Modelling and Simulation of Acoustic Metamaterials for Architectural Application

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Abstract. Acoustic metamaterials are novel engineered materials with geometric features of subwavelength size that create highly exotic acoustic behaviors such as negative refractive indexes, perfect sound absorption and sound waveguiding. While these new materials hold much promise to be useful for the architectural engineering and construction sector, there has been little research done on the application of acoustic metamaterials for architectural application. The research presented in this paper investigates acoustic metamaterials for architectural acoustics and demonstrates how architects can leverage parametric design, digital fabrication, and computer performance simulation to develop new metamaterial designs tuned for customized acoustic performance. This paper proposes a new definition of 'metamaterials for architectural acoustic application' and provides a brief overview of the history and theory of acoustic metamaterials alongside a discussion of the relevance of such materials for implementation in architectural acoustic applications. A design and simulation workflow is presented that demonstrates the parametric design and iteration of metamaterial geometry, performance evaluation through computer simulation, and digital fabrication of functional prototypes. A set of well-performing metamaterial geometries are presented that can be used to design architectural acoustic surfaces.

Keywords: Acoustic metamaterials · Acoustic surfaces · Performance simulation · Computational design

1 Introduction

Since the early 2000s, metamaterials gained interest from academic researchers and led to the discovery of many exotic properties and the proposal of many new electromagnetic and acoustic metamaterials (Liu et al. 2000; Pendry 2000; Shelby et al. 2001). The diverse range of metamaterial properties, material composites, and geometries has made it difficult to formulate one distinct definition for acoustic metamaterials (Shamonina and Solymar 2007). Discussion around the term "metamaterials" itself was part of this turn of the century emerging field (Welser 1999). Especially in comparison to other composite materials, metamaterials were distinguished to go beyond any composite

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properties that solely rely on the addition of their constituent properties. Walser (2003) points out that metamaterial geometry "is aimed at achieving performance beyond that of conventional macroscopic composites", hence the prefix "meta". These exotic new properties are possible by carefully designing the composite unit cell and achieving homogenized overall properties based on individual unit cell effects. More recently Cummer et al. (2016) define metamaterials as "a material with 'on-demand' effective properties" where the "internal structure is used to induce effective properties in the artificial material that are substantially different from those found in its components".

2 Background

2.1 Metamaterials History

In acoustic metamaterials, exotic behaviors such as acoustic cloaking (Popa et al. 2011) or perfect sound absorption (Jiménez et al. 2016) and the creation of complex sound fields from simple tones (Xie et al. 2016) become possible. Manmade geometry has been used to modulate the sound in rooms for a long time. Vitruvius claimed that the Greeks used resonating vases, to control sound and improve the room acoustics (Vitruvius 1960). Today, Helmholtz resonators and perforated panels are used to tune the acoustic properties in large rooms to absorb sound at specific frequencies. Acoustic scattering geometry is used in theaters and music venues to improve the quality of reflected sound. However, these structures must be in the same spatial order as the operating wavelength to function. Audible low frequency wavelengths (20–800 Hz) are in the range of 0.4–17 m, therefore rendering application of traditional geometries unpractical. Porous materials such as mineral wool or open-cell foam, are commonly used in architectural acoustic absorber products, but these do not perform well at low sound frequencies (Maekawa et al. 2011). Low frequency sounds are not well incorporated in current acoustic design strategies although they penetrate walls readily and contribute to room modes due to their large wavelengths. One of the potential benefits of acoustic metamaterials is to break the effective size limits as the individual unit cell can be tuned to function for lower frequencies.

Metamaterial properties were first proposed for the electromagnetic wave spectrum. Veselago (1968) speculated that artificially modifying material properties into the negative would result in negative material parameters and unusual wave characteristics. Electromagnetic emission was observed to not propagate in periodically changing dielectric constant media (Yablonovitch 1987). In 1993 these electromagnetic waves stopping effects were translated to pressure acoustic wave propagation, and when this was done, the "acoustic bandgap" was observed (Kushwaha et al. 1993). The "acoustic bandgap" or sonic or phononic band gap is a frequency range where no sound propagation is possible, this is analogous to the electromagnetic band gap. The sonic bandgap occurs due to destructive interference patterns caused by the periodic scattering of sound waves. This phenomenon is called "Bragg scattering" and is named after W. H. Bragg and W. L. Bragg who in 1934 observed destructive and constructive X-ray wave patterns when the wavelength was in the same order as the atom structure in a crystal (Bragg and Bragg 1934).

