Wood Based Liquid Deposition Modeling for Sustainable Hybrid Acoustics Components

Addressing sound absorption and scattering through non-planar 3d printing techniques.

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Abstract. Acoustics significantly impacts human comfort in built environments. Traditional approaches to acoustic solutions typically involve porous materials aimed at reducing reverberation; however, these materials often constrain design flexibility and customization. Recent advancements have focused on additive manufacturing, particularly 3D printed materials, to create advanced, hybrid acoustic treatments that effectively combine sound absorption and scattering. This research investigates liquid deposition modelling as a method for printing wood-based hybrid acoustic panels, using non-planar printing techniques to enhance acoustic properties. Four types of wood panels were developed and tested to assess their effectiveness in sound absorption and scattering within a controlled environment. Experimental results demonstrated that the 3D-printed hybrid wood panels significantly reduced reverberation, and enhanced clarity in compare to flat panels. Key factors influencing performance included surface complexity and the density of patterns, both of which contributed to optimized acoustic behaviour. The findings underscore the potential of AM for creating sustainable, customizable acoustic solutions, empowering architects to design acoustically optimized spaces with reduced environmental footprints.

Keywords. 3D Wood Printing, Architectural Acoustics, Toolpath Design, Hybrid Acoustic, Acoustic Performance

1. Introduction

Acoustics is an essential element of architectural design that highly impacts human comfort, well-being, and the overall spatial experience, alongside temperature and lighting. Traditionally, acoustical treatments have been considered late in the design process, focusing on post-construction adjustments aimed at managing sound characteristics. These adjustments typically involve the use of materials that absorb sound energy or geometries that scatter sound waves to control reverberation, a

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common challenge in many interior environments (Foged et al., 2022). However, hybrid solutions that integrate both techniques by combining a porous layer for absorption with surface irregularities to promote sound diffusion, are rarely utilized. The early integration of acoustic solutions during the design phase is still limited, as traditional materials often restrict the designer's flexibility and can compromise the aesthetic and functional goals of a space. In recent years, additive manufacturing (AM), also known as 3D printing, has created new opportunities for innovative and customized acoustic treatments (Cohen & Barath, 2023), also involving engineered sound-absorbing materials with micro-level precision that enhance both acoustic performance and visual appeal (Sailesh et al., 2021; Tsiokou et al., 2023).

Additionally, the aim for sustainability in architecture has further fueled interest in eco-friendly materials. This includes the development of biodegradable, non-toxic materials through methods like liquid deposition modelling (LDM), which allow for sustainable acoustic solutions that align with environmental goals (Cohen et al., 2024). These advances lay the groundwork for the use of 3D-printed wood-based materials to create hybrid acoustic components, meeting the technical, aesthetic, and sustainability requirements of modern architectural design.

2. Background

In recent years, research into AM has expanded significantly, with a notable focus on acoustic applications. A considerable portion of this research has concentrated on developing 3D-printed sound-absorbing materials, exploring innovations such as controlled porosity, microperforated panels, and intricate microstructures to enhance acoustic performance (Sailesh et al., 2021; Tsiokou et al., 2023). Numerous studies demonstrate the potential of 3D printing for creating effective sound absorbers. Setaki et al. (Setaki et al., 2023) created absorbers based on the principle of destructive interference, while Boulvert et al. (Boulvert et al., 2020) investigated how geometric factors affect acoustic properties. Additionally, Liu et al. (Liu et al., 2017) used 3D printing to produce multi-layer perforated panels, which allow for refined control over sound absorption characteristics. Despite substantial progress in understanding absorptive properties, research at an architectural scale remains limited, and few studies have examined the potential of 3D-printed hybrid solutions to improve acoustic comfort in larger spaces (Cohen & Barath, 2023; Tsiokou et al., 2023a) .Recent studies addressing this gap have also tackled technical challenges inherent in 3D printing, such as "stair-stepping," a common artifact in layer-by-layer printing that affects surface smoothness and sound scattering. To address this, Cohen and Barath (Cohen & Barath, 2023) proposed a novel approach using non-planar printing, where layers are printed in curved, rather than flat, forms to achieve smoother surfaces that enhance scattering. However, while this technique demonstrates promise, empirical data confirming the scattering performance of these non-planar surfaces remains limited.

