Mechanical Systems and Signal Processing 117 (2019) 138–156

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Improvement of the sound absorption of flexible micro-perforated panels by local resonances

S.W. Ren [a,c,d,e,*], L. Van Belle [c,f], C. Claeys [c,f], F.X. Xin [d,e,*], T.J. Lu [b,d,e,*], E. Deckers [c,f], W. Desmet [c,f]

[a] School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an 710072, PR China
[b] State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China
[c] Department of Mechanical Engineering, KU Leuven Celestijnenlaan 300 B, B-3001 Heverlee (Leuven), Belgium
[d] MOE Key Laboratory for Multifunctional Materials and Structures, Xi'an Jiaotong University, Xi'an 710049, PR China
[e] State Key Laboratory for Mechanical Structure Strength and Vibration, Xi'an Jiaotong University, Xi'an 710049, PR China
[f] DMMS lab, Flanders Make, Belgium

ARTICLE INFO

Article history:
Received 9 September 2017
Received in revised form 13 June 2018
Accepted 21 July 2018

Keywords:
Metamaterial
Micro-perforated panel
Absorption improvement
Stop band
Effective medium method

ABSTRACT

To further improve the sound absorption enhancement of flexible micro-perforated panels (FMPPs), a new sort of perforated sound absorbers – metamaterial-based micro-perforated panels (MMPPs) – is proposed by combining a micro-perforated host panel and local resonators (LRs) attached on a sub-wavelength scale, targeting the flexural waves. Theoretical and numerical models show that MMPPs are able to further enhance sound absorption in a wide frequency range. The theoretical model is developed based on the effective medium method as the structural wavelength in the host panel is much larger than the distance between the LRs, and the full simulation model, including visco-thermal effects, is conducted by utilizing multi-physical coupling integrated in COMSOL. Besides, a structural finite element unit cell method is used to evaluate the stop band behavior of the MMPP. Good agreement is achieved between the theoretically predicted acoustical properties and the simulation results for both conventional FMPPs and the proposed MMPPs, validating the numerical and theoretical models. Both models reveal that the sound absorption enhancement of the MMPP stems from the resulting acoustic surface impedance improvement, caused by the sub-wavelength attached local resonances. The effect of key properties of the LRs (*i.e.* mass, damping and multiple resonances) on the sound absorption performance of MMPPs is then analyzed by applying the theoretical model and effective frequency-adjustability of the absorption enhancement performance is found. The proposed MMPP shows great potential for the noise reduction industry.

1. Introduction

As artificial materials with distinctive microscopic structures, acoustic metamaterials [1–3] possess a range of peculiar properties, such as negative mass density [4,5], negative modulus [6], negative refraction index [7], *etc*. These characteristics prompt a wide spectrum of novel engineering applications, including acoustic cloaking [8,9], power harvesting [10] and acoustic imaging [11]. The application areas of acoustic metamaterials are still being further explored and expanded.

---

* Corresponding authors at: MOE Key Laboratory for Multifunctional Materials and Structures, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail addresses: shuwei.ren@hotmail.com (S.W. Ren), fengxian.xin@gmail.com (F.X. Xin), tjlu@mail.xjtu.edu.cn (T.J. Lu).

https://doi.org/10.1016/j.ymssp.2018.07.046
0888-3270/

Recently, sound absorption improvement, regarded as a conventional yet challenging issue in numerous applications, through utilizing metamaterial concepts attracts increasing attention. Among existing works, viscous-thermal dissipation [12–16] has been adopted as the key mechanism underlying the sound energy absorption. In particular, the strategy of space-coiling [17] significantly condenses the thickness of materials to achieve total sound absorption [18] and the smallest thickness-to-wavelength ratio can even reach $\sim$1/223 [19]. However, the induced side effect – large acoustic reactance mismatch – shrinks the functional frequency range to a very narrow band. Extraordinary absorbers [20,21] further developed from conventional porous structures/materials exhibit magnificent sound absorption performance in a broad frequency range, but their thickness-to-wavelength ratios are typically rather large. Upon manipulating the acoustical anisotropy of the metamaterial-composed impedance-matching shells [22,23], omni-directionally impinging sound waves can be bent into an internal dissipative core and hence be absorbed effectively, but large material volumes are still needed. Besides viscous-thermal dissipation, alternative sound absorption mechanisms have also been explored, such as coherent control [24,25] of sound waves, multiple resonance [26], and critical coupling [27]. Nonetheless, at present, an applicable balance between the width of the functional frequency range and the limited allowable material/structure thickness is not yet achieved using the abovementioned approaches.

