Sound Absorption Performance of Light-Frame Timber Construction Wall Based on Helmholtz Resonator

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In order to improve the sound absorption performance of the light-frame timber construction wall, this paper combined the aperture embedded wall unit structure with the actual building wall structure based on the Helmholtz resonance structure principle to design and fabricate two sets of wall structures: a new aperture embedded Helmholtz resonance structure (experimental group) and a conventional structure (control group). The sound absorption coefficients of the two wall structures were measured by the reverberation chamber test, and related analysis was carried out. The results showed that the aperture embedded Helmholtz resonance wall structure exhibited good sound absorption performance in the low frequency range; in particular, a perfect sound absorption effect was basically achieved at a frequency of 100 Hz. Compared with the conventional wall structure, the sound absorption performance of the aperture embedded Helmholtz resonance wall structure in the test frequency range was enhanced greatly. While the value of the sound absorption coefficient was increased in the low frequency range, the bandwidth of sound absorption frequency was expanded to a certain extent, and the average sound absorption coefficient and noise reduction coefficient were both improved. This paper explored the applicability of Helmholtz resonance structure in practical wall structure. The research results could provide reference for reducing indoor noise pollution and creating a better living environment.

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INTRODUCTION

Among the building materials used in the structural element, wood is a natural resource with renewable characteristics that can be used efficiently after being processed into engineered wood (He *et al*. 2020; Ponzo *et al*. 2021; Tudor *et al*. 2021; Tan *et al*. 2022). The application of engineered wood is of great significance for energy saving, emission reduction, and sustainable development of the construction industry (Thelandersson 2003; Pajchrowski *et al*. 2014; Li *et al*. 2021; Yang *et al*. 2021). As a typical representative of modern timber constructions, light-frame timber construction is characterized by short construction time, prefabricated assembly, good thermal insulation, earthquake resistance, energy saving, and good environmental performance, which meets the current requirements for the development of energy-saving and environmentally-friendly housing (Wang *et al*. 2014; Alinoor *et al*. 2020; Liang *et al*. 2021; Niederwestberg *et al*. 2021). Some progress has been made in researching the mechanical, thermal, and acoustic properties of engineered wood used in light-frame timber constructions (Wang *et al*. 2015, 2016; Caniato *et al*. 2021; Wang and Ghanem 2021). However, timber construction is still in the development stage, and the problem of its poor acoustic performance needs to be solved (Fu *et al*. 2021; Huang *et al*. 2021). Common methods to improve the sound absorption performance of the timber structural walls mainly include the following: The internal materials of the wall can be changed by using high-absorbing sound performance composites, such as porous materials (Fukuta *et al*. 2017; Peng 2018). The internal structure of the wall can be changed, such as stud spacing, specifications, *etc*. (Liu *et al*. 2018). These methods and measures only improve the noise reduction of the walls to a limited extent. It was demonstrated that sound absorbing materials within timber frame structures have a limited influence and especially using a thickness of at about 10 cm is enough for acoustics (Brunskog and Hammer 2003; Caniato *et al*. 2017). Furthermore, the noise absorption is difficult to regulate, and control of large broadband noise cannot be achieved.

In the current engineering application, the improvement in the sound absorption performance of the wall is mainly based on the two main categories of the sound absorption principle (Sakagami *et al*. 2011; Geng and Li 2012; Ning and Zhao 2016). One is the sound-absorbing material composed of porous materials, such as sound-absorbing cotton, where most of the sound waves gradually consume sound energy by friction with the material. The other is the resonant sound absorption structure, which uses the incident sound wave to create a resonance in the structure. The resonance converts the sound energy into other energy, such as heat energy, so that a large amount of sound energy is dissipated. In general, the porous sound-absorbing materials are characterized by better sound absorption performance at high frequencies than at low frequencies, so they are often used to absorb medium and high frequency noise. The resonant sound absorption structure mainly uses the resonance effect to achieve the sound absorption effect, which has a certain frequency band limit. It is generally suitable for low frequencies, especially when the noise spectrum has a clear peak in the low frequency range.

The Helmholtz resonance structure consists of a closed cavity and a perforated plate, one end of which is connected to the cavity and the other end of which is connected to the tube. The perforated plate and the cavity form an elastic vibration system. When the acoustic frequency of the fluid matches the natural frequency of the cavity vibration system, the vibration system will have a strong resonance, so that the motion velocity of the fluid column with a certain mass in the short pipe is accelerated. The frictional resistance is increased, and a large amount of sound energy is converted into heat energy and consumed to achieve the purpose of sound attenuation (Bedout *et al*. 1997; Everest 2001; He *et al*. 2007; Yuan 2007).

There have been numerous studies on the Helmholtz resonance structure. Guan *et al.* (2015) studied the existence of a low-frequency band gap in the Helmholtz resonance structure and calculated the energy band structure and transmission spectrum using finite element method. It was found that there are three band gaps and two adjacent partial band gaps in the range of 0 to 4000 hz, and the geometrical parameters affecting the width of the band gap or the width and length of the inlet were analyzed. Assouar *et al.* (2018) outlined the main design of the acoustic element surface, including an element surface design based on the curvature space, the Helmholtz resonance structure, and the membrane structure. and discussed their applications, such as beam focusing, asymmetric transmission and self-bending beam. Langfeldt *et al.* (2020) established a new analytical model using the effective material parameters (bulk modulus and density) of the fluid volume of Helmholtz resonance structure to describe the acoustic behavior of the double wall vibration with Helmholtz resonance structure. The relevant design parameters were determined through parameter research and the transmission loss of the Helmholtz resonator was optimized. The acoustic super-structured surface technology represented by the Helmholtz resonance structure is undoubtedly a research focus for improving the acoustic performance of structures.

