Characterization of Membrane-Type Acoustic Metamaterial Unit Cells Fabricated by Additive Manufacturing Methods

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ABSTRACT

Membrane-type acoustic metamaterials fall into the category of metamaterials with locally resonant behavior. Adjusting the unit cell properties brings the opportunity to tune resonance/anti-resonance frequencies. Moreover, noise attenuation might be achieved in the desired frequency range using artificially engineered lightweight structures. Conventional methods for the realization of membrane-type acoustic metamaterials cause such uncertainties on the fundamental parameters: positioning and shape limitation of the masses and adjustment of membrane pre-stress. Subsequently, those methods are time-consuming considering large-scale structure fabrication. Additive manufacturing approaches minimize the side effects caused by conventional methods with a repeatable and robust process. In this research, various membrane-type acoustic metamaterial unit cells are manufactured using multi-material printing via the fused deposition modeling (FDM) method. Flexible (TPU) filament is used for the membrane, while relatively rigid filament (PETG) is chosen for the frame and the masses. Initially, the unloaded unit cells are examined in order to evaluate 3-D printed membrane pre-stress and repeatability of the fabrication approach. Afterwards, the effects of membrane and mass properties on the sound transmission loss (STL) behaviors of the unit cells are investigated using an impedance tube in order to implement in multi-celled membrane-type acoustic metamaterials.

Keywords: *Membrane-type Acoustic Metamaterial, Fused Deposition Modeling, Sound Transmission Loss*

1. INTRODUCTION

Nowadays, humans are exposed to different kinds of sound emitted from various sources from the surroundings. Although there are willful and pleasant sound sources (concerts, conversations, etc.) among those, considering the sound such as in an aircraft or any vehicles on the ground often is annoying and unwanted, that is what we refer to as noise. Noise reduces the quality of life of people continuously exposed to it and this causes serious health problems [1]. Regarding these issues, avoiding the pollution caused by noise and minimizing its detrimental effects have been emerging topics for research in the past.

The attenuation of low- and mid-frequency (≤1000 Hz) sound in lightweight structures as used in the above-mentioned applications has been challenging for decades since due to the limitation with respect to the mass-frequency law (Eqn.1) conventional acoustic materials such as foams or sound panels are not feasible [2].

$$\text{Sound Transmission Loss} = 10\log\left(\frac{\pi f \rho_s}{\rho_0 c_0}\right)^2 \text{dB} \qquad (1)$$

In the equation, f represents the frequency in Hz, ρ_s is the surface density of the partition and ρ_0 and c_0 are surrounded fluid density and speed of sound in the fluid, respectively.

As can be seen from Equation 1, doubling the partition thickness leads to 6 dB increase in sound transmission loss. Moreover, in the presence of lightweight restrictions, innovative approaches have emerged to overcome low-mid frequency sound reduction [3].

Metamaterials are kind of artificially engineered composite structures for desired properties to achieve extraordinary material characteristics which are not found in nature. Thanks to this form of material, acoustic metamaterials propose to break the mass-frequency law and be able to

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manipulate the acoustic characteristics of materials. Membrane-type acoustic metamaterials (M-AMM) are one of these concepts with locally resonant properties [1,3-7].

In the previous researches, membrane-type acoustic metamaterials were manufactured using conventional -in other words hand-made- methods [1, 3-7] which might be inefficient considering the gluing of all the parts or using self-adhesive materials [1, 3-7], positioning the mass correctly each time and adjusting the membrane tension robustly. In addition, the attached mass structure strongly affects the STL properties of the unit cell of M-AMMs [1,3-7]. Conventional methods are suitable for mass production only in commercially available magnitudes and shapes. Therefore, it is not possible to use mass in the required dimensions. For this reason, it may not be easy to obtain tunability at desired frequencies.

To overcome these limitations and obtain robustly manufactured metamaterials, additive manufacturing methods might be used for fabricating the membrane-type structures via multi-material printing. In this way, side effects can be minimized, and fine-tuned anti-resonance properties might be obtained with a quick and repeatable process.

This research is mainly encouraged by the limited sources in the literature on the realization and experimental analysis of M-AMM. For this purpose, various membrane-type acoustic metamaterial unit cells were printed using a multi-material printing approach for experimental characterization of the sound transmission loss properties. Whereas the total masses remained stable for each unit cell, the mass distribution was changed to investigate the STL behavior of the membrane-type unit cells.

2. MATERIALS AND METHODS

2.1 Unit cell fabrication

In order to minimize the side effects of conventional methods, new fabrication approaches have emerged for both implementation points of view of membrane-type acoustic metamaterials and widening their application area. For this purpose, an additive manufacturing method, Fused Deposition Modeling (FDM), is used via the Original Prusa i3 MK3S+ 3-D printer that allows multi-material printing.

