Energy Conversion and Management 168 (2018) 454–466

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A multimodal hybrid energy harvester based on piezoelectric-electromagnetic mechanisms for low-frequency ambient vibrations

R.M. Toyabur, M Salauddin, Hyunok Cho, Jae Y. Park*

Department of Electronic Engineering, Kwangwoon University, Seoul 139-701, Republic of Korea

A R T I C L E I N F O

Keywords:
Hybrid energy harvester
Multi-degree-of-freedom
Low-frequency vibrations
Piezoelectric
Electromagnetic

A B S T R A C T

In this paper, we proposed and experimentally validated a vibration-based multimodal hybrid piezoelectric–electromagnetic energy harvester having multiple mechanical degrees-of-freedom. This multimodal hybrid energy harvester (MHEH) has a unique design, which helps it to achieve multiple close resonant modes of vibration in a certain frequency range. Using a low-spring-stiffness material (polyacrylate) as a substrate assists MHEH in reducing the higher resonant frequencies into a low frequency range. The two combined conversion mechanisms (piezoelectric–electromagnetic) are exploited to obtain higher output power from low input accelerations at ambient vibrations. The finite element method simulation model is employed to predict and optimize the mode shapes of the proposed MHEH for different vibration modes. The simulation and experimental result imply that the proposed MHEH can operate at four resonant modes of vibration in the range of 12–22 Hz, which are concentrated around 12, 15, 17, and 22 Hz. An MHEH prototype is fabricated, where four lead-zirconate-titanate elements are used as piezoelectric materials, and NdFeB magnets with conductive coils are used as electromagnetic parts in the same system. Here, a single piezoelectric generator can produce a maximum of 250.23 μW of power across an optimum load of 90 KΩ at the 3rd resonant mode (17 Hz) under 0.4 g (3.92 ms^{-2}) acceleration. On the other hand, a single electromagnetic generator can deliver a maximum power of 244.17 μW to a 10 Ω optimum load under the same conditions. Meanwhile, all eight generators of the MHEH operate simultaneously at their respective resonant frequencies.

1. Introduction

Recently, harvesting energy from mechanical vibration has drawn significant attention due to its ubiquitous existence in the environment and perennial sources [1–3]. Many efforts have been made to research and develop efficient vibration energy harvesters (VEHs) based on various energy conversion mechanisms, such as electromagnetic (EM) [4], electrostatic [5], piezoelectric (PE) [6], thermoelectric [7], and triboelectric [8] mechanisms. Of these, PE and EM mechanisms are considered best suited for generating energy from mechanical vibrations [9,10]. The energy harvested from ambient mechanical vibrations can be used to power many interesting applications, including ultra-low power electronic devices, autonomous wireless sensor networks, biomedical applications, wearable electronic devices, and remote hostile environment sensors [11–14]. However, most conventional VEHs comprise single-degree-of-freedom (SDOF) models and perform well at a single resonant frequency, which makes them efficient for a narrow operating frequency bandwidth [15]. When the external operating frequencies are shifted away from the resonant frequency, the performance of the harvester degrades dramatically [16]. Moreover, the resonant frequency of the VEH increases sharply when the harvester size is reduced. In contrast, most practical vibration sources around us are random, time-varying, and low-frequency. Besides, the power (*P*) generated by a low-frequency (ω) resonant generator decreases dramatically because of the relation $P \propto \omega^3$ and is too low to be utilized [17]. Therefore, researchers are mainly concerned with scavenging energy effectively from low-frequency vibration sources.

Several solutions have been proposed so far to improve VEH performance at a lower frequency range, including nonlinear spring stiffness [18,19], generator array [20–22], magnetic coupling [23–26], active/passive tuning [27–29], mechanical impact [30,31], and hybrid conversion [32,33]. However, these proposed energy harvesters have some limitations, such as having a single dominant frequency or being effective in a continuous higher frequency range. To generate energy from wide-range vibration frequency sources, Chew and Li [34] reported a PE energy harvester formed of multiple end-to-end connected PE beams. The resonant frequencies of the harvester for different numbers of beams varied from 100 to 1000 Hz. Ferrari et al. [35]

* Corresponding author.
E-mail address: jaepark@kw.ac.kr (J.Y. Park).

https://doi.org/10.1016/j.enconman.2018.05.018
Received 12 April 2018; Received in revised form 1 May 2018; Accepted 4 May 2018
0196-8904/

proposed an array-type energy harvester composed of three PE bimorphs, whose fundamental resonant frequencies were about 113, 183, and 281 Hz. Liu et al. [36] reported a multiple-vibration-mode EM energy harvester for three-dimensional (3D) excitation, with three resonant modes of 1285, 1470, and 1550 Hz. Furthermore, Yang et al. [37] designed a PE generator with a nonlinear spring oscillator to harvest energy from multiple frequency vibration sources; the resonant frequencies of the proposed harvester were 89, 104, and 160 Hz. In recent studies on energy harvesting, hybrid energy harvesting technology has been introduced. Tadesse et al. [38] represented a multimodal hybrid VEH using EM and PE transduction mechanisms; the reported harvester had two resonant modes of 20 and 300 Hz. Most of the multiple-mode VEHs proposed so far have higher resonant frequencies and the high-order resonant modes are far away from the first resonant mode. These phenomena limit their applicability in some ambient vibration source applications, such as a low frequency range below 30 Hz.

