CHALLENGES IN SCATTERING PROPERTIES CHARACTERIZATION OF 3D-PRINTED HYBRID ACOUSTIC MATERIALS

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Abstract

Additive manufacturing technologies enable the development of innovative and high- performance acoustic materials, allowing the design of complex structures and a high degree of geometric customization. One aspect that remains relatively unexplored is the design and characterization of hybrid acoustic materials (HAMs) that integrate sound absorption and diffusion within a single element. This contribution focuses on the sound scattering performances of 3D printed HAMs and explores the challenges of their characterization in a small-scaled reverberation room. The effects of ten 3D quarter- circle Truchet tiles combined in two different configurations have been fabricated using a large format industrial LCD 3D printer and daylight resin. The experimental investigations aimed at providing insights on the sensitivity of the measurement procedure of the random-incidence scattering coefficient, as defined in ISO 17497-1. The results showed that the two tested scattering surfaces do not show any appreciable differences despite the variation of the two configurations, which allows for a higher flexibility in the design applications. It is highlighted that the characterization method is particularly demanding, as it relies on two custom 3D printed scaled samples which requires higher accuracy and precision in the printing process, consequently increasing fabrication costs.

Keywords: *additive manufacturing, hybrid acoustic materials sound scattering coefficient, 3D printing, acoustic characterization*

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1. Introduction

The growing demand for sustainable and high-performance acoustic solutions has fostered interest in additive manufacturing (AM) as a tool for developing innovative acoustic materials [1]. Through the fabrication of complex and customizable structures, 3D printing enables the exploration of material architectures combining sound absorption, and diffusion within a single component [2,3]. Among the most promising developments in this field is the concept of Hybrid Acoustic Materials (HAMs), which aim to combine multiple acoustic functions within a single element [4]. However, their acoustic characterization using existing standards presents several challenges related to sample preparation including geometrical and acoustic features. Current standards have been primarily developed for conventional treatments designed either for sound absorption or sound diffusion. Previous investigations by Tsiokou et al. [2] demonstrated the feasibility of producing highly customizable HAMs using additive manufacturing, focusing primarily on sound absorption performance and highlighting the challenges associated with their acoustic characterization. Their work emphasized the importance of developing suitable measurement methodologies capable of capturing the acoustic behavior of geometrically complex and customizable materials.

Despite these explorations, the characterization of sound scattering properties remains relatively unexplored for additively manufactured HAMs [5]. Sound scattering [6] plays a fundamental role in room acoustics because it influences the spatial distribution of reflected sound energy, contributes to diffuseness, and affects subjective acoustic quality [4,7–10]. Unlike sound absorption measurements, which are now well established for many acoustic materials, the assessment

of sound scattering performance remains little explored [11] and presents additional challenges due to the complexity of the measurement procedures and the sensitivity of the results to sample geometry, mounting conditions, and test environment [5,12–14]. To ensure consistency and comparability of results, the random-incidence scattering coefficient is commonly measured according to ISO 17497-1 [15], which specifies a methodology based on reverberation room measurements conducted either at full scale or using physical scale models. The application of standardized characterization methods to highly customized 3D-printed materials present additional challenges. It is highlighted that a full scale sample would have a significant impact on the prototyping costs [12]. On the other hand, owing to the complex geometrical features enabled by AM, the preparation of scaled test specimens requires high manufacturing precision and strict dimensional control [16]. Small deviations introduced during fabrication may influence the measured acoustic response, particularly in scattering measurements where surface geometry is directly responsible for acoustic performance. Consequently, the reliability, repeatability, and practical applicability of existing standards require further investigation when applied to additively manufactured acoustic materials.
In this context, the present study investigates the sound scattering performance of novel 3D-printed Hybrid Acoustic Materials developed by BioG3D and examines the applicability of ISO 17497-1 characterization procedures within a small-scale reverberation room. Attention is put on evaluation of the influence of different geometric configurations of quarter-circle Truchet tiles on the measured scattering coefficient and to the identification of the limitations and opportunities associated with the acoustic characterization of highly customizable additively manufactured acoustic surfaces. This work contributes to the growing body of research on AM-enabled acoustic materials and supports the development of reliable characterization methodologies for future hybrid acoustic systems.

