# 3D printed acoustic metamaterial sound absorbers using functionally-graded sonic crystals

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**Summary**
Acoustic metamaterials have been utilized in recent years to achieve extreme acoustic properties, which have enabled enhanced acoustic characteristics and performance beyond the bounds of traditional materials. In this paper, a thin functionally-graded acoustic metamaterial sound absorber is presented and discussed. In this paper, it is shown that the proposed design can attain an absorption coefficient near unity, which implies that the acoustic metamaterial sound absorber must simultaneously possess near zero reflectance and transmittance over a given frequency band. To achieve this, the acoustic metamaterial structure consists of a multilayer arrangement of an interwoven sonic crystal lattice with varying filling fractions, backed by a thin elastic coating that acts as a flexural acoustic element. The overall thickness of the sound absorber is about one tenth of the wavelength in air, and it was fabricated using additive manufacturing (3D printing) with a thermoplastic polyurethane (TPU). Samples were fabricated and acoustically tested in an air-filled acoustic impedance tube to determine absorption and effective acoustic properties. A theoretical formulation for the effective acoustic properties of the interwoven sonic crystal lattice was used to guide the design process, and good agreement was found between measured and theoretically predicted results. A range of filling fractions and thicknesses were tested to verify the fabrication process and robustness of the modeling, and both were found to be in excellent agreement.

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## 1. Introduction

Acoustic metamaterials have been the subject of significant interest, and over the last decade extraordinary effective physical characteristics beyond those of traditional materials have been demonstrated, such as negative dynamic mass density and bulk modulus. Through the realization of such properties, acoustic metamaterials and fluid-like acoustic metafluids enable exotic acoustic wave phenomena including near-zero phase speed (slow sound) and negative phase speed (i.e. backwards traveling) propagating waves [1, 2]. Acoustic metamaterials and metafluids are able to achieve such previously unattainable exotic properties through the careful design of the microstructure, which create microscale dynamics that result in the desired macroscopic properties. In most applications, the presence of losses in acoustic metamaterials and metafluids has been seen as a detriment to the design. However, acoustic waves in fluids such as air have inherent losses due to thermoviscous effects, and are a necessary aspect of absorbing acoustic energy.

In this work, structured acoustic metafluids based on interwoven perpendicular arrangements of cylinders which act as sonic crystals are utilized as a highly effective and adaptable sound absorber. To realize the proposed metafluid and achieve a versatile design process, 3D printed thermoplastic polyurethane (TPU) with the tradename of NinjaFlex is used to fabricate the structure. The NinjaFlex TPU enables precise lattices of rods to be arranged in repeatable manner, while enabling functional grading in the sonic crystal arrangement and very high filling fractions to be

