


Article

# Development of a Panel Membrane Resonant Absorber

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**Abstract:** The bass ratio describes the relationship between the reverberation energy in the low frequency region and that of the middle frequency. An appropriate bass ratio can create a warm sound; however, too much bass can influence speech clarity ( $C_{50}$ ) and work efficiency and can even cause listeners to feel tired or exhausted. Using perforated plate resonance theory and membrane resonance theory, this research developed the panel membrane resonant absorber (PMRA), which not only provides an outstanding continuous absorption spectrum in the broadband range of 100–800 Hz but also presents an aesthetic appearance at a low cost. We divided this study into two parts: (1) PMRA development and experiment and (2) field application and measurement to confirm the sound absorption performance of the PMRA. In part 1, PMRA was developed by combining different materials and thicknesses of the air cavity. In the field study of part 2, the PMRA with the appropriate sound-absorbing curve was installed in a small auditorium, where we conducted field measurements for reverberation time (RT) and speech clarity ( $C_{50}$ ). According to the experimental results, the PMRA had great absorption performance at a low frequency. In the field validation, the PMRA was found to effectively decrease the low-frequency RT while also maintaining the RT of middle-high frequency. The  $C_{50}$  of the auditorium was also improved.

**Keywords:** speech clarity; bass ratio; sound absorption; reverberation time



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## 1. Introduction

At the beginning of the 20th century, Sabine proposed the famous reverberation time (RT) theory, which brought room acoustics into the scientific realm. However, many acousticians have proposed different methods to inspect the pros and cons of room acoustics. Knudsen and Harris [1] believe that a RT below 500 Hz used in the field of music should be higher than the middle frequency. Ehmer [2] experimented with 250 Hz and found that when the masking sound is 20 dB, the 250 Hz threshold of the same frequency is increased by about 10 dB, the masking sound is 80 dB, and the 250 Hz test signal threshold is raised by about 50 dB. Beranek [3] proposed the bass ratio (BR) indicator and believed that in the acoustic design of a hall, the RT for low frequencies (125–250 Hz) should be increased by 20% compared to intermediate frequencies (500–1000 Hz), suggesting that a concert hall could be even up to 50%, which can make the sound warm and brilliant. Therefore, while low frequency is of considerable importance in a space, too much low-frequency energy will have the opposite effect. Fuchs and Zha [4] proposed that both language and music have non-negligible energy in the low frequency, which may generate standing waves in space, indirectly strengthen the low-frequency sound field energy, and shield the middle and high frequencies that are extremely important for clarity, thus affecting speech clarity ( $C_{50}$ ).

Furthermore, in addition to the feedback on the physical level of the low-frequency sound, the psychological impact is also an important factor. Vasudevan and Gordon [5] found that low-frequency noise mainly occurs in indoor environments, while Leventhall [6] considered the low-frequency noise band to be 10–200 Hz and pointed out that LAeq underestimated low-frequency noise most of the time. Alimohammadi et al. [7] found

that low-frequency noise caused users to feel annoyed, whereas Waye and Rylander [8] proposed that the low-frequency noise of ventilation equipment was prone to higher levels of psychosocial symptoms, sleep disturbance, and headaches for people who are annoyed. Caniato [9] found that underestimating the interference caused by LAeq can affect sleep conditions, and Falourd et al. [10] found that low-frequency background noise causes reduced speech intelligibility and users feel stressed and fatigued. Abbasi et al. [11] conducted a noise test with 35 young males aged 20 to 30 years old and found that noise between 65 dB and 75 dB obviously caused psychological fatigue, increased heart rate, and reduced working memory. Therefore, in order to reduce the likelihood of generated low-frequency sound, some researchers have proposed the sound absorption method.

Common sound absorption systems on the market, such as Helmholtz resonance, perforated panel resonance (PPR), micro-perforated panel (MPP), and membranous vibration (MV), each have sound absorption characteristics at a different frequency. Helmholtz resonance is for mid-low frequency, but the frequency band is narrow. PPR is also for mid-low frequency but is wider than that of Helmholtz. The MPP has better sound absorption performance than PPR, but the manufacturing cost is higher. MV is the only one that can facilitate artistic creation with sound absorption ability at mid-low frequency. Since this research is focused on low frequency, we adopted the PPR and MV systems. As a result, in this paper, we took advantage of the sound absorption characteristics of PPR and MV to reach better performance at a low frequency.

A bass trap is normally used to solve the problem of acoustics at a low frequency. Some people will create a bass trap by themselves since they are expensive and enormous, but such DIY products are without measurements to confirm the sound absorption performance. Therefore, this research designed an absorbent material for low frequency (125 and 250 Hz). Common methods for improving sound absorption on building walls include installation of curtains, wood panels, porous cotton materials with perforated panels, and sandwich structure. Considering price, porous cotton materials with perforated panels have been commonly adopted in interior renovations but have not shown outstanding sound absorption performance at low frequency. Ćudina et al. [12] designed a sound absorber by hanging a painting to reduce the RT and found that canvas without an oil color layer and different air layer behind had a low performance of sound absorption coefficient at low frequency. The result showed the sound absorption coefficients at 125 and 250 Hz were under 0.1. Considering the influence of sound absorption performance via canvas surface tension, Zainulabidin et al. [13] found that surface tension has no significant effect on sound absorption properties.

Traditional absorbers such as porous materials necessitate a thick absorbing material when working at a low-frequency range [14]. Hybrid materials have been proposed for broadband of low-frequency absorption with a thinner structure. Zhao et al. [15] proposed a double porosity material (DPM) that combined the micro-pore from the porous layer and the meso-pore made by the labyrinthine channel to absorb low-frequency sound. Dupont et al. [16] proposed a multi-pancake material that connected perforated materials to provide a collection of periodically spaced materials as resonant absorbers of low frequency. Liu et al. [17] proposed a perforated composite Helmholtz resonator (PCHR) that combined separating plates with a Helmholtz resonator and provided a continuous absorption spectrum in the broadband range of 450–1360 Hz. Furthermore, Zhu et al. [18] combined periodic acoustic metamaterial resonators (AMRs) with a porous layer and provided a broadband absorption of the audible sound wave at the low frequency of 180–550 Hz. Tang et al. [19] proposed a perforated honeycomb-corrugation hybrid (PHCH) model that combined a lightweight sandwich panel with a perforated honeycomb-corrugation core, providing outstanding sound absorption over a broadband low-frequency range. However, most of these hybrid materials are still in the research and development stage, their prices are relatively high, and they have not yet been verified in the field.

