# Resonant Hexagon Diffuser

## Designing Tunable Acoustic Surfaces by Combining Sound Scattering and Helmholtz Resonators

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1 Hex CLT absorber and surface scatter assembly for airport lounges

## ABSTRACT

Wood as a building material has been used in architecture for millennia. In recent years, technological advances have led to new timber products, mass timber, to be used in bigger and more complex building construction projects. The surge in mass timber buildings being constructed introduces unique acoustical challenges as mass timber is more permissible for sound to travel across floors, ceilings, and walls, especially for lower frequencies. In order to address these acoustical challenges, the absorption qualities of Helmholtz resonators and surface diffusion of scattering surfaces are leveraged by combining the two systems in an integrated structure using the tectonics of mass timber construction. Both the absorption behavior and the diffusive characteristics are tunable via geometric methods; this allows for the control of a gradient acoustic behavior to produce a surface ranging across frequency and sonic behavior. This paper investigates the potential of Helmholtz resonators to be used in combination with sound scattering surfaces to achieve optimal performance in cross laminated timber (CLT) panels through the use of a hexagonal pattern as the underlying design strategy. Prior design studies have researched Helmholtz resonators or sound scattering surfaces for architectural purposes, but none combined both sound design strategies to leverage the well depth requirements of the scatters as Helmholtz resonant cavities. The results from our investigation indicate that it is a functional approach towards creating prefabrication assemblies with optimized acoustical properties.

## INTRODUCTION

Architects have been fascinated by resonant acoustic absorbers since the early days of western architecture. Early documentation of resonant absorbers can be found in Vitruvius' *The Ten Books on Architecture* where he describes how empty bronze vases were placed underneath rows of Roman and Greek theater seating to create better acoustic performance (Vitruvius 1960). Vases found built into the ceiling and walls throughout many European churches were thought to have been placed there for their acoustic properties (Crunelle 1993). However, the efficacy and application of these vases as acoustic absorbers is a topic debated amongst researchers (Kanev 2020). Experiments conducted by Bruel (2002) inside Danish churches, Mijic and Sumarac-Pavlovic (2004) in old Serbian churches, and Zakinthinos and Skarlatos (2007) inside an old Byzantine church concluded that their respective vases did not significantly contribute to better acoustic performance of the spaces. In contrast, Godman (2007) states that the reason many of these spaces do not perform as intended is due to how vases were cemented in place instead of being placed freely as Vitruvian examples indicated. A relationship between geometrical proportions and performance of acoustic resonators exists allowing for the dimensions of absorbers to be adjusted to tune for specific resonant frequencies (Cox and D'Antonio 2009). Although resonant absorbers are a powerful tool, their absorption spectrum and bandwidth are limited to the restrictions of neck friction losses (Lee, Nomura and Lizuka 2019). Resonant absorbers are the most powerful tool when dealing with low frequencies (Everest 2001). In order for broadband absorption to be achieved, multiple resonators need to be coupled together (Godbold 2008). New advances in the realm of digital modeling and simulation tools are making accessibility to study resonators much more feasible in the realm of architecture (Cop, Nguyen, and Peters 2021). Large scale Helmholtz prototypes can now be performance tested at original scale. This type of investigation has previously not been possible to test at scale as mainstream physical impedance tubes are limited to diameters ranging from 16 mm to 100 mm (Brüel & Kjær n.d.; Placid Instruments n.d.). Software packages such as Comsol Multiphysics Acoustic Modules can simulate complex geometries at 1:1 scale through virtual impedance tubes. Recently released Comsol Multiphysics software updates to improve native meshing capabilities has improved the granularity level for simulations at finer geometrical scales. This has made the study of broadband absorbers with shared resonator volumes much more accessible. In this research investigation, various types of Helmholtz resonator hexagonal assemblies are simulated for single band frequency studies that are then used to inform broadband absorption arrangements. This resulted in the creation of hexagonal cluster assemblies at 25 Hz intervals where the depth created on the flipped surface side was utilized as a scattering surface.

## BACKGROUND

### Helmholtz Resonators in Architecture

A resonant absorber functions through the science of vibrations where sound waves are pressured into cavities through air flow (Cox and D'Antonio 2009). The earliest form of documentation for the concept of the resonant absorber dates to the time of architect Vitruvius. Yet this remains a point of contention amongst researchers as limited forms of documentation remain (Crunelle 1993). According to the publication by Arns and Crawford (1995) the majority of vase type resonators are located throughout European churches and cathedrals numbering in the hundreds; St. Petronio Cathedral in Bologna, Italy contains four hundred resonators cavities (Crunelle 1993) and St. Nicholas Church in Pskov, Russia contains 300 pots inserted into wall cavities. Kanev (2020) and Crunelle (2011) state that the plans for how to arrange the location of resonant absorbers would have been a secret known only to the designated guilds responsible for overseeing their construction. Zakinthinos and Skarlatos (2007), in their investigation of resonators in an old Byzantine church, arrived at the conclusion that the vases did not provide noticeable acoustic improvements to the space, as their analysis of the resonator's effects revealed that the limited quantity of resonators in the church had an unobservable difference. This may be the reason for the discontinuation of resonant absorbers throughout Europe. The study of churches through Serbia by Mijic and Sumarac-Pavlovic (2004) arrived at similar conclusions where the resonant vases frequencies were too low to be excited by the human voice and that the quantity of resonators was too limited for any noticeable acoustic difference. They concluded that the building of acoustic resonators was a result of orally transmitted tradition rather than any proper understanding of their acoustic qualities or functions.

