International Journal of Engineering Science 116 (2017) 88–103

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Non-linear flexoelectricity in energy harvesting

K.F. Wang[a,*], B.L. Wang[a,b]

[a] Graduate School at Shenzhen, Harbin Institute of Technology, Harbin 150001, PR China
[b] Centre for Infrastructure Engineering, School of Computing, Engineering and Mathematics, Western Sydney University, Penrith, NSW 2751, Australia

ARTICLE INFO

Article history:
Received 23 September 2016
Revised 13 February 2017
Accepted 17 February 2017

Keywords:
Nonlinear vibration
Energy harvesting
Flexoelectric effect
Piezoelectric effect
Geometric nonlinearity

ABSTRACT

Efficiently converting vibration energy from surrounding environment to electric energy for powering micro/nano-electromechanical systems (MEMS/NEMS), without using batteries, is an interesting research subject. One of the most important applications of flexoelectricity is in the field of transducers in energy harvesters where flexoelectric effect is significant at micro/nano-scale. In this paper, a theoretical model incorporating flexoelectricity and piezoelectricity for energy harvesting is developed. The model includes geometric nonlinearity deformation and damping effect so that it can more accurately predict the electromechanical behavior of energy harvesters. A special case study for a cantilever beam (which is the most common configuration of vibration energy harvesters) is carried out. Two types of commonly-used cantilevered energy harvesters, a single layer and a unimorph energy harvester, are derived. It is found that, in some cases, voltage output contributed by flexoelectric effect is extremely (e.g., five times) higher than that solely contributed by piezoelectric effect.

1. Introduction

Harvesting energies from ambient mechanical vibrations has received enormous attentions in recent years (Elvin & Erturk, 2013; Hudak & Amatucci, 2008). This focus is due to the low power requirement of small electronic devices, such as micro/nano-electromechanical system (MEMS /NEMS) (Zhou, Liao, & Li, 2005) and sensors(Inman & Grisso, 2006; Roundy & Wright,2005). Converting vibration energy to electric energy for powering small electronics could decrease the requirement of external powers such as batteries, thus reducing the associated costs (Anton & Sodano, 2007). On the other hand, piezoelectric materials are commonly-used for such energy harvesting(Oudich & Thiebaud, 2016; Abdelkefi, Nayfeh, & Hajj, 2012a,2012b; Erturk & Inman, 2008; Abdelkefi & Barsallo, 2016; Kim et al., 2016; Changki, Joseph, & William, 2014). This is largely due to their efficient translation of mechanical energy into electrical energy and easy application. Micro/nanoscale piezoelectric energy harvesters are also attracting enormous attentions from researchers, due to the developments in ferroelectric nanofilms (Jeon, 2005; Muralt, Polcawich, & Trolier-McKinstry, 2009) and non-ferroelectric nanowires (Wang & Song, 2006; Xu et al., 2010). For example, with consideration of nonlinear strain, Rafiee, He, and Liew (2014) analyzed the energy harvesting of nanocomposite plate. Wang and Wang (2014) analyzed the effect of surface energy on the energy-harvesting performance of a piezoelectric circular nanomembrane.

Recently, flexoelectricity has attracted surge of attentions from both fundamental science and technological applications points of view leading intensive experimental (Cross, 2006; Ma & Cross, 2003,2006; Catalan, Sinnamon, & Gregg, 2004)

---

[*] Corresponding author.
E-mail address: wangkaifa@hitsz.edu.cn (K.F. Wang).

http://dx.doi.org/10.1016/j.ijengsci.2017.02.010
0020-7225/

and theoretical studies (Chen, Zheng, Feng, & Wang, 2015; Shen & Hu, 2010; Majdoub, Sharma, & Cagin, 2008a,2008b; Sharma, Landis, & Sharma, 2010, 2012). Piezoelectric effect only exists in crystalline materials and describes the relationship between mechanical strain and electric field, and vice versa. Unlike piezoelectric effect, flexoelectric effect exists in all dielectrics where strain gradients can induce electric polarization and conversely electric polarization gradient induces mechanical strain (Batchko, Shur, Fejer, & Byer, 1999). At micro/ nanoscale, strain gradient can easily obtained high values therefore flexoelectricity is significant. Therefore, the electromechanical properties of micro/nanomaterials are different from that of macro materials. For example, the so-called "piezoelectric effect" of nanobeams ($BaTiO_3$) with a thickness of 5 nm experienced inhomogeneous strain is almost five times that of macro $BaTiO_3$ (Majdoub et al., 2008a), due to contribution of flexoelectricity. Researchers have advocated some potential applications based on the exploitation of flexoelectricity. For example, Sharma et al. (2010), Chandratre and Sharma (2012) and Fu, Zhu, Li, Smith, and Cross (2007) suggested the creation of so-called "piezoelectric materials" without using piezoelectric materials. Majdoub et al. (2008a,2008b) enhanced piezoelectricity of nanostructures by introducing inhomogeneously deformed. Deng, Kammoun, Erturk, and Sharma (2014) and Wang and Wang (2016) investigated flexoelectric energy harvesters. Flexoelectricity is also used to explain the size-dependent electromechanical coupling behavior of nanoscale materials, such as nanobeams(Yan & Jiang, 2013a,2013b) and nanoplates(Zhang, Yan, & Jiang, 2014).

