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Increasing the efficiency of Piezoelectric Energy Harvester Using Trapezoidal Auxetic booster

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Abstract

A model of an auxetic piezoelectric energy harvester consisting of a cantilever, auxetic substrate and piezoelectric layer is developed in this study. Firstly, the auxetic harvester model with an auxetic cell is presented. Harvested power for this model is compared with a plain piezoelectric energy harvester. In the next step, the new auxetic model with trapezoidal geometry is presented. Harvested power of the trapezoidal harvester is compared with a plain harvester and rectangular harvester with an auxetic cell. All the analysis has been performed using the finite element method. Mesh size sensitivity analysis of the models is presented, and the finite element model is verified by previous experimental studies. Present investigation illustrates that harvested power of trapezoidal auxetic energy harvester in resonant frequency could improve to twenty times more than plain harvester. Utilizing trapezoidal auxetic booster as the substrate in piezoelectric energy harvester leads to increasing the density of harvested power of the auxetic energy harvester by 82.5%.

Keywords: Finite element method, Auxetic structures, Piezoelectric energy harvester.

1. Introduction

Energy could be harvested from some sources such as heat, wind, ambient vibrations, magnetic fields, and many others to power wireless sensors for structural health monitoring and wearable electronic devices. The interest in converting vibrations into usable electrical energy has increased rapidly over recent years as the world places a great emphasis on renewable energy to improve our environment and health. Wiring and battery replacement are the challenges of powering sensors such as accelerometers and velocity meters. Self-powered sensors can overcome these challenges by using energy harvesting approaches [1–4]. Compared with other energy harvesting methods such as electromagnetic and electrostatic, piezoelectric energy harvesting has attracted more attention due to its advantages, including simple structure, scalability, and high power output[5]. In the present context, piezoelectric transducers are investigated to convert the mechanical energy of vibration or applied force to electrical energy. This harvested energy could be utilized to power electronic portable devices that are not dependent on traditional methods of energy supply such as lithium batteries [6]. The model of a cantilever beam with a piezoelectric layer has been presented by Ertutk and Inman [7–9]. Their theoretical model had good agreement with the experimental results. They have investigated base excited beam with various form of dynamic loading. Harvesting energy under non-linear vibration and broadband excitation have been studied by Friswell[10] and Adhikari [10]. They have presented a new configuration consisting of a cantilever beam with a tip mass that is mounted vertically and excited in the transverse direction at its base. Siddiqui et al. experimentally investigated the differences in power output between a rectangular and triangular bimorph to evaluate power output, with a goal to understand the controlling parameters most affected with shape change[11]. Zhang et al. [12] utilized trapezoidal cantilever beam for low-frequency piezoelectric energy harvesting. They also presented a theoretical model, optimization method and comparison with experiment. A high-power energy harvester device through a two-piece trapezoidal geometry approach has been designed by Chen and Bedekar [13]. They simulated the performance of the composite two-piece trapezoidal piezoelectric PZT-PZN polycrystalline ceramic material using COMSOL Multiphysics. Another method for increasing the efficiency of piezoelectric energy harvesters and tuning their resonant frequency is utilizing engineered structures such as metamaterials.

