Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 120 (2015) 345 – 348

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2015

A Flexible Piezoelectric Energy Harvesting System for Broadband and Low-frequency Vibrations

Hasan Göksenin Çetin[a], Bilsay Sümer[a,*]

[a]*Mechanical Engineering Department, Hacettepe University, Beytepe, Ankara 06800, Turkey*

Abstract

A piezoelectric energy harvesting system, where elastomer pillars stand on a piezoelectric polymer layer is designed, fabricated and tested for low and broadband frequency vibrations. In this configuration, elastomer pillars behave like a set of oscillators on the vibrating structure, which provide absorption of vibration energy and act as an energy sink. Then, the stored elastic energy is converted to electrical energy in the clamped boundary via stress concentration on the piezoelectric layer. A single pillar system with 10 mm diameter and aspect ratio of 3 with an active area of 39 mm^2 and thickness of 28 µm generate a voltage of 4.5 V and an output power of 58.4 µW for an input acceleration of 3 g at 62 Hz with optimized load resistance condition.

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015

Keywords: Piezoelectric energy harvesting; Elastomer; Multi-frequency

---

1. Introduction

Nowadays, the usage of batteries tends to decrease for sensor feeding since they have limited lifetime, require recharging and replacement, complicated and expensive recycling operation. Besides that, energy harvesting has become important for powering small electronic devices (SED) such as battery-less sensors by using scavenged ambient energy. Primary energy sources available in the environment can be listed as solar, thermal, wind, acoustic and mechanical energies. Although solar, thermal and wind energy have higher power output capacities such as in scale of kW, they are not practical for powering SED due to their requirement of large surface areas and dependence

---

* Corresponding author. Tel.: +903122976207-118; fax: +903122976208.
E-mail address: bsumer@hacettepe.edu.tr

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015
doi:10.1016/j.proeng.2015.08.631

on weather conditions [1]. However, mechanical vibrations can be used as an energy source of such devices which require power in the order of μW. Three principal mechanisms including electrostatic, electromagnetic and piezoelectric are widely used for transforming vibration energy into electrical energy. Since piezoelectric materials have higher energy density capacities, no requirement for an external power source, producible in small sizes and are suitable for low frequency vibration applications, they become very popular in vibration based energy harvesting systems (EHS) for self-powered SED [2]. A common configuration of the piezoelectric energy harvesters is to sandwich an elastic layer between two rigid piezoelectric layers which is called a bimorph structure [3].

There are several ways to improve the power output and efficiency of piezoelectric energy harvesters such as tuning the resonant frequency, increasing the operation bandwidth and optimizing the geometrical parameters of the harvesters. Cornwell *et al.* worked on tuning the resonant frequency of an auxiliary beam to the fundamental mode of a host structure using a proof mass and output power of the harvester was increased by almost a factor of twenty five [4]. Han *et al.* designed a wide band piezoelectric energy harvester using three cantilevers with different lengths and proof masses where three separate voltage peaks were observed at the first bending modes of the cantilever beams [5].

Many previous studies showed that piezoelectric ceramics generate more power than polymers, since they have larger electromechanical coupling factor [6]. However, piezoelectric polymers have a unique property of flexibility. In a recent study, output voltages of PVDF and PZT harvesters are compared experimentally under variable wind speeds and water droplet weights. As a result, PVDF harvester generated more power than PZT one, since it undergoes larger deformation due to its flexibility, while rigidity of piezoelectric ceramic hinders the oscillation of the structure [7].

Unlike prior efforts, this paper presents a novel piezoelectric EHS where elastomer pillars with different dimensions stand on a 28 μm thick piezoelectric polymer layer (PVDF). A multiphysics modeling with finite element methods (FEM) is performed to study the modal and steady-state characteristics of the system. In the experimental section, a single pillar and multiple pillars with patterned electrodes are characterized for their power outputs.

2. Modeling and Simulation

EHS designed in this study mainly consists of elastomer pillars (polydimethylsiloxane (PDMS) or polyurethane (PU)) and a piezoelectric polymer layer (PVDF). In this configuration elastomer pillars behave like a set of oscillators on the vibrating structure, which provide absorption of vibration energy and act as an energy sink. Then, the stored elastic energy is converted to electrical energy in the clamped boundary via stress concentration on the piezoelectric layer (Fig. 1.a). The layer consists of electrodes which are patterned in a half-electrode configuration. In case of a lateral vibration of a pillar, the bending stresses acting on the interface between pillar and piezoelectric layer are in compression in one side and tension in the other side with respect to neutral axis. Therefore, the objective of configuring half-electrode on the piezoelectric layer is to separate voltage for each stress state. As expected, the charge generation in each side of the electrodes is out of phase due to the stress states under harmonic lateral base excitation according to the numerical analysis as shown in Fig. 1.b.