### Acoustic Absorption of Helmholtz Resonators

In the field of acoustics, there exist two main types of acoustic resonators which can absorb acoustic waves through resonance: membrane absorbers and Helmholtz resonators. The membrane type absorbs acoustic energy by converting the acoustic pressure wave into mechanical oscillation of a membrane (Frommhold et al. 1994). Membrane absorbers are commonly implemented as large panels suspended from ceilings or walls to absorb low frequencies in a room. Likewise, Helmholtz resonators are also used to provide low frequency absorption but over broader ranges (Everest 2001). The Helmholtz resonator is named after Hermann von Helmholtz, who was the first person to calculate the resonant frequency where the most absorption could be obtained (Long 2006). The Helmholtz resonator can be configurable as many forms, as it is simply an enclosed volume of air with a small opening neck. It functions like an air spring where the sound wave enters the opening neck of the resonator, thereby pushing the air into the larger cavity, causing the compression of air. At resonance, the period of high and low pressure of a propagating pressure wave interacts with the geometric proportions of the resonator in such a way that an oscillating system is formed. Air moves faster in the neck of the resonator, operation as a mass on the spring of the larger resonator body. This oscillating system takes acoustic energy out of the room and convers it mostly into heat energy due to increased friction at the neck of the resonator. This process forms an oscillating system with a specific resonance frequency (Cox and D'Antonio 2009). The most common forms of Helmholtz resonators are empty bottles, string instruments, or perforated wood, or gypsum board. The control of absorption properties and their relation to reverberation time is one of the key criteria in architectural acoustics still relevant today (Sabine 1922). Helmholtz resonators may also be used for dampening specific eigenmodes of a space, which develop at low frequencies. A noticeable shortcoming of Helmholtz resonators is the ability to only absorb waves over very narrow frequency bands. A way to overcome this issue is to utilize absorbing material such as fleece, foam, or mineral wool within the resonator cavity (Fuchs 2013). It has been shown that Helmholtz resonators can play a key role in providing a solution to architects when designing for low frequency absorption scenarios (Cop, Nguyen, and Peters 2021).

The Helmholtz resonator equation is (Long 2006):

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

For circular holes, the error adjustment is (Long 2006):

$\delta \cong 0.8d$, 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 |

#### Sound Scattering Surfaces

The terminology for scattering and diffuse reflections are often used interchangeably throughout the field of acoustics. In this paper, Cox and D'Antoni's (2009) definition is used, where scattering refers to the measurable quantity of sound that is scattered away from the incoming specular reflection direction. The past decade has seen a rise in interest from researchers and designers towards leveraging computational power for the exploration of sound scattering surfaces (Peters et al. 2019), as scattering surfaces are beneficial not only to traditional acoustical spaces such as concert halls and performance venues (Haan and Fricke 1997), but also in regular classrooms and meeting rooms (Choi 2013). A key criterion for any acoustic surface is the sound scattering coefficient, which is used to define the quality of sound in a space (Cox and D'Antonio 2009). The scattering coefficient is the ratio of scattered sound waves to the total reflected sound (Peters et al. 2019) and can be extracted from the attenuation curve provided by the exponential-power formula and measured in a room with uneven distribution of absorption wall qualities (Lavrova and Kanev 2020). The definition of sound scattering surfaces, associated diffusion coefficients and methods of measurement have been internationally agreed upon under ISO (2012) due to its importance. The scattering coefficient is also very important in providing accurate simulation results for computational simulations conducted (Peters et al. 2019). A relationship exists between the depth of a surface geometry in relation for the optimal sound frequency scattering to occur (Cox and D'Antonio 2009). Any surface detailing can have an impact on the scattering performance (Peter and Olesen 2010).

Sound Scattering equation (Cox and D'Antonio 2009):

$$s = \frac{\alpha_{spec} - \alpha_s}{1 - \alpha_s}$$

| | |
|---|---|
| $s$ | is the Scattering Coefficient |
| $\alpha_{spec}$ | is the Apparent Specular Absorption Coefficient |
| $\alpha_s$ | is Absorption Coefficient |

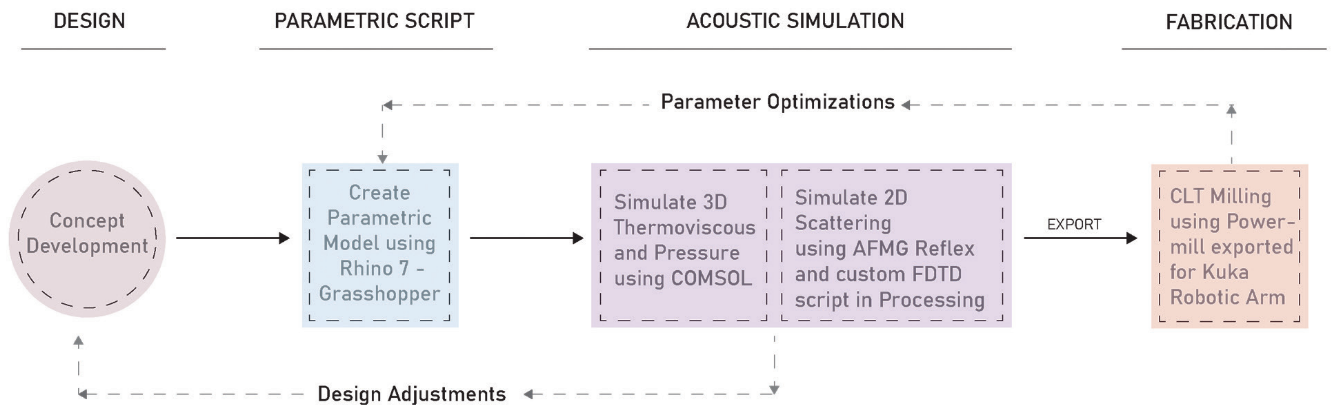
Absorption Coefficient equation (Cox and D'Antonio 2009):

$$\alpha = 1 - |R|^2$$

| | |
|---|---|
| $\alpha$ | is the Absorption Coefficient |
| $\lvert R \rvert$ | is the Magnitude of the Pressure Reflection Coefficient |