The periodically changing acoustic impedance of two media produces strong scattering and interference when the distance between the scatterers is a multiple of the operating wavelength (Hussein et al. 2014). In 2000, this acoustic “stop band” was produced by periodic local resonance (Liu et al. 2000). The locally resonant unit cell produces scattering similar to the impedance difference induced scattering. However, instead of scattering at the interface of a media change, the wave scattering was produced by a mass spring system, or resonance. The resonance mechanism functions for far lower frequencies and local scattering is therefore no longer linked to a spatial period. This meant that geometry could remain effective for much lower frequencies at a much smaller scale. Since the application of local resonance in acoustic metamaterials, a diverse range of sonic metamaterials has emerged following suite to their electromagnetic counterparts.

2.2 Defining Architectural Acoustic Metamaterials

Although metamaterial properties are mentioned to be very applicable for sound control in the build environment, not much research has emerged on the specific integration and application. A literature review discussed various metamaterial geometries for their application to the architectural and urban context (Setaki et al. 2014) and (Kumar and Lee 2019). A few projects using acoustic metamaterials have been proposed: a soundproof, air and light transparent window was constructed (Kim and Lee 2013), an air flow permitting metamaterial is used to suppress fan noises (Ghaffarivardavagh et al. 2019), a omnidirectional sound mitigating and air transparent structures is investigated (Shen et al. 2018), and resonant U-shaped scatterers are proposed as traffic noise barriers (Romero-García et al. 2011). A few metamaterials have become commercially available for sound mitigation in the built environment (MetaAcoustic and Acoustic Metamaterial Group - AMG).

In this paper we define acoustic metamaterials as engineered structures that are designed to interact with sound waves in a specific and desired way. They exhibit acoustic properties that are not attainable by existing materials found in nature. The structure is usually composed of many elements smaller than the wavelength that they operate on. Due to their micro, subwavelength unit cell structure, they can obtain new homogenized material properties for the macro, overall structure and appear as a cohesive continuous material to the propagating pressure wave. Since the performance is inherent to the geometry of the structure, the acoustic absorption, diffusion, and transmission characteristics can be modified as needed, making it enticing for designers to explore geometries that fit their performance needs.

2.3 Selected Metamaterials

Based on the outlined benefits, the following will select acoustic metamaterials best suited for architectural deploy. Metamaterials will be differentiated by whether they produce acoustic effects solely due to their geometry or if they rely on a specific material configuration to achieve overall acoustic effects. Different media engineered metamaterials such as rubber coated lead scatterers (Liu et al. 2000) will not be discussed. This research also does not address active acoustic metamaterials such as the sensing and electronically tunable membranes to control wave propagation (Popa et al. 2015). Our studies will focus on geometry-based metamaterials due to ease of fabrication and practical implementation in room acoustic surfaces. Three different acoustic metamaterial types and their applications will be discussed in greater detail.

Small Subwavelength Coiled Channel Metamaterial
Coiled structures have been inserted in the body of a Helmholtz resonator to allow smaller resonators to maintaining sound absorption performance (Li and Assouar 2016) see Fig. 1(1). Coiled spaces with different coupled apertures have been used to produce resonators with a broader absorption peak (Chen et al. 2017) see Fig. 1(6). The sound propagation direction or refraction can be controlled by coiled space unit cell assemblies (Liang and Li 2012) see Fig. 1(9). The coiling of space has also been used to produce destructive interference for sound absorption (Godbold et al. 2007) see Fig. 1(11).

Helmholtz-Like Resonance Metamaterials
A Helmholtz acoustic absorber is an air-spring and mass-based system that takes acoustic energy out of a room (Maekawa et al. 2011). Helmholtz-like resonators have been used in metamaterials. Jimenez et al. (2016) have demonstrated perfect sound absorption by inserting Helmholtz resonators into quarter wavelengths resonant slits; by inserting the Helmholtz resonators, the slit resonant frequency can effectively operate for subwavelength overall dimensions, and the overall assembly remains air transparent see Fig. 1(7). Furthers studies have shown that nested resonators with multiple neck apertures can be used to achieve broadband absorption. (Wu et al. 2019) see Fig. 1(5).