2. Methods

2.1 Sample design

The HAM panels (160 × 160 mm) investigated in Tsiokou et al. [2] were scaled down at a ratio of 1:5 and combined into larger sub-regions. The effects of ten 3D quarter- circle Truchet tiles combined in two different configurations have been fabricated (Figure 1). A total of 12 sub-regions were modelled for both case-study testing formations (i.e., R1 and R2), which together formed a circular surface with a diameter of 768 mm (Figure 2 and 3). The two arrangements were selected to test the differences between tiles distribution considering the two different heights of the elements (5 and 7 cm, Figure 1) maintaining the same elements. R1 and R2 are considered as two randomly built samples obtained by the combination of the tile's typology reported in Figure 2.

Based on findings from previous studies, all sub-regions were oriented and sliced using Photocentric Studio v1.182 (Photocentric Ltd., UK) at a build orientation of 30°, to promote adequate adhesion to the build platform and prevent structural collapse during printing. The panels were manufactured using Magna Hard Black Daylight Resin (Photocentric Ltd., UK), a strong and rigid photopolymer aimed for minimal shrinkage and precision, resistance to compression and plastic deformation, and high tensile strength in large components. Fabrication was carried out using an LC Magna large-format industrial LCD 3D-printer (Photocentric Ltd., UK), with a 4K LCD screen (3840 × 2160 pixels), an XY resolution of 137 µm, and a selected layer thickness of 25µm, representing the highest available printing resolution. Finally, the 12 sub-regions were assembled and measured in a small reverberation room (SSRR).

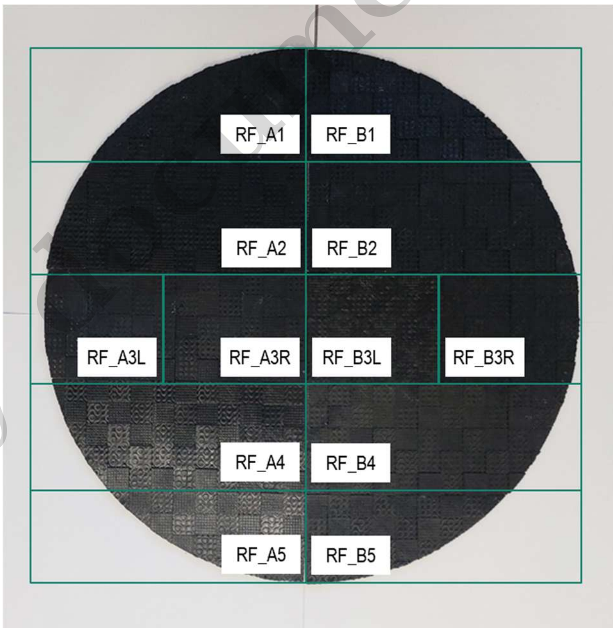

Figure 1. Hybrid Acoustic Material formed with tiles of 160x160 mm 3D quarter- circle Truchet [2].

2.2 Sound scattering measurements

The measurements presented in this work have been performed according to the standard ISO 17497-1; in this standard, the conventional estimation of the absorption coefficients is based on the ISO 354. Besides the measurements indicated in the ISO 354, further measurements are required, which account for different sample orientations, since the initial parts of the impulse response reflections result highly correlated. In contrast, the later parts are not in phase and strongly depend on the specific orientation of the sample: the scattered energy is contained in this part of the impulse response [15].
Based on this concept, four reverberation times Tj are calculated in order to determine two absorption coefficients, i.e. the random incidence absorption coefficient and the random incidence specular

absorption coefficient. The four reverberation times are evaluated in four different conditions of the sample: T1 is the reverberation time when the test sample is not present and the turntable is not rotating, and T2 is the reverberation time when the test sample is present and the turntable is not rotating; T3 is the reverberation time when the test sample is not present and the turntable is rotating, and T4 is the reverberation time when the test sample is present and the turntable is rotating. T3 and T4 are estimated after a phase-locked averaging of the impulse responses in each measuring position, which allows to extract the specular energy from the reflected pulses since the late incoherent parts are canceled.

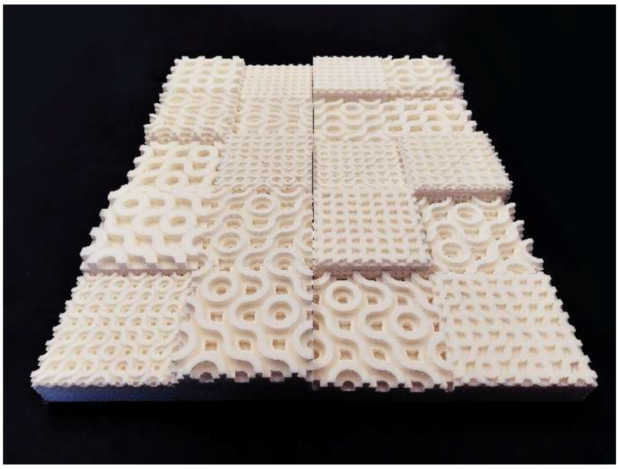

Figure 2. Scattering measurement sample with 12 sub-regions modelled for both case-study testing formations (i.e., R1 and R2), forming a circular surface with a diameter of 768 mm.

