# Tunable Acoustic Properties in Reconfigurable Kerf Structures

Di Liu[1], Zaryab Shahid[2], Yung-Hsin Tung[3], Anastasia Muliana[4], Youngjib Ham[5], Negar Kalantar[6], Theodora Chaspari[7], Ed Green[8], James E. Hubbard[9]

## Abstract

Freeform structures are appealing in architecture owing to their ability to combine pleasing aesthetics and functionality. Regarding architectural functionality, freeform structures have the potential to meet desired acoustic requirements in indoor architecture through the proper design of materials and geometries. Kerfing is one of the practical methods to generate reconfigurable freeform structures from rigid planar construction materials. This study aims to explore tunable room acoustic characteristics through the use of kerf structures. In this study, we investigate acoustic responses of kerf structures out of a medium density fiber (MDF) board having a hexagon spiral kerf pattern with varying cut densities. Experiments are conducted to measure the acoustic properties (e.g., absorption coefficient) of the kerf unit cells with different cut densities. We then

[1]Ph.D. Student, Department of Construction Science, Texas A&M University, 3137 TAMU, College Station, TX 77843; E-mail: catsquito@tamu.edu

[2]Ph.D. Student, J. Mike Walker '66 Dept. of Mechanical Engineering, Texas A&M University, College Station, TX, 77843, U.S.A., email: zaryab94@tamu.edu

[3]Former Bachelor Student, Department of Multidisciplinary Engineering, Texas A&M University, College Station, TX, 77843, U.S.A., email: yhc.tung@tamu.edu

[4]Linda & Ralph Schmidt '68 Professor, J. Mike Walker '66 Dept. of Mechanical Engineering, Texas A&M University, College Station, TX, 77843, U.S.A., email: amuliana@tamu.edu

[5]History Maker Homes Endowed Associate Professor, Department of Construction Science, Texas A&M University, 3137 TAMU, College Station, TX 77843; E-mail: yham@tamu.edu (Corresponding Author)

[6]Associate Professor, Architecture Division, California College of the Arts, San Francisco, CA 94107, U.S.A., email: kalantar@cca.edu

[7]Assistant Professor, Department of Computer Science and Engineering, Department of Computer Science and Engineering, Texas A&M University, College Station, TX, 77843, U.S.A., email: chaspari@tamu.edu

[8]Principal Consultant, Hottinger Bruel & Kjaer Inc, Canton, MI, 48187, U.S.A., email: ed.green@hbkworld.com

[9]Professor, J. Mike Walker '66 Dept. of Mechanical Engineering, Texas A&M University, College Station, TX, 77843, U.S.A., email: jhubbard@tamu.edu

design kerf patterns using the parametric design method and explore the flexibility of kerf structures with different kerf cut densities. We model the kerf structures of varying kerf cut density and shape reconfiguration and use a ray-tracing simulation to study their impacts on the acoustic performance i.e., reverberation times (RT) of a small office space. Overall, this study leverages the unique attributes of kerf structures such as different cut densities and shape reconfigurations to tune the room acoustics in addition to their usage in indoor architectures due to their pleasing aesthetics.

## 1. Introduction and Background

The acoustic performance is a major component of the architectural design that should consider occupant's comforts and needs (Varjo et al. 2015). For example, noise pollution in space is detrimental to the occupants' performance, health, and well-being. Moreover, a study has shown that increasing human performance in an office environment can boost the U.S. economy by $450 to $550 billion annually (Hung 2017). Architects and acousticians have developed various types of materials and structural configurations to meet the acoustic requirements of indoor spaces. Recently, freeform structures which are known for their aesthetic appeal are primarily being used in indoor architectures to control acoustic performance. For example, Vercammen used concave and convex surfaces which can focus and diffuse the sound waves, thus, amplifying and reducing the sound effects as desired (Vercammen 2013). Similarly, Peters et al. designed, fabricated, and tested responsive acoustic surfaces which is a system of trihedral folded plates that have hard reflective Dibond and sound absorbent surfaces to create sound-amplified and sound-dampened zones respectively (Peters 2011). Belanger et al. studied the effect of curvature on the acoustic properties of glass panes formed by the combination of parametrically driven auxetic pattern generation (Belanger 2018). They concluded that the curved panes could influence the room acoustics, as well as control the distribution of acoustic energy.

The kerfing technique, also known as relief cutting, is used to create flexible freeform structures from stiff planar materials such as metal and processed woods (Medium Density Fiberboard (MDF), plywood) (Zarrinmehr et al. 2017a; b; c). The kerf structures are commonly used in both indoor and outdoor architectural design due to their pleasing aesthetics and their ability to be reconfigured in any complex nonplanar shape (**Fig. 1.**). There are a variety of complex kerf patterns such as spiral, Archimedean squares, and hexagon patterns (Capone and Lanzara 2018; Kalantar and Borhani 2018). The interplay between kerf patterns and cut densities is used to vary the stiffness of the kerf structures (Chen et al. 2020). As the kerf structures can be easily reconfigured into any non-planar shape, they have the potential to vary the acoustic environment of the space on demand. Recently, Holterman experimentally studied sound absorption coefficients and reverberation times of kerf cells and beams with different cut gaps and bending curvatures at frequencies 125-4000 Hz. Varying cut gaps and bending curvatures altered the reverberation time and absorption coefficients, and the amount of changes was frequency-dependent (Holterman 2018). Overall, Holterman’s study showed the potential of kerf structures in manipulating room acoustic characteristics. Future study needs to investigate the influence of multiple kerfing parameters such as the kerf density, kerf pattern, and shape reconfiguration on altering the acoustic properties of the kerf structures and their impact on room acoustic characteristics. Recent studies have shown that kerf-cut densities and materials influence the modal frequencies and shapes of the kerf cells and panels, and reconfiguring the cells and panel shapes altered the modal frequencies and shapes (Shahid et al. 2021, 2022b; a). These findings showed the potential of reconfiguring kerf cells and panels for tuning acoustic properties. Further investigation of these kerf parameters is necessary as it not only allows the design researchers to clearly understand the dynamic relation between kerf structures and their acoustic responses but also enhances the adaptivity and responsivity of indoor acoustic design in practice. With an understanding of the overall effect of kerf structures on the indoor acoustic environment, architects and acousticians can deploy reconfigurable kerf structures according to the acoustic requirement of the indoor space.