#### Mass Timber

The origins of utilizing mass timber as a construction material date to the period of the Mesopotamians during 3400 BC (NRC 2021). During this time, wood strips were glued together at opposing angles, which is similar in form to current day mass timber products called Glued Laminated Timber (GLT) or Cross Laminated Timber (CLT). In recent time, technological advances in assembly methods and manufacturing have allowed mass timber products to innovate rapidly to a point where numerous high rises are currently under construction or being proposed (Kesik and Martin 2021). The key development to this new mass timber technology is that it consists of a family of products that can be interconnected to other smaller mass timber elements, allowing for larger systems to




**2** Workflow diagram

be formed. The benefit of this approach is that the primary load-bearing structure is not limited to just solid wood but can be combined with engineered lumber products. The label *engineered lumber* refers to composite materials where the dominant material is based on soft woods (Kesik and Martin 2021). The use of composite materials allows architects to design for more idealized forms consisting of complex geometries for structural elements such as beams, columns, arches, roofs, floors, and walls. In recent years the demand for more sustainable building materials has seen increased interests as the environmental costs of concrete and steel constructions projects have become more apparent as made evident by the Paris Climate Agreement to call for a carbon free environment by 2050. In order for this deadline to be met, architects need to actively use building materials with lower embodied carbon emissions. The use of carbon sequestering materials such as mass timber is a beneficial alternative option as global forests store a large quantity of the planets carbon and any building constructed out of mass timber continues to retain it too. It is widely known that the building industry is a significant contributing factor to climate change (Dangel 2017), which is why mass timber is such an appealing material to address the problem. Many architects have already begun to design entire high-rises using primarily mass timber as the main building material (Orta et al. 2020). This strategy of using entire mass timber buildings will introduce unique acoustical challenges as mass timber assemblies are not as dense as concrete, allowing for the transmission of sound to travel across floors, ceilings, and walls. This is especially true for lower frequencies, which provides an opportunity for the integration of Helmholtz resonators and sound scattering surfaces to be implemented as a solution.

## METHODS

The methods used in this investigation builds upon our experience and knowledge gathered in prior and ongoing research related to Parametric Acoustics (Peters et al. 2010), Surface Scatter (Peters et al. 2019), Simulation Techniques (Peters and Nguyen 2021), Helmholtz Resonators (Cop, Nguyen, and Peters 2021), and Acoustic Metamaterials (Cop, Nguyen, and Peters 2022).

### Parametric Modeling

3D modeling was conducted in Rhinoceros 3D (McNeel et al. 2010), where data derived from acoustic simulation software was used to inform Grasshopper scripts for parametric geometry creation that could be generated for the sought-after acoustic performance qualities. Controllable parameters were hex depth, diameter, neck width, neck depth, increment size, and cluster quantity. The use of a parametric model allows for quicker and precise generation of options using manual slider adjustments or in combination with genetic algorithms plugins such as Galapagos (refer to Figure 2 for workflow integration).

### Ray-based Acoustic Simulation

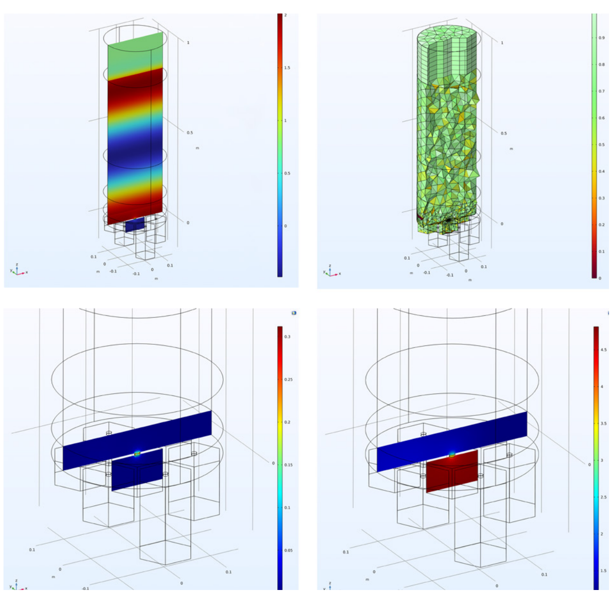
Room acoustic performance simulations are divided into two categories: wave-based and ray-based (Siltanen et al. 2010). The ray-based approach abstracts sound travel as linear reflections and is computed using the geometric method. This method is the most common approach in which architectural acoustic performance is predicted and used in most commercial room acoustic simulation software packages. A shortcoming to the ray-based approach is that it cannot be used to simulate for the performance of resonators and requires the complete values for all absorption coefficients. This makes the ray-based approach more suitable to study scattering surfaces for room acoustics.

### Wave-based Acoustic Simulation

Wave-based simulation methods utilize numerical modeling to predict solutions for the wave equation as it is unable to solve it directly. 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). Numerical techniques involve the discretization of a space which makes for a computationally intensive calculation. In this study, the FEM software COMSOL Multiphysics (Littmarck and Saeidi 2022) was used to model the acoustic wave interaction with the Helmholtz resonator geometry, while a customized FDTD script using the Processing(p3) language was used to animate the wave propagation against the scattering surface, and the BEM software AFMG Reflex (Ahnert and Feistel 2011) was used to conduct two-dimensional scattering studies.

