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Energy harvesting from vibration of Timoshenko nanobeam under base excitation considering flexoelectric and elastic strain gradient effects

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A B S T R A C T

The coupling between polarization and strain gradients is called flexoelectricity. This phenomenon exists in all dielectrics with any symmetry. In this paper, energy harvesting from a Timoshenko beam is studied by considering the flexoelectric and strain gradient effects. General governing equations and related boundary conditions are derived using Hamilton's principle. The flexoelectric effects are defined by gradients of normal and shear strains which lead to a more general model. The developed model also covers the classical Timoshenko beam theory by ignoring the flexoelectric effect. Based on the developed model, flexoelectricity effect on dielectric beams and energy harvesting from cantilever beam under harmonic base excitation is investigated. A parametric study was conducted to evaluate the effects of flexoelectric coefficients, strain gradient constants, base acceleration and the attaching tip mass on the energy harvested from a cantilever Timoshenko beam. Results show that the flexoelectricity has a significant effect on the energy harvester performance, especially in submicron and nano scales. In addition, this effect makes the beam to behave softer than before and also it changes the harvester first resonance frequency. The present study provides guidance for flexoelectric nano-beam analysis and a method to evaluate the performance of energy harvester in nano-dielectric devices.

1. Introduction

The flexoelectric effect was discovered in the mid-20th century. However, it was ignored by researchers for a long time because of its insignificant effect in macroscopic level. Piezoelectricity only exists in central asymmetric materials; however, strain gradients can locally break central symmetry and induce polarization even in centrosymmetric crystals. It is called flexoelectricity. It is noticeable that most of references and studies on the flexoelectricity have been concerned with its nature while the application of this effect, such as energy harvesting, crack detection in structures and etc. has been neglected to a large extent.

The review part of this study was carried out in two parts. First, theoretical and experimental studies on flexoelectricity are mentioned. Second, a brief review of energy harvesting from piezoelectric materials is presented in terms of interest field of this study.

In 1964, Kogan [1] introduced a phenomenological description for electric polarization due to strain gradient in solid crystals. Later, Indenbom proposed the flexoelectricity for liquid crystals [2]. In the 1980s, Tajantsev [3] conducted a broader

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study on the flexoelectric effect based on lattice dynamics theory and he presented an explicit expression for the coefficients of flexoelectricity. Using lattice dynamics prediction and Tajantsev theory, numerous studies have been conducted concerning flexoelectricity. Marangati et al. [4] evaluated the effects of flexoelectricity and non-local size effects associated with non-uniform strain. Next, Majdoub [5] utilized molecular dynamics method to explain the flexoelectric effect, and he analyzed size-depended elastic and piezoelectric behavior which depend on the size. In contrast to previous developed theories on hard ceramic crystals, Deng et al. [6] extended the nonlinear theoretical framework of flexoelectricity due to soft materials and biological membranes.

Experimental measurement of the flexoelectric coefficients of ferroelectric materials is another issue that can be referred to it [7]. The results suggested that perovskite ferroelectrics may exert stronger flexoelectric effect than lattice dynamics predictions. Theoretically and computationally, the variation principle is utilized for calculation of electromechanical problems for a long time. Hu and Shen [8] offered the variation principle basis of electric enthalpy for nano-sized dielectrics. With introducing flexoelectric effect, Shuling et al. [9] studied nano-scale dielectric with concurrent consideration of polarization gradient, strain gradient, and effects of electrostatic force. They obtained governing equations such as the electrostatic force using variation principle. Yan et al. [10] investigated the flexoelectric effect on the static bending and free vibration of a simply supported piezoelectric nanobeam.

The process of obtaining energy from the environment and converting it into usable electrical energy is called energy harvesting. Among different mechanisms that convert mechanical energy (vibrations) into electrical energy, the piezoelectric mechanism has attracted attention due to ease of use. There are numerous literature reviews of this mechanism in terms of certain intrinsic properties of electromechanical coupling (e.g. high power density) [11,12].

