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Theoretical analysis and experimental study of the effect of the neutral plane of a composite piezoelectric cantilever

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ABSTRACT

Piezoelectric energy harvesters have been studied extensively because they show considerable promise for use in both military and commercial applications. In this work, research was conducted into the core component of a piezoelectric energy harvester, i.e., the piezoelectric cantilever. The phenomenon where the piezoelectric cantilever has a very low output when no substrate layer is present can be explained using neutral plane theory. The relationship between the neutral plane's position and the piezoelectric cantilever's output power can be studied in depth through analysis of this phenomenon. A mathematical model of a vibrating piezoelectric cantilever is established and the neutral plane position and open-circuit voltage of a vibrating piezoelectric cantilever are deduced based on Euler-Bernoulli beam theory. Calculations and finite element simulation results show that the neutral plane's position in the piezoelectric cantilever is dependent on the elastic moduli and thicknesses of the piezoelectric and substrate layers and that the output of the piezoelectric cantilever is also closely related to the neutral plane's position. To study how the neutral plane's position affects the output power of the piezoelectric cantilever, polyvinylidene fluoride (PVDF) piezoelectric cantilevers with different substrate layers but the same piezoelectric layer were fabricated and the output powers of these layers were measured. Experimental results show that the composite piezoelectric cantilever's performance is enhanced in terms of its output voltage, average power and power density as the neutral plane is gradually moved further away from the mid-plane of the piezoelectric layer.

1. Introduction

Piezoelectric energy harvesters convert vibrational energy into electrical energy via the piezoelectric effect [1–4]. The research community is showing increasing interest in this phenomenon and has undertaken theoretical and experimental studies of piezoelectric energy harvesters, which have many potential applications in fields including wireless devices, wearable electronics, and even military equipment. Jeong et al. [5] proposed a new soft-push type piezoelectric energy harvester, which is a multi-array system, and used this system to develop a self-powered wireless switch that uses infrared communication. Guan et al. [6] presented a piezoelectric energy harvester for rotational motion applications that can generate high output voltages at low rotational speeds to produce high output powers over a wide range of rotation speeds; this device thus offers sufficient power for low-power wireless transmitters. Additionally, Wang et al. [7] proposed a novel pre-rolled flexible piezoelectric cantilever structure that uses wind energy to power a submunition electrical device.

Piezoelectric energy harvesters represent an effective alternative to use of conventional chemical batteries and meet many power supply requirements, including strong electromechanical coupling capabilities, simple structure, and long service life [8,9]; however, the output powers of these harvesters could still be improved. Therefore, many researchers are attempting to improve this particular aspect of piezoelectric energy harvesters. Liu et al. [10] investigated a power generator array based on thick-film piezoelectric cantilevers with the aim of improving harvester output power. In addition, Huang [11] proposed a novel beating design that used polymeric piezoelectric materials in conjunction with a beating mechanism; their results demonstrated that this design could potentially provide significant improvements for future piezoelectric energy harvesters. Furthermore, Anderson and Sexton [12] found that variations in the length and width of the proof mass both affect the harvested output power. Yang et al. [13] explored a new way to use arc-shaped piezoelectric patches as core transducing elements in energy harvesters to improve their output performance. Shin et al. [14] investigated one-to-three-story-structured piezoelectric

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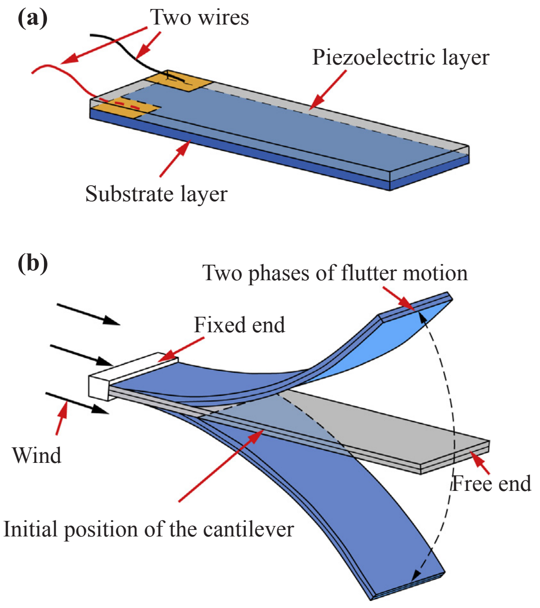

Fig. 1. Schematic diagram of piezoelectric cantilever.

energy harvesters based on multi-layered lead zirconate titanate (PZT) actuators to maximize harvester output power for various loads. In addition, researchers have proposed a variety of methods to improve the output powers of piezoelectric energy harvesters based on optimization of material, circuitry, or structural aspects of these devices.

