Mechanical Systems and Signal Processing 112 (2018) 305–318

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A low-frequency, wideband quad-stable energy harvester using combined nonlinearity and frequency up-conversion by cantilever-surface contact

Chen Wang [a,b], Qichang Zhang [a], Wei Wang [a,c,*], Jingjing Feng [d]

[a] *Tianjin Key Laboratory of Nonlinear Dynamics and Control, Department of Mechanics, School of Mechanical Engineering, Tianjin University, Tianjin 300350, China*
[b] *Department of Civil and Environment Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China*
[c] *School of Computing and Engineering, Huddersfield University, HD 4, United Kingdom*
[d] *Tianjin Key Laboratory for Advanced Mechatronic System Design and Intelligent Control, School of Mechanical Engineering, Tianjin University of Technology, Tianjin 300384, China*

ARTICLE INFO

Article history:
Received 2 November 2017
Received in revised form 6 February 2018
Accepted 15 April 2018

Keywords:
Nonlinear energy harvesting
Multi-stability
Nonlinear cantilever-surface spring

ABSTRACT

This paper proposes models and experiments of a wideband piezoelectric vibration energy harvester with a quadruple-well potential induced by the combined nonlinearity of cantilever-surface contact and magnetoelasticity. The cantilever-surface contact introduces frequency up-conversion mechanism into the present energy harvester and provides favorable mechanical properties such as minimal moving parts, low frictional losses and high shock resistance. The magnetoelasticity, combined with the cantilever-surface contact, can make the present energy harvester exhibit multi-stability, ranging from mono-stability to quad-stability. The formation mechanism of this multi-stability is investigated by a static bifurcation analysis to the harvester's mathematical model. Dynamic responses of the present energy harvester with a quadruple-well potential are explored by numerical simulations and validated by experiments. The results show that the combined nonlinearity can not only improve the efficiency of electrical power transfer under low intensity excitations, but also extend the wide operating band of harvester to low frequencies.

1. Introduction

Energy harvesting from ambient vibration via piezoelectric transducer has drawn the attention of many researchers as a means of powering small sensors and MEMS [1–3]. In the last few years, various energy harvesters, which operate based on the principle of resonance and, typically, use linear piezoelectric cantilevers with tip mass, have been exploited to generate energy. Since the ambient vibrations in our surroundings generally take place at low frequencies [4]; machine motion and human based applications are also characterized by low frequencies and large amplitudes [5], it is necessary to confine the operating frequencies of the resonance-based harvesters in low frequency range. However, the harvesters with low resonant frequency cannot generate power efficiently, especially at low frequencies below 30 Hz [6]. One reason is the generated power of a vibration energy harvester is proportional to the cube of the vibration frequency [7]. Another lies in the fact that,

---

* Corresponding author at: Tianjin Key Laboratory of Nonlinear Dynamics and Control, Department of Mechanics, School of Mechanical Engineering, Tianjin University, Tianjin 300350, China.

E-mail address: wangweifrancis@aliyun.com (W. Wang).

https://doi.org/10.1016/j.ymssp.2018.04.027
0888-3270/© 2018 Elsevier Ltd. All rights reserved.

to resonate at lower frequencies, increasingly compliant springs are required, which consumes extra space to permit large mechanical displacement and results in a decrease in power density.

One strategy to improve the harvesting efficiency in low-frequency applications is frequency up-conversion. In a frequency up-converted harvester, a low-frequency oscillator is utilized to couple the external low-frequency excitation and transfers its kinetic energy to a high-frequency transducer. Consequently, the transducer operates at its own frequency, regardless of the external excitation [8]. Mechanical plucking and impact are the common methods to implement frequency up-conversion. For instance, Refs. [9,10] presented a mechanical plucking-based knee-joint energy harvester, in which the frequency up-conversion is obtained by deflecting the piezoelectric bimorph via a plectrum. Frequency up-converted energy harvesters using mechanical impact to deflect the piezoelectric bimorphs were investigated in [4,8,11–14]. Further strategies for harvesting energy on piezoelectric beams with up-conversion techniques were presented in [15,16], and the examples on the MEMS scale are reported in [17,18]. However, mechanical plucking and impact are prone to mechanical wear out, and may lead to chipping and damage to the piezoelectric ceramics [19]. To avoid physical impact, non-impact magnetic interaction is employed, such as in the piezoelectric windmill [20] or the wearable systems presented in [19,21–23], where the frequency up-conversion is implemented by using magnets to pluck piezoelectric beams. The magnetic interaction method can improve the harvesting efficiency at low frequencies, but requires extra space and large accelerations to drive the low-frequency actuator [23]. Therefore, new frequency up-conversion mechanism with the characteristics of low friction, low space consumption, low acceleration driven and against excessive deformation on piezoelectric transducer is still needed for harvesting energy at low frequencies.

