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ADDITIVE MANUFACTURE OF FLEXIBLE LATTICE ABSORBERS FOR ENHANCED LOW FREQUENCY PERFORMANCE

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ABSTRACT

Traditionally porous materials have been used to mitigate a range of noise problems with excellent performance in the mid to high-frequency range, but these materials struggle to attenuate low frequencies. Recently, additive manufacturing (AM), including stereolithography (SLA), has enabled the fabrication of engineered porous structures that can create tuneable acoustic materials. This research focuses on the further development of flexible lattice structures, with inclusions that can add local resonances as an additional dissipation mechanism. This study systematically designs, manufactures, and tests flexible lattice absorbers for low-frequency noise control. By controlling the print parameters and lattice geometry, the acoustic properties can be varied and evaluated through impedance tube testing. Numerical modelling is utilised to iteratively manufacture an optimised flexible lattice structure for low-frequency sound absorption. This study focuses on refining the relationship between printing parameters and acoustic properties to enhance sound absorption while also maintaining structural integrity. These flexible lattice structures provide a tuneable lightweight solution for low-frequency sound absorption while also progressing the fabrication process of engineered porous materials. This offers a novel solution that helps to broaden the scope of engineered porous materials, benefiting the field of noise control.

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1. INTRODUCTION

Noise pollution is a growing concern in urban and industrial environments, as exposure to excessive levels can lead to hearing impairment, psychophysiological distress, and cardiovascular diseases [1]. While mid to high-frequency noise is well addressed by conventional materials, low-frequency noise has remained difficult to attenuate [2]. This highlights the need for new engineered noise control solutions to innovate and solve these low-frequency issues. Engineered porous materials are a new area of study, made possible by the significant improvements in computing power and manufacturing techniques, which allow these complex shapes to be fabricated more easily [3]. Lattice structures have demonstrated potential for sound absorption similar to that of traditional materials but can allow increased tuneability by controlling their geometric parameters [4, 5]. The lattice structure attenuates the noise through viscous and thermal dissipation. This has been shown to be similar to traditional foam materials, with higher broadband absorption and shallow resonance peaks [3]. Tuned Helmholtz resonators (HR) can provide low-frequency noise absorption and can have high attenuation peaks, but they suffer from a narrow frequency range [6].

This work combines lattices for acoustic absorption with embedded resonators using a flexible material and demonstrates a new potential for noise control materials. This complex geometry has been enabled through increases to computational power required for both design and modelling. Additionally due to the introduction of low-cost commercial 3D printers, such a structure is becoming more readily manufacturable at industrial scales. With the use of SLA, the two designs are merged to enable a single-step manufacturing process that incorporates tunable broadband and peak absorption, utilising local resonances through the embedded HR's. This combination allows for low-frequency noise absorption, while also maintaining broadband absorption at the mid and high frequencies of traditional materials. The use of a flexible material can allow for these lattices to be contoured and bent to fit a chosen profile under space constraints. The use of SLA allows for the flexible and precise lattice-Helmholtz resonators to be fabricated in a single step, and subsequently tested using ISO 10543-2 standard impedance tube testing to examine the noise absorption performance.

2. METHODOLOGY

The lattice structure's design was based on a Kelvin cell geometry for its isotropic and energy-absorbing qualities while remaining relatively simple to fabricate [5, 7]. The lattice parameters were determined using LattSAC, which is a software for the acoustic modelling of lattice sound absorbers [8]. The final design parameters included a cell size of 4.25 mm and a strut width of 0.66 mm. These values provided a good balance between what the LattSAC software could simulate, manufacturability, and testable acoustic properties. The HR design was based on Eqn. (1) [9]. The correction factor δ_R is $0.849r$, where r is the neck radius, and is based on the Rayleigh equation for the resonance frequency of a HR.

$$f = \frac{c}{2\pi}\sqrt{\frac{A_0}{V\left(l_0 + 2\,\delta_R\right)}}. \tag{1}$$

This was used to design both embedded HR's. The parameters used and the resulting resonance frequency can be seen in Tab. 1. The three final designs can be seen in figure Fig. 1 below, with a section view to show the embedded HR. The design features, (a) Bare Lattice, (b) Helmholtz resonator set at the middle for a low resonant frequency (LHL), and (c) Helmholtz resonator lowered to the bottom for a mid-resonant frequency (MHL).