In general, historical buildings are usually decorated with smooth, hard, and high-reflex skin materials, such as glass, concrete, and wood, which result in long RT. On the

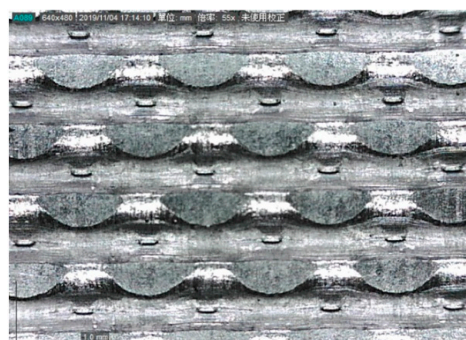
other hand, according to Taiwan's Cultural Assets Protection Law, decoration can only be carried out after being approved regarding its configuration, shape, color, and style, thus placing restrictions on decoration. As described above, sound absorption performance has to be improved at low frequency. Therefore, for this paper, we designed public art with two sound absorption systems in order to study panel membrane resonant absorber (PMRA) sound absorption performance at low frequency.

The theory of sound absorption of PPR combined with sound absorption of MV was adopted in this research. The former has better sound absorption performance at middle frequency, while the latter has better performance at low frequencies. Therefore, the specimens, including different combinations that consisted of expanded metal mesh (EMM) and canvas, were tested to develop the PMRA with better absorption performance. This study had two parts—PMRA development and field verification. First, the PMRA was developed with different combinations of EMM and canvas; then, the sound absorption performances of the materials and PMRA were tested using ISO 354 [20]. Last, the PMRA with the best performance at 125 Hz was installed in a historic building, and its performance in the field was measured and verified. The field verification was focused on room acoustics of long RT at low frequency.

## 2. PMRA Development and Prototyping

### 2.1. Specimens

The development process of the PMRA included two stages. In stage 1, the sound absorption performances of single materials (EMM and canvas, as shown in Figure 1) with different air cavities were measured. Then, in stage 2, different air thicknesses in the PMRA composed of EMM and canvas were measured. The size of each PMRA was  $1.8 \times 1.2$  m. The thickness and density of EMM were 1.2 mm and  $2.25 \text{ kg/m}^3$ , respectively, while the density of the canvas was  $0.36 \text{ kg/m}^3$ . Group A consisted of a 10 cm high wooden frame, canvas covered the surface and fixed the periphery as a membrane structure, and EMM was installed inside as a resonator, which was collocated at different heights to study sound absorption performance. Group B used a 20 cm high wooden frame and the same installation method as Group A. The detailed information of the materials and specimens are provided in Tables 1 and 2, and Figures 2–5.



(a) Expanded metal mesh



(b) Canvas

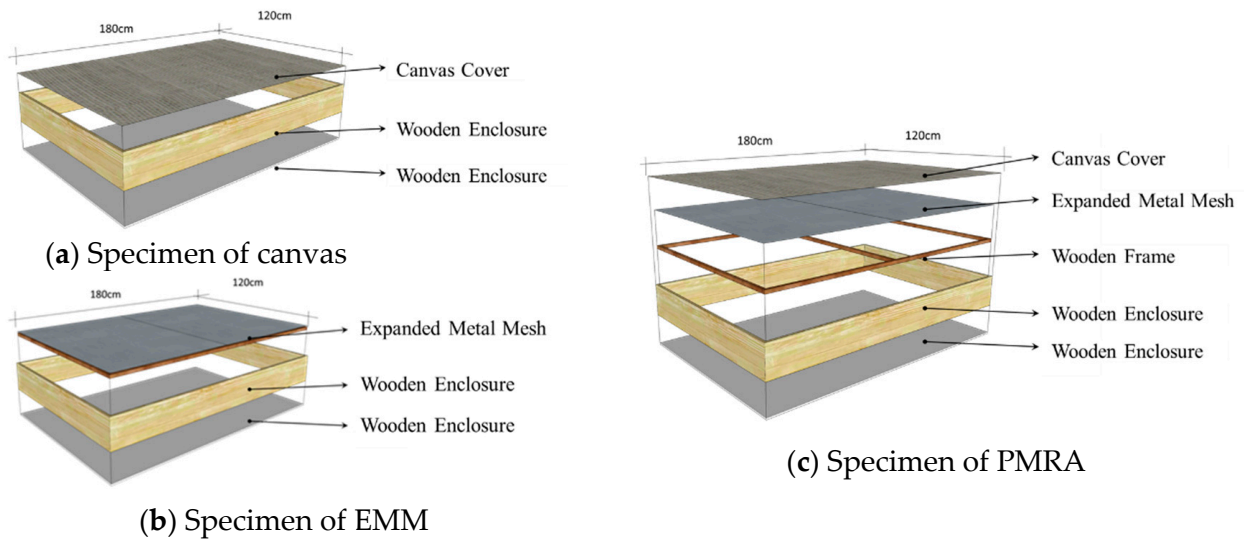
Figure 1. Materials.

Table 1. Detailed thickness of stage 1 specimens.

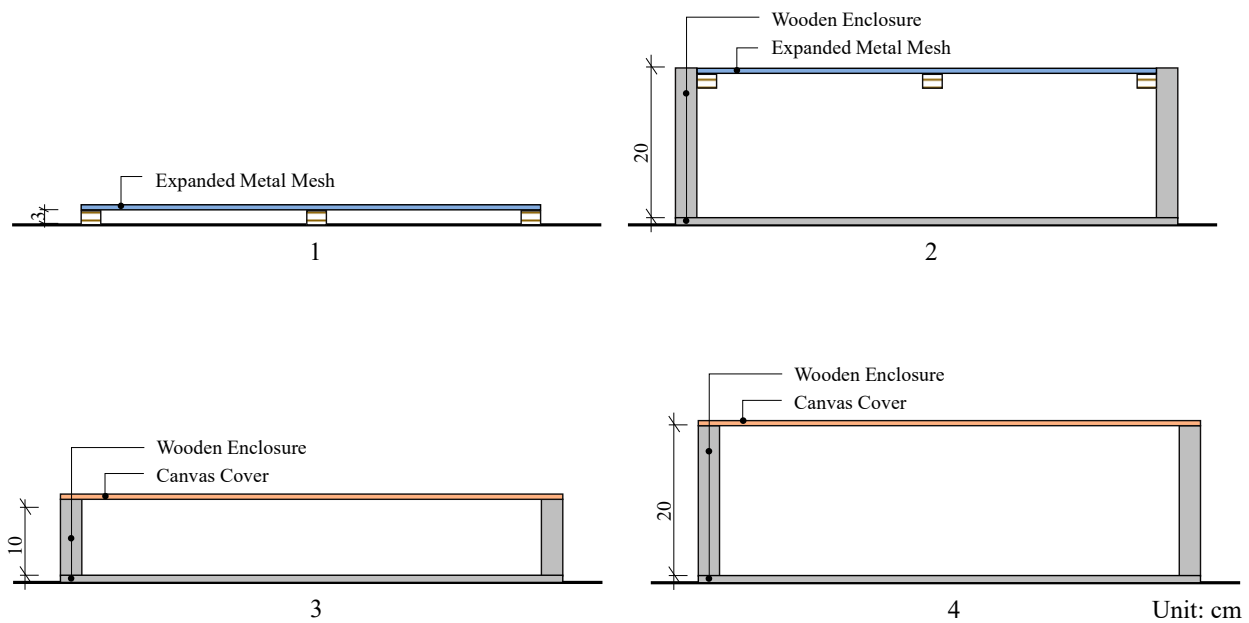
No.	Surface Texture	Air Layer (cm)	Height (cm)
1	EMM	3	3
2		20	20
3	Canvas	10	10
4		20	20

