ARTICLE IN PRESS

Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

# Effect of eddy current damping on phononic band gaps generated by locally resonant periodic structures

Efe Ozkaya, Cetin Yilmaz *

*Department of Mechanical Engineering, Bogazici University, 34342, Bebek, Istanbul, Turkey*

ARTICLE INFO

*Article history:*
Received 11 April 2016
Received in revised form
31 October 2016
Accepted 16 November 2016
Handling Editor: A.V. Metrikine

*Keywords:*
Phononic band gap
Periodic structure
Eddy current damping
Local resonator

ABSTRACT

The effect of eddy current damping on a novel locally resonant periodic structure is investigated. The frequency response characteristics are obtained by using a lumped parameter and a finite element model. In order to obtain wide band gaps at low frequencies, the periodic structure is optimized according to certain constraints, such as mass distribution in the unit cell, lower limit of the band gap, stiffness between the components in the unit cell, the size of magnets used for eddy current damping, and the number of unit cells in the periodic structure. Then, the locally resonant periodic structure with eddy current damping is manufactured and its experimental frequency response is obtained. The frequency response results obtained analytically, numerically and experimentally match quite well. The inclusion of eddy current damping to the periodic structure decreases amplitudes of resonance peaks without disturbing stop band width.


## 1. Introduction

The frequency ranges, in which propagation of acoustic or elastic waves are hindered, are called phononic band gaps [1–5]. Various methods can be used to generate phononic band gaps. In Bragg scattering method, the interference of the incident and reflected waves attenuates the energy of the propagating wave to create phononic band gaps [6,7]. In inertial amplification method, the wave propagating medium's effective inertia is amplified via embedded amplification mechanisms [3,6,7]. In local resonance method, when the frequency of the incident wave upon the periodic structure is close to the resonance frequency of the resonators, the wave energy excites the resonators and wave propagation is hindered. As a result, a band gap is formed around the resonance frequencies of the local resonators [8–13]. When there is no damping in a locally resonant structure, deep anti-resonance notches can be observed in its frequency response function enabling excellent vibration isolation around these frequencies [14]. However, in an undamped structure with local resonators, sharp resonance peaks are observed. Consequently, if the structure is excited around these frequencies, large undesired amplifications can be seen.

Former studies have considered the effect of damping in lattices with local resonators [15–17]. Generally, viscous damping is investigated in these studies. In this paper, eddy current damping will be included to the local resonators in a periodic structure with the aim of decreasing the amplitudes of the resonance peaks while preserving a deep and wide stop band.

Eddy currents are created when a non-magnetic conductor is moving in a region imposed upon a stationary magnetic field or when a time varying magnetic field has an impact upon a stationary non-magnetic conductor. According to Lenz's

* Corresponding author.
*E-mail addresses:* efe.ozkaya@boun.edu.tr (E. Ozkaya), cetin.yilmaz@boun.edu.tr (C. Yilmaz).

http://dx.doi.org/10.1016/j.jsv.2016.11.027
0022-460X/

Please cite this article as: E. Ozkaya, & C. Yilmaz, Effect of eddy current damping on phononic band gaps generated by locally resonant periodic structures, *Journal of Sound and Vibration* (2016), http://dx.doi.org/10.1016/j.jsv.2016.11.027

Law, eddy currents circulating in a conductor create their own magnetic field. As a result, a resistive force which opposes the motion of the moving part is created. When vibration between a conductor and a magnet is considered, a damping force proportional to the velocity of the vibration is generated and this is called eddy current damping [18–25].

Both viscous and eddy current damping forces are proportional to the velocity of the vibration. Therefore, mathematically these two damping mechanisms are equivalent. However, when the physical structure of these dampers are considered, one can see that eddy current damping offers certain advantages. In viscous dampers, generally a fluid is forced through a small opening by a moving piston. Due to sliding motion, there may be wear problems. Moreover, compressibility of the fluid inside these dampers introduce some stiffness besides damping [26]. Stiffness change due to compressibility effect is more pronounced at high frequencies. If eddy current damping is added to a structure, its stiffness is not disturbed as eddy current damping is a non-contact type of damping. Due to its non-contact nature, it is not prone to wear.

Eddy current damping method has been used in various applications. Sodano et al. [27] used eddy current damping to impede the transverse vibrations of a cantilever beam. Ebrahimi et al. [28] studied a design that involves two permanent magnets and a conductive aluminum plate to generate both stiffness and variable damping. Elbuken et al. [29] applied eddy current damping to magnetically levitated miniaturized objects. Bae et al. [30] introduced a tuned mass damper with eddy current damping.

In this paper, eddy current damping will be combined with the local resonance method for the first time. In order to generate eddy current damping, concentric copper tube and magnet assemblies will be used. To enforce one-dimensional (1D) motion between these components, a novel periodic structure with parallel spiral springs will be designed. Parametric studies will be conducted with the aim of obtaining a wide local resonance induced gap. The periodic structure will be manufactured to see the effect of eddy current damping on resonance peaks, stop band width, and depth in frequency response plots.

## 2. Models and methodology

The study consists of three main sections. Firstly, analytical calculations are done to determine the values of the design parameters. Depending on these parameter values, a prototype design is established numerically and modal analysis is conducted. In the final phase, experimental validation is performed for the prototype produced. In this study, small deformations are considered, hence the structure is assumed to be linear and strength is not an issue.

### 2.1. Analytical model of the locally resonant periodic structure

A one-dimensional locally resonant periodic structure that includes eddy current damping is modelled as in Fig. 1. During modelling of the periodic structure, five parameters are taken into account, which are resonator mass ($m_r$), total mass of the remaining parts in the unit cell when the resonator mass is excluded ($m$), stiffness of the spring connecting the resonator mass to the unit cell ($k_r$), total stiffness between the unit cells ($k$) and the eddy current damping constant ($c$). As eddy current damping force is proportional to the velocity of vibration, $c$ can be considered as a viscous damping constant.

Phononic band structure and the frequency response of the periodic structure will be determined by the transfer matrix method [31]. Through mechanical impedance to mass conversion, periodic structure's effective mass can be calculated to be used in its overall transfer matrix. Mechanical impedance representations for mass, spring and damper elements are $j\omega m$, $k/j\omega$ and $c$, respectively [32]. By using these impedances, effective mass of the unit cell of the system shown in Fig. 1(b) is obtained as follows:

$$m_{eff} = m + \cfrac{1}{\cfrac{1}{m_r} - \cfrac{\omega^2}{k_r + j\omega c}} \tag{1}$$

The point transfer matrix for $m_{eff}$ (Eq. (2)) and the field transfer matrix for $k$ (Eq. (3)) are used [31] to obtain the relationship between consecutive unit cells (Eq. (5)) through the state vector relationship as shown in Eq. (4).

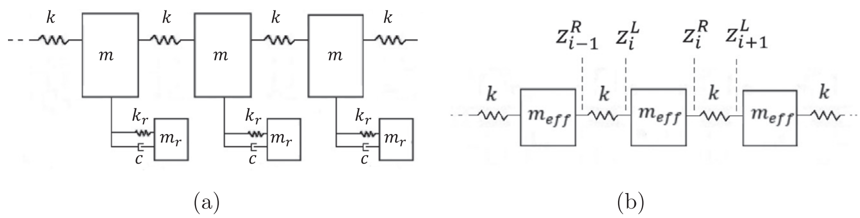


**Fig. 1.** Lumped parameter model of the locally resonant periodic structure including eddy current damping (a) 1D array with local resonators, (b) the equivalent array with effective mass.