Fabrication and Characterization of 3D Printed Thin Plates for Acoustic Metamaterials Applications

Cecilia Casarini, Student Member, IEEE, Vicent Romero-García, Jean-Philippe Groby, Ben Tiller, James F. C. Windmill, Senior Member, IEEE and Joseph C. Jackson

Abstract—This paper presents a 3D printing technique based on stereolithography and direct light processing for the fabrication of low resonance frequency thin plates suitable for acoustic metamaterials applications. It was possible to achieve a better resolution with respect to other 3D printing methods such as fusion deposition modeling and to obtain plates with a thickness of 70 μm. The plates were characterized using three different methods: laser Doppler vibrometer supported by modal analysis, impedance tube measurements backed by a transfer matrix model and nanoindentation. All results are in good agreement. The physical parameters retrieved through the characterization methods can be used for future designs and integrated into finite element analysis to better predict the noise impact of these materials. Thanks to the small radius and thickness of the plates presented in this paper and to their low resonance frequency, it is suggested that they could be arranged in various configurations and used as unit cells in acoustic metamaterials applications for noise attenuation in small-scale electroacoustic devices.

Index Terms—Acoustic Metamaterials – Thin Plates – Membranes - 3D Printing – Characterization – Noise Attenuation

I. INTRODUCTION

Recent advances in additive manufacturing techniques have now made it possible to fabricate thin membranes and plates that are essential for the study of several acoustic applications — for example, microphones and loudspeaker prototyping and acoustic metamaterials [1]–[4]. In laboratories, these membranes are usually obtained through a procedure where a piece of material is cut and glued on a rigid frame or support. On the other hand, industrial fabrication typically relies on other techniques - such as clean room manufacturing - that have high maintenance costs. In comparison with these established production processes, additive manufacturing provides with a cheap and reliable fabrication approach, which additionally offers the opportunity to choose the material for the membrane. Furthermore, 3D printing software allows to create abstract shapes and to integrate the product inside other structures, for example by 3D printing a membrane inside a Helmholtz resonator. Haque et al. [2] fabricated a thin silver layer on a purchased Mylar film using a inkjet 2D printer, that deposits drops of liquid material on pre-existing substrate. Previous research on 3D printing membranes relied on fusion deposition modeling [3], which deposits a filament layer by layer through a heated extruder nozzle head. Stereolithography via direct light processing has recently been used to 3D print thin layers with thickness down to 35 μm [1], thanks to new techniques that rely on absorbers that allow to control shapes and thickness of the materials in a finer way with respect to fusion deposition modelling, that has a minimum thickness of 0.1 mm. The advantages of these new stereolithography techniques can be found not only in the practical utility of fabricating a thin layer, but also in the opportunity to finely control its material. Moreover, multilayer plates made of different materials can be fabricated, paving the way of manufacturing a sensor or even an entire device in one print [1], [2]. In particular, when using polymers it is possible to choose the desired physical properties of the plate, given the vast range of different options available within the polymers.
realm [1, 5]. In this work, polymer-based thin low-frequency circular acoustic plates are fabricated using stereolithography and experimentally characterized via three different techniques. Although the fabrication technique described in this paper could be useful for many different applications based on membranes and plates, e.g. in microphones manufacturing [1] and non-destructive evaluation [6], the design presented here is specifically tailored to noise control through acoustic metamaterials. Plate-type acoustic metamaterials, originally proposed by Yang et al. [7]–[9], present a new and promising solution to the problem of low-frequency noise attenuation. Their small thickness and light weight could make them more desirable, for certain applications, than traditional materials used for noise control. Plates with or without a mass attached present a region of negative effective density with high sound transmission loss between the first and the second resonance, when backed with a rigid cavity, while plates suspended on an open support – as the ones presented in this paper – show this behavior in the frequency band preceding the first mode [10]–[16]. Thin membranes and plates can be used as unit cells in acoustic metamaterials presenting different configurations. For example Yang et al. [9] arranged them in a panel, Sui et al. [16] sandwiched the membranes between honeycomb panels and Naify et al. [17] built stacked membranes arrays. The thin plate presented in this paper could be arranged in any of the configurations described above. Furthermore, the fabrication technique presented here provides the opportunity to directly 3D print and integrate the plates inside other complex unit cells such as Helmholtz resonators and pipes to broaden their band gap. Being able to control the thickness, radius and material properties of the plates through additive manufacturing allows to choose the best combination of parameters to match a specific frequency range to be attenuated, while respecting the dimension constraints of a specific application. For example, in this paper the goal is to fabricate thin plates that could be included in small-scale devices, such as headphones and smart speakers, and at the same time having a low resonance frequency. Therefore, a polymer that had a low Young’s modulus with respect to other materials used in previous work [4] was selected. The 3D printing technique here developed made it possible to fabricate layers 70 μm thick. The chosen materials allowed to obtain a small-scale thin plate with a low resonance frequency.