**Table 2.** Detailed thickness of stage 2 specimens.

Group	No.	Air Layer Behind the Material (cm)		Height (cm)
		Canvas	EMM	
A	A1	5.8	3	10
	A2	3.8	5	
	A3	1.3	7.5	
	A4	None	10	
B	B1	15.8	3	20
	B2	8.8	10	
	B3	3.8	15	
	B4	None	20	



**Figure 2.** Composition of specimens.



**Figure 3.** Specimen section in stage 1, as Table 1.



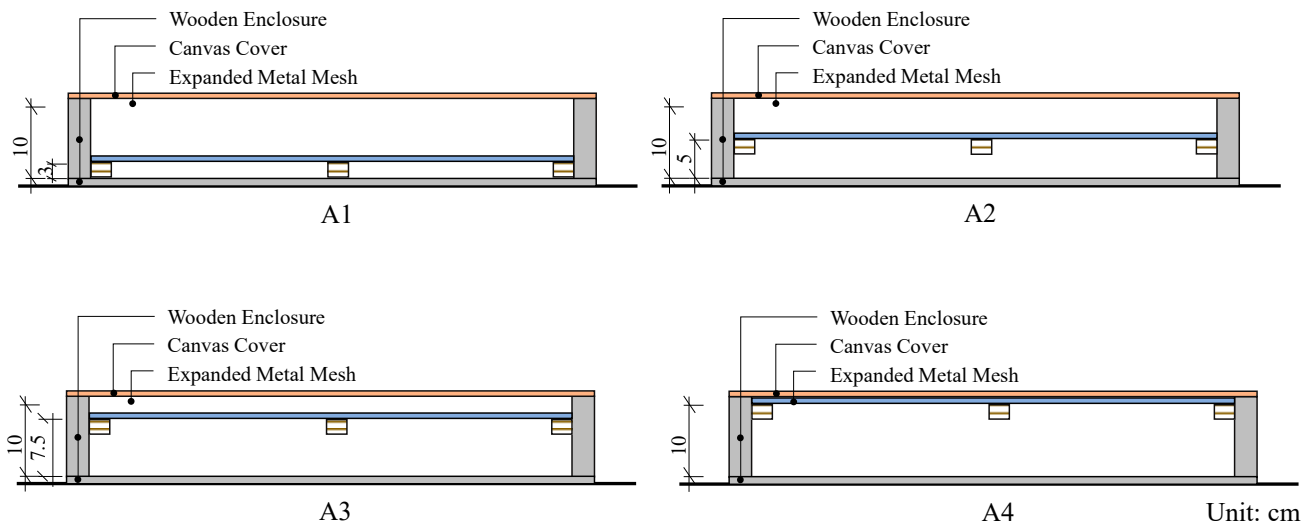


Figure 4. Group A section in stage 2, as Table 2.

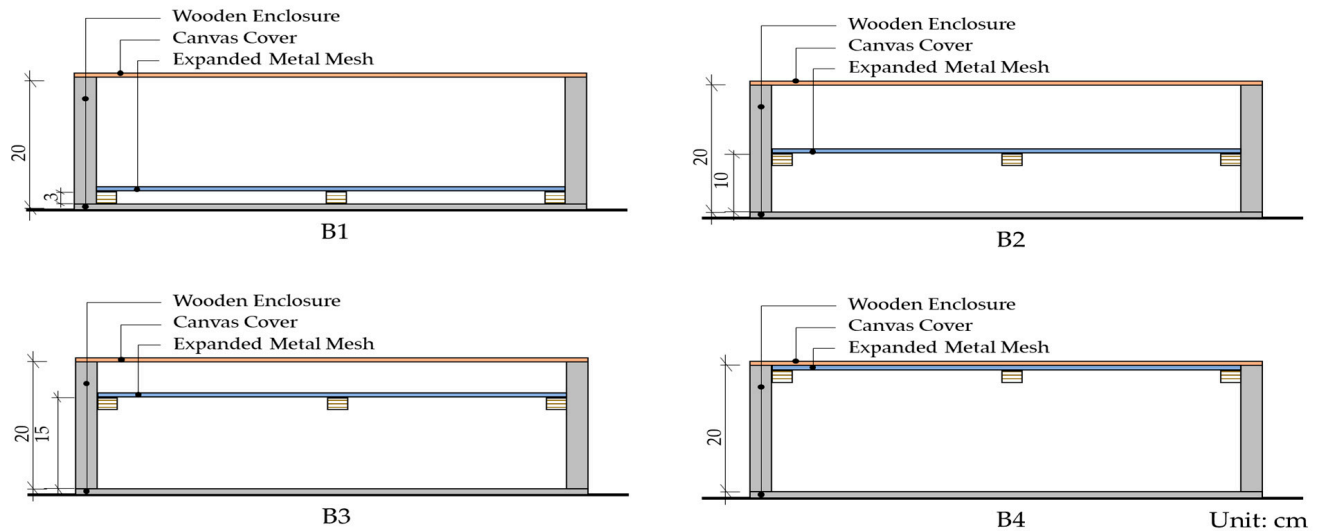


Figure 5. Group B section in stage 2, as Table 2.

### 2.2. Experiments

In this study, the sound absorption efficiency was measured using the reverberation room, which conforms with the ISO/IEC 17025 [21] testing and calibration laboratory operation regulations, and the methodology of measurement suite is in accordance with ISO 354:2003 [22]. The reverberation room is an unshaped hexahedron. The volume of the reverberation room is 171.3 m<sup>3</sup>, its surface area is 184.3 m<sup>2</sup>, and its floor area is 32.8 m<sup>2</sup>. The laboratory adopts a floating structure to reduce the outside interference on the experiment. As described above, the single PMRA was 2.16 m<sup>2</sup> (1.8 m × 1.2 m), and the total area of the test specimen was 4.32 m<sup>2</sup> (1.8 m × 2.4 m), which was placed on the center of the floor. Figure 6 shows the reverberation room environment, and the receive point and calculation of the sound absorption coefficient are shown in Equation (1).

$$\alpha_s = 55.3 \times V \left( \frac{1}{c_2 T_2} - \frac{1}{c_1 T_1} \right) - 4V(m_2 - m_1) \tag{1}$$

where  $V$  is the volume of the empty reverberation room (m<sup>3</sup>);  $c$  is the propagation speed of sound in air (m/s);  $T_1$  is the reverberation time of the empty reverberation room (s);

$T_2$  is the reverberation time of the reverberation room after the test specimen has been introduced (s); and  $m_1, m_2$  is the power attenuation coefficient ( $m^{-1}$ ).