Based on this concept, four reverberation times Tj are calculated in order to determine two absorption coefficients, i.e. the random incidence absorption coefficient and the random incidence specular absorption coefficient. The four reverberation times are evaluated in four different conditions of the sample: T1 is the reverberation time when the test sample is not present and the turntable is not rotating, and T2 is the reverberation time when the test sample is present and the turntable is not rotating; T3 is the reverberation time when the test sample is not present and the turntable is rotating, and T4 is the reverberation time when the test sample is present and the turntable is rotating. T3 and T4 are estimated after a phase-locked averaging of the impulse responses in each measuring position, which allows to extract the specular energy from the reflected pulses since the late incoherent parts are canceled.

2.2.1 Measurement Set up

The measurements have been performed in a 1:5 scaled reverberation room (Figure 3) at Politecnico di Torino (Italy). The room has been primarily built for random-incidence scattering coefficient measurements according to ISO 17497-1. It is an oblique angled room with pairs of nonparallel walls.

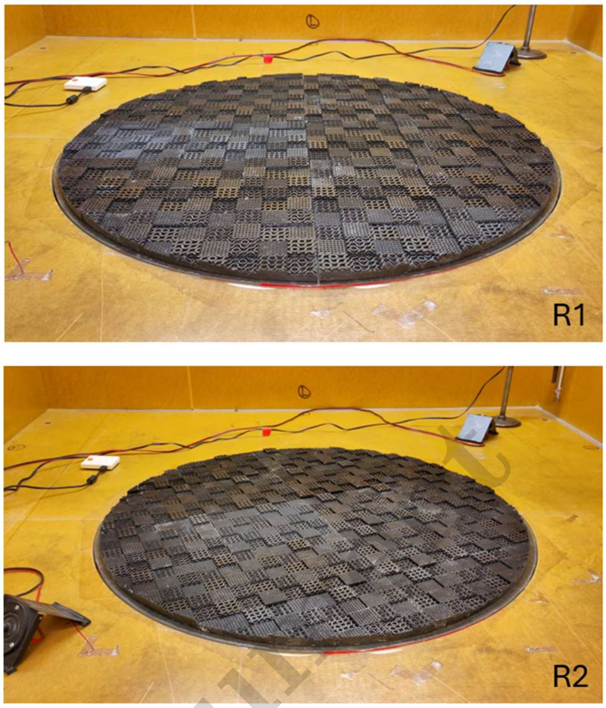

Figure 3. Scattering samples with a different distribution of the Truchet-tile pattern R1 and R2.

The floor area is about 2.38 m^{2}and the height in the range 1-1.2m, which leads to a maximum volume of 2.86 m^3 and a total area of 12.12 m^2. The structure is raised from the ground on a wooden structure and damping layers have been used along the joints and openings. One of the sides consists of two movable parts that allow to have a large opening to ease the positioning of the sample. The construction material is self-supporting lightweight partitions of MDF (Medium Density Fibreboard) with a thickness of 3.8 cm, which has been further covered by a layer of adhesive film in order to maximize its reflective properties. The rotation is perfomed through an Arduino Board that controls the discrete stepwise positioning of the rotating table. A 5° angle has been chosen based on the standard recommendation and literature in order to control the measurement duration and its accuracy [17]. Therefore, 72 impulse responses have been recorded for each measurement.

