ENERGY HARVESTING DEVICE WITH SEGMENTED PIEZOELECTRIC LAYER

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Abstract: A new bimorph cantilever design that for scavenging energy of ambient vibration is presented. The key difference between this work and classical structures is that there are many segmented patches with small gaps in the piezoelectric layer in this design. It is envisaged that the proposed structure will maximise the power output and lower the resonant frequencies. Finite element modelling is used to validate the idea. Models of classical design and proposed new structures are constructed, and subsequent static and dynamic simulations are conducted. It is shown in the results that the new structures have optimised the power output, and for this particular case, device with 20 patches has the maximum power output of 3.76 x 10^{-14} J when subjecting to a 0.001 N point force. With respect to resonant frequency, the new structure with 20 patches has resonant frequency of 966.8 Hz, compared with 1119.5 Hz of the classical structure.

Keywords: Piezoelectric scavenging device, segmentation, output power

INTRODUCTION

During the last decade, Energy harvesting systems based on piezoelectric materials have become more and more attractive, especially for powering wireless sensors, as it generally has higher electromechanical coupling efficiency and requires no external voltage sources. It is particularly attractive in application areas such as MEMS. However, to achieve energy harvesting devices with higher output power is still a big challenge [1-3]. The principle of the piezoelectric energy harvesting devices is based on transduction between mechanical strain and electrical charges. Most of the previous works have mainly focused on cantilever-type sandwiched piezoelectric bimorph that consists of piezoelectric layer and supporting layer. [4], [5]. In the conventional cantilever design, one of the cantilever is fixed to a solid bulk substrate, and the other end is freely suspended. Thus the bending of the cantilever subjecting to an external load such as acceleration results in electrical charges generated in the piezoelectric layer. For the reason of non-uniform strain distributed along the beam, some areas of the cantilever generate more electrical charges than other areas. In some cases, even negative charges are generated in areas where have complete different strain type. As a result, positive and negative charges are cancelled out each other, leading reduced electrical power output.

In order to address this issue and generate as much power as possible, we are proposing to design a bimorph cantilever structure which is composed of a segmented piezoelectric layer and a supporting layer. In doing this, there are two advantages: one is to increase power output, the other is to reduce the resonant frequency of the structure, so that it can matches mechanical excitation frequencies from environments that are usually very low. To the best of our knowledge, this idea has not been reported previously in literatures. In this paper, the finite element modeling of the new structure has been performed to obtain the open circuit output voltage and stored electrical energy. Classical bimetallic piezoelectric cantilever with exactly same dimensions have also been modeled for the purpose of comparison. The paper is shaped as follows: section 2 of this paper describes construction of the model; simulation results are shown in section 3, and finally section 4 lists some conclusion remarks.

MODEL CONSTRUCTION

The configuration of the energy harvesting piezoelectric cantilever is sketched out in Figure 1. It is seen that the device consists of a segmented layer of piezoelectric material (Aluminium Nitride) and a substrate layer (single-crystal silicon). In order to quantitatively investigate the impact due to segmented piezoelectric layer, models with various segmentation numbers ranging from 2 to 30 are constructed. All these models have the same total length and width, and the dimensions of the substrate layer are remained constant. Figure 1 (a) shows an example of the new design, Figure 1(b) shows the meshed model for the new structure, and Figure 1(c) shows the traditional configuration. In all these models, the overall dimensions (summing all piezoelectric sections) of the piezoelectric layer are 14 mm in length, 2 mm in width, and the thickness is 0.2 mm. The substrate has length, width, and thickness as 18 mm, 3.6 mm and 0.2 mm respectively. In all segmented models, the gap in between two sections is the same, 0.5 mm. The model has been constructed using commercial FEM software − COMSOL. The software calculates the output voltage and stored electrical energy following well

known equations that govern the transduction in the piezoelectric layer:

$$S = S^E T + d^T E \qquad (1)$$

$$D = \varepsilon^T E + dT \qquad (2)$$

where S is mechanical Strain vector, T is mechanical stress vector, S^E is elastic compliance tensor, d is piezoelectric strain constant, D is electric displacement vector, E is electric field vector, ε^T is dielectric permittivity tensor. Piezoelectric strain constants and dielectric permittivity constants are directly taken from the software library. The cantilever is mechanically fixed at one end and the other end is suspended in the air. In terms of electrical boundary conditions, the bottom face of piezoelectric layer is grounded, while the top one is set to "Floating potential" condition. For the rest of faces of the piezoelectric layer the condition of "Zero charge/Symmetry" is applied.
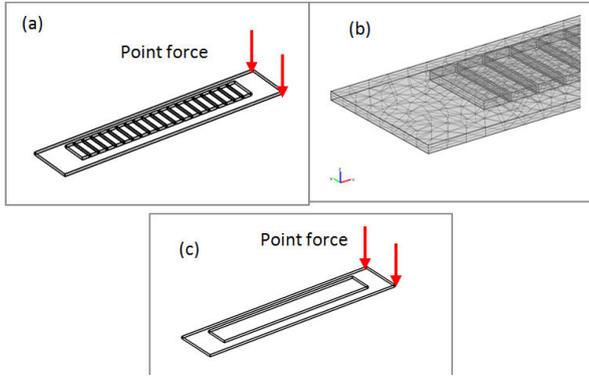

Fig.1 (a): Layout of 20 segmented piezoelectric scavenging device, (b): mesh of the segmented modal (c): Layout of conventional bimorph piezoelectric scavenging device.

STATIC AND DYNAMIC ANALYSES

The structure has been meshed before performing any simulations. The meshing has resulted in 6486 elements for a total number of degrees of freedom of 101797. Each material layer is divided into 3 linearly spaced elements along the thickness (Fig. 1 (b)). After building the solid model of the proposed design, static analyses for all these models are conducted. Point force of 0.001 N is applied here to induce mechanical strain upon the device. The charge induced on the piezoelectric layer due to mechanical strain is governed by the following equation:

$$Q_{out} = \int_{A_p} D_{z,p} dA_p \qquad (3)$$

where $D_{z,p}$ is electric displacement, A_p is the area of the piezoelectric. The stored electrical energy of the piezoelectric cantilever E_{stored} can be expressed by:

$$E_{stored} = \sum_{i=1}^{N} \frac{Q_i * U_i}{2} = \frac{1}{2} \sum_{i=1}^{N} \frac{(\int_{A_{p,i}} D_{z,p,i} dA_{p,i})^2}{C_i} \qquad (4)$$

where Q_i, U_i, C_i, $D_{z,p,i}$, $A_{p,i}$ are the induced charge, potential capacitor, electric displacement, area of the ith segmented piezoelectric piece respectively. It is seen from equation (4) that the induced electrical energy is proportional to the square of the total electric displacement. As for the bending motions, the electric displacement distributions along y- axis are uniform, so the stored electric energy of the piezoelectric materials very much depends on the electrical displacement distribution along x- axis. Upon above conditions, same mechanical point load has been applied to the free tip of the cantilevers. Open circuit voltages along the length of the cantilever for classical design and 6 and 20 segmented devices are shown in Figure 2. It is seen that for the classical design, the generated voltage is a constant, since the top surface of the piezoelectric layer is electrically connected. But for the segmented devices, as expected, the open circuit voltages on piezoelectric patches are different; the patches closer to the anchor have much higher voltage values than patches closer to the free end. That is because the mechanical strains near the anchor area are much bigger. Electric displacement distribution along x- axis for the classical design and 6, 20 segmented devices are shown in Figure 3, and it is observed that the electrical displacement reduces as moving away from the anchor. Stored electrical energy in conventional cantilever and segmented configurations in static mode were shown in Figure 4. It is shown that the stored energy increases while increasing number of segments until the number of segments reaches 20, after which the stored energy decreases. It means that for segmentation from 1-30, there is an optimal number for segmentation. The simulated stored electrical energy for 20-segmented device is 3.76×10^{-14} J. Compared with classical configuration, envelops of electric displacement distribution of
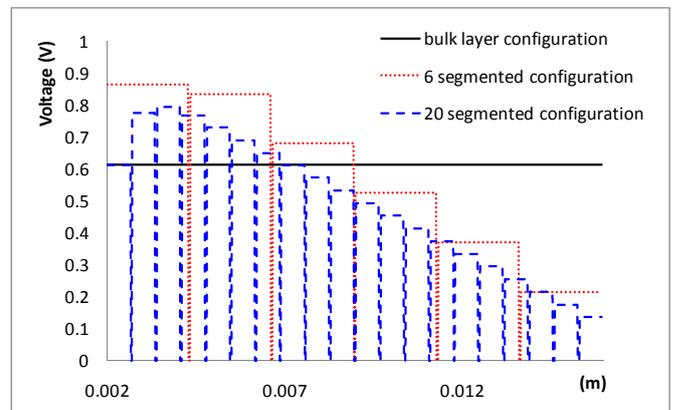

Fig.2: Surface potential along the x- axis for classical configuration and segmented configuration.

segmented ones are higher, which means generating much more electrical charges.