Characterization is a crucial step in the production process to predict the acoustic behavior of a device at the design stage. This is particularly true for 3D printing applications, where the physical quantities of the materials change throughout the polymerization process. A good estimate of properties such as Young’ s modulus, Poisson’s ratio and loss factor is very important to design more complicated devices that include these plates and to predict their acoustic impact before fabrication using finite element analysis or other modeling techniques. In the following sections the fabrication process used to 3D print the plates is first described in detail, then, three different characterization methods are introduced. Laser Doppler vibrometer is used to show that the 3D printed layer presents the typical modes of vibration found in circular plates and membranes. Impedance tube measurements assessed by the transfer matrix modeling approach are employed to retrieve the main physical parameters such as Young’s modulus, density, Poisson’s ratio and loss factor, and to obtain the acoustic coefficients, namely absorption, transmission and reflection. Finally, nanoindentation together with scanning electron microscopy give further insight on the properties of the plate. Future work and potential industrial applications are outlined in the Conclusion section.

II. MATERIALS AND METHODS

A. Plates Fabrication

This section firstly presents the design choices in terms of geometry and materials and secondly describes in detail the thin plate fabrication steps. An Asiga Pico Plus 27 (Sidney, Australia) with a pixel image resolution of 27 by 27 μm, and a minimum build layer thickness of 1 μm was used to 3D print the samples. A circular shape was selected for the plate, since the analytical model of circular membranes and thin plates is well known and also due to previous research based on cylindrical Helmholtz resonators [4] that could be integrated with thin plates in future work. A hollow cylinder 1 mm in height and with 1 mm thick walls was also designed to support the plate. The 3D printer build plate size is 33.49 x 20.99 x 76 mm and the outer diameters of the support and plate were set at 20 mm, which is the maximum diameter. Therefore, the effective diameter of the membrane was 15 mm. There are two main reasons for selecting the maximum possible diameter. Firstly, in order to characterize the plate with an impedance tube, the diameter should be as large as possible, given the standard dimension of the tube, in this case having a 30 mm diameter. Secondly, since the resonance of a thin plate is inversely proportional to the square of its radius, a larger diameter would result in a lower frequency, as required for noise applications.

