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Sandwich piezoelectric energy harvester: Analytical modeling and experimental validation

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ABSTRACT

Piezoelectric energy harvesting from ambient vibration sources has great potential for powering microelectronic devices and wireless sensors. Almost all the conventional piezoelectric energy harvesters (CPEHs) in the literature have been designed with a single metallic layer as substrate along with the piezoelectric material bonded over it. In this work, a novel sandwich structure is used as substrate for designing harvester. The substrate structure comprises of a soft-core material sandwiched between metallic layers. The proposed sandwich piezoelectric energy harvester (SPEH) has lower resonant frequency and generates higher voltage output than the CPEH with the same geometrical dimension. Furthermore, the SPEH offers high design flexibility in terms of tuning the resonant frequency through selection of materials and geometric parameters for the core and metal layers. The mathematical formulation of a generalized electromechanical model of the SPEH is developed using the Lagrange approach. The natural frequencies, displacement and voltage frequency response functions of the harvester are obtained analytically. A single-degree-of-freedom model for the SPEH is also derived. Subsequently, the analytical modeling is validated by finite element simulations and experimental results. When excited at 0.1 g, the SPEH generates 18.8% more voltage output at resonance as compared with a CPEH with the same geometrical dimension and tip mass accompanied by 24% reduction in resonant frequency. At 30 Hz resonance frequency, CPEH generates open-circuit voltage 17.6 V using 15 g of tip mass whereas SPEH uses only 8.2 g of tip mass to generate 16.6 V. SPEH generates 130.8 μW, 426.6 μW and 1158.0 μW at base accelerations 0.05 g, 0.1 g and 0.2 g with optimal resistance, respectively. Finally, the influence of geometric and material properties of core and metallic layers on the performance of SPEH are analyzed comprehensively. The proposed novel SPEH together with its analytical modeling is intended to serve as a basis for future sandwich harvester designs.

1. Introduction

In recent years, low-power electronic devices and wireless sensors [1,2] have been increasingly deployed with the rapid development of smart systems and structures. These devices and sensors are commonly powered by chemical batteries which require periodic replacement that results in considerable maintenance cost. More importantly, chemical batteries commonly produce hazardous substances and contaminate the environment. Energy harvesting [3–13] from structural vibrations or other ambient energy can be an alternative solution for replacing chemical batteries. Piezoelectric energy harvesters (PEHs) [3–7,13] have drawn much attention as they are pollution-free as compared with fuel energy for powering low-power electronic devices and wireless sensors. Moreover, piezoelectric transduction mechanism has a higher power density when compared with other vibration-to-electricity transduction mechanisms [3]. In general, a PEH comprises of a substrate and a patch of PZT composite (PZT-5A or PZT-5H) [3,9,11] or macro fiber composite (MFC) [8,10,12] bonded over the substrate.

Most of the PEHs are linear designs and generate useful power output only near the resonant frequency. At the same time, most of mechanical devices generate vibrations in the low frequency range (10–200 Hz), which distribute over a frequency interval [14]. Therefore, enhancing the power output at low frequencies and broadening the bandwidth of the PEHs are the key challenges for practical implementation of this technology.

Erturk and Inman [15] presented an exact analytical solution of a cantilevered PEH based on the Euler–Bernoulli beam theory and a parametric study for a unimorph harvester was investigated in detail.

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Nomenclature

L	length of the sandwich beam
b	width of the sandwich beam
d_t	thickness of the top face
d_c	thickness of the core
d_b	thickness of the bottom face
d_p	thickness of the piezoelectric layer
E_t	Young's modulus of the top face
E_c	Young's modulus of the core
E_b	Young's modulus of the bottom face
E_p	Young's modulus of the piezoelectric layer
G_c	shear modulus of the core
ρ_t	density of the top face
ρ_c	density of the core
ρ_b	density of the bottom face
ρ_p	density of the piezoelectric layer
w_b	base excitation
u_{t0}	axial displacement of the middle plane
w	transverse displacement of the mid-plane
ψ	cross-section rotation
u_t	displacement in x direction of the top face
u_c	displacement in x direction of the core
u_b	displacement in x direction of the bottom face
u_p	displacement in x direction of the piezoelectric layer
ε_{txx}	normal strain of the top face
ε_{cxx}	normal strain of the core
γ_{cxz}	shear strain of the core
ε_{bxx}	normal strain of the bottom face
ε_{pxx}	normal strain of the piezoelectric layer
σ_{txx}	normal stress of the top face
σ_{cxx}	normal stress of the core
τ_{cxz}	shear stress of the core
σ_{bxx}	normal stress of the bottom face
σ_{pxx}	normal stress of the piezoelectric layer
U	total strain energy
T	total kinetic energy
W_{ie}	internal electrical energy
C_p	internal capacitance of the piezoelectric layer
φ_m	basic mode shape function for transverse displacement
α_m	basic mode shape function for axial displacement
β_m	basic mode shape function for cross-section rotation
a_m	unknown generalized coordinate for transverse displacement
b_m	unknown generalized coordinate for axial displacement
c_m	unknown generalized coordinate for cross-section rotation
A	complex value of transverse displacement
B	complex value of axial displacement
C	complex value of cross-section rotation
f_i	force component
$\zeta_m^{a(b,c)}$	electromechanical coupling coefficient
v	voltage output
V	complex value of voltage
Q	electric charge output
R	resistance
$\mathscr{L}$	impedance matrix
P	power output