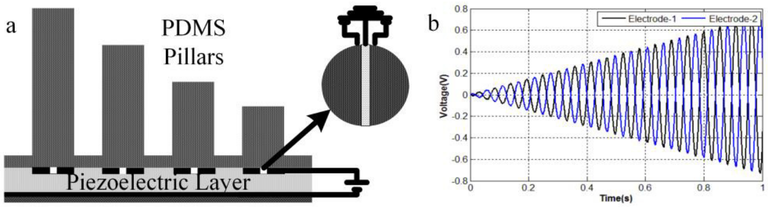

Fig. 1. (a) EHS with half-electrode configuration; (b) Output voltages from each half electrode under undamped harmonic base excitation at the resonance condition according to the FEM.

Finite element model of the EHS is created considering single elastomer pillar with a backing layer standing on a piezoelectric polymer layer. In all type of analysis, boundary conditions are specified such that half electrodes are defined between the bottom surface of the elastomer backing layer and top surface of the piezoelectric layer. Modal analysis is firstly performed in order to determine the natural frequencies of the pillars (Fig. 2.a,b). First resonant frequencies are tuned to 62 Hz and 24 Hz for without and with tip mass configurations, respectively (Fig. 2.c). Then, the effect of the backing layer of elastomer on the output voltage of the system is also investigated. As the thickness of the backing layer increases, first natural frequency of the structure is decreased, whereas output voltage also declines due to the reduction of the transmitted vibration energy to the piezoelectric layer (Fig 2.d). Therefore, the backing layer of the system should be minimized as much as possible in the manufacturing process.

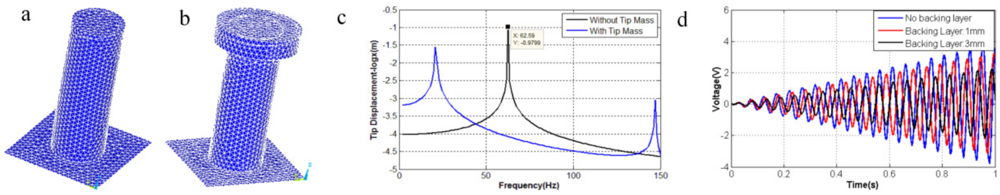

Fig. 2. (a) First mode of pillar without tip mass; (b) First mode of pillar with tip mass; (c) Tip displacement of the pillar in frequency domain; (d) Output voltage of the structure for different backing layer thicknesses.

In time domain analysis, harmonic base excitation is applied laterally at the natural frequency of the structure and output voltage signals are compared by assuming different material properties such as an undamped situation, elastic material with Rayleigh damping or viscoelastic material. Results show that elastic material with Rayleigh damping model has similar damping properties with the viscoelastic material (Fig. 3.a,b).

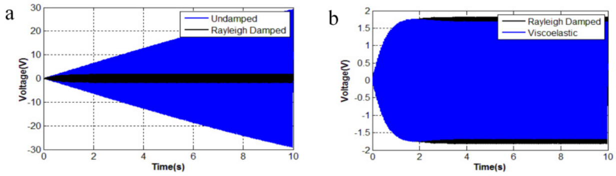

Fig. 3. Output voltage (a) from undamped situation and Rayleigh damping model; (b) from Rayleigh and viscoelastic damping models.

3. Experimental Results and Discussion

The EHS is obtained using a combination of a soft molding and additive manufacturing techniques. Firstly, a polymer plate (politetrafloroetilen) is drilled compatible with the design stage. Then, an elastomer solution (polyurethane or polydimethylsiloxane (PDMS)) is poured on the mold following vacuum and high temperature curing process (71°C). In the meantime, the patterned silver electrodes are patterned on a commercially available PVDF thin film (28 µm) using a screen printing technique. The two layers are aligned and combined using a thin pressure sensitive adhesive layer which has an approximately 10 µm thickness. The structure can be manufactured in single pillar or multiple pillar arrays with same or different aspect ratio configurations (Fig. 4.a,b). A custom-built experimental setup is prepared in order to analyze the performance of the EHS (Fig. 4.c,d). Simply, the experimental setup consists of a signal generator, a vibration shaker, an accelerometer and a data acquisition system.