## 2. Kerf Structure

Zarrinmehr et al. proposed an algorithm for remeshing 2D meander patterns to achieve local flexibility (Zarrinmehr et al. 2017b; c). Kerf patterns can be obtained from polygons such as Voronoi and hexagons. Kalantar et al. showed that facilitated with parametric adjustment, kerf panels can be utilized to create various types of formworks in architecture design to control the reconfigurability as desired (Kalantar and Borhani 2018). In this study, the hexagon spiral pattern is studied as shown in **Fig. 2.** The hexagon unit cell has a symmetric structure which makes it easier to layout and generates flexible kerf structures used in freeform architecture. The hexagon spiral pattern is laser cut on a stiff 3.175 mm thick MDF panel. The MDF is a composite material formed from chopped wood fibers pressed together and bonded with epoxy. MDF is a common material used in indoor architectures (Ivanovic-Sekularac et al. 2012; Jakimovska Popovska et al. 2016). The basic mechanical properties of the MDF panel are that the elastic modulus is 4 GPa, Poisson's ratio is 0.25, the tensile strength is 18 MPa, and the ultimate tensile strain is 0.5%.

The large kerf structures studied in this paper are made up of a hexagonal domain with triangular unit cells which have a side length of 25.4 mm and thickness of 3.175 mm as shown in **Fig. 2**. The hexagonal domain with triangular unit cells can be cut with different kerf densities depending on the desired flexibility and load-bearing capability (Chen et al. 2020). In this study, high density (HD), medium density (MD), and low density (LD) kerf densities are studied. Detailed information about the geometrical parameters of these kerf unit cells is shown in **Table 1**. The HD cut unit cell has a higher number of cutlines per unit cell compared to an MD and LD unit cell which leads to its higher air gap area. The HD unit cell will be more flexible which increases its reconfigurability but decreases load-bearing capacity (**Fig. 2.**). Additionally, the ratio of the air gap to total surface area is highest for the HD unit cell which leads to higher absorption compared to other unit cells considered in this study.

## 3. Methodology

In this paper, we study the attributes of kerf structures such as kerf cut density and shape reconfiguration which can be used to tune the acoustics of an indoor space. The kerfing technique is used to develop flexible freeform structures with different kerf cut densities. In this study, the flexible form of the kerf structure is designed building on the algorithm developed in Grasshopper3D named Relief Cut (Kalantar and Borhani 2018; Zarrinmehr et al. 2017a; b; c). Subsequently, acoustic properties of kerf structures (e.g., absorption coefficient) are experimentally determined using a custom-built impedance tube. The experimentally determined absorption coefficients are used in the ray-tracing simulations to study the effects of cut density and shape reconfiguration of kerf structures on the indoor acoustic environment, i.e., office space. From the ray-tracing simulations, acoustic properties used for indoor spaces such as Reverberation Time (RT) are determined to understand the effect of both kerf densities and shape reconfigurations of kerf panels on the overall room acoustic characteristics. Among various types of acoustic measurements, it is well-accepted that reverberation time (RT) is one of the most used metrics to reflect the room's acoustic performance in design. RT is quantified by material types and room geometries, and the range of RT is implemented depending on the room size and function.

The experimental tests for the absorption measurement of the kerf unit cells were performed at Bruel and Kjaer (B&K), Detroit, MI. A custom-built 3-D printed tube is used to test the specimens. The tube is connected with a 100 mm diameter B&K 4206T Impedance Tube using a reducer as shown in **Fig. 3**. The loudspeaker is placed at the bottom end of the setup and the kerf specimen is clamped in between the orange and black tube. The microphones are inserted at four different locations on the 3-D printed tube to measure the standing wave sound field and determine the absorption of the specimen. The 3200 Hz bandwidth is chosen for all the measurements and a similar procedure is repeated for different density kerf unit cells. Detailed discussion on the experimental test and characterization of the absorption coefficient is given in Olivieri et al. 2006.

The absorption coefficients for HD, MD, and LD MDF specimens are shown in **Table 2**. It can be noticed from the results that the LD unit cell has the highest absorption coefficient across the frequency range compared to HD and MD unit cells, although for frequencies 125 and 250 Hz, the difference in the absorption coefficients for HD, MD, and LD is not significant (less than 10% variation). As the LD unit cell has a more solid area (fewer cut lines) which leads to higher energy being absorbed and less sound energy being transmitted relatively, thus increasing the absorption coefficient. At the frequencies 500 and 1000 Hz, the absorption coefficients are relatively low (less than 0.5), which can result in more sound reflection compared to other frequencies, as will be shown later. We will explore whether kerf panels can be used to manipulate room acoustic properties at these frequencies. Additionally, the Noise Reduction Coefficient (NRC) is also calculated to compare the average absorption of kerf panels with different cut densities (**Table 2**). NRC is the average absorption coefficient from all frequencies.

## 4. Investigating Reconfigurable Kerf Structures for Small Office Acoustic

Small-sized office spaces, which are often found in renovated buildings, are commonly used for group study rooms or offices that can accommodate 2-4 occupants. Repurposing the spaces in renovated buildings can result in poor acoustic quality. Acoustic design for small office spaces preliminary focused on preventing undesired interior noise, ensuring speech intelligibility, and maintaining auditory comfort (Jaramillo and Steel 2015). The hearing frequency range is usually from 300 Hz to 3000 Hz (SEA n.d.) and the conversational speech frequencies are ranged from 250 Hz to 4000 Hz (Quam et al. 2012). It is well-accepted to use the reverberation time (RT60) which is the time required for sound in space to decay by 60 decibels (dB) to measure the room's acoustic performance. It has been recommended that the RT60 of indoor spaces should be less than 1 second (Jaramillo and Steel 2015). The space which has RT higher than 2 seconds is echoic, while lower than 0.3 seconds is acoustically dead. Some design guideline recommends the appropriate range of reverberation time for an office space is between 0.7s to 0.4s (Anna n.d.). According to WELL standard, indoor acoustic performance is specified by the optimal reverberation time to control the ambient noise and ensure the auditory comfort ("Reverberation time | WELL Standard" n.d.). The optimal reverberation time is associated with the room volume and function. For office and learning spaces no more than 260 $m^3$, the optimal RT60 should be no more than 0.6s ("Reverberation time | WELL Standard" n.d.).

