Flexible energy harvesting from hard piezoelectric beams

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Abstract. This paper presents design, multiphysics finite element modeling and experimental validation of a new miniaturized PZT generator that integrates a bulk piezoelectric ceramic onto a flexible platform for energy harvesting from the human body pressing force. In spite of its flexibility, the mechanical structure of the proposed device is simple to fabricate and efficient for the energy conversion. The finite element model involves both mechanical and piezoelectric parts of the device coupled with the electrical circuit model. The energy harvester prototype was fabricated and tested under the low frequency periodic pressing force during 10 seconds. The experimental results show that several nano joules of electrical energy is stored in a capacitor that is quite significant given the size of the device. The finite element model is validated by observing a good agreement between experimental and simulation results. the validated model could be used for optimizing the device for energy harvesting from earcanal deformations.

1. Introduction

Energy harvesting from human body power can make wearable technologies pervasive by providing alternative, clean, free, and life-long energy sources. Mechanical energy of human body can be transfomed to electrical current running the electronic circuits of wearable devices, more efficiently among others, by piezoelectric devices. For example, piezoelectric transducers can be incorporated in backpacks [1], gloves [2], helmet chinstraps [3], shoes [4] and garments [5] for energy harvesting from different types of human motions. Integration of flexibility and stretchability to wearable piezoelectric generators is the key to make them convenient to wear. Polymer-based piezoelectric materials such as PVDF are intrinsically flexible, but they have a low electromechanical coupling and hence barely efficient for energy harvesting. Ceramic-based piezoelectric materials like PZT are very efficient in terms of energy conversion, but too rigid to conform to the curves of the human body. To tackle this defect, several composite piezoelectric structures have been developed in recent years by integrating piezoelectric ceramics in form of microfibers [6], nanowires [7] or ribbons [8] onto a flexible substrate. However, they present complex mechanical structure, need fabrication of interdigitated electrodes and suffer from the small total volume of the piezoelectric elements contributing to the power output.

This paper reports a new architecture that integrates a bulk piezoelectric ceramic onto a flexible platform for energy harvesting from the human body pressing force. The key advantage of the proposed energy harvesting device is its simplicity of manufacturing while using a bulk PZT beam for the maximum efficiency. Also, the flexible silicon body of the energy harvesting device makes it safe for biomedical applications.

2. Design and finite element modeling

The proposed energy harvesting device consists of a piezoelectric beam cut in form of “I” from a PZT-5A sheet (Piezo Systems Inc, USA) with the square section of 1 mm at the beam stem. Two tiny aluminum washers are placed at two extremes of the beam stem and the whole space between them is molded by a flexible medical grade liquid silicon rubber (MED4910, NuSil Technology Inc., USA) as shown in Fig. 1. Any pressing force applied to the silicon cylinder stretches the piezoelectric beam through the washer caps, and generates an electric charge in response to the applied mechanical stress.

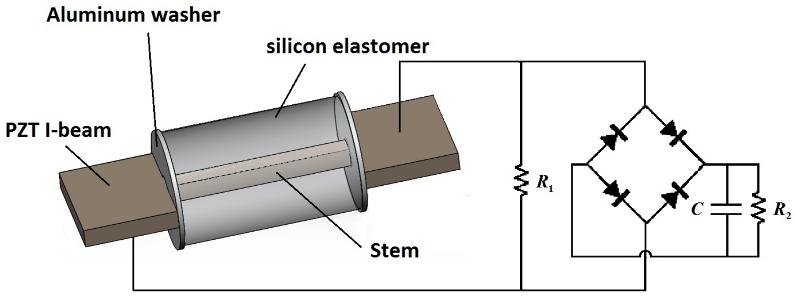


Figure 1. Energy harvesting device

A multiphysic finite element 1/4 symmetric model of the device has been developed in COMSOL and simulated for 10 seconds under the sinusoidal mechanical load with the very low frequency of $f = 1\,\text{Hz}$ that represents the average frequency of normal human motions. The finite element model includes the piezoelectric model of the PZT beam and the linear elastic model of the non-piezoelectric parts. The coupled piezoelectric and mechanical structure models are linked to the electrical circuit model that consists of a diode bridge, a $C = 22\mu F$ capacitor and two resistive loads representing the impedance of the measuring probe (R_1) and the leakage current (R_2) of the capacitor as illustrated in Fig. 1.