Poisson's ratio of a material is the ratio of the lateral contractile strain to the longitudinal tensile strain for a material undergoing tension in the longitudinal direction; it shows how much a material becomes thinner when it is stretched. Therefore, most of the materials have a positive Poisson's ratio. In the case of counterintuitive behavior of the auxetic materials, this kind of material undergoes lateral expansion when stretched longitudinally and becomes thinner when compressed. Auxetic materials offer some unique properties in comparison with the common materials. Classical elasticity theory predicts that auxeticity of materials should lead to enhancements in specific mechanical properties, such as increased plane strain fracture resistance and increased shear modulus, indentation resistance, fracture toughness, and acoustic response compared to conventional materials [14]. In particular, it has been shown that auxetic behavior could be achieved in various highly porous materials, including foams with re-entrant and chiral microstructure, microporous polymeric materials, networks of rigid units, and skeletal structures. Moreover, negative Poisson's ratio has also been shown in non-porous systems, such as laminates, sheets assemblies of carbon nanotubes, composites, and polycrystalline thin films [15]. Li et al. have presented a piezoelectric bimorph with auxetic behaviors for increased power output in vibration energy harvesting [5]. Their piezoelectric harvester comprises a 2D auxetic substrate sandwiched between two piezoelectric layers. The FE modelling results indicated that the auxetic substrate could increase the transverse stress of a bimorph by 16.7 times, and the average power generated by the auxetic bimorph is 2.76 times that generated by a conventional bimorph. Periodic anti-tetrachiral auxetic lattice structures and their mechanical and piezoelectrical response have been investigated by De Bellis and Bacigalupo [16]. They studied the acoustic behavior of the periodic piezoelectric material with auxetic topology and detected the possible band gaps. Umino et al. [17] have proposed a vibration energy harvester with high power generation efficiency in a low-frequency wide band. The suggested device is a bimorph type made of two piezoelectric layers and a middle elastic layer having a flexible mechanical metamaterial structure. The strain of the piezoelectric layer and the power generation amount have increased by controlling the flexibility of the elastic layer by the microstructure. The harvested power of the proposed devise is 1.6 times larger than that of the conventional flat plate and provides the minimum electric power required as a sensor node for WANs. Ferguson et al. [18] have developed an auxetic piezoelectric energy harvester to increase the output power of transducers which are excited by limited strain vibrations. Their harvester consisted of a piezoelectric element bonded to an auxetic substrate. Their experimental results showed that the auxetic energy harvesters could produce electricity power up to 191.1 microwatt, which is 14.4 times that of the peak power produced by the plain harvesters. Eghbali et al. [19] proposed an auxetic booster to enhance the efficiency of vibration energy harvesting. Their model had auxetic structures and exerted extra stretching strain in two perpendicular directions. Compared with the case in which the PZT is straightly attached to the cantilever, they have shown that adding such intermediate boosters at a low-frequency range can increase the extracted power by factors of 3.9 and 7.0 for the two proposed geometries.

To the best of the authors' knowledge, only the effect of rectangular auxetic substrate on piezoelectric energy harvesters has been investigated in the previous studies, and the effect of substrate geometry has not been explored yet. This study has developed a new auxetic model to increase energy harvesters' output power.

2. Auxetic piezoelectric energy harvesters

The constitutive equations for piezoelectric materials can be derived by considering an electric enthalpy function H defined, for the linear static case without body charge or forces, as [20]

$$H(\varepsilon,E)=\iiint_V\left(\frac{1}{2}\varepsilon_{ij}C_{ijmn}\varepsilon_{mn}-\frac{1}{2}E_i k_{in}^{\varepsilon}E_n+E_n e_{nij}\varepsilon_{ij}\right)dv \tag{1}$$

In this equation, elastic strain ε_{mn} and the electric field E_n are the independent variables. On the right side of the equation, C_{ijmn} are the elastic constitutive constants measured at constant electric field, e_{nij} are the piezoelectric constants (measured at a constant strain or electric field) and k_{in}^{ε} are the dielectric constants measured at constant strain. Constitutive equations of piezoelectricity can be derived by differentiating this equation with respect to the independent variables, as

$$\sigma_{ij}=\frac{\partial H(\varepsilon,E)}{\partial\varepsilon_{ij}}=C_{ijmn}\varepsilon_{mn}+e_{nij}E_n \tag{2}$$

$$D_i=\frac{\partial H(\varepsilon,E)}{\partial E_i}=e_{imn}\varepsilon_{mn}-k_{in}E_n \tag{3}$$

where σ_{ij} is the stress and D_i is the electric displacement. Eq. (6) indicates the relation between the electrical field and voltage, and the electrical field is related to the electrical displacement through Eq. (5)

$$\varepsilon_{mn}=\frac{1}{2}\left(u_{m,n}+u_{n,m}\right) \tag{4}$$

$$D_m=k_{mn}E_n \tag{5}$$

$$E_m=-\phi_{,m} \tag{6}$$

From Eq. (2), in the linear case, the stress applied to a piezoelectric material is converted to elastic deformation and an electrical field proportional to the piezoelectric constitutive matrix. This electrical field will also create a gradient through Eq. (6), which will generate the voltage from the energy harvester. Interestingly, this electrical field also provokes energy loss, since Eqs. (3)- (5) shows that the electrical field will create a self-induced electrical field with opposite sign, proportional to the permittivity constants. Hence the voltage output from the energy harvester is maximized by reducing the permittivity constants and increasing the piezoelectric constants.

