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MEASUREMENT OF THE ABSORPTION COEFFICIENT OF INHOMOGENEOUS MICRO-PERFORATED PANELS IN A SMALL-SCALE REVERBERATION ROOM

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ABSTRACT

Due to their resonant nature, inhomogeneous Micro-Perforated Panels (MPPs) have shown great potential in achieving wideband acoustical absorption by integrating the right design. However, they are being explored in simplified boundary conditions, mainly in terms of their normal incidence absorption coefficient. Bearing in mind that measurements in the diffuse field using large-scale samples are mandatory for materials for use in architectural settings, this study purports to measure the absorption coefficient of an acrylic-based MPP with a parallel arrangement in a Small Scale Reverberation Room (SSRR). The MPP designs, featuring various micro-perforations ranging from 0.7 mm to 1 mm and different back cavities, were fabricated using CNC machining tools. The panel was then mounted as a tile system composed of wood frames in the SSRR and measured with DIRAC software. Pre- and post-acoustic measurements were taken in two conditions, with and without the sample on the floor, using the integrated impulse response method at five microphone positions. Results show that the SSRR results regarding the absorption coefficient of the proposed material are slightly lower that predicted by the Equivalent Circuit Method. This method can be employed when the frequencies of interest are above 500 Hz for inhomogeneous MPPS.

Keywords: *Micro-Perforated Panels, Absorption Coefficient, Random Incidence, Reverberation Time.*

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1. INTRODUCTION

Acoustic comfort is a qualitative and quantitative process aimed at minimizing variables that may cause discomfort to occupants. Quantitative evaluation of building and finishing materials' absorption coefficients is necessary to reduce indoor noise levels [1]. Hard and stiff materials like stone, metal, glass, and plaster, which are commonly used as finishes in the built environment, tend to reflect sound waves repeatedly. Those reflections lead to issues such as high reverberation and amplified noise, especially in spaces like schools and offices [2] making them unfit for their purpose.

Absorbers are used in different spaces to improve acoustic comfort and minimize reverberation. Schmitz [3] suggests that acoustic treatments should consist of absorbers that can attenuate sound in *all relevant frequency ranges*. Conventional porous and fibrous materials are effective in reducing high-frequency noises, whereas resonant structures such as Micro-Perforated Panels (MPPs) are often employed to address low-frequency issues in room acoustics. Although they have a narrow absorption bandwidth, they offer a fiberless alternative that can satisfy high hygiene standards and can achieve wideband effectiveness with the proper design and without damping materials. To broaden the absorption bandwidth, researchers have explored various structures based on MPP arrangements in series, parallel and combined, which by introducing multiple resonances yield efficient and wideband sound absorption [4-6]. Previous works by the authors [7] investigated the potential of transparent parallel arrangement of four MPPs in the impedance tube. Preliminary results have shown that a wider band and higher absorption can be achieved simultaneously by tuning each resonator to an overlapping resonance frequency with the precedent. The proposed material was implemented in a simulated classroom setting and found that transparent

MPPs could effectively absorb sound in the speech frequency range [7].

Literature shows that the models continue to develop in the field of engineering. However, since the nature of the previously mentioned studies is quite exploratory regarding their constituting theory, the experimental validation is done by producing very small samples. The absorption coefficient is measured in the impedance tube with significantly simplified boundary conditions when only a plane wave interacts with the designed material. While this approach can provide initial results, it does not accurately reflect real-life acoustic conditions, where absorbing materials are installed in various incident angles, and scattering occurs. In the current work, an inhomogeneous MPP arrangement is produced on a larger scale and is being assessed for its random incidence absorption coefficient in a SSRR.

2. THEORETICAL BACKGROUND

The basic system of a single-layer MPP consists of a Micro-Perforated Panel, a rigid back wall, and the air cavity in between where *d* is the hole diameter, *t* is panel thickness, *b* is the distance between the holes constituting in *p* as perforation ratio and *D* is the distance from the back wall. After calculating the acoustic impedance of the structure according to Maa's model [8], the normal incidence absorption coefficient can be obtained. To roughly approximate the random incidence absorption coefficient from normal incidence data, literature agrees on approximating the random incidence value at $\theta = 45\text{-}55^{o}$ for Eq.1 [9].

$$\alpha = 1 - \left|\frac{(Z_{tot}\cos\theta) - \rho c}{(Z_{tot}\cos\theta) + \rho c}\right|^2 \quad (1)$$

