Journal of Sound and Vibration 416 (2018) 258–278

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Vibration properties of a rotating piezoelectric energy harvesting device that experiences gyroscopic effects

Haohui Lu, Tan Chai, Christopher G. Cooley*

Department of Mechanical Engineering and Energy Processes, Southern Illinois University Carbondale, Carbondale, IL 62901, USA

ARTICLE INFO

Article history:
Received 6 April 2017
Received in revised form 23 October 2017
Accepted 15 November 2017

Keywords:
Energy harvesting
Piezoelectric
Gyroscopic
Electromechanical coupling
Instability

ABSTRACT

This study investigates the vibration of a rotating piezoelectric device that consists of a proof mass that is supported by elastic structures with piezoelectric layers. Vibration of the proof mass causes deformation in the piezoelectric structures and voltages to power the electrical loads. The coupled electromechanical equations of motion are derived using Newtonian mechanics and Kirchhoff's circuit laws. The free vibration behavior is investigated for devices with identical (tuned) and nonidentical (mistuned) piezoelectric support structures and electrical loads. These devices have complex-valued, speed-dependent eigenvalues and eigenvectors as a result of gyroscopic effects caused by their constant rotation. The characteristics of the complex-valued eigensolutions are related to physical behavior of the device's vibration. The free vibration behaviors differ significantly for tuned and mistuned devices. Due to gyroscopic effects, the proof mass in the tuned device vibrates in either forward or backward decaying circular orbits in single-mode free response. This is proven analytically for all tuned devices, regardless of the device's specific parameters or operating speed. For mistuned devices, the proof mass has decaying elliptical forward and backward orbits. The eigenvalues are shown to be sensitive to changes in the electrical load resistances. Closed-form solutions for the eigenvalues are derived for open and close circuits. At high rotation speeds these devices experience critical speeds and instability.

1. Introduction

Review articles for research in vibration energy harvesting are found in Refs. [1–5]. Anton and Sodano [1] reviewed early work in piezoelectric vibration energy harvesting. Harne and Wang [2] reviewed research on bistable vibration energy harvesters. Daqaq et al. [3] reviewed research related to nonlinearities in vibration energy harvesting. Emam and Inman [4] reviewed and summarized research on bistable composite laminates for energy harvesting. McCarthy et al. [5] reviewed research on vibration energy harvesting from vibrations excited by aerodynamic flutter.

Lumped-parameter models of piezoelectric vibration energy harvesters are investigated in Refs. [6–14]. duToit et al. [8] derived closed-form expressions for the dynamic response and power generated by devices with sinusoidal base excitation. Erturk and Inman [9] assess modeling techniques for piezoelectric vibration energy harvesters. Correction factors for lumped-parameter modeling of piezoelectric vibration energy harvesters are given in Ref. [10]. Adhikari et al. [11] studied

* Corresponding author.
E-mail address: chris.cooley@siu.edu (C.G. Cooley).

https://doi.org/10.1016/j.jsv.2017.11.028

energy harvesting from the random vibrations of a piezoelectric stack device. Renno et al. [12] used the Karuch-Kuhn-Tucker method to optimize the power generated by piezoelectric stack devices. They considered electrical circuits with resistance only and with resistance and inductance. Circuits with inductance outperform those with only resistance. Seuaciuc-Osorio and Daqaq [13] analyzed the response of piezoelectric stack devices that are dynamically excited by base excitations with time-varying frequency. Xiao et al. [14] analyzed the power harvested by devices with multiple proof masses that have a piezoelectric elements between each mass.

