MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

A sound-absorbing metaporous material with coiled-up space

Wang Yang, Zhao Honggang[1], Yu Dianlong, Xiao Yong, Cai Li and Wen Jihong

[1]Laboratory of Science and Technology on Integrated Logistics Support, National University of Defense Technology, Changsha 410073, P. R. China

ABSTRACT

The concept of coiled-up space, which is particularly effective for designing acoustic metamaterials whose physical properties are under spotlight, has attracted a great deal of interests in recent years. This paper further extends the concept of coiled-up space into porous material to design a metaporous for improving low-frequency sound absorption. Both the theoretical and numerical results demonstrate the metaporous possessing two absorption peaks which are located at 1120Hz and 2060Hz, respectively. The absorption coefficient of the metaporous is greater than 0.8 over a bandwidth of 1620Hz from 880Hz to 2500Hz within a thin layer of 30mm. Experimental results further validate the low-frequency absorption of the proposed metaporous.

Keywords: Metaporous material, coiled-up space, sound absorption
I-INCE Classification of Subject Number: 35

1. INTRODUCTION

Using a thin layer material for low-frequency noise dissipation has attracted more interests in noise control field recently. Various acoustic porous materials [1] have been widely used to dissipate sound energy, however, the thickness of the porous material requires approximately a quarter of the sound wavelength to realize efficient absorption, which result in the material is too thick if the low-frequency sound absorption is to be a target. In the last decades, the investigations of acoustic metamaterial have opened a new perspective for acoustic wave manipulation [2-5]. Following the growing interest in acoustic metamaterial, the concept of acoustic metaporous material (MPM), which is formed by a porous matrix embedded with inclusions, has been later developed [6-10].

This work is initially inspired by the concept of coiled-up space in acoustic metamaterial, which is firstly proposed by Z. Liang and J. Li [11]. Recently, the coiled-up space has been widely introduced to Helmholtz resonators [12-14] and Fabry–Pérot channels [15-17] to design sound absorbers with deep-subwavelength thickness. However, the absorption bandwidth of these absorbers is always very narrow around the resonant frequency. The present work extends the coiled-up space to the porous layer to design a MPM, as shown in Figure. 1(a). The MPM consists of periodic arrangement of unit cells along *x* axis. Owing to the MPM are invariant along the *y* direction such that the sound absorption problem can be simplified as a two-dimensional problem in the *xz* plane. The one unit of the MPM has sizes of *L* and *H* in the *y* and

[1] zhhg9603@sina.com

z directions, respectively. By inserting two L shape rigid panels (thickness b_0) into the porous matrix, a straight channel (has sizes of x_1 and H along x and z directions) and a side coiled-up channel are formed. The height of the ith-layer of the coiled-up channel along the z axis is w_i.

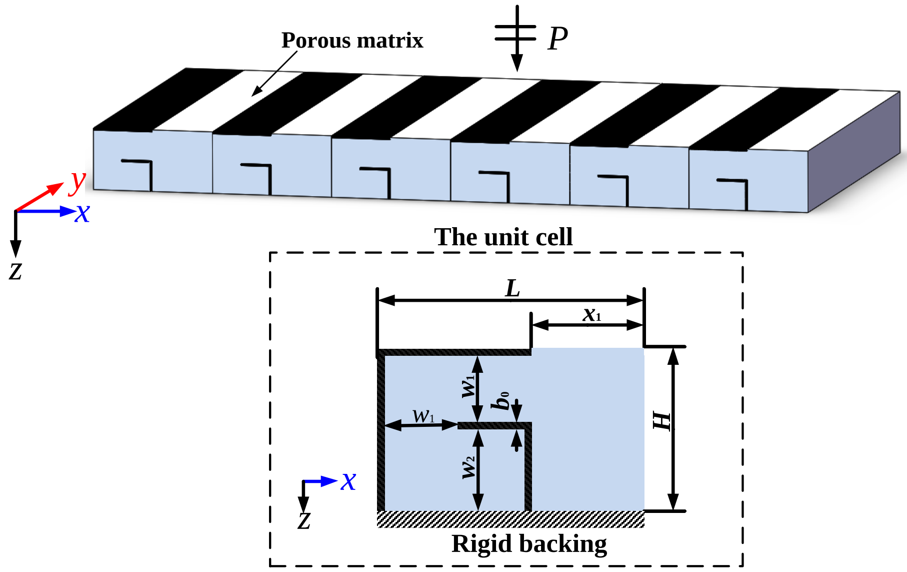

Figure 1. Three dimensional Diagrams of the MPM and the cross-section diagram of unit cell in the xz plane