To obtain elastic properties in the membrane structures a flexible thermoplastic polyurethane (TPU) (Ninjaflex 85A) filament, and for the frame and the mass parts, a relatively rigid filament, Polyethylene Terephthalate Glycol Copolymer (PETG) (Prusament PETG), are used for fabrication process of the unit cells (Fig. 1 (a)). All the parts mentioned above are printed in a one-shot process. Also, a secondary structure (Cap) (Fig. 1 (b)) is designed and printed using PETG filament to keep the pre-stress distribution stable along the membrane surface and both parts are parts are assembled via commercially available lightweight polyamide (PA) bolts and nuts.

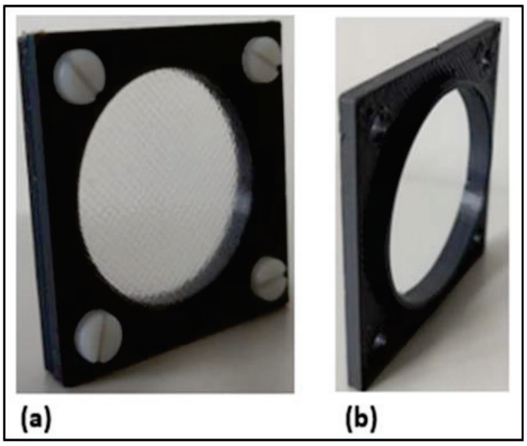

Figure 1. (a) unloaded unit cell (UC_0); (b) cap structure.

The physical properties of the unit cells are given in Table 1. Whereas the magnitude of the printed masses is kept constant as 0.4 g by means of manipulating volume of the masses, configurations of the unit cells are given in Figure 2.

Table 1. Physical properties of the unit cell components.

Parameter	Dimension (mm)
Membrane Thickness	0.1
Membrane Diameter	30
Frame Thickness	2.8
Frame Length	36
Frame Width	36
Hole Diameters	3
Cap Height	1.7
Cap Width	1

2.2 Unit cell characterization

Initially, unloaded membrane-type acoustic metamaterial unit cells (UC_0) are fabricated and measured via a sample holder (fits into the impedance tube to keep the boundary conditions stationary) using an impedance tube (AcoustiTube®) to characterize the dynamic behavior under the bandlimited white noise excitation. The first resonance frequencies of the samples are extracted to evaluate the pre-stress -which is also identified as a crucial parameter for the

M-AMMs [1]- of the membranes and calculated for fixed rim using Equation 2 [2].

$$f_{0,1} = \frac{J_{0,1}}{\pi D} \times \sqrt{\frac{\sigma_0}{\rho}}\ \text{Hz} \tag{2}$$

Where $f_{0,1}$ is the measured first resonance frequency (for the fundamental mode (0,1)), ρ is density of the membrane with the diameter D under the stress σ_0 while $J_{0,1}$ is zero value for Bessel function for the first nodal circle (0,1) that is 2.40 [2].

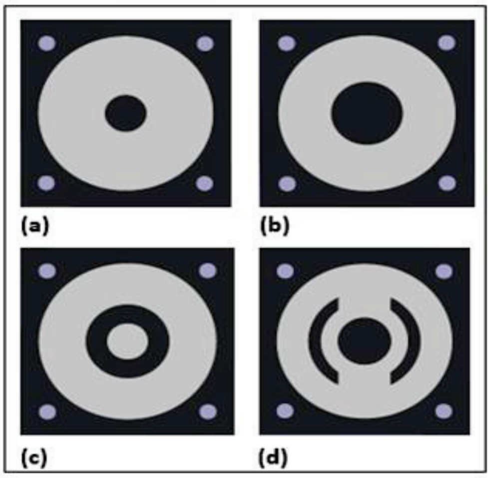

Figure 2. Unit cells: (a) UC_1 with 7 mm dimeter mass; (b) UC_2 with 12 mm diameter mass; (c) UC_3 with 14 mm inner mm and 7 mm outer diameters mass; (d) UC_4 with a central mass and two identically divided arc masses.

To determine the sound transmission loss characteristics of the M-AMMs, the Two Load Method [8] is performed on the printed samples via Ø100 mm diameter standard impedance tube (AcoustiTube®) using four microphones and the results are post-processed in the measurement software AED 1401.