Periodic Scatterers
Periodically arranged scatterers produce a "stop band" where no sound is permitted to propagate. This happens due to the interference patters that emerge when the period of scattering matches the wavelength of the operating frequency. The scattering unit cell can either be an impedance different medium or a locally resonant unit cell. The impedance different scatterer or also known as sonic crystal produces the previously discussed Bragg scattering. The locally resonant unit cell scatters sound as an effect of resonance in the unit cell. Both phenomena produce periodic scattering and produce a "stop band". In the early 90s a sonic crystal was adopted to an outdoor sculpture for noise mitigation (Martínez-Sala et al. 1995) and sonic crystals have been explored as road noise control barriers (Peiró-Torres et al. 2016) see Fig. 1(3). Sound stopping was achieved by locally resonance of lead spheres in soft matrix see Fig. 1(4). Other assemblies, such as lattice systems, with a solid inclusion and a soft matrix material have been shown to produce sound stopping effects due to local resonance in combination with simultaneous Bragg scattering (Chen and Wang 2014) see Fig. 1(8). Local resonance is also produced by single-material unit cells to dissipate sound energy mechanically (Krushynska et al. 2017) see Fig. 1(12). C-shaped Helmholtz like unit cells have been tuned to perform as locally resonant scatterers for attenuation of sound energy, these assemblies have also been nested to achieve more broadband results (Elford et al. 2011.) see Fig. 1(10).

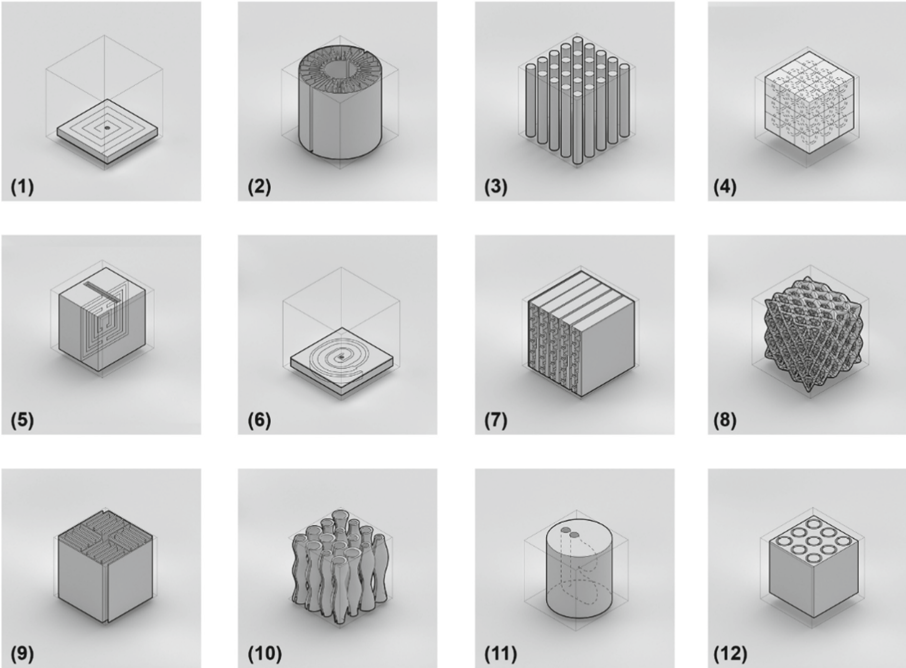

Fig. 1. (1) Li and Assouar 2016 (2) Shao et al. 2019 (3) Peiró-Torres et al. 2016 (4) Liu et al. 2000 (5) Wu et al. 2019 (6) Chen et al. 2017 (7) Jimenez et al. 2016 (8) Chen and Wang 2014 (9) Liang and Li 2012 (10) Elford et al. 2011 (11) Godbold et al. 2007 (12) Krushynska et al. 2017