2. ANALYTICAL METHOD

To obtain sound absorption performance of the MPM, we establish an equivalent model, as shown in Figure 2. The one unit of MPM can be regarded as two different elements (A and B) connected in parallel.

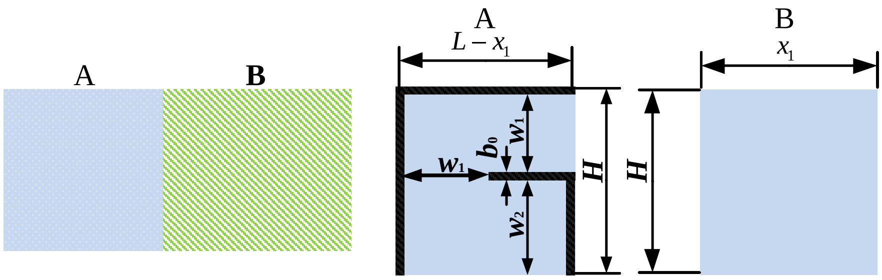

Figure 2. An equivalent model for predicting the sound absorption performance of the MPM.

Generally, the sound absorption coefficient α can be derived by the surface impedance Z_s , the equation can be expressed as

$$\alpha = 1 - \left| \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0} \right|^2, \tag{1}$$

where ρ_0 is the density, c_0 the sound speed of the air and Z_s is

$$Z_s = -j\sqrt{\rho^{eff} K^{eff}} \cot\left(\frac{\omega}{\sqrt{K^{eff} / \rho^{eff}}} H \right). \tag{2}$$

where $j=\sqrt{-1}$. Based on effective medium [18], the effective density ρ^{eff} and the effective bulk modulus K^{eff} of the MPM are given by

$$\frac{1}{\rho^{eff}}=\frac{\varepsilon}{\rho^{\mathrm{A}}}+\frac{(1-\varepsilon)}{\rho^{\mathrm{B}}}, \tag{3}$$

$$\frac{1}{K^{eff}}=\frac{\varepsilon}{K^{\mathrm{A}}}+\frac{(1-\varepsilon)}{K^{\mathrm{B}}}, \tag{4}$$

where ρ^{m} and K^{m} ($m=\mathrm{A}$ or B) are the effective density and bulk modulus of the element. $\varepsilon=L-x_1/L$ is the volume ratio of A. The element A can be regarded as rigid along the direction of the incident wave, thus the ρ^{A} and K^{A} are set as infinite values. Further, the surface acoustic impedance of A at $x=L-x_1$ from the left-hand hard wall ($x=0$) is

$$Z_A^{x=L-x_1}=\frac{Z_p}{\delta_2}\frac{-j\frac{Z_2^T}{\delta_1}\cot\left[k_p\left(L-x_1\right)\right]+Z_p}{\frac{Z_2^T}{\delta_1}-jZ_p\cot\left[k_p\left(L-x_1\right)\right]}, \tag{5}$$

and

$$Z_2^T=-jZ_p\cot\left[k_p\left(L-x_1-2b_0\right)\right], \tag{6}$$

where $\delta_1=w_2/w_1$ and $\delta_2=w_1/H$ are the area correction factors. Z_p and k_p are the characteristic impedance and effective wavenumber of the porous matrix, respectively, which can be acquired by Johnson-Champoux-Allard (JCA) model [1].