Base vibration of the cantilever beam would lead to appearing longitudinal stress and deformation. Using auxetic structures in the cantilever provides the transverse deformation of the beam, and bonding uniform layer on the auxetic beam leads to appear the transverse stress on the bonded layer and auxetic beam. Fig. 1 illustrates the auxetic piezoelectric energy harvester model. Stiffness ratio of the bonded layer and auxetic beam affects on amplitude and distribution of transverse stress.

Also, the design of auxetic cells is the effective parameter on the stress distribution of the bonded layer. The piezoelectric layer has been used as a bonded layer on the auxetic beam to assemble the auxetic energy harvester. Energy harvesters are usually employed to provide sensors and other electronic devices power. Harvested power, which depends on the cantilever base acceleration and stress distribution on the piezoelectric layer, is the most significant parameter in energy harvesters. Improving the harvested power of the piezoelectric energy harvester would be investigated by using auxetic structures and changing the shape of the substrate in this research.

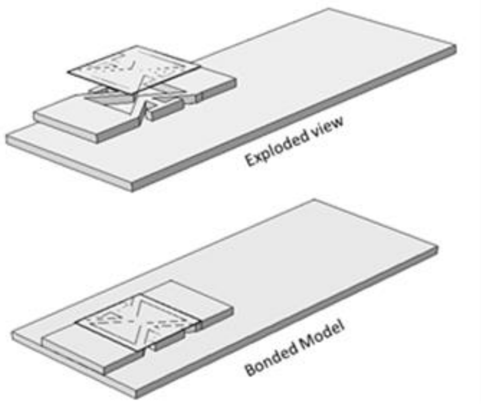

Figure 1. Auxetic piezoelectric energy harvester.

3. Mesh Convergency

The present study has investigated using an auxetic structure to improve the harvested energy in vibration energy harvesters. This investigation has been performed by employing the finite element method. Auxetic energy harvesters employed by previous experimental researches [18,19], have been utilized to verify the present finite element model. Fig. 1 indicates the model's geometry of previous studies, and their model's physical and mechanical properties have been explained in [19]. This model consists of a steel cantilever, a steel substrate, and a piezoelectric layer fabricated by PZT8. Reducing the size of elements causes a considerable influence on unconverged finite element models. The finite element model results should be independent of decrease in element size. Due to the importance of strength analysis and vibration characteristic of the harvester in the vibrational surrounding, the model's convergence would be investigated by free vibration and static response. Boundary distributed force is applied to the free end of the cantilever for static analysis. Fig. 2 and Fig. 3 show maximum deflection, and the first natural frequency of the energy harvester's model converge by increasing the number of elements. Fig.2 indicates that ten thousand elements are adequate for converged response in free vibration analysis. The first natural frequency grew up less than 0.1 percent after increasing the number of elements by more than ten thousand. Also, Fig. 3 illustrates that this number of elements is enough to converge the first natural frequency of energy harvester, which has not changed by increasing elements by more than ten thousand. It should be noted that hexahedron element (20 node) has been used in the present study. The model has been designed and analyzed in Comsol Multiphysic® version 5.6.
In order to validate the present finite element model, the results of the experimental investigation [28] are simulated by this model. The geometry of this model is shown in Fig. 1. A harmonic strain at an amplitude of 250$\mu\varepsilon$ peak-to-peak has been applied to this sample at a frequency of 10Hz. In the FE model, the bonding between the piezoelectric layer and the auxetic substrate has been modelled by a thin elastic layer. The adhesion strength of this layer has been defined by the spring constant per unit area (KA).

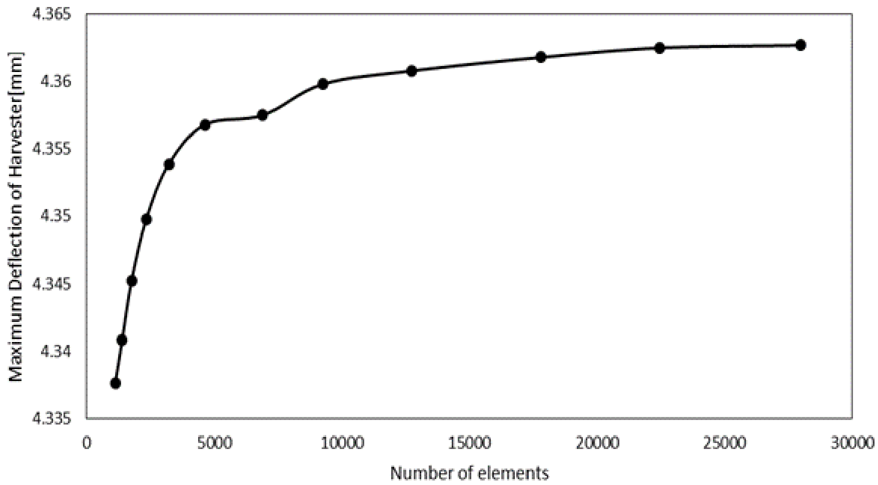

Figure 2. Mesh convergency investigation of static response.

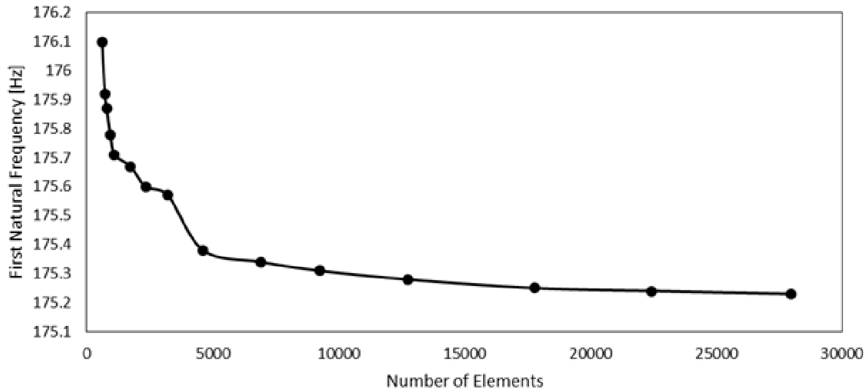

Figure 3. Mesh convergency investigation of first natural frequency.

Fig. 4 illustrates the comparison of harvested power of the experimental sample and the FE model's results. This comparison has been performed for the plain harvester and auxetic harvester. Spring constant per unit area for these harvesters are 173GN/m3 and 159GN/m3, respectively. This figure shows good agreement between the experimental results and simulation results for both plain and auxetic models.

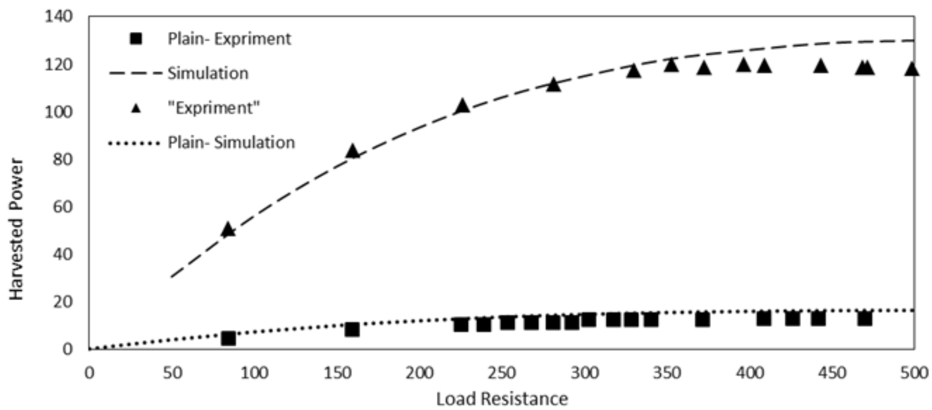

Figure 4. Comparison of Present FE model and experimental sample.