### 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 material's reflection and absorption coefficient. In architectural acoustics practice, the impedance of a material sample is analyzed in a physical impedance tube. An impedance tube consists of a loudspeaker installed one side of the tube, a material sample is positioned on the opposite side of the tube, and microphones to measure the reflected sound intensity are placed in between. By implementing the acoustic transfer function, two measurements are related, and the absorption and reflection coefficients can be calculated. Mainstream impedance tubes are limited to diameters ranging from 16 mm to 100 mm, requiring prototypes to be scaled due to the physical limitations. In contrast, a benefit of utilizing a virtual impedance tube is that geometries can be prototyped at 1 to 1 scale allowing for reliable simulation results. In this study a virtual impedance tube was created in COMSOL using a perfectly matched layer on the top of the tube, where an infinite tube was simulated. This yields more accurate results as compared to a finite tube length. A background pressure field is assigned to establish the incident plane wave, which interacts with the virtual hex samples that are positioned at the end of the tube. The reflected energy is virtually measured and the energy of the incident plane wave is known, then the reflection and absorption coefficient can be derived. The virtual impedance tube was set up to calculate the absorption and reflection coefficient as can be seen in Figure 3.



3 Virtual Impedance Tube setup within COMSOL for pressure acoustics

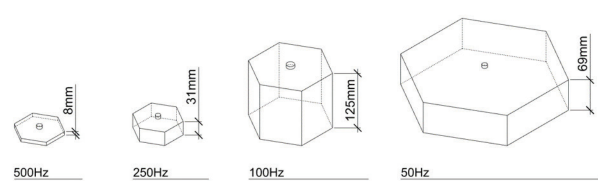
### Digital Fabrication

New commercially available systems with varying levels of prefabrication have been created by the construction industry, which are targeting multi-story residential and commercial buildings (Kesik and Martin 2021). The prefabrication of mass timber assemblies within open floor building system that are flexible and customizable require the increased use of computer-controlled materials handling. The use of these fabrication equipment ensures the quality and precision of products for smooth assembly on site (Dangel 2017). The innovative use of mass timber in this context of prefabrication to a high degree of precision offers a stronger coordination between architects and fabricators. This high precision process and relative ease of multi-axis milling is providing new approaches to ornamentation and performance-based design.

## RESULTS AND REFLECTION

### Parametric Helmholtz Resonator Model

The Helmholtz resonator designs were based on results of select single band frequency simulations, where spatial parameters such as hex diameter, depth, and neck sizes were adjusted, see Figure 4. These results informed configuration layouts of hex clusters specialized for broadband absorptions. The frequencies of study ranged from 50 Hz to 500 Hz at 25 Hz intervals for single band frequencies and broadband frequencies ranged from 100 Hz to 750 Hz at 5 Hz and 25 Hz intervals.




4 Hex resonator types, 1:1 Scale (100 mm)

### Simulating Absorption at Single Frequencies

The single band frequency study achieved absolute absorption at 500 Hz as is seen from the absorption coefficient chart in Figure 5, Hex Resonator6. At 250 Hz and 100 Hz the frequency absorption coefficients of 0.95 and 0.92 were achieved respectively. In terms of interval rate, our prior experience conducting Helmholtz resonator studies for cubic and rectangular shaped volumes showed that 50 Hz intervals were sufficient. However,

## Hex Resonator 1

Frequency: 50 Hz
Interval: 25 Hz
Neck Length: 7.5 mm
Volume: 8839181 mm³
Depth: 58 mm

## Hex Resonator 2

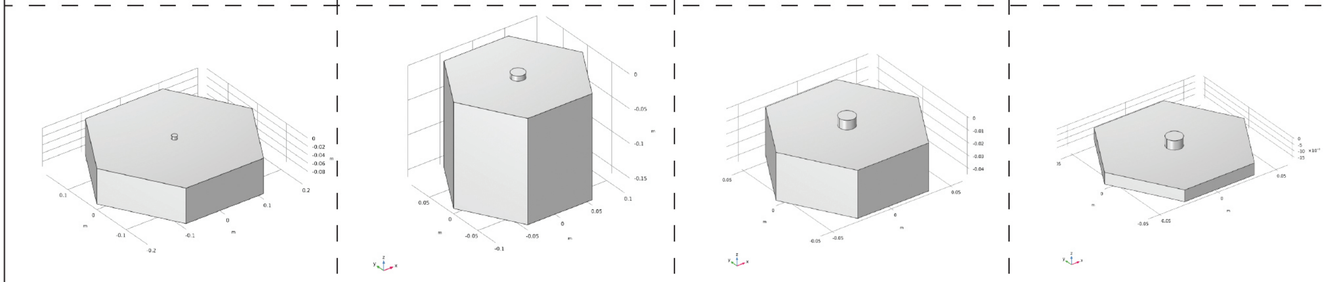
Frequency: 100 Hz
Interval: 25 Hz
Neck Length: 7.5 mm
Volume: 3983919 mm³
Depth: 153 mm