From a materials perspective, many traditional acoustic materials such as glass wool and foams, pose environmental and health risks due to their toxic, non-biodegradable nature, creating challenges for disposal and sustainability (Sailesh et al., 2021). In response, researchers have turned to biodegradable polymers and natural fibers to create eco-friendly acoustic materials. Studies on these materials, such as those by Matei et al. and Sailesh et al. (Matei et al., 2024; Sailesh et al., 2021) have shown that natural fibers exhibit favorable acoustic properties, both with and without micro-perforation, indicating their potential for sustainable sound absorption. Current research explores sustainable, high-performance materials for creating perforated acoustic panels from natural resources, yet producing complex perforations with diverse geometries from these biodegradable materials remains challenging and demands detailed acoustic analysis (Zaharia et al., 2023). LDM has emerged as a promising AM technology for the efficient use of biobased materials like wood composites, though it has yet to be fully tested for acoustic performance. By enabling complex material distribution, LDM allows precise control over material properties and can incorporate a higher proportion of natural materials compared to other AM technologies, aligning with the growing demand for sustainable solutions (Cohen et al., 2024). This research investigates the use of LDM to print wood-based materials for architectural-scale hybrid acoustic components, enhancing performance through non-planar printing techniques that amplify the natural acoustic qualities of wood in 3D-printed designs.

3. Setting up a Design-to-Fabrication Workflow for Non-Planar Printing of Hybrid Acoustic Components

The research methodology to explore the feasibility of hybrid acoustic elements and their properties was separated to four phases: 1) Designing the scattering surface of a hybrid panel for a defined environment utilizing Pachyderm simulation tool on Grasshopper (GH) 2) Designing through GH the absorption pattern that builds up the scattering surface 3) Generating Gcode and printing the panels 4) Conducting empirical acoustic measurements of the hybrid panel.

In order to explore the scattering surface and absorption pattern influence on acoustic behaviours, four types of panels were parametrically designed, one flat panel with no scattering surface design, and three non-planar surfaces with different absorption densities to understand the density influence on the acoustic properties.

3.1. MATERIAL AND MACHINERY SETUP

The printed experiments employed a WASP3d 40100 LDM printer. The printer based on an air pressure feeding system allowed to facilitate the need of high forces due to the materials frictional behaviour and a printing bed of 40cm diameter which allowed exploration at the scale of an architectural panel.

The printing material is a composition of sawdust, carboxymethyl cellulose binder and water which enables a natural material that is 100% biodegradable and recyclable. The dried material is composed of ~ 65% wt wood content, capable of leveraging the inherent acoustic performance of wood. The water in the composition was adjusted to ensure extrudability of the material while promising the buildability of the print. Additionally, a custom adapter for the nozzle was created to allow more conical shape of the print head. This adjustment prevents the chances of collisions during the non-planar printing. All models were dried on a steel mesh, with a fan to prevent mold and in room temperature (Cohen et al., 2024) . Following a drying period of 5 days, all models were trimmed to designed dimensions.

3.2. ACOUSTIC MEASUREMENTS

From the perspective of acoustic measurements, recent research has explored the trade-offs associated with reducing sample size and environment dimensions in comparison to full-scale reverberation rooms, as described in ISO 354. Shrtrepi et al. (Shtrepi et al., 2019) investigated the creation of small-scale rooms for conducting random-incidence acoustic measurements, aligning with ISO 354 while following the guidelines outlined in the SAE J2883 standard. Their research highlights that the usable frequency range for small-scale rooms is generally above 400 Hz. This work, along with SAE J2883, has established a framework for measuring small sample sizes, enabling extensive experimentation while minimizing material use and costs. Building on Shtrepi's guidelines for small-scale acoustic measurements, we developed a Grasshopper (GH) script to design a minimally dimensioned test box suited for printed samples measuring 300 x 300 mm. The script ensured a minimum distance of 50 cm between the speaker and receiver, while also maximizing the angular spread between the speaker and receiver positions to capture a broad range of acoustic data. To further refine the test box design, we utilized Galapagos, an optimization tool, to maximize the simulated RT60 while adhering to the design principles. The RT60 calculations were performed using the Pachyderm plugin, with the box material set to 3/8" plywood, consistent with the physical construction material. The optimization process resulted in a box with dimensions of 1510 x 445 x 445 mm, achieving a simulated RT60 of 0.164 seconds. The setup covered angles ranging from -30° to 30°, allowing us to estimate the acoustic properties of each panel from various perspectives.

