Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

An efficient piezoelectric energy harvester with frequency self-tuning

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ARTICLE INFO

Article history:
Received 14 July 2016
Received in revised form
10 February 2017
Accepted 14 February 2017

Keywords:
Energy harvesting
Piezoelectric materials
Frequency self-tuning
Transient vibration
Iteration numerical method

ABSTRACT

A beam energy harvester made of an aluminum substrate surface bonded with piezoelectric patches and a stack actuator is developed to achieve an efficient energy harvesting technology with a new developed frequency self-tuning process. To accomplish the self-tuning process, an adjustable axial force applied to the energy harvester is generated by the piezoelectric stack actuator. The stack actuator is controlled by a charged voltage on a small tuning capacitor, which is connected to and charged by the harvester. The function of the stack actuator is to automatically tune the natural frequency of the harvester to match the major exciting frequency of the ambient vibration through the tuning capacitor. To describe the energy harvesting and the self-tuning process, an iteration numerical method is developed to solve the dynamic response of the harvester and the generated electric charge. Effects of the piezoelectric patch sizes on the energy harvester's power generation are conducted and discussed. Research findings show that the self-tuning process significantly increases the power output from the harvester by more than 26 times compared to the one without the developed tuning process. Furthermore, the finite element method (FEM) is employed to verify the effectiveness of the proposed self-tuning method.

1. Introduction

Energy harvesting is a process that collects energy from ambient sources, such as dynamic motions of mechanical structures, wind and waves, and converts the ambient vibrations to useful power, which can be stored for powering the electronic devices. This field has attracted much attention [1–3] over the past few decades due to the increasing demands of portable electronic devices and wireless sensor networks. Self-powering of those devices can be realized by effective harvesting energy from ambient sources, thus the small electronics devices will no longer be restricted by the limited life span of electrochemical batteries.

There are many ways for energy harvesting processes, such as applications of electrostatic generators [4], electromagnetic conductors [5] and piezoelectric harvesters [6]. Owing to their ability to efficiently transform mechanical strain energy into electrical charge, high power generation density [7,8] and flexible shape design that can fit in different structures for various applications, piezoelectric vibration-to-electricity converters have been widely employed in transducers for energy harvesting applications [9–14].

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http://dx.doi.org/10.1016/j.jsv.2017.02.036

Please cite this article as: Y. Cheng, et al., An efficient piezoelectric energy harvester with frequency self-tuning, *Journal of Sound and Vibration* (2017), http://dx.doi.org/10.1016/j.jsv.2017.02.036

In recent years, the piezoelectric energy harvesting has been studied and realized by different approaches. Priya [15] presented a prototype piezoelectric windmill consisting of ten piezoelectric bimorph transducers, which can convert air currents into electrical energy. Mateu and Moll [16] proposed an optimal design of bending beam structures of shoe inserts based on their former study [17]. They examined the combination of materials as well as the coupling mode and shape of the harvester, and concluded that the maximum power output comes with a heterogeneous unimorph subjected to a distributed load applied to a simply supported triangular beam. Rather than the conventional beam energy harvesters, Erturk et al. [18] employed a novel L-shaped beam-mass structure as a broadband energy harvesting system. This L-shaped structure can be tuned to make the first two natural frequencies relatively close to each other, which enables it to harvest energy from random or varying-frequency excitations. A piezoelectric coupled cantilever structure attached by a proof mass was developed by Xie et al. [19] to achieve efficient energy harvesting from high-rise buildings. By investigating the dimensions and locations of the piezoelectric patch, as well as the mass and radius of the attached mass, they obtained an optimal geometry of the proposed structure for achieving an energy harvesting efficiency as high as 28%. Ali et al. [20] designed a single piezoelectric energy harvester embedded inside a bridge deck to generate energy from the motions of vehicles. The converted energy can be useful for wireless sensor networks for structural health monitoring of bridges by reducing or even eliminating the need for battery recharging.

