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Development of Vibration Piezoelectric Harvesters by the Optimum Design of Cantilever Structures

Prateek Asthana and Gargi Khanna

Abstract

Piezoelectric energy harvesting is a way of converting waste mechanical energy into usable electrical form. The selection of mechanical devices for conversion of mechanical to electrical energy is a significant part of vibration energy harvesting. The articles provide designing and optimization of a cantilever piezoelectric energy harvester. At first, is the selection of best mechanical device for energy harvesting application. A cantilever without proof mass is then analyzed for the selection of substrate, and piezoelectric material also plays a key role in the performance of the device. Aluminum is selected as a substrate, while zinc oxide acts as the piezoelectric layer. Addition of proof mass reduces the resonant frequency of the device to about 51 Hz as compared to 900 Hz for an aluminum cantilever beam. An electro-mechanical study shows an active conversion of mechanical input energy to electrical output energy. Power frequency response functions of the resultant structure are able to generate 0.47 mW power having 6.8 μ A current at 1 g input acceleration.

Keywords: piezoelectric, cantilever, energy harvesting, microscale, vibration-based energy harvesting

1. Introduction

The electronic world is moving toward smarter, smaller, portable, and reliable devices. With the range of evolution in microelectronics and wireless technologies, wireless sensor network is one of the most growing areas of research. Wireless sensor network has a wide range of application in defense and military to healthcare and industrial and structural health and environmental monitoring. WSN consists of low-power microsensors, which collect data from the environment and transmit to the base controlling station [1]. These nodes are spread over a large area forming an integrated network. In military purposes for monitoring of remote area and unreachable terrains, sensor networks are used. Environmental monitoring for temperature and CO₂ emission can be analyzed using sensor networks. These sensor networks find a wide range of applications in healthcare sector, finding applications in wearable smart clothing and in monitoring patients' blood pressure. Monitoring the health and stability of civil structures like bridges and buildings are few other areas of applications for sensor nodes. These nodes have three important

components, i.e., transmitter, sensing device, and power supply. The transmitter is utilized in communicating with controlling node, while the sensing device senses environmental characteristics [2]. A sensor node needs an uninterrupted power supply to operate throughout its lifetime, and hence the life of a sensor node is governed by the battery. These energy harvesters could provide power to sensor nodes for transmitting and monitoring purposes. Battery maintenance and refurbishment are not possible in WSN. Hence, energy harvesting to power these sensor nodes is the most desirable area of research. Microscale energy harvesting (micro-nano watt) can be used to drive small microscale nodes for environmental monitoring and medical health monitoring purposes. The focus of micro/nano-scale energy harvesting is using energy from the environment [3]. Energy from the environment, harvested in the form of vibrations, is generally small, as is the power requirement for microscale devices; hence these ambient vibrations due to their ubiquitous existence everywhere are a popular source of energy harvesting [4]. There has been a great focus in the past few years in the design and development of vibration-based micro-energy generation to power low-power wireless devices. Ambient vibration provides a viable option for harvesting energy through piezo-electric mode [5].

2. Device design

Device geometry plays an important role in determining the output power of the device. The amount of power produced by the harvester depends on the amount of

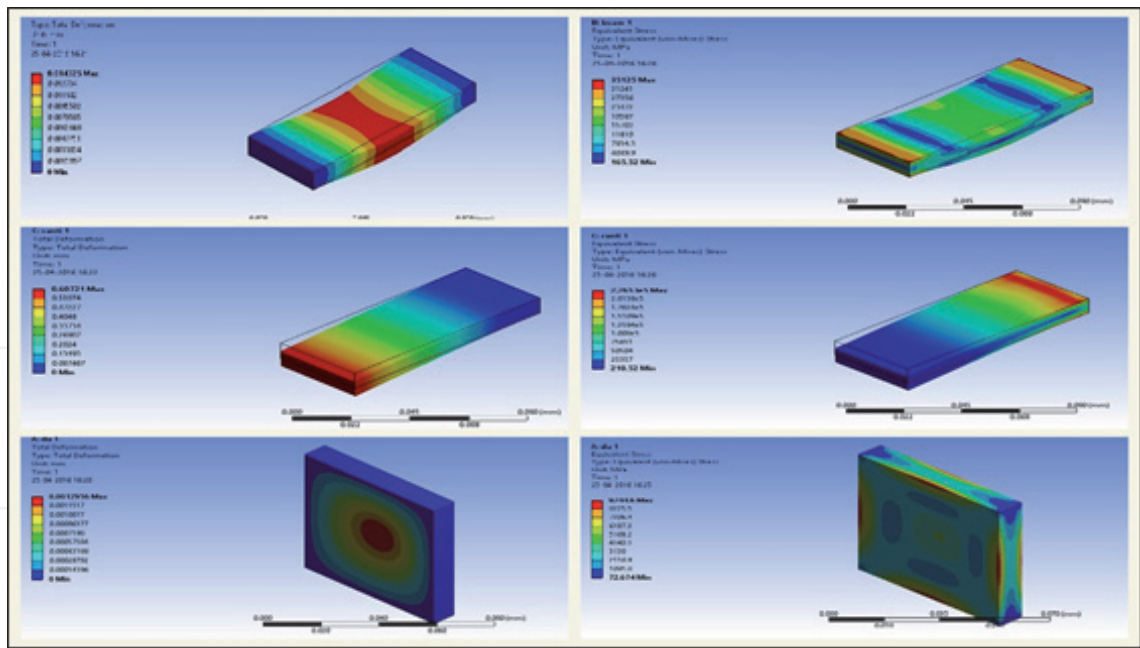


Figure 1. Total deformation and stress for a beam, cantilever, and a diaphragm.

Device	Total deformation (mm)	Equivalent stress (MPa)
Diaphragm	0.0012956	9244.6
Beam	0.014325	35,125
Cantilever	0.60721	2.2653×10^5

Table 1. Deformation and stress comparison for mechanical devices.

stress developed on the device. Hence, one of the main criteria is the appropriate structure in order to harvest ambient mechanical vibrations. The mechanical devices that can be used for this purpose are cantilever, beam, and a diaphragm. A diaphragm is a mechanical device which is fixed on four ends, while the cantilever

S. no.	Parameter name	Parameter symbol	Parameter value [units]
1.	Length of substrate layer	L_{sh}	20 [mm]
2.	Width of substrate layer	w_s	8 [mm]
3.	Thickness of substrate layer	t_{sh}	0.04 [mm]
4.	Length of piezoelectric layer	L	20 [mm]
5.	Width of piezoelectric layer	w_p	8 [mm]
6.	Thickness of piezoelectric layer	t_p	0.06 [mm]

Table 2.
Device dimensions.