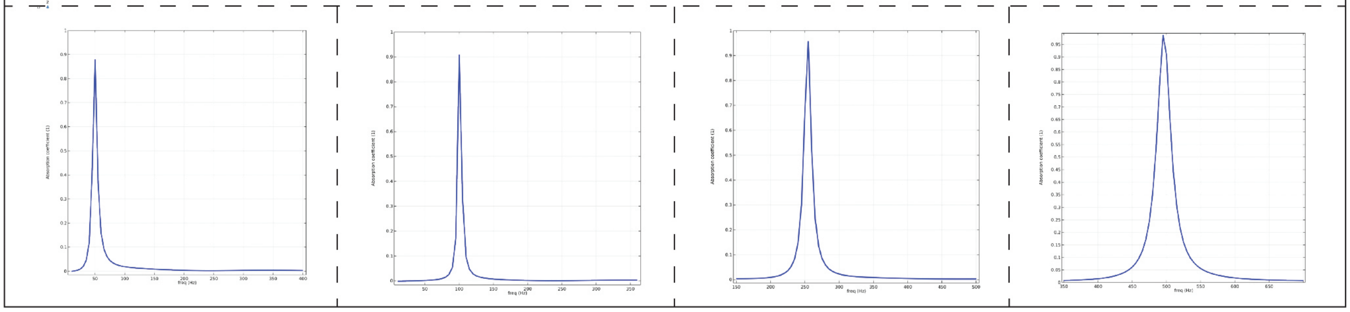
## Hex Resonator 3

Frequency: 250 Hz
Interval: 25 Hz
Neck Length: 7.5 mm
Volume: 353567 mm³
Depth: 38 mm

## Hex Resonator 4

Frequency: 500 Hz
Interval: 25 Hz
Neck Length: 7.5 mm
Volume: 8839181 mm³
Depth: 58 mm





5 Single band frequency absorbers

## Hex Resonator A

Frequency: 400 - 490 Hz
Interval: 5 Hz
Neck Length: 7.5 mm
Min. Volume: 51213 mm³
Max. Volume: 70134 mm³
Min.Depth: 27 mm
Max.Depth: 36 mm

## Hex Resonator B

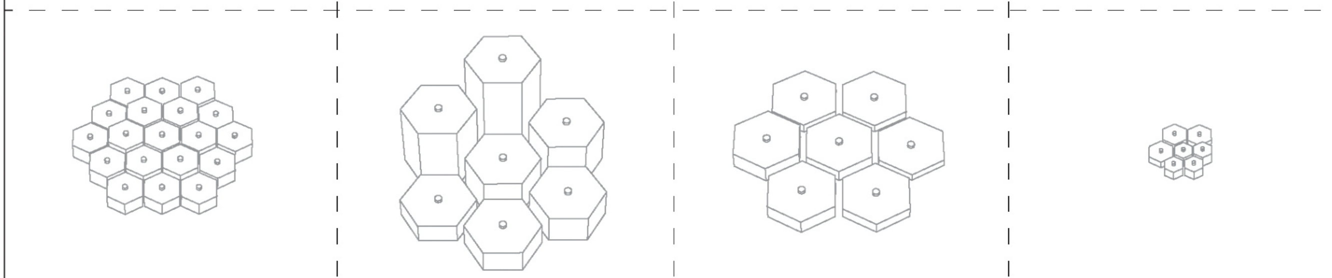
Frequency: 125 - 275 Hz
Interval: 25 Hz
Neck Length: 7.5 mm
Min. Volume: 256423 mm³
Max. Volume: 1239830 mm³
Min.Depth: 37 mm
Max.Depth: 163 mm

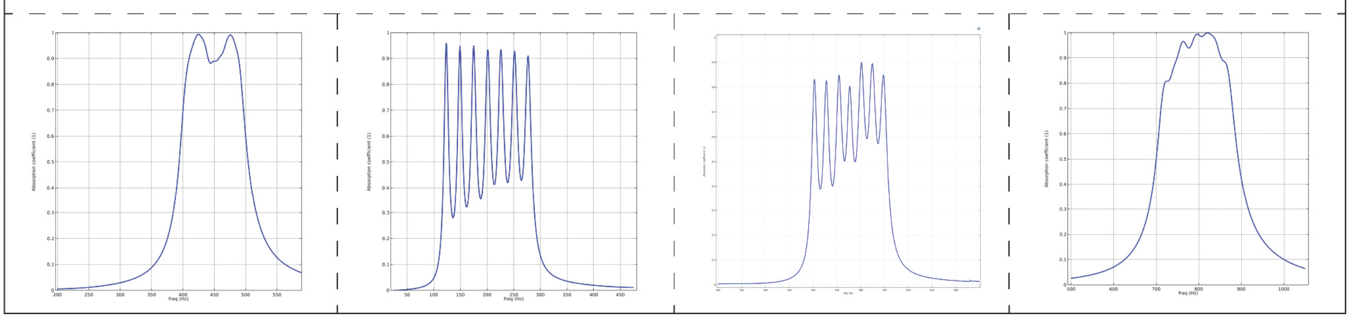
## Hex Resonator C

Frequency: 300 - 450 Hz
Interval: 25 Hz
Neck Length: 7.5 mm
Min. Volume: 95969 mm³
Max. Volume: 215519 mm³
Min.Depth: 16 mm
Max.Depth: 32 mm

## Hex Resonator D

Frequency: 700 - 750 Hz
Interval: 25 Hz
Neck Length: 7.5 mm
Min. Volume: 9386 mm³
Max. Volume: 13805 mm³
Min.Depth: 15 mm
Max.Depth: 23 mm



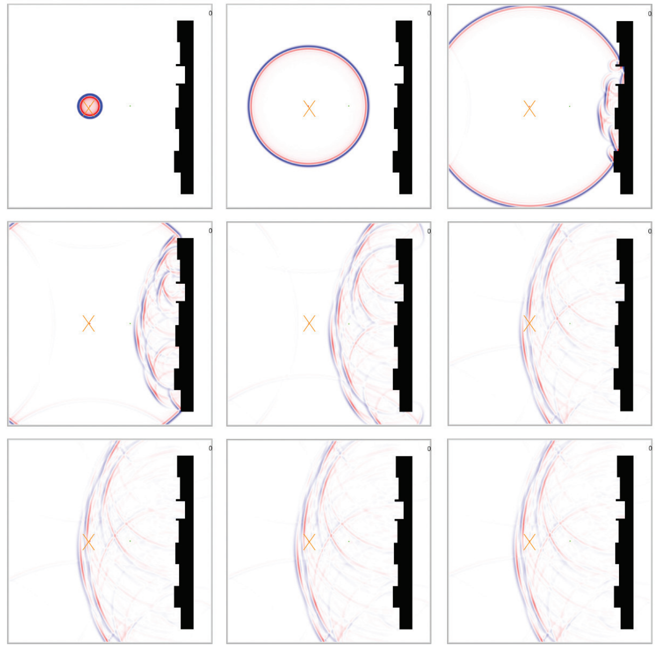


6 Broadband frequency absorbers

this hexagonal geometry investigation revealed that an interval frequency of at least 25 Hz was required to achieve broadband absorption results as indicated in the charts in Figure 6.

