Mechanical Systems and Signal Processing 93 (2017) 255–266

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Enhancement of elastic wave energy harvesting using adaptive piezo-lens

K. Yi [a], M. Collet [a,*], S. Chesne [b], M. Monteil [b]

[a] LTDS UMR5513 Ecole Centrale de Lyon, 36 Avenue Guy de Collongue, 69130 Ecully, France
[b] Université de Lyon, CNRS INSA-Lyon, LaMCoS UMR5259, F-69621 Villeurbanne, France

ARTICLE INFO

Article history:
Received 29 August 2016
Received in revised form 4 January 2017
Accepted 4 February 2017

Keywords:
Piezoelectric material
Negative capacitance
Wave focusing
Energy harvesting

ABSTRACT

This paper exploits an adaptive piezo-lens to improve the harvested power (energy) from traveling waves. The piezo-lens comprises a host plate and piezoelectric patches bonded on the plate surfaces. The piezoelectric patches are shunted with negative capacitance (NC) circuits. The spatial variation of the refractive index inside the piezo-lens domain is designed to fulfill a hyperbolic secant function by tuning the NC values. This design allows the piezo-lens to continuously bend the incident waves toward a designed focal point, resulting in an energy concentration zone with a high level of energy density. This energy concentration effect may be exploited to improve the harvested power from waves. In addition, the piezo-lens is tunable - the waves can be focused at different locations by designing the NC values. This tunability may make the harvesting systems incorporating a piezo-lens be adaptable to environment changes. The above expected practical interests of the piezo-lens for wave energy harvesting are discussed and verified in the paper. Fully coupled numerical models are developed to predict the dynamical responses of the piezoelectric systems.

1. Introduction

Small electronic devices are increasingly employed in many applications in the aerospace, transport and civil engineering fields. Such devices typically require continuous low power supply [1]. This fact motivates massive researches dedicated to the transformation of ambient energy into electricity. Due to the ubiquitous presence of vibration in structures, extensive efforts have been made to harvest vibration energy through piezoelectric, electromagnetic and electrostatic transducers [2]. In practical applications, vibration levels can be low [3] and the vibration energy is typically distributed over a broad frequency band, consequently a lot of these researches were dedicated to obtain higher harvesting efficiency and to extend the operating frequency band of the harvesting system. Examples include (i) tuning the harvesting system through passive or active methods to match the operating frequency with the environment [3,4]; (ii) exploiting nonlinear mechanical mechanisms to widen the operating frequency band [5] or nonlinear circuits to improve the extracted power from the transducers [6–14]; (iii) using phononic crystals [15], metamaterials [16] or acoustic black holes [17] to increase energy densities near the harvesters.

Harvesting vibration energy in structures is well studied, however limited effort has been devoted to harvest energy from traveling waves. Harvesting traveling wave energy is important when built-up structures are involved. In a built-up

---

* Corresponding author.
E-mail address: manuel.collet@ec-lyon.fr (M. Collet).

http://dx.doi.org/10.1016/j.ymssp.2017.02.008
0888-3270/© 2017 Elsevier Ltd. All rights reserved.

structure, the mechanical power transmits from one component to another in the form of traveling waves especially at higher frequency bands [18,19]. Due to the wave propagation, the mechanical energy is distributed in the whole structure with quite low energy densities everywhere. Therefore, the level of the harvested energy from waves could be very low.

In recent years, several innovative harvesting systems have been developed to increase harvested energy from traveling waves. The fundamental idea is to steer waves to increase the energy densities at particular positions and harvest there. Therefore, these systems not only include transducers with connected circuits, but also include structures used to enhance the energy density. The first examples use an elliptical acoustic mirror [20,21] or a parabolic acoustic mirror [22] to focus propagating waves near a specific point. The others are mainly based on metamaterials. Examples include using a defect in an artificial periodic array to localize energy at specific frequencies or building an acoustic funnel formed by arrays of acoustic scatters to guide waves into a narrow channel [22]; exploiting a gradient-index phononic crystal lens to focus waves [23]. However, all these systems are based on unadaptable wave steering methods, they have no ability to adjust themselves to the environment.

Different from the aforementioned methods to steer waves, recently an adaptive piezo-lens is proposed to focus waves [24]. The piezo-lens is designed based on a gradient index medium concept [25]. It is obtained by periodically bonding piezoelectric patches on the surfaces of a host plate. These patches are shunted with negative capacitance (NC) circuits. The NC values are delicately designed to obtain a hyperbolic secant profile of the effective refractive index inside the piezo-lens. Results show that the piezo-lens can focus flexural waves near a designed point in a broad frequency band, and the piezo-lens has the ability to focus waves at different locations by just tuning the NC values. All these qualities make the piezo-lens a potential candidate to develop advanced harvesting systems for waves.

In this paper, a novel system is proposed for improving energy harvesting from traveling waves. This system is composed of a piezo-lens to focus waves and a harvester to yield energy from the focused waves. An analytical relationship which connects the effective refractive index of piezoelectric system to the shunting NC value is developed to design the piezo-lens. Fully coupled finite element models of the piezoelectric systems are developed to predict the dynamic responses. With these tools, we will study the focusing effects and adaptive capability of the piezo-lens, and how can these qualities be exploited to improve the harvesting performances.

2. Piezo-lens for wave focusing

The concept and designing process of the piezo-lens are introduced in this section. The piezo-lens is obtained by periodically bonding piezoelectric patches on the surfaces of a host aluminum plate in a collocated fashion, as depicted in Fig. 1(a). The host plate is lying in the $x-y$ plane and occupying the spatial region $-h_b/2 \leqslant z \leqslant h_b/2$. The piezo-lens zone could be divided into a 14-by-6 array of piezoelectric cell, the patches in each of these cells are shunted with a NC circuit, as shown in Fig. 2.

To focus flexural waves, the refractive indexes of flexural wave inside the piezo-lens zone are designed to fulfill a hyperbolic secant function:

$$n(y) = n_0 \cdot \mathrm{sech}(\alpha(y-\beta)) \tag{1}$$

in which, n_0 represents the refractive index of the background plate, α is the gradient coefficient and β represents the y coordinate of the symmetry axis of the refractive index profile, as illustrated in Fig. 1(b). Due to this design, waves incident into the lens from the Ox direction will be focused at a focal point at the $y=\beta$ line, with a focal length $f=\pi/2\alpha$ measuring from the left boundary of the lens [25]. It should be noted that the piezo-lens is primarily designed for waves from the Ox direc-

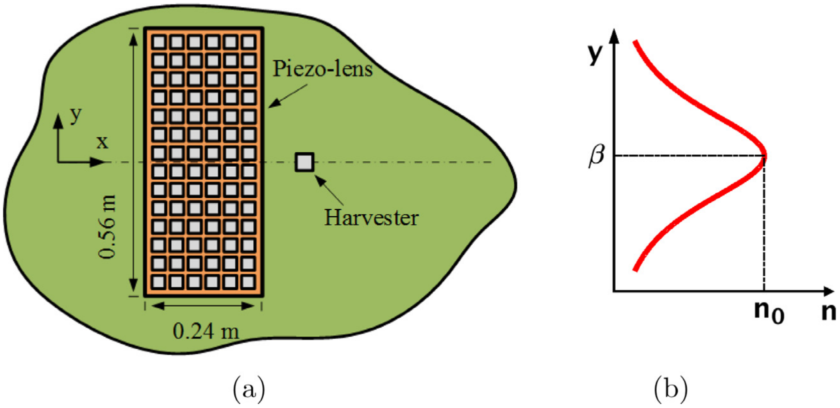

Fig. 1. (a) The harvesting system with piezo-lens and (b) the gradient variation profile of the refractive index $n(y)$.