For the element *B*, the relationship between wave vector components (k_x and k_z along the *x* and *z* directions) is

$$k_p=k_x^2+k_z^2. \tag{7}$$

The surface acoustic impedance of *B* at $x=L-x_1$ from the right-hand ($x=L$) can be expressed by

$$Z_B^{x=L-x_1}=-jZ_p\cot\left(k_x x_1\right). \tag{8}$$

At $x=L-x_1$, the $Z_A^{x=L-x_1}$ and $Z_B^{x=L-x_1}$ should meet the interface condition $Z_A^{x=L-x_1}=Z_B^{x=L-x_1}$. Then, the effective density and effective bulk modulus of *B* along z axis is obtained by

$$\rho^B=\rho_p, \tag{9}$$

and

$$K^B = \rho^B \frac{\omega^2}{k_z^2}. \tag{10}$$

3. ABSORPTION PERFORMANCE

To validate the theoretical model of the MPM, simulations are conducted by the Pressure Acoustic, Frequency Domain (acpr) module of commercial finite element (FE) software COMSOL Multiphysics. Figure 3 compares the theoretical absorption of the MPM with that obtained by the FEM and shows that the two are consistent. Two absorption peaks appear at 1120Hz and 2060Hz with a over 80% absorption bandwidth of 1620Hz (from 880Hz to 2500Hz). The overall thickness of the MPM, H=30mm, is only 1/10 of the first resonance wavelength, which means that the MPM possesses a subwavelength thickness. To further demonstrate the advantage of the MPM, Figure. 3 also shows the absorption spectrum of the conventional porous material with identical thickness. One can readily see that the MPM possesses better absorption for low-frequency sound than that of the porous material.

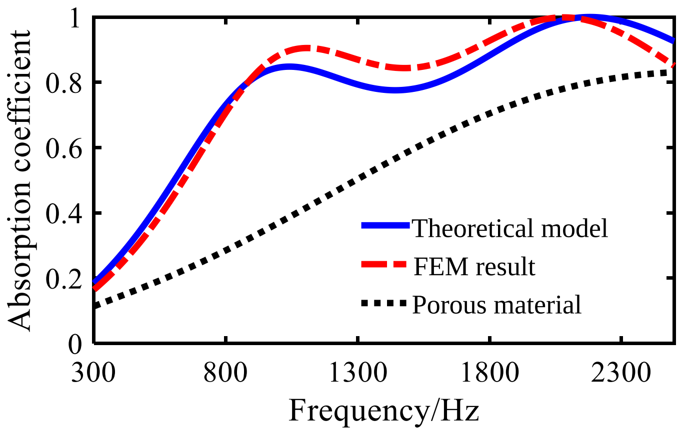

Figure 3. Absorption spectrums of the MPM and the porous material. The dimensions of the MPM are $L = 60\text{mm}$, $H = 30\text{mm}$, $x_1 = 30\text{mm}$, $b_0 = 1.5\text{mm}$ and $w_1 = w_2 = 13.5\text{mm}$. The porous layer is a melamine foam with acoustical parameters of the porosity $\phi = 0.95$, the tortuosity $\alpha_\infty = 1.42$, the viscous characteristic length $\Lambda = 180\text{um}$, the thermal characteristic length $\Lambda' = 360\text{um}$, and the flow resistivity $\sigma = 8900\text{N}\cdot\text{s}\cdot\text{m}^{-4}$.

4. EXERIMENTAL VERIFICATION

For further verification purpose, the experment is carried out using the two-microphone method [19] in a square acoustic impedanc, as shown in Figure4(a). The photo of sample is illustrated in Figure 4 (b). Figure 4(c) depicts that the experimental results are consistent with the theoretical prediction, which further demonstrate the low-frequency absorption performance of our MPM.