To date, there have had generally two methods to increase the operation range of the energy harvesters [21], hence, enhancing the efficiency of energy harvesting processes. The first is to widen the bandwidth in the spectrum of the generator by combining with other equipment, such as non-linear springs, dampers and other oscillators. Cornwell et al. [22] proposed a tuned auxiliary structure consisting of a mechanical fixture and a PZT element, which can be attached to any vibrating system, to significantly improve the power generation. Xue et al. [23] presented an approach for designing broadband piezoelectric harvesters by integrating multiple piezoelectric bimorphs with different aspect ratios into a system. It shows that the bandwidth of a generator can be widened by connecting piezoelectric bimorphs in parallel and in series. The second method is to tune the resonant frequency of a harvester to match the major frequency of ambient vibrations. Wu et al. [24,25] have proven that, for a piezoelectric coupled beam under a periodical dynamic point force, higher power-harvesting efficiency can be obtained with an optimal design of a piezoelectric layer at resonance. However, the ambient excitation frequency is usually unknown and variable.

Many works have focused on developing a tuning mechanism [26–28]. Roundy and Zhang [29] analyzed the feasibility of vibration-based generators with an active tuning process. Due to the continuously power consumption, the energy required to actively tune the device could not be compensated by the harvester. It is noted that the energy consumed by the tuning mechanism can never exceed the increase in the output power resulting from the frequency tuning [21]. Therefore, the passive tuning has an advantage over the active tuning because the tuning process is switched off once the resonant frequency matches the ambient vibration frequency. A frequency self-tuning scheme for broadband vibration energy harvesting was presented by Lallart et al. [30]. It has been validated that the exposed technique allows a fine tuning of the resonant frequency on a wide range. Inspired by the work, Eichhorn et al. [31] investigated a piezoelectric energy-harvesting system, which is able to self-tune its resonant frequency in an energy-autonomous way. By setting the control unit set every 22 s for frequency adjustments, a large power surplus was obtained. Through the use of a predefined look-up table, the power consumption of the tuning procedure is reduced. A passively self-tuning energy harvester for rotating applications was studied by Gu and Livermore [32,33]. They exploited the centrifugal force of a rotational system to provide a tensile stress to adjust the resonant frequency of the harvester.

From previous studies, it can be seen that the frequency tunable energy harvesting has been approached in various methods. Nevertheless, in applications of amplifiers and complex electric circuits, the power consumption in deteriorating the tuning process cannot be avoided and hence considerably decreases the efficiency of energy harvesting. This research aims at accomplishing an efficient energy harvesting with a new developed self-tuning process. A simply supported beam energy harvester coupled with piezoelectric patches and stack actuators subjected to a dynamic load is proposed. Since the resonant frequency of the vibrating beam can be adjusted by controlling the compressive axial loads [34], the self-tuning process of the harvester is realized by the piezoelectric stack actuator. The piezoelectric stack actuator is controlled by a tuning capacitor, which is charged by the piezoelectric patches, to realize the self-tuning of the harvester. It is noted that the presented self-tuning scheme is a closed-loop feedback tuning process, and does not require any external energy input. Therefore, it can realize high efficient energy harvesting by transforming kinetic energy from ambient vibrations to the electric power.

2. Methodology and modeling

The proposed energy harvesting system consists of a simply supported beam energy harvester coupled with piezoelectric patches, a filtering circuit, a tuning circuit and a piezoelectric stack actuator as shown in Fig. 1. The detailed dimensions of the harvester are given in Section 2.1. The dynamic deformation of the beam harvester is induced by a dynamic loading, and hence an electrical charge is generated on the piezoelectric patches attached on the host beam to convert the input mechanical energy to the electrical energy. To realize the self-tuning process of the harvester, the generated voltage from the piezoelectric patches is also used to quickly charge a small tuning capacitor through a diode bridge circuit. The charged voltage on the tuning capacitor is applied to the piezoelectric stack actuator to generate an axial force on the beam harvester so as to tune the harvester automatically. By changing the layout of the piezoelectric stack actuator shown in Fig. 1(b), a tensile/compressive axial load can be applied to the beam harvester so as to increase/reduce its natural frequency. It is noted that with an increase in the charged voltage on the tuning capacitor, the axial force generated by the stack actuator is

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