Different types of base excitations are applied to the backing layer of the pillars in order to get the lateral vibration. First, the output voltage from each half electrode is measured for single pillar case under harmonic base excitation as shown in Fig. 5.a. As expected, the output voltage of one of the half-electrode is out of phase with the other one. The sweep of the frequency reveals that the resonance frequency occurs at 62 Hz which is consistent with the numerical analysis results (Fig. 2.c and Fig. 5.b). In the power measurement experiments, only output of the one half-electrode is considered and the amplitude of the vibration is set to 3 g. Also, the device is tested under different load impedance values where voltage output is observed. A single pillar system with 10 mm diameter and aspect ratio of 3 with an active area of 39 mm^2 and thickness of 28 μm generate an output power of 58.4 μW for an input acceleration of 3 g at resonance condition. Output voltages of four pillars with different heights are also measured under a constant harmonic base excitation at 15 Hz and a magnitude of 1 g (Fig. 5.d). The discrete frequency components are proved that multiple array pillars with different dimensions successfully harvest energy from the multi-frequency vibrations.

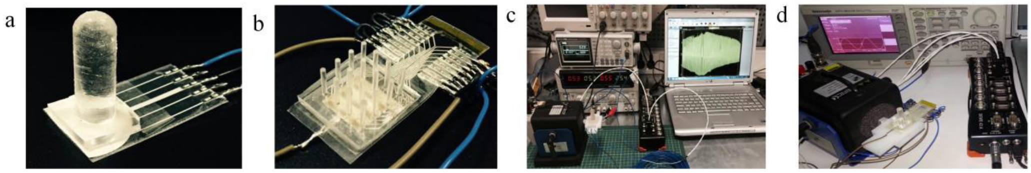

Fig. 4. EHS with (a) single pillar; (b) multiple pillar arrays; (c) Experimental setup for single pillar; (d) Experimental setup for multiple pillars

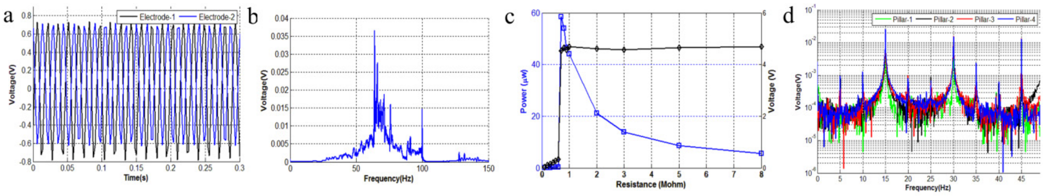

Fig. 5. (a) Voltage signal from each half electrode of the single pillar; (b) FFT of the output voltage from single pillar; (c) Power and output voltage with different resistance values for single pillar; (d) FFT of output voltage from multiple pillar array.

4. Conclusion

In this study, a piezoelectric EHS which provides broadband energy absorption by manufacturing as multiple pillar arrays with patterned electrodes is designed, fabricated and tested. The proposed energy harvester provides broadband energy absorption by manufacturing as multiple pillar with patterned electrodes and tuning the resonant frequencies of each pillar either changing diameter or length. In addition, the system can be mounted on curved shape surfaces and provides a flexible, stretchable and wearable solution to the energy harvesting applications where classical piezoelectric ceramic energy harvesting solutions cannot be applied. Future work includes a study for an optimized energy transfer to the pillars using elastic pillars with low damping ratio.

References

[1] E. Worthington, Piezoelectric Energy Harvesting: Enhancing Power Output by Device Optimization and Circuit Techniques, PH.D, Cranfield University, 2010.

[2] S. Boisseau, G. Despesse, A. Seddik, Electrostatic Conversion for Vibration Energy Harvesting, in: M. Lallart (Ed.), Small-Scale Energy Harvesting, 1st ed., InTech, 2012: pp. 91-134.

[3] S. Roundy, P. K. Wright, A piezoelectric vibration based generator for wireless electronics, Smart Mater. Struct. 13 (2004) 1131–1142.

[4] P. Cornwell, J. Goethal, J. Kowko, M. Damianakis, Enhancing Power Harvesting using a Tuned Auxiliary Structure, J. Intel. Mat. Syst. Str. 16 (2005) 825-834.

[5] M. Han, X. Zhang, W. Liu, X. Sun, X. Peng, H. Zhang, Low-frequency wide-band hybrid energy harvester based on piezoelectric and triboelectric mechanism, Sci. China Technol. Sci. 56 (2013) 1835–1841.

[6] D. Shen, S.-Y. Choe, D.-J. Kim, Analysis of Piezoelectric Materials for Energy Harvesting Devices under High-g Vibrations, Jpn. J. Appl. Phys. 46 (2007) 6755–6760.

[7] D. Vatansever, R. L. Hadimani, T. Shah, E. Siores, An investigation of energy harvesting from renewable sources with PVDF and PZT, Smart Mater. Struct. 20 (2011) 055019.