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A conceptual study on the dynamics of a piezoelectric MEMS (Micro Electro Mechanical System) energy harvester

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A B S T R A C T

The mechanical behavior of a bimorph piezoelectric micro cantilever exposed to harmonic base excitation is investigated. The governing motion equation coupled with the equation of the output electrical circuit is discretized using Galerkin method and numerically integrated over the time. Two different types of output circuits including parallel and series connections are examined and the most effective output circuit from the power delivery point of view on the domain of the governing parameters is introduced. The energy conservation is examined by comparing the input and harvested energies. It is concluded that the energy harvesting in the absence of mechanical damping resembles the behavior of a damped mechanical oscillator due to the exponential attenuation of the motion amplitude. It is shown that the output power in terms of the load resistance of the output circuit, exhibits Lorenzian behavior revealing the multi factorial dependency of the power on the governing parameters. The effect of load resistance and the effective piezoelectric stress constant on the equivalent damping ratio is investigated. Subjected to harmonic base excitation, the steady state voltage, current and power responses are presented. The results are presented for various piezoelectric materials and on the plane of load resistance and effective piezoelectric stress constant, the output power delivery as well as the equivalent non-dimensional damping coefficient is determined.

1. Introduction

Energy harvesting is the scavenging of ambient energy in order to make an autonomous and self-powered electronic devices for numerous applications, most particularly electronics and electrical systems ranging from wireless sensor networks to medical implants [1–4]. In past decade this field of research has generated a lot of interest within the scientific community and industrial area since it provides a route for the realization of alternatives for the conventional battery. Energy harvestings methods are categorized into two major groups including motive and non-motive. The motive class containing mostly vibrational and kinetic energy transforming method such as piezoelectric [5–7] electromagnetic [8–10] electrostatic [11–14] and Magnetostrictive [15–17] while non-motive ones, include solar, thermal and etc. [3].

Piezoelectric energy harvesting is highly focused since a piezoelectric material can convert mechanical vibration into electrical energy based on a very simple structure [18] and large power densities [1]. Piezoelectricity is a property of certain crystalline materials such as quartz that develop electricity when pressure is applied and undergo deformation when an electric field is applied [7]. In the last few years many studies focused on estimation of electric charge output for energy harvesting and parameters that affected on harvested energy [16,19–21]. Flynn et al. [19] reported fundamental limitations on PZT (lead zirconate titanate) material. They stated for PZT-5H a mechanical stress-limited work cycle was 330 at 100 kHz. Shen et al. [21] designed and fabricated a PZT piezoelectric cantilever with a micromachined Si proof mass for a low frequency vibration energy harvesting application. They applied 0.75 g ($g = 9.81\ m/s^2$) acceleration amplitude to the cantilever and attained 101 mV AC output measured across resistive load of 16 kΩ of resonance frequency 183.8 kHz. Liu et al. [20] developed an array of power generator based on thick-film piezoelectric cantilevers in order to improve frequency flexibility and power output. They reported an

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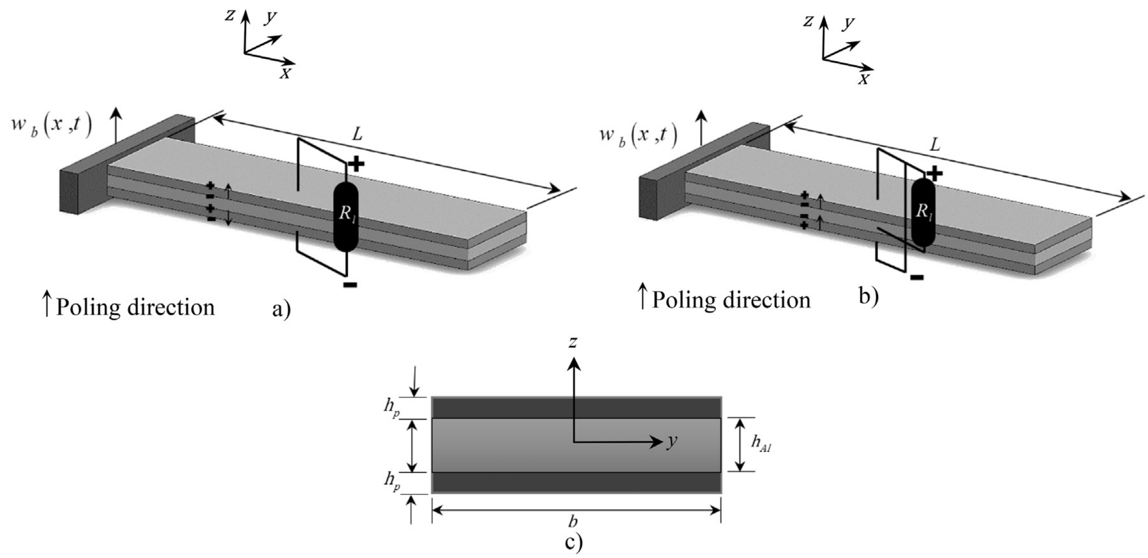