3. Prototype and testing

A prototype of the energy harvester was fabricated as illustrated in Fig. 2 and tested by applying controlled deformations using a mechanical wave driver (shaker) as shown in Fig. 3.

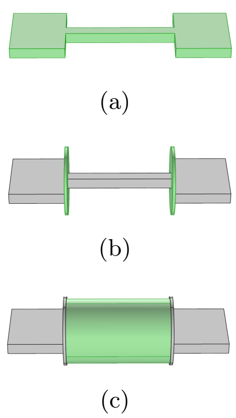


Figure 2. Fabrication steps: (a) PZT cut (b) washer installation (c) silicon molding

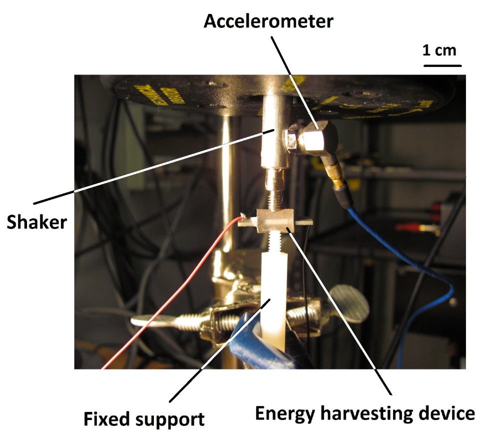
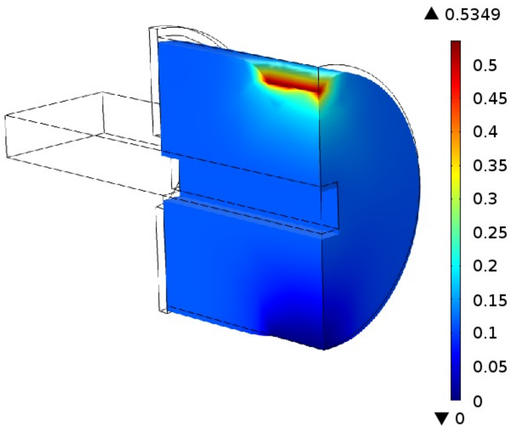


Figure 3. Test setup

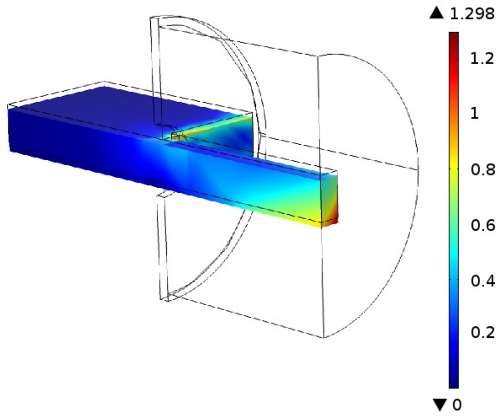
The energy harvesting device is clamped between the shaker arm and a fixed support. An accelerometer is used to measure the displacement of the shaker arm that implies the deformations applied to the energy harvesting prototype.

4. Results and conclusion

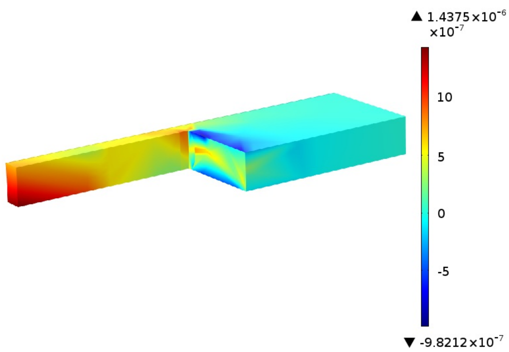
The device is designed for the maximum silicon deformation of 0.5 mm. Figure 4(a) shows the maximum deformation of the silicon body under the transversal pressing force. The von Mises yield criterion is investigated using finite element analysis to make sure that the PZT beam tolerates the applied stresses. The simulation results demonstrated in Fig. 4(b) confirm that the maximum von Mises stresses in the beam is about 1 MPa which is substantially below the tensile strength of PZT-5A (80 MPa). The maximum beam strain and voltage output are also computed and the results are illustrated in Figs. 4(c) and 4(d)