In view of the poor sound absorption performance of light-framed timber construction walls and the lack of introduction of acoustic superstructure surface technology in relevant research, the Helmholtz resonance structure with ultra-thin and efficient adjustment of acoustic characteristics was used in the design and application of the wall structure. In previous research (Fu 2021), the indoor environmental noise of buildings was investigated. It was found that the equipment noise represented by air conditioning mainly affects the medium and low frequency band, especially the indoor environmental noise near 200 Hz and 1000 to 2000 Hz. The sound absorption principle of a Helmholtz wall unit structure was described, and the wall unit structure was designed according to the specimen requirements of impedance tube test method and the basic form of light wood wall structure. The acoustic performance of wall unit structure was studied by impedance tube test method, and the test piece was simulated and verified by multi physical field COMSOL MULTIPHYSICS.

In order to improve the acoustic performance of light-frame construction wall and reduce the low-frequency noise pollution in indoor environment, this paper applied the Helmholtz resonance principles to a practical wall structure. The test specimens of the test group (Helmholtz resonance wall structure with embedded aperture) and the control group were designed and manufactured. The sound absorption coefficients of two groups of composite wall structures were measured in the reverberation chamber to verify the feasibility of the application of aperture embedded structures in engineering practice.

EXPERIMENTAL

Design and Fabrication of Wall Structure

A large-size aperture embedded Helmholtz resonance sound-absorbing layer was designed in combination with the wall structure, and the corresponding wall cell structure is shown in Fig. 1. The wall structure studied in this paper was divided into two groups: the conventional structure (control group) and the aperture embedded Helmholtz structure (experimental group). The conventional structure was designed based on GJBT-1303 (2015). The cross-section of the wall structure is shown in Fig. 2. The acoustic performance of the two wall structures was compared.

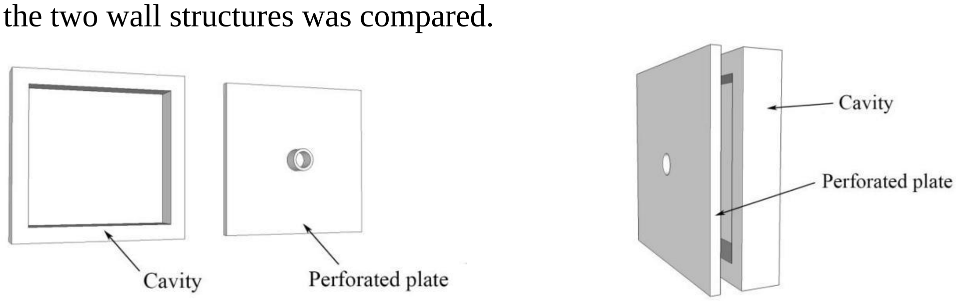
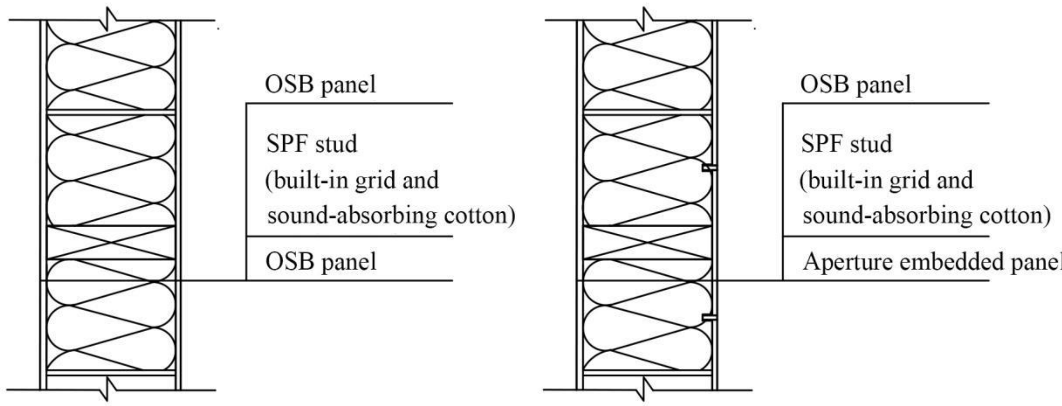


Fig. 1. Aperture embedded Helmholtz resonant wall-cell structure



(a) Conventional structure **(b)** Aperture embedded Helmholtz structure

Fig. 2. Section of light-framed timber construction wall structure

Design of Wall Structure

The hole diameter of the plug-in used in the aperture embedded Helmholtz resonance wall structure was 10 mm, and the hole length was 20 mm. The structural design of the walls of the experimental group and the control group is shown in Fig. 3.

Figure 3 shows that the two groups of wall structures mainly consisted of the upper OSB panel - SPF stud (filled with sound absorbing cotton and grid partition) - lower OSB panel. Because the specimens in this study should be suitable for building walls, the specimen size was large. Therefore, it was necessary to combine the requirements of sound absorption test for reverberation chamber and the requirements for the design of lightweight wooden wall in the design. The main work was as follows:

(1) To ensure the consistency of structural sound volume, the specimens were divided twice during construction. The plane dimension of the whole wall member was 3 m × 3 m. The frame was divided into nine 1 m × 1 m individual specimens for the first time; for the second time, the interior of the individual specimen was divided into 110 mm × 110 mm cells in the form of a grid insert plate.

(2) To ensure the integrity of the structure, the upper panel was arranged symmetrically and spliced with OSB of three specifications (Fig. 3 (a)), with the gap between adjacent OSB panels not exceeding 1mm and the reserved joint located above the stud.

(3) To facilitate the installation and enhance structural stability, the internal grid partition of the single test piece was connected with tenon and mortise.