A wooden box from 3/8" plywood was fabricated to match the exact dimensions used in the Pachyderm simulation. The floor of the box was marked to indicate the precise positions for the speaker and receiver, ensuring repeatable and comparable measurements (Fig 01 a). The box allowed for measurements at six different positions. For the sound source, a Dayton Audio DMA80 driver, with a frequency range of 80–16,000 Hz, was selected, while a U-MIK1 calibrated microphone was chosen as the receiver. Measurements were conducted using REW (Room EQ Wizard) software, a standard tool in the industry for evaluating acoustic comfort.

To establish the baseline acoustic properties of the box, initial measurements were taken with an empty box. After each frequency sweep, the software provided key parameters for each frequency indicative for acoustics comfort (Foged et al., 2022), including: RT60: the time it takes for a frequency's sound level to decrease by 60 dB (lower value is better), C80: Clarity, the ability for easily distinguishable and intelligible of sound in space (higher value is better). All of the models were measured in the same environment condition of room temperature 26 degrees and 55% humidity in the range frequency of 80 to 10k Hz.

4. Design-to-Fabrication of an Acoustic Hybrid Panel

4.1. SCATTERING DESIGN OF HYBRID PANEL

In the initial phase, a GH script was developed to define the scattering surface of the hybrid acoustic panel for the defined environment. Key design parameters included the number of curvature sections, the depth of each wave (ranging from -15 mm to 15 mm), and the overall panel thickness (ranging from 20 to 35 mm). To optimize this surface for enhanced scattering performance, we utilized the Pachyderm plugin to simulate sound wave interactions. In this simulation, three source points were set to reflect the empirical test conditions, allowing an evaluation of scattering performance over a range of angles from -30° to 30° from the center point (Fig. 01 b). The optimization process was based on three criteria: a) Percentage of Reflected Rays: The proportion of sound rays reflected from the panel surface back to a hemispherical receiver, relative to the source output. b) Average Distance of Reflected Rays: The average distance of reflected rays on the hemispherical receiver, which indicates the uniformity of the scattering distribution. c) Coverage Area of Reflected Rays: The spatial coverage of reflected rays on the hemispherical receiver, which reflects the surface scattering efficiency (Fig. 01 c).

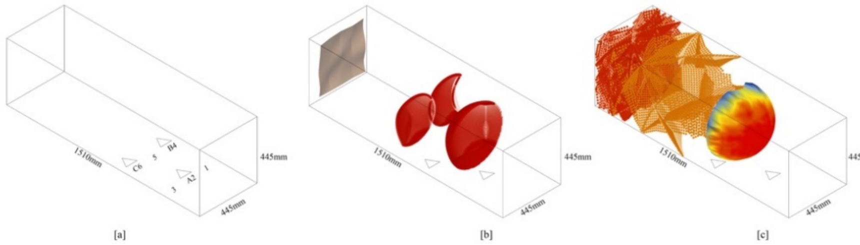


Figure 1. [a] box environment dimensions, [b] Set three point of source to allow further scattering simulation [c] Acoustic rays simulation and hemisphere receiver, colours represents uniformity of scattering distribution.