Among the most widely used sound absorbing materials/structures are micro-perforated panels (MPPs) [28]. These have been optimized from different perspectives [29–32] to dissipate sound energy in lower and/or broader frequency ranges. It has been shown that the flexibility [29,30] of MPPs leads to overall panel vibrations, which can cause extraordinary absorption peaks before those achieved by conventional panels. However, these additional peaks are always followed by undesired dips, which also stem from the overall panel vibrations. More specifically, "the magnitude and phase of the air-frame relative velocity over the MPP determines the beneficial or detrimental effect of these resonances" [33]. In literature, adding local resonators (LRs) to bare panels is an effective way to prevent undesired panel vibrations. Metamaterial panels [34–37] have shown potential for enhanced sound insulation relative to conventional bare panels, at least in targeted frequency zones, referred to as stop bands. Inspired by this concept, as well as the work of Ruiz et al. [14] to combine micro-slits of sub-millimeter dimensions with a metamaterial panel, this work introduces a new sort of MPP, the metamaterial-based MPP (MMPP), by attaching structural local resonances to a conventional flexible MPP (FMPP). Mass-spring-damper resonators are attached to one face of an FMPP, targeting the acoustically relevant flexural waves, to further enhance their sound absorption ability, especially in the frequency range where the FMPP cannot work well due to overall panel vibration. The spacing of the resonators is sub-wavelength compared to the wavelength of the flexural waves in the FMPP, according to the rules of local resonant metamaterial design [35]. The applied enhancement strategy is as follows. Firstly, the overall panel vibration of an FMPP is utilized to enhance sound absorption in the frequency range below the pore-cavity peak of a rigid MPP. Secondly, the stop-band behavior of a metamaterial panel is exploited to impair the overall panel vibrations in a specific frequency range to avoid undesired absorption dips. It will be shown that the introduced local resonances not only lift the undesired dips but also produce superior peaks compared to a rigid MPP having the identical perforation diameter and perforation ratio. Consequently, the MMPP is demonstrated as a further step towards a practical balance between a broad operating frequency range and a low structure thickness.

This work is organized as follows. In Section 2, the proposed MMPP is defined. Next, the theoretical modeling based on the effective medium method is described in Section 3. In Section 4, a full acoustic-structural simulation model is established to validate the theoretical model as well as to reveal the physical mechanism underlying the absorption enhancement. A finite element unit cell method to extract the stop band behavior is briefly explained in Section 5. The influence of the key properties of LRs on the MMPP performance is investigated in Section 6. Finally, the main conclusions are given in Section 7.

2. Metamaterial-based micro-perforated panels

The objective of combining FMPPs with locally resonant metamaterial behavior is to further improve the sound absorption performance of FMPPs. It has been proven that the FMPPs, via panel-cavity resonances, are able to enhance the sound absorption of rigid MPPs in the lower frequency range [30], when the fundamental frequency of FMPP is proposed to coincide with that corresponding to the pore-cavity peak of a rigid MPP. In the present study, the attached LRs are designed to improve the undesired absorption dips due to overall vibrations that follow the enhanced peaks.

The proposed MMPP is composed of a micro-perforated host panel combined with a number of local resonators (LRs), which are attached to one face of the host panel, as depicted in Fig. 1. The considered host panel has a rectangular shape with length a, width b and thickness h. The micro-perforations in the host panel are circular with diameter d and the center-to-center distance between the micro-perforations is a_0 and b_0, along the length- and width-direction respectively. Since this paper proposes a conceptual idea to utilize stop band behavior to enhance sound absorption, idealized mass-spring-damper resonators [34,35] are adopted as LRs, consisting of a point-mass m_r and a spring with complex spring constant $k_r(1 + i\eta_r)$ to take into account the damping through a loss factor η_r. In literature, some state-of-art resonators [14,38] (*e.g.* the mass-cantilever resonant structure [38]) have been proven capable of resulting in stop bands for metamaterial-panels, which are potential realizations of the mass-spring-damper resonators. For the single-degree-of-freedom mass-spring-damper resonators, the damping loss factor η_r is the most simplified form of the structural damping, which has been validated as a simple but realizable way to include damping in real LRs [38]. Some other more complicated but more accurate forms of damping, such as viscous and visco-elastic damping, are not included here. Moreover, in following theoretical