Providing a discrete model consists of mass, spring and damper, Mikio et al. presented the first model for energy harvesting [13]. In next years, Roundy et al. improved the previous developed models [14]. Ajitsaria et al. investigated on a bimorph piezoelectric cantilever beam using assumptions of Euler-Bernoulli and Timoshenko beam and they presented an analytical solution for the harvesting problem [15]. According to studies of some researchers on the cantilever piezoelectric energy harvester, Erturk and Inman [16] presented an analytical solution for bimorph beams with series and parallel layers. The expression for closed form steady state was developed at arbitrary frequencies of harmonic excitation and electromechanical frequency response was defined based on from single- and multi-mode solutions. Junior et al. [17] presented an electromechanical finite element model for piezoelectric energy harvester plates. They expressed a finite element plate model to predict the output electric power of piezoelectric harvester plates based on Kirchhoff plate assumptions. Finally, they validated their finite element model by analytical solution. In piezoelectric energy harvesting topic, Cheng et al. [18] investigated the beam energy harvester made of an aluminum substrate surface bonded with piezoelectric patches and a stack actuator. They achieved an effective energy harvesting knowledge with a new frequency self-tuning method. The natural frequency of the harvester is tuned by the function of the stack actuator. They utilized an iterative numerical technique to solve the dynamic response and the produced electric charge in order to present the energy harvesting and the self-tuning process. They studied the sizes of the piezoelectric patch and its effects on the energy harvester performance. Their results show that the self-tuning process is very important and significantly increases the power output by several times. Finally, the effectiveness of the proposed self-tuning method is validated with finite element method.

De Paula et al. [19] illustrated influences of nonlinearities in the energy harvesting from a piezo-magneto-elastic structure subjected to random vibrations. In their research, numerical studies enable comparison of generated voltages by single-stable and bi-stable linear and nonlinear systems. Recently, Leng et al. [20] studied a tri-stable piezoelectric energy harvester with external magnets. They employed a method based on equivalent magnetizing current theory to evaluate the magnetic force and the potential function with triple wells. They explored that the method is appropriate for different magnet intervals. They applied Gaussian noise for excitation of the harvester (random excitation). Results show that the TPEH's frequency bandwidth is broader than BPEH and improves the output voltage compared to BPEH.

On the other hand, development of technology in the field of electronic circuits enabled design and manufacturing of electronic devices with very low energy consumption and small dimensions. Therefore, the novel use of empowering micro and nano-systems without batteries is most favored. The use of vibrational energy to generate the power for low-power devices such as micro and nano-electromechanical systems has attracted a lot of attention [21,22]. Thus, many research activities have been conducted concerning piezoelectric energy harvesting. For example, Muralt and Xu studied piezoelectric energy harvesting of micro and nano-scales developing thin ferroelectric films and non-ferroelectric nanowires [23,24]. In another study, Deng et al. [25] addressed the Euler-Bernoulli beam energy harvesting based on a mathematical framework for flexoelectric coupling. In this study, linear constitutive equations are used to describe the elastic, dielectric and flexoelectric behavior of different materials. Wang et al. [26] developed an analytical model for unimorph Euler-Bernoulli piezoelectric energy harvester, which includes the flexoelectric effect. Their research was carried out on the nanoscale with the desired length and position of the piezoelectric layer. Approximate solution has been obtained to check the output voltage, power and load resistance optimum. The results showed that the maximum power output of the model with flexoelectric effect is several times more than the classic model that has only piezoelectric effect. Also, in their study, methods have been proposed to increase the efficiency such as appropriate length of the piezoelectric layer.

Based on the review of previous studies, analysis of dynamic behavior of beams at nano-scale requires consideration of flexoelectricity effect and study of this effect in small scales is necessary due to larger strain gradient in such scales. Up to now, a few researches on flexoelectric effect and in particular its ability in energy harvesting has been carried out. Works are often concentrated on flexoelectric nature and conducted researches on its application such as energy harvesting have used simple