On the other hand, to experimentally measure the sound absorption characteristics of a sample when subjected to sound from arbitrary directions and of random phase relations, the reverberation chamber method is functional [10]. It can be achieved by measuring the room's reverberation time (T60) before and after introducing an absorbing sample while maintaining the same controlled acoustic conditions. By utilizing Sabine's theory, the difference between the two measures determines the difference of the sound absorption area (A_T) (Eq.2).

$$A_T = 55.3V\left(\frac{1}{c_1 T_1} - \frac{1}{c_0 T_0}\right) - 4V(m_1 - m_0) \quad (2)$$

Where T_0 and T_1 are the reverberation times (T60) of the empty reverberation room and when the sample is introduced, respectively; V is the volume of the room; c_0 and c_1 are the speed of sound in the air and m_1 and m_2 are the air absorption constants for the room, given its temperature and humidity level. The random absorption coefficient of the room can therefore be calculated by Equation 3 where S is the area of the introduced material. To get an accurate measurement, it is necessary to have a big difference between T_0 and T_1 [9].

$$\alpha = \frac{A_T}{S} \quad (3)$$

On the other hand, Small-Scaled Reverberation Rooms (SSRR) have recently gained popularity as a practical and sustainable method for testing and characterizing new material samples that are smaller than 12 m^2, particularly for their random incidence absorption coefficient [11]. Primarily used by the automotive industry, the Society of Automotive Engineers [12] has established a standard for SSRRs, which suggests that rooms with volumes ranging from 3-10 m^3 and sample areas varying from 0.4 to 2.5 m^2 are sufficient for testing.

3. METHOD

3.1 Production of the MPPs

The parameter values chosen for this study are based on the previous parametric analysis by the Equivalent Circuit Method [13] and concerned at the same time with manufacturing limitations (applicability). The material was assumed to be rigid so that it does not vibrate and has enough mechanical strength. Each subpanel (MPP1, MPP2, MPP3, MPP4) has different perforations and back cavities partitioned so that each of them faces a specific cavity (*D*) tuned at a different resonant frequency. Their parameters are shown in Table 1.

Table 1. Parameters of the produced MPPs.

	d (mm)	*t (mm)*	*p (%)*	*D(mm)*
MPP1	0.9	2	1.38	60
MPP2	0.7	2	2.81	60
MPP3	0.9	2	3.01	30
MPP4	1	2	7.67	30

In the context of this study, a four-axis 2021 model Etasis CNC machine with double clamps as shown in Figure 1, was employed to produce the four MPP combinations resulting in eight 40 x 30 cm acrylic tiles produced by Işık Plastik Cast Plast PIA (Figure 2). Two panels were manufactured for each MPP combination. The overall surface area of the manufactured material was 0.96 m^2 as per a 5.3 m^3 SSRR.

The proposed material tiles were mounted in a frame of two MDF profile layers with different back cavities as seen in Figure 2. The solid part at the back of the tiles is constructed from MDF (Medium Density Fibreboard). While the rigid parts facing the 3 cm cavities were painted in white, the rigid back walls facing the 6 cm cavities were added adhesive films to make the MDF more reflective. Moreover, aluminum tape was applied to the edges of the frames to minimize the edge effect.

Figure 1. CNC machines while drilling the MPPs.

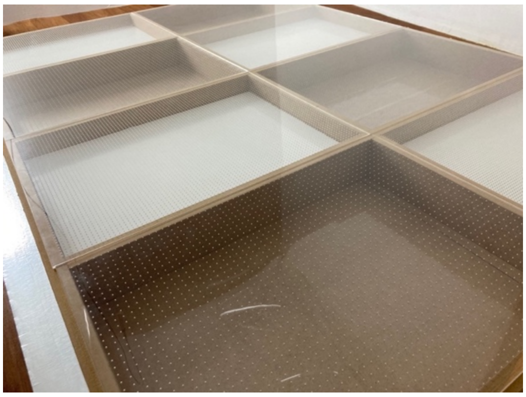

Figure 2. Assemble of the MPPs with the frame and different back cavities.

3.2 Small Scale Reverberation Room (SSRR)

The Reverberation Room's design and construction was done in accordance to the Society of Automotive Engineers standard [12] restricted in dimensions by the surrounding space. The newly built SSRR size and geometry in Bilkent University are shown in Figure 3 (L:2.34 m, W:1.39 m, and H:2 m). It has non-parallel walls in order to avoid standing waves produced by the normal modes of the room. The floor area is about 3 m^2, and the height is in the range of 1.8–2 m, leading to a volume of 5.3 m^3 and a total area of 19 m^2. The cut-off frequency for this volume range is 414 Hz, meaning that accurate results regarding absorption coefficients can be obtained after this frequency value. It is raised from the ground on a wooden structure, and damping layers have been used along the joints. The construction of the walls and ceiling is made of lightweight dry plasterboards with a 10 cm mineral wool in order to minimize the sound transmission to and from the inside of the SSRR. The partition walls from the KNAUF catalog (W111), providing sound insulation of more than 45dB. Moreover, the room had an aluminum framed glass acoustic door providing 45dB sound insulation. All room surfaces apart from the ceiling and door were covered in ceramic tiles so that the room becomes reverberant. The average absorption coefficient of the indoor surfaces was lower than $\alpha = 0.05$ in the frequency range (250–4000 Hz). Five low absorptive PVC diffusers (15,7 % of the total surface area) were hung from the ceiling. Measurements regarding the temperature and humidity of the room were continuously taken and averaged to 18 degrees Celsius and 60%, respectively.

The setup and the material samples were arranged in agreement with the recommendations of the SAE standard [12]. The measuring procedure used an integrated Impulse Response method for consecutive measurements on five different microphone positions, in two conditions, with and without the sample on the room floor. The microphones' were hung 90 cm from the floor of at least 40 cm from each other and 20 cm from the room surfaces (ISO 354, 2003). The sound sources consisted of 2 corner loudspeakers (M-AUDIO Studiophile AV40) connected in parallel, each having a power of 15 watts; the microphone was ½ inch Bruel & Kjaer 4155 connected to a microphone preamplifier Bruel& Kjaer Type 2669. The system was connected to a Bruel & Kjaer 2230 Sound Level meter and then to the sound card of an HP computer workstation. The microphone was previously calibrated with a Bruel & Kjaer sound level calibrator Type 4230. The software used for the measurements, sound generation, recording, and signal processing, is a building acoustic analyser software DIRAC 7841 version 4.00. A 5.34-second internal e-sweep signal sampled at 48 kHz was emitted from the loudspeakers, acting as the source. The signal was recorded for each microphone at least three times. The extrapolation of data for the reverberation time (T60) was achieved using the same building acoustic analyzer software. The data from each microphone was spatially averaged in order to obtain T_0 and T_1 without and with the sample on the room floor, respectively. Eqs. (2) and (3) are then applied to estimate the random incidence absorption coefficient of the inhomogeneous MPPs.

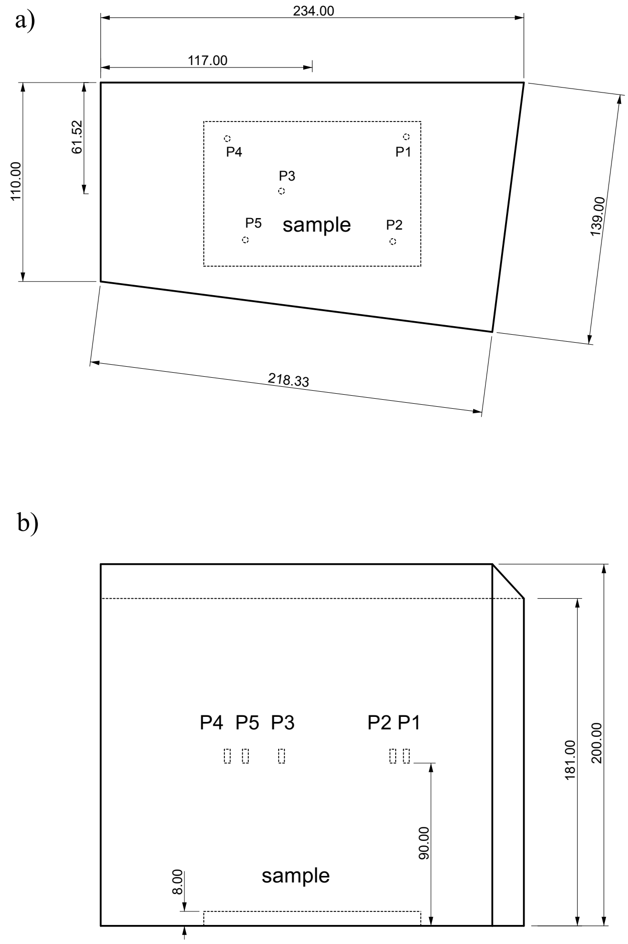

Figure 3. a) the plan and b) section of the SSRR in Bilkent University.