Based on the above static analysis, dynamic response covering natural frequency on classical configuration and 20-segmented device were explored. It is seen from Figure 5 that the natural resonant frequency of classical configuration is 1119.5 Hz which is higher than that of 20-segmented configuration (966.8Hz), as the segmentation decreases the stiffness of the mechanical structure.
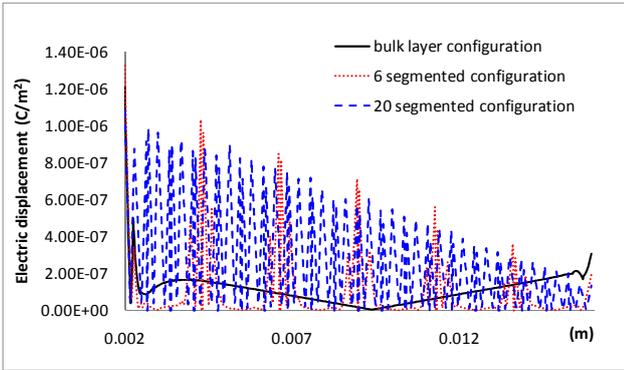

Fig.3: Electric displacement along the x- axis for classical configuration and segmented configuration.
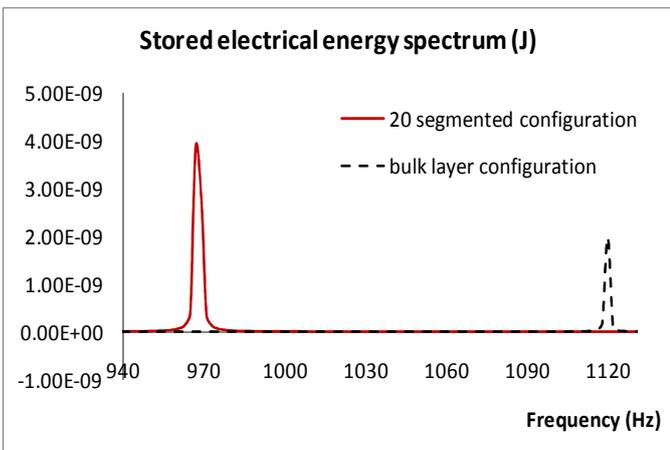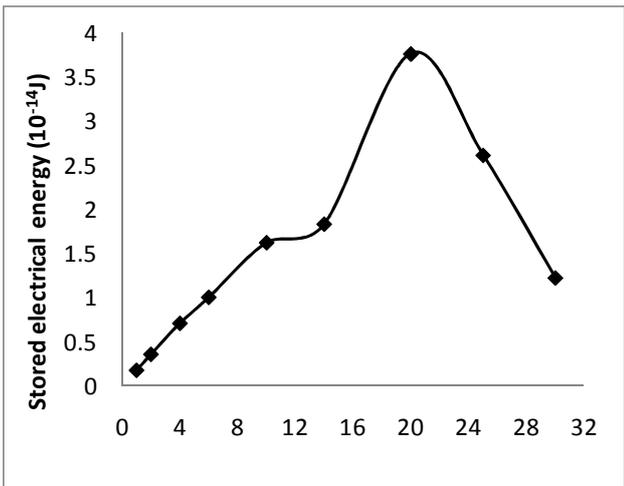

Fig.4: stored electrical energy vs. number of segmentations.

Fig. 5: Dynamic response of bulk layer configuration and 20 segmented one.

CONCLUSION

In this paper, a novel bimorph cantilever design with segmented piezoelectric layer for the purpose of maximising power output and reducing resonant frequency has been presented. The models of classical and new designs have been built with FEM software. Comparisons of output voltage and stored energy were made amongst classical structure and new configuration with different segmentations. Static and dynamic analyses of the proposed structures have been conducted, and it is concluded that the proposed configuration has a lower resonant frequency than that of conventional configuration. The lower resonant frequency has advantage to better match the environmental vibrations. Theoretical analysis and simulation results lead the conclusion that the new segmented configuration has higher electrical energy output as well as lower frequency than the conventional one.

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