4.2. ABSORPTION DESIGN OF HYBRID PANEL

Following the definition of the scattering surface, the surface model was utilized as a global reference geometry for designing the hybrid acoustic panel. Using GH, we developed a case study based on the Truchet absorption pattern of Tsiokou et al. (Tsiokou et al., 2023), which also served as the tool path for printing. The Truchet pattern enables an infinitely non-repeating configuration, enhancing the acoustic functionality of the spatial system. Unlike the planar implementation in Tsiokou et al., our Truchet pattern was applied to a non-planar surface (defined in the previous phase) to mitigate the stair-stepping effect, thereby enhancing the scattering performance of the print. This approach also considers the impact of printing techniques on the sound absorption coefficient, as explored by Zielinski (Zieliński et al., 2020). Drawing from the studies of Sailesh et al. and Cohen and Barath (Sailesh et al., 2021, Cohen and Barath, 2023), we structured the hybrid panels with a layered design consisting of two corresponding densities: a higher density at the base and a lower density at the top. This configuration creates a divergent porous structure (Fig. 02), which is targeted at improving sound absorption in the lower frequency range. Additionally, three types of absorption densities were defined: high density, with pore sizes of 2 mm and 8 mm; medium density, with pore sizes of 5 mm and 14 mm; and low density, with pore sizes of 8 mm and 12 mm.

The resulting hybrid element combines a porous structure designed for sound absorption with an additional non-planar layer to facilitate sound scattering. This dual-density layers structure aims to achieve effective acoustic control across a broader frequency spectrum, addressing both absorption and scattering requirements.

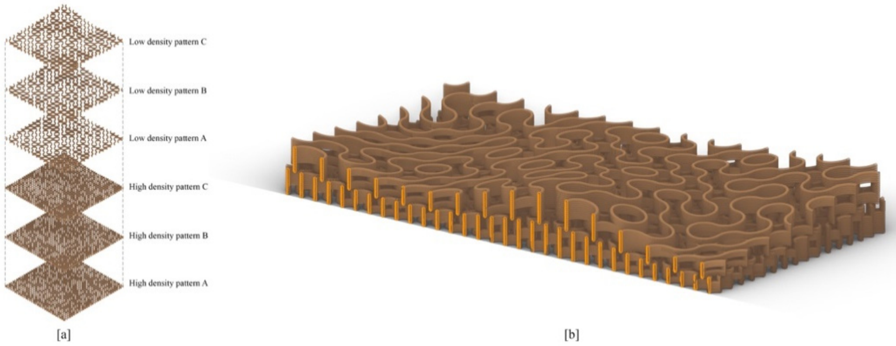


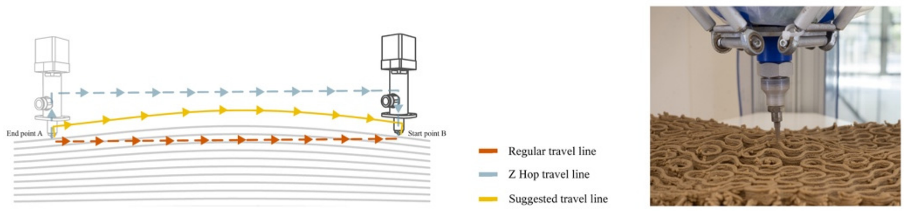
Figure 2. [a] layers order along the Z axis of the hybrid element, [b] element section showcasing the divergent porous structure

4.3. PLANAR PRINTING - FLAT PANEL

The tool path for the flat panel was designed with two Truchet pattern densities. Each density was further divided into three pattern variations to enhance print adhesion between the layers and the buildability of the panel. The panel was printed in medium density, with a denser pattern (5 mm) as the base layer, followed by a layer with lower pattern density (14 mm). Printing different patterns on separate layers meant that some areas of the model lacked continuous extrusion, leading to minor bridging effects during the printing process. To address this, the print speed was adjusted in the G-code to improve layer adhesion and minimize bridging.

