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Piezoelectric power extraction from bending waves: Electroelastic modeling, experimental validation, and performance enhancement

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HIGHLIGHTS

- Fully-coupled electroelastic modeling and analysis of piezoelectric power extraction from bending waves are presented.
- Experimental validations, power flow and efficiency analyses are given for resistive and inductive electrical loading.
- Performance enhancements are presented by wavelength matching, conjugate impedance matching, and by exploiting an obstacle.
- An energy-harvesting anechoic boundary condition is presented to minimize reflected waves while generating electricity.
- Effects of structural, dielectric, and parasitic circuit losses are demonstrated along with the limits of efficiency.

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ABSTRACT

Existing research in vibration-based energy harvesting has focused mostly on the harvesting of deterministic or stochastic vibrational energy available at a fixed position in space. Such an approach is convenient for designing and employing linear and nonlinear vibration-based energy harvesters, such as base-excited cantilevers with piezoelectric laminates. This work presents a mathematical framework for the harvesting of one-dimensional bending waves propagating in infinite and semi-infinite beams as an alternative. For this purpose, the fully coupled electroelastic problem with piezoelectric patches bonded to a long slender beam is solved and conversion of incident wave energy into usable electricity while minimizing the traveling waves reflected and transmitted from the harvester domain is analyzed. The analysis shows that the efficiency of power transfer from elastic waves can be significantly improved beyond the typical wavelength matching in terms of both efficiency and bandwidth by resistive–inductive loading. It is also shown that enhancements to efficiency can be obtained by localized obstacles in mechanical domain, and fully anechoic boundary conditions can be obtained on finite beams by resistive–inductive impedance matching. These enhancement methods are most effective and practical when piezoelectric patch lengths and obstacle to patch distances are $\sim> \lambda/4$, where evanescent fields become insignificant, while the model can readily accommodate the presence of evanescent waves for arbitrary patch lengths. The validity and application of the proposed methods are demonstrated with experimental case studies using a long slender beam.

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1. Introduction

Over the last decade, several research groups have worked on energy harvesting in order to power small electronic components by scavenging ambient energy available in their environment. The ultimate goal of these efforts is to create self-powered electronic devices for various wireless applications ranging from structural health monitoring sensors to medical implants [1–4]. Ambient energy exists in various forms, such as waste heat, solar, vibration, and flow energy. While each of these sources of energy can be used to power remote sensors, the harvesting of vibrational energy has been most heavily studied as a viable alternative source [5–10]. Among different transduction mechanisms that can be used for vibration-to-electric energy conversion, piezoelectric transduction has become the most popular method due to the ease of application, the high power density, and the relative maturity of the manufacturing methods of piezoelectric materials at different scales [11]. Most of the piezoelectric energy harvesters are in the form of unimorph or bimorph cantilevered beams. An alternating voltage output is obtained by applying harmonic base motion to the structure, and maximum power is generated typically at the fundamental resonant frequency of the composite structure [12]. Although it is a common practice to characterize the resonance behavior of a piezoelectric energy harvester with harmonic excitation, different models may be required for other loading conditions, especially in the absence of standing waves. For instance, scavenging energy from vibrations due to fluid–structure interaction requires a more complex analysis because of the coupling of piezoelastic structure with the surrounding airstream [3]. In literature, flow energy harvesting through aeroelastic [13–20] and hydroelastic [21–23] vibrations has been studied. Yet, researchers have given little effort to exploiting the energy of traveling waves in fluids and structures. Few research groups have studied this area with a focus on polarization-patterned piezoelectric solids [24], quarter-wavelength resonators [25], Helmholtz resonators [26,27], or phononic crystals [28–31]. In addition, Yang et al. [32] combined the sonic crystal concept with the Helmholtz resonators to improve acoustic energy harvesting. Furthermore, acoustic metamaterials can be used to enhance energy harvesting by changing wave propagation characteristics. For instance, Carrara et al. [33,34] implemented metamaterial-inspired structures in order to guide, localize, and focus elastoacoustic waves for more efficient piezoelectric energy harvesting. Since wave equation is the common theoretical basis for metamaterial-based elastoacoustic and electromagnetic energy harvesting, the combination of structural configurations with metamaterials and wave propagation is essential for performance enhancement [35].

We also note that various researchers combined the wave propagation theory with the piezoelectric sensing/actuating mechanisms to study passive and active structural health monitoring (SHM) systems [36–39]. For instance, the electromechanical impedance technique for SHM utilizes traveling waves and the electrical impedance of a surface-bonded PZT transducer to obtain the change in the electromechanical impedance signature of the structure and detects the structural damage by monitoring this change [40–43]. In various SHM applications, researchers utilized ultrasonic waves such as Rayleigh surface waves and Lamb modes [36,44,45]. In these studies, the focus has been either only on the forward problem to excite these waves more efficiently, or to sense with small size piezo patches where the important factor is signal to noise ratio, not efficiency of energy transfer. In those cases, for example, the effects of piezo patch electrical impedance and load termination on the propagating wave amplitudes through backward coupling are not considered.

This work fully combines the bending waves and the piezoelectric theory in the wave energy harvester to investigate the energy transfer from propagating wave energy in the structures to resistive and reactive electrical loads. As a specific and tractable example, piezoelectric patches bonded to a slender thin beam are considered. Incident wave energy is transformed into usable electricity while minimizing the traveling waves reflected and transmitted from the harvester domain. Electroelastic models are developed for the harvester bonded to infinite and semi-infinite beams by implementing the wave equation solution in the compatibility and equilibrium conditions at the harvester boundaries which are then solved simultaneously with the coupled electrical equation yielding the amplitudes of the traveling waves and the voltage response of the harvester. Hence, both electrical to mechanical and mechanical to electrical coupling problems are simultaneously solved. This allows one to obtain harvested power and the harvester efficiency for different electrical loading conditions and performance enhancement by wavelength matching, resistive–inductive circuits, and spatially localized obstacles. Additionally, an energy-harvesting end condition in a semi-infinite beam is introduced to minimize the reflection in the sense of creating ideally an anechoic boundary condition. The validity and application of the proposed model and the performance enhancement methods are demonstrated with several experimental studies by using a long slender beam.

2. Electroelastic modeling

When a wave, propagating along a waveguide such as a beam, encounters discontinuity, it is reflected and transmitted across that discontinuity [46]. As shown in Fig. 1, piezoelectric patches, symmetrically bonded to the top and bottom of a thin beam, are the sources of the discontinuity. The reflected and transmitted wave properties can be obtained from wave elastodynamics in the beam, as explained in Section 2.1. In Section 2.2, piezoelectric energy harvesting is combined with the wave propagation theory, and the power flow to the electrical load through the piezoelectric patches is extracted. In Section 2.3, a lumped mass is introduced to the system in order to increase the energy harvested in the piezoelectric patches. Finally, in the last section, the energy harvester is implemented at the end of the structure with a resistive–inductive circuit, resulting in a multifunctional energy harvester which ideally realizes an anechoic boundary condition while converting all incident elastic energy to electricity.