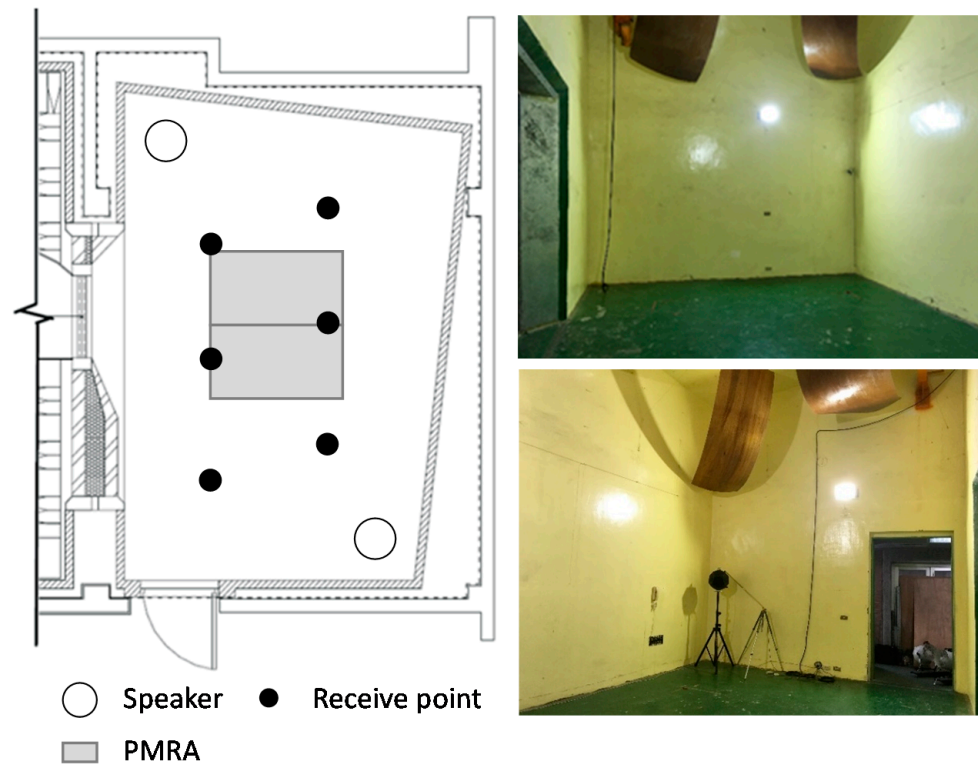


Figure 6. Reverberation room of National Cheng Kung University Architectural Acoustics Lab.

### 3. Measurement Results of PMRA

Figures 7 and 8 demonstrate the results of the first stage. By increasing the air layer behind the expanded metal mesh, we found that the absorption frequency band became wider, and the resonance frequency moved to low frequency. The surface density of the canvas was small. Although the low frequency was slightly improved by increasing the air layer behind it, the sound absorption efficiency was relatively weak throughout the entire frequency band. Due to the limitation of the materials' surface density, changing the air layer had a greater impact on the low frequency of absorption efficiency with the expanded metal mesh than with the canvas.

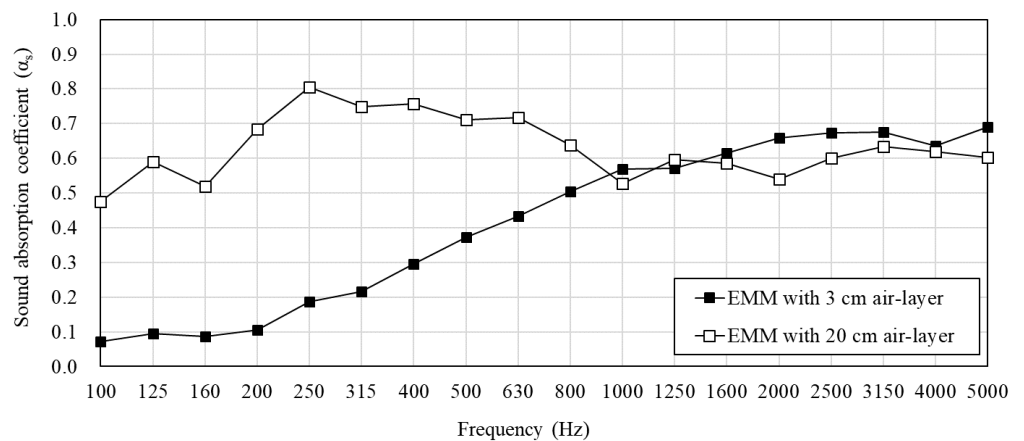


Figure 7. The sound absorption coefficient of expanded metal mesh (EMM) with single-layer structure in stage 1.

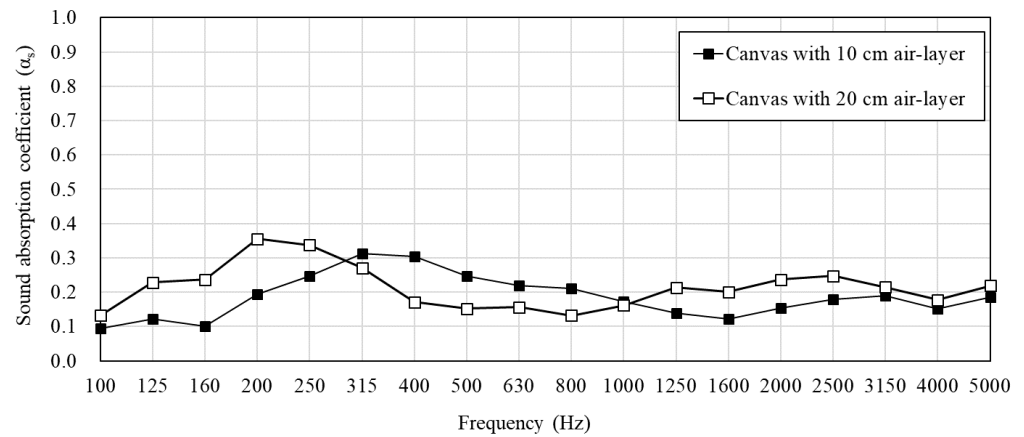


Figure 8. The sound absorption coefficient of canvas with single-layer structure in stage 1.

