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Modeling and parametric analysis of a unimorph piezocomposite energy harvester with interdigitated electrodes

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ABSTRACT

This study investigates the derivation of an accurate parameterized analytical model of a vibration-based energy harvester using piezocomposite material and interdigitated electrode. The derived model is used to analyze and optimize the harvested electrical energy under different resistance loads and excitation frequencies. The energy harvester is composed of a unimorph design cantilever beam partially covered by a piezocomposite material with interdigitated electrodes. The model provides an improved approach to optimize the performance of the system by taking into account the nonlinear electrical potential distribution and nonuniform vibration mode shapes over the beam's length due to the presence of the piezocomposite patch. We use a Galerkin procedure along with the Gauss's law to derive the analytical reduced-order model and study the dynamic response of the energy harvesting system. We demonstrate that different parameters are involved into the optimization process of the system such as the number of electrodes, the different layer thicknesses, the piezocomposite patch length, the fiber volume fraction and the substrate material. The proposed analysis shows that significant increase of the harvested energy could be obtained if all design parameters are correctly chosen. A numerical finite element model is also developed to validate the obtained analytical results.

1. Introduction

Recent advances in the electronics industry have made wireless electronic devices require less power to operate. Thus, autonomous wireless systems can be developed if the required electrical energy to feed the system could be harvested from the environment. Many methods have been investigated to develop suitable power supply by converting an ambient energy source into electricity. Electric energy can be produced from light using photocells, from strain using magneto-electric or piezoelectric generators and from temperature gradient using thermo-couples. The abundance of vibrations in ambient environment, in addition to simplicity of integration and self-power capability of the piezoelectric transduction mechanism, encourage to give significant attention to piezoelectric vibration-based energy harvester (PVEH).

During the last decade, several researchers provided many efforts to increase the output electrical power of PVEH. Different approaches have been proposed to reach this goal ranging from proposing new mechanical designs to engineer new composite material structures. Next, we present some of these approaches.

In general, PVEH are composed of a mechanical bender in which the active piezoelectric material has been incorporated. An additional inertial component can be added to increase the transduced energy since it is proportional to the strain generated inside the bender through displacement due to the PVEH's vibration. This later case was studied by Jiang et al. [1]. They used a cantilever beam bender with a proof mass attached to its free end and studied the effect of physical and geometrical parameters of the system on the performance of the harvested electrical power. The PVEH is supposed to vibrate around its lowest natural frequency where the majority of environmental excitations frequencies are (from 20 to 200 Hz [2]). As a result, the maximum strain is generally confined near the clamped region of the bender. Therefore, researchers proposed to optimize the strain distribution along the bender's length in order to increase the harvested energy. Within this scope, Roundy et al. [3] demonstrated that a trapezoidal cantilever bender generate more than twice the electrical power compared to a classical rectangular shape. Ben Ayed et al. [4] investigated the effects of linear and quadratic shape variations of the PVEH. They concluded that, for specific electrical resistance loads, the quadratic

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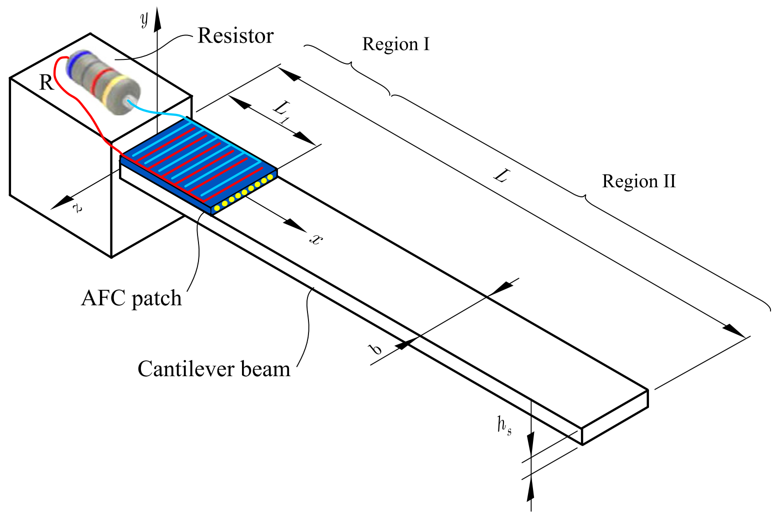

Fig. 1. Schematic of the unimorph energy harvester bender using IDE.

shape can yield up to two times the energy harvested by a rectangular shape PVEH.