3 Methods

In architectural acoustics, computational tools for performance evaluation are focused on fast computation times to facilitate rapid design evolution, as well as good integration with the design CAD environment. As most acoustic simulation tools are created to solve room acoustic problems, these tools rely on geometric methods and their algorithms approximate sound as rays. The results from these simulation tools can describe room scale acoustics in sufficient resolution. Tools such as Pachyderm, a plugin to Rhino3D CAD software, integrate well into the architectural design environment (Peters and Nguyen 2021). However, tools that integrate well into an architectural design workflow for acoustic metamaterials do currently not exist. Metamaterial geometry is frequency dependent and operates based on specific wave characteristic behavior that require the numerical modelling of the propagating wave. In our experiments, geometries were designed using Grasshopper in the Rhino3D CAD software. To evaluate the performance of metamaterial geometries, the Finite Element Modelling software COMSOL Multiphysics version 6 was employed. Metamaterials from the literature were used to establish control simulations to verify the simulation set-up, and the geometry exchange pipeline between the modelling environment and the simulation environment. The intention is to propose a proof-of-concept strategy to integrate these novel acoustic performance possibilities into an architectural parametric design workflow (see Fig. 2). Relevant acoustic performance metrics are quantified and evaluated through graphical plots of sound transmission, and sound absorption.

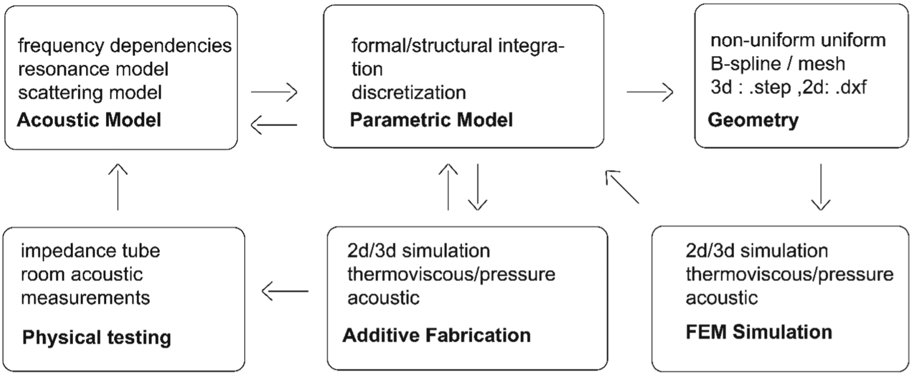

Fig. 2. Geometry generation, simulation, fabrication, and testing workflow diagram

4 Results

Of the selected geometry in Sect. 2.3 we have identified five geometries for further investigation: resonators with coiled backed space (Li and Assouar 2016); resonators with inserted channels (Shao et al. 2019); periodic spatial scatterers (Martínez-Sala et al. 1995); locally resonant unit cells based on Helmholtz resonance (Elford et al. 2011); and resonators inserted in slits (Jiménez et al. 2016). The selection criteria were based on our ability to model, fabricate, and simulate the given geometries. Single material geometries were favored over multi-material assemblies for architectural integration and digital fabrication processes. For each type, a control geometry from the literature was modelled and simulated and evaluated for their potential for architectural application (Fig. 3).

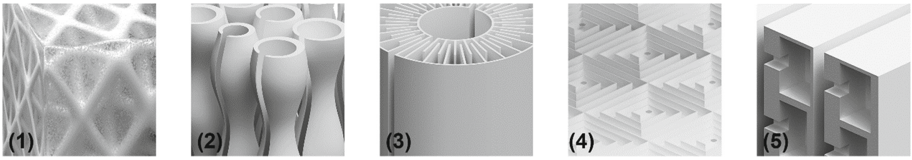

Fig. 3. Selection of 5 geometries: (1) Krushynska et al. 2017 (2) Elford et al. 2011 (3) Shao et al. 2019 (4), Li and Assouar 2016 (5) Jimenez et al. 2016

4.1 Periodic Scatterer

The periodic scatterer is not a metamaterial due to its large size, however it is an example of geometry producing exotic wave stopping effects. A transmission reduction can be observed in the frequency range that corresponds to the period of the scatterer. The lattice period was adjusted in the geometry model to perform at a design frequency, simulation results are in good agreement with the geometry model and produce sound stopping effects at the design frequency, see the graphical plots in Fig. 5.

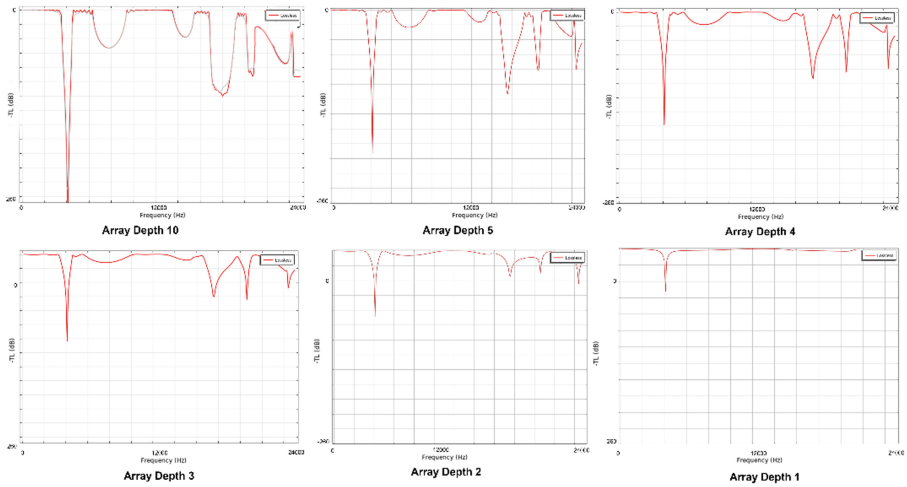

Fig. 4. C-shaped resonators sound transmission loss plot with different unit array depth

To shrink the size of a sonic crystal scattering system, Elford et al. 2011 replaced the cylindrical unit cell scatterer with a Helmholtz-like resonator. An array of periodic resonators produces the same periodic scattering and therefore a sound stop band. In our simulations we have replicated the wave stopping effect, the resulting transmission reduction can be seen in Fig. 4. The depth of required resonator count was tested for multiple different array depths.

4.2 Coiled Channels in Helmholtz Resonator

Coiled channel metamaterial resonators are investigated for sound absorption. Li and Assouar (2016) have shown that it is possible to reduce the overall size of a resonators by introducing coiled structures in the resonator body. The volume of the resonator must be sufficiently large to effectively function as an air spring for a given frequency. To decrease the overall thickness, Li and Assouar have proposed to introduce coiled structure in the resonator body as they have found that the length of the channel is important in providing a compensation for the viscosity and reactance in the neck of the resonator and providing a sufficient air spring to move air in a resonant state. By introducing coiled channels, the effective length of the channel can be increased while maintaining a thin profile. Then, resonance and sound absorption can be produced with a geometry well below the operating wavelength scale. In our simulation we have found that a normal Helmholtz resonator of the same frequency tuning must be 5 times as deep (see Fig. 6) to produce the same absorption coefficient as the coiled counterpart.

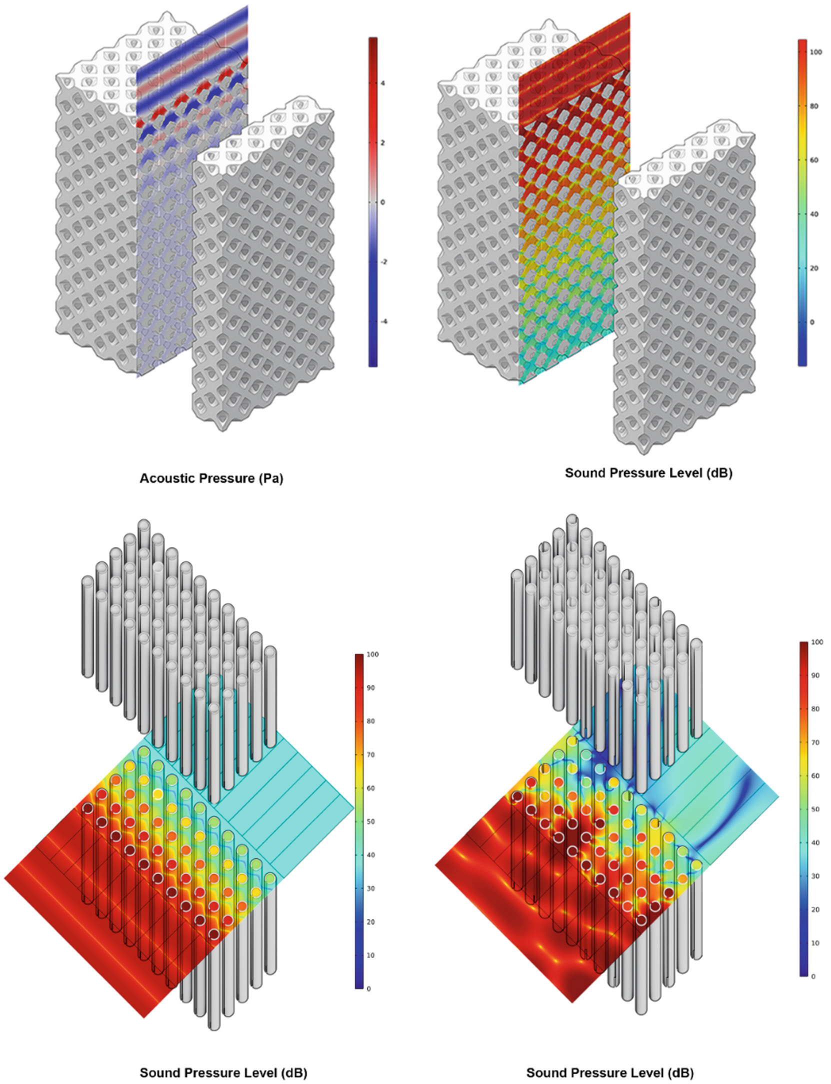

Fig. 5. (1) Sound pressure level across octet lattice, (2) Sound pressure level across locally resonant c-shaped scatterers

Shao et al. (2019) have demonstrated low frequency subwavelength by rigidly backed resonators with an inserted coiled channel for resonance absorption. The coiled space amplifies the energy concentration in the resonator and sound energy is lost. Our simulation results show multiple absorption peaks for the coiled resonator. The absorption coefficient in our tests peak at 0.75 at 130 Hz, the location of the resonant peak is in good agreement with the literature.

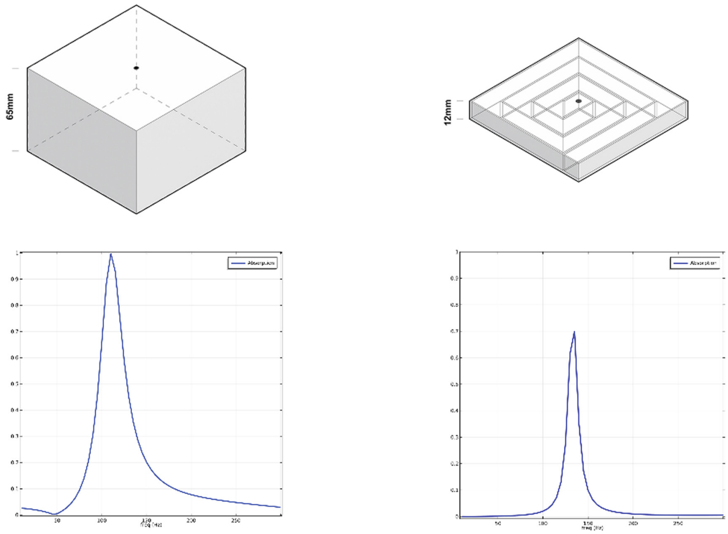

Fig. 6. Sound absorption plots and renders of regular Helmholtz resonator and coil inserted in Helmholtz resonator

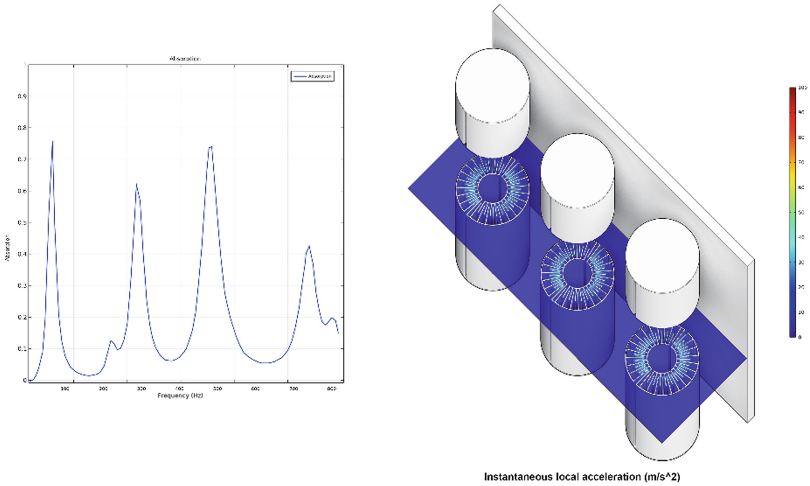

Fig. 7. (1) Sound absorption plots, (2) Instantaneous local acceleration plot

Jimenez et al. (2016) have demonstrated perfect sound absorption through inserting Helmholtz resonators into quarter wavelengths resonant slits. By inserting the Helmholtz resonators, they are able to reduce the resonant frequency of the slit to operate in subwavelength dimensions. We have verified their geometry performance for a design frequency. The absorption peak occurs at the same time as increased transmission loss is apparent (see Fig. 8). When these two conditions occur at the same time, perfect absorption is apparent with no propagating sound energy and no reflected sound energy for the frequency range in which these two conditions are true. The slit however also remains air transparent which could have promising applications. They describe that the dispersion of the incident wave occurs at the inserted Helmholtz resonators design frequency, and that the strongly dispersive environment creates slow sound environment in the slits which effectively decreases the operational frequency of the slit. The geometry parameters from the literature were used to replicate the results both in two-dimensional and three-dimensional simulations.

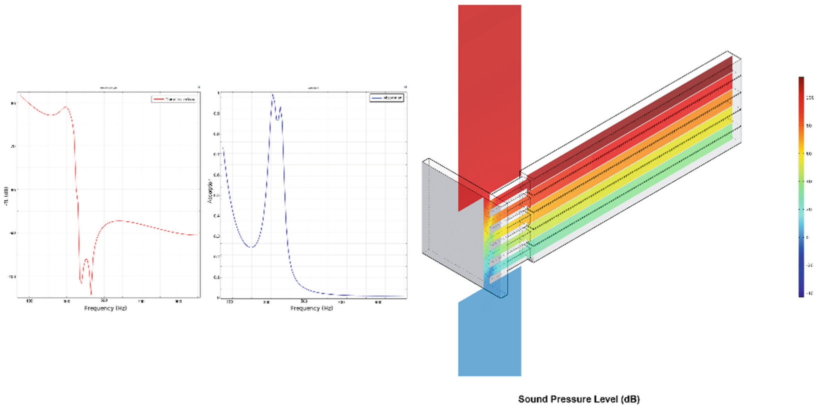

Fig. 8. Transmission loss plot, absorption plot, sound pressure level plot

5 Discussion

In this experiment, five metamaterial geometries were modelled and simulated. The simulation data was to be validated against several 3D printed starch models (see Fig. 10) to be tested in a physical impedance tube. Covid-19 lockdowns at the time, hindered us from accessing facilities to produce and test physical model, future research will address these shortcomings. Instead, we verified our simulation and modeling methods against the acoustic models within our reviewed papers. The results show that spatial and locally resonant scattering in acoustic metamaterials as well as resonance behavior in intricate bulk resonator assemblies is possible using metamaterials. The tuning of acoustic performance based on geometry parameters was demonstrated. We were most successful in tuning the scatterers both for sonic crystals and Helmholtz based locally scatterers. These rely on simple geometry models such as the simplified Helmholtz equation to retrieve the resonance frequency and thereby tune the scattering and sound stopping frequencies for the periodic resonant scatterer.

The first geometry investigated was the octet lattice as a sonic scatterer (see Fig. 4). The simulation demonstrated that the lattice period could be tuned to produce sound transmission loss through the sample for a desired frequency due to Bragg scattering. The performance is however locked to the lattice period and therefore is not ideal for low frequencies due to the large scale required. The c-shaped locally resonant periodic scatterers (see Fig. 5) proved to reduce the size required for sound transmission loss to occur as outlined by the background. This Helmholtz like resonance is a simple and geometric way of producing local resonance and would therefore be very beneficial for fabrication and implementation. The next geometry simulated was the coiled channels inserted in a resonator (see Fig. 6). This geometry produced similar sound absorption levels comparable to its non-coiled space counterpart however with a 5 times thinner profile. The other coiled structure sample also produced high absorption values see Fig. 7. In an architectural context coiled space inserted in resonators might help in tuning perforated panels for much lower frequencies while retaining at thin profile for practical fabrication and application. Lastly, we simulated the Helmholtz resonators inserted in a quarter wavelength slit (see Fig. 8). Both strong transmission loss (−105 dB) and high absorption values (0.9) occur simultaneously. This geometry could be applicable to the architectural context as it is single materials and produces very good results that are applicable both for sound blocking and sound absorption.

It is clear that the promise of acoustic metamaterials could be very beneficial to architectural acoustic and their application in our surrounding environment is an inherently architectural problem. A successful integration is however reliant on several factors. They must be easily tunable and therefore parametrically defined through a simple rule set, they must be fabricable by single material means and further a simulation and testing workflow must be feasible for a rapid design environment to be able to adapt to performance and design goals (Fig. 9).

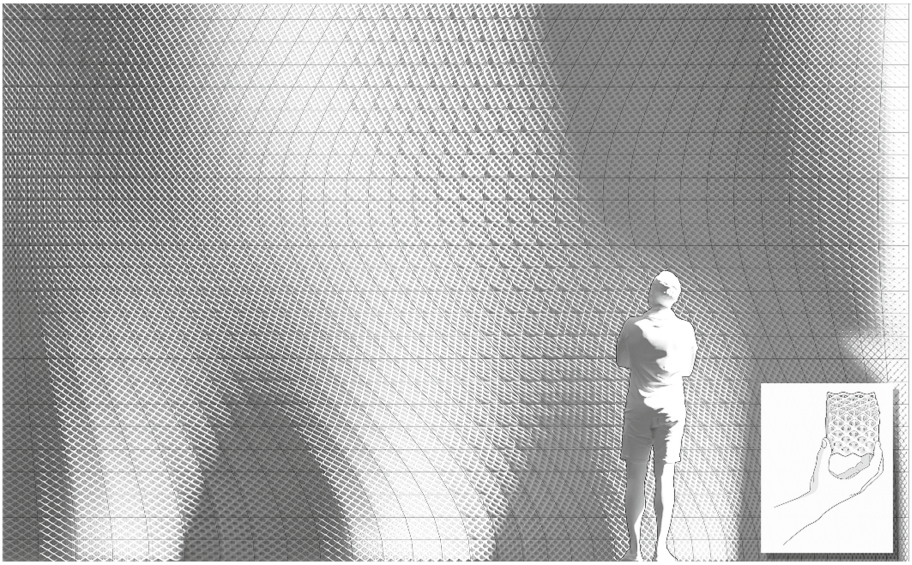

Fig. 9. Octet lattice, locally resonant sonic crystal

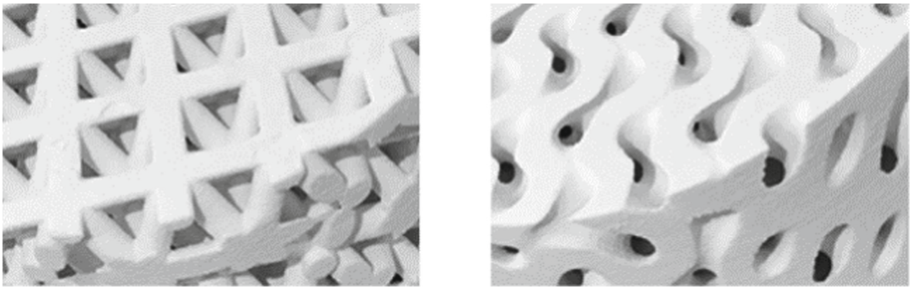

Fig. 10. Starch 3D-printed octet lattice and gyroid minimal surface

6 Conclusion/Future Outlook

Acoustic metamaterials exhibit great potential for architectural acoustic application. Industry today relies on an exclusive selection of sound-mitigating materials that have performance constraints, especially in the low frequency regime, in addition these materials are difficult to custom-tune for specific spaces or desired performance and might be impractical to implement. With acoustic metamaterials, performance can be embedded in the geometry. The acoustic effects can be custom designed for a desired outcome by adjusting simple parameters in the geometry model. This proves highly valuable for an architectural workflow as there is no need to rely on specific materials and could enable an integrated strategy to embed performance tuning through geometry to ultimately design for sound more effectively. Current advances in digital fabrication and computational simulation enable us to design, verify and fabricate these novel materials for use in architectural acoustics.

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