The results of the second stage are shown in Figures 9 and 10. In Group A, the sound-absorbing performance significantly increased at a frequency range from 125 to 250 Hz via increased air space behind EMM, that is, at 125 Hz, it increased from 0.14 to 0.33, and at 250 Hz from 0.53 to 0.75. Although the sound absorption coefficient at low frequency increased, it was still lower than 0.6 when under 250 Hz.

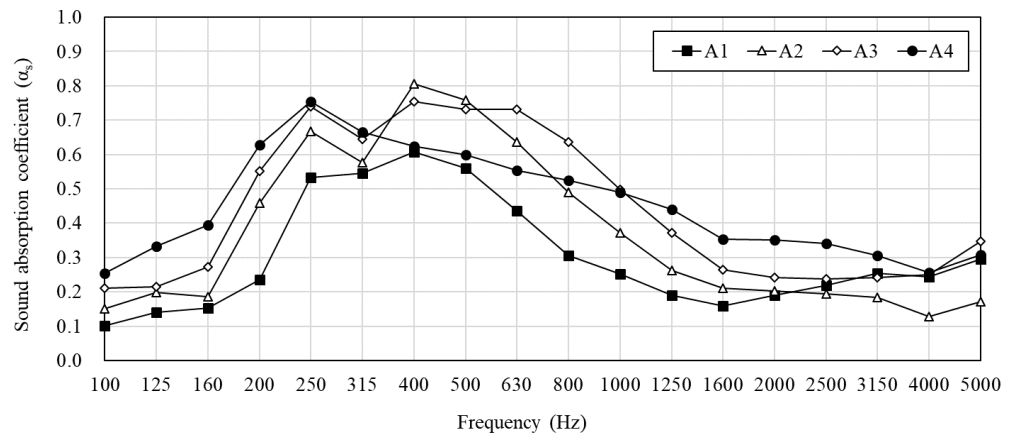
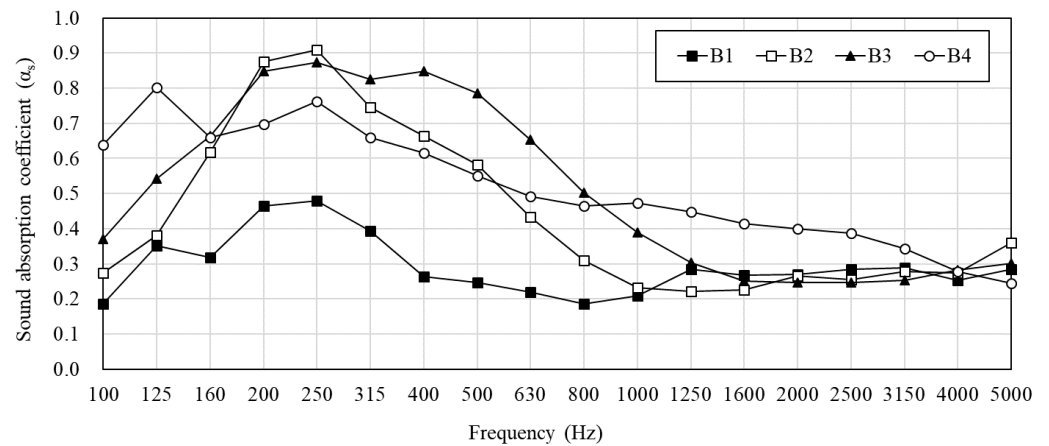


Figure 9. The sound absorption coefficient of Group A in stage 2 (specimen height 10 cm). A1: canvas with 5.8 cm air-layer + EMM with 3 cm air-layer; A2: canvas with 3.8 cm air-layer + EMM with 5 cm air-layer; A3: canvas with 1.3 cm air-layer + EMM with 7.5 cm air-layer; A4: canvas with 0 cm air-layer + EMM with 10 cm air-layer.

In Group B, the air space was increased to 20 cm, and the overall sound absorption performance was significantly improved at low frequencies compared to Group A. Therefore, the sound absorption coefficient rose above 0.4; at 250 Hz, it increased from 0.48 to 0.91, at 125 Hz, from 0.35 to 0.80. B4 sound absorption performance not only performed better than the other specimens in Group B at 100 Hz and 125 Hz, but also at medium and high frequencies.

As shown above, in Group A, as the air layer increased, the sound absorption coefficient of each frequency band improved. The sound absorption coefficients of A2 to A4 at 250–500 Hz were all above 0.6. However, the objects of this study were 125 and 250 Hz. Therefore, in Group B, we increased the air layer to 20 cm and found that the sound absorption coefficient moved to low frequency. B4 performed well at 125 Hz, and the 250 Hz sound absorption coefficient was 0.76. Therefore, this study chose B4 as the specimen for subsequent development.



**Figure 10.** The sound absorption coefficient of Group B in stage 2 (specimen height 20 cm). B1: canvas with 15.8 cm air-layer + EMM with 3 cm air-layer. B2: canvas with 8.8 cm air-layer + EMM with 10 cm air-layer. B3: canvas with 3.8 cm air-layer + EMM with 15 cm air-layer. B4: canvas with 0 cm air-layer + EMM with 20 cm air-layer.

**4. Field Validation of PMRA**

**4.1. The Historic Building**

In this study, we adopted Ge-Chi Hall of National Cheng Kung University as the object of field verification. Ge-Chi Hall has a historical and cultural background and is a typical small auditorium, as shown in Figure 11. The building is approximately 220 m<sup>2</sup>, with a volume of 1600 m<sup>3</sup>, and a total interior surface area of 1060 m<sup>2</sup>. The overall wall was made of cement, the first floor was made of wood and cement, and the second floor was made of wood without fixed seats. The first floor was for the auditorium, while the second floor was for the media. As described, these materials were all smooth surface materials, which causes a long RT. However, Ge-Chi Hall is primarily used for ceremonial activities, including musical performances, speeches, dinner parties, and evening parties. As a result, we targeted the RT and C<sub>50</sub> in this study, especially at low frequency.



**Figure 11.** Ge-Chi Hall environment and section diagram.

**4.2. Acoustic Index**

This study refers to the bass ratio by Beranek [3], which is identified as the ratio of RT between 125 Hz, 250 Hz, and middle frequency (500 Hz and 1000 Hz), as shown in Equation (2). Beranek classified the ratio of RT into four levels, as shown in Table 3.

$$\text{Ratio of RT} = \begin{cases} T_{125}/T_{mid} \\ T_{250}/T_{mid} \end{cases} \tag{2}$$

$$T_{mid} = (T_{500} + T_{1000})/2$$

where  $T_{125}$  is the reverberation time of 125 Hz (s),  $T_{250}$  is the reverberation time of 250 Hz (s), and  $T_{mid}$  is the reverberation time of 500 and 1000 Hz (s).