The kerf structures can be reconfigured into various shapes due to their flexible nature to potentially control the room acoustic. In this regard, we examine how this unique attribute of kerf structures affects the acoustic response of a small office space. Among different shapes, curved surfaces have a great influence on the room's acoustics. Convex and concave shapes can render acoustic performance to be absorptive and reflective, as well as create various aesthetic features

(Vercammen 2013; Wulfrank et al. 2014). Concave shapes can cause sound amplification on the focusing point; while convex shapes can diffuse the reflected sound in different directions and balance the uneven sound distribution (Wulfrank et al. 2014). The implementation of curved shapes is often limited by material reconfigurability. Rigid materials often require extra frame structures and fabrication techniques to build into a curved shape. Kerf structures can address the challenges in fabricating curved surfaces out of rigid panels as they can be designed with controlled flexibility by changing kerf cut densities to enable for forming desired curved shapes. The flexible kerf structures can be easily reconfigured to potentially tune room acoustic characteristics. Limited efforts have been made to investigate how the curved kerf structure affects the room's acoustic characteristics.

We implemented the reconfigurable kerf structure for small office space (3m x 3m x 3m) and assessed how the designed parameters, such as kerf-cut densities and shapes of reconfigurations (i.e., flat, convex, concave, and a combination of convex and concave), affected the RT60 by using raytracing method. Further, we evaluated if occupants could be affected differently when their spatial positions were changed in the same office space.

### 4.1. Ray-tracing method validation

The acoustic evaluation of the kerf panels is performed using the ray-tracing method. The simulation is set up in Rhino3D for a small office with a size of 3m x 3m x 3m, which is commonly found in renovated buildings (**Fig. 4.**). Gypsum is selected as floor and wall materials. We first access if the different air gaps of kerf structures affect the acoustic results as well as the validation of the ray-tracing method. The air gap is measured by the distance between the ceiling and the suspended kerf structure. In the demonstration, the kerf panels suspended from the ceiling at 24, 12, and 6 mm are examined respectively. The measured absorption coefficients from the experimental tests are input into the model for the respective kerf density (**Table 2**). A point source of sound is located 0.5 m from the wall, and the receiver is at the center of the room as shown in **Fig. 4**. The positions of the sound source of the receiver mimic a simplified daily scenario with two people speaking in conversation, where the speaker is standing close to the wall and the listener is sitting in the center of the room. An acoustic simulation engine, the Pachyderm plugin in Rhino3D is used to conduct the ray-tracing simulations (Harten 2013). Convergence studies were conducted to empirically determine the sufficient numbers of rays and cut-off time, and in this study, 30,000 rays and a cut-off time of 10,000 ms were used for the ray-tracing simulations.

To validate the ray-tracing simulations, a theoretical model of the Eyring equation (Beranek 2006) is used to determine the reverberation time of a space having a solid MDF panel suspended at a 24 mm distance from the ceiling (Beranek 2006). The reverberation time from the ray-tracing simulation was compared to the one determined by the Eyring model. The Eyring equation uses absorption coefficients of the materials on the walls and ceiling materials to output the Reverberation Time. It is a common method used by acousticians to determine the reverberation time before using computer-aided simulation methods to understand the acoustic behavior of indoor space. It is evident from **Fig. 5.** that the ray-tracing simulations can capture the results from the Eyring equation at all frequencies. The percentage error of results between ray-tracing simulations and the Eyring equation at 125Hz, 500Hz, 1000Hz, and 2000Hz are less than 5%. The reverberation time increases up to a maximum value at the 1000 Hz frequency band and it starts decreasing at higher frequency bands (>1000 Hz). The validation analysis also helped us decide on simulation parameters such as rays, and the cut-off time for ray-tracing simulations, which are mentioned earlier.

## 4.2. Acoustic Performance for Different Air Gaps of Planar Kerf Panels

The acoustic performance of different densities (HD, MD, LD) of planar kerf panels is evaluated through ray-tracing simulations. RT60 caused by different densities of kerf panels and positions of kerf panels is measured. The results are compared to the responses of the solid panel, as shown in **Fig. 6**. By leveraging the kerf process, lower reverberation times (under 1 second) are achieved compared to solid MDF panels suspended from the ceiling. Also noted that at frequencies lower than 500 Hz and 2000 Hz, the RT60 of this studied room is low (around or less than 0.3) for all kerf panels, which is attributed to the high absorption coefficient (**Table 2**), and thus no further intervention is needed to tune room acoustic at these frequencies.

We can also observe that the desired RT60 can be achieved by having different positions and cut densities of kerf panels. For example, the LD kerf panel position at 24 mm from the ceiling achieved the recommended reverberation time for the office (<0.7s). Therefore, based on RT60 results in this analysis, the kerf panels suspended 24 mm will be a suitable option in indoor spaces where less echo and higher speech intelligibility is preferred. This analysis shows that varying the kerf cut density of the kerf panels has a marginal effect on RT60.

## 4.3. Acoustic Performance for LD and HD Reconfigurable Non-planar Kerf Structures

The reconfigurability of the kerf structure depends on the kerf-cut densities, higher cut density results in a more flexible panel, hence easier for shape reconfiguration into non-planar shapes. We used raytracing simulation to examine the influence of reconfiguring kerf panels on RT60 for a small-sized office. Specifically, we considered HD panels with the highest reconfigurability and LD panels with the lowest reconfigurability. Kerf panels suspended 24mm from the ceiling are selected for the simulation. We compared the acoustic performance of the HD and LD kerf structures, with flat and non-planar reconfigurations. The kerf structures were generated in Grasshopper3d. Specifically, the non-planar reconfiguration is modeled with four convex and concave kerf structure units to achieve a balanced sound distribution (**Fig.7a.**). A point source of sound is located 0.5 m from the wall with a height of 1.67m to mimic a standing speaker, and the receiver is in the center of the room with a height of 1m to mimic a sitting listener. The reverberation time of these reconfigurations is simulated. Results are discussed in **Section 5**.