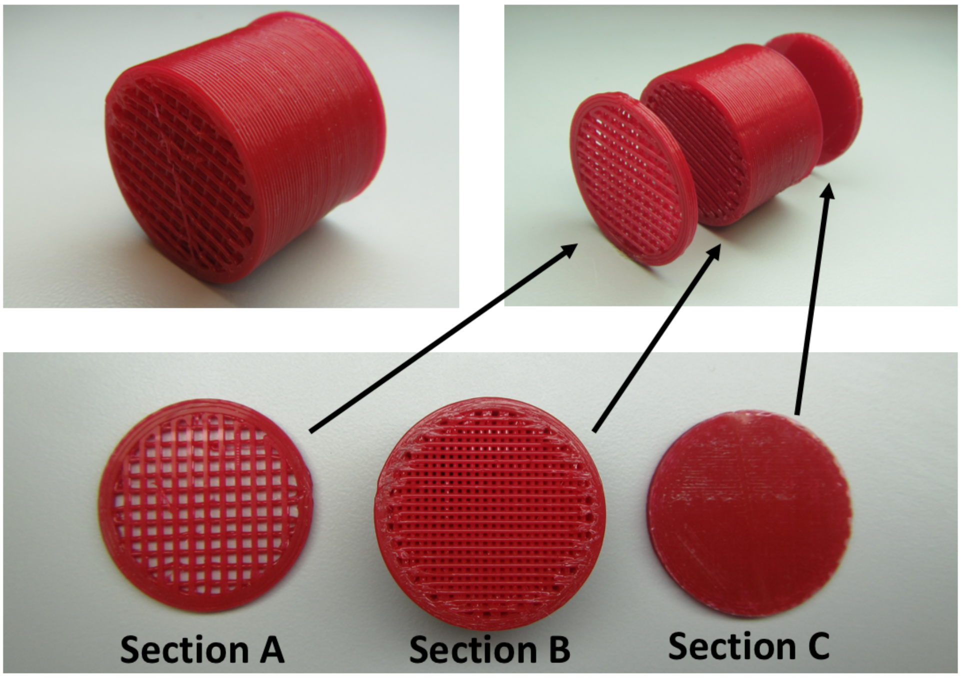


Figure 1. Compact 3D printed TPU metamaterial sound absorber, consisting of 3 sections. Sections A and B are sonic crystal arrangements with filling fractions of 20% and 40%, respectively, and Section C is a flexural element made from solid TPU.

achieved. Furthermore, unlike many other commercially available 3D printed materials, the TPU arrangement can be printed without the need for additional support material, which is an important consideration due to the intricate structure and small feature sizes of the metafluid.

## 2. Design and Formulation

The design for the proposed sound absorber is based on a layered sonic crystal structure, and is shown in Fig. 1. The theoretical formulation for this was first explored by Guild *et al.* [3], as well as experimental aspects that affect the thermal and viscous boundary layers, and therefore the predicted absorption. In the previous work, a key finding was that a structured sonic crystal lattice offered significantly higher absorption due to the extremely close arrangement (high filling fractions) that are achievable compared with randomly oriented fibrous sound absorbers. While this previous work demonstrated excellent agreement between model and experiment, the overall small size of the test samples and inherent impedance mismatch lead to high broadband intrinsic absorption but only achieved an absorption coefficient of about 0.5.

Here, new fabrication and design approaches are explored, and a demonstrative case is shown, achieving a subwavelength absorber with an absorption coefficient near unity. This is accompolished by a combination of acoustic metafluid and metamaterial elements, namely multiple filling fractions of sonic crystal lattices and a flexural acoustic metamaterial element. The absorption coefficient, $\alpha$, for a slab of material is given by [4]

$$\alpha = 1 - R^2 - T^2, \tag{1}$$

where $R$ and $T$ are the reflected and transmitted pressure coefficients, and $R^2$ and $T^2$ are referred to as the reflectance and transmittance, respectively. From this equation it is clear that unity absorption coefficient occurs when both the reflected and transmitted pressure magnitudes become zero. To achieve this, two types of metastructures are used: (1) a sonic crystal (metafluid), with low effective sound speed and high intrinsic absorption [3], and (2) a flexural acoustic metamaterial element which exhibits high transmission loss (TL) [5]. Through this combination, the transmission is blocked by the flexural element, and absorbed over a subwavelength space by the sonic crystal. The reflected wave is driven to zero by a quarter wave thickness design of the lossy sonic crystal

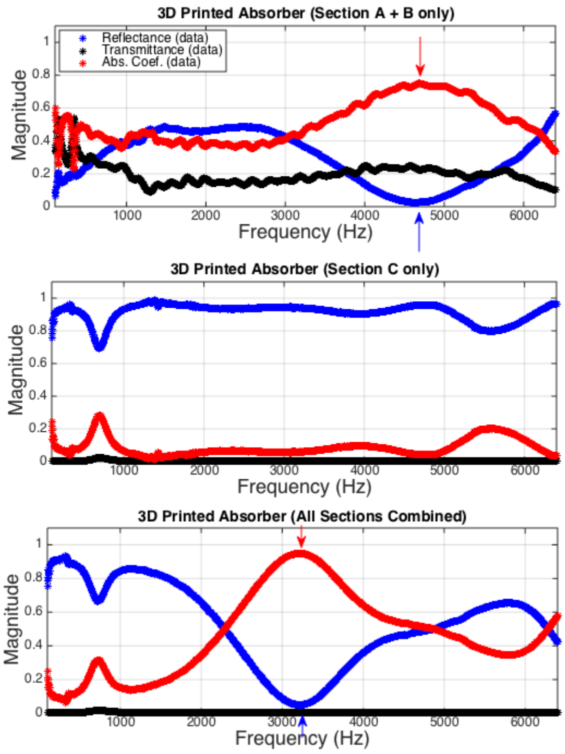


Figure 2. Measured reflectance, transmittance and absorption coefficients for 3D printed samples, for (top) Sections A + B, (middle) Section C and (bottom) Sections A, B and C combined.

structure. Since the sonic crystals have higher density and lower sound speed than the surrounding fluid (air), the overall acoustic impedance difference compared with air is minimal, which leads to the broadband nature of the absorption observed. Furthermore, the low sound speed relative to air enables a compact design that is highly absorptive and broadband but subwavelength in size.