**Table 3.** Ratio of reverberation time (RT) at low frequency (Beranek, 1962).

Category	$T_{250}/T_{mid}$	$T_{125}/T_{mid}$
Excellent bass	1.14	1.27
Good bass	1.06	1.03
Fair bass	0.97	0.95
Poor bass	0.90	0.86

According to ISO 3382-1 [22], the  $C_{50}$  is the ratio of early-to-late arriving sound energy ratio, and it can be calculated through Equation (3). When  $C_{50} > 0$ , the early sound energy dominates the sound field and satisfies basic speech intelligibility. In general, the  $C_{50}$  have a high relation with RT—the lower the RT, the better the  $C_{50}$ .

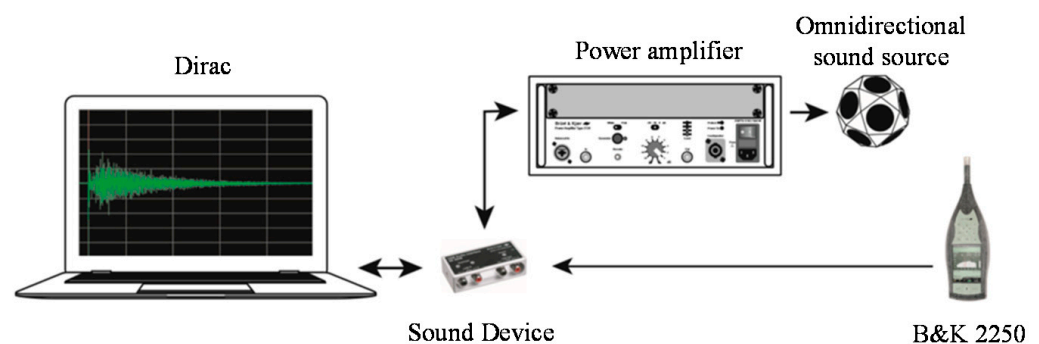
However, the target in this paper is to compare the RT and  $C_{50}$  at a low frequency in Ge-Chi Hall with and without PMRA. RT is valued by BR, and we observed how much  $C_{50}$  increased.

$$C_{50} = 10 \lg \frac{\int_0^{50} p^2(t) dt}{\int_{50}^{\infty} p^2(t) dt} \text{ dB} \tag{3}$$

where  $C_{50}$  is the early-to-late index, and  $p(t)$  is the instantaneous sound pressure of the impulse response measured at the measurement point.

#### 4.3. Field Measurement

The measurement environment had air conditioning, NC was 35, temperature was 26 °C, and relative humidity was 55%. In this study, the sound source was an omnidirectional loudspeaker via B&K Dirac software that output MLS digital signals and analysis after a 1/2 free-field microphone received the sound power, as shown in Figure 12. In Figure 13, the sound source is shown set on the stage, and all receive points are evenly distributed on the first floor (P1–P5) and second floor (P6–P7); the measured data were the total average.



**Figure 12.** System of the field measurement.

Figure 14 shows the RT results of Ge-Chi Hall without PMRA. At 125, 250, 500, and 1000 Hz, the RT values were 1.74, 1.53, 1.31, and 1.21 s, respectively. According to the RT ratio proposed by Beranek [3], 500 and 1000 Hz of RT were substituted into Equation (2) for the field measured, and the calculation revealed that the 125 and 250 Hz RT of the space



should be between 1.19 and 1.60 s, and 1.22 and 1.43 s, respectively. The comparison result shows that 125 and 500 Hz need to be reduced by at least 0.14 s and 0.1 s, respectively, to fall within an appropriate RT.

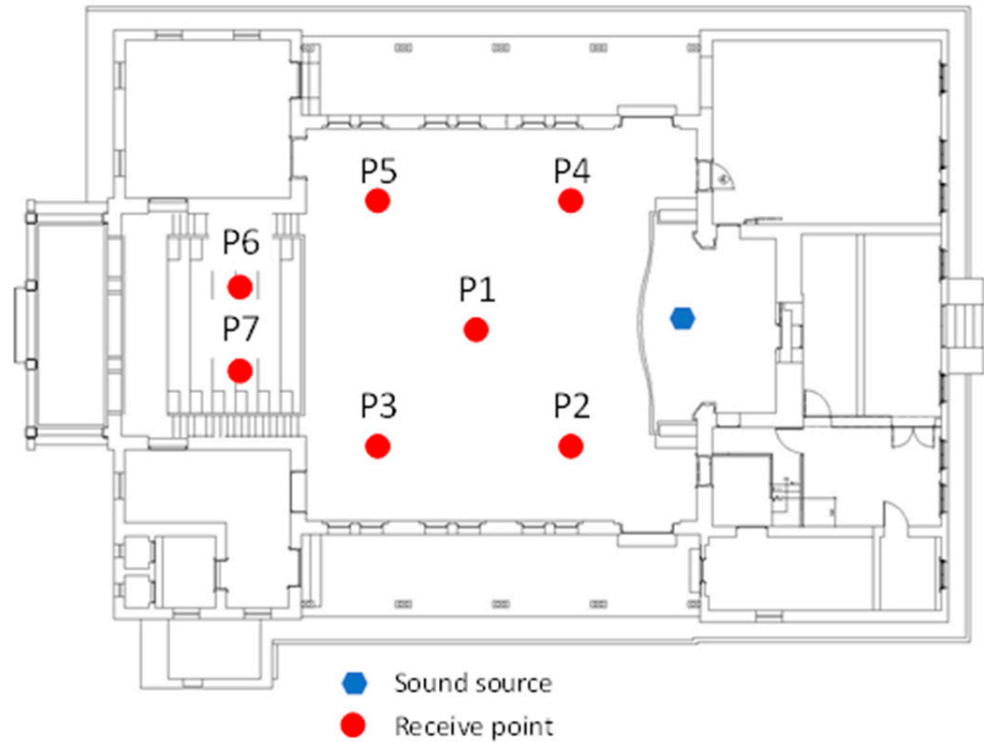


Figure 13. Sound source and measurement points.