4. RESULTS

Numerical results by employing the Equivalent Circuit method and Eq. 1, show that when the proposed MPPs are connected in parallel, they are expected to provide an α value of more than 0.5 from 373 Hz until 1500 Hz (Figure 4). Those values are pretty promising for a fibreless structure with an overall thickness of 6.2 cm.

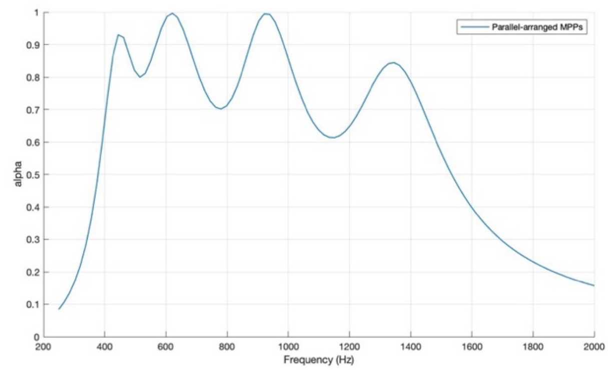

Figure 4. Alpha values for the inhomogeneous MPPs according to the Equivalent Circuit Method and Eq.1.

In the SSRR, three measurements were made for each microphone position, and the T30 values were then averaged first for each position and then for the entire room. The T60 (T_0) values in Table 2 for the empty room were extrapolated from the T30 values. The mean reverberation time of the empty room between 400 Hz and 2000 Hz is 4.14 seconds. T_1 describes the T60 values obtained by three measurements in the same position as in the first case, with the absorbing material introduced to the room. In this case, the mean reverberation time is 1.69 seconds, 2.45 seconds shorter than the one in the empty room.

Table 2. T_0 and T_1 values per 1/3 octave bands.

Octave bands	T_0 (s)	T_1 (s)
400 Hz	2.19	2.06
500 Hz	2.63	2.16
630 Hz	6.31	1.28
800 Hz	6.45	1.11
1000 Hz	6.01	1.25
1250 Hz	4.91	1.35
1600 Hz	3.68	2.16
2000 Hz	3.38	2.15

Furthermore, by implying T_0 and T_1 values to Equations 1 and 2, the alpha values of the proposed MPPs are calculated and shown in Table 3.

Table 3. α values of the material measured in the SSRR.

Octave bands	α values
400 Hz	0.03
500 Hz	0.09
630 Hz	0.64
800 Hz	0.77
1000 Hz	0.65
1250 Hz	0.55
1600 Hz	0.20
2000 Hz	0.17

Even though the α values are lower than predicted by the ECM, it is reasonable to assume that they exhibit a similar incremental trend across the frequency range of interest, except for frequencies below 500 Hz. As a result, the resonance frequency of MPP1 occurring at 444 Hz could not be effectively observed. The main reason behind those discrepancies is believed to be due to the low diffusivity of the SSRR in frequencies below 500 Hz. However the increasing α values at 630 Hz, 800 Hz and 1250 Hz show the effectivity of the resonances enhanced by MPP2 (600 Hz), MPP3 (939 Hz) and MPP4 (1400 Hz).

5. CONCLUSIONS

This work aimed to investigate the acoustic absorption coefficient of inhomogeneous Micro Perforated Panels (MPPs) in a Small Scale Reverberation Room (SSRR), which offers the advantage of analyzing samples with larger dimensions than the impedance tube and smaller than the full scale Reverberation Room. After being fabricated through laser and CNC tools, the material was mounted in a tile system in SSRR, recently built in the Department of Interior Architecture and Environmental Design at Bilkent University. Results show a difference between the pre - and post - measurement reverberation times especially between the 630 Hz and 1250 Hz. Although the absorption coefficients of the suggested material are slightly lower than what was predicted by the Equivalent Circuit Method, they still exhibit a consistent trend, excluding frequencies below 500 Hz. These findings pave the way for further exploration of the suggested materials at various incident angles and potential combinations suitable for architectural applications. The materials offer the advantage of significantly reduced thickness while eliminating the need for fibrous or porous substances.

6. ACKNOWLEDGMENTS

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