4.4. NON-PLANAR PRINTING METHOD - HYBRID PANEL

To fabricate hybrid panels with optimized scattering surfaces, a non-planar printing method known as Curved Layer Fused Deposition (CLFD) was utilized. This technique, widely explored in polymer printing (Ahlers et al., 2019; Mitropoulou et al., 2020), offers smoother surface finishes, reduced printing time, and the ability to create complex geometries with steep overhangs without additional supports. For acoustic applications, CLFD enhances scattering performance by reducing the stair-stepping effect, which compromises surface continuity and acoustic quality (Cohen & Barath, 2023). While non-planar methods have been extensively studied in polymer printing and perimeter-based models, their application to LDM remains limited. For instance, Vele et al. (2024) demonstrated the benefits of non-planar LDM in concrete printing, highlighting improvements in structural integrity and print quality. Cohen and Barath (2023) further advanced non-planar printing by developing a slicer that prevents collisions during continuous layer printing. In our study, we adopted a custom non-planar slicer to address the challenges of printing the Truchet pattern, a geometry unsuitable for continuous-layer printing. The slicer generates paths from the top surface downward, forming curved layers that replicate the scattering surface while avoiding collisions. Building on the methods of Ahlers, Cohen and Barath, and Vele, our approach optimizes layer continuity and surface quality. However, the intricate geometry of the Truchet pattern required additional in-layer travel lines, necessitating precise travel path planning. Most non-planar slicing strategies rely on a Z-hop method for travel, in which the extruder moves up along the Z-axis, traverses horizontally, and then descends to resume printing. While effective for perimeter-based designs, this method can cause collisions in non-perimeter-based non-planar printing, often requiring a large Z-hop setting that compromises print efficiency. To address this, we implemented a novel three-phase travel approach: (A) the extruder moves vertically to the next layer height without extruding; (B) it travels along a non-planar path that mirrors the surface curvature; and (C) it descends to the current layer height. This sequence reduces collision risk and enhances printing efficiency (Fig 03). To further ensure print clarity and prevent over- or under-extrusion on curved layers, a dynamic extrusion rate (E-value) adjustment was applied. The E-value was calculated based on the normal vector of each surface point and its relative distance from the layer beneath, allowing the extrusion rate to vary according to surface complexity. This differs from standard printing methods, where the E-value remains constant, and ensures that extrusion adapts in real-time to the model's complex geometry.



[a] [b]

Figure 3. [a] Suggested travel lines compared to Z hop strategy and regular slicing travel line. [b] Non-planar printing to avoid stair stepping affect and targeting scattering performance

Three panels with different densities were successfully printed, each panel was constructed from 2 densities separated to 3 variations of the pattern to promise stability and adherence of the print.

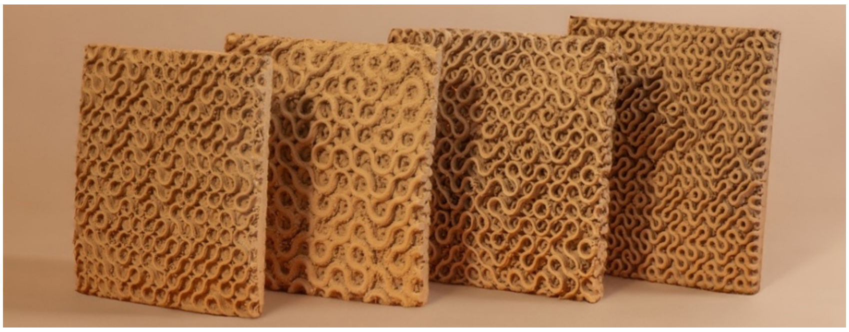


Figure 4. Four printed panels: Flat panel medium density, Nonplanar low, medium and high density

5. Acoustic Results

Looking at the RT60 graph results we can observe that non-planar panels performed better than the flat panel in reduction of reverberation time, corresponding to their density. We see that density of the absorption pattern affects the reduction of reverberation time mainly on upper-mid to high frequencies (2k-10k Hz). In the low-mid to middle frequencies (400-2k Hz) it can be observed that medium density achieves better results. This can be explained by the relationship between the air pore sizes, which are created by the tool path density, and their correspondence to specific frequency wavelengths.