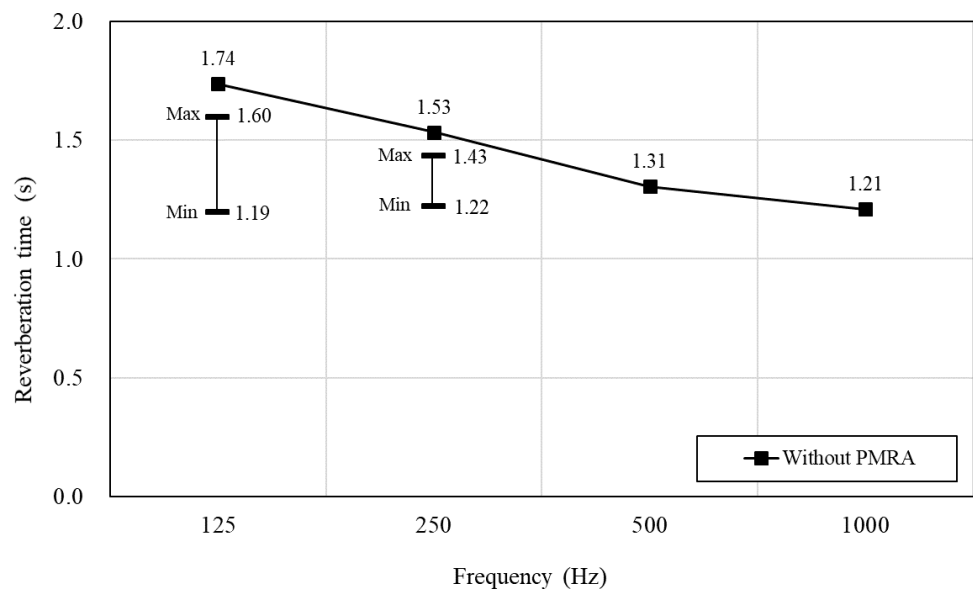


Figure 14. RT of Ge-Chi Hall without panel membrane resonant absorber (PMRA).

#### 4.4. Installation of PMRA

As described herein, for the field verification, we conducted a two-phase measurement of current situation investigation and improvement investigation, followed by the position measurement of RT and C<sub>50</sub>. After improvement, the survey installed PMRA on both sides of the front and back walls of the auditorium on the first floor, as well as on both sides of

the back and the walls on both sides of the media booth on the second floor. The PMRA was based on type B4 for field verification implementation. The following two sizes were used: 180 (L) × 125 (W) × 20 cm (H) with seven pieces and 120 (L) × 90 (W) × 20 cm (H) with two pieces. The installation position is shown in Figure 15.

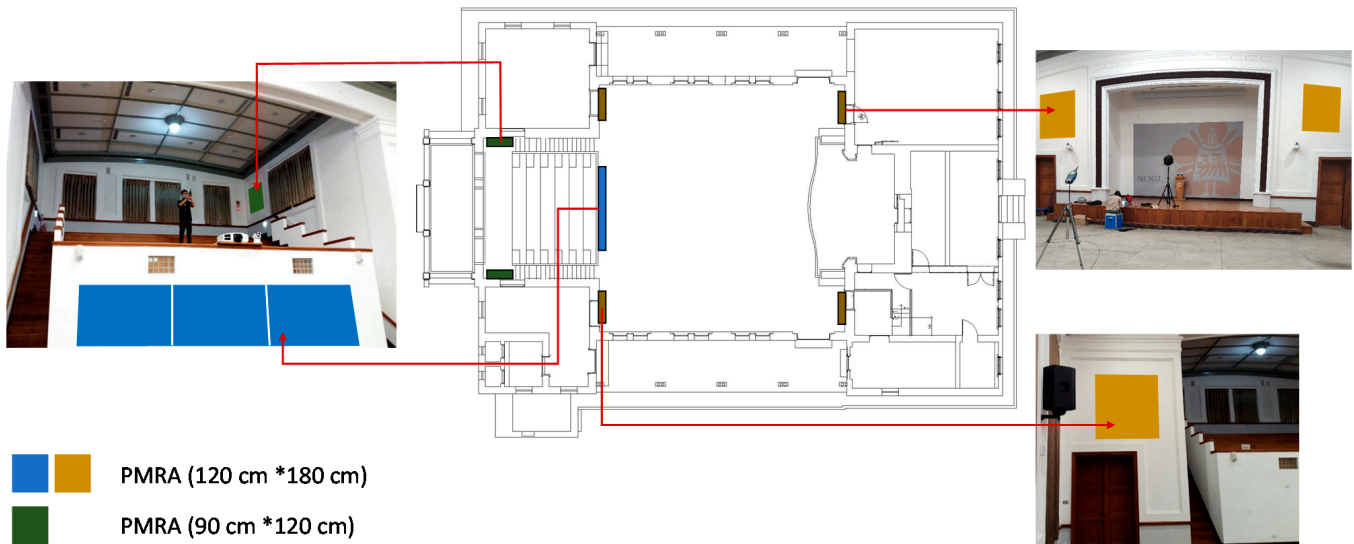


Figure 15. PMRA setting position.

#### 4.5. Field Performance of PMRA

Figure 16 shows the RT of Ge-Chi Hall with PMRA. The RT results were 1.55, 1.40, 1.28, and 1.16 s at 125, 250, 500, and 1000 Hz, respectively. The 500 Hz and 1000 Hz of RT in the measured field were substituted into Equation (2), which indicated that 125 Hz and 250 Hz should be between 1.16 and 1.47 s, and 1.19 and 1.37 s, respectively. Therefore, the PMRA effectively reduced the RT at low frequency, which was within a suitable RT range at both 125 and 250 Hz. Overall, by minimizing the high-frequency sound absorption as much as possible in this study, we found that PMRA can effectively reduce the RT at 125 and 500 Hz; thus, the result was consistent with the purpose of this research.

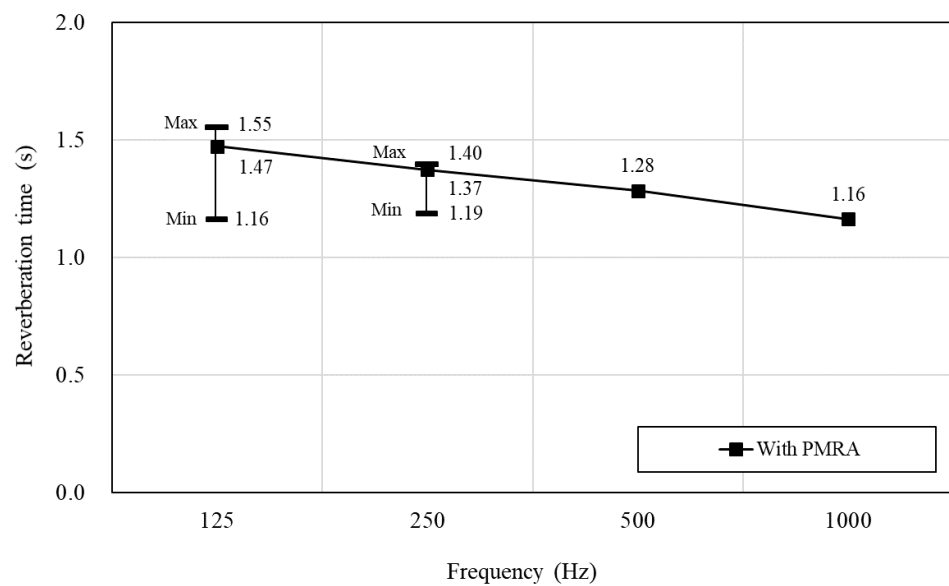


Figure 16. RT of Ge-Chi Hall with PMRA.