On the other hand, electric fatigue is a commonly encountered obstacle for some potential applications of piezoelectric materials. It is found that the switching polarization in some piezoelectric materials decays with increasing number of switching cycles (Jiang, Cao, & Cross, 1994). Although the mechanism for electric fatigue is not well understood, some possible factors includes: the porosity (Jiang et al., 1994) and the appearance of microcracks(Kim & Jiang, 1996). Cracks in piezoelectric materials have been widely investigated (Zhou, Wu, & Wang, 2005a,2005b,2007; Ma, Wu, Zhou, & Guo, 2005a,2005b; Ma, Li, Abdelmoula, & Wu, 2007; Guo, Wu, Zeng, & Ma, 2004; Guo, Wu, & Zeng, 2004). Using of flexoelectricity, which exits in all dielectrics, provides more choice for us to select some materials with higher fatigue resistance.

Because of small scale displacements and motions, nonlinearity of structures becomes important when more accurate measurement is needed. Researchers have shown that nonlinearity could significantly affect the behaviors of micro/nano structures, such as vibration of micro/nanobeams (Mojahedi & Rahaeifard, 2016; Sahmani, Bahrami, & Aghdam, 2016; Dai, Wang, & Wang, 2015) and plates (Wang, Kitamura, & Wang, 2015; Ghayesh & Farokhi, 2015) and electromechanical coupling behavior of micro/nano piezoelectric energy harvesters(Rafiee et al., 2014). Moreover, the nonlinear characteristics can be explored to improve the energy harvesting performance of vibration energy harvesters (Cottone, Vocca, & Gammaitoni, 2009; McInnesa, Gormana, & Cartmell, 2008; Mann & Sims, 2009; Erturk & Inman, 2011; Harne & Wang, 2014; Tehrani & Elliott, 2014). For example, the power output peak value and bandwidth of a vibration energy harvester with bi-stable oscillator have been much improved (Mann & Sims, 2009; Erturk & Inman, 2011), due to the nonlinear stiffness and damping characteristics. The nonlinearity of coupled beam structures subject to impacts was also investigated (Vijayan & Woodhouse, 2014; Vijayan, Friswell, Khodaparast, & Adhikari, 2015). It is found that the energy harvesting system employing nonlinear vibration-impacting can outperform the corresponding linear system in a wider frequency range. Combining the mode coupling effect and the nonlinear characteristics of the X-shaped structures, Liu and Jing (2016) found that the vibration energy harvesting performance of the X-shaped structures can be significantly enhanced, both in the frequency range and broadband spectrum. In their work, they also found that the proposed 2-DOF nonlinear vibration energy harvester can achieve a better harvesting performance than the corresponding 2-DOF linear one. Abdelkefi (2016) suggested that the risks and potential of energy harvesting can be best evaluated from assessing its nonlinear responses. Recently, Zhou, Gao, Liu, and Guan (2017) found that by introducing nonlinear components, the output performances of hybrid energy harvesters under random excitation can be improved effectively. Pasharavesh and Ahmadian (2017) found that the operational bandwidth of the nonlinear harvester is enhanced considerably with respect to linear models.

At nanoscale, both flexoelectricity and geometric nonlinearity could significantly affect the electromechanical coupling behaviors of nanostructures. Naturally, it is important to establish analysis models to simultaneously combine the flexoelectricity and geometric nonlinearity to study the electromechanical coupling behaviors of micro/nano energy harvesters. Unfortunately, such models do not exist at this time.

Motivated by above considerations, this paper establishes a nonlinear theoretical analysis model for micro/nanoscale flexoelectric energy harvesting. The paper is organized as follows: Section 2 applies flexoelectricity and piezoelectricity effects to the geometrically nonlinear deform of materials to form the theoretical base of the analysis.

Section 3 presents a case study for a cantilevered flexoelectric energy harvester which is a most common configuration of energy harvesters. The reduced-order models for both single layer and unimorph energy harvesters are derived by using the Galerkin method. Method of multiple time scale is applied to solve the nonlinear reduced-order model. In Section 4, some important factors, such as excitation amplitude, damping ratio, resistor and thickness of the piezoelectric layer, which could considerably affect the electromechanical behavior of the energy harvester, are discussed. Conclusions are drawn in Section 5.

2. Nonlinear model incorporating flexoelectricity

The system is nonlinear in nature and has strong mechanical and electrical coupling. In order to obtain the governing equations of the system, the variational principle can be used. For flexoelectric materials, the following equation must hold