(4) The single test piece was connected by toothed plate, and the connection between the panel and the stud was nailed and supplemented by glue.

Fabrication of Wall Structure

The processing and fabrication of the wall structure of the experimental group were carried out according to Fig. 3. The main process was: material preparation → assembly of a single test piece (stud frame assembly and internal grid partition assembly) → assembly of the wall frame → drilling of the upper panel → installation of the embedded plug-ins → filling of the sound-absorbing cotton → assembly of panels and frame. The basic parameters and number of components are listed in Table 1.

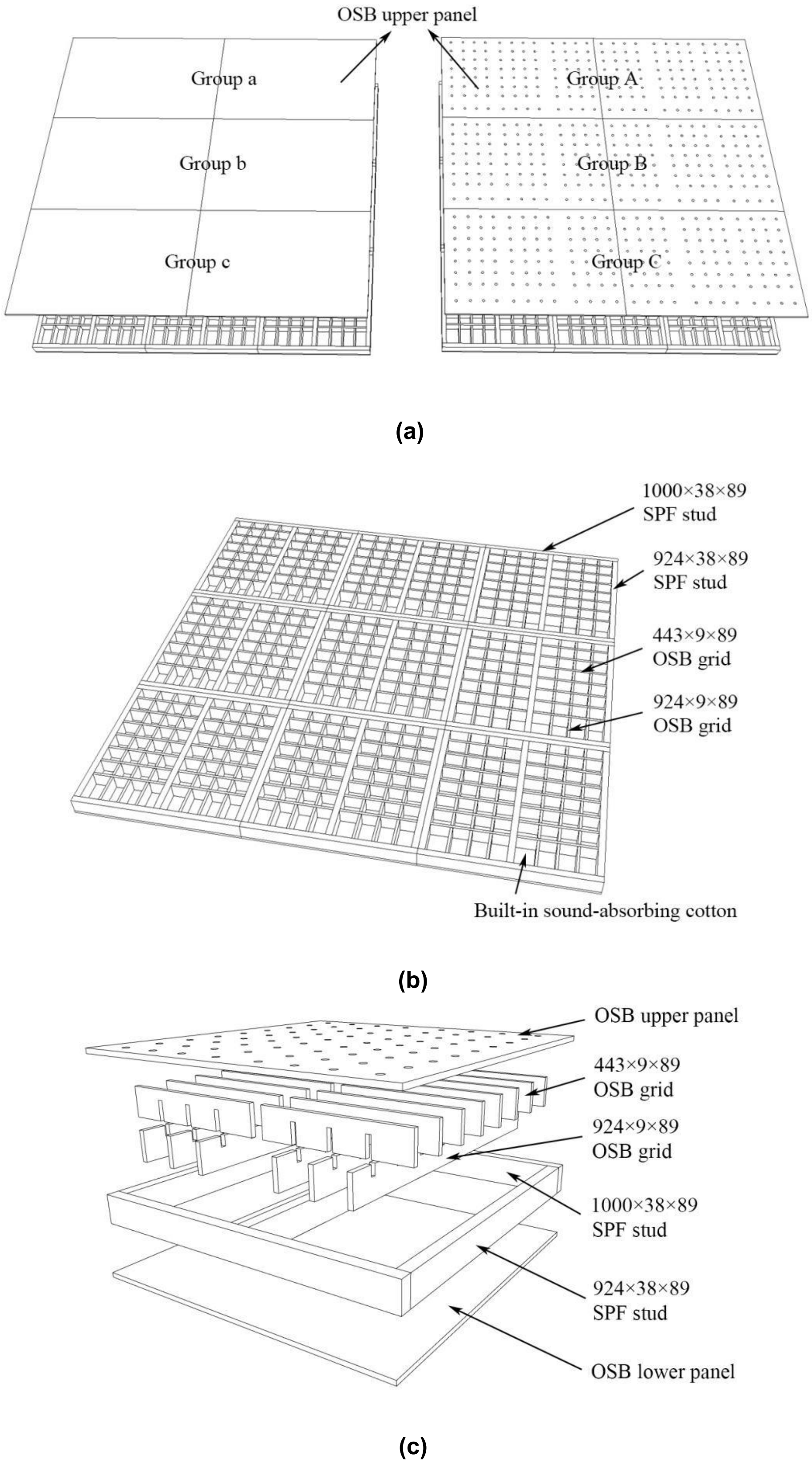


Fig. 3. Structural design of the walls of the experimental group and the control group. (a) upper panel combination, (b) internal frame, (c) single test piece (experimental group)

Table 1. Basic Parameters and Quantity of Components

Component	Size (mm)	Quantity (piece)	Density(kg/m^3)	Moisture Content(%)
SPF stud	924×38×89	27	480	10.5
	1000×38×89	18	480	10.5
OSB upper panel (group a/b/c)	c: 1500×1020×15	2	610	9
	b: 1500×1000×15	2	610	9
	a: 1500×980×15	2	610	9
OSB upper panel (group A/B/C) (with perforation, 10mm in diameter and 20mm in length)	C: 1500*1020×15	2	610	9
	B: 1500×1000×15	2	610	9
	A: 1500×980×15	2	610	9
OSB lower panel	1000×1000×15	9	610	9
OSB grid	443×9×89	126	650	9
	924×9×89	54	650	9

Note: the gap distance of the perforated panel (group A/B/C) is normally symmetrical.

Test Object and Device

According to the ISO 354 (2003), the specimens in this test adopted the form of splicing combination, with an area of 3 m × 3 m and a thickness of 119 mm, and each specimen was composed of 9 single pieces with the same structure of 1 m × 1 m.

