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Acoustic porous metasurface for excellent sound absorption based on wave manipulation

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ABSTRACT

Making use of the phase gradient method for diffracted wave manipulation, we propose an acoustic metasurface with a periodic structure backed with a rigid wall for sound absorption. The system consists of four slits filled with a metal-based fibrous material with various thicknesses in one period enabling a linear phase gradient of the reflected waves. The ability to manipulate the reflected waves using the designed metasurface is first validated by both simulations and experiments. Its oblique-incidence sound absorption performance is then studied at the frequency of interest. The broadband sound absorption property of the proposed metasurface is also evaluated within the frequency range from 500 Hz to 3500 Hz. The simulated and experimental results demonstrate that the designed metasurface possesses remarkable advantages in sound absorption capability compared with the individual porous elements. This study provides an effective method to enhance the sound absorption performance of uniform porous materials. The proposed metasurface has a good potential to be applied for sound absorption in practice.

1. Introduction

Passive methods of noise control generally involve energy dissipation using sound absorption materials and structures. The main classifications of the sound absorbers are porous materials and resonators. The resonators include typical Helmholtz resonators, panel or membrane resonators, and perforated panel resonators [1]. To obtain good sound absorption performance, the combinations of different sound absorbers and the redesigns of traditional sound absorbers are usually employed. There arises a special category of acoustic structures called acoustic metamaterials [2,3], which are carefully designed according to different mechanisms to achieve unusual acoustic behaviours. Some metamaterials as sound absorbers are designed based on membranes [4–6], resonators [7,8], and certain geometric structures [9–11]. Most resonance-based absorbers are effective in a narrow frequency range. For the membrane-based structure, it is a great challenge to apply them on a large scale, and the flimsy membrane is also a limiting factor for robust use. So far, there are not many studies on acoustic metamaterials made of porous materials. In the current studies of porous sound absorbers, the size of the devices may reach O (0.5) m [12] so that the good sound absorption can be achieved. Alternatively, some complex geometric structures are carefully designed inside the porous material [13,14].

Previous studies [15–23] show that the acoustic metasurface, whose sub-units are designed to form a phase gradient on reflecting or transmitting surface, is able to manipulate the propagation directions of reflected or transmitted waves. In addi-

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tion to geometric configurations [15–18], the phase gradient can be realized by combinations of different media in a series of sub-units of a metasurface [19–23]. Some metasurfaces based on a porous medium were studied before [21–23]. The three-dimensional acoustic fields of non-uniform structures composed of different porous materials were analytically studied [21]. The proposed metasurface could potentially provide good sound absorption. However, the assumed parameters of porous materials were not demonstrated in practice with proper samples. The authors, in the previous work [22], experimentally showed that the metasurface composed of porous materials with the same thickness and different parameters could result in anomalous refractions. However, it is difficult to tune the phase gradient at the reflecting surface of the designed metasurface to cover 2π in one period to obtain the excellent sound absorption. The authors then presented a simple way to fabricate the metasurface using only one kind of porous material with the same parameters [23]. By adjusting the thickness of the porous material in each element of the structure, the phase responses at the reflecting surface of the whole structure could cover 2π in one period. Although the ability of wave manipulation was experimentally demonstrated in Ref. [23], the sound absorption of the proposed metasurface was not systematically studied.

In this work, a metasurface backed with a rigid wall, whose sub-unit is also composed of a porous layer and an air layer, is further studied to explore the sound absorption performance caused by the phase gradient. In Section 2, the construction of the metasurface is introduced first, followed by the procedure of the design. In Section 3, the ability of wave manipulation of the designed metasurface is demonstrated. Then, the sound absorption performance is systematically studied in both simulations and experiments in Section 4. Finally, concluding remarks are given in Section 5.

2. Metasurface design

With the inspiration from our previous work [23], a metasurface backed with a rigid wall, whose sub-unit is composed of a porous layer and an air layer, is studied further in this work to explore the sound absorption performance caused by the phase gradient.

To generate the desired phase gradient, a periodic metasurface consisting of four slits in one period is designed. Here, four slits are chosen to guarantee that the number of the discrete elements in one period is enough to characterize acoustic behaviour accurately through forming discrete phases responses to replace the continuously varied phases [21]. Each slit is filled with an air layer and a porous layer, as shown in Fig. 1. The thicknesses of the air and the porous layers in slits are adjusted to form a linear phase gradient in one period on the upper surface of the whole structure. The individual elements are separated by rigid walls to ensure that there are only the interactions between the incident sound waves and the media in each slit without the effects from adjacent slits.

To define a porous material in the proposed metasurface, Johnson-Champoux-Allard model (JCA model) [24,25] is used to describe its acoustic characteristics, and the model is detailed in Appendix A. There are five parameters in the JCA model associating with acoustic properties, which are porosity $\phi(-)$, flow resistivity $\sigma(\mathrm{Nm}^{-4}\mathrm{s})$, tortuosity $\alpha_\infty(-)$, viscous characteristic length $\Lambda(\mathrm{m})$, and thermal characteristic length $\Lambda'(\mathrm{m})$.

A metal-based fibrous material with a fiber diameter $D = 12\ \mu\mathrm{m}$ and a porosity $\phi = 0.91$, which possesses good mechanical properties [26], is selected to realize the metasurface. To build up the relationships between the micro-structural parameters and acoustic properties of fibrous materials, a two-dimensional (2D) bottom-up approach [27–30] and a three-dimensional (3D) approach [31–33] can be used. Although the 3D approach considering the 3D arrangements of fibers can provide more accurate predictions, the 2D bottom-up approach is enough to characterize the fibrous material used here. It is assumed in the 2D bottom-up approach that the fibers are parallelly arranged in a hexagon manner. Using the 2D bottom-up approach, the five parameters in the JCA model can be obtained as: $\phi = 0.91$, $\sigma = 184269\ \mathrm{Nm}^{-4}\ \mathrm{s}$, $\alpha_\infty = 1.045$, $\Lambda = 3.30 \times 10^{-5}$ m, and $\Lambda' = 6.07 \times 10^{-5}$ m. These five parameters are used to specify the porous material in numerical simulations. The micro-structures of the fibrous material and the simplified arrangements of fibers are presented in Fig. A.1 in Appendix A. To validate the accuracy of the bottom-up approach, the acoustic properties are partially validated through measurements using a Brüel & Kjær Type 4206 Four-microphone Impedance Measurement Tube [34]. The comparisons of characteristic impedance and characteristic wavenumber between the predictions based on the bottom-up approach and the measurements are shown in Fig. A.2 in Appendix A. Good agreements can be obtained within the wide range of frequencies from 500 Hz to 4000 Hz, where

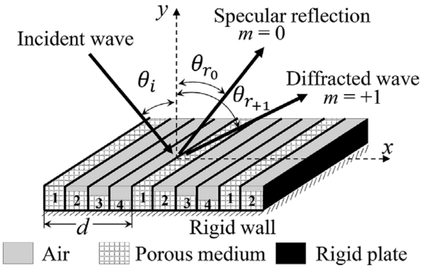

Fig. 1. Schematic of the metasurface backed with a rigid wall.