### 4.4. Acoustic Performance for Reconfigurable Kerf Structures by Varying Occupant Positions

As it is common for a small office space to have multiple occupants or room layouts, it is important to understand if the office acoustic is consistent or adaptive by changing listener positions. We examined if RT60 of different non-planar reconfigurations would be varied along with changing the position of occupants. Here the HD kerf structure with 24mm suspended from the ceiling is chosen due to the highest reconfigurability among all three densities (**Fig.2**). Three types of non-planar reconfigurations are modeled and assessed: (1) multi-uniform convex reconfiguration, (2) multi-uniform concave reconfiguration, and (3) multi-mixed reconfiguration. For each type, multiple convex and/or concave units were included as shown in **Fig.8**. The 3D shapes of these non-planar reconfigurations can be referred to in **Fig.7a**. An omnidirectional sound source is placed 1.67m high from the floor, 0.5 m from the front wall, and 1.5 m to both sidewalls (**Fig. 9**). The position of the sound source was decided to be close to the wall aiming to mimic the speech voice standing next to one side of the room. Two parameters are taken into consideration to position receivers, namely, receiver height ($H_R$) and distance from a sound source to each receiver ($D_{SR}$). A total of four receivers at two heights (1m and 1.75m) are placed at 1m and 2m from the sound source, respectively (**Fig. 9**, **Table 3**). The first set of receivers, A ($H_{R\_A}$ = 1.75m) and B ($H_{R\_B}$ = 1) are placed at 1 m from the sound source ($D_{SR\_AB}$ = 1). The second set of receivers, C ($H_{R\_C}$ = 1.75m) and D ($H_{R\_D}$ = 1m) are placed at 2m from the sound source ($D_{SR\_CD}$ = 2). We examined several multi-uniform and multi-mixed configuration cases combining multiple convex and concave reconfigurations to achieve balanced acoustic results for each receiver. To do so, the ceiling area is evenly divided into sub-regions along the u direction and v direction, in which both u, v = 2, 3, 4, 5 (**Fig.8**). For example, when u, v = 2, the ceiling is evenly divided into four sub-regions. Convex or concave units are placed at each sub-region. Ray-tracing simulations are performed in Pachyderm for all shape reconfigurations at all four positions and reverberation time is determined. Results are discussed in Section 5.

# 5. Results and Discussion

## 5.1. Results of LD and HD Reconfigurable Non-planar Kerf Structures

**Fig.7b.** shows the office acoustic performance with varying configurations of kerf structure among the different kerf-cut densities. Significant differences in RT can be found between the flat surface and non-planar reconfigurations at 500Hz and 1000Hz, and non-planar reconfiguration yields much lower RT values than the flat surface for both HD and LD kerf structures. For both non-planar reconfigurations, RT values at 500 Hz and 1000 Hz range from 0.49s to 0.65s, satisfying the office acoustic design requirement that the reverberation time is between 0.7s to 0.4s. Additionally, for LD and HD non-planar reconfigurations, the significant difference in RT60 (>10%) can be found at 1000 Hz, and a marginalized difference (2% - 10%) can be found at 500 Hz. However, in both LD and HD non-planar reconfigurations insignificant changes in RT60 are seen at frequencies 125, 250, and 2000 Hz due to the high absorption coefficient (>0.5) at these frequencies. We conclude that for non-planar reconfigurations with four convex and concave units, kerf structures with different kerf-cut densities (HD and LD) can be used to tune RT60 to meet the office acoustic design requirement (0.7s to 0.4s) at 500Hz and 1000Hz which fall into the human hearing frequency range. Considering the HD kerf structure also has higher reconfigurability than the LD kerf structure, the HD structure is selected for the future reconfiguration test. This study also shows the potential of reconfiguring kerf panels to improve the room's acoustic condition at specific frequencies where an intervention is needed.

### 5.2. Results of Reconfigurable Kerf Structures by varying Occupant positions

It is evident from the results in **Fig. 10a** that reconfiguring kerf structures affects reverberation time. Although with reconfiguring the kerf ceiling, the trend of the reverberation time remained the same across the frequency range, the reverberation time varies for different shape configurations. Especially, for all twelve non-planar reconfigurations, the reverberation time shows a significant variation between different ceiling configurations at 500 Hz and 1000 Hz frequency bands among all four receiver positions. Due to the increase in overall surface area of 3x3 concave and convex reconfigurations compared to 2x2 convex and concave configurations, the total absorption of the indoor space increases ($A = S_n \alpha_n$). This leads to lower reverberation times for 3x3 concave and convex reconfigurations (0.51s at 500Hz, 0.6s at 1000Hz) compared to 2x2 configuration (0.56s at 500Hz, 0.65s at 1000Hz), especially at 500Hz and 1000Hz. Similarly, the reverberation time declines from 3x3 mixed shape to 4x4 mixed shape and 5x5 mixed shape ceiling. The 5x5 mixed-shape ceiling results in the highest surface area which increases the total absorption and thus leads to the lowest reverberation time compared to all ceiling shape reconfigurations investigated in this study. However, there is a marginal difference in reverberation times of 2x2 multi-uniform (convex, concave) and 2x2 multi-mixed configurations. Similarly, there is an insignificant difference between 3x3 multi-uniform (convex, concave) and 3x3 multi-mixed configurations. This is because with the same number of sub-divisions, the total volume and surface areas of indoor space ($A = S_n \alpha_n$) remain the same. Additionally, for all twelve non-planar reconfigurations, reverberation time remains similar at 125 Hz, 250 Hz, and 2000 Hz, which is attributed to the relatively high absorption coefficient of kerf panels at these frequencies as discussed above.

**Fig. 10b.** shows that RT60 is similar between different receiver positions. As the receiver heights or the distance between the receiver and sound sources are changed, the RT60 remains consistent. Thus, regardless of the receiver's spatial locations, the reverberation time declined as the ceiling area has increasingly reconfigured sub-divisions, and this is likely because of the small size of the room.

Overall, these results demonstrate that by reconfiguring the kerf structures into different geometrical shapes, the acoustic response of the indoor space can be altered depending on reconfigured space geometries and serve the specific purpose of the space. Considering the human hearing frequency range is usually from 300 Hz to 3000 Hz, the reconfigurability of kerf structures has the potential to actively adjust room acoustic characteristics to enhance the sound quality such as the RT60 at the frequency of 500Hz and 1000Hz to fulfill the hearing demand. Specifically, as the total area of the subdivided reconfigurable surface increases, the RT60 is lowered to optimize the acoustic performance. We can conclude that, for small office spaces, the reverberation time is dependent on the overall number of reconfigurable kerf units and independent of the occupant positions. Moreover, although a previous study shows that changes in reverberation time are frequency-dependent (Holterman 2018), it is more likely to occur only at certain frequencies (i.e., 500Hz, 1000Hz in this case study). Since the reconfigurable kerf structure is composed of various numbers of kerf units (n x n), it has the potential to be rapidly assembled and deployed based on different morphological and acoustic considerations and can be implemented as temporary structures to adapt to rich spatial functions and aesthetic requirements in buildings.