The relevant information of the test device is as follows:

(1) Reverberation chamber: its dimensions were 7.7 m × 6.10 m × 4.85 m. The volume was 228 m^3. A rotating diffuser was provided, which was made of asymmetric partial cones and installed indoors to improve sound field diffusion, and distribute the characteristic frequency of the simple harmonic vibration mode uniformly in the low-frequency range. The test site was the reverberation room of the Institute of Acoustics of Nanjing University.

(2) Test equipment: 2 loudspeakers, 1 set of B&K Pulse 3610 (Nærum, Denmark), 1 set of TS5871 power amplifier (Shanghai, China), 1 B&K 4165 microphone (Nærum, Denmark) and 1 HS6288 sound level meter (Shanghai, China).

(3) Supporting equipment: computer and measurement software.

Test Principle and Method

Test principle

The length of the reverberation time is related to the efficiency of sound absorption and the volume of the room. Namely, the former determines the sound energy absorbed at each reflection and the latter determines the number of reflections of sound waves per second. Therefore, for a fixed room size, the reverberation time is only related to the sound absorption capacity of the room, so the sound absorption coefficient of sound absorbing materials or objects can be measured by reverberation time in the reverberation room.

At the beginning, the reverberation time T_1 (s) was measured from 100 to 5000 hz in the empty chamber, then the reverberation time T_n (s) was measured for each frequency after the sample under test was placed. Equation 2 can be derived from Eq. 1, as follows,

$$A = \frac{55.3V}{cT} - 4mV \tag{1}$$

$$A_{\mathrm{n}} - A_1 = 55.3V\left(\frac{1}{c_{\mathrm{n}}T_{\mathrm{n}}} - \frac{1}{c_1T_1}\right) - 4(m_{\mathrm{n}} - m_1)V \tag{2}$$

where A is the sound absorption of the room (m^2); V is the volume of the reverberation chamber (m^3); c_1 and c_n are the sound velocity during two measurements (m/s); and m_1 and m_n are the sound intensity absorption coefficients during two measurements. If the difference between the room temperature and humidity during two measurements is very small, $c_1 = c_n = c_0$, $m_n = m_1$, then the expression can be obtained as follows,

$$\Delta A = A_{\mathrm{n}} - A_1 = \frac{55.3V}{c_0}\left(\frac{1}{T_{\mathrm{n}}} - \frac{1}{T_1}\right) \tag{3}$$

$$\Delta A = a_{\mathrm{S}}S_1 \tag{4}$$

where a_S is the random incidence sound absorption coefficient of the specimen; S_1 is the area of the tested specimen (m^2). For the three parameters T_n, c_n and m_n, note that n = 2 means that the tested specimen is a conventional structural wall (control group); n = 3 means that the tested specimen is a aperture embedded Helmholtz structure wall (experimental group).

Test method

The test was carried out according to ISO 354 (2003). The distance between the specimen and any edge of any partition interface in the room should not be less than 1 m. Two loudspeakers were located in the two corners of the room facing the main diagonal. The distance between the microphone and the corner was in accordance with the standard requirement. The arrangement of the measurement points is shown in Fig. 4. The main test steps are:

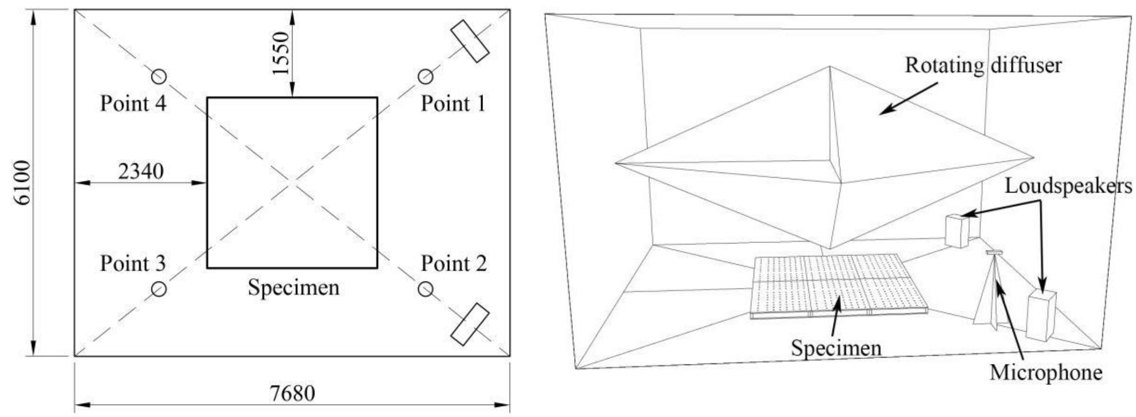
1) Preparation phase: The tested specimen was laid out flat according to the standard specifications, and the test system was connected and checked. The connection of the system is shown in Fig. 5. The sound level meter was the main device used to monitor the sound level in environments. In order to measure the reverberation time more accurately, the sound level of the instrument was adjusted to more than 100 dB. The temperature and humidity during the test were set as 24 °C and 67%, respectively.

2) Measurement of empty chamber reverberation time T_1: The reverberation time was measured using the interrupted sound source method. The sound source and microphone were placed at position 1 as required, and the measurement software was used for testing. After the test results were saved and recorded, position of the sound source and microphone were changed and placed at measuring points 2, 3, and 4, respectively, to perform the tests. Then the average value of the test results was obtained.

3) Measurement of reverberation time T_2 after putting in the conventional specimen (control group): The test process was the same as the measurement of reverberation time in the empty chamber.

4) Measurement of reverberation time T_3 after putting in the aperture embedded Helmholtz specimen (experimental group): The test process was the same as the measurement of reverberation time in the empty chamber.

5) Data processing: The random incident sound absorption coefficient was calculated using Eqs. 1 through 4.