## 3. Experimental Results

A notional absorber sample is shown in Fig. 1. The absorber contains 3 sections, as illustrated in the figure: section A, which is 0.2 cm thick and has a filling fraction of 20% TPU; section B, which is 2 cm thick and a filling fraction of 40% TPU, and section C, the flexural element which is 0.2 cm and is solid TPU (100% filling fraction). In each case, the nominal radius of the TPU cylinders is about 200 $\mu$m. The samples were made out of NinjaFlex TPU and fabricated using fused deposition modeling (FDM) technique with a Hyrel 30M Multihead Printer. In addition to the multilayer sample (containing Sections A, B and C), a sample of each individual section was fabricated and tested.

The acoustic measurements of the 3D printed TPU were performed using an air-filled Brüel & Kjær acoustic impedance tube. The acoustic impedance tube consisted of a circular metal tube having an inner diameter of 29 mm in which the 3D printed samples were tested. The experiment was performed using a 4-microphone configuration [6] to determine the magnitude and phase of reflection and transmission coefficients for a given sample for frequencies up to 6400 Hz. In addition to the reflectance and transmittance show in Fig. 2, the real and imaginary effective acoustic properties of the samples were determined from direct measurement of the complex-valued acoustic impedance and wavenumber, and provided a basis for comparison between the acoustic metafluid theoretical models and experimental impedance tube data.

The measured data of reflectance (blue), transmittance (black) and absorption coefficient (red) from the 3D printed samples are shown as a function of input frequency in Fig. 2. In the top panel, the two-part sonic crystal arrangement is shown, consisting of Sections A and B. For this case, there is moderate absorption, with low but consistent transmittance and a varying level of reflectance. The peak in the absorption coefficient corresponds to a minimum in the reflectance, and is denoted by the red arrow. This point corresponds to where the thickness of the sample is equal to half of an acoustic wavelength inside the absorber (though the sample length is only about one-third of a wavelength relative to the surrounding air). The data from the flexural metamaterial element, Section C, is shown in the middle panel of Fig. 2. From this data, a flexural resonance is observed around 700 Hz leading to a local decrease in the reflectance (increase in the transmittance), but otherwise the sample leads to a very large reflectance and negligible transmittance across the rest of the frequency band. The bottom panel of Fig. 2 show the case where Sections A, B and C are combined together into a single absorber. Although the total thickness is only 2.4 cm, the flexural element (Section C) ensures no transmission while the metafluid structure (Sections A and B) leads to a reflectance near zero, and therefore absorption near unity, which is denoted by the arrows. Due to the reflective (nearly sound hard) boundary condition from the flexural element, the absorption peak occurs where the thickness is equal to one-quarter of a wavelength within the absorber (instead of half a wavelength in the top panel). Therefore, for nearly the same thickness absorber, there is an increase in the absorption coefficient to 0.95, occurring a lower frequency.

## 4. CONCLUSIONS

This work has reported experimental results based on a theoretical formulation and multilayer acoustic metafluid and metamaterial design, which achieves an absorption coefficient of 0.95 with an absorber that is less than a quarter of a wavelength thick compared with the surrounding air. The design is based on sonic crystals with filling fractions much larger than traditional porous absorbers, paired with a thin, lightweight but reflective backing made from a flexural acoustic metamaterial element. Samples were fabricated using a commercially available 3D printer, using a flexible and durable TPU. Compared with traditional acoustic absorbers, this work presents a novel design for creating compact, highly effective acoustic absorbers. By using 3D printing and controlling the filling fraction of the sonic crystals, a wide design space is possible, and the process is both repeatable and scaleable to sizes of interest to the architectural and noise control communities.

## Acknowledgement

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