Sensors and Actuators A 234 (2015) 17–22

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Magnetic coupling between folded cantilevers for high-efficiency broadband energy harvesting

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ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form 25 July 2015
Accepted 15 August 2015
Available online 24 August 2015

Keywords:
Energy harvesting
Non-contact magnetic coupling
Frequency detuning
Multi-cantilevers
Broad bandwidth

ABSTRACT

In this paper, we proposed and characterized a high-efficiency piezoelectric energy harvester based on a non-contact coupling technique. The proposed design takes advantage of a frequency detuning technique and multi-cantilevers to enhance its power generation efficiency at ambient excitation. The energy harvester consists of two folded piezoelectric cantilevers with different resonance frequencies. A piezoelectric cantilever with a low resonance frequency (L-part) is coupled with another piezoelectric cantilever with a high resonance frequency (H-part) by a non-contact magnetic force. The output characteristic of each piezoelectric cantilever is improved using the magnetic coupling technique and a broad bandwidth is also realized under environmental vibrations. A feasibility of the fabricated energy harvester is experimentally confirmed to demonstrate the power generation capability in practical applications. With a load resistance of 50 kΩ, a maximum output power of 20 μW and an average power of 7.1 μW are achieved with the energy harvester, thus making it a suitable power supply for sensor nodes in wireless sensor network applications.

1. Introduction

As the demand for real-time information communication increases, wireless sensor network (WSN) technology plays a key role in various fields, owing to its advanced continuous detection and information monitoring capability [1–3]. However, because batteries employed in commercial WSNs have a limited life, the frequent replacement of batteries results in significant maintenance costs and considerable inconvenience. To overcome this limitation, various energy harvesters that can scavenge unlimited ambient energy to power the sensor nodes in WSNs have been developed as substitutes for batteries [4–6].

Vibration energy exists pervasively in our living environment and is therefore considered as the main power source for energy harvesting. Although several mechanisms have been designed for harvesting vibrational energy, piezoelectric energy harvesting has become one of the most effective methods to scavenge energy from environmental vibrations owing to its power efficiency and favorable miniaturization ability [7–10]. However, ambient vibration often spans a broad low-frequency range, i.e., 0–40 Hz [11]. Because of the frequency mismatch between the high resonant frequency (∼hundreds or thousands of Hertz) of many vibration energy harvesters and the ambient low-frequency vibrations, power is generated inefficiently [12]. To overcome the frequency gap between the environmental vibration and energy harvesters, various designs based on the frequency up-conversion concept have been developed to improve the power generation efficiency [13,14]. For example, Liu et al. [15] proposed a piezoelectric energy harvesting device based on a frequency up-conversion cantilever stopper to collect energy from low-frequency vibrations. A frequency up-converted piezoelectric energy harvester using mechanical impact is introduced by Halim et al. [16]. Tang and Li [17] presented a frequency up-converted energy harvester with a two-stage vibratory structure. Based on this concept, low-frequency vibration energy can be scavenged by the above designs. Unfortunately, the performance of this type of energy harvester is significantly dependent on the driving element, which is designed for harvesting ambient low-frequency vibrations. The narrow bandwidth of the driving part largely confines the power generation efficiency under the broad range of vibrations in the environment. Furthermore, the physical impact method reduces the reliability and service life of the energy harvester. Additionally, the large frequency gap between a driving part and a power generation part influences to the efficiency in power generation. Aiming for a broad bandwidth to match the environmental vibration, Shahruz [18] presented an energy harvester that consists of 13 piezoelectric cantilevers with various resonant frequencies to provide voltage response over a frequency range of 50–62 Hz. Microelectromechanical system (MEMS)-based piezoelectric cantilever array for vibration energy harvesting that covers a bandwidth of 226–234 Hz was developed by Liu et al. [19]. How-

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http://dx.doi.org/10.1016/j.sna.2015.08.009

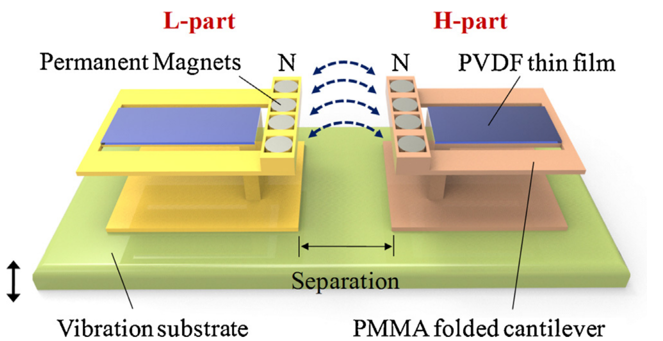

Fig. 1. The designed high-efficiency broadband energy harvester with magnetically coupled folded cantilevers.