## 6. Conclusion

In this study, we explored the ability of kerf structures to tune the room acoustics in addition to their usage in small office spaces due to their pleasing aesthetics. We designed kerf structures made up of MDF with several cut densities (HD, MD, LD). To measure the absorption of MDF kerf structures, we conducted experiments on kerf unit cells in a custom-built impedance tube. To investigate how the kerf structure can improve the indoor acoustic for a small office, we modeled a small office space with kerf structures suspended from the ceiling with different kerf cut densities. The ray-tracing simulations are performed to determine reverberation time in the space having kerf panels installed on the ceiling. The measured absorption coefficients were used as input material parameters in the simulations. The results from these simulations demonstrate that the kerf cut densities affect the room's acoustic characteristics. As kerf structures are flexible and can be reconfigured to arbitrary freeform shapes, we investigated this attribute of kerf structures in altering the room's acoustic characteristics. We first investigated the compensated acoustic response caused by reconfigurability and kerf-cut densities, with multiple reconfigurations of non-planar kerf structures suspended from the ceiling of the space. Furthermore, we examined multiple non-planar reconfigurable structures by varying the occupant positions. It is demonstrated that the reconfiguring kerf structures influence RT60 such that the configuration with multiple area divisions has a better acoustic response, especially at 500 Hz and 1000 Hz if echo reduction is desired in space, and the acoustic response remains consistent regardless of the occupant positions. Overall, the desired acoustic response can be achieved by varying kerf cut densities and reconfiguring the kerf structures. The next step will be to explore the association between kerf structure dynamics reconfigurations and their acoustic response. Another future work will be to examine the acoustic response of these kerf structures when they are placed in multiple locations in a space with increased volume.

## Data Availability Statements

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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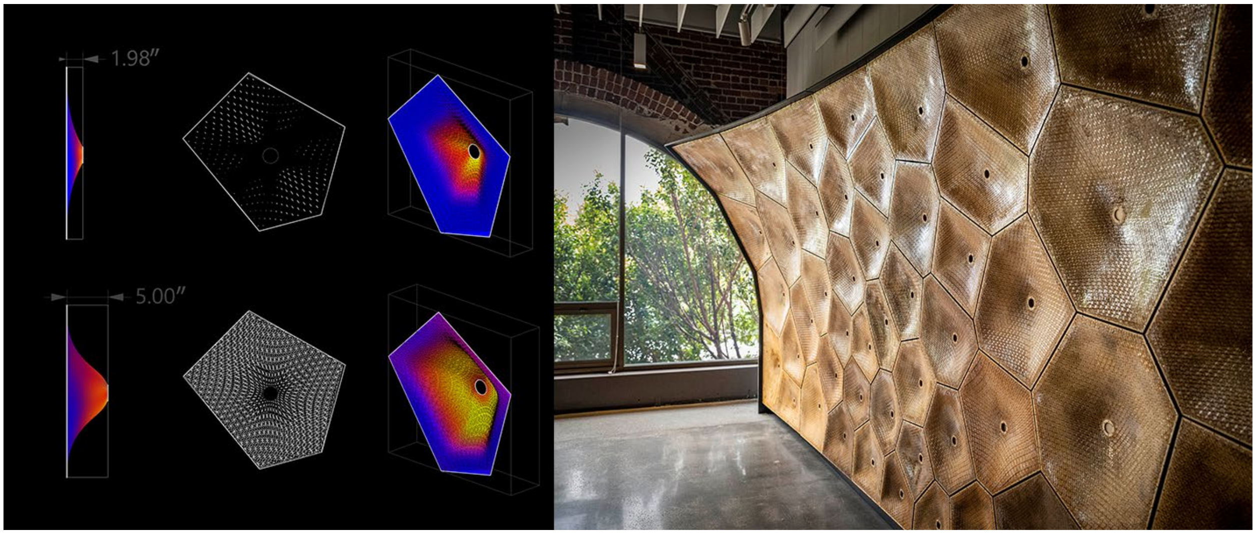



