Mechanical Systems and Signal Processing 115 (2019) 418–433

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Design multi-stopband laminate acoustic metamaterials for structural-acoustic coupled system

X. Xiao [a], Z.C. He [a,c,*], Eric Li [b,*], A.G. Cheng [a]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China
[b] School of Science, Engineering & Design, Teesside University, Middlesbrough, UK
[c] The State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, China

ARTICLE INFO

Article history:
Received 24 October 2017
Received in revised form 7 April 2018
Accepted 1 June 2018

Keywords:
Laminate acoustic metamaterials
Stop-band
Structural-acoustic coupled system
Local resonance

ABSTRACT

This paper designs the laminate acoustic metamaterials with multi-stopband for structural-acoustic coupled system. The laminate acoustic metamaterials are composed of carbon-fiber-reinforced polymer (CFRP) and a periodic array of two degrees of freedom (2-DOF) mass-spring-damper subsystems attached to the laminate. According to the dispersion analysis, two stopbands are observed around the absorbers' resonant frequency. Based on the finite element modeling, the multi-stopband behavior has been confirmed. In addition, the effects of damping of vibration absorbers are discussed in this work. By adding the appropriate damping to the vibration absorbers, the two stop bands can be combined into a wider stopband. Subsequently, the analyses of multi-stopband laminate acoustic metamaterials in the structural–acoustic coupled system are performed. The excellent performance of multi-stopband laminate acoustic metamaterials has been applied to the front panel of vehicle, and the noise of passenger compartment cavity is reduced significantly.

1. Introduction

In the late 1960s, the concept of metamaterials was first proposed by Veselago [1] and used in the field of electromagnetic waves. Veselago has theoretically proved that materials with negative constitutive parameters can exist and be manufactured. Due to the mathematical similarity between the acoustic and electromagnetic waves, acoustic bandgap materials known as phononic crystals were proposed recently [2–10]. Phononic crystals are usually constructed of two materials with distinctive elastic properties, and the periodic arrangement of the two materials causes the destructive Bragg scattering of the acoustic waves propagating within the phononic crystal, thereby forming a stopband or bandgap in a particular frequency range. However, the bandgap frequency is fundamentally dependent on the geometry of basic scatterer. More specifically, the wavelength of the acoustic wave corresponding to this type of bandgap is the same order of magnitude of the lattice constant.

Due to the limitations of Bragg type phononic crystals in low frequency applications, Liu et al. took the lead in applying the concept of local resonance to the phononic crystals [11]. This type of phononic crystals is also known as local resonance acoustic metamaterials (LRAMs) [12]. The LRAMs are composite materials in which the basic scatterer is further designed as micro-local resonator and the bandgap can be obtained two orders of magnitude lower than that of the Bragg gaps. The

* Corresponding authors at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China (Z.C. He), School of Science, Engineering & Design, Teesside University, Middlesbrough, UK (E. Li).
E-mail addresses: hezhicheng815@hnu.edu.cn (Z.C. He), q.li@tees.ac.uk (E. Li).

https://doi.org/10.1016/j.ymssp.2018.06.004
0888-3270/

in-depth studies found that the local resonance can produce exotic acoustic material characteristics such as negative effective mass density [11,13–17], negative effective bulk modulus [18] or shear modulus [19,20] as well as simultaneously negative modulus and mass [21–24]. Some new concepts that exploit these special properties have emerged, including superlensing [25–27], cloaking [28–32], subwavelength imaging [33] and artificial acoustic black hole [24,34].

Recently, acoustic metamaterials with engineering structures (such as bars, beams and plates) have gained widespread attention. The pioneering idea of local resonance was applied in engineering structures by Wang et al. [35]. A simple quasi-one-dimensional mechanical analog model was introduced to investigate the physical insight of the locally resonant mechanism. In 2006, Wang et al. proposed a basic model of locally resonant bars [36]. The propagation of longitudinal elastic waves in locally resonant bars was studied. In both theoretical and experimental results, the sub-frequency locally resonant band gap with highly asymmetric attenuation was observed and two results were in great agreement. Yu et al. have studied the flexural vibration in Timoshenko beams with periodical local resonators theoretically and experimentally [37]. Then the model was improved with double mass-spring subsystem integrated to the Euler-Bernoulli beams [38]. The measurements showed that an attenuation of more than 20 dB occurred over the frequency range of the bandgaps. The existence of the low frequency bandgaps in beams provides a method for flexural vibration control of beams. Oudich et al. theoretically demonstrated the waveguiding of Lamb waves in a two-dimensional locally resonant plate [39,40]. They mainly focused on the formation of the complete bandgap of Lamb waves propagating in the locally resonant plate and the influence of the parameters, but the experimental verification was not involved. In 2011, Oudich et al. provided experimental evidence for the existence of locally resonant acoustic band gaps in two-dimensional plates [41]. The locally resonant acoustic bandgap at about 2.2 kHz was observed. In addition, the potential of locally resonant thin plates with a periodic array of resonators for the application of low frequency vibration suppression has been investigated [42–44].

In short, the dynamic vibration absorber as a substitute for the mass-spring subsystem can be combined with bars, beams, plates and other engineering structures to form the locally resonant structures [45]. The purpose of vibration and noise reduction would be achieved by utilizing the bandgap characteristics of periodic structures. It is found from above structures that the stiffness and mass are two factors that affect the actual attenuation of the locally resonant bandgap. Review of the existing locally resonant structures [35–41,46,47], it can be seen that the mass of the dynamic vibration absorber is much greater than that of the substrate, which is very unfavorable in engineering applications. Therefore, it is necessary to consider not only the weight of the structure but also the low-frequency range of the bandgap. At the same time, due to the limitations of the oscillator mass, a smaller stiffness of the oscillator is preferred in order to obtain the low-frequency bandgap. Hence the equivalent stiffness of the substrate should be appropriately reduced, which will lead to lower overall system stiffness. Thus, it would be a great idea to integrate the composite materials like carbon-fiber-reinforced polymer (CFRP) [48], which have high ratio of strength to weight, into acoustic metamaterials to control the propagation of low-frequency sonic waves. Composite materials have recently been widely used in the automotive, aerospace and other fields due to its light weight and good performance [49]. The material property of the composites can be engineered according to the application requirements [48,50–52]. However, some undesirable behaviors like extensional-shear coupling and bending-twist coupling may exist in unsymmetrical laminate, which can cause performance degradation in the application of composite materials [53]. Therefore, the symmetrical laminate widely used in engineering is applied to design acoustic metamaterials to avoid these unsatisfactory behaviors.

In addition, with the increasing demand for Noise Vibration and Harshness (NVH) performance, noise control of the closed cavity such as aircraft cabins and passenger compartments has become an urgent problem for engineers. It has been found that the interior noise is affected significantly by the structural vibration, acoustic domain and coupled interface. The structural vibration produces noise, and noise in turn reacts to the structure as a result of the sound pressure. The acoustic analysis of structural-acoustic coupled system based on finite element method (FEM) can predict the vibration and noise in the early design stage [54,55]. It can be widely used in the design of aircraft and vehicle for vibration and noise control.

This work aims to design multi-stopband laminate acoustic metamaterials with the superior strength to weight ratio for broadband vibration absorption and noise reduction in the structural-acoustic coupled system. The multi-stopband laminate acoustic metamaterials consist of orthotropic laminates and multi-frequency mass-spring-damper, which show the extraordinary performance for noise and vibration mitigation in the structural-acoustic coupling system. The paper is structured as follows. Firstly, in Section 2, the dynamic equilibrium equation of the structural-acoustic coupled system is derived in detail. The dispersion analysis of the multi-stopband behavior of laminate acoustic metamaterials is conducted in Section 3. Afterwards, the multi-stopband of laminate acoustic metamaterials is verified by frequency response analysis. In addition, the working mechanism of the bandgaps is revealed based on the concept of conventional dynamic vibration absorbers. The influences of the absorbers' resonant frequencies and damping ratios of the multi-frequency vibration absorbers as well as the laminate's mode shapes are investigated. In Section 4, two numerical models are conducted to demonstrate the excellent performance of the multi-stopband laminate for interior noise and vibration reduction. Finally, the results as well as the conclusions drawn from the paper are given.

2. Basic theory of laminate acoustic metamaterials for structural-acoustic coupled system

The structural-acoustic coupled system with laminate acoustic metamaterials is shown in Fig. 1. The system consists of three parts: the structure domain Ω_s, the acoustic domain Ω_f, and the coupled domain $\partial\Omega_{sf}$ [56–60]. The external and natural