In this article, a hybrid multi-degree-of-freedom (MDOF) VEH has been proposed to overcome the previously reported constraints and produce energy effectively from low-frequency vibrations. A novel MDOF system is developed to reduce the multiple high-mode resonant frequencies to ambient frequency range as well as increasing the bandwidth of the MHEH. The paper is organized as follows: In Section 2, the proposed design and working principle are explained. In Section 3, the proposed MHEH is modeled by lumped parameter model to predict the output behavior of a single secondary hybrid system. Subsequently, finite element method (FEM) is utilized to comprehend the mode shape of corresponding eigenfrequencies of the proposed hybrid energy harvester. The prototype fabrication and experimental setups are described in Section 4. The experimental results of the harvester and comparison with analytical results are presented in Section 5. The output interface and application of the proposed MHEH are demonstrated in Section 6. Finally, the conclusions and the future work are presented in Section 7.

2. Design and working principle

To generate electrical energy from the input mechanical excitation, the proposed energy harvester employs a hybrid conversion mechanism on an MDOF system. The MDOF system comprises multiple SDOF spring-mass systems, which help the harvester couple with the multiple higher-mode resonances. The schematic of the hybrid energy harvester is shown in Fig. 1, where the MDOF system consists of a primary beam clamped to both sides of the housing of the harvester and the four lateral symmetrical beams constitutes secondary systems. The secondary beams are like cantilever structure that connected to the primary beam. The piezoceramic elements are placed on the secondary cantilever beams to use the bending moment of the secondary beams. A proof mass is attached at the free end of each cantilever beam, while the constrained end of the secondary beams is engaged at the middle of the primary beam. As the secondary beams are symmetrical, the total weight of the four proof masses is concentrated in the middle of the primary beam. The base of secondary beam functions as a dynamic magnifier. The advantage of the dynamic magnifier is to magnify the deflection of secondary beams with respect to the primary beam [39]. The large deflection helps to induce higher mechanical strain on the piezoelectric elements in order to amplify the harvester output under small external vibrations.

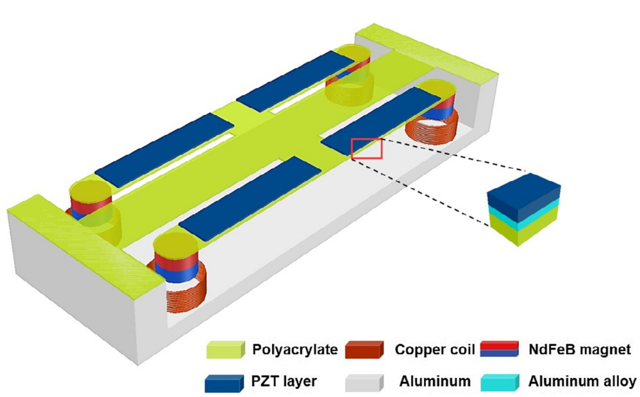

Fig. 1. 3D Schematic structure of the proposed multimodal hybrid energy harvester (MHEH).

The primary beam is made of a low-spring-stiffness material, which performs as a linear first-order transmission beam that vibrates transversely. The length of the primary beam is higher than the secondary beams. This geometric discrepancy results difference in spring stiffness of the secondary beams from primary beam. Additionally, the mass of the assumed dynamic magnifier is four times higher than the proof mass of the secondary beams. These properties change the mass matrices as well as the stiffness matrices of the secondary beams from primary beam. The difference between stiffness and mass matrices help the proposed MDOF system to shift the higher resonant frequencies to lower frequency range as well as close resonances to each other. When the external mechanical vibration is applied to the harvester base, the primary beam vibrates with respect to the base excitation and transfers oscillation to the symmetrical secondary beams. Under excitation, the system oscillates as a whole. Therefore, the overall system exhibit MDOF behavior.

Meanwhile, the EM generators are made of conductive coils placed below the axis of motion of the moving magnets, where the proof masses of the secondary beams are used as magnets. By placing the coils underneath the secondary beams, as well as utilizing the same mechanical motion of the cantilevers, the device volume remains same. Therefore, the EM generators follow the same frequency responses as PE generators. When the external mechanical vibrations are applied to the housing of the harvester, the magnetic proof mass follows the motion of the cantilever tip displacement and moves in and out of the coil, and the magnetic flux density changes through the coils. The relative movement of the magnets induces an electromotive force (emf) inside the conductive coils by Faraday's law of EM induction.

3. System modeling

3.1. Lumped parameter modeling

A vibration energy harvester is often modeled as a mass + spring + damper system. Here, the proposed hybrid energy harvester has modeled as the lumped parameter system by neglecting the distributed masses of the beams. Fig. 2 shows a schematic of the equivalent mechanical model of the hybrid energy harvester with primary and secondary system altogether. The proposed MHEH harvester could be presented as n-DOF electromechanical lumped parameter model where n = 5. In this equivalent model, the base of the harvester is subjected to an applied harmonic acceleration that changes the displacement of the base as well as the primary and secondary masses simultaneously.

For the proposed MHEH, the primary mass, m_1 could be reckoned as the summation of all secondary masses which concentrate at the midspan of the primary beam. In this approach, the primary system is composed of the primary effective mass m_1, a spring of effective stiffness k_1, and a damper of coefficient c_1. While, each secondary system is composed of individual effective mass ($m_2,m_3,...m_n$) spring stiffness ($k_2,k_3,...k_n$) and damper ($c_2,c_3,...c_n$). Here, the displacement of the base under external excitation is u_0. While, $u_2,u_3,...u_n$ are representing the displacements of the corresponding masses. For convenience, the relative displacement between the base, primary mass, and secondary mass during external excitation can be represented by

$$x = u_1-u_0,\ y_1 = u_2-u_1,\ y_2 = u_3-u_1,...,y_{n-1} = u_n-u_1,$$