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Modelling and Simulation of Helmholtz Resonators for Broadband Sound Absorption

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ABSTRACT

Helmholtz resonators are one of the oldest concepts in architectural acoustics, and they have very good acoustic absorption characteristics; however, they are rarely used in contemporary architectural practice. While resonant absorbers are only able to absorb sound over a very narrow frequency range, their performance can be tuned for specific frequencies through modifying the resonator geometry. This paper speculates that advances in digital design tools, computational building performance simulation, and fabrication techniques enable the exploration, testing, and fabrication of new resonator geometries. We propose that through the use of multiple tuned resonators, a broadband Helmholtz resonator is possible. This study reports on the performance results for nine Helmholtz resonator geometries that were digitally modelled in CAD software and parametrically defined using neck width, length, and volume as parameters. These single and multi-frequency geometries were tested in a virtual impedance tube using the COMSOL FEM simulation software. We outline a method by which these geometries can be simulated and that produces needed absorption coefficients for further room acoustic simulations. The results suggest that frequency intervals of not more than 50Hz are recommended to produce broadband acoustic absorption, and that absorption coefficients of almost 1.0 are possible for tunable frequencies.

Author Keywords

Architectural Acoustics; Acoustic Simulation; Acoustic Resonator

1 INTRODUCTION

The concept of the acoustic resonator is one of the oldest concepts in architectural acoustics (Vitruvius 1960); however, they are rarely used in contemporary architectural practice. Resonant absorbers pose an interesting problem in acoustics as they are powerful absorbers but are highly frequency selective; they absorb sound only over a narrow frequency range. Broadband absorption therefore requires many resonators to function effectively. The relationship between the geometry of the resonator and its performance are widely recognized and applied; changing the geometry, tunes the resonant absorber for use at different frequencies. With advances in digital design tools, fabrication technology, and simulation techniques, acoustic resonator might be reimagined and incorporated into new acoustic tectonics in architecture. This research hypothesizes that arrays of acoustic resonators can be combined to create broadband acoustic absorbers. This research serves as a basis for future investigations in smaller bulk resonator assemblies as found in acoustic resonant metamaterials. In these experiments, broadband and single-band resonators are developed through digital parametric modelling and tested through acoustic simulation to analyze acoustic performance of different design options.

2 BACKGROUND

2.1 A Brief History of Acoustic Resonators

The acoustic resonator as a concept has been around for a long time. The architect and writer Vitruvius outlined the use of resonators (Vitruvius 1960), and Marc Crunelle (1993) writes that though little written evidence remains, extensive evidence from historical buildings demonstrates a continued and developing experimentation with resonators. The use of resonators has been said to have been used in over 200 churches across Europe, for example, in Bologna, the cathedral St. Petronio is said to contain four hundred resonators (Crunelle, 1993). Crunelle speculates that the design guidance for their use would have been a secret kept and guarded by the mediaeval guilds responsible for their design and installation. Zakinthinos and Skarlatos (2007), in their study of resonators in Greek orthodox churches, speculate that the design intention of these resonators was related to solving the acoustic problems since vases were the only available way to control and adjust the acoustic response of rooms. However, in their analysis the effect of the resonators was very weak, and that the small number of resonators found would have had an unobservable effect on the acoustic quality of the church. They speculate that this is

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why the use of resonators did not continue. Mijic and Sumarac-Pavlovic (2004) have similarly found, in a study of Serbian churches, that though resonators have been discovered, their resonant frequency was too low to be excited by the human voice, and that they were installed in too small a number to have an audible impact. Mijic and Sumarac-Pavlovic (2004) speculate that, in terms of acoustic knowledge and design tools, the building of acoustic resonators was a result of orally transmitted tradition, without any knowledge of their acoustic function.