**Fig. 1.** Creating reconfigurable surfaces from kerf structures

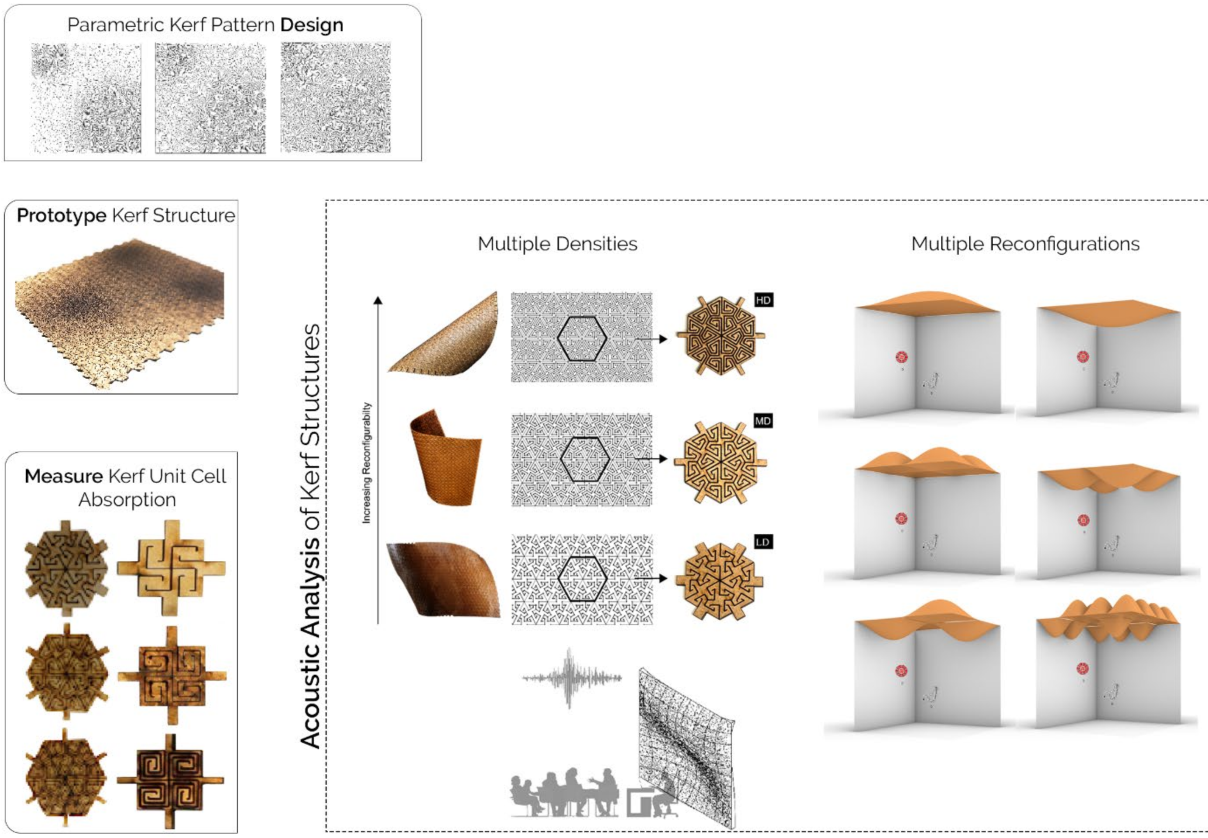



**Fig. 2.** Design and Assessment of Reconfigurable Kerf Structure

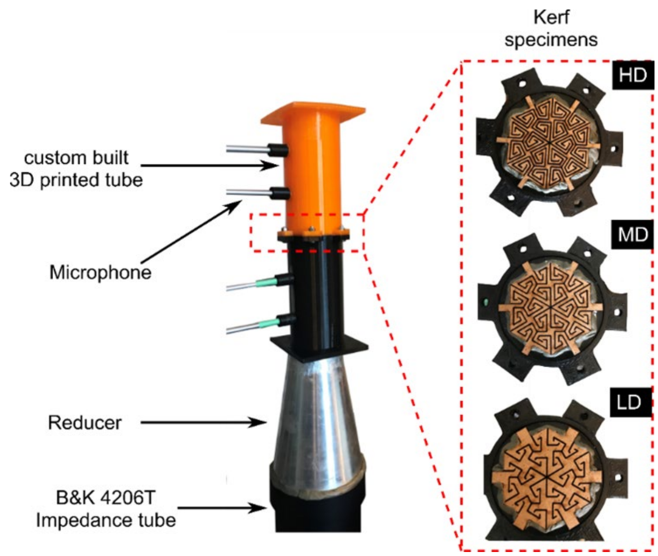



**Fig. 3**. Experimental test setup for measuring the absorption of kerf unit-cells using two-load method

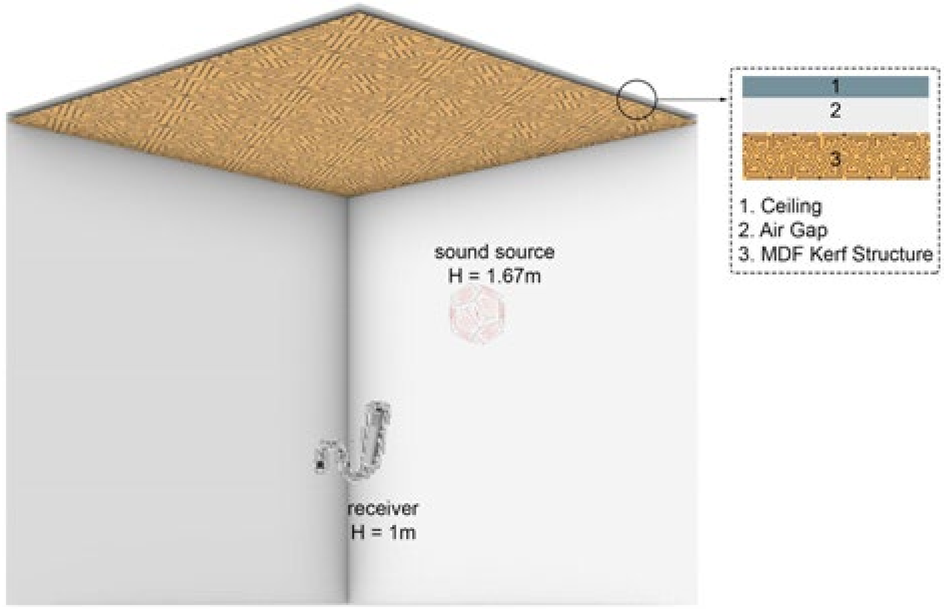



**Fig. 4.** Model set up for raytracing simulations

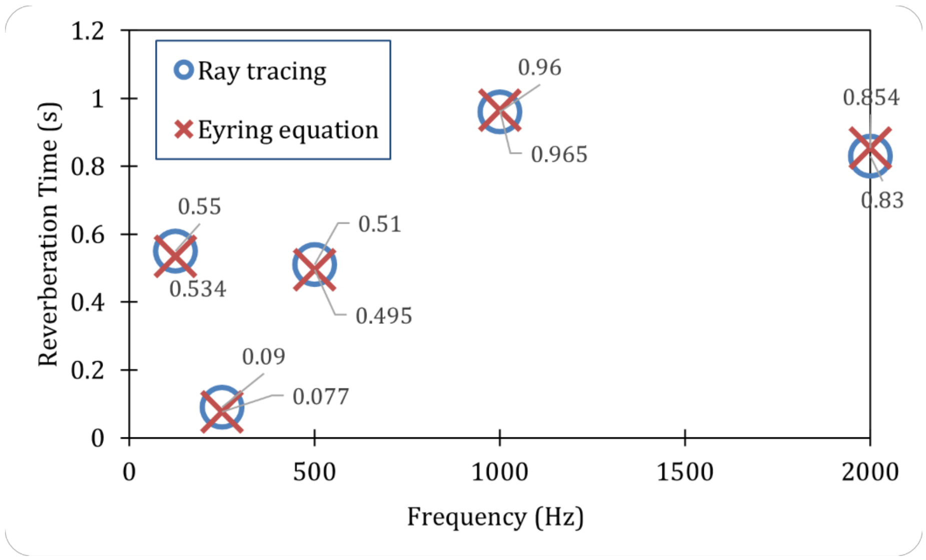



**Fig. 5.** Comparison of reverberation times from Ray-tracing simulation and Eyring equation method in a room with solid MDF panels suspended at 24 mm from the ceiling

