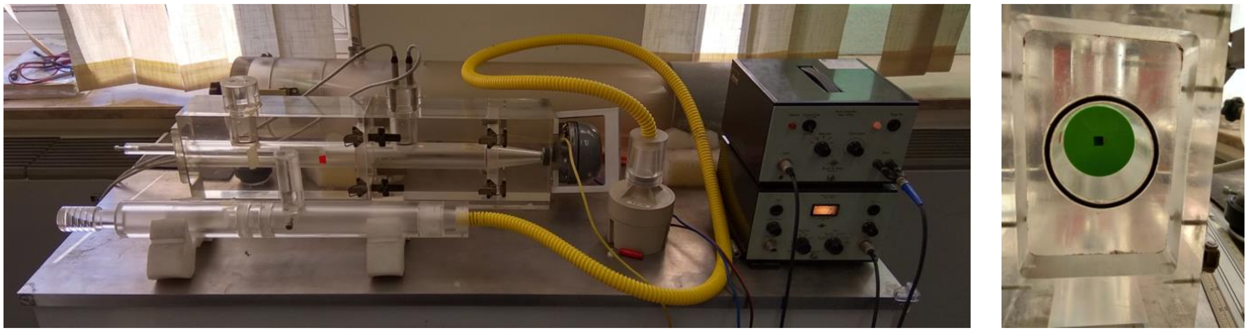

Figure 4: The two impedance tubes of 30 mm and 50 mm diameter (left) and a 50 mm sample mounted into the impedance tube (right).

5. Experimental results

5.1 Reproducibility measurements on a single sample

The five sound absorption measurements on a single sample of 30 mm and 50 mm diameter in different mounting conditions are reported in the graph of Fig. 5. Curves are very similar and reproducibility is high. From the 30 mm diameter sample, the first main resonant frequency lays between 1330 Hz and 1332 Hz with sound absorption values between 0.89 and 0.90, and the second peak between 3815 Hz and 3876 Hz with absorption values between 0.22 and 0.24. From the 50 mm sample, the first main resonance frequency lays between 659 Hz and 653 Hz with sound absorption values between 0.53 and 0.56, and the second peak between 1592 Hz and 1596 Hz with absorption values between 0.41 and 0.43. Absorption fundamental resonance frequencies are different from the expected ones from theory (Table 1). This is discussed in the following Section.

5.2 Reproducibility measurements among three nominally equal samples

Sound absorption measurements on three 30 mm and 50 mm samples, nominally equal, are reported in the graph of Fig. 6 and summarized in Table 2. Samples 1 are the ones previously tested in the different mounting conditions. From the 30 mm diameter samples, curves show two resonant peaks: the main one f_0 around 1300 Hz and a small one f_1 around 4000 Hz. The curve of Sample 2 presents also some spurious peaks around 2500 Hz, 4250 Hz and 5000 Hz, likely due to noise disturbances in those frequency ranges without effective absorption. The main resonance frequency f_0 lays between 1324 Hz and 1330 Hz with sound absorption values between 0.69 and 0.89, while the second peak f_1 lays between 3810 Hz, and 4243 Hz with absorption values between 0.17 and 0.24. From the 50 mm diameter sample, the first main resonant frequency f_0 lays between 499 Hz and 713 Hz with sound absorption values between 0.56 and 0.62, and the second peak f_1 lays between 1525 Hz and 1867 Hz with absorption values between 0.21 and 0.43. Only Sample 3 presents a third peak at 2534 Hz.

In both cases, comparison between theoretical full absorption resonance frequencies and main experimental ones (Table 1 and 2) shows discrepancies, in terms of relative deviation, for most of the samples, except for Sample 1 with 50 mm diameter. For 30 mm diameter samples, differences are in the order of 58%, while for 50 mm samples differences are between 0.2% (Sample 1) and 43%. These are likely due to small imperfections in the deposition of the PLA filaments by the 3-D printer or in the front and back panels gluing process, whose effects are to reduce the effective tube length. The only thermal and viscous dissipations, caused by the bending of the tube, which are in the order of 1%-2%, can not explain this behavior themselves [10]. Furthermore, absorption values, especially for the 50 mm diameter samples, are below 1 due to the presence of a second resonance peak occurring at higher frequencies which is around the third harmonics of the fundamental resonant frequency, as expected from quarter-wavelength absorbers theory [11].

In general reproducibility among different samples is lower than reproducibility on a single sample with different mounting conditions, as expected. Therefore, the variability in the realization of the objects by the 3-D printer is more impacting than measurement method uncertainties. Furthermore, samples with 30 mm diameters seem to be more reproducible than 50 mm samples. This could be due to the fact that possible imperfections during the 3-D printing and gluing processes might occur more often on larger samples, entailing a higher impact on the acoustic performances.

Compared to porous materials, whose sound absorption uncertainty due to reproducibility among different samples in impedance tubes are, in the worst cases, around 10% [12,13], the tested acoustic metamaterial shows a lower reproducibility (standard deviations of sound absorption among the three samples are around 20% as average).

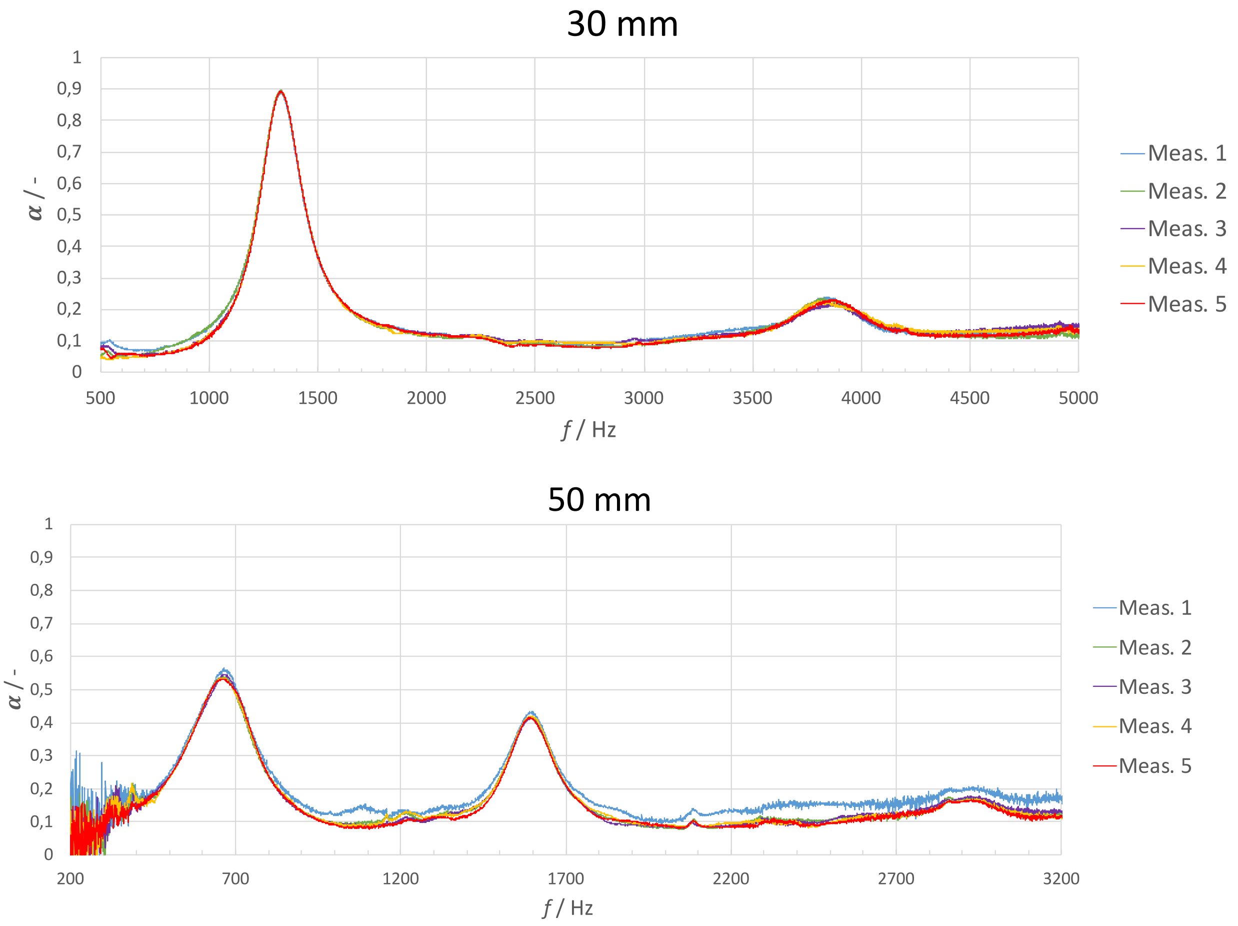

Figure 5: Reproducibility between five sound absorption measurements on a single sample with diameter of 30 mm (upper) and 50 mm (lower).

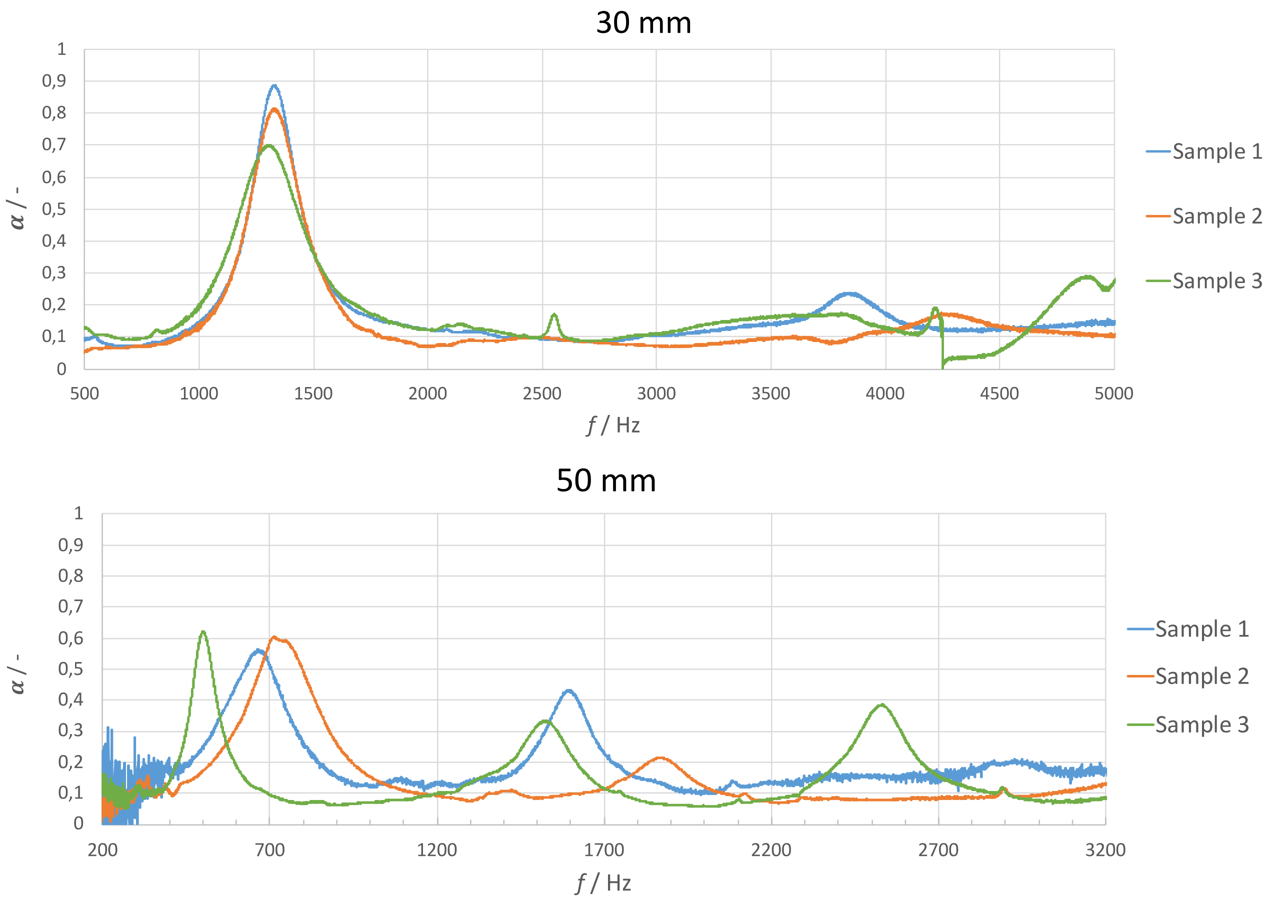

Figure 5: Reproducibility of sound absorption measurements on three samples with diameters of 30 mm (upper) and 50 mm (lower)

Table 2: Sound absorption resonant peaks of the three samples with diameters of 30 mm and 50 mm.

