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Invited Paper

Tunable Bandgap in Active Acoustic Metamaterials Controlled with Electric Shunt Circuits

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ABSTRACT

We represent that tunable bandgap on the propagation of acoustic waves can be achieved by using a vibro-acoustic metamaterial composed of waveguide and a series of unit cells with shunted piezoelectric structure. Each of unit cells consists of a shunt circuit and an embedded single crystal PMN-PT structure (SCPPS) which is used as sensing-actuator.

1. INTRODUCTION

Acoustic metamaterials have been studied because of their peculiar characteristics on the wave propagation such as bandgap where wave propagation is blocked. These phenomena are occurred due to the sub-wavelength size of unit cells of metamaterials at local resonance state of unit cells as shown in Ding (2010), Fang (2006) and Seo (2012). In addition to the bandgap by local resonance of unit cells, the acoustic metamaterials with unit cells exhibit another bandgap at different frequency by Bragg scattering resulted from the periodic variation of unit cell. Moreover, simultaneous negative effective mass density and bulk modulus have been revealed by 1D metamaterials composed of Helmholtz resonators at the resonant frequency of unit cells as shown in Fang (2006) and Lee (2009). However, to realize the bandgap without transmission loss of acoustic wave, a large number of unit cells are required. Also, it is difficult to change the bandgap frequency by local resonance of unit cells since the geometry of unit cells are fixed. In an effort to resolve the invariable bandgap issues, recently, several tunable concepts were reported, however, existing tunable vibro-

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acoustic waveguides made of smart materials are capable of broadening only limited bandwidths as shown in Akl(2011), Lapine (2012), Pryce (2010) and Pryce (2011).

2. VIBRO-ACOUSTIC WAVEGUIDE

In the present study, we propose a vibro-acoustic waveguide composed of a series of unit metamaterial cells with single crystal PMN-PT structures (SCPPSs). Bandgap frequency can be varied using this waveguide by a combination of two mechanisms; wave interferences by structural vibration and electrical energy dissipation. When acoustic waves pass through the waveguide, wave interferences can occur decreasing the intensity of acoustic waves by longitudinal vibration of a SCPPS and electrical energy dissipation by the resonant shunt circuit. Thus, multi-bandgap and tunable bandgap can be realized by the local resonance of a SCPPS and by a variation of electrical elements in the shunt circuit.

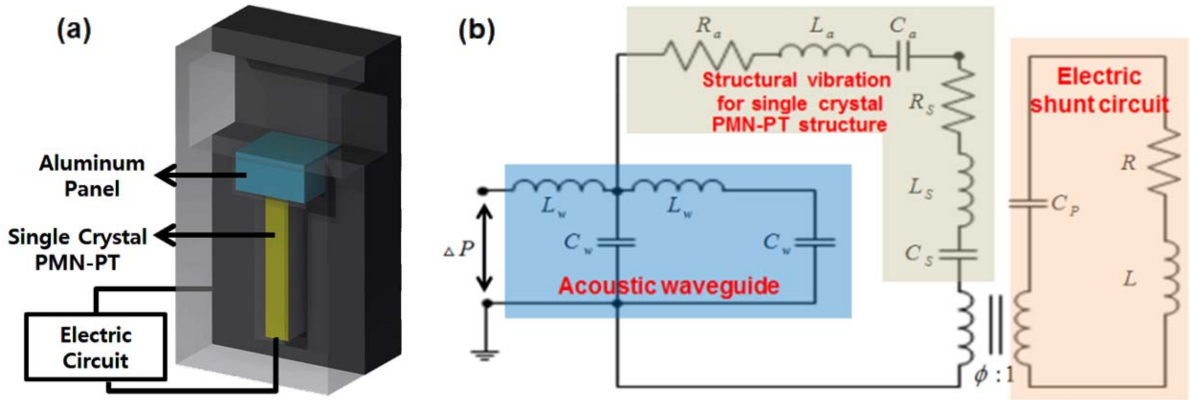

Fig. 1 Structure of 1D vibro-acoustic waveguide with SCPPSs: (a) configuration of a SCPPS unit cell and (b) vibro-acousto-electric coupled equivalent circuit for a unit cell

A SCPPS unit cell is made of an aluminum panel, a single crystal PMN-PT bar and a shunting electric circuit, as shown in Fig. 1(a). Different from the conventional piezoelectric materials, PMN-PT makes increased displacement of SCPPS under the influence of its superior dielectric and electro-mechanical properties. These results give rise to improved bandwidth and sensitivity, and consequently show increased acoustic wave interferences. Furthermore, the SCPPS unit cell is designed to yield an improved piezoelectric charge constant. The aluminum panel is placed on top of the unit cell in order to increase the acoustic wave pressure that the crystal PMN-PT bar receives. Of the two longitudinal vibration frequencies (32kHz and 110kHz), the first vibration mode (32kHz) is utilized in designing the unit cells. The repetitive lattice spacing (L) between the unit cells is chosen to be between 1/5 and 1/4 of the wavelength of the first longitudinal vibration mode frequency of the unit cell.