3. RESULTS

Regarding the repeatability of the fabrication using additive manufacturing via multi-material printing approach, five unloaded unit cells (UC_0) are printed individually and analyzed using the impedance tube. The results demonstrated in Fig. 3 show that the curves of the unloaded unit cells show a nearly similar tendency around 750 Hz that is the first resonance frequency. In addition, tension of the membrane structures calculated using Eqn. 2 and values are given in Fig. 4. According to results, less than 10% variation is observed between the unloaded unit cells pre-stress values.

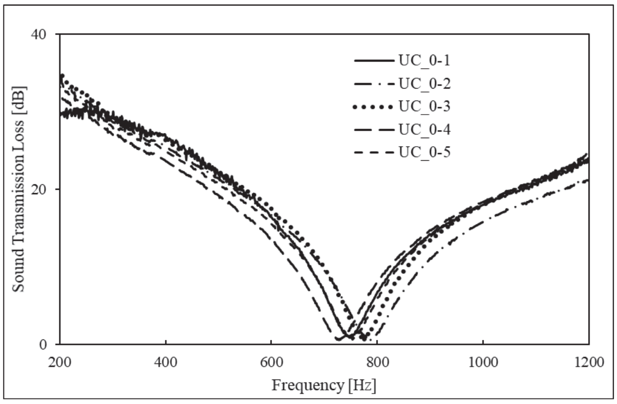

Figure 3. The curves of UC_0 samples under the bandlimited white noise excitation.

In order to investigate the mass effect on the transmission loss characteristics, four different unit cell configurations with same mass magnitudes are printed and measured. At a glance at Fig. 5, each unit cell shows particular acoustic behavior due to the mass shape and distribution on the membrane. When comparing UC_1 and UC_2, it observed that increasing the diameter of the central mass shifts the transmission loss peak and the resonance frequencies to higher values as also proven by Naify et. al. [5]. Instead of a cylindrical shape mass, the effect of a ring mass analyzed using UC_3, and the peak and dip frequencies alters to higher values [6]. Moreover, in UC_4, in the presence of additional masses on the membrane, extraordinary transmission loss peaks and dip frequencies are observed [6,7].

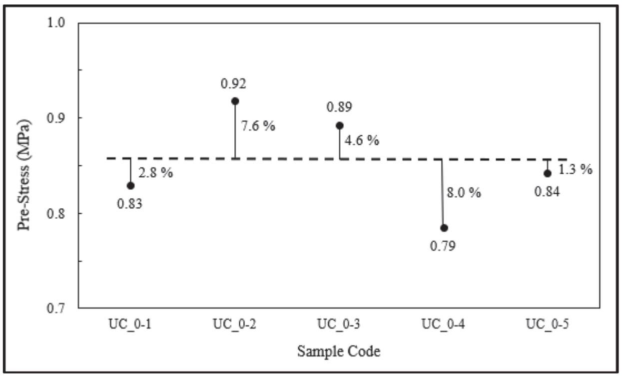

Figure 4. Calculated pre-stress values of UC_0 samples

4. CONCULUSION

In this work, as the main object to fabricate the membrane-type acoustic metamaterial using additive approaches to avoid the side effects and inefficiencies of conventional methods, frame, and membrane components are manufactured using multi-material printing in a one-shot process. According to the results obtained by impedance tube measurements, repeatability of the approach is discussed. In order to minimize the deviation in pre-stress, optimization of the printing process might be implemented and installation of the cap structure carried through a controllable tool during the mounting. Afterward, the transmission loss behavior of the samples that possess the masses directly printed on the membrane structure with the same magnitude are investigated. Measurement results show that manipulating the sound in desired frequency, various configurations might be selected while keeping the total weight constant. In addition, the fabrication of membrane-type acoustic metamaterial via additive approaches will allow further unit cell designs and metamaterial realization for structures with multiple unit cells.

5. ACKNOWLEDGEMENTS

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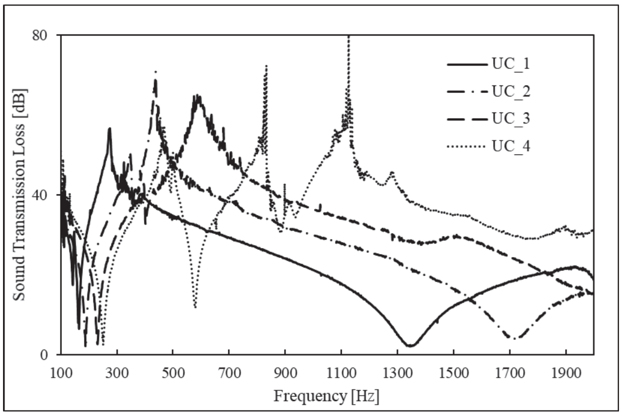

Figure 5. Effects of the mass shape and distribution on the transmission loss behavior of the unit cells.

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