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Magnetostrictive vibration energy harvesting using strain energy method

Saber Mohammadi*, Aboozar Esfandiari

Mechanical Engineering Department, Engineering Faculty, Razi University, 67149-67346 Kermanshah, Iran

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ABSTRACT

Harvesting energy has experienced a significant development in recent years, due to high demand on the mobile electrical devices and self powered systems. Thus, it is interesting to convert mechanical energy into suitable electrical energy using Magnetostrective materials. In this paper, a class of vibration energy harvester based on MsM (magnetostrictive material) is introduced and developed. The method used is strain energy that is straightforward and simple enough in comparison to others, such as finite element method. To analyze the MSM-based energy harvester, a beam equipped with Metglas 2605SC material wound by a pick-up coil has been considered. In order to power optimization a parametrical study has been performed and the results have been presented. The output power under base excitation can reach 9.4 mW which compete favorably with the piezoelectric vibration energy harvesters.

1. Introduction

Harvesting energy has experienced a significant development in recent years and has been a center of attention of researchers. Many aspects of energy have been studied in the literature by the researchers that some of them are mentioned at the following. An optimal sizing method is the key factor to achieve the technical and economical feasibility of the hybrid power systems that consist of different renewable generators, which produce electricity from renewable energy sources [1]. Thus, in order to optimal power allocation in hybrid systems, power pinch analysis technique can be applied to set a guidelines for proper sizing [2,3]. Also, small, portable, and lightweight power generation systems are currently in very high demand in commercial markets, due to a dramatic increase in the use of personal electronics and communication equipments. The batteries are the simple way to satisfy these demands; however, nonrechargeable batteries are becoming useless upon discharging, and rechargeable batteries require portable power generation units to recharge them. Although, the quality of the new lithium ion batteries with its micro-/nano-V_2O_5 electrode is high [4]. But, a portable small scale power generation system that can either replace batteries entirely or recharge them is of considerable interest. Furthermore, proposing of self-powered devices open new application possibilities for the systems with limited accessibility such as biomedical implants; structure embedded microsensors or safety monitoring devices. Harvesting devices generate usable electrical energy from environmental energy sources. Among these, vibration energy harvesting techniques can be classified as electromagnetic, electrostatic, piezoelectric, and magnetostrictive approaches. Electromagnetic energy harvesting is based on the relative motion of a conductor mass in a magnetic field, provided by a permanent magnet. Typically the mass is wound in a coil to form an inductor. Based on Faraday's Law, an AC voltage is induced by the relative motion between the mass and the pick-up coil. The electrostatic energy harvesting relies on the changing capacitance of the vibration-dependent variable capacitors whose electrodes are moveable related to each other and separated by a dielectric to form a capacitor. Mechanical motion can be converted into electrical energy by moving the electrodes related to each other [5]. Also, the state-of art in vibration energy harvesting for wireless, self-powered microsystems has been reviewed by Ref. [6]. The coupling factor of each mechanism was discussed and all the devices presented in the literature were summarized and classified in tables. Different conversion mechanisms have been investigated and evaluated by Ref. [7] that leading to optimized designs for both capacitive and piezoelectric converters. A power density of 70 mW/cm^3 has been achieved for the PZT converter. A design methodology and a prototype fabrication

* Corresponding author.
E-mail address: saberm7@yahoo.com (S. Mohammadi).

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device for linear micro-generators were developed by Ref. [8]. Also, a chip has been designed and tested to demonstrate the feasibility of operating a digital system from power generated by vibrations [9]. Design of miniature generators that capable of converting ambient vibration into electrical energy for powering of intelligent sensor systems has been described by Glynne-Jones et al. [10]. This generator has been tested on a car engine with an average produced power of 157 μW. With the growing use of sensors in various structural systems, the powering of these sensors will become a critical factor. With the technology of wireless communication and also low power consuming of electronic circuits, power generation from mechanical energy into electrical energy is now feasible [11]. An analytical expression for the optimal power flow from a piezoelectric device was derived, and an "energy harvesting" circuit was proposed in Ref. [12]. Also, thermoelectric and photovoltaic are the other phenomena to harvest ambient energy. Recently, some hybrid systems consist of photovoltaic–thermoelectric have been developed. Hybrid systems with different photovoltaic cells were studied, including crystalline silicon photovoltaic cell, silicon thin-film photovoltaic cell, polymer photovoltaic cell [13,14].