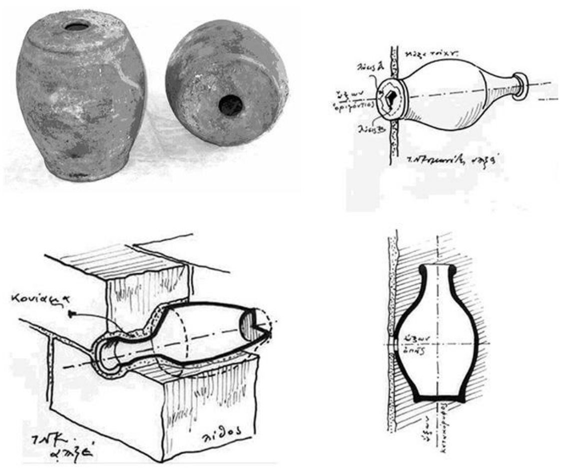

Figure 1. Examples of Acoustic Resonators from Historical Churches (from Zakinthinos and Skarlatos, 2007)

2.2 Helmholtz Resonators

Helmholtz resonators are used to provide low frequency absorption (Everest, 2001), and are named after Hermann von Helmholtz who first calculated the resonant frequency - the frequency where there will be the most absorption (Long, 2006). The Helmholtz resonator is a geometric configuration that pairs a small opening connecting to a narrow neck paired with a larger enclosed volume of air behind. The Helmholtz resonator works on the principle of an air spring where the air in the opening oscillates on the elastic cushion formed by the volume of air in the resonator. Together they form an oscillating system with a specific resonance frequency. There are many different forms of Helmholtz resonators: an empty wine bottle, a string instrument, bass reflex enclosures of loudspeakers, and wall linings made from perforated wood or gypsum boards.

The careful control of material absorption properties and their relation to room reverberation time is one of the cornerstone ideas of contemporary architectural acoustics (Sabine 1922). The ubiquitous fibrous absorption panels often specified by architects are best at absorbing medium and higher frequencies of sound, and so one of the primary reasons to use Helmholtz resonators in an architectural context is that they are able to absorb low frequencies. Helmholtz resonators can be used to damp the individual eigenmodes of a room, which develop at low frequencies, and are particularly problematic in small rooms. However, one of the problems is that Helmholtz resonators absorb sound only over a very narrow frequency band. One of the ways to increase the size of the frequency band absorbed by the resonator is to put an absorbing material such as fleece, foam, or mineral wool in the resonator, however, this research looks to an alternate, geometric approach to achieving broadband absorption.

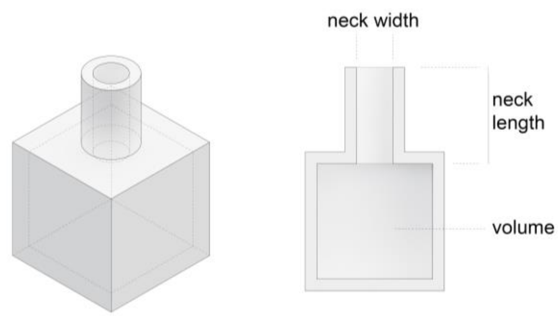

Figure 2. Diagram of the Helmholtz Resonator

The basic equation for a Helmholtz resonator (Long 2006) is:

(1) $$f_0 = \frac{c}{2*\pi} * \sqrt{\frac{S}{V*(l+\delta)}}$$

For circular holes, the error adjustment is:

(2) $$\delta \cong 0.8 * d$$

where,

f_0 is the design frequency
c is the speed of sound in air
S is the area of the opening
d is the diameter of the opening
V is the volume of the resonating chamber
l is the length of the neck.

2.3 Resonators in Acoustic Metamaterials

Metamaterials are a new area of research in acoustics, and promise to be very beneficial in a variety of contexts including architectural acoustics. Acoustic metamaterials gain their acoustic effects from their geometry and are characterized by working with geometries significantly smaller than the wavelengths of sound they effect. They have proven to be effective and efficient and have highly exotic acoustic behaviors including: negative refractive index, absolute reflection, absolute absorption, and low loss sound wave lensing. Usually, metamaterials are comprised of a unit cell that in bulk behaves as a continuous cohesive material with effective material parameters for the whole assembly (Cummer et al., 2016).

In architecture, sound mitigation can become very challenging in the low frequency sound domain. This is due to the mass density law that dictates that the geometry modifying the acoustic incident wave must become increasingly large as the frequencies lowers or the sound level increases. Metamaterials can break the mass density law and therefore are very interesting for low frequency sound absorption in architecture. A limitation of traditional Helmholtz resonators is the spatial requirement of the resonator, that with decreasing frequency increases further. In addition, granted that only a very narrow frequency range can be absorbed by one resonator, many resonators are required to achieve any practical application.

In acoustic metamaterials, resonators are implemented as highly tuned elements which function within a larger assembly that have behaviors previously unachievable in traditional acoustic sound wave modulation. Highly controlled and full phase modification of an incident sound wave, for instance, become available through the use of resonators in metamaterial acoustics (Jiménez et al., 2017). This allows for diffusive scattering, tuned absorption and tuned reflection through resonance. Understanding the resonance mechanics on a larger scale will allow insight into some of the finer tuned and bulk acoustic resonance behaviors in acoustic metamaterials. While the experiments described here are not metamaterials, the questions and methods used will contribute to this exciting new area of study.

3 METHODS

3.1 Modelling and Parametric Studies

This research uses methods from computational architectural design, architectural acoustic measurement, and computer acoustic simulation. For modelling tasks the Rhinoceros CAD software was used in conjunction with the Grasshopper parametric engine. The parametric model followed the mathematical logic explained in section 2.2.

3.2 Acoustic Computer Simulation

The computer simulation of room acoustic performance can be grouped into two approaches: wave-based, and ray-based (Siltanen et al., 2010). Ray-based techniques, also called geometric methods, assume that sound travels in a straight line and its reflection from surfaces is computed using geometrical methods. Geometric techniques are the primary way in which architectural acoustic performance is predicted, and used in all commercial room acoustic simulation software. However, ray-based techniques cannot be used to simulate the performance of resonators, and absorption coefficients for all surfaces are necessary. Absorption coefficients are not available for customized Helmholtz resonators. This research addresses this issue.

Wave-based simulation techniques attempt to solve the wave equation numerically. They are also called numerical techniques, and are while these wave-based methods do not solve the wave equation directly, they try to approximate its solution. The main numerical methods for acoustic simulation are: the finite element method (FEM), the boundary element method (BEM), and the finite-difference time-domain method (FDTD) (Cox and D'Antonio, 2009). Computationally intensive, numerical techniques involve the discretisation of either the space of the room, or its bounding surfaces, and model the interactions between all of the resulting elements. This element interaction must be calculated for each element in a time-step sequence. Even with very small spaces, this leads to large calculation times for large numbers of elements and long durations. In this experiment the FEM software COMSOL Multiphysics was used to model the acoustic wave interaction with the Helmholtz resonator geometry.

3.3 Virtual Impedance Tube

Impedance is the resistance to flow of acoustic wave propagation through a medium; this resistance to flow can be used to understand a materials reflection and absorption coefficients. In architectural acoustics practice, the impedance of a material sample is analyzed in a physical impedance tube. An impedance tube consists of a loudspeaker is installed one side of the tube and a material sample is positioned on the opposite side of the tube.

In our experiments a virtual impedance tube was created. Using a perfectly matched layer on the top of the tube, an infinite tube was simulated. This yields more accurate results as compared to a finite tube length. Then a background pressure field is simulated to create an incident plane wave. The plane wave interacts with the virtual sample that sits at the end of the tube, then the reflected acoustic pressure is measured at two spatially offset positions. Two microphones measure the acoustic pressure at two positions of the reflected acoustic pressure field. In comparing the data recorded form both microphones through the transfer function, the absorption coefficient can be calculated.

The virtual impedance tube was set up to calculate the absorption and reflection coefficient of a 100mm diameter sample, see Figure 3. By implementing the acoustic transfer function, the two measurements are related, and the absorption and reflection coefficient can be calculated. Due to bi-lateral symmetry in our resonator digital models, only a quarter of each sample needed to be modelled and simulated. This saved significant computation time. Results were extrapolated based on symmetry cases along two perpendicular planes.

