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Active tuning of vibration and wave propagation in elastic beams with periodically placed piezoelectric actuator/sensor pairs

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ABSTRACT

A novel strategy is proposed to actively tune the vibration and wave propagation properties in elastic beams. By periodically placing the piezoelectric actuator/sensor pairs along the beam axis, an active periodic beam structure which exhibits special vibration and wave propagation properties such as the frequency pass-bands and stop-bands (or band-gaps) is developed. Hamilton's principle is applied to establish the equations of motion of the sub-beam elements i.e. the unit-cells, bonded by the piezoelectric patches. A negative proportional feedback control strategy is employed to design the controllers which can provide a positive active stiffness to the beam for a positive feedback control gain, which can increase the stability of the structural system. By means of the added positive active stiffness, the periodicity or the band-gap property of the beam with periodically placed piezoelectric patches can be actively tuned. From the investigation, it is shown that better band-gap characteristics can be achieved by using the negative proportional feedback control. The band-gaps can be obviously broadened by properly increasing the control gain, and they can also be greatly enlarged by appropriately designing the structural sizes of the controllers. The control voltages applied on the piezoelectric actuators are in reasonable and controllable ranges, especially, they are very low in the band-gaps. Thus, the vibration and wave propagation behaviors of the elastic beam can be actively controlled by the periodically placed piezoelectric patches.

1. Introduction

Periodic structures (or phononic crystals) consisting of many identical sub-structures according to certain regularity and periodicity are widely used in practical engineering applications such as aerospace deployable structures, bridges, railway tracks and bladed disk assemblies. Some special mechanical properties of the periodic structures have been observed, such as the frequency pass-band and stop-band (or band-gap) behaviors [1–3]. The mechanical vibration and acoustic/elastic waves whose frequencies lie in the pass-bands can propagate through the periodic structures without any spatial attenuation. However, if the frequencies of the mechanical vibration and acoustic/elastic waves are in the stop-bands, they are all forbidden to propagate through the whole structures but attenuate in the structures. So the band-gap characteristics of

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the periodic structures are of great significance in practical applications such as elastic wave filtering, vibration isolation and noise reduction [4,5].

Because of the importance of the band-gap property, scientists and engineers often wish to achieve more and wider band-gaps in the periodic structures, and many investigations have been conducted in obtaining different kinds of periodic structures with better band-gap characteristics. Gao et al. [6] investigated the flexural vibration band-gaps in functionally graded periodic beams, and found that the widths of odd-order band-gaps can be enlarged by using the functionally graded materials. Acar and Yilmaz [7] and Taniker and Yilmaz [8,9] numerically and experimentally studied the existence of wide and deep phononic band-gaps induced by inertial amplification mechanisms in two-dimensional (2D) and three-dimensional (3D) periodic structures. Aryadoust and Salehi [10] analyzed the dependence of the band structures and the widths of the band-gaps on the lattice angle in 3D phononic crystals with rhombohedral (II) lattice. Aly et al. [11] studied the effects of the physical parameters on the properties of phononic band-gaps, and discovered that the band structure and band-gaps could be changed by varying the composite materials and surrounding material. Su et al. [12] designed one-dimensional (1D) functionally graded phononic crystals, and analyzed the influences of the material composition, material properties and geometrical parameters on the band-gaps by comparing with conventional phononic crystals.

Recently, some research works were also devoted to the investigations on various periodic structures with tunable band structures, which makes it possible to obtain the desired band-gap characteristics. Huang et al. [13,14] applied the mechanical and mechanical/electrical biasing fields to study the control ability on the band structure and tunability of elastic waves in periodic structures by changing the effective stiffness of the structures. Feng and Liu [15,16] experimentally and numerically investigated the mechanisms of the shift of the band-gaps in phononic crystals with different initial confining pressures, and found that the confining pressures could efficiently tune the locations and widths of the band-gaps. Wang et al. [17] introduced the grading concept to design the topological structure of pores and investigated the effects of the grading on the band structures in porous phononic crystals, and wider absolute band-gaps were obtained at lower frequencies with the increase of the porosity. Bian et al. [18] studied the thermal tuning properties of band structures in a 1D phononic crystal.

Moreover, some attempts have been made to employ active materials such as magnetoelastic materials [19–23], dielectric elastomer composites [24], magneto-electro-elastic materials [25,26], piezomagnetic materials [27], magnetostrictive materials [28], electroactive composites [29] and so on to design periodic structures with tunable band-gap performances. In addition, due to their special electromechanical coupling properties, the piezoelectric materials are particularly popular in practical engineering applications for designing tunable periodic structures such that the band-gap locations and widths can be changed to satisfy some special demands [30–41]. From the beginning of the 21st century, Ruzzene and his colleagues [42–45] systematically investigated the vibration and wave propagation control in rods, beams and plates with periodic shunted piezoelectric patches. They designed multi-resonant circuits to generate multiple attenuation frequency ranges, i.e. band-gaps, which could be tunable to target different structural modes. Recently, the periodic arrays of shunted piezoelectric patches were further developed by some other authors to control the wave propagation in structures [46–48]. Zhao et al. [49,50] derived the dispersion equations and transmission coefficients of the periodically layered piezoelectric structures to study the propagation behaviors of elastic waves in the structures. Degraeve et al. [51] designed a homogeneous piezoelectric rod with periodic electrical boundary conditions and analyzed the tunability of the Bragg band-gaps in this peculiar periodic structure. Oh et al. [52] studied the wave propagation in piezoelectric phononic crystals and found that the active wave-guiding could be realized in a stop band frequency range if the piezoelectric inclusions were electrically controlled. Huang et al. [53] designed a phononic plate model with periodically corrugated surfaces and analyzed the tunability of the band-gap behaviors of Lamb waves by adjusting the structural parameters. It should be noted that the first author and his co-workers also systematically investigated the wave propagation behaviors in various piezoelectric periodic structures taking into account of the electromechanical coupling effects, and found some remarkable changes in the band-gaps compared with the purely elastic periodic structures [54–57].

Although many strategies have been proposed to design different kinds of periodic structures possessing tunable band structures, including the multi-branch shunts by means of the periodic shunted piezoelectric patches [44] and the piezoelectric periodic structures [54–57], they belong to passive vibration and wave propagation control categories since no external energy input into the periodic structures is required. Inspired by the above facts, in this paper, a novel strategy is proposed by periodically placing the piezoelectric actuator/sensor pairs along the beam axis to obtain an active periodic beam structure. By employing a negative proportional feedback control method to design the controllers, a positive active stiffness is added to the beam, which can enhance the dynamical stability of the beam. By actively tuning the magnitude of the added active stiffness, the band-gap properties of the elastic beams with periodically placed piezoelectric patches can be

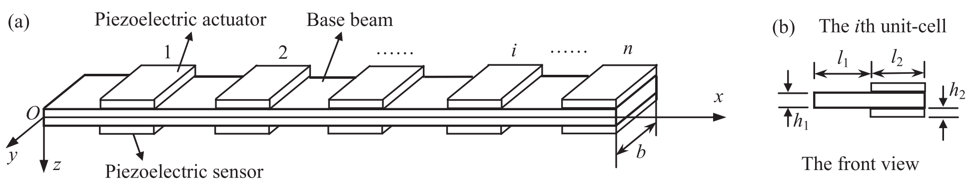

Fig. 1. A beam with periodically bonded piezoelectric actuator/sensor pairs (a), and the front view of unit-cell (b).

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