3. Results and Discussion

Figure 4 presents the random-incidence scattering coefficient measured for the two investigated surface configurations, R1 and R2, according to ISO 17497-1. The measurements show similar frequency-dependent behavior for both configurations across the investigated frequency range. In both cases, the scattering coefficient increases with frequency, reflecting the greater effectiveness of the geometric features in redirecting acoustic energy as the wavelength becomes comparable to the characteristic dimensions of the Truchet-tile pattern. Considering the relationship f=c/(2a), where c is the speed of sound and a represents a characteristic dimension of the surface irregularities, the primary tile dimension of 160 mm is expected to produce significant scattering at approximately 1062 Hz. However, no distinct increase in scattering can be observed at this frequency. For both samples, a scattering coefficient of s=0.5 is reached around 2000 Hz. According to the relevant standard, surfaces exhibiting scattering coefficients of s ≥ 0.5 s above this frequency threshold can be classified as diffusers for the specified range of frequencies. The scattering coefficient remains close to zero below 500 Hz and gradually increases with frequency, reaching a maximum value of approximately 0.9 at 5000 Hz. Furthermore, the two samples often contain adjacent tile combinations that create an effective dimension of 320 mm, corresponding to a predicted scattering frequency of approximately 531 Hz (f=c/(2a)). This larger characteristic dimension may explain the observed increase in scattering beginning at frequencies around 500 Hz. It is highlighted that the Truchet-tile pattern reports small elements that may have affected only high frequencies.

The comparison between the two arrangements reveals only minor variations, with differences generally remaining within the expected uncertainty associated with the measurement procedure [5,12]. No consistent trend indicating superior scattering performance for either configuration was identified. This suggests that the redistribution of the quarter-circle Truchet tiles does not substantially alter the overall scattering response of the hybrid acoustic surface.

From a characterization perspective, the measurements highlighted the sensitivity of the ISO 17497-1 procedure when applied to additively manufactured materials. The fabrication of the scaled specimens required a high degree of dimensional accuracy to preserve the geometric features responsible for sound scattering. Furthermore, the preparation of two complete circular samples, each comprising 12 individually printed sub-regions, resulted in a considerable increase in manufacturing time and prototyping costs. Small deviations in assembly and printing accuracy may also contribute to the variability observed in the measured scattering coefficients. This confirms that the characterization of diffuser scattering performance remains experimentally demanding because it requires large, carefully fabricated test samples, specialized acoustic facilities, and measurement procedures prescribed by ISO 17497-1, which have been described as demanding and requiring expensive laboratory setups [4].

Overall, the results indicate that the investigated 3D-printed HAMs exhibit stable scattering behaviour regardless of the specific tile arrangement considered, demonstrating the potential of Truchet-based geometries for customizable acoustic applications.

4. Conclusions

This study investigated the random-incidence scattering performance of two configurations of 3D-printed Hybrid Acoustic Materials composed of quarter-circle Truchet tiles and characterized in a small-scale reverberation room according to ISO 17497-1.

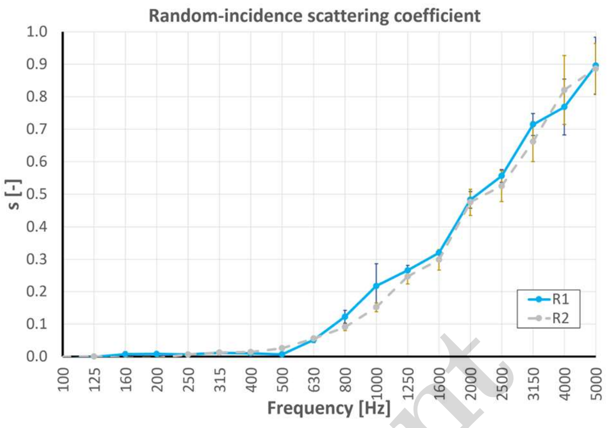

Figure 4. Random-incidence scattering coefficient results measured for sample R1 and R2.

The experimental results showed that the two surface configurations provide comparable scattering coefficients across the analysed frequency range, with no appreciable differences observed between the tested arrangements. This outcome suggests that the acoustic scattering performance of the proposed HAM concept is relatively insensitive to the specific distribution of the tiles, offering greater flexibility for architectural design and customization without substantially affecting acoustic behaviour.

The study also highlighted several challenges associated with the characterization of additively manufactured acoustic materials. In particular, the ISO 17497-1 methodology requires the fabrication of accurate scaled specimens, making the process demanding in terms of production precision, assembly, time, and cost. Since scattering behaviour is strongly dependent on surface geometry, maintaining dimensional fidelity during the printing process is essential to ensure reliable measurements. Despite these challenges, the results demonstrate the feasibility of applying standardized scattering measurements to complex 3D-printed acoustic surfaces and support the further development of hybrid absorptive-diffusive materials produced through additive manufacturing. Future work will investigate the combined assessment of absorption and scattering properties, together with the influence of different geometric patterns, printing resolutions, and manufacturing tolerances on the overall acoustic performance of Hybrid Acoustic Materials.

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