In addition to the study of frequency up-conversion mechanisms, utilizing nonlinearity in frequency-increased harvesters to extend the operating bandwidth has received great research interest. Particularly, frequency-increased harvesters with mono-stable hardening induced by stoppers or large deformations have been intensively investigated [4,11,24–27]. The research results have indicated that, when carefully introduced, the mono-stable hardening can enhance the transduction of harvesters under broadband excitations. However, such hardening type harvesters can only extend their working bands to high frequencies. An actuator with low stiffness and large seismic mass is still needed to couple the low-frequency excitations, which leads to an extra space consumption. To address this issue, mono-stable softening [28,29] and bi-stable nonlinearity [30,31] are introduced into the frequency up-conversion technology. However, those methods need large accelerations to resonant at low frequencies, especially the bi-stable one that has a high threshold of interwell motions. Several theoretical and experimental studies show that more stable states in multi-stable nonlinearity can be beneficial to harvest energy from low-intensity vibrations over a wide range of low frequencies [32–34]. A multi-stable nonlinearity (more than two stable states) coupled frequency up-conversion technology may be an efficient method for energy harvesting from low-intensity, low-frequency vibration source.

This paper presents a wideband, frequency up-converting piezoelectric vibration energy harvester with a quadruple-well potential induced by the combined nonlinearities of cantilever-surface contact and magnetoelasticity. The cantilever-surface contact can introduce frequency up-conversion with favorable mechanical properties such as minimal moving parts, low friction and against excessive deformation on cantilever. The quad-stable nonlinearity can improve the efficiency of electrical power transfer under low intensity excitations and extend the wide operating band of harvester to low frequencies. The paper is organized as follows. Section 2 describes the working principle of the quad-stable oscillator and the formation mechanism of the quad-stability. The mathematical model of the harvester and its numerical solution are presented in Section 3. The experimental demonstrations of the harvester's high power density and wideband performance are made in Section 4. Conclusions are drawn in the final section.

2. Low-frequency wideband quad-stable oscillator via combined nonlinearities of cantilever-surface contact and magnetoelasticity

In the proposed energy harvester, a low-frequency wideband quad-stable oscillator is employed. This oscillator comprises two parts: a nonlinear spring based on the cantilever-surface contact, and a group of magnets that provide magnetoelasticity to the spring. Through a proper combination of those two parts, this oscillator not only could exhibit a quad-stable nonlinearity, but also has the favorable mechanical properties of low friction (the relative sliding between cantilever and surface is very small), long fatigue lifetime (the oscillator only has one moving part) and prevention of excessive deflection (the surfaces can protect the cantilever from yielding). This section introduces the working principle of the quad-stable oscillator and the formation mechanism of the quad-stability, respectively.

2.1. Nonlinear spring based on cantilever-surface contact

To harvest vibration energy at low frequencies, a cantilever beam and two symmetric surfaces with given geometry are employed, as shown in Fig. 1. This structure is a modification of Timoshenko's design in which the cantilever wraps along the surfaces when it bends [35,36]. The purpose of this modification is to insure the cantilever-surface contact occurs immediately after the cantilever deformation (to prevent the impact between cantilever and surfaces). Since the curvature radius of the cantilever will be smallest at the root and largest at the tip when a force acts on the cantilever tip, the curvature radius of the contact surface in this modification should have a reverse trend. In other words, the second derivative of the contact