	30 mm diameter				50 mm diameter			
	Theor.	Sample 1	Sample 2	Sample 3	Theor.	Sample 1	Sample 2	Sample 3
f_0 / Hz	839	1330	1325	1324	500	661	713	499
$\alpha\,(f_0)$ /-	1	0.89	0.81	0.69	1	0.56	0.60	0.62
f_1 / Hz	-	3832	4243	3810	-	1596	1867	1525
$\alpha\,(f_1)$ /-	-	0.24	0.17	0.17	-	0.43	0.21	0.33

6. Conclusions

In this work, the reproducibility of sound absorption measurements in impedance tube of a 3-D printed acoustic metamaterial is evaluated. Measurements were performed on an ultra-thin sound absorbing panel based on coplanar spiral tubes, found in literature, specifically designed for low-frequency sound absorption, whose dimensions were scaled in order to fit the available impedance tubes with diameters of 30 mm and 50 mm. Five repeated measurements in different mounting conditions on a single sample showed highly reproducible results, while measurements among three different samples, nominally equal, showed some discrepancies with standard deviations in the order of 20%, which are higher than typical values occurring with porous materials, and with differences between experimental and theoretical absorption resonance frequencies of 40%-50% as average. This analysis allowed to understand the intrinsic variability of these materials, especially if designed for the absorption of narrow frequency bands like this prototype, and the naturally occurring inhomogeneity in 3-D printing and realization processes. In fact, even small defects might have a huge impact on the acoustic performance of the designed prototypes. Future works should be aimed at performing similar measurements on other narrow- and broad-band absorbing acoustic metamaterials by means of high-quality 3-D printers, without gluing process, in order to evaluate their impact on the acoustic performances.

REFERENCES

1 Yang, M. and Sheng, P. Sound absorption structures: from porous media to acoustic metamaterials, *Annu. Rev. Mater. Res.,* **47**, 83–114, (2017).

2 Tang, Y., Ren, S., Meng, H., Xin, F., Huang, L., Chen, T., Zhang, C. and Lu, T.J. Hybrid acousticmetamaterial as super absorber for broadband low-frequency sound, *Scientific reports*, **7**:43340, 1-10, (2017).

3 Wang, Y., Zhao, H., Yang, H., Zhong, J. and Wen, J. A space-coiled acoustic metamaterial with tunable low-frequency sound absorption, *EPL*, **120**:54001, (2017).

4 Long, H., Gao, S., Cheng, Y. and Liu, X. Multiband quasi-perfect low-frequency sound absorber based on double-channel Mie resonator, *Appl. Phys. Lett.*, **112**:033507, (2018).

5 Song, G. Y., Cheng, Q., Huang, B., Dong, H. Y. and Cui, Broadband fractal acoustic metamaterials for low-frequency sound attenuation, *Appl. Phys. Lett.*, **109**:131901, (2016).

6 Wu, F., Xiao, Y., Yu, D., Zhao, H., Wang, Y. and Wen, J. Low-frequency sound absorption of hybrid absorber based on micro-perforated panel and coiled-up channels, *Appl. Phys. Lett.*, **114**:151901, (2019).

7 Huang, S., Fang, X., Wang, X., Assouar, B., Cheng, Q. and Li, Y., Acoustic perfect absorbers via spiral metasurfaces with embedded apertures, *Appl. Phys. Lett.*, **113**:233501, (2018).

8 Cai, X., Guo, Q., Hu, G. and Yang, J., Ultrathin low-frequency sound absorbing panels based on coplanar spiral tubes or coplanar Helmholtz resonators, *Appl. Phys. Lett.*, **105**:121901 (2014).

9 ISO 10534-2:2001. Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes - Part 2: Transfer-function method.

10 Cambonie, T., Mbailassem, F., and Gourdon, E. Bending a quarter wavelength resonator : Curvature effects on sound absorption properties, *Applied Acoustics*, **131**, 87–102, (2018).

11 Hannink, M. Acoustic resonators for the reduction of sound radiation and transmission, *PhD Thesis*, University of Twente, (2007).

12 Shtrepi, L. and Prato, A. Towards a sustainable approach for sound absorption assessment of building materials: Validation of small-scale reverberation room measurements, *Applied Acoustics*, **165**, 1–16, (2020).

13 Schiavi, A. and Prato, A. Evaluation of sound absorption: an experimental comparative study among reverbaration room, impedance tube and airflow resistivity-based models, Proceedings of the 26th International Congress on Sound and Vibration, Montreal, Canada, 7–14 July, (2019).