Piezoelectric cantilevers based on cantilever beam structures have been attracting increasing attention for energy harvester applications [15,16]; these structures are composed of both a substrate and a piezoelectric layer [17,18]. In general, either metal materials (e.g., copper or steel) or plastic materials (e.g., polytetrafluoroethylene (PTFE) or polyethylene terephthalate (PET)) can be used to form the substrate layer. Both polyvinylidene fluoride (PVDF) and PZT can be used to form the piezoelectric layer. Fig. 1 shows a schematic diagram of a piezoelectric cantilever. The neutral plane, which is not under stress, is a conceptual plane within the piezoelectric cantilever structure. Two wires are connected to the top and bottom surfaces of the piezoelectric layer, where the orange regions shown in Fig. 1(a) indicate the joint regions between the wires and the piezoelectric cantilever. One end of the piezoelectric cantilever is fixed, while the other end is free. When immersed in an otherwise uniform axial flow, the cantilever may flutter with a large amplitude and at high frequency if the flow velocity is high enough [19], thereby ensuring that it is capable of generating electrical energy. Flutter is a self-excited motion that occurs when structural damping is insufficient to damp motion caused by aerodynamic effects [20]. Watanabe et al. [21] studied the vibration characteristics of flexible cantilevers and found that the vibration frequency and vibration order of the cantilever both change with increasing wind speed. When the vibration frequency of the piezoelectric cantilever is equal to its resonance frequency, the vibration amplitude and the output power reach peak values. Fig. 1(b) shows an example of first-order vibration of the cantilever.

Piezoelectric cantilevers are generally used to harvest wind energy because they can flutter when subjected to flow loads. When the piezoelectric cantilever flutters, bending stress is generated within the piezoelectric layer. The induced strain is then converted into electrical charge within the piezoelectric layer [22]. Enhancement of the output powers of piezoelectric cantilevers is a hot research topic at present. Because the amount of charge generated is proportional to the magnitude of the stress, researchers have mainly focused on methods to increase the stress in the piezoelectric layer to date. For example, Zou et al. [23] designed a piezoelectric cantilever with a tip proof mass to increase the stress. However, few researchers have analyzed the stress in the piezoelectric layer of the piezoelectric cantilever from the perspective of its neutral plane. Because the stress of the piezoelectric layer is affected by the position of the neutral plane and because the neutral plane's position is determined by both the substrate layer and the piezoelectric layer material, changes in the substrate layer or the piezoelectric layer affect the output of the resulting piezoelectric cantilever. Therefore, the output power of the piezoelectric cantilever must be known to enable analysis of the effect of the neutral plane's position via calculations, simulations and experiments.

2. Research background

The piezoelectric cantilever can harvest wind energy from a wind filed. When the piezoelectric cantilever flutters in the wind field, it converts the wind energy into mechanical energy. The piezoelectric layer is periodically subjected to tensile and compressive stresses, and the top and bottom surfaces of the piezoelectric layer then periodically generate positive and negative charges via the piezoelectric effect, which can convert the vibrational energy into electrical energy. In the piezoelectric cantilever, the low-order vibration plays a leading role even at a relatively high wind speed. In this work, to simplify the required mathematical model, only the vibrations of the piezoelectric cantilever at low-order natural frequencies (i.e., first order or second order) are analyzed.

A displacement called the tip deflection d occurs when the tip of the piezoelectric cantilever is subjected to an external force. Tan [24] studied the outputs of piezoelectric energy harvesters and determined that the open-circuit voltage V that is generated by a vibration-based piezoelectric wind energy harvester can be estimated based on the tip deflection d of the piezoelectric cantilever, which can be expressed as

$$V=\frac{9d_{31}EI}{2\varepsilon_{33}L^{3}wt(1-k_{31}^{2}/4)}d \tag{1}$$

Here, Eq. (1) indicates that the output voltage of the piezoelectric cantilever is closely related to its vibration amplitude. A higher vibration amplitude should theoretically lead to a higher output voltage from the piezoelectric cantilever. Therefore, the stiffness of the piezoelectric cantilever should be reduced to maximize the vibration amplitude under a constant wind load.

As mentioned above, piezoelectric cantilevers are composite devices composed of a piezoelectric layer and a substrate layer. Selection of a material with low stiffness to act as the substrate layer can reduce the integral stiffness of the piezoelectric cantilever; furthermore, removal of the substrate layer can also reduce the integral stiffness significantly. Because the vibration amplitude of the piezoelectric cantilever increases as its stiffness decreases, the electrical output of the harvester should be improved by simply removing the substrate layer to maximize the vibration amplitude. The substrate-free piezoelectric cantilever used here consists of piezoelectric layers only, with no substrate layer, and its output voltage in a wind field is shown in Fig. 2. The test results demonstrate that this substrate-free piezoelectric cantilever flutters strongly in the wind field (at a low wind velocity), but also show that it has an output voltage that is close to zero, which is the opposite to the expected result. Therefore, it is proposed that a d_{31} mode piezoelectric cantilever must consist of a composite beam. The composite beam's neutral plane and its mid-plane are not located in the same plane. The neutral plane's position affects the cancellation of the positive and negative charges in the piezoelectric layer, which is why the substrate-free piezoelectric cantilever generates hardly any electricity, while composite piezoelectric cantilevers can produce higher output voltages.

3. Modeling and theoretical derivation

In material mechanics, a neutral plane is a conceptual plane within