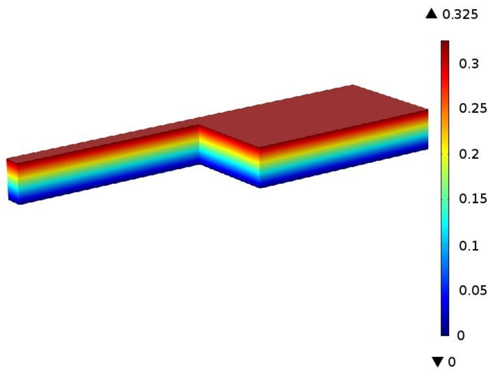
(a) Total deformation (mm)



(b) von Mises stress (MPa)



(c) Axial strain



(d) Voltage output (V)

Figure 4. Finite element modeling of the flexible energy harvesting device

The finite element model is then verified by comparing the experimental and simulation results shown in Fig. 5 and is validated with reasonably little differences between the numerical and measured results. The relatively large amplitude of the voltage output show that the proposed energy harvesting device is efficient in terms of transferring the applied deformation from the flexible medium to the rigid part. Also, the voltage peaks in Fig. 5 are not symmetric in positive

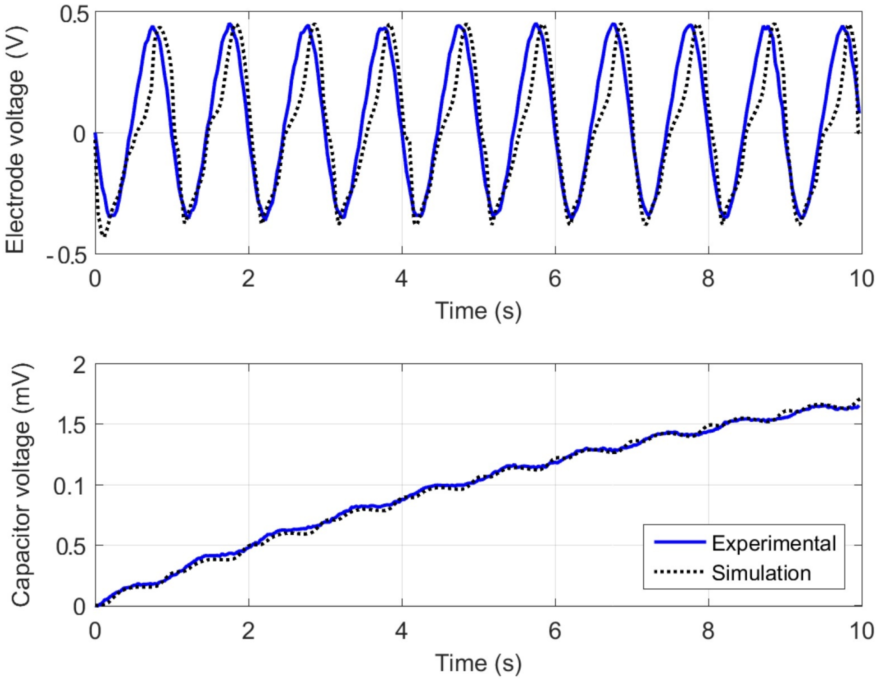


Figure 5. Experimental and simulation results

and negative regions that can be explained by the elastic hysteresis associated with the flexible silicon body.

Moreover, the energy stored in the capacitor is calculated to be $Q = \frac{1}{2}CV^2 \simeq 4\,\mathrm{nJ}$. The developed finite element model could be used to investigate the effect of geometric parameters and electric components on the energy output and enables optimizing the device dimensions and design parameters. The proposed device can be primarily used for energy harvesting from the earcanal deformations, but could also be used for energy harvesting from other human power sources such as heel strikes and finger presses.

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