As shown in Figure 17, the  $C_{50}$  of Ge-Chi Hall without PMRA were  $-4.26$ ,  $-2.41$ , and  $-2.23$  dB at 125, 250, and 500 Hz, respectively. After PMRA was installed, the  $C_{50}$  was  $-2.19$ ,  $-0.73$ , and  $-1.35$  dB, reflecting increases of 2.07, 1.68, and 0.98 dB, respectively. Therefore, PMRA can effectively increase  $C_{50}$  performance at 125, 250, and 500 Hz. However, whether PMRA was installed or not, we observed no significant effect at 1000 Hz to 8000 Hz.

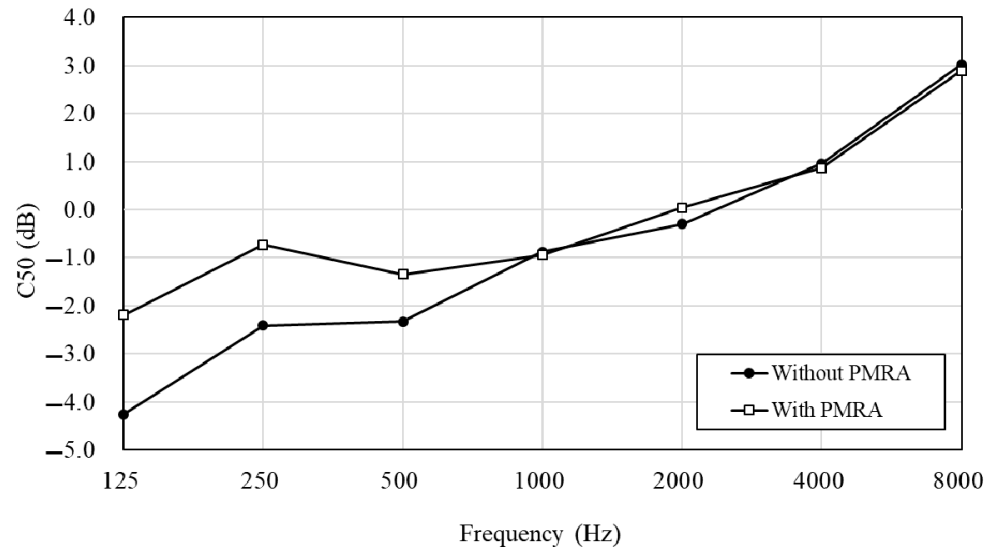


Figure 17. A comparison of  $C_{50}$  with or without PMRA at each band.

Figure 18 shows the comparison of the  $C_{50}$  with and without the PMRA at 500 Hz. Due to the PMRA installed point, speculated P1 had a long distance with PMRA, and P2 was close to outside noise. Therefore,  $C_{50}$  had an increased limitation, while the others were significantly increased.

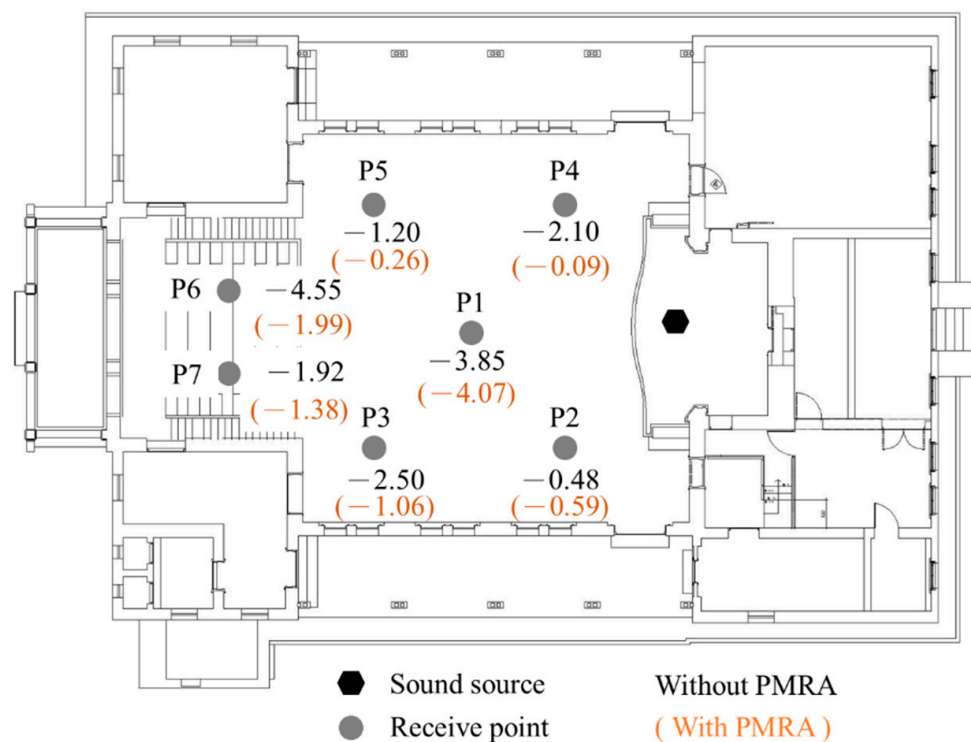


Figure 18. A comparison of  $C_{50}$  with or without PMRA at 500 Hz.

## 5. Conclusions

In this paper, we developed a PMRA prototype set with different structure combinations and used laboratory measurements to confirm the basic sound-absorbing characteristics of PMRA, choose a better sample on the basis of the research results, apply it to the actual field, and then study the low-frequency improvement of building acoustics.

The laboratory measurement was separated into two stages. In the first stage, we studied the sound absorption performance of the surface materials. The second stage was to study the membrane structure with single-layer EMM and to design a composite plate mold resonance sound absorber, which we used to explore each group's sound absorption characteristics of different materials and air space. We ultimately found that B4 had a better sound absorption performance than others at low frequency (125 Hz), and thus we chose and installed B4 in field validation.

For the difference between PMRA being installed in Ge-Chi Hall or not, the RT was reduced by 0.19 s at 125 Hz and 0.13 at 250 Hz, while  $C_{50}$  increased by 2.07 and 1.68 at 125 and 250 Hz, respectively. The overall results show that PMRA not only effectively reduced low frequency and increased  $C_{50}$ , but also was both practical and aesthetic as a sound absorber.

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