1. Introduction

Additive manufacturing (AM) is the process of adding material, usually layer-by-layer, in order to concretize objects whose 3D model is created by computer-aided design (CAD) or digital scanner software [1]. This technology, also known as 3D printing, makes possible to rapidly fabricate objects of complex shape that would be difficult or impossible to produce otherwise. Moreover, it allows functionalization of employed matter at microscopic level avoiding material waste and increasing efficiency of structures for different applications [1].

Recently, this technology has been largely used for the fabrication of proof of concept acoustic absorbing metamaterials. Ordered porous structures made of micro-lattices with circular [2] or cubic cross-section [3] platelet-like beams are examples of large band absorbers made possible by AM methods. Coiled resonators in form of 3D helicoidal [4], co-planar spiral [5], [6] or more complex 3D structures [7], [8] are other examples of the potential of AM for innovation in the conception and fabrication of absorbing materials.

Incoherence between modeled and experimental response of 3D printed acoustic absorbing materials is reported. It is mostly explained by geometrical discrepancies between ideal structure and 3D printed samples especially surface roughness [5]. The main objective of this paper is the assessment of the
appearance of a non-expected absorption resonance of a 3D printed acoustic resonator. To clarify the phenomenon two hypotheses were explored:

1. Viscous friction on 3D printed induced porosity in the thin-wall: induced porosity is a known issue largely reported and studied by AM community and it is responsible for reduction of mechanical resistance of 3D printed parts [9], [10]. However, the influence of this induced porosity on the acoustic behavior of 3D printed resonator has never been evaluated;

2. Membrane absorption behavior: Polymeric thin-wall vibrates under the acoustic wave excitation and energy dissipation could occur through periodic deformation of a viscoelastic material. This behavior was evidenced and materialized in the development of silencers with porous and non-porous metal membranes [11].

### 2. Experimental procedure

Two types of samples were fabricated with fused deposition modeling (FDM) Raise3D Pro2 3D printer. A coplanar resonator designed (CHR, Figure 1b) by Cai [6] was used to expose and observe the presence of the unexpected absorption resonance. To simplify the analysis of the unexpected peak, a second type of resonator having the same cavity volume but closed by thin wall, here called hollow cylinder, was printed as well (Figure 5). The 3D printing materials used were Polylactic acid (PLA) and Ninjaflex. PLA with 1.7 GPa tensile modulus and 6% elongation at yield and at break is the most common and easy-to-use 3D printing material. Ninjaflex with 12 MPa tensile modules, 65% elongation at yield and 660% elongation at break is a thermoplastic polyurethane (TPU) based material developed by NinjaTek® to provide superior flexibility and longevity to 3D printed structures. The characteristic of all samples used in this study are gathered in Table 1. They were tested for normal-incident-absorption-coefficient in a 30-mm-diameter impedance tube in 400 Hz–6400 Hz frequency range and noise level around 94 dB.

<table>
<thead>
<tr>
<th></th>
<th>Material</th>
<th>Wall thickness (mm)</th>
<th>Cavity thickness (mm)</th>
<th>Neck length (m)</th>
<th>Neck surface area (m²)</th>
<th>Cavity volume (m³)</th>
</tr>
</thead>
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<tr>
<td>CHR</td>
<td>PLA</td>
<td>3</td>
<td>7</td>
<td>27.1×10⁻³</td>
<td>18.5×10⁻⁶</td>
<td>3.43×10⁻⁶</td>
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<td></td>
<td>1</td>
<td>9</td>
<td>24.8×10⁻³</td>
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<td>4.74×10⁻⁶</td>
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<td></td>
<td>0.45</td>
<td>9.55</td>
<td>23.9×10⁻³</td>
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<td>5.11×10⁻⁶</td>
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<td>Hollow cylinder</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
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</tr>
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<td>3</td>
<td></td>
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<tr>
<td></td>
<td>Ninjaflex</td>
<td>0.45</td>
<td></td>
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</table>

### 3. Results and discussion

Created by X. Cai et al. [5], the coplanar Helmholtz resonator (CHR) is an absorbing metamaterial composed of a closed cavity of volume V that communicates with the outside via a small tube of length L and area A, called neck (Figure 1). The absorption principle of the CHR is the same as that of traditional
Helmholtz resonators (THR) [12]. The mainly difference between THR and CHR is that coplanar resonator’s neck is folded into the cavity volume. Especially for low frequency absorption, this strategy allows a significant reduction of treatment thickness. As in the case of THR, the natural frequency of CHR can be estimated using Eq. (1).

\[
f_0 = \frac{c}{2\pi} \sqrt{\frac{A}{V L}}
\]

Figure 1 – Neck design of traditional and coplanar Helmholtz resonators

A strategy to decrease resonance frequency of CHR without changing total sample thickness is to reduce the entrance wall thickness, \(t_w\), and increase cavity thickness, \(t_c\), (Figure 2). Figure 2b shows absorption coefficient (AC) of two CHR both with 10 mm of total thickness (\(t = t_c + t_w\)) but with different entrance wall thickness. For the same total thickness, the natural frequency of CHR with smaller entrance wall thickness, \(t_w = 1\) mm, is lower (Figure 3). Furthermore, with the reduction of the entrance wall thickness, an unexpected absorption resonance appears at 2655 Hz. Resonances beyond 5000 Hz are probably harmonics of fundamental resonance.