4. Trapezoidal auxetic energy harvester

As the best knowledge of the writers, auxetic cells were only utilized in rectangular energy harvesters in previous researches. Using auxetic cells with the trapezoidal pattern on the trapezoidal beam to increase the harvested power is investigated in this section. As it has been shown in Fig. 5, the size of the one edge of the harvester remains constant, and the size of the other side has been decreased. Also, the size of the one side of the auxetic cell has been decreased. The ratio between edges size of the auxetic cell is the same as the ratio of harvester base edge size. In other words, '*a*' remains constant in Fig. 5 while '*b*' is decreasing. The present investigation shows changes in the shape of the harvester base leads to changes in the natural frequency of the harvester. The natural frequency of the harvester is a significant factor for harvesting energy from vibrating surroundings. Changing the geometry of the auxetic cell and harvester base from rectangular to trapezoidal leads to two consequences: first, decreasing the harvester's natural frequency, and second, increasing the harvested energy in comparison to the rectangular harvester. It should be noted perfect bonding assumption has been simulated for thin elastic layer in this investigation.

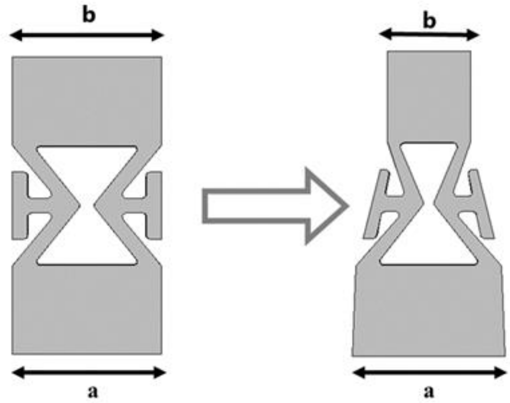

Figure 5. Changing the geometry of rectangular auxetic energy harvester to trapezoidal harvester.

Fig. 6 indicates that the trapezoidal harvester can harvest more energy than the rectangular harvester. Investigation of harvested power in just one frequency could not clarify the potential of harvesting in greater or lower frequency. Comparing the harvested energy of two harvesters should be performed in the frequency range before and after natural frequency. So harvested energy frequency response of 4 harvesters has been compared in Fig.6. The clamped edge of the harvester (a) is 20mm in all these harvesters, but the free edge of the harvester (b) has been reduced from 20mm to 5mm with a 5mm step. It should be noted that reducing the free edge size leads to area reduction in piezoelectric layer surface. The obtained results from the investigation illustrate that decreasing the size of the harvester's free edge leads to an increase in the harvested power from the energy harvester.

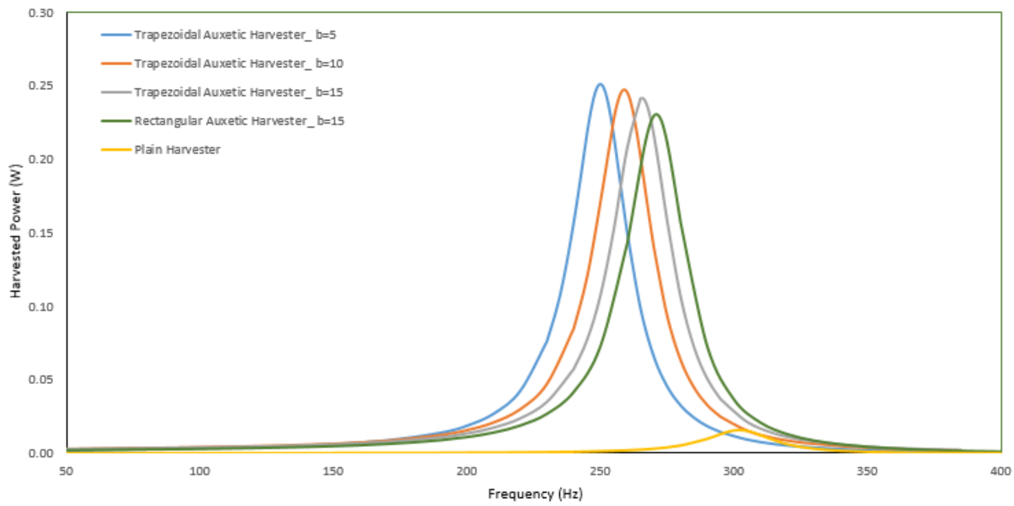

Figure 6. Harvested power frequency response of 4 harvester with different edge's size.