Many energy harvesting devices consist of cantilevered structures with layers of piezoelectric material. Shahruz [15,16] studied energy harvesting from an array of cantilevered beams. These devices have broadband frequency energy harvesting ability. Erturk and Inman [17] analytically studied the vibration of cantilevered beam piezoelectric energy harvesters using Euler-Bernoulli beam theory. They derived closed-form solutions for the response due to sinusoidal base excitation. Erturk et al. [18] developed an “L” shaped piezoelectric beam vibration energy harvester. Erturk and Inman [19] analyzed and experimentally validated the power harvested by cantilevered piezoelectric beam vibration energy harvesters with bimorph configurations. They investigated independent, series, and parallel circuit connections of the two separate piezoelectric layers. Bonello and Rafique [20] analyzed piezoelectric beam vibration energy harvesters using analytical modal analysis and the dynamic stiffness method. Karami and Inman [21] presented a “zig zag” design to lower the device's natural frequencies so that optimal power can be harvested from low frequency excitations. Bryant and Garcia [22] predicted the power harvested by a piezoelectric energy harvester driven by aeroelastic flutter vibrations. Abdelkefi et al. [23] proposed a cantilevered unimorph piezoelectric beam with an asymmetrically mounted two-mass system attached to its free end. This system can harvest 30 percent more power than a device with symmetric masses because of additional torsional coupling that occurs from the asymmetry. Gu and Livermore [24] studied piezoelectric beam energy harvesters excited by low frequency impacts. Wu et al. [25] developed a compact piezoelectric beam device that consists of a large external beam that has another smaller piezoelectric beam within it.

Nonlinear vibration energy harvesters have wider frequency bandwidths than linear devices. Stanton et al. [26] developed analytical models for the dynamic response of bistable nonlinear vibration energy harvesters. Stanton et al. [27] investigated the influence of quadratic damping on nonlinear vibration energy harvesters. Masana and Daqaq [28] investigated the nonlinear vibrations of axially loaded vibration energy harvesters. Masana and Daqaq [29] analytically and experimentally studied super-harmonic resonance in nonlinear vibration energy harvesters. Cotton et al. [30] showed that nonlinear vibration harvesters have large frequency bandwidths that allow more energy to be harvested from the host system. Harne and Wang [31] analyzed piezoelectric beam vibration energy harvesters with a compliant axial support. Bibo et al. [32] developed an aero-electromechanical model to study the nonlinear response of a cantilevered beam piezoelectric energy harvester due to base excitation and aerodynamic forcing.

Comparatively few piezoelectric vibration energy harvesters are intended for spinning systems. Yeatman [33] analyzed the energy harvested by devices with rotating and gyroscopic proof masses. Gu and Livermore [34] developed a piezoelectric beam device with a tip mass for harvesting energy from rotating systems. The natural frequency of this device increases with increasing speed due to the tension stiffness that develops in the beam due to its constant rotation. Later, the same authors developed a compact device based on this configuration for harvesting energy from rotating systems [35]. Khameneifar et al. [36] analyzed the vibration of piezoelectric bimorph cantilever beam devices with a tip mass that harvest energy from rotating host systems. These authors designed, fabricated, and tested a prototype device in Ref. [37]. Hsu et al. [38] analyzed the power harvested by rotating piezoelectric beam devices using the finite element method. Roundy and Tola [39] developed an off-set pendulum vibration energy harvester for rotating systems like vehicle wheels, where the rotation axis of the system is perpendicular to the earth's gravitational field. Guan and Liao [40] developed a radially inward mounted piezoelectric beam vibration energy harvester for rotating systems. All of the devices referenced above harvest energy from the rotations of the host system. Cooley and Chai [41] investigated energy harvesting from the vibrations of rotating host systems using typical electromagnetic and piezoelectric devices. The device proposed in this work harvests energy from the vibrations of the rotating host system.

In this work, the vibration properties of a rotating piezoelectric vibration energy harvesting device are investigated using an analytical model. The governing equations of motion for the electromechanically coupled system are derived using Newtonian mechanics and Kirchhoff's circuit laws. The device's eigenvalue problem is used to investigate the free vibration behavior for devices with identical (tuned) and nonidentical (mistuned) piezoelectric support structures. The device's natural frequencies and decay (or growth) rates are calculated for a wide range of rotation speeds, including at extremely high speeds where the device has unstable vibrations. An analytical proof is presented for the modal properties of tuned devices. The vibration behavior is investigated for varying load resistances, including the limiting cases of open and closed circuit conditions.

2. Analysis

2.1. Analytical model

A schematic of the piezoelectric vibration energy harvester is shown in Fig. 1. The system consists of a proof mass M that is supported by two orthogonal piezoelectric support structures. The device attaches to a host system (like a rotor or vehicle wheel) that rotates at constant speed Ω. During the device's operation, motion of the proof mass deforms the piezoelectric