The hexagonal shape of the unit structures was chosen for space-saving reasons and it allowed units to be easily combined in different arrangements. The dimensions for the individual hexagons were 50.95 mm tall and 33.43 mm from flat side to flat side. The included partition that created the HR was 1 mm with the neck wall

Table 1: Helmholtz Resonators Equation Parameters

Parameter	**Large**	**Small**
Neck area, A_0 (m^2)	$1.96{\times}10^{-5}$	$2.83{\times}10^{-5}$
Cavity volume, V (m^3)	$1.75{\times}10^{-5}$	$1.70{\times}10^{-6}$
Neck length, l_0 (m)	$5{\times}10^{-3}$	$3{\times}10^{-3}$
Neck radius, r (m)	$5{\times}10^{-3}$	$6{\times}10^{-3}$
Res. frequency (Hz)	**601**	**2480**

thickness being 0.75 mm, this is highlighted in red in figure Fig. 1. Both experimental tests included a PLA holder that fit tightly around the hexagonal design and into the respective impedance tube. The large holder could accommodate seven hexagons and the smaller could fit a single unit.

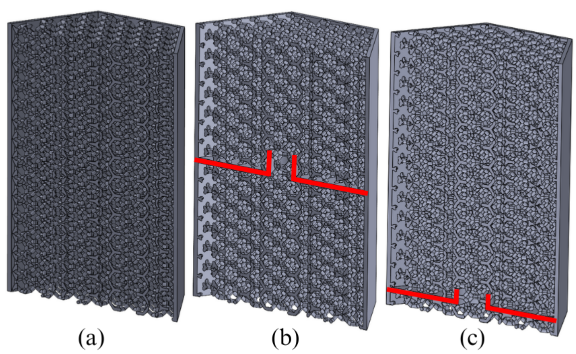

Figure 1: CAD designs, (a) Bare Lattice, (b) Low-Frequency Helmholtz-Lattice (LHL), (c) Mid-Frequency Helmholtz-Lattice (MHL)

The samples were made from Prusa Flex 80A and printed on a Prusa SL1S Speed. The relevant printing parameters for reliable fabrication can be seen in Tab. 2. These were the necessary changes from the default Prusa print settings. In total, 17 samples were made, seven Bare Lattices, seven LHL's, and three MHL's. This was to allow a mixture of the Bare Lattice and LHL designs to be tested in the larger impedance tube.

Absorption measurements were conducted in accordance with ISO 10534-2 using two impedance tubes, one low-frequency (50-1500 Hz), and one high-frequency (300-4500 Hz). The two tubes had respective internal diameters of 127 mm and 40 mm, where the schematic can be seen in Fig. 2. Acoustic measurements were taken using GRAS 40PH microphones (50 Hz - 5 kHz, ± 1.5

Table 2: Print Parameters

Parameter	Value
Layer height	0.05 mm
Exposure time	4 s
Initial exposure time	32 s
Support	Build plate only
– Pillar diameter	1.7 mm
– Base diameter	3.7 mm
– Base height	1.7 mm

dB). A National instruments DAQ, amplifier, and MATLAB GUI controlled the system. For sample testing in the high-frequency tube, each sample design was fabricated three times and tested three times, totalling to nine results per design. This ensured repeatability and reproducibility within the designs. The low-frequency tube tests, because they consisted of seven single samples, were tested three times to obtain an average.

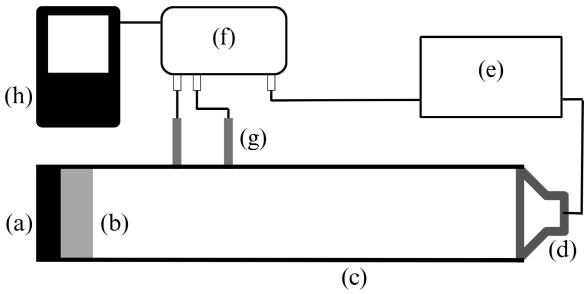

Figure 2: Impedance tube schematic (a) Hard end, (b) Sample, (c) Impedance tube, (d) Speaker, (e) Amplifier, (f) Data acquisition system, (g) Microphones, (h) Computer

3. RESULTS AND DISCUSSION

Fig. 3 shows the predicted absorption coefficients from the LattSAC model. The Bare Lattice (black line) shows 2 peaks at 1500 Hz and 4100 Hz, with absorption coefficients of 0.44 and 0.61 respectively. Once a HR is embedded in the lattice the effective thickness is reduced to the distance from the resonator division to the top of the sample. The two coloured dashed lines are calculated based on this reduced lattice thickness from Fig. 1. These thicknesses are 50% and 94% thickness of the LHL and MHL designs. As expected, the 94% lattice (MHL) is very similar to the bare design, with a small lowering and shift to

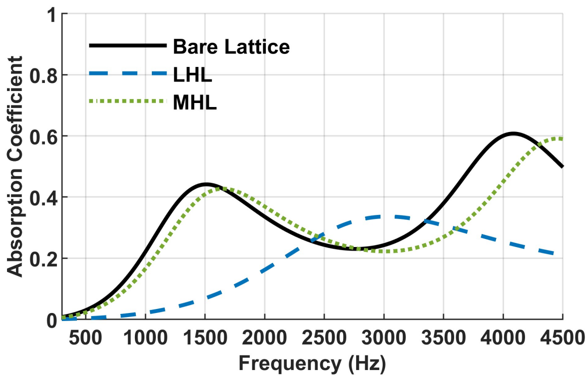

Figure 3: LattSAC numerical absorption coefficient tests

the right, due to the small decrease in available lattice. The 50% lattice (LHL) has its peak lowered to 0.34 and shifted considerably to the right at 3000 Hz.

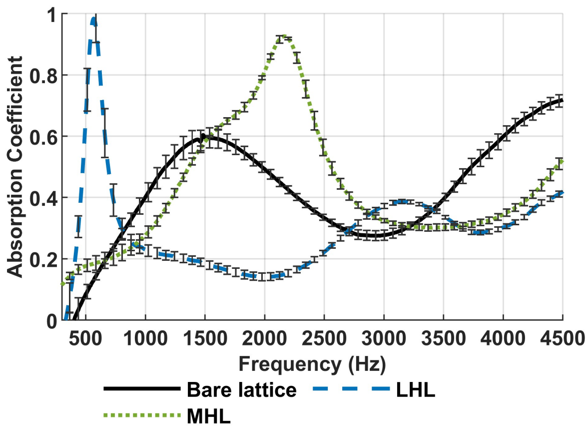

Figure 4: High-frequency impedance tube tests

Fig. 4 shows experimental results from the designs in Fig. 1. The bare lattice matched the LattSAC model with a peak absorption at 1500 Hz but has increased the absorption coefficient to 0.6. This is likely due to LattSAC's inability to take into account surface roughness which will increase the peak absorption [10, 11]. The MHL (green dotted) curve showed a similar peak shift to the right at the beginning. Then the peak from the HR occurs at 2170 Hz with an absorption coefficient of 0.92. This is lower than analytically expected due to the reduced accuracy of the Helmholtz model at higher frequencies. The LHL (dashed blue) curve showed an excellent absorption at 570 Hz with a peak absorption of 0.98. This aligned well with both the analytical and LattSAC models, with its lattice-only portion showing a peak at 3150 Hz and an absorption of 0.39.

Fig. 5 presents four tests where seven individual samples were configured as an array in a PLA holder. An example design of 4 LHL - 3 Bare Lattice can be seen within the figure. The Bare Lattice design (black line) matched well with the single test and LattSac by showing a rising peak up to around 1400 Hz. The LHL (blue dashed) curve agreed with the individual tests and had a peak of absorption of 0.91 at 570 Hz. The other two tests consisted of a blended array of the Bare lattice and LHL designs. The 4 LHL - 3 Bare Lattice array showed a lower peak at 560 Hz but maintained absorption above 0.43 over the 800 Hz to 1400 Hz range due to the increased lattice content. The standalone LHL design did not exceed 0.2 in the same range. To confirm this, the 3 LHL - 4 Bare Lattice array was also tested, which had a lower Helmholtz peak, as expected.

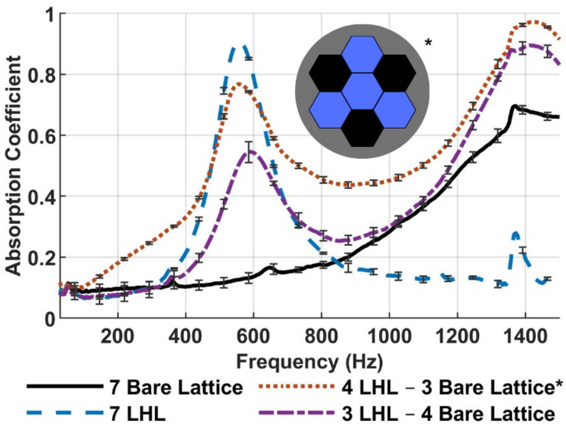

Figure 5: Low-frequency impedance tube tests

4. CONCLUSION

To summarise, an acoustic modelling software was used to design a lattice structure with enhanced performance through the inclusion of embedded Helmholtz resonators. The resonant frequencies were controlled through simple geometric modifications to the unit cells. The samples were manufactured in a flexible material with high precision. Repeatable and reproducible designs were successfully manufactured with the acoustic properties and printing parameters being optimised for enhanced mid and low-frequency sound absorption. The performance was validated through impedance tube testing of individual and grouped sample combination designs that demonstrated how a variety of unit cells can be combined to achieve a target performance. This work demonstrates that a tuneable, lightweight, and flexible material for low-frequency absorption can be designed and fabricated successfully. Future work on further design optimisation and the ability to fabricate larger-scale samples could see applications to real-world noise control.

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