As shown in Figure 1, two different samples were fabricated. The first sample had as main component polyethylene glycol diacrylate 250 (PEGDA 250) and the second polyethylene glycol diacrylate 700 (PEGDA 700). The numbers 250 and 700 represent the molecular weights (MW) of the two different types of PEGDA. In particular, PEGDA 700 was preferred for this work as it is characterized by a lower Young’s modulus than PEGDA 250 and hence a lower resonance frequency, that could match and attenuate lower frequencies. BaTiO3 nanopowder with a 500 nm diameter average particle size, purchased from US-NANO, was added to the resin with a 50% weight with respect to PEGDA when fabricating the plate. BaTiO3 main function was to scatter the light in a uniform way on the horizontal plane, to obtain a flat plate, since previous attempts that did not include BaTiO3 resulted in a curved plate. It is important to notice that by adding BaTiO3 to the resin, a piezoelectric material can be obtained [1] and it could be used as such in future implementation of this work. Irgacure 819 (I819) was added to both mixtures as a photoinitiator with a 1% weight with respect to PEGDA and 0.1 % Sudan I (SI) was added as absorber to better control the amount of light that could contribute to the polymerization of the resin. These chemicals were purchased from Sigma Aldrich. While the resin described above was used to print the thin plate, the support material was made of PEGDA 250, 0.1% Sudan I and 1%
Irgacure 819. The exposure time to light contributes to determining the thickness of the membrane [18] and different exposure times between 0.5 second and 9 seconds were tried for different materials as reported in [4]. Since the Asiga 3D printer software does not allow to change the exposure time to light or other parameters while the print has started, the chosen exposure time of 5 seconds was of a duration that allowed to print both the materials of the support and the materials of the membrane.

The first step in the fabrication process, as shown in Figure 2, consisted in mixing the chemicals to obtain the resin for the thin plate and the resin for the support. The two resins were then independently mixed for 2 minutes using Thinky ARE 250 planetary mixer (INTERTRONICS) and then sonicated for 15 minutes. The CAD design was then uploaded into the Asiga Composer 3D Printing Software and automatically sliced into 101 layers, each 10 μm thick. The Layers 1 to 100 corresponded to the support and layer 101 to the thin plate. The resin for the support was then poured into the build tray and the 3D printing process was started. The support and the plate were printed in one piece, by pausing the 3D printer in correspondence to the layer before the plate, i.e. layer 100, leaving the 3D printed PEGDA part attached to the build platform to keep the right calibration. After cleaning the part on the build platform with isopropyl alcohol (IPA), the liquid resin in the build tray was changed to the resin of the thin plate and the last layer was fabricated. It is important to notice that, while the chosen layer thickness is 10 μm, when printing on a void the final thickness is determined by the intensity of light, the absorption coefficient of the fluid and the exposure time to light [18]. With commercial resins, even when the build layer thickness was set to 10 μm or less, the plates resulted to be 1 mm thick. As shown in Figure 3, when adding SI to the resin to reduce the amount of light, it was instead possible to finely control the resolution and to obtain a thickness down to 35 μm [1], [4]. In this case, the fabricated plate had a thickness of 70 μm, which was measured using a digital micrometer. Panel (a) of Figure 3 shows the 3D printing process of the support first 100 layers. When the last layer is fabricated (panel (b)), the part of fluid that polymerizes underneath the air cavity expands beyond the expected position in the z axis, resulting in a thicker membrane. When SI is added to the resin (panel (c)), the polymerization process can be finely controlled, and the last layer corresponds to the selected thickness.

B. Characterization Using Laser Doppler Vibrometer

A Polytec 3D scanning laser Doppler vibrometer (LDV) was used to perform the first characterization of the modes and fundamental resonance of the plates under test. Each sample was fixed to a glass support, and a loudspeaker (ESS Heil Air Motion Transformer) was used to create a sweep between 100 and 20000 Hz. The vibration of the plate was mapped by 289 scanning points. The Polytec software was used to analyze the results and plot the vibration modes of the plate under test.
where $M_{\text{endcorr}}$ is the transfer matrix of the end correction $\Delta l$ \cite{23}:

\[ M_{\text{endcorr}} = \begin{pmatrix} 1 & iZ_t k_t \Delta l \\ 0 & 1 \end{pmatrix}. \]

\[ M_{\text{tube}j} \] is the transfer matrix of the sample holder on the left ($j = 1$) and right ($j = 2$) sides of the plate \cite{24}:

\[ M_{\text{tube}j} = \begin{pmatrix} \cos(k_t l_j) & iZ_t \sin(k_t l_j) \\ \frac{i\sin(k_t l_j)}{Z_t} & \cos(k_t l_j) \end{pmatrix}. \]