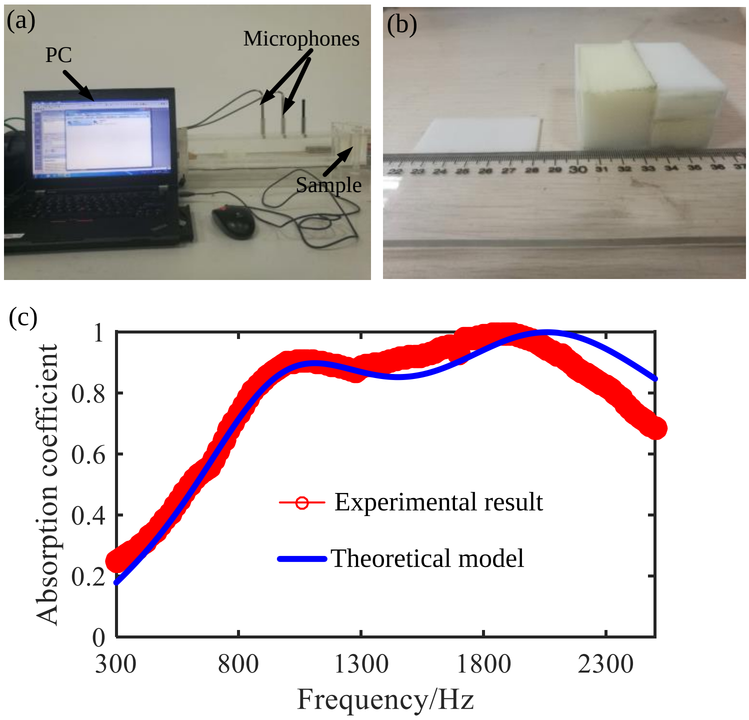

Figure 4. Photos of (a) the experimental set-up and (b) the sample. (c) Theoretical and measured absorption spectrums.

5. CONCLUSIONS

A metaporous material with coiled-up space is presented in this work. The theoretical analysis, numerical simulation, and experimental results demonstrate that the metaporous material possesses better low-frequency sound absorption than that of the conventional porous material. Our proposed metaporous material may be an excellent alternative in many practical situations where both low-frequency noise dissipation and space utilization are critical concerns.

6. ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Grant No. 51775549).

7. REFERENCES

1. J. F. Allard and N. Atalla, Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials (Wiley, Chichester, 2009).
2. Liu Z, Zhang X, Mao Y, Zhu Y Y, Yang Z, Chan C T, Sheng P. Science. **289**, 1734-1736 (2000).
3. He H, Qiu C, Ye L, Cai X, Fan X, Ke M, Zhang F, Liu Z. Nature. **560**, 61-64 (2018).
4. Fang X, Wen J, Bonello B, Yin J, Yu D. Nature Communications. **8**,1288 (2017).
5. Ma G, Sheng P. Science Advances. **2**, e1501595 (2016).
6. Groby J P, Brouard B, Dazel O, Nennig B, Kelders L. The Journal of the Acoustical Society of America. **133**, 821-831(2013).
7. Groby J P, Dazel O, Duclos A, Boeckx L, Kelders L. The Journal of the Acoustical Society of America. **130**, 3771-3780 (2011).
8. Yang J, Lee J S, Kim Y Y. Journal of Physics D: Applied Physics. **50**, 015301 (2017).
9. Groby J P, Lagarrigue C, Brouard B, Dazel O, Tournat V, Nennig B. The Journal of

the Acoustical Society of America. **137**, 273-280 (2015).
10. Yang J, Lee J S, Kim Y Y. Journal of Applied Physics. **117**, 174903(2015).
11. Liang Z, Li J. Physical Review Letters**. 108,** 114301 (2012).
12. Wang Y, Zhao H, Yang H, Zhong J, Wen J. EPL (Europhysics Letters). **120**, 54001 (2017).
13. Li Y, Assouar B M. Applied Physics Letters. **108**, 063502 (2016).
14. Wang Y, Zhao H, Yang H, Zhong J, Zhao D, Lu Z, Wen J. Journal of Applied Physics. **123**, 185109 (2018).
15. Liu L, Chang H, Zhang C, Hu X. Applied Physics Letters. **111**, 083503 (2017).
16. Chang H, Liu L, Zhang C, Hu X. AIP Advances. **8**, 045115 (2018).
17. Zhang C, Hu X. Physical Review Applied. **6,** 064025 (2016).
18. Li J, Fok L, Yin X, Bartal G, and Zhang X. Nature Materials. **8**, 931 (2009).
19. ISO 10534–2: 1998 Acoustics—Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes—Part 2: Transfer Function Method First Edition.