(a) Layout plan of measuring points **(b)** 3D rendering of reverberation room test

Fig. 4. Schematic diagram of reverberation room test

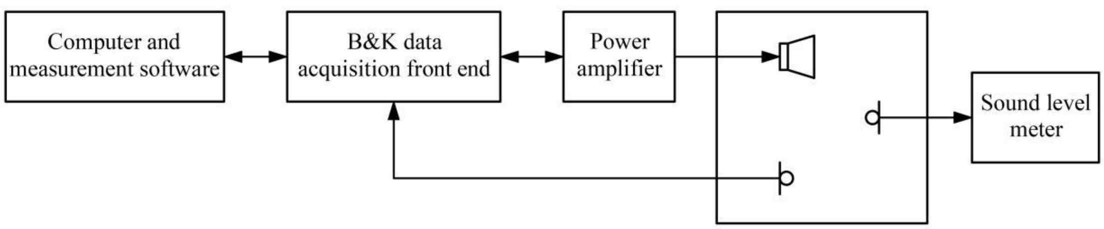


Fig. 5. Connection diagram of reverberation chamber method measurement system

RESULTS AND DISCUSSION

Test Results

The reverberation time T_1, T_2, and T_3 in the frequency range of 100 to 5000 Hz were obtained, as shown in Table 2. The corresponding sound absorption coefficients were obtained by substituting the data in Table 2 into Eqs. 1 through 4, as shown in Table 3.

According to ISO 354 (2003), for the test frequency range of 100 to 5000 Hz, the average sound absorption coefficient of the specimen was obtained after averaging the sound absorption coefficient in this frequency range, as shown in Eq. 5. According to the results in Table 3 and Eq. 5, the average sound absorption coefficients of the two groups were calculated, as shown in Table 4.

$$\text{Average sound absorption coefficient} = (\alpha_{100Hz} + \alpha_{120Hz} + \cdots + \alpha_{5000Hz})/18 \quad (5)$$

The noise reduction coefficient (NRC) is a comprehensive evaluation index to measure the sound absorption capacity of materials and structures in an enclosed space. For the test frequency range of 100 to 5000 Hz, the NRC value is the arithmetic mean of the sound absorption coefficient of the test frequencies of 250, 500, 1000, and 2000 Hz, as shown in Eq. 6. It should be noted that the value was accurate to two decimal places, and the last digit was 0 or 5. The NRCs of the two sample structures of the control group and the test group were calculated based on the results in Table 3 and Eq. 6, as shown in Table 5.

$$\text{NRC} = (\alpha_{250Hz} + \alpha_{500Hz} + \alpha_{1000Hz} + \alpha_{2000Hz})/4 \quad (6)$$

Table 2. Reverberation Time Test Results

f (Hz)	T_1 (s)	T_2 (s)	T_3 (s)
100	6.25	2.83	2.49
125	6.22	3.43	3.14
160	5.86	4.84	3.74
200	6.13	5.33	4.56
250	6.02	5.35	5.21
318	5.43	5.15	4.85
400	5.15	4.54	4.40
500	5.33	4.90	4.81
630	5.51	5.20	4.85
800	4.89	4.64	4.56
1000	4.85	4.48	4.56
1250	4.31	4.19	4.07
1600	4.13	3.90	3.85
2000	4.01	3.77	3.70
2500	3.72	3.48	3.41
3150	3.36	3.10	3.05
4000	2.99	2.79	2.73
5000	2.50	2.40	2.36

Table 3. Sound Absorption Coefficients of Two Groups at Different Frequency

f (Hz)	*α* (control group)	*α* (experimental group)
100	0.79	0.99
125	0.53	0.64
160	0.15	0.39
200	0.10	0.23
250	0.08	0.11
318	0.04	0.09
400	0.11	0.14
500	0.09	0.08
630	0.04	0.10
800	0.05	0.06
1000	0.07	0.05
1250	0.03	0.06
1600	0.06	0.07
2000	0.06	0.09
2500	0.07	0.10
3150	0.10	0.12
4000	0.10	0.13
5000	0.10	0.10

Table 4. Average Sound Absorption Coefficients of Two Groups

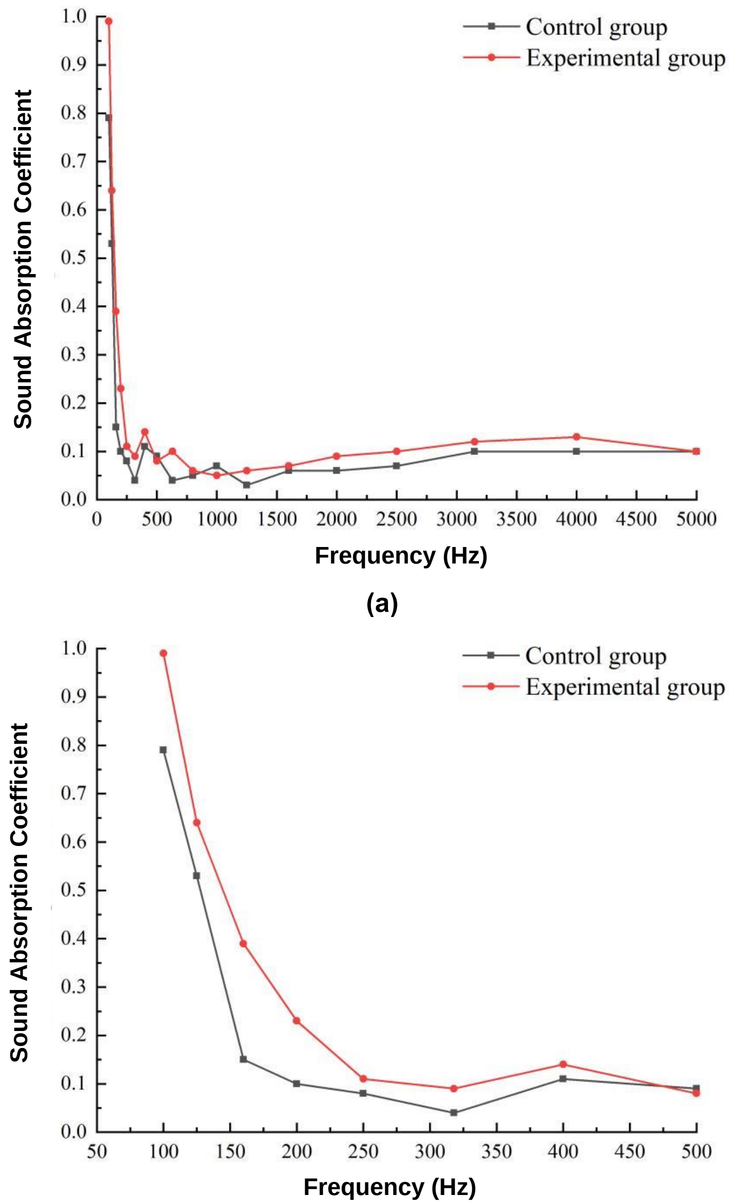
Test object	Average sound absorption coefficient
Control group	0.14
Experimental group	0.20
Variation (percentage increase%)	0.06 (42.9%)

