Journal of Sound and Vibration 337 (2015) 150–160

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Locally resonant band gaps achieved by equal frequency shunting circuits of piezoelectric rings in a periodic circular plate

Longxiang Dai [a,b], Shan Jiang [a,b], Ziyang Lian [a,b], Hongping Hu [a,b,*], Xuedong Chen [c]

[a] Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, PR China
[b] Hubei Key Laboratory of Engineering Structural Analysis and Safety Assessment, Huazhong University of Science and Technology, Wuhan 430074, PR China
[c] State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan, PR China

A R T I C L E   I N F O

Article history:
Received 1 June 2014
Received in revised form
21 September 2014
Accepted 18 October 2014
Handling Editor: L.G. Tham
Available online 10 November 2014

A B S T R A C T

This work presents an investigation on vibration transmission in a circular thin plate consisting of metal rings and piezoelectric rings arrayed periodically. Each piezoelectric ring is linked to an independent resistive–inductive (RL) resonant shunting circuit. For a periodic rectangular piezoelectric plate, equal inductances are commonly used in resonant shunting circuits. However, for the circular one, the locally resonant (LR) band gap (BG) cannot be formed by shunting circuits with equal inductances, because different periodic cell has a different capacitance. Instead of equivalent inductance circuits, the equal frequency shunting circuits are employed to tune the resonance frequency of each circuit into the same, thus an integrating LR BG is obtained. A transfer matrix method is used to calculate transmission factor in the low frequency range. The theoretical model is verified by finite element method (FEM). The impact of geometric and circuit parameters on the properties of the LR BG and vibration attenuation band (VAB) has also been analyzed.

1. Introduction

The vibration and waves in some frequency ranges can be attenuated when elastic or acoustic waves propagate in phononic crystals (PCs). The PC is a structure arrayed periodically by different materials. The frequency ranges with large attenuation are called band gaps (BGs). The BGs can be induced by two mechanisms, which are named Bragg BG and locally resonant (LR) BG [1], respectively.

Environmental noise and mechanical vibration excitation are within low frequency range. Therefore low frequency is the focus on isolation or absorption of vibration. For the PCs with Bragg BG, the spatial modulation of the elasticity must be of the same order as the wavelength in the gap, which means that the PC structures should be with a bigger size for the vibration isolation of machines since the vibration frequency is low. In other words, a PC structure with a normal size only can bring Bragg BGs with high frequencies, which are far beyond the vibration frequency. However, the LR BGs with low

* Corresponding author at: Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, PR China. Tel.: +86 27 87559409.
E-mail address: huhp@hust.edu.cn (H. Hu).

http://dx.doi.org/10.1016/j.jsv.2014.10.026
0022-460X/

frequency can be generated by PCs with small dimensions, which enable the LR PCs to absorb low-frequency vibration for the machine [1–3].

Yet every cell of conventional LR PCs commonly consists of a heavy core with a soft coat, which is equivalent to a mass–spring oscillator, to obtain a low resonance frequency. Therefore, it means producing a lower LR BG needs a heavier PC. While piezoelectric patches connected by shunting circuits can compose inductor–capacitor oscillators as light oscillators instead of the heavy mass–spring structures in the LR PCs. Beams attached by periodic arrays of piezoelectric patches connected by resonant shunting circuits was studied to control the propagation of vibration [4–7]. All the circuits were the same and were tuned synchronously. Locally resonant BGs were achieved.

Besides, PCs with piezoelectric materials usually have another significant advantage that its BGs can be tuned by the circuits and its parameters [8–13]. Aperiodicity was also introduced in the shunting circuit parameters [14]. Recently, periodic arrays of hybrid-shunted piezoelectric patches, connected by resonant resistive/inductive circuit and negative impedance converter respectively, were applied to suppress vibrations of a plate. An attenuation band of 500 Hz wide was achieved with 19 dB of maximum vibration reduction [15]. A thin rectangular plate with piezo-patches was studied, the location and attenuation constants of the Bragg gap was tuned by resistive shunts, while the internal resonances of resonant shunting system split the dispersion curves and form a LR BG [16]. However, to the best of our knowledge, little research has been done on the periodic circular plate structure.

It is crucial to control and isolate microvibration for precision semiconductor manufacturing equipment such as lithography, highly precise instruments such as atomic force microscopes [17], and machine tools for Ultra High Precision Machining [18]. All mechanical devices mentioned above have at least one workbench. Compared with a rectangular workbench, a round one has better dynamic characteristics, especially for the rotary motion. Therefore circular plate is one of common structures of the workbench. The workpiece can be conveniently placed at its center. In this paper, the emphasis is placed on studying the isolation on vertical vibration incoming from the side of the circular plate. Flexural elastic waves propagate in the circular plate consisting of periodically arrayed metal rings and piezoelectric rings. The electric field in the flexural piezoelectric rings is analyzed by precise electric field method by taking into account a distribution of the electric field over the thickness, instead of as a constant [19]. Although every cell has a metal ring and a piezoelectric ring with a same width, and the cells are periodically arrayed in radius direction, different cell has a different capacitance. It is because that the electrode areas of piezoelectric rings increase with radius. That is to say, the plate is not a periodic structure as usual, and Bloch theorem is not applicable here. Frequency response function (FRF) is an effective tool to describe BG for a PC structure of limited size in practical application. What's more, different resonant shunting circuit for each cell is necessary to achieve LR BG due to variation in capacitance. A unified resonance frequency may not be obtained if all resonant shunting circuits are the same.

This paper is organized in five sections. This introduction (Section 1) is followed by the description of the formulation for circular thin plates consisting of metal rings and piezoelectric rings (Section 2). A harmonic analysis of the plate is conducted in Section 3. Numerical examples are given in Section 4 where the features of LR BGs are discussed. The effects of different parameters on the BGs of the plate are also illustrated in this section. Finally, a summary is presented and some conclusions are drawn in Section 5.

2. Governing equations of a periodic circular plate

The circular thin plate model consists of metal rings and piezoelectric rings arrayed periodically with inner radius R_0, outer radius R, and thickness h, and a concentrated mass m_0 attached in the middle, as shown schematically in Fig. 1. The plate is simply supported at outer edge which is also acted by input vibration. The input vibration is assumed to be along the vertical direction, and harmonic with a certain frequency ω and amplitude A. As illustrated in Fig. 1, a periodic cell, with width a, is composed of a metal ring and a piezoelectric ring, with width a_1 and a_2 respectively. Two layers of annular piezoelectric plates with same thickness are bonded into a piezoelectric ring by conductive adhesive. In order to make the upper and lower layers be connected in series, the lower layer is polarized along the z-direction, while the upper one is

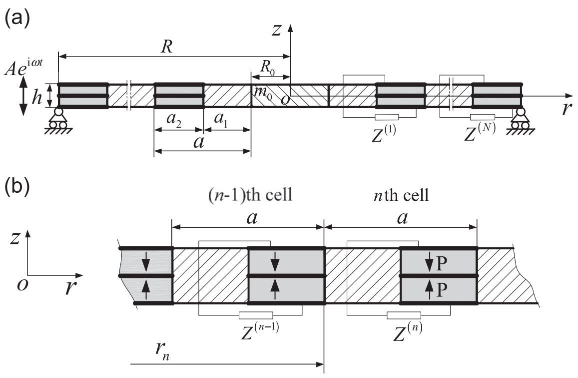

Fig. 1. Cross section of circular thin plate with metal rings and piezoelectric rings arrayed periodically: (a) whole graph, (b) partial enlarged detail.