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A novel composite multi-layer piezoelectric energy harvester

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ABSTRACT

A typical linear piezoelectric energy harvester (PEH) is represented by a unimorph or bimorph cantilever beam. To improve the efficiency of linear PEHs, classical strategies involve the increase of the beam length, tapering or adding additional cantilever beams to the free end. In this work we discuss the design of novel type of composite linear multi-layer piezoelectric energy harvester (MPEH). MPEHs here consist of carbon fibre laminates used as conducting layers, and glass fibre laminas as insulating components. We develop first a electromechanical model of the MPEH with parallel connection of PZT layers based on Euler-Bernoulli beam theory. The voltage and beam motion equations are obtained for harmonic excitations at arbitrary frequencies, and the coupling effect can be obtained from the response of the system. A direct comparison between MPEH and PEH configurations is performed both from the simulation (analytical and numerical) and experimental point of views. The experiments agree well with the model developed, and show that a MPEH configuration with the same flexural stiffness of a PEH can generate up to 1.98–2.5 times higher voltage output than a typical piezoelectric energy harvester with the same load resistance.

1. Introduction

The development of wireless sensor networks and the reduction of their power requirements has significantly driven research activities related to vibration piezoelectric energy harvesting technologies, which possess high energy conversion efficiencies from mechanical vibrations to electrical power, all within the use of simple designs [1]. In 1996, Williams and Yates first introduced the concept of vibration energy harvesting [2]. Wang et al. (1999) then presented the constitutive equations of symmetrical triple layer piezoelectric benders, and introduced different types of piezoelectric benders, like unimorphs and bimorphs with series or parallel connection [3]. Erturk and Inman have established the fundamental electromechanical model of a piezoelectric cantilever beam, with their 2008 papers related to a single-degree-of-freedom (SDOF) harvester beam with one PZT layer [4,5]. The same Authors then investigated the analytical model of bimorph cantilever configurations with series and parallel connections of PZT layers [6]. Micro-fibre composites (MFC) can also be used in vibration energy harvesters. Song et al. developed the theoretical model for energy harvesting devices with two types of MFC materials, and the influence of the beam thickness, natural frequency and electrical resistance were also experimental investigated [7]. Nonlinear PEHs have been additionally designed and developed in recent years to expand the operational frequency bandwidth. Erturk et al. [8,9] have presented a nonlinear broadband piezoelectric power generator with two magnets near the free end of the cantilever beam and with two piezoelectric layers on the surface. The piezo-magnetoelastic configuration proposed could generate a power one order of magnitude larger than the one provided by a linear PEH at several frequencies. The performance of a nonlinear magnetopiezoelastic energy harvester driven by random excitations was described by Litak et al. [10] and Ali et al. [11]. Their work shows that it is possible to optimally design the system by using analytical techniques, such that the mean harvested power is maximized for a given strength of the input broadband random ambient excitation. Ferrari et al. utilized two layers of PZT films to fabricate a piezoelectric bimorph, and the resulting nonlinear converter proposed implements nonlinearity and bistability by using a single external magnet [12]. Friswell et al. have also designed a new type of highly nonlinear piezoelectric cantilever beam, exhibiting two potential wells with large tip masses, when the beam is buckled [13]. Other nonlinear PEHs with magnets can be found in Refs. [14–16], and in the review article [17]. Betts et al. presents an arrangement of bistable composite

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plates with bonded piezoelectric patches to perform broadband vibration-based energy harvesting from ambient mechanical vibrations [18]. Arrieta et al. have designed a cantilevered piezoelectric bi-stable composite concept for broadband energy harvesting with two piezoelectric layers attached on the surface of bistable composites [19]. Pan et al. used bistable hybrid symmetric laminates to make a broadband piezoelectric energy harvester, and have discussed the influence of the lay-up design on the performance of the bistable PEH [20,21]. Qi et al. have designed a multi-resonant beam with piezoelectric fibre composites (PFC) to produce a broadband PEH [22]. A double cantilever energy harvester was evaluated via a distributed parameter modelling and experimental tests by Rafique et al. [23]. Adhikari et al. have used a stack configuration piezoelectric energy harvester, and generated power from broadband vibration [24]. Paknejad et al. have presented a distributed parameter electroelastic model for various multilayer composite beams and discussed the influence of the composites layups [25]. Akbar et al. have studied the dynamic response of piezoelectric energy harvesters embedded in a wingbox structure [26]. Some new piezoelectric energy harvester configurations have also been presented to improve the efficiency during vibration, such as the L-shape [27], the V-shape [28] and the compressive-mode energy PEHs [29].

From the above literature review it is possible to observe that both linear and nonlinear PEHs are in general designed using a symmetrical triple layer structure (i.e., one mid-structure with two piezo-layers on the surfaces). This baseline configuration has been modified by using different beam/plate lengths or shapes (tapering), however the fundamental layout remains the same. In this study we propose a PEH structure with a more complex through-the-thickness topology. The electromechanical model of the composite multi-layer piezoelectric energy harvester (MPEH) is here established based on the use of the Euler-Bernoulli beam theory. The fundamental natural frequency and the power output of the MPEH beam are then extracted, and the performance of the MPEH is discussed based on simulations and experimental data. A parametric analysis of the voltage density and resonant frequencies is also performed versus different stacking sequences of the MPEHs and PEHs leading to different specific flexural stiffness (i.e., normalized by the mass of the beams). From the simulations, experimental data and the parametric analysis we will demonstrate that the MPEHs can generate significantly more power than the PEHs configurations, in particular for small specific flexural stiffness configurations. The variations of the natural frequencies in MPEHs and PEHs with similar specific flexural stiffness are less pronounced, with the PEHs having larger fundamental natural frequencies compared to the MPEHs cases.