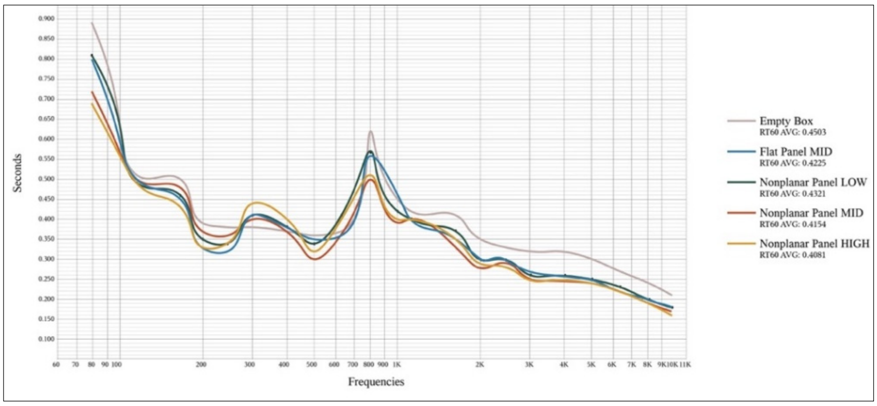


Fig 05 : RT60 graph results in comparison to empty box

C80 results showcased that overall non-planar panels performed better than the flat panel in improving clarity. Examining the results indicates that a non-planar panel with low density performs better than a flat panel with medium density suggesting that a scattering surface improves clarity in the space. From the mid-range to high frequencies (800-10k Hz), higher pattern density achieves better accuracy to the digital scattering surface due to the higher density, which affects the clarity properties.

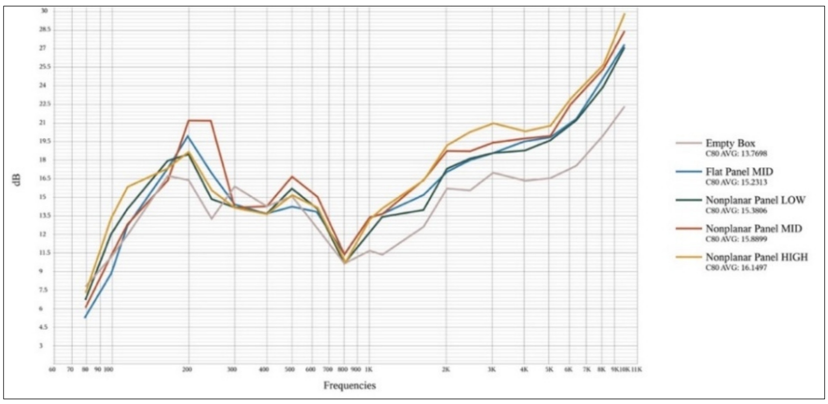


Fig 06: C80 graph results in comparison to empty box

This result can also be related to the affection of the surface based on the λ/4 rule of wavelength scattering, which states that surface irregularities must be at least λ/4 of the targeted sound wavelength to effectively scatter sound waves (Cox & D'Antonio, 2016). Overall, the results indicate that hybrid panels improved acoustic properties of reverberation time and clarity for a defined space. Different behaviours and peaking along the frequency range can point to the ability of customization of acoustic behaviour through the choice of pattern density and scattering surface. While the absorption pattern density mainly influences the reverberation time, the non-planar surface affects the clarity of sound in space. Although we demonstrate the effect of geometry on clarity and reverberation, this should be further tested on full scale room to better understand the effect on specific frequency ranges.

6. Conclusion

By systematically analysing the results, the research explores the impact of pattern density and surface curvature on reverberation time and clarity parameters. These factors collectively indicate the acoustic behaviour of the panels, affected by both absorption and scattering properties. The results indicate that the printed wood panels increased clarity properties and reduced the reverberation time. The choice of pattern density allows for peak clarity and RT at different ranges of frequency response; for example, medium density enhances clarity at low-mid frequencies while high density patterns target lower bass frequencies. The implementation of curvature surfaces overall increased clarity percentages, which indicates the scattering performance of the surface.

This research demonstrates the feasibility of 3D-printed hybrid acoustic panels made from wood-based materials, paving the way for sustainable and customizable architectural acoustic solutions. To accurately assess the overall frequency range of acoustic performance, additional measurements must be conducted in a full-scale room following ISO 354 standards. By integrating advanced manufacturing techniques like LDM non-planar printing with natural materials, the study enhances acoustic performance and reduces environmental impact. This provides architects and designers with a versatile toolkit to create acoustically optimized spaces that enhance occupant comfort and promote sustainability

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