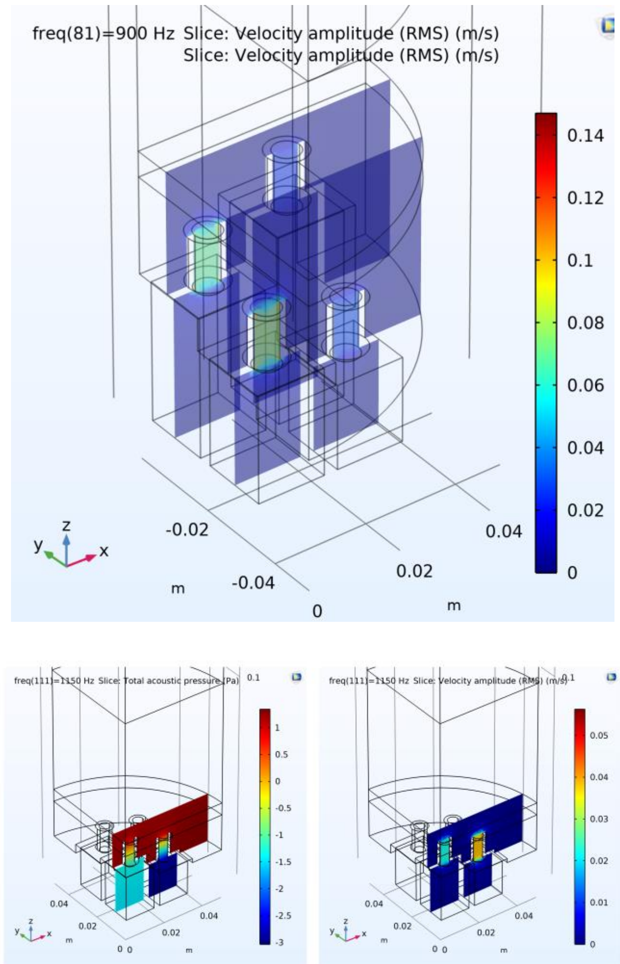

Figure 3 Virtual Impedance Tube study of Helmholtz Resonator Geometry inside COMSOL Multiphysics. Quarter sample of modelled Helmholtz resonator shown with acoustic pressure and acoustic velocity results.

4 RESULTS

4.1 Resonator Experiments

A variety of experiments were carried out to confirm the acoustic performance of Helmholtz resonator geometry, and to test different ways of combining resonators to achieve broadband acoustic absorption. Table 1 shows the experiments carried out and discussed in this paper. Figure 4 illustrates the nine different virtual resonators tested using the virtual impedance tube.

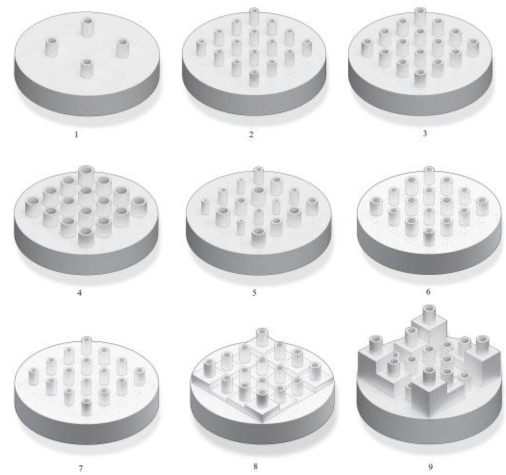

Figure 4 Digital Models of Virtual Resonators

(1) 500 Hz Frequency Single Band Resonator
(2) 800 Hz Frequency Single Band Resonator
(3) 1100 Hz Frequency Single Band Resonator
(4) 1600 Hz Frequency Single Band Resonator
(5) 500 – 1400 Hz Frequency Broadband Resonator
(6) 900 – 1200 Hz Frequency Broadband Resonator
(7) 800 – 950 Hz Frequency Broadband Resonator
(8) 700 – 1000 Hz Frequency Broadband Resonator
(9) 800 – 950 Hz Frequency Broadband Resonator

Fig	Parameter	Frequency	Volume	Neck Width	Neck Length	Interval
SINGLE BAND RESONATOR						
1	Volume	500 Hz	17,526.5 mm^3	5.7 mm	10.6 mm	N/A
2	Neck Width	800 Hz	3,010 mm^3	3.4 mm	10.6 mm	N/A
3	Neck Width	1100 Hz	3,010 mm^3	5.1 mm	10.6 mm	N/A
4	Neck Width	1600 Hz	3,010 mm^3	7.9 mm	10.6 mm	N/A
BROADBAND RESONATOR						
5	Neck Width	500 - 1400 Hz	3,010 mm^3	3.5 – 7.9 mm	10.6 mm	300 Hz
6	Neck Width	900 - 1200 Hz	3,010 mm^3	4.1 – 5.1 mm	10.6 mm	100 Hz
7	Neck Width	800 - 950 Hz	3,010 mm^3	3.6 – 4.3 mm	10.6 mm	50 Hz
8	Volume	700 – 1000 Hz	4,384 – 8,970 mm^3	5.6 mm	10.6 mm	100 Hz
9	Volume	800 – 950 Hz	3,010 – 4,485 mm^3	4.8 mm	10.6 mm	50 Hz

4.2 Single Frequency Helmholtz Resonators

A Helmholtz resonator at resonance oscillates air at high velocities in the neck. The air in the neck acts as a mass attached to the elastic cushion that is the volume of the resonator. The air in the neck oscillates at a higher velocity compared to air moving outside of the resonator and the pressure difference between the inside and the outside of the resonator is maximal. This results in thermoviscous damping that occurs at resonance near the walls of the neck. To simulate the sound energy dissipation through viscous and thermal damping, the thermoviscous acoustic module in COMSOL was implemented in the resonator neck and body areas for the simulation. For thre digital models of resonators, the parameters of the resonators are given as the width and the length of the neck as well as the volume of the resonator body. In the experiments conducted, neck width and body volume were identified as the variables to be changed and analyzed.

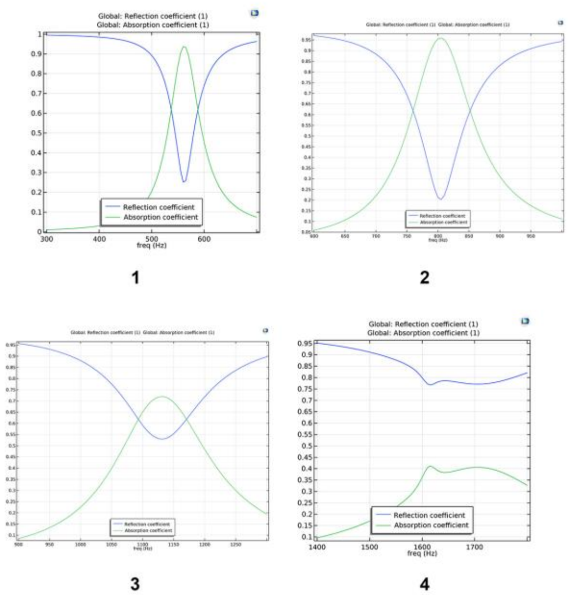

Figure 5 Absorption Coefficients for Single Frequency Resonators: (1) 500 Hz (2) 800 Hz (3) 1100 Hz (4) 1600 Hz

4.3 Multi-frequency Helmholtz Resonators

Due to the very narrow absorption peak of a Helmholtz resonator the practical applications for sound absorption are limited; therefore, the design of a broadband, multi-frequency resonator is needed to be useful in real world application. One solution to attain broadband absorption is to add multiple resonators which cover a specific broader frequency range. In our experiments we investigated three different intervals of design resonant frequencies: 300 Hz, 100 Hz, and 50 Hz. Because we only modelled four resonators this meant that the range between frequencies also changed between options. We also changed the parametric part of the geometry that creates the frequency change. As can be seen in equation (1), changes in the area of the neck, or changes in the length of the neck, or changes to the volume will change the fundamental frequency of the resonator. In our experiment we tested both changes in neck width and resonator volume. For or the 300 Hz interval we tested 500/800/1100/1400 Hz resonators with changes in neck width; for the 100 Hz interval we tested 900/1000/1100/1200 Hz resonators with changes in neck width; for the 100 Hz interval we also tested 700/800/900/1000 Hz with changes to the volume; and for the 50 Hz interval we tested 2 options at 800/850/900/950 Hz with changes either neck width or volume, see Figures 6 and 7.