\[ M_{\text{mem}} = \begin{pmatrix} 1 & Z_m \\ 0 & 1 \end{pmatrix}. \]

where $Z_m$ is the acoustic impedance of the thin plate \cite{25}:

\[ Z_m = -i\omega m \cdot \frac{l_1(k_m a) j_2(k_m a) + j_1(k_m a) j_0(k_m a)}{l_1(k_m a) j_2(k_m a) - j_1(k_m a) j_0(k_m a)}. \]

\[ k_m \] is derived in \cite{25} $a$ is the radius of the plate, $J_n$ and $I_n$ are respectively regular and modified Bessel’s functions of the first kind of order $n$ and $m$ is the mass of the plate. The wave number of the plate $k_m$ is equal to \cite{25}:

\[ k_m^2 = 2\pi f \sqrt{\frac{\rho_m k h^2}{\rho_m h^2}}, \]

where $\rho_m = \rho_m h$ is the surface mass density of the plate with mass density $\rho_m = \frac{m}{sh}$, where $m$ is the mass of the plate and $S$ its cross-section. The resonance frequency $f_0$ is given in terms of the the Young’s Modulus $E$, Poisson’s Ratio $\nu$ and loss factor $\eta$ and the geometry by \cite{26}:

\[ f_0 = 0.4694 \frac{h}{a^2} \sqrt{\frac{E}{\rho_m(1-\nu^2)}}. \]

Transmission, reflection and absorption coefficients can be retrieved from the total transfer matrix $T$ according to \cite{27}, \cite{28}.

As shown in Figure 5, the system to be modeled consisted of the plate with thickness $h$, the sample holder modeled as two air cylinders of length $l_1$ and $l_2$ on both sides of the plate and their end corrections. The sample holder is modeled as a circular tube and its wave number $k_t$ and the impedance $Z_t$ are derived as in \cite{21}. Therefore, the transfer matrix

\[ T = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}, \]

as discussed in \cite{19}, \cite{22}, is equal to:

\[ T = M_{\text{endcorr}}M_{\text{tube}1}M_{\text{mem}}M_{\text{tube}2}M_{\text{endcorr}}. \]

\[ M_{\text{endcorr}} \] represents the transfer matrix of the end correction $\Delta l$.

\[ M_{\text{mem}} \] is the transfer matrix of the sample holder.

\[ M_{\text{tube}1} \] is the transfer matrix of the first cylinder.

\[ M_{\text{tube}2} \] is the transfer matrix of the second cylinder.

\[ M_{\text{endcorr}} \] is the transfer matrix of the end correction.

\[ T = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}, \]

as discussed in \cite{19}, \cite{22}, is equal to:

\[ T = M_{\text{endcorr}}M_{\text{tube}1}M_{\text{mem}}M_{\text{tube}2}M_{\text{endcorr}}. \]
The impedance tube used to measure the acoustic coefficients had four microphones, an anechoic termination on one side and a loudspeaker on the other termination, as illustrated in Figure 6 (a). A sine sweep between 20 Hz and 2500 Hz was used as input [29]. Each sample was measured 10 times to assess the repeatability of the measurements. The reflection, transmission and absorption coefficients were retrieved from the measurements [19], [28]. Then, the physical quantities, chosen to initialize the model, namely density, Poisson’s ratio loss factor and Young’s modulus, were optimized to fit the experiments.

D. Characterization Using Nanoindentation

In order to compare different characterization methods and to determine which one is most suitable for this kind of samples, a 3D nanoindenter was also used to retrieve the Young’s modulus of the plate. The 3D printed plate was cut and just a small sample of it was used during this process. A Berkovich tip made of single crystalline diamond was used for nanoindentation and an IBIS software retrieved the Young’s Modulus of the materials. The values of the reduced elastic modulus were determined using the method of Oliver and Pharr [30]. The Young’s modulus was then obtained from the reduced Elastic modulus assuming a Poisson’s ratio of 0.35. To better understand if this characterization process was compatible with the 3D printed plate, a scanning electron microscope was used to obtain a detailed image of the sample and to analyze the distribution of BaTiO3 and PEGDA particles.