### Simulating Absorption at Multiple Frequencies

Using results extracted from the single band frequency absorbing geometries, hexagonal dimensions were modified to achieve broadband absorption as seen in Figure 6, Group A, where certain size hex resonators required lower than the average 25 Hz interval, at 5 Hz to achieve optimal performance. Neck lengths remained the same through the investigation due to the CLT layer thickness minumums after milling. The best performing group of broadband absorption occurred for the 700 to 750 Hz frequency as most of the absorption coefficient remained above 0.8, see Figure 6, Group D. The lower 125 Hz to 275 Hz and 300 Hz to 450hz frequencies did achieve suboptimal performance for broadband absorption as increased drops in absorption coefficient values are noted, as seen in Figure 6, Groups B and C.



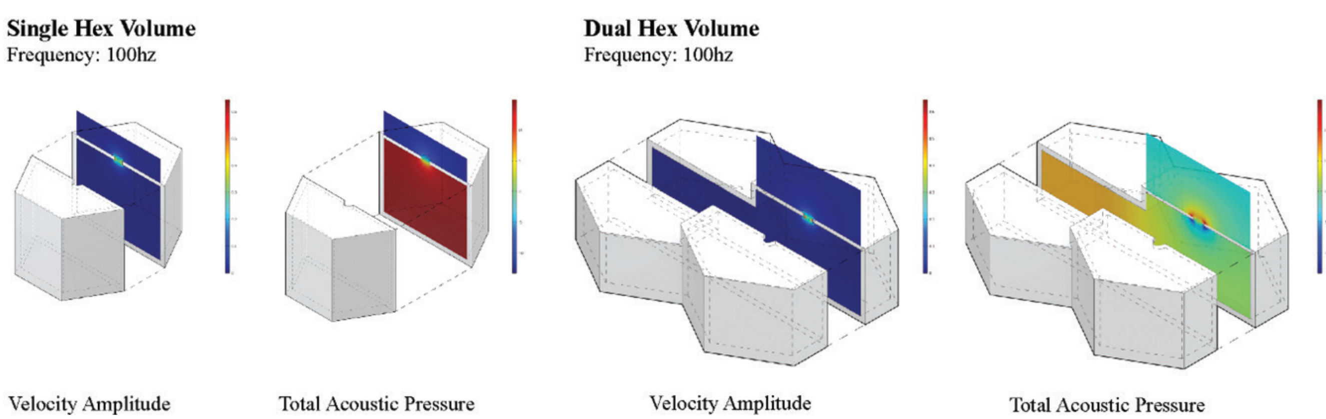
8 Finite Difference Time Domain scattering simulation against Hex section

### Acoustic Absorption Performance of Coupled Hex

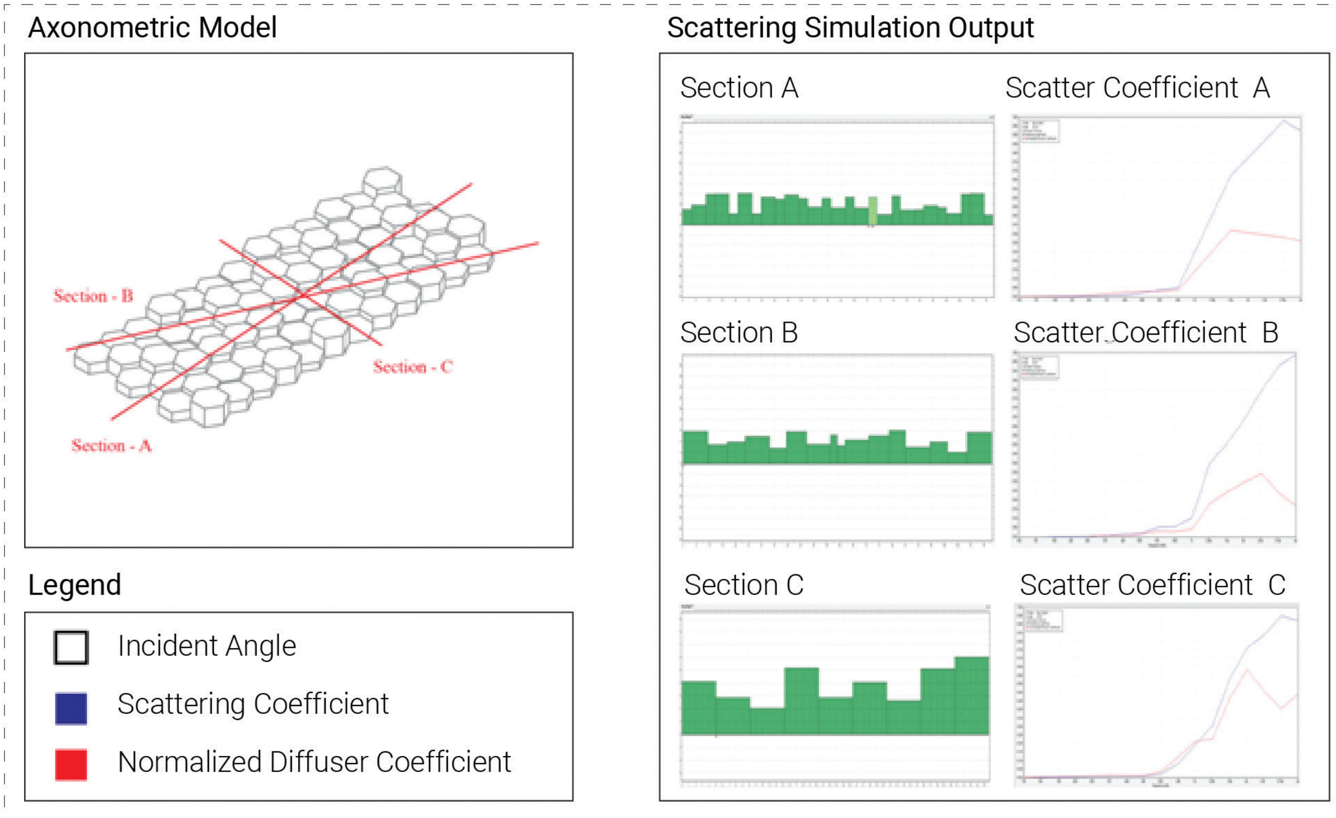
The coupling and sharing of hexagonal volumes were also tested in dual configuration to see if shallower volumes could be combined and leveraged to capture various frequencies that are not attainable of the individual volumes. In Figure 7, a comparison between a single and coupled hex can be seen where the Velocity Amplitude displays faster moving air at the neck and stale air inside the volume for the energy to dissipate. The Acoustical Pressure diagram shows us the pressure disparity between inside of the resonator volume and the outside, forming the air spring and oscillating actions to occur. The increased air velocity in the narrow region of the neck causes thermo-viscous damping to transpire at resonance at the boundary layer near the walls of the neck region.

### Scattering Performance of Hexagon Geometries

An approach to study sound scattering performance is to visualize the procedure. A custom Finite Difference Time Domain program that was developed inside Processing to demonstrate the visualization approach. In Figure 8, stills from the animation were created to document how the sound energy is dispersed spatially and temporally as the reflections are




7 Single Hex and Shared Hex Volume studies




9 AFMG Reflex simulation output

spread throughout the space and come back to the listening positions numerous times as seen by the red and blue waves hitting the orange X.

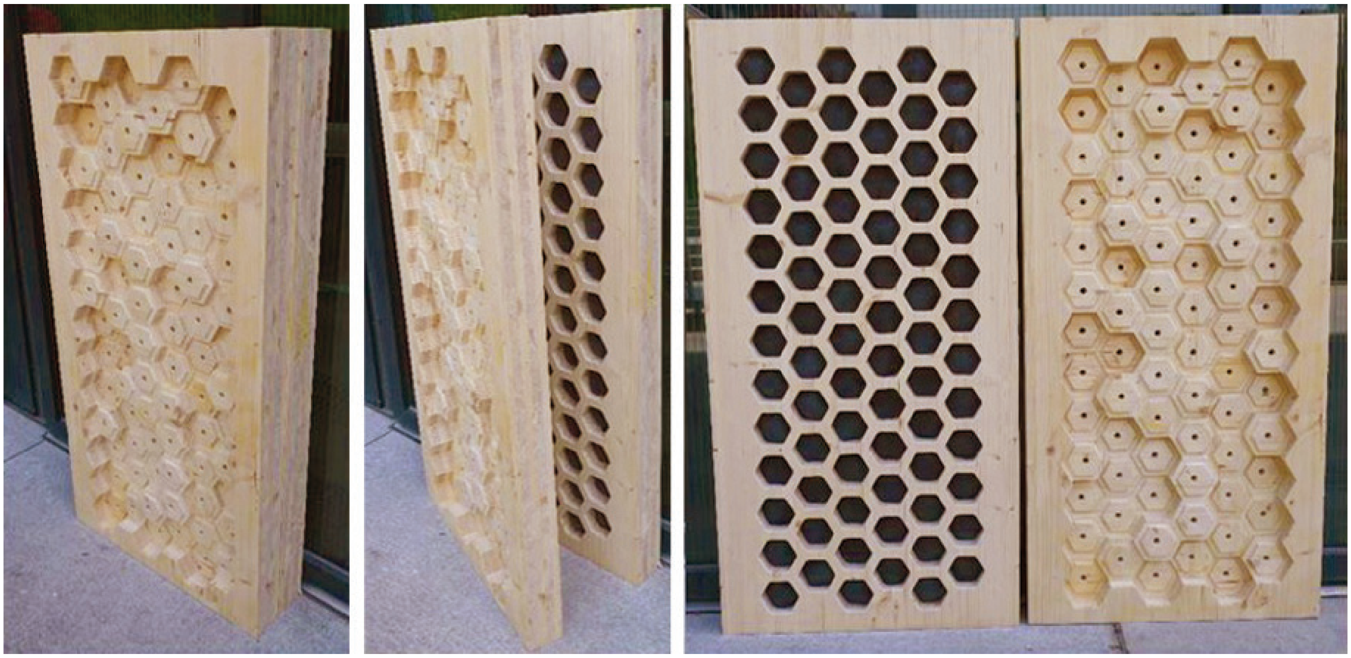
Another approach to measure surface scattering is through the use of BEM simulation inside AFMG Reflex. The sound scattering simulation results showed that the hex geometries provided scattering in lower frequencies while maintaining strong scattering tendencies in the upper frequency ranges, refer to Figure 9. The shallow hexagon regions also showed good scattering from 200 kHz and above, and the deep hexagon from 630 Hz and above. The AFMG Reflex software also demonstrated that all the surfaces had good scattering performance at the incident angle. An issue encountered with the BEM simulation software Reflex is that it does not allow for geometries to be imported, forcing geometries to be recreated in a time-consuming manner within the software.