Harvested energy in Fig. 6 depends on Geometry and the natural frequency of harvester and auxetic cells. The effect of resonant frequency has been omitted using dimensionless frequency, and the influence of different geometry on harvested power distinctly can be seen in Fig. 7. Dimensionless frequency has been obtained by dividing the vibration frequency into the natural frequency of each harvester. This figure indicates using a trapezoidal harvester can improve the harvested energy by almost 8.8%, from 230.67 mW (for rectangular harvester, b=20) to 250.93 mW (for trapezoidal harvester, b=5). The density of harvested power for the piezoelectric layer improved by 82.5%, from 5.77 W/m2 to 10.37 W/m2, considering a 37.5% reduction in the area of the piezoelectric layer. This investigation illustrates that using a trapezoidal auxetic harvester increases the efficiency of the piezoelectric energy harvester and reduces the natural frequency. In addition, it is strongly proposed to use this kind of harvester for pre-resonance frequencies. In other words, geometric parameters of trapezoidal energy harvester help tune the natural frequency of the harvester relevant to the frequency of surrounding vibration.

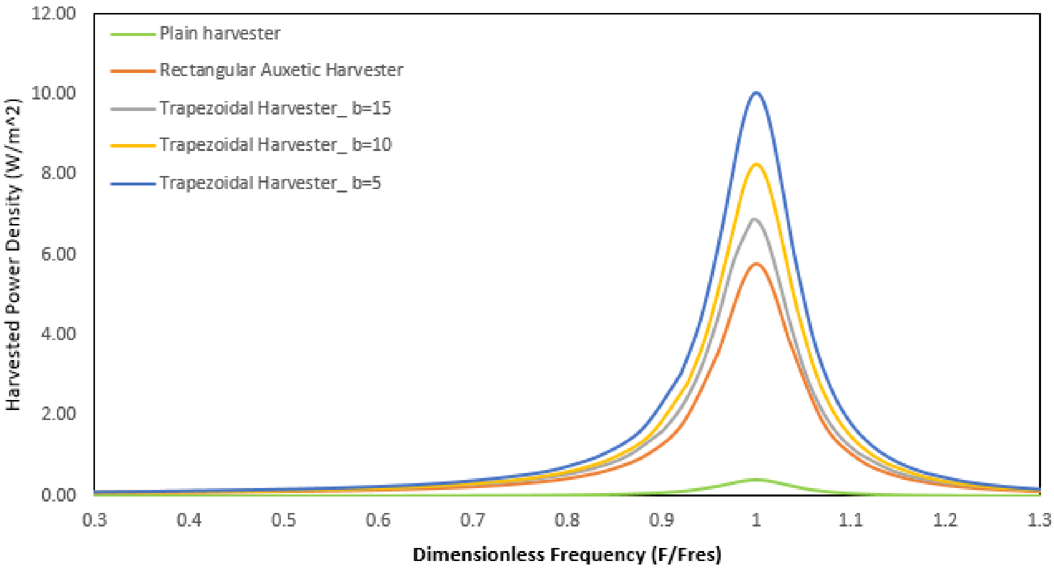

Figure 7. Harvested power frequency response of 4 harvester with different edge's size.

5. Conclusion

The present study investigated the effects of using auxetic structure in harvested power of piezoelectric energy harvester. The numerical model was verified by some experimental researches.

The investigation about the effect of using the trapezoidal harvester on harvested power was performed in the present study. Results indicated that trapezoidal auxetic harvester could improve the efficiency of harvester by 82.5%. Using the trapezoidal harvester also caused a decrease in the natural frequency of the piezoelectric energy harvester. Finally, a study on geometric parameters of trapezoidal energy harvester was performed and changes in first natural frequency, and harvested power of energy harvester were investigated.

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