All the above mentioned research works can only harvest energy near the fundamental natural frequency of the bender. To increase the bandwidth at which the PVEH is efficient, Abdelkefi et al. [5] proposed a multimodal design of a bender that undergoes coupled bending-torsion vibrations. They showed that the proposed design yields an increase about 30% of the harvested power when compared to the case of an energy harvester undergoing bending only. Abdelkefi et al. [6] also demonstrated that their proposed design can be used for a multifrequency excitation without compromising the harvested electrical energy.

Other, looked at the arrangement of the piezoelectric layers inside the bender in order to optimize the strain distribution in the thickness direction. In this framework, Zheng and Xu [7] investigated an asymmetric air-spaced layers cantilever beam and they claimed that their proposed design increases the harvested electrical energy. Erturk and Inman [8] studied analytically and experimentally a bimorph cantilever PVEH using different layers with independent electrodes. They concluded that the type of electrical connection (series or parallel) highly influence the harvested electrical energy. Erturk et al. [9] investigated the case of a unimorph PVEH with segmented electrodes in the longitudinal direction. They proved that an increase of the harvester performance is possible.

Interdigitated electrodes (IDEs) could also be used to segment active layers and form juxtaposed regions of piezoelectric patches. This approach allows the use of the d_{33} mode instead of the classical d_{31} mode. It was shown that the d_{33} mode could produce higher harvested power as shown in [10–12]. Within this framework, Bent and Hagood [13] designed, in 1995, a new piezoelectric actuator where IDE have been integrated. They combine it with a piezoelectric composite material to increase the flexibility of the actuator, the new design is known as the Active-Fiber Composite (AFC). The proposed AFC piezocomposite is a combination of circular PZT fibers inclusion into an epoxy matrix. A Similar design was proposed by Wilkie et al. [14] in 2000, but using square piezoelectric fiber instead of the circular cross section. Their piezoelectric actuator is known as Micro-Fiber Composite (MFC) [15].

Unfortunately, AFC and MFC based PVEH have weak performances. Sodano et al. [16] demonstrated experimentally that the electrical energy generated from a PVEH integrating IDE was very low when compared to a classical monolithic PZT PVEH with parallel electrodes. They justified this drawback by the reduced effective capacitance due to the IDE configuration. Sodano et al. [17,18] presented experimental results showing that the current generated from PVEH integrating IDE was not sufficient to recharge small batteries. Therefore, it is necessary to identify the influential geometrical and physical parameters that contribute to the reduction of the harvested energy.

Besides the complexity of modeling and simulation of such energy harvester, because of the presence of the piezocomposite and the IDE configuration that produce complex electric field distribution, several attempts were made to propose analytical and numerical models of AFC and MFC. Bowen et al. [10] presented Finite Element (FE) analysis and optimization of AFC actuator assuming that the polarization is uniform and unidirectional. Beckert and Kreher [20] also developed an FE analysis, however they use an inhomogeneous poling state via a two-steps processing technique. It consists to examine first the electric field distribution which determines the local poling state in the piezocomposite, and second to update the electric field distribution according to the new polarization. However, these FE-based models are not suitable to optimize AFC and MFC based PVEH, especially when one wants to integrate the dynamic effects.

Mo et al. [21,22] developed an analytical model of an IDE harvester with monolithic piezoelectric material assuming unidirectional and uniform electric field using a quasi-static approach. They presented a detailed parametric study to optimize the electrical charge and power generated by the harvester. Knight et al. [23] presented an optimization study of the same design implemented using a MEMS technology. They used the analytical model developed by Mo et al. [21] and introduced a poling correction factor to investigate the losses associated with non-uniform poling. They presented a parametric study in terms of electrode patterns, piezoelectric layer and electrode dimensions to examine their effects on the poling correction factor. Erturk et al. [24] investigated the use of MFC for energy harvesting. They presented a parametric study to investigate the effects of substrate material and piezoelectric layer thickness on the harvested power. They derived a semi-analytical model of the unimorph MFC harvester and introduced different correction factors in order to handle the non-uniform field into the MFC configuration. The developed model successfully predicted the dynamics of the MFC unimorph design especially for low values of electrical resistance load. Jemai et al. [25] developed an analytical and numerical model for a unimorph AFC harvester. They assumed unidirectional and uniform electric field between successive electrodes in the case of relatively large electrode separation and small electrode's width. They demonstrated that the proposed closed-form solution is in good agreement with