### Fabrication Experiments

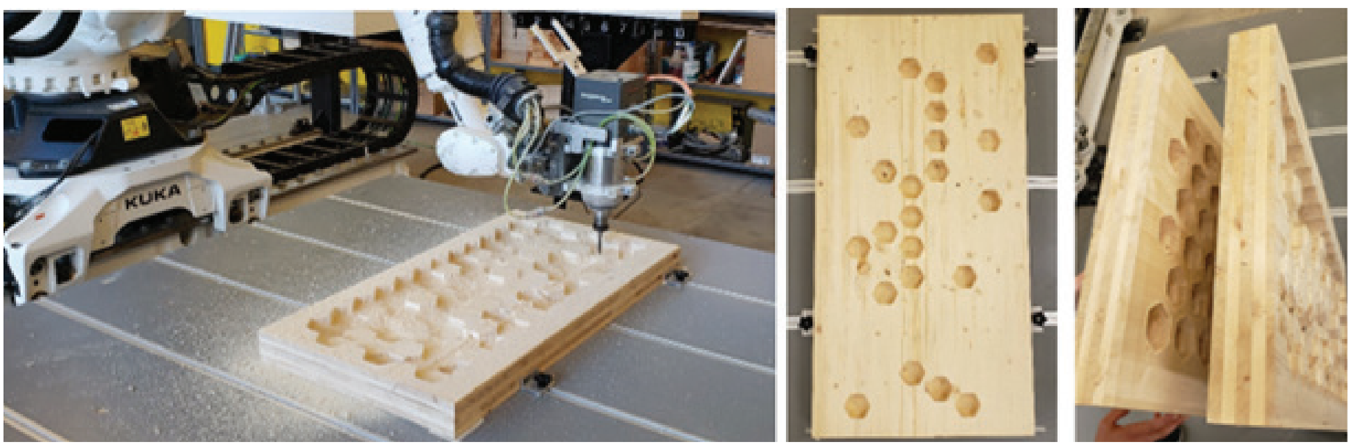
Using results from the Helmholtz resonators and surface scattering experiments, we proceeded to produce a 1 to 1 scale prototype out of CLT using a PushCorp 10hp spindle end effector connected to an industrial grade Kuka KR150 R2700 robotic arm situated on a KL4000 linear axis with a movement range of 4500 mm. Although the established design is supposed to be one unified CLT assembly, the fabrication procedure requires two separate CLT blocks to be milled with the scatter facing side requiring a flip mill process to maximize available hex well depths prior to gluing the pieces back together, see Figure 11. It is important to note that this specific project can also be manufactured using a computer numerically controlled (CNC) router with more optimized milling routines. The choice to utilize a robotic arm for this research was primarily due to accessibility and logistical reasons. The final result can be seen in Figure 10, where the image on the left side displays the finished product after being combined together into one CLT block. The middle and right image show how the scattering surface has neck openings drilled into the surface to create a direct connection to the honeycombed volumes of the accompanying CLT panel, allowing for air spring actions to occur. To increase broadband absorption for frequencies that dropped below an absorption coefficient of 0.5, it was decided to insert high density acoustic foam towards the base of all volumes on the honeycombed backplate.

### Future Work

The next step in this research will be to use the data acquired from this investigation to develop new design patterns for acoustic testing, and to fabricate a full wall assembly to be installed within a space using CLT to record physical acoustic measurements for the validation of our simulation results.



**10** CLT Hex scatter panel flip milling using a Kuka robotic arm




**11** CLT Hex scatter panel flip milling using a Kuka robotic arm

Future scattering simulations will be tested in COMSOL Multiphysics using 3D Scattering to overcome AFMG Reflex's limitations of two-dimensionality to provide for improved acoustic performance accuracy. The outlook is to develop a system for mass timber assemblies that can combine Helmholtz resonators, surface scattering with acoustic metamaterials for optimization of tunable gradient acoustic surfaces as seen in Figure 12.

## CONCLUSION

The key contribution from this paper is a novel approach where sound design strategies are combined to leverage well depth requirements of surface scatterers as Helmholtz resonant cavities to create prefabricated CLT assemblies that are sustainable and functional in improving room acoustics. Unlike systems with exclusive absorption or scattering behavior, our combined approach addresses both the reflected and transmitted sound fields in mass timber architecture to produce a more comfortable sound environment. The absorption behavior and the diffusive characteristics result from geometric proportions and are therefore directly addressable and tunable. Gradient acoustic performance across a surface ranging across frequency and sonic behavior is attainable. This research establishes a workflow where data from COMSOL, FDTD, and AFMG Reflex simulations inform CAD dimensions of 3D models adjusted through parametric modeling parameters inside Grasshopper to produce a milled CLT sonic surface. This paper displays the

12 Open office floorplan with a CLT wall consisting of hexagonal Helmholtz resonators coupled with Schröder diffusers and scattering surfaces

outcomes of our investigation of prefabricated mass timber assemblies to produce tuned gradient sound surfaces for sound absorption, diffusion and reflection. The relationship between digital forms to physical manifestation also revealed challenges and opportunities where two separate CLT panels could be strategically processed and combined as not just an acoustic performance solution, but also a space saving option for spaces with limited or restricted surface space such as airports or open floorplan offices (Figures 1 and 12).

## ACKNOWLEDGMENTS

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