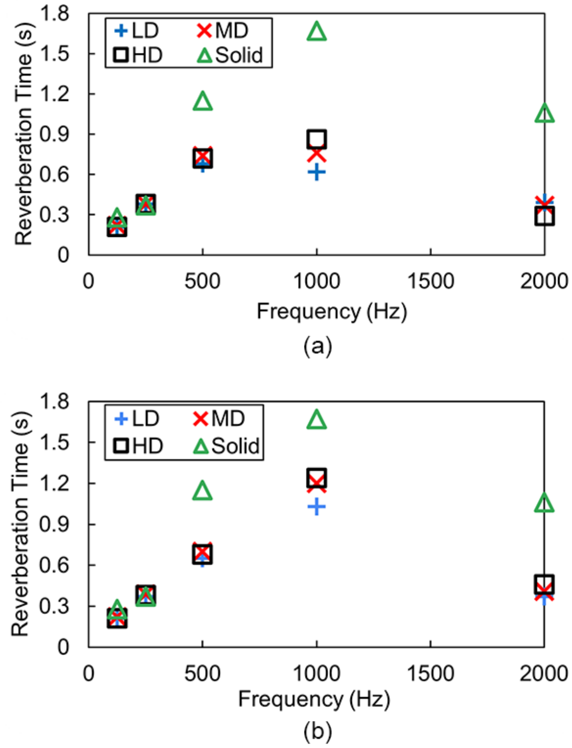
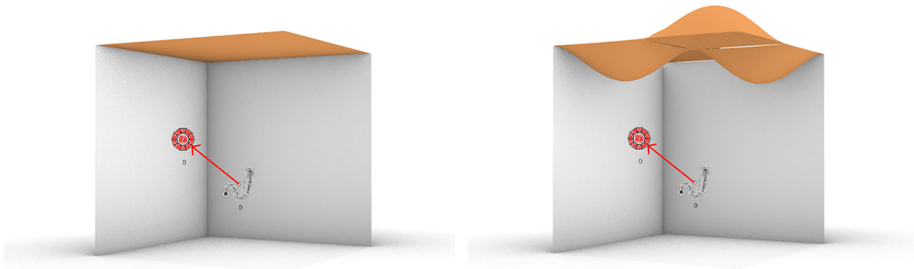
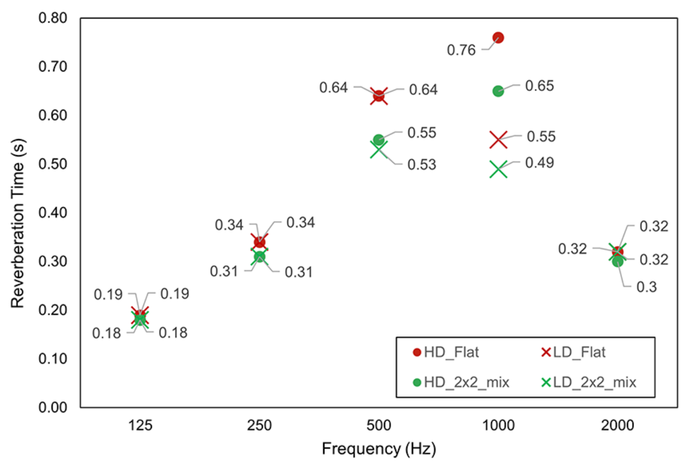



**Fig. 6.** Reverberation times from ray-tracing simulations for different densities of kerf panels suspended at: (a) 24 mm, (b) 12 mm



(a) Flat vs. 2x2 non-planar reconfigurations for HD and LD structures




(b) Results of Reverberation Time (s) Comparing with flat structure

**Fig. 7. Reverberation time of LD and HD reconfigurable kerf structure**

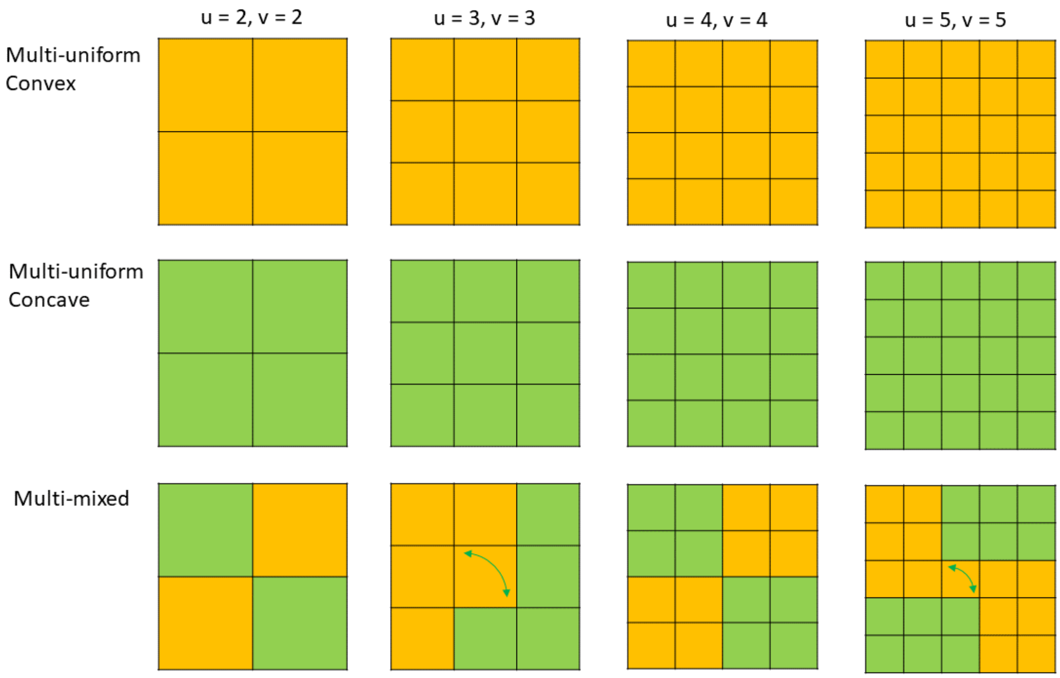



**Fig. 8.** Three types of non-planar reconfiguration of HD kerf structures suspended 24mm from a ceiling in a small office space: (1) Multi-uniform convex: 2x2, 3x3, 4x4, 5x5 (2) Multi-uniform concave: 2x2, 3x3, 4x4, 5x5 (3) Multi-mixed: 2x2, 3x3, 4x4, 5x5