III. RESULTS

A. Laser Doppler Vibrometer Results

The measurements obtained using laser Doppler vibrometer method showed that the 3D printed samples presented in this paper behave as thin plates. Two models exist in the literature to predict the modes of vibration of circular thin layers. The model of a membrane considers a thin layer only dependent on tension, while the model of the plate is only dependent on stiffness. Furthermore, a membrane resonance frequency is inversely proportional to its thickness, while a plate is directly proportional to it [26]. While fabricating the samples, it become clear that a thicker sample had a higher resonance frequency and therefore a thin plate model was chosen (see Eq. 7). As shown in Figure 7a for PEGDA 250 and in Figure 7b for PEGDA 700, it can be clearly seen that the plates present several modes of vibration, both radial and circular modes. It is possible to predict the frequency of the modes of vibration of a circular plate as reported in [26], where modes (1,1) and (0,2) are predicted to be respectively 2.091 and 3.909 times higher than mode (0,1). The 3D printed plates present all the modes of vibrations predicted by [26] and their frequencies are in good agreement with those predicted in the literature.

Table I shows the average resonance frequency for the two types of PEGDA samples. These values were useful while modeling the plates with the transfer matrix method, as they were used as initial guess to initiate the optimization procedure to retrieve the other parameters.

![Image](https://via.placeholder.com/150)

**Figure 7.** Modes (0,1), (1,1), (0,2), (0,3) for the PEGDA 250 sample (a). Modes (0,1), (1,1), (0,2), (1,2) for the PEGDA 700 sample (b).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>PEGDA 250</th>
<th>PEGDA 700</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$ (0,1)</td>
<td>Fundamental frequency (Hz)</td>
<td>940</td>
<td>400</td>
</tr>
<tr>
<td>(1,1)</td>
<td>First radial mode (Hz)</td>
<td>1500</td>
<td>1070</td>
</tr>
<tr>
<td>(0,2)</td>
<td>First circular mode (Hz)</td>
<td>2300</td>
<td>1530</td>
</tr>
</tbody>
</table>

Values of fundamental frequency and first circular and radial modes for samples of PEGDA 250 and PEGDA 700 having a 15 mm diameter.

B. Impedance Tube Results

The transmission and reflection coefficients were first retrieved through impedance tube measurements and are represented respectively by the solid magenta and green lines in Figure 8 for PEGDA 250 (a) and 700 (b). The same coefficients together with absorption were then retrieved using the transfer matrix model and initialized using the values given by laser Doppler vibrometer for the resonance frequency and by vendors data sheets and literature values for density, Young’s modulus, Poisson’s ratio and loss factor. To minimize the difference between transmission, reflection and absorption coefficients obtained experimentally with those obtained analytically, the
values of density, Young’s modulus, Poisson’s ratio and loss factor assumed at the modeling stage where changed iteratively during an optimization process, until the modeled coefficients graph in Figure 8 fit into the graph representing the experimental coefficients. Therefore, the density, Young’s modulus, Poisson’s ratio, loss factor and fundamental frequency listed in Table II. The differences between the values of fundamental frequency given by laser vibrometer and the impedance tube approach might be due to the differences in samples preparation. In the first case, the plate is in the free field and its support is glued to a piece of glass. Hence, a tiny volume of air is created between the plate and the support. In the second case, there is no enclosed volume of air underneath the plate, which is in a tube instead than the free field. The values retrieved through LDV measurements should therefore be used just as initial values for our model and to show the presence of the modes in the plates. Figure 8 shows that the plates fabricated in this work would be suitable for acoustic metamaterials applications. In fact, both kinds of samples show a high reflection coefficient hence low transmission before the first mode of resonance, which corresponds to a region of negative effective density [16], [31], [32].