Figure 2 – Scheme of CHR highlighting treatment entrance (a) and cavity and entrance wall thickness (b)

Figure 3 – AC of two CHR with different entrance thickness wall.
A comparison of acoustic tests with opened and closed entrance area (EA) of CHR with $t_w = 1$ mm shows that the unexpected absorption peak is not related to the structure of the CHR (Figure 4). It is a result of sound wave interaction with the thin entrance-wall. Moreover, peaks beyond 5000 Hz disappear, indicating that they are effectively harmonics of first resonance. In order to simplify the study, a hollow cylinder sample in which only the unexpected absorption resonance is observed was manufactured (Figure 5). It has two mainly parameters: entrance wall thickness, $t_e$, and cavity thickness, $t_c$. Samples with different values for these parameters will be used to determine whether the mechanism behind the absorption phenomenon is related to printed-induced porosity or the membrane like behaviour.

![Figure 4 – Acoustic test comparing CHR with opened and closed entrance](image)

**Figure 4** – Acoustic test comparing CHR with opened and closed entrance

![Figure 5 – Design (a) and 3D printed hollow cylinder (b) without entrance area for experimental investigation](image)

**Figure 5** – Design (a) and 3D printed hollow cylinder (b) without entrance area for experimental investigation

### 3.1 Viscous friction on 3D printed-induced porous thin-wall hypothesis

According to the first hypothesis the presence of induced porosity between 3D printed fibers would make hollow cylinder sample to behave as a standard perforated panel or Helmholtz resonator. Scanning Electron Microscopy (SEM) images of the entrance wall of a hollow cylinder sample highlights irregularities, contact between fibers (Figure 6b) and indeed detailed porosity between two fibers (Figure 6c). Using Figure 6c and Eq. (2) a porosity of 1.25% was estimated. Void and total area are 60 $\mu m^2$ and 4800 $\mu m^2$, respectively.

$$\phi = \frac{\text{void area}}{\text{total area}}$$  \hspace{1cm} (2)

To asses the influence of induced porosity on the absorption peak, the acoustic absorption of hollow cylinder samples with 1 mm entrance wall thickness and 9, 30 and 50 mm cavity thickness (Figure 7) was measured with the impedance tube. Helmholtz resonance frequency was calculated using Eq. (1). The cavity volume and neck area were evaluated with Eq. (3) and (4). The radius of the cylinder, $r$, was
considered 14.2 mm and the length of the neck 1 mm. Theoretical and experimental natural frequency of the Helmholtz resonator are gathered on Table 2.

\[ V = t_c \cdot \pi r^2 \]  
\[ A = \phi \cdot \pi r^2 \]  

\[ (3) \]

\[ (4) \]

![Image of hollow cylinder sample pictures](image)

**Figure 6 – Hollow cylinder sample picture** (a) SEM images highlights irregularities, contact between fibers (b) and induce porosity (c)

**Table 2 – Helmholtz parameters, theoretical and experimental natural frequency**

<table>
<thead>
<tr>
<th></th>
<th>Hollow cylinder 1 ($t_c = 9$ mm)</th>
<th>Hollow cylinder 2 ($t_c = 30$ mm)</th>
<th>Hollow cylinder 3 ($t_c = 50$ mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity volume ($10^{-5}$ m$^3$)</td>
<td>0.57</td>
<td>1.900</td>
<td>3.17</td>
</tr>
<tr>
<td>Neck surface ($10^{-6}$ m$^2$)</td>
<td>7.92</td>
<td>7.92</td>
<td>7.92</td>
</tr>
<tr>
<td>Neck length (mm)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Theoretical natural frequency (Hz)</strong></td>
<td><strong>2017</strong></td>
<td><strong>1105</strong></td>
<td><strong>855</strong></td>
</tr>
<tr>
<td><strong>Experimental natural frequency (Hz)</strong></td>
<td><strong>2902</strong></td>
<td><strong>3056</strong></td>
<td><strong>3010</strong></td>
</tr>
</tbody>
</table>

**Figure 7 - Experimental test of hollow cylinder with 9, 30 and 50 mm of cavity thickness**

If the Helmholtz resonance was responsible for the absorption peak, an increase of cavity thickness, and consequently of the cavity volume, would lead to a significant decrease of resonance frequency. However, no significant variation of resonance frequency was observed. On Table 2, a difference of 30%,
64% and 72% of theoretical natural Helmholtz frequency with respect to experimental value was measured for samples with 9mm, 30mm and 50mm thickness, respectively. This result suggests that, on the analysed frequency range, induced porosity has no effect on the absorption behaviour of 3D printed resonators. Induced porosity has unpredictable occurrence. The entrance wall is produced with a superposition of layers. Voids observed on Figure 6c are not necessarily repeated at the same place in all layers, therefore there is no guarantee that this superficial porosity emerge on cavity volume allowing a resonance phenomenon. Moreover, the observed porosity is low and the entrance wall is not thick enough to significantly dissipate the acoustic wave by viscous and thermal friction.

3.2 Membrane absorption behaviour hypothesis

The second hypothesis is that acoustic waves would excite vibration modes of the structure entrance wall and energy would be dissipated by heat during periodic deformation of viscoelastic material. Polymers frequently deviate from purely elastic behaviour. They are then said to be “inelastic”, in which deformation under applied loads is an irreversible process and hence the net work done is positive. Net work done can then be dissipated as heat, or locked inside the material as a permanent change in structure (eg. plastic strain) [13].

Eq. (5) predicts vibration modes of circular membrane [14]. $X_{mn}$ are discretized solutions of first kind Bessel function, $a$ is the radius of the circular membrane, $\tau$ tension per unit length and $M_s$ is mass per unit of area.

$$f_{mn}^{\text{theo}} = \frac{1}{2\pi} \frac{X_{mn}}{a} \sqrt{\frac{\tau}{M_s}}$$

(5)

According to Eq. (5), an increase in membrane tension or a decrease of membrane mass per unit of area would increase resonance frequency. Even if the samples are printed with the same material, PLA for instance, higher entrance wall thickness represents higher tension per unit length because thicker plates has greater flexural modulus. So, if the absorption peak reported here is result of a membrane-like dissipation, increasing of $t_e$ would lead to an augmentation of absorption frequency. This behavior was experimentally confirmed. It can be seen on Figure 8 that an increase of the wall thickness from 0.45 mm to 3mm shift the resonant frequency from 1671 Hz to about 6000Hz. It can be concluded that the second absorption peak of the CRH (Figure 3) is related to a membrane-like absorption phenomenon rather than to viscous friction on porous induced by the manufacturing.

![Figure 8 – Absorption coefficient of 5 PLA hollow cylinder samples with different $t_e$](image)

In order to confirm this result and evaluate the potential for low frequency absorption of 3D printed membrane, a hollow cylinder sample with $t_c = 9$ mm and $t_w = 0.45$ mm was printed with a material with low tension per unit length: the flexible Ninjaflex filament. Compared to PLA, resonance frequency of 3D printed acoustic membrane is indeed shifted towards lower frequency (763 Hz). In addition to a lower absorption frequency compared to PLA sample, the bandwidth of absorption is clearly larger.
Figure 9 – Absorption coefficient of 3D printed membrane absorber with PLA and Ninjaflex

Usually, analytical and FE acoustic models consider porous skeleton to be rigid. The present work highlights the resonance effect related to the vibration of thin 3D printed resonators. It suggests that, besides geometrical discrepancies between ideal and 3D-printed structures, sample vibration can be an additional cause of incoherence between modelled and experimental response of 3D printed acoustic structures. Another example of this resonance effect around 3200 Hz is highlighted by normal incident acoustic test of a 3D-printed ordered porous micro-lattice structure (Figure 10). This result suggests that for acoustic modelling of thin plastic 3D-printed the hypothesis of flexible structure should be adopted.

Figure 10 – 3D printed-micro lattice (a) and fibers resonance (b)

This non-rigid behaviour regarding acoustic response can be used to create absorbers integrating two or more different dissipation mechanisms opening new possibilities for the development of 3D printed sound absorbing materials. For instance, CHR integrating Helmholtz resonance and membrane-type dissipation was 3D-printed with PLA (Figure 11). Two absorption resonances below 2000 Hz were observed. The first resonance (659 Hz) is the result of the membrane deformation and the second one (1810 Hz) is due to the volume of Helmholtz resonator cavity.

Figure 11 – CHR with 0.45 mm entrance thickness wall and 9.55 thickness
4. Conclusions

A comprehensive experimental investigation about an unexpected absorption phenomenon on a 3D printed CHR was conducted. Two hypotheses were explored: viscous friction in 3D printed-induced porosity and periodic deformation of viscoelastic material in a membrane-like absorber behaviour. Experiments and simple analytical models lead to the conclusion that the second absorption of CRH is the result of a membrane-like energy dissipation caused by vibration of a flexible thin wall. The behaviour of membrane absorber has been extensively discussed and the present work represent the first important step towards printing membrane absorber with high absorption capability at low frequency. Due to the flexibility offered by 3D printing process, this finding opens a new avenue of possibilities for the development of innovative absorbers. For instance, membranes can be integrated with ordered porous structures and resonators. Moreover, 3D printed structures with flexible material can combine two dissipation mechanisms in order to provide broadband and low frequency absorption.

REFERENCES