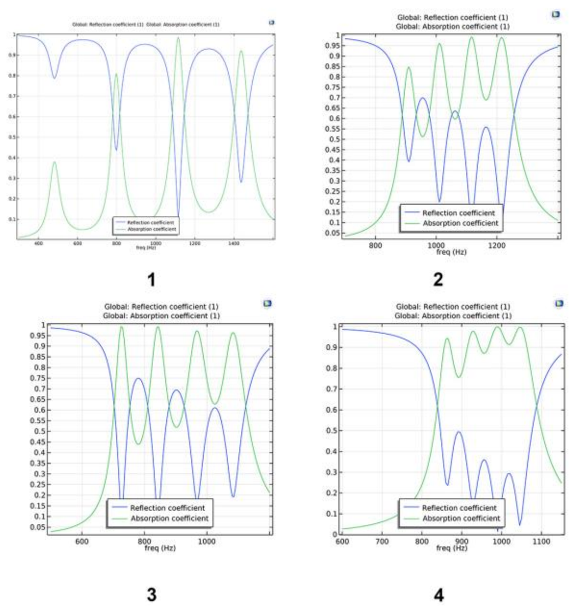

Figure 6 Absorption Coefficients for Multi-Frequency Resonators:
(1) 500-1400 Hz vary neck width – 300 Hz interval
(2) 900-1200 Hz vary neck width – 100 Hz interval
(3) 700-1000 Hz vary volume – 100 Hz interval
(4) 800-950 Hz vary volume – 50 Hz interval

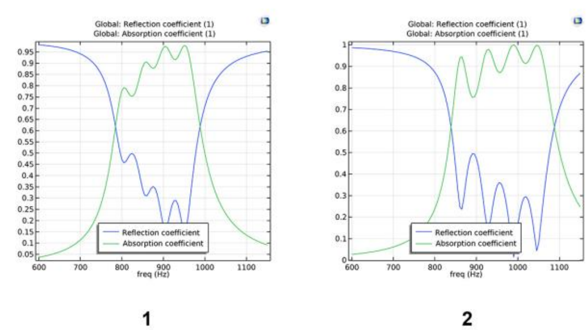

Figure 7 Absorption Coefficients for Multi-Frequency Resonators, comparing variations in neck width and resonator volume:

(1) 800-950 Hz vary neck width (2) 800-950 Hz vary volume

5 DISCUSSION AND CONCLUSIONS

5.1 Single Frequency Resonators

A series of four single-frequency resonators were modelled and simulated in COMSOL. The results from these confirmed our modelling methods and helped refine our simulation techniques. The results, shown in Figure 5, confirm that Helmholtz resonators perform well at a singular, narrow frequency band. The results further confirm that the equation (1), which was used to inform our parametric model, is a reasonable predictor of the fundamental frequency at which the Helmholtz resonator will perform best. However, what we also discovered was decreasing performance as the resonators were pushed to perform at higher frequencies. The 1100 Hz resonator has only about a 0.72 peak value for absorption coefficient at its fundamental frequency, and the 1600 Hz resonator is worse, with only about a 0.42 peak value. This decreasing amount of performance is hypothesized to be the result of increased neck width in relation to a fixed volume. As neck width increase, the difference between the volume of air in the neck and in the resonator decreases and so the resonator will no longer function as an air spring.

5.2 Multi-frequency Resonators

A series of five different digital models were tested in our virtual impedance tube. These digital models each had four resonators of different fundamental frequencies, and these four resonators represented a quarter of the total amount of resonators that would have been present in the actual 100mm diameter sample. As mentioned previously only one quarter of the bi-symmetrical sample was modelled to reduce calculation time.

The results showed that a 300 Hz interval between fundamental frequencies did not provide a broadband acoustic absorption. The acoustic absorption coefficient varied from almost 1.0 at the design frequency to almost 0.0 in-between. At a 100 Hz interval between fundamental frequencies we began to see improved performance in terms of a broadband acoustic absorption response; however, the absorption coefficient still dipped to about 0.5 in-between design frequencies. At a 50 Hz interval we observe a good broadband frequency absorption with the absorption coefficient remaining at about 0.8 and above for the entire frequency design range. It is not expected that these small changes in absorption would be noticeable.

Decreasing the frequency interval spacing grants a more consistently high absorption coefficient between absorption peaks but also warrants the need of a higher number of total resonators. This becomes a spatial requirement. In metamaterials the reduction of space required is a key objective. The investigation of the application of this knowledge to the generation of new acoustic resonator metamaterials could provide further developments.

The relation of body volume to neck width is important for the performance of the resonator. When the difference between the two parameters is too large, absorption performance decreases. The broadband analysis showed the volume to be a more variable parameter as absorption stayed above 0.8 over a 200 Hz interval as compared to the neck width example in which the absorption dropped below 0.7, see Figure 7. The experiments comparing the variation in volume and neck width indicate that: resonators with variation in neck width perform almost exactly at the predicted design frequency; however, the option studying the effects of varying volume on broadband absorption show absorption at higher frequencies with strong absorption continuing to about 100 Hz higher than the highest design frequency of 950 Hz.

It should be noted that the sound level for which the simulated absorption coefficient remains valid was not determined. This requires more a detailed simulation that we did not take into account in the presented results. It should be further noted that sound wave interference plays a role in shifting some of the simulated pressure fields. This interference is created by the interaction of the scattered wave and incident sound wave and is captured by the COMSOL FEM simulations.

5.3 Future work

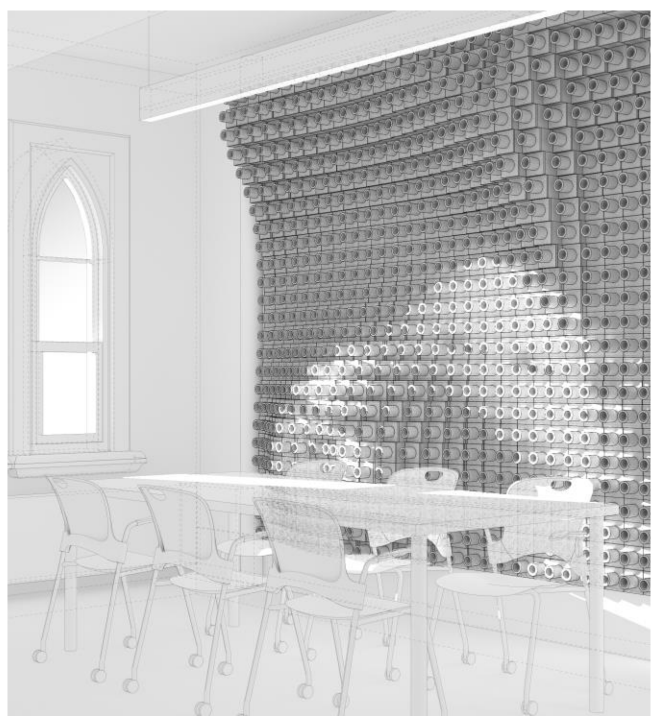

Figure 8 Broadband Helmholtz Wall 1

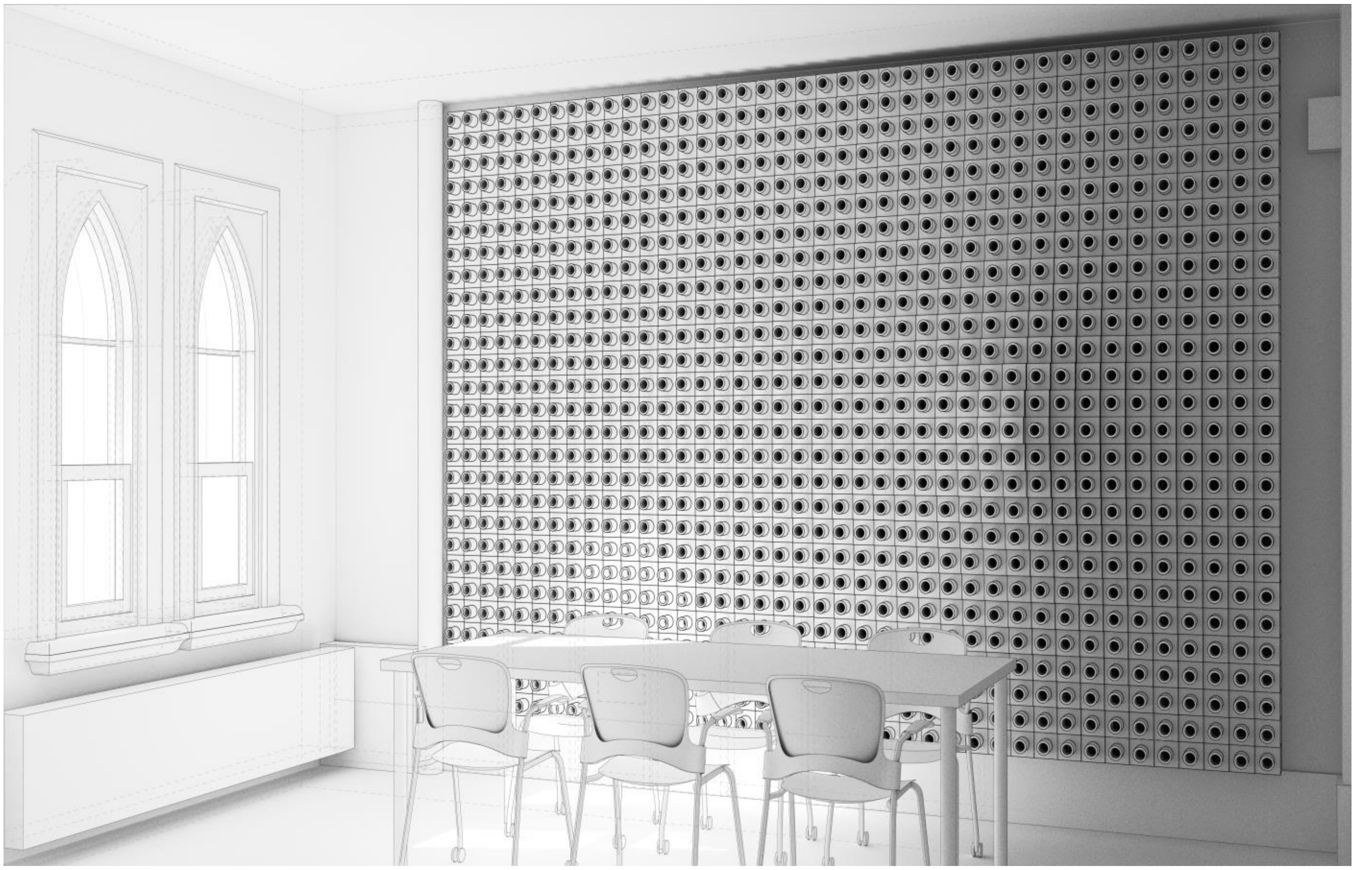

Figure 9 Broadband Helmholtz Wall 2

The results indicate that a broadband acoustic absorber consisting of Helmholtz resonators is possible. Considering that human hearing ranges from 20 Hz to 20 kHz, sound absorbers need to cover a considerable range of frequencies. If the maximum absorption frequency is kept to only about 1200 Hz, this resonator geometry should still be paired with porous absorbers for higher frequency absorption. However, the considerable ability of this geometry to tune absorption to very precise frequencies would make this a benefit to smaller rooms that suffer from long reverberation times in the lower frequency domain and also annoying resonant frequencies due to room modes.

Traditional Helmholtz resonators have limitations for practical application as broadband sound absorbers in architecture due to their spatial requirements. In metamaterials, resonators are used as highly tuned bulk assemblies that are effective on a subwavelength scale, challenging the spatial requirements of traditional Helmholtz resonators. Understanding every variable of the resonator allows the implementation of overall smaller geometric relationships as well as small variations within the geometry that effect specific and diverse acoustic responses. Nesting resonators as well as combining the resonator with other geometries and materials, as composites, creates new effective behaviors not typically observed in single traditional resonators. Resonant metamaterials prove to have effective behaviors that arise from their overall assembly and promise highly effective implementation of resonators for use in architectural acoustics.

The mathematical relationship of geometry to performance has been confirmed and this associative relationship can be made into an algorithmic design tool that can generate performance-driven geometries. These geometries can be digitally fabricated and used to create visually and aurally exciting new acoustic surfaces, see Figure 8 and Figure 9.

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