Table 5. Noise Reduction Coefficients of Two Groups

Test object	Noise reduction coefficient (NRC)
Control group	0.05
Experimental group	0.10
Variation (percentage increase%)	0.05 (100%)

Results Analysis

According to the test results in Table 3, the curves of the sound absorption coefficients of the specimens of the control group and the test group with frequency are shown in Fig. 6.



(b)

Fig. 6. Sound absorption coefficients of two groups of specimens at different acoustic frequencies

The structures of the experimental group and the control group had a peak sound absorption coefficient of 0.99 and 0.79 near 100 Hz, respectively, in the frequency range of 100 to 5000 Hz, which means they had good sound absorption performance at low frequencies. The peak sound absorption coefficient of the experimental group was 0.99, indicating that the aperture embedded Helmholtz structure fabricated in this test basically achieved perfect sound absorption at 100 Hz. However, in the medium and high frequency range, the sound absorption coefficients of the structures in the two groups did not exceed 0.1, which means they were basically not sound absorbing.

The two groups were compared with each other. Within the test frequency range, the sound absorption coefficient of the experimental group was significantly higher than that of the control group, especially in the low frequency range of 100 to 250 Hz. The difference of sound absorption coefficient was 0.2 at 100 Hz and 0.24 at 160 Hz. Compared with the control group, the peak frequency bandwidth of the experimental group was wider. This shows that the sound absorption performance of the designed experimental group was greatly enhanced in the test frequency range. While the sound absorption coefficient was improved, the sound absorption bandwidth was also widened to a certain extent, especially in the low frequency range.

According to the average sound absorption coefficient and noise reduction coefficient of the specimens shown in Tables 4 and 5, the two performance indices of the two groups were compared and analyzed, as shown in Fig. 7.

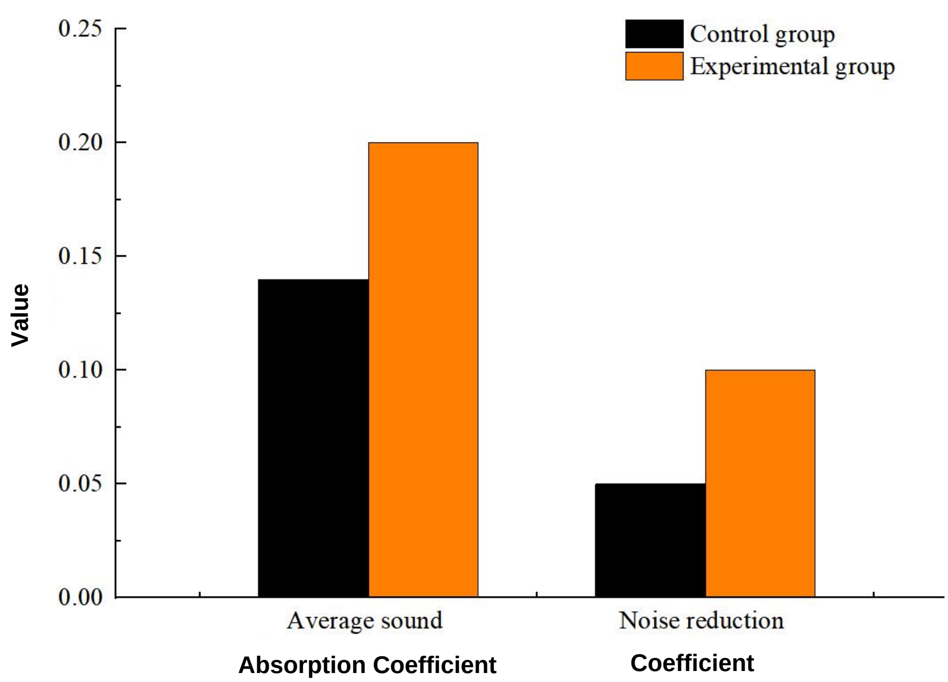


Fig. 7. Comparison of performance indexes of two groups

Table 4, Table 5, and Fig. 7 show that the average sound absorption coefficient and NRC of the experimental group were 42.9% and 100% higher than those of the control group, respectively. However, according to GB/T 16731 (1997), the material structure has sound absorption performance only when NRC ≥ 0.2. Obviously, NRCs of the two groups were not satisfied. The main reason was that the sound absorption performance of the tested specimen structure was mainly reflected in the range of 250 Hz, and it basically did not have sound absorption performance in the medium and high frequency range, while Eq. 6 for NRC was calculated from 250 Hz. This result showed that the sound absorption band of the structure was narrow and had good sound absorption performance for specific frequencies, the overall sound absorption performance still needed to be optimized and improved in the future study.