Harvesting energy using smart materials has become increasingly attractive over the last decade due to high demands on the portable micro-generator systems. Because of the bulky size and limited life-span of external chemical battery, the mobile devices need to be developed in order to self-powering of autonomous sensors. A promising approach to self-powering of WSN (Wireless Sensor Networks) is to harvest energy from ambient by the sensor. This energy that is typically lost or dissipated is therefore recovered and used to power the wireless sensor. Also, the advances in low power VLSI (Very Large Scale Integration) design have reduced the power requirements that enhance the feasibility of energy harvesting techniques. Smart materials such as piezoelectric and magnetostrictive are a class of materials that can be used for vibration energy conversion. Piezoelectric materials are probably the best developed and best understood of all smart materials. The piezoelectric-based approach converts the strain energy to electrical energy by direct piezoelectric effect. It is the most popular one among all these vibration-based methods because of reasonable electro-mechanical coupling coefficient, no bulky accessories, and feasibility of being deposited on substrates for MEMS (Micro-Electro-Mechanical Systems) applications. Recently, a new method of piezoelectric vibration energy harvesting called "SSHI" (Synchronized Switch Harvesting on Inductor) was developed. It adopted an electrical circuit containing an inductor and an electrical switch to maximize charge extraction from PZT, and could enhance the output power [15]. Also, mechanical energy can be converted into electric power using an escapement-based power regulation mechanism and piezoelectric energy conversion. In this system, the carbon nanotube yarns operate as mechanical springs and can be used to drive both electrical and mechanical loads [16]. The most remarkable characteristics of metallic glasses as well as their main technological applications are reviewed in Ref. [17]. Preliminary results from study of a magnetostrictive energy harvesting transducer have been presented by Staley and Flatau [18]. The magnetostrictive samples are the cylindrical rods of commercially available Terfenol-D and a new ductile Iron–Gallium alloy known as Galfenol. Terfenol-D/PZT/Terfenol-D composite harvester has been developed in which Terfenol-D has been used as a medium to provide large extensional strains in a PZT layer for energy harvesting [19]. In brief, piezoelectric vibration energy harvesting offers a straightforward and simple approach, whereby structural vibrations are directly converted into a voltage as output. However, other disadvantages such as depolarization and charge leakage also exist in PZT. Also, piezoelectric materials except for PVDF are very brittle and can not endure large strains. Due to the capacitive property, this method is capable of producing relatively high output voltage and low electrical currents.

MsMs which are a class of metallic compounds has been recently considered in applications of vibration energy harvesting. It utilizes Villari effect or magnetomechanical effect, where vibration induces MsM deformation, consequently a change in the magnetization of material produces. Upon dynamic or cyclic loading, this change in magnetization is converted into electrical energy using a pick-up coil surrounding the magnetostrictive layer according to Faraday's law. With development of these materials in the last decade, they have been increasingly applied in a wide variety of smart structures as actuators and sensors, However only a few attempts have been made to introduce MsMs in energy harvesting recently such as that in Refs. [20,21]. These researches proposed the feasibility of using amorphous metallic glass Metglas 2605SC in order to harvest energy from ambient vibrations. They introduced an equivalent electrical–mechanical circuit model to analyze the performance and optimization of the harvester. The maximum output power and power density of this MsM harvester can reach 200 μW and 900 μW/cm^3, respectively. Compared to piezoelectric based harvesters, Metglas-based harvesters have higher coupling efficiency (>0.9), higher Curie temperature, higher flexibility to be integrated with curved structures, and no depolarization problem (because magnetostriction is an inherent material property) [22]. Thus, it can be used for almost unlimited vibrational cycles with significantly enhanced reliability. However, it has relatively large dimension, which is hard to be integrated with MEMS, because of the pick-up coil.

The first objective of this study is to develop a vibration energy harvester based on MsM materials. Since the piezoelectric-based energy harvesters operate at low frequency [6]. Then, the second objective is to provide an alternate scheme for energy harvesting which overcomes the drawbacks of piezo-based harvesters and operates at higher frequency range. In this study the Metglas 2605SC has been used that has higher magnetomechanical coupling and do not need the bias magnetic field. To analyze the MSM-based energy harvester, a beam equipped with the MSM material wound by a pick-up coil under base excitations has been considered. The following section describes the multimodal model used for the simulation. Results are presented and discussed in Section 3 and paper is concluded in Section 4.

2. Theoretical model of the MsM-based of magneto-mechanical systems

A prototype of the MsM harvesting device with Metglas 2605SC laminate bonded on a cantilever beam wound by a pick-up coil has been proposed (Fig. 1).

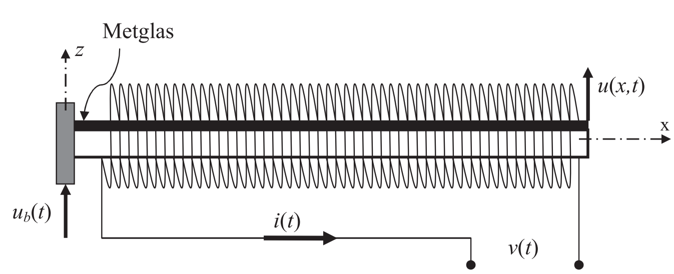

Fig. 1. Schematic diagram of cantilever beam consisting of substrate beam and Metglas ribbon. $u(x,t)$ is the beam deflection along the transverse direction (z) and $u_b(t)$ is the base excitation.