C. Nanoindentation Results

Nanoindentation measurements were gathered on both top and bottom sides of the samples. By looking at Figure 9, it can be seen that the particles distribution is different on the two sides of the plate. The bottom side tends to contain more BaTiO3 particles than the top side. Therefore, two different values for the Young’s Modulus of both PEGDA 250 and PEGDA 700 samples were retrieved, as outlined in Table III. This non-homogeneous distribution of particles in the plate can possibly explain the different values of Young’s modulus given by nanoindentation and retrieved through impedance tube measurements. Since the tip used for nanoindentation is small in comparison to the dimension of the particles of PEGDA and BaTiO3 in the plate, it can be inferred that, for this specific type of plates, impedance tube measurements are more reliable than nanoindentation. Moreover, the sample required for nanoindentation must be small and cut from the support, hence possibly eliminating the small stress that the plate could have received while being attached to the support during the 3D printing process. This sample preparation process could cause a modification of the physical properties of the plate. Therefore, in future designs containing these plates, the results from impedance tube measurements will be preferred when modeling the system.
preferred, in that the tip is very small and could randomly sample a part of the plate where BaTiO3 is not present. The obtained physical parameters will be integrated in future designs where the plates will be incorporated in more complicated structures. The fabrication technique presented in this paper could be scaled to cover different frequency ranges and for larger structures, for example to attenuate noise in the field of aerospace and other transportation industries. Nevertheless, this specific design would be more suitable for small-scale applications, such as headphones, smart speakers and other electroacoustic devices.

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Cecilia Casarini (S’17) is a PhD student in Electronic & Electrical Engineering within the Centre for Ultrasonic Engineering at the University of Strathclyde in Glasgow, UK. Her doctoral research focuses on 3D printed acoustic metamaterials for applications to noise and sound control in electroacoustic devices such as hearing aids and headphones. In 2018 she was a Senior Audio and Acoustic Engineering Intern in the Acoustics Hardware team at Apple, Inc. in Cupertino, CA. She received a MSc degree in Acoustics and Music Technology in 2016 at the University of Edinburgh, UK.

Vicente Romero-García is CNRS researcher at the Acoustic Laboratory of Le Mans University (LAUM, UMR CNRS 6613) since 2014. His research interests cover a wide range of subjects in wave physics. In particular wave propagation in periodic media as phononic and sonic crystals, random media, complex structures as well as acoustic metamaterials, and metasurfaces.

Jean-Philippe Groby is CNRS researcher at the Acoustic Laboratory of Le Mans University (LAUM, UMR CNRS 6613) since 2009. His research interests cover the design, characterization and application of complex structures for the control of audible sound, e.g. metamaterials, meta surfaces, and metafluid.

Benjamin Tiller is a Postdoctoral researcher in the Department of Electronic and Electrical Engineering at the University of Strathclyde, Glasgow, United Kingdom. He graduated from the University of Nottingham with an MSc degree in Physics and then received his PhD degree in Biomedical Engineering from University of Glasgow in 2016. His PhD research focused on the Physics of acoustic streaming in microfluidic channels, and phononic sensors. His current research interests focus on 3D printing of functional materials and novel acoustic sensors and hearing systems. His research also covers such as the physical basis for various engineering application topics.

James F. C. Windmill (M’99-SM’17) is a Professor in the Department of Electronic and Electrical Engineering at the University of Strathclyde, Glasgow, United Kingdom. He has over 18 years of research and development experience in the areas of sensors and hearing systems. His research interests are in the field of biologically-inspired acoustic systems, from the fundamental biology to hearing, sound production and reception in biology and bio-inspired transducer design. 

Joseph C. Jackson is a Lecturer in Electronic and Electrical Engineering at the University of Strathclyde, based in the Centre for Ultrasonic Engineering. His research interests cover a wide range of subjects, such as the physical basis for