Fig. 1. 3-D model of the proposed piezoelectric bimorph cantilever a: series connection b: parallel connection c: cross section.

improved performance of 3.98 effective electrical power and 3.93 DC output voltages to resistance load. Erturk et al. [22] imposed an improved mathematical model and made an attempt to correct the oversimplified issues related to mathematical formulation. They also presented a closed form analytical solutions of bimorph cantilever configurations with series and parallel connections of piezoceramic layers. Shu et al. [23] investigated the energy conversion efficiency under steady state condition for a rectified piezoelectric power harvester. They stated that optimization criteria depend upon the relative strength of the electromechanical coupling. Marzencki et al. [24] propounded a passive, wideband adaptive system by employing mechanical nonlinear strain stiffening. They related experimentally verified frequency adaptability of over 36% for a clamped–clamped beam device at 2 g input acceleration. They asserted that the proposed solution was perfectly suited for autonomous industrial machinery surveillance systems, where high amplitude vibrations are abundant.

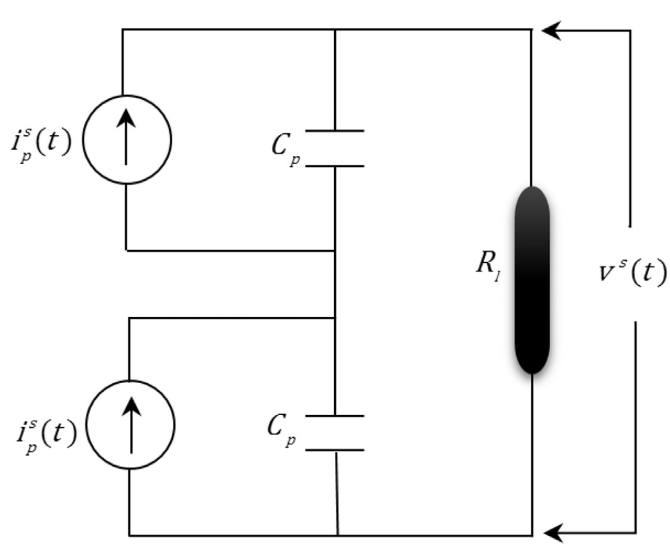

Fig. 2. Electrical circuit representing the series connection of the piezoelectric layers with two dependent current sources.

Dietl et al. [25] proponed a Timoshenko model of transverse piezoelectric beam to overcome the over predicted parameter values in Euler–Bernoulli beam models. They stated the exact expressions for the voltage, current, power, and tip deflection of the piezoelectric beam. They also optimized the shapes of beam for harvesting power using heuristic optimization code and the attributes of this optimal beam was validated with the experimental results [26]. Gammaitoni et al. [27] modeled piezoelectric harvesting oscillator dynamics with nonlinear stochastic differential equation and highlighted the benefit of noise and nonlinearity. More studies was demonstrated in a review by Salem Saadon, Othman Sidek [28]. Most recently Kang-Qi Fan et al. [29] designed and experimentally verified a compact bi-directional nonlinear piezoelectric energy harvester, sensitive to two orthogonal directions. Their model was composed of two magnetically coupled piezoelectric cantilever beams with orthogonal directions of deflection. They stated that the proposed energy harvester can not only harvest vibration energy from various directions but also provide an enhanced output voltage as compared to its linear counterpart. Zhengbao Yang, Jean Zu [30] presented high-efficiency compressive-mode piezoelectric energy harvester. Due to the superior compressive strength of piezoceramics, the high-efficiency compressive-mode piezoelectric energy harvester showed superior capability of high power output at low frequency range. They asserted that under an acceleration of 0.5 g (g = 9.8 m/s2), a maximum power of 19 mW is produced at 21 Hz. Kangqi Fan et al. [31] designed and developed a beam-roller piezoelectric energy harvester. The beam-roller harvester was composed of a piezoelectric cantilever beam, a roller, and a frame. The energy captured by the roller was transferred to the beam via magnetic coupling. They used a lumped parameter model and also experimentally validated the theoretical predictions.

In this paper the dynamics of a cantilever bimorph piezoelectric energy harvester [1,32] is investigated. The structure undergoes base excitation which produces mechanical vibration along the beam. As subjected to mechanical stress induced by the vibration of the beam, electrical potential field is generated along the height of the piezoelectric layers and this is directly converted to electrical power throughout an electrical circuit. In the absence of mechanical damping sources, the energy conservation is verified. It is