CONCLUSIONS

1. In the frequency range of 100 to 5000 Hz, the peak sound absorption coefficients of the aperture embedded Helmholtz resonance wall structure (experimental group) and conventional wall structure (control group) appeared near 100 Hz, and the peak sound absorption coefficient of the experimental group at 100 Hz was 0.99. In the medium and high frequency range, the sound absorption coefficients of the two groups of structures did not exceed 0.1, which shows that the two groups have good sound absorption performance in the low frequency range, especially the experimental group has significant sound absorption performance at the frequency of 100 Hz, but the two groups of test structures basically did not absorb sound in the medium and high frequency range;
2. Compared with the control group, the sound absorption coefficient of the experimental group was significantly improved in the test frequency range, especially in the low frequency range of 100 to 250 Hz, and the peak frequency bandwidth of the experimental group was wider. Thus, the designed experimental group had strong sound absorption performance in the test frequency range. While the sound absorption coefficient was improved, the sound absorption bandwidth was also widened to a certain extent, which was mainly reflected in the low frequency range;
3. In the frequency range of 100 to 5000 Hz, the average sound absorption coefficient and NRC of the experimental group were improved by 42.9% and 100%, respectively. However, the sound absorption band of the structure was narrow and had good sound absorption performance for specific frequencies. The overall sound absorption performance could not meet the specified requirements and still needed to be optimized and improved.
4. To improve the sound absorption performance of the aperture embedded Helmholtz resonance wall structure, the structural design to optimize the diameter and length of the embedded aperture will be further carried out in the future. It is expected that the sound absorption peak, resonance frequency and sound absorption bandwidth of the embedded aperture wall unit structure can be adjusted to a certain extent within a certain range of the frequency of the incident sound waves. Furthermore, the possibility of using multiple sizes to reduce noise in different frequency ranges will explored.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES CITED

Alinoor, F., Sharafi, P., Moshiri, F., and Samali, B. (2020). "Experimental investigation on load bearing capacity of full scaled light timber framed wall for mid-rise buildings," *Construction and Building Materials* 231, 117069. DOI: 10.1016/j.conbuildmat.2019.117069

Assouar, B., Liang, B., Wu, Y., and Li, Y. (2018). "Acoustic metasurfaces," *Nature Reviews Materials* 3, 460-472. DOI: 10.1038/s41578-018-0061-4

Bedout, J.-M., Franchek, R.-J., Bernhard, R.-J., and Mongeau, L. (1997). "Adaptive-passive noise control with self-tuning Helmholtz resonators," *Journal of Sound and Vibration* 202, 109-123. DOI: 10.1006/jsvi.1996.0796

Brunskog, J., and Hammer, P. (2003). "Prediction model for the impact sound level of lightweight floors," *Acta Acustica united with Acustica* 89(2), 309-322.

Caniato, M., Bettarello, F., Ferluga, A., Marsich, L., Schmid, C., and Fausti, P. (2017). "Acoustic of lightweight timber buildings: A review," *Renewable and Sustainable Energy Reviews* 80, 585-596. DOI: 10.1016/j.rser.2017.05.110

Caniato, M., Marzi, A., Silva, S.-M., and Gasparella, A. (2021). "A review of the thermal and acoustic properties of materials for timber building construction," *Journal of Building Engineering* 43, 103066. DOI: 10.1016/j.jobe.2021.103066

GJBT-1303 (2015). "Timber structure," China Planning Press, Beijing, China.

Everest, F.-A. (2001). *The Master Handbook of Acoustics* (4 ed.), McGraw-Hill, New York.

Fu, H.-Y. (2021). *Research and Analysis of Acoustics Performance of Light Timber Construction Wall based on Helmholtz Resonance*, Master's Thesis, Nanjing Forestry University, Nanjing.

Fu, H.-Y., Zhao, X.-Y., Adjei, P., Wang, Z., and Wu, X.-L. (2021). "Study and analysis on sound absorbing and noise reducing performance of timber construction wall based on acoustic spiral matasurface," *Wood Research* 66(3), 341-352. DOI: 10.37763/wr.1336-4561/66.3.341352

Fukuta, S., Ogawa, K., Nomura, M., Yamasaki, M., and Sasaki, Y. (2017). "Sound insulation of walls using wood insulation mat and plywood jointed with a combination of adhesive tape and wood dowels," *European Journal of Wood and Wood Products* 75, 595-602. DOI: 10.1007/s00107-016-1085-3

GB/T 16731 (1997). "The gradation of sound absorption property of absorbent products," Standards Press of China, Beijing, China.

Geng, S.-L., and Li, F.-J. (2012). "Design of the sound insulation chamber for stored grain insect sound detection," *Applied Mechanics and Materials* 220-223, 1598-1601. DOI: 10.4028/www.scientific.net/AMM.220-223.1598

Guan, D., Wu, J.-H., Jing, L., Gao, N.-S., and Li, M.-M. (2015). "Application of a Helmholtz structure for low frequency noise reduction," *Noise Control Engineering Journal* 63, 20-35. DOI: 10.3397/1/376303

He, L., Zhu, H.-C., Qiu, X.-J., and Du, G.-H. (2007). *Acoustic Theory and Engineering*

Application, Science Press, Beijing.
He, T., Liu, Y., Yu, Y.-B., Zhao, Q. and Hu, Z.-K. (2020). "Application of deep convolutional neural network on feature extraction and detection of wood defects," *Measurement* 152, 107357. DOI: 10.1016/j.measurement.2019.107357
Huang, Y.-J., Zhu, H., Assima, D., Wang, Z., Li, M.-M., and Zhao, X.-Y. (2021). "Test and analysis of the sound insulation performance of four types of timber structure floors under jumping excitation," *Journal of Renewable Materials* 9(4), 829-840. DOI: 10.32604/jrm.2021.014610
ISO 354 (2003). "Acoustics-Measurement of sound absorption in a reverberation room," International Organization for Standardization, Geneva, Switzerland.
Langfeldt, F., Hoppen, H., and Gleine, W. (2020). "Broadband low-frequency sound transmission loss improvement of double walls with Helmholtz resonators," *Journal of Sound and Vibration* 476, 115309. DOI: 10.1016/j.jsv.2020.115309
Li, X., Ashraf, M., Subhani, M., Kremer, P., and Li, H.-T. (2021). "Experimental investigation on rolling shear properties of cross-laminated timber made from Australian Radiata Pine," *Structures* 33, 423-432. DOI: 10.1016/j.istruc.2021.04.067
Liang, R.-F., Stanislawski, D., and Hota, G. (2021). "Material characterization and structural response under earthquake loads of hakka rammed earth building," *Sustainable Structures* 1, 000003. DOI: 10.54113/j.sust.2021.000003
Liu, M.-B., Ge, K.-Y., Sun, Y.-F., and Yang, X.-L. (2018). "Effect of constitution on sound insulation performance of wood-frame walls," *Wood Research* 63(5), 855-870.
Niederwestberg, J., Daneshvar, H., Chui, Y., and Chen, Z.-Y. (2021). "Contribution of partition walls in lateral load–resisting systems of low-rise light wood frame buildings," *Journal of Structural Engineering* 147, 04021010. DOI: 10.1061/(ASCE)ST.1943-541X.0002960
Ning, J.-F., and Zhao, G.-P. (2016). "A fractal study of sound propagation characteristics in roughened porous materials," *Wave Motion* 68, 190-201. DOI: 10.1016/j.wavemoti.2016.09.013.
Pajchrowski, G., Noskowiak, A., Lewandowska, A., and Strykowski, W. (2014). "Wood as a building material in the light of environmental assessment of full life cycle of four buildings," *Construction and Building Materials* 52, 428-426. DOI: 10.1016/j.conbuildmat.2013.02.055
Peng, F. (2018). "Sound absorption of a porous material with a perforated facing at high sound pressure levels," *Journal of Sound and Vibration* 425, 1-20. DOI: 10.1016/j.jsv.2018.03.028
Ponzo, F.-C., Antonio, D.-C., Nicla, L., and Nigro, D. (2021). "Experimental estimation of energy dissipated by multistorey post-tensioned timber framed buildings with anti-seismic dissipative devices," *Sustainable Structures* 1(2), 000007. DOI: 10.54113/j.sust.2021.000007
Sakagami, K., Kobatake, S., Kano, K., Morimoto, M., and Yairi, M. (2011). "Sound absorption characteristics of a single microperforated panel absorber backed by a porous absorbent layer," *Acoustics Australia* 39, 95-100. DOI: 10.1109/TUFFC.2011.2143
Tan Y.-J., Yang, X.-J., Bai, X.-C., Dong, H.-R., Liu, J.-M., and Zhang, L. (2022). "Inspection and evaluation of wood components of ancient buildings in the South-Three Courts of the Forbidden City," *Bioresources* 17(1), 962-974. DOI: 10.15376/biores.17.1.962-974
Thelandersson, S. (2003). *Timber Engineering*, John Wiley & Sons, New Jersey.

Tudor, E.-M., Kristak, L., Barbu, M.-C., Gergeľ, T., Němec, M., Kain, G., and Réh, R. (2021). "Acoustic properties of larch bark panels," *Forests* 12(7), 887. DOI: 10.3390/f12070887

Wang, Z.-H., Wang, Z., Wang, B.-J., Wang, Y.-L., Rao, X., Liu, B., Wei, P.-X., and Yang, Y. (2014). "Dynamic testing and evaluation of modulus of elasticity (MOE) of SPF dimension lumber," *BioResources* 9(3), 3869-3882. DOI: 10.15376/biores.9.3.3869-3882

Wang, Z.-H., Gao, Z.-Z., Wang, Y.-L., Cao, Y., Wang, G.-G., Liu, B., and Wang, Z. (2015). "A new dynamic testing method for elastic, shear modulus and Poisson's ratio of concrete," *Construction and Building Materials* 100, 129-135. DOI: 10.1016/j.conbuildmat.2015.09.060

Wang, Z.-H., Wang, Y.-L., Cao, Y., and Wang Z. (2016). "Measurement of shear modulus of materials based on the torsional mode of cantilever plate," *Construction and Building Materials* 124, 1059-1071. DOI: 10.1016/j.conbuildmat.2016.08.104.

Wang, Z.-H, and Ghanem, R. (2021). "An extended polynomial chaos expansion for PDF characterization and variation with aleatory and epistemic uncertainties," *Computer Methods in Applied Mechanics and Engineering* 382, article no. 113854. DOI: 10.1016/j.cma.2021.113854

Yang, R.-Y., Li, H.-T., Lorenzo, R., Sun, Y.-F., and Ashraf, M. (2021). "Flexural behaviour of steel timber composite (STC) beams," *Steel and Composite Structures* 41,193-207. DOI: 10.12989/scs.2021.41.2.193

Yuan, J. (2007). "Active Helmholtz resonator with positive real impedance," *Journal of Vibration and Acoustics* 129, 94-100. DOI: 10.1115/1.2345678

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