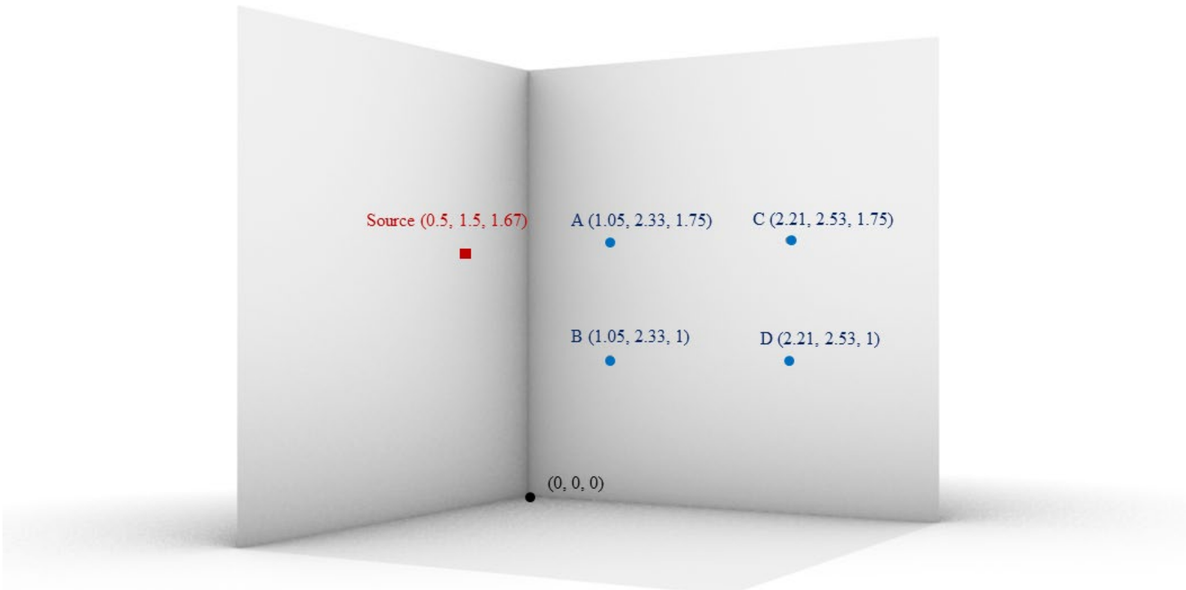
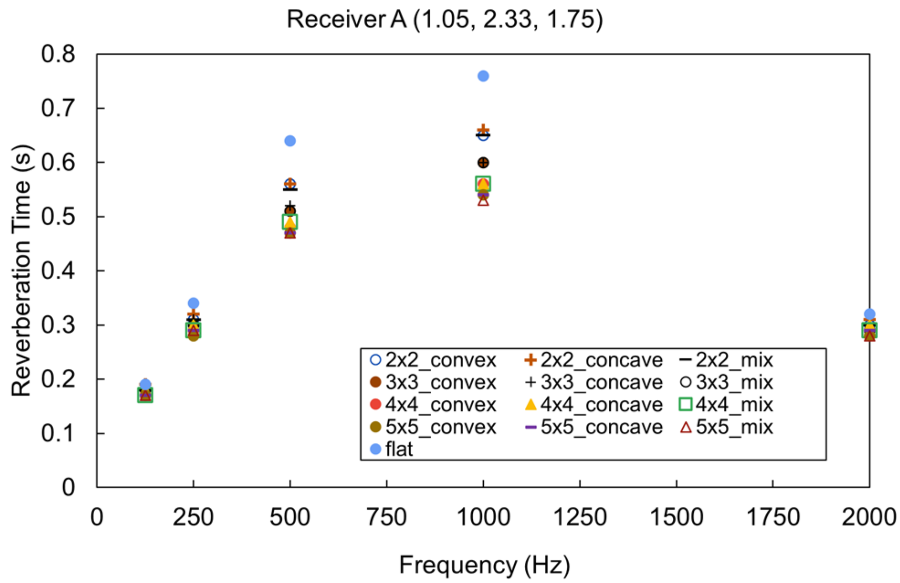
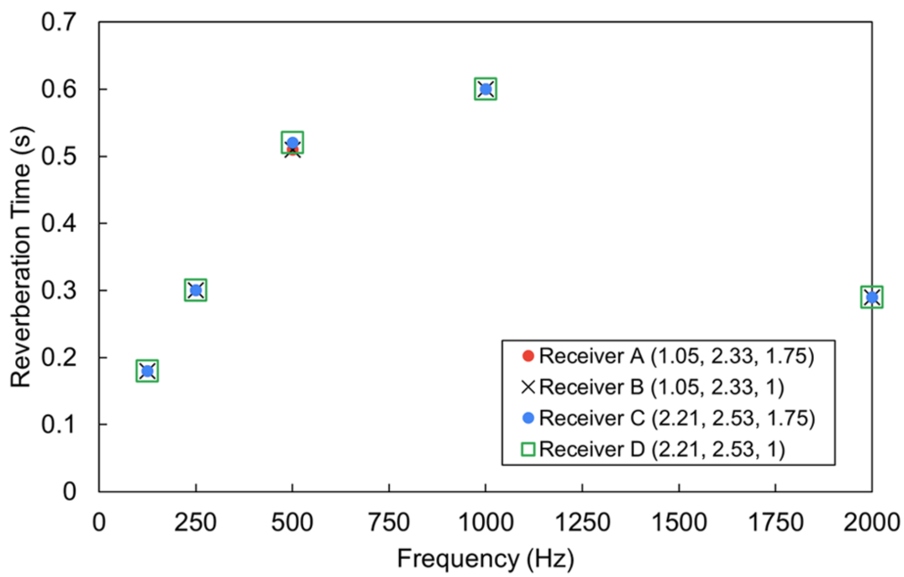



**Fig. 9.** Perspective View of Spatial Positions of Sound Source and Four Receivers (A, B, C, D)




(a) Reverberation Time of all Non-Planar Reconfigurations and Flat surface at Receiver A




(b) Reverberation Time of 3x3 multi-mix reconfiguration at Receiver A, B, C, D

**Fig. 10.** Comparison of Reverberation times for different types of kerf structure reconfigurations for four receiver positions

**Table 1.** Geometrical properties of hexagonal domain with triangular pattern unit cell (HD, MD, and LD)

| Unit cell | Total surface area ($\times 10^{-3} m^2$) | Solid surface area ($\times 10^{-3} m^2$) | Air gap area ($\times 10^{-3} m^2$) | Ratio of $\frac{\text{Air gap}}{\text{Total surface area}}$ |
|---|---|---|---|---|
| HD | 1.65 | 1.33 | 0.32 | 0.20 |
| MD | 1.65 | 1.45 | 0.20 | 0.12 |
| LD | 1.65 | 1.51 | 0.14 | 0.08 |

**Table 2.** Absorption coefficients from experiments

| | Frequency (Hz) | | | | | |
|---|---|---|---|---|---|---|
| Material | 125 | 250 | 500 | 1000 | 2000 | NRC |
| HD MDF | 0.54 | 0.63 | 0.37 | 0.32 | 0.83 | 0.55 |
| MD MDF | 0.51 | 0.62 | 0.35 | 0.38 | 0.82 | 0.55 |
| LD MDF | 0.57 | 0.65 | 0.40 | 0.51 | 0.76 | 0.60 |

**Table 3.** Receiver Spatial Locations.

| Receiver # | Distance to front wall and one side wall (m) | Height (m) ($H_R$) | Distance to sound source (m) ($D_{SR}$) |
|---|---|---|---|
| A | 1.05, 2.33 | 1.75 | 1 |
| B | 1.05, 2.33 | 1 | 1 |
| C | 2.21, 2.53 | 1.75 | 2 |
| D | 2.21, 2.53 | 1. | 2 |

Note: see also **Fig. 10**.