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Design and analytical modeling of magneto-electro-mechanical characteristics of a novel magneto-electro-elastic vibration-based energy harvesting system

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ABSTRACT

In order to effectively design an energy harvesting system for any specific application, a model that accurately characterizes the energy harvesting parameters is needed. In the present paper a novel magneto-electro-elastic (MEE) cantilever beam has been proposed and modeled as an effective means to increase the harvested electrical power in a vibration-based energy harvesting system. The cantilever beam is composed of a linear homogeneous elastic substrate and two MEE layers with perfect bonds between their interfaces. Using the constitutive equations, Gauss's and Faraday's laws, based on the Euler–Bernoulli beam theory, the coupled magneto-electro-mechanical (MeM) differential equations are derived for a harmonic base excitation in the transversal direction with a superimposed small rotation. The resulting equations are then solved analytically to obtain the dynamic behavior as well as the harvested voltages and powers of the proposed energy harvesting system. Finally, parametric numerical studies are used to examine the effect of excitation frequency, external resistive loads, and material properties on the performance of the MEE energy harvester. The study reveals that the implementation of the coil circuit has resulted in an increase in the total useful harvested power. According to the numerical results, any increase in the Young's modulus and density of the substrate layer (across the ranges that have been studied and while the properties of the MEE layer are kept constant), increases the magnitude of the magnetoelectric harvested power in the unimorph MEE energy harvester system.

1. Introduction

Energy harvesting or energy scavenging that has seen significant development over the past decade is a broad term which refers to the process of converting environmental energy into electricity. For many low-powered portable and wireless electronic applications, the finite energy density of chemical batteries limits their functional lifetime. Through the use of energy harvesting techniques, non–electric ambient energy can be captured and converted into usable electricity in order to create self-powering systems which are not limited by finite battery energy. The primary goal is to obtain an energy

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autonomous, maintenance–free system with (at least theoretically) unlimited life time [1–3]. A typical energy harvesting system consist of a transducer, a power converter and an electronic load. The function of the transducer is to harvest the environmental energy and convert it into electricity. Therefore, the transducer is a multiple energy domain device, which couples the energy domain of the source to the electrical domain. The environmental energy sources available for this conversion may be heat [4], light [5], and vibration [6]. The type of energy source available in the environment determines the type of energy harvesting system which must be implemented.

One of the commonly used environmental energy sources with a high energy density is the kinetic energy in the form of vibrations, which is a promising source for industrial applications. The principle behind vibration energy harvesting is the displacement of a moving part (or mechanical deformation of a structure) inside an energy harvesting device. This displacement or deformation can be converted into electrical energy by three different methods: (1) electrostatic varactance [7,8], (2) electromagnetic induction [9,10] and (3) piezoelectric effect [11–13].

The basis of the electrostatic generator is the variable capacitor. The variable capacitance structure is driven by mechanical vibrations. Here, the capacitance varies between maximum and minimum values. If the charge on the capacitor is constrained, it will move from the capacitor to the storage device or to the load as the capacitance decreases. Thus, mechanical energy is converted into electrical energy. An electrostatic generator can be easily used in micro-electro-mechanical systems (MEMS). Unfortunately, electrostatic generators require an initial polarizing voltage or charge. The output impedance of the devices is often very high, which makes them less suitable as a power supply [8].

In an electromagnetic generator, permanent magnets are used to produce strong magnetic field and a coil is used as the conductor. Either the permanent magnet or the coil is fixed to the frame while the other is attached to the inertial mass. The relative displacement caused by vibration makes the transduction mechanism work and generate electrical energy. An electromagnetic generator which is characterized by high output current level at the expense of low voltages performs better in macro-scale than in micro-scale [9] level. Particularly, generators integrated with MEMS with electroplated coils and magnets may not be able to produce useful power levels due to poor electromagnetic coupling.

The piezoelectric effect is the ability of some materials to generate an electric potential in response to the applied mechanical stress (or vice versa). The electrical polarization is proportional to the applied strain. Commonly used materials for piezoelectric power generation are lead zirconate titanate (PZT), polyvinylidene difluoride (PVDF) [14] and macro-fiber composite (MFC) [15]. A piezoelectric energy harvester has the ability to produce relatively high powers (>200 μW'*s*) and favorable voltages compared to an electromagnetic generator. For typical voltages between 2 and 10*V*, the output voltage of a piezoelectric transducer is high enough to overcome the diode drops in a rectifier, but still low enough to interface with typical single integrated circuit (IC) technologies [16–18].

Recently in the field of materials science, there has been a great interest in smart materials that have piezoelectric and piezomagnetic characteristics. These materials, called MEE composites, have the ability of converting energy from one form (among magnetic, electric and mechanical energies) to another and vice versa [19–25].

Although in Ref. [26] the behavior of a coupled magneto-electro-mechanical lumped parameter model for a novel vibration-based magneto-electro-elastic energy harvesting system was investigated based on a single degree of freedom (SDOF) model, there are yet important scientific questions which have to be answered; namely, (1) Does a SDOF correctly model the total harvested energy in a real MeM system? (2) What really happens to the magnitude of the harvested power at other modes of vibration that a SDOF can not predict? (3) What is the effect of a multi-degree of freedom model (beam theory) on the overall behavior of the harvester? (4) Can one really use a SDOF harvester with confidence without any major loss in the total generated power compared to a multi-degree of freedom system? (5) What are the effect other parameters such as R_1, R_2, coil winding turns N, and others on the total harvested power in presence of other modes?

For this reason, this paper makes the first attempt to present a coupled MeM distributed parameter model for the response of the proposed MEE energy harvesting system under a base excitation. To develop an energy harvesting system with higher voltage and power density, it is proposed to use MEE composites to harvest the ambient energy, since they offer a magnetoelectric effect which is not observed in the single-phase piezoelectric or piezomagnetic materials. The mathematical model of a unimorph cantilever beam will be developed and solved analytically to estimate the voltage, current and electrically harvested power when the base excitation is harmonic in both transversal and rotational directions. The exact analytical solution for the cantilevered MEE energy harvester is obtained based on the Euler–Bernoulli beam assumptions which uses all vibration modes. Therefore, the results of the presented model become more realistic and reliable in the vicinity of all vibration modes. Numerical results will be presented to examine the influences of the excitation frequency, external resistive loads and MEE material properties on the performance of the MEE energy harvester. Finally, some of the results obtained based on the new distributed parameter model are compared with those of the SDOF model given in Ref. [26].

2. Formulation of the coupled MeM modal equations for MEE energy harvesting system

2.1. Prototype of MEE energy harvesting device

A schematic configuration of the proposed unimorph cantilever MEE energy harvester with the length l and a uniform rectangular cross-section of width b and thickness t is shown in Fig. 1. The beam density along the longitudinal direction is assumed to be uniform, while it is excited by a base input displacement along the transversal and rotational directions. The harvester unimorph beam has two different layers: an inactive substrate layer at the bottom and a MEE layer at the top with