In order to identify the wave propagation characteristics of the proposed tunable vibro-acoustic waveguide, theoretical analysis for a unit cell is presented using lumped-parameter modeling approach as shown in Fig. 1(b). The equivalent circuit consists of three components: a rectangular waveguide section, vibrating structure including both an aluminum panel and a crystal PMN-PT bar, and a series resonant shunting electric circuit. When the shunt circuit is integrated with the vibrating structure, the equivalent impedance of the unit cell is obtained as

$$Z_{total} = \frac{\rho_w Ls}{2A_w} + \frac{R_a + \frac{M_a s}{A_a^2} + \frac{K_a}{A_a^2 s} + R_s + \frac{M_s s}{A_s^2} + \frac{K_{CS}}{A_s^2 s} + Z'_{shunt}}{\frac{A_w Ls}{B_w}\left\{R_a + \frac{M_a s}{A_a^2} + \frac{K_a}{A_a^2 s} + R_s + \frac{M_s s}{A_s^2} + \frac{K_{CS}}{A_s^2 s} + Z'_{shunt}\right\} + 1}, \quad (1)$$

Coupling of acoustic, mechanical and electric systems is theoretically confirmed through the effec-tive admittance. By varying electric resonance frequency of the shunt circuit, effective admittance is computed theoretically indicating different frequency peaks. It was verified that the frequency peaks from varied electric resonances agree with those by simulation from corresponding electric characteristic.

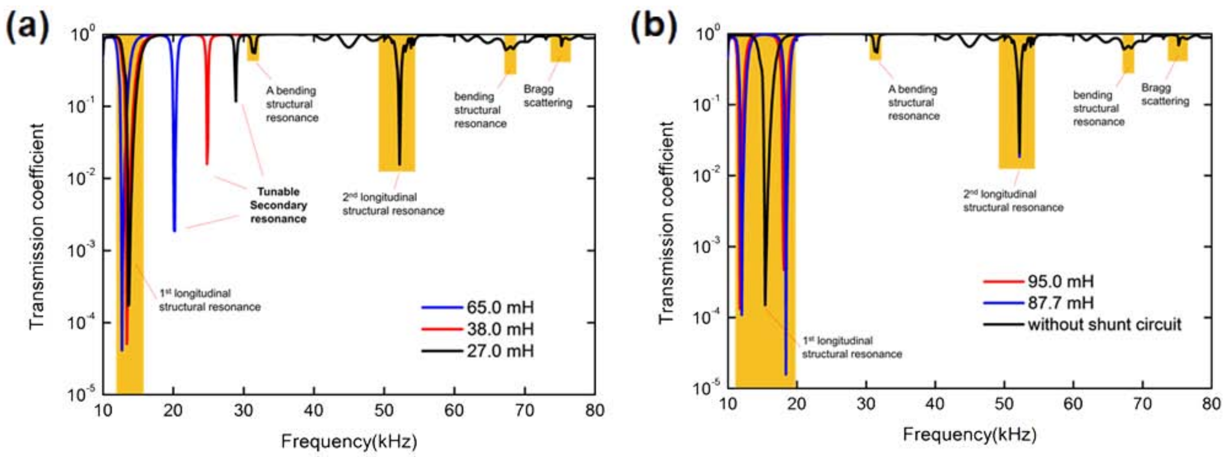

Fig. 2 Transmission coefficients by electric resonance of shunt circuit with the variations of inductance showing (a) multi-bandgap and (b) tunability of transmission loss level

The tunability of proposed vibro-acoustic waveguide can be easily assessed by altering the inductance of the circuit as shown in Fig. 2(a). As the operating frequency of acoustic waves is close to the resonant frequency of SCPPS or the electric resonance frequency of shunt circuit, acoustic wave interferences occur. Not only the bandgap by Bragg scattering, two peaks by structural and electrical resonance frequency are also observed for each inductance which points out multi-bandgap.

The main advantage of the proposed tunable vibro-acoustic waveguide is in its ability that tunes the loss level of transmission coefficient as shown in Fig. 2(b). By matching the electric resonance frequency of shunt circuit with the structural resonant frequency of SCPPS, blocking performance of acoustic wave in bandgap will be enhanced as longitudinal vibration of the SCPPS affecting on the acoustic wave is significantly improved. Hence, the energy of acoustic waves passing through the waveguide is decreased such that the blocking performance is improved compared to the existing acoustic waveguides composed of unit cells with fixed dimensions.

3. CONCLUSIONS

Even if the loss of transmission coefficient by Bragg scattering is not tunable because the periodicity of unit cells which is unaffected by shunt circuit, multi-bandgap and tunable transmission loss can be conven-iently attained by the variation of resonant shunt circuit.

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