Subsequently, they introduced a correction factor [16,17] to modify the commonly used single-degree-of-freedom (SDOF) model to improve the accuracy of the SDOF model for both transverse and longitudinal vibrations. Tang and Yang [18,19] developed an equivalent circuit model using the analogy between electrical and mechanical domains to study PEHs with complex mechanical structure and nonlinear electronic circuitry. They focused on two configurations of 2-DOF model and obtained an optimized configuration to achieve two close and effective power peaks in frequency response. Finite element modeling has been used for study of piezoelectric harvester systems for which mathematical modeling is difficult or time consuming [20]. Wu et al. [21,22] proposed a two-degree-of-freedom PEH comprised of one main cantilever beam and one inner beam and the first two resonances were tuned close to each other by varying the tip masses. Wang and Tang [23] studied a 2-DOF PEH with magnetic coupling by attaching a linear parasitic oscillator to the main energy harvesting beam. Zhou et al. [24] proposed a flexible longitudinal zigzag PEH to harvest ambient vibration energy from low frequency vibration sources. The harvester comprised of orthogonally oriented beams harvesting energy in two directions. Abdelmoula et al. [25] derived and validated experimentally a zigzag PEH with torsion-bending characteristics for low frequencies (< 100 Hz). It was found that the torsion-dominant mode decreased the operating frequency and enhanced power output at low excitation frequencies. Izadgoshasb et al. [26] studied the effect of orientation of the cantilever beam with tip mass on the efficiency of the power generated from human motion.

The harvester designs proposed so far in the literature comprise of a single metal layer as substrate with piezoelectric material bonded over it partially or fully. Big tip masses or big structures are usually used to harvesting low frequency vibration energies. However, energy harvesters with higher system mass and volume have lower power density, which are not preferred as a source of power for portable electronics and wireless sensors. Actually, the performance of the harvester including the open circuit voltage, power and power density can be improved through structural and material optimization. Replacing the middle part of the substrate along the thickness direction by soft materials can reduce the resonant frequency and enhance the voltage output of the PEH. Therefore, a novel PEH with sandwich substrate is proposed in this paper. The proposed sandwich piezoelectric energy harvester (SPEH) has lower resonant frequency and higher voltage output than the conventional energy harvester with the same geometric parameters including the weight of tip mass. SPEH offers wide design flexibility to achieve the same resonant frequency as the conventional harvester with much less system mass and volume and also achieves better performance in terms of power density. The objective of the study is to use sandwich structures instead of conventional metal substrates to improve the performance of piezoelectric harvester in terms of open-circuit voltage, power output, system mass and volume reduction.

A sandwich structure [27] results from bonding or welding of two thin face sheets on a core material. The sandwich structure has good designability and it can have excellent thermal insulation, noise reduction and other properties by selecting the appropriate core material. A sandwich structure can be used as the substrate of PEH by proper selection of the core material to enhance the power output of the harvester. Rao and Desai [28,29] presented a mixed theory assuming a nonlinear variation of axial displacements through the thickness to study the vibration characteristics of sandwich plates and results were in good agreement with those derived by three-dimensional elasticity solutions. Frostig and Thomsen [30,31] presented the free vibration analysis of sandwich structure with a soft core with temperature-dependent mechanical properties based on the high-order sandwich theory. Frostig and Phan [32,33] studied the free vibration response of the unidirectional sandwich structure by applying various models and compared them with closed-form elasticity solutions and finite element results. Li et al. [34] developed a piecewise shear deformation theory for composite and sandwich structures. Subsequently, they [35–37] studied the vibro-acoustic response of the sandwich structure in