2. Analytical electro-mechanical model

Fig. 1 presents the design of the MPEH, which consists of multiple PZT layers and composites laminates. The MPEH is a cantilever beam with carbon fibres, glass fibres laminates and PZT layers. The length of cantilever beam is L, and b is the width. Fig. 1(b) and (c) represent the cross section of the MPEH, h_{ci}, h_{cj} are the thickness of the carbon fibre laminates, h_{gi} is the thickness of the glass fibre laminate. The thickness of the PZT layer is h_p, and h_s is the total thickness of the beam except for the external layers PZT. In the design, the polarization direction for all the PZT layers is the same, which means that each pair of PZT layers are connected in parallel. The carbon fibre laminates are here used as conducting layers, and the glass fibre laminates constitute the insulating layers.

2.1. Basic equations and fundamental natural frequency

The thickness is relatively small than the length of the composite beam, so the general governing equation of motion of an Euler-Bernoulli beam with embedded piezoelectric layers can be written as [6],

$$\frac{\partial^2 M(x,t)}{\partial x^2} + c_s I\frac{\partial^5 w(x,t)}{\partial x^4 \partial t} + c_a\frac{\partial w(x,t)}{\partial t} + m\frac{\partial^2 w(x,t)}{\partial t^2} = -(m+M_t)\frac{\partial^2 w_b(x,t)}{\partial t^2} \tag{1}$$

In Eq. (1), $M(x,t)$ is the bending moment of the beam; $w(x,t)$ is the beam transverse deflection relative to its base, and $w_b(x,t)$ is the base excitation motion on the beam along the z-direction. The tip mass at $x = L$ is M_t. The bending moment can be related to the internal stresses of the layers in the following manner:

$$M(x,t) = -b\int_{t_c}\sigma_c z dz - b\int_{t_g}\sigma_g z dz - b\int_{t_p}\sigma_p z dz = -b\sum_{k=1}^{N_c}\int_{t_{ck}}\sigma_c z dz - b\sum_{k=1}^{N_g}\int_{t_{gk}}\sigma_g z dz - b\sum_{k=1}^{N_p}\int_{t_{pk}}\sigma_p z dz \tag{2}$$

In Eq. (2), σ_c, σ_g, σ_p correspond to the normal stress of carbon and glass fibre laminates, and of the piezoelectric layers along the x-axis, respectively. For the kth layer of the elastic composite laminate, the bending stress is defined:

$$(\sigma_c, \sigma_g)_k = -z(\overline{Q}_{11})_k\frac{\partial^2 w}{\partial x^2} \tag{3}$$

The kth layer stiffness $\overline{Q}_{11}$ can be defined by using the traditional classical laminate theory [30]:

$$\begin{aligned} \overline{Q}_{11} &= Q_{11}\cos^4\theta + 2(Q_{12}+2Q_{66})\sin^2\theta\cos^2\theta + Q_{22}\sin^4\theta \\ Q_{11} &= \frac{E_1}{1-\nu_{12}\nu_{21}} \\ Q_{12} &= \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} \\ Q_{22} &= \frac{E_2}{1-\nu_{12}\nu_{21}} \\ Q_{66} &= G_{12} \end{aligned} \tag{4}$$

where E_1 is the Young's modulus along the fibre direction, E_2 is the Young's modulus along the transverse direction, and G_{12} is the shear modulus. The Poisson's ratios are ν_{12} and ν_{21}, and θ is the fibre orientation.

The stress in the PZT layer can be expressed by the constitutive equations for a piezoelectric slab:

$$\sigma_p = E_p\varepsilon_1^p(x,t) - \bar{e}_{31}E_3(t) \tag{5}$$

In Eq. (5) E_p is the elastic modulus of piezoelectric layer, ε_1^p is the axial strain components, $\bar{e}_{31}$ is the piezoelectric constant and E_3 is the electric field across the thickness of the beam.

From the Euler-Bernoulli beam theory, the internal bending moment can be obtained by substituting Eqs. (3), (5) into Eq. (2):

$$M(x,t) = -YI\frac{\partial^2 w(x,t)}{\partial x^2} + \vartheta_p[H(x) - H(x-L)] \tag{6}$$

where YI is the flexural rigidity of the piezoelectric elastic composites. The Heaviside function $H(x)$ limits the location of the piezoelectric layer along the x-direction on the host structure. The flexural rigidity can be described by:

$$YI = b\sum_{k=1}^{N_c}(\overline{Q}_{11})_k^c\int_{z_{k-1}}^{z_k} z^2 dz + b\sum_{k=1}^{N_g}(\overline{Q}_{11})_k^g\int_{z_{k-1}}^{z_k} z^2 dz + E_p b\sum_{i=1}^{N_p}\int_{z_{k-1}}^{z_k} z^2 dz \tag{7}$$

For a parallel connection the polarization direction is the same, therefore the $\bar{e}_{31}$ coefficient has the same sign for the top and bottom layers. The directions of $\bar{e}_{31}$ and $E_3(t)$ are expressed in Fig. 2, with black and redarrows separately.

The piezoelectric coupling term ϑ can be derived from Eq. (2), which is a function of time only. The internal moment in PZT layer is: