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Piezoelectric energy harvester based on bi-stable hybrid symmetric laminate

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ABSTRACT

A bi-stable piezoelectric energy harvester (BPEH) based on bi-stable hybrid symmetric laminate (BHSL) is proposed for energy harvesting. Due to its large deformation and low actuation, BPEH has better energy harvesting performance at low frequencies compared with traditional resonance cantilever-type energy harvester. Two types of stacking sequence and two types of piezoelectric ceramics (PZT) shapes with identical area were considered, and four types of BPEHs were designed. The stable configurations of the BPEHs and the stress states of PZT bonded on the surface of the BSHL were simulated and analyzed by finite element analysis. In addition, the four types of BPEHs were fabricated and experimentally evaluated. The BPEHs were actuated by hand shaking to transition between the two stable configurations. Using this method, the voltage outputs and power outputs were measured at two frequencies (2 Hz and 5 Hz). The results demonstrate that the BPEHs exhibited high output power because the PZTs on their surface were fully utilized due to their double curved shape and uniform deformations. The generated powers from the BPEHs were significantly higher than that observed from a similar sized cantilever-type piezoelectric harvester. Simultaneously, the influences of stacking sequence and shape of PZT on the energy harvesting performance were evaluated. The BPEHs with the second stacking sequence generated higher power than those of first stacking sequence, and the rectangular PZT performed better compared to the square. The measured maximum power output generated by the BPEH with the second stacking sequence and rectangular PZT was 37 mW at 5 Hz.

1. Introduction

Energy harvesting is defined as the process of capturing minute amounts of energy from one or more surrounding energy sources, accumulating and storing the energy for later use [1]. Vibrations are one of the most commonly available forms of ambient energy, which can be found in civil structures, machines, the human body, etc. Piezoelectric materials can generate electrical charge under applied mechanical load, which enables such materials to function as energy harvesting transducers. Over the past years, piezoelectric energy harvesting from vibrations has received overwhelming attention when compared with other methods due to its major advantages, such as large power density, easy application, and the fact that the output voltage is obtained directly from the piezoelectric material itself [2].

Previous studies of piezoelectric energy harvesting technology have been focused on designing energy harvesting devices, or modeling and theory [3–7]. Typically, a piezoelectric energy harvester is a cantilevered beam with one or two piezoelectric layers. The cantilever type energy harvester has a very simple structure and can produce large deformation under vibration. Generally, the harvester beam is located on a vibrating host structure and the dynamic strain induced in the piezoelectric layers generates an alternating voltage output across the electrodes covering the piezoelectric layers. Most of these piezoelectric energy harvesters are designed working within a narrow frequency range situated around the cantilever's natural frequency for amplification to trigger resonance. However, these resonant piezoelectric energy harvesters are less efficient in many realistic environments, where the scavenge energy is distributed over a wide spectrum, and is particularly dominated by very low frequencies, such as from human activity and water wave [8]. Recently, some concepts for non-resonant piezoelectric energy harvesters have been reported continuously. These harvesters no longer rely on high frequency vibrations to trigger the resonance for more energy, and are designed for low frequency and broadband energy sources, such as

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wind, hydroenergy, and human motion. Taylor [9] presented an energy harvesting eel to convert the mechanical flow energy to electrical power. Mateu [10] optimized the configuration of piezoelectric film-bending beams inside a shoe for harvesting energy from walking activity. Vatansever [11] discussed the possibility of energy generation from two renewable energy sources (wind and water drops) with ceramic-based piezoelectric fiber composite structures and polymer-based piezoelectric strips. Cha [12] investigated energy harvesting from underwater base excitation with a piezoelectric composite beam. Li [13] fabricated a polymer piezoelectric energy harvester with high sensitivity to wind, capable of generating electric power at wind speeds of less than 4.7 m/s.

In recent years, bi-stable energy harvesting devices have attracted significant attention due to some of their unique features. Through a snap-through action, bi-stable systems can transform from one stable state to another, which can lead to large amplitudes and dramatically increase power generation [14]. Moreover, the nonlinearity of bi-stable systems can extend the working frequency for broadband energy harvesting. Generally, the bi-stable characteristics for energy harvesting were obtained in two ways: magnetic repulsion or attraction [15–17] and structure with bi-stable characteristics [18–20]. Structurally bi-stable energy harvesting devices are easy to implement, as they have a simple structure and no need for extra auxiliary device. Bi-stable laminates are of interest for energy harvesting because they provide large structural deformations in response to a relatively small vibrational energy input [21–23]. Bi-stability arises from anisotropic thermal expansion during cooling from an elevated cure temperature, leading to curved deformation [24–26]. Hybrid laminates [27–29] have better designability compared with the traditional asymmetric bi-stable laminates, due to the variation of position for metallic layer. The bi-stable hybrid symmetric laminate (BHSL) operates under thermal residual stress, which is on account of the thermal expansion mismatch between the aluminum and carbon fibers [29]. It has two basic stable configurations which have identical curvatures with opposite signs. The configurations of such hybrid symmetric laminates are illustrated in Fig. 1, where the dash line is the unstable flat configuration, and blue line and red line are the stable cylindrical configurations. In the present work, a bi-stable piezoelectric energy harvester (BPEH) was proposed, consisting of piezoelectric transducers bonded on each surface of a BHSL to obtain large strain and electric power. This BPEH experiences large and homogeneous deformation under small actuation loads due to its bi-stability such that it can snap between the two basic configurations, and it has high energy harvesting efficiency. It is suitable for harvesting energy from low frequency vibrations with large amplitude, such as human activity.

2. Design of BPEHs

Lead zirconate titanate (PZT) is chosen for implementing harvesters in this paper, which is widely used as an energy harvesting material due to its advantages of compact size, low price and high power density. Generally, PZT is bonded on elastic supporting structures, such as a cantilever beam, because of its brittleness and susceptibility to accidental breakage when a mechanical strain is applied. However, the cantilever type harvesters usually have low efficiency in non-resonant case, due to underutilization of the PZT with the small and uneven strain. To improve the conversion efficiency of PZT, BPEHs were introduced, which can produce large deformation under low actuation loads to capture low frequency vibrational energy. The BPEHs are designed to snap between two basic configurations such that the PZTs bonded on the surface of the BHSL can deform and obtain large strains to produce the output voltage. The roughly cylindrical configurations of a BHSL promote the uniform deformation of PZT to improve its conversion efficiency of PZT.

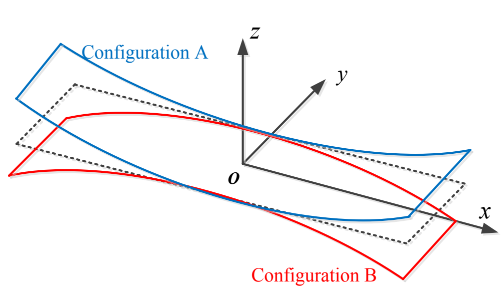

Fig. 1. Basic configurations of bi-stable hybrid symmetric laminate.

With layers of carbon fiber, aluminum slices and PZT thin slices, the BPEHs are designed to have two stable configurations with identical and opposite-signs curvatures. BPEHs with two types of stacking sequence are illustrated in Fig. 2, where the stacking sequences are $[90_2/Al/90_2]_T \cup [90_2/0_2/90_2]_T \cup [90_2/Al/90_2]_T$ and $[90_2/Al/90_2]_T \cup [0/90/0_2/90/0]_T \cup [90_2/Al/90_2]_T$, respectively. To maintain the bi-stability of the BHSL, 10 pieces of PZTs are bonded symmetrically about two axes on each side of the BHSL. One characteristic of the BHSL is that the curvatures are unevenly distributed. The Finite Element Analysis (FEA) predictions for bending curvatures and out-of-plane displacement w (represented by U3 in ABAQUS) about the symmetric axis $y = 0$ for the first stacking sequence are given in Fig. 3. The coordinate system is similar to that in Fig. 1, and the lay-up and laminate dimensions are identical to those in Fig. 2(a). The curvature curves consist of linearly varying segments and stable segments. At the two ends of the BHSL, the curvatures are roughly linear with x; nonetheless, the curvatures remain almost constant in the middle of the BHSL. Therefore, the PZTs were arranged in an array in the middle of the BHSL with equal transverse space to optimize the deformation. It must be noted that BHSL has two directions of curvatures and the curvatures along the x-direction are larger than those in the y-direction.

For better adhesive performance, the PZTs were arrayed on the two surfaces of the BHSL before curing, and underwent the curing process with carbon fiber prepreg. After the curing process, the PZTs were bonded firmly on the BHSL with resin matrix. Because the Curie temperature of PZT for this paper is 280 °C, it is assumed that the temperature cycles do not affect the piezoelectric property. Due to the electrical conductivity of the carbon fiber, the BHSL can act as an electrode. The PZTs on the two surfaces of the BHSL can be in different stress states in the same configuration. The polarization direction of the PZTs on both sides should be identical, to produce like charges on the BHSL electrode. However, a parallel connection among the PZTs was employed. A BPEH connected in parallel is illustrated in Fig. 4, where the PZTs on the two surfaces have the same poling axis to share the BHSL electrode.

During fabrication, the curing process causes the BPEHs to have thermal residual stress in the PZTs because of a mismatch in the coefficients of thermal expansion between the carbon fiber layers and the PZTs. Because the bi-stability of the BHSL is induced by thermal residual stress, the residual stress in the PZT transducer has an effect on the BPEH's configuration. To confirm the effect of thermal residual stress in the PZTs on the BPEH configuration and energy harvesting performance, two types of stacking sequences were employed in this paper. Due to the tremendous differences in thermal expansion coefficients between 90° and 0° plies, the outer 90° plies bonded with PZTs in the first type of stacking sequences as shown in Fig. 2(a), are replaced by 0° plies to form the second type of stacking sequences as shown in Fig. 2(b). Two shapes were used