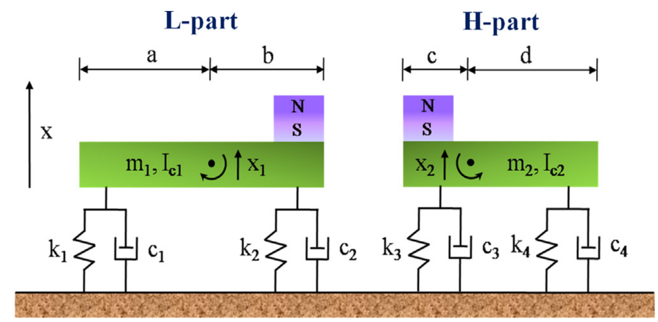

Fig. 2. The dynamic model of the designed energy harvester.

ever, for such multi-cantilever (or cantilever array)-based energy harvesters, not only does the narrow response bandwidth of each cantilever restrict the total frequency range of the device, but the numerous cantilevers also decrease space efficiency. Moreover, the frequency-selecting mechanism (only one cantilever can achieve resonance for each excitation frequency) leads to low power generation efficiency when the excitations cover a broad frequency range. Frequency detuning is also one of useful techniques to cover wide ambient frequency range in energy harvester applications. This is realized by adjusting various parameters such as the applied force or the stiffness. Vijayan et al. [20] developed a non-linear energy harvesting method by carefully detuning the frequencies of coupled impacting beams. Neumeyer et al. [21] discussed the possibility of applying the frequency detuning to energy harvesting application.

In this study, a design of an energy harvester based on magnetically coupled folded cantilevers is proposed, which can scavenge environmental vibration energy with high efficiency in a broad frequency range. The proposed energy harvester takes an advantage of the frequency detuning technique and multi-cantilevers to enhance its power generation efficiency for ambient low-frequency excitation.

2. Design and modelling

A schematic of the design is shown in Fig. 1. It can be seen that one piezoelectric energy harvester with a low resonant frequency (L-part) is coupled with the other piezoelectric energy harvester with a high resonant frequency (H-part) through a non-contact magnetic force. To provide the non-contact magnetic force, eight identical permanent NdFeB magnets are mounted on the ends of the cantilevers with the same magnetic pole arrangements. A thin polyvinylidene fluoride (PVDF) film is uniformly attached on the cantilevers to generate power when stress is accumulated on the cantilevers during vibrations. In order to allow both parts to possess their own high-efficiency range in the ordinary range of ambient vibrations in normal conditions, the resonant frequencies of both L-part and H-part are designed within a range of 0–40 Hz (L-part: 18 Hz, H-part: 32 Hz, the detailed process of resonant frequency optimization can be found in Supplementary materials) by adjusting the dimension parameters (i.e., the thickness and length of the cantilever). Moreover, owing to the effect of magnetic coupling, the two parts can enhance each other's output performance even if the ambient excitations deviate from the original resonant zones of the cantilevers. This mechanism is illustrated in detail as the following reasons: (a) When the energy harvester is vibrated in a low-frequency range, the L-part can sufficiently generate power because the ambient excitation matches with its own resonant frequency, meanwhile driving the H-part to produce power with a high efficiency through the non-contact magnetic force. (b) On the other hand, when the ambient vibration frequency is close to the high-efficiency zone of the H-part (near its natural frequency), the H-part can also promote the deformation/stress of the L-part owing to the non-contact magnetic force; this contributes to the output of the L-part. (c) The variable magnetic forces during the vibration control the resonant frequencies of the two parts in a certain small range due to the frequency detuning mechanism, which allows a broader bandwidth of the energy harvester at ambient conditions. It is noted that the gap between the two resonant frequencies of L-part and H-part will affect the coupling efficiency. If the frequency gap is too large, the coupling efficiency would be weak. On the other hand, the total bandwidth would be narrowed if the two resonant frequencies approaches too close with each other. Aiming for a wide bandwidth and high power generation efficiency, 18 Hz and 32 Hz are utilized as the resonant frequencies for L-part and H-part, respectively. The resonant frequency optimization for the two parts is discussed in the Supplementary materials. Considering that the separation between the L-part and H-part influences the magnetic coupling effect, the separation should be maintained with an optimized distance to achieve maximum output. In addition, folded cantilever structures are designed to further enhance power generation and space efficiency.

In order to investigate the characteristics of the designed energy harvester, a simplified dynamic model is established. As shown in Fig. 2, each part of the designed energy harvester can be modeled as a damped two degree-of-freedom (DOF) mass-spring system. Supported by damped springs with spring constant k_i and damping coefficient c_i (i = 1–4), the equation of motion for the complete model can be expressed as:

$$\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & I_{c1} & 0 & 0 \\ 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & I_{c2} \end{bmatrix} \begin{bmatrix} \ddot{x}_1 \\ \ddot{\theta}_1 \\ \ddot{x}_2 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} c_1 & 0 & 0 & 0 \\ 0 & c_2 & 0 & 0 \\ 0 & 0 & c_3 & 0 \\ 0 & 0 & 0 & c_4 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{\theta}_1 \\ \dot{x}_2 \\ \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} k_1+k_2 & -(k_1a-k_2b) & 0 & 0 \\ -(k_1a-k_2b) & k_1a^2+k_2b^2 & 0 & 0 \\ 0 & 0 & k_3+k_4 & -(k_4d-k_3c) \\ 0 & 0 & -(k_4d-k_3c) & k_4d^2+k_3c^2 \end{bmatrix} \begin{bmatrix} x_1 \\ \theta_1 \\ x_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} F_{G1}+F_{\text{mag}} \\ -F_{\text{mag}}b \\ F_{G2}-F_{\text{mag}} \\ F_{\text{mag}}c \end{bmatrix} \quad (1)$$

where m_j and I_{cj} (j = 1 and 2) are the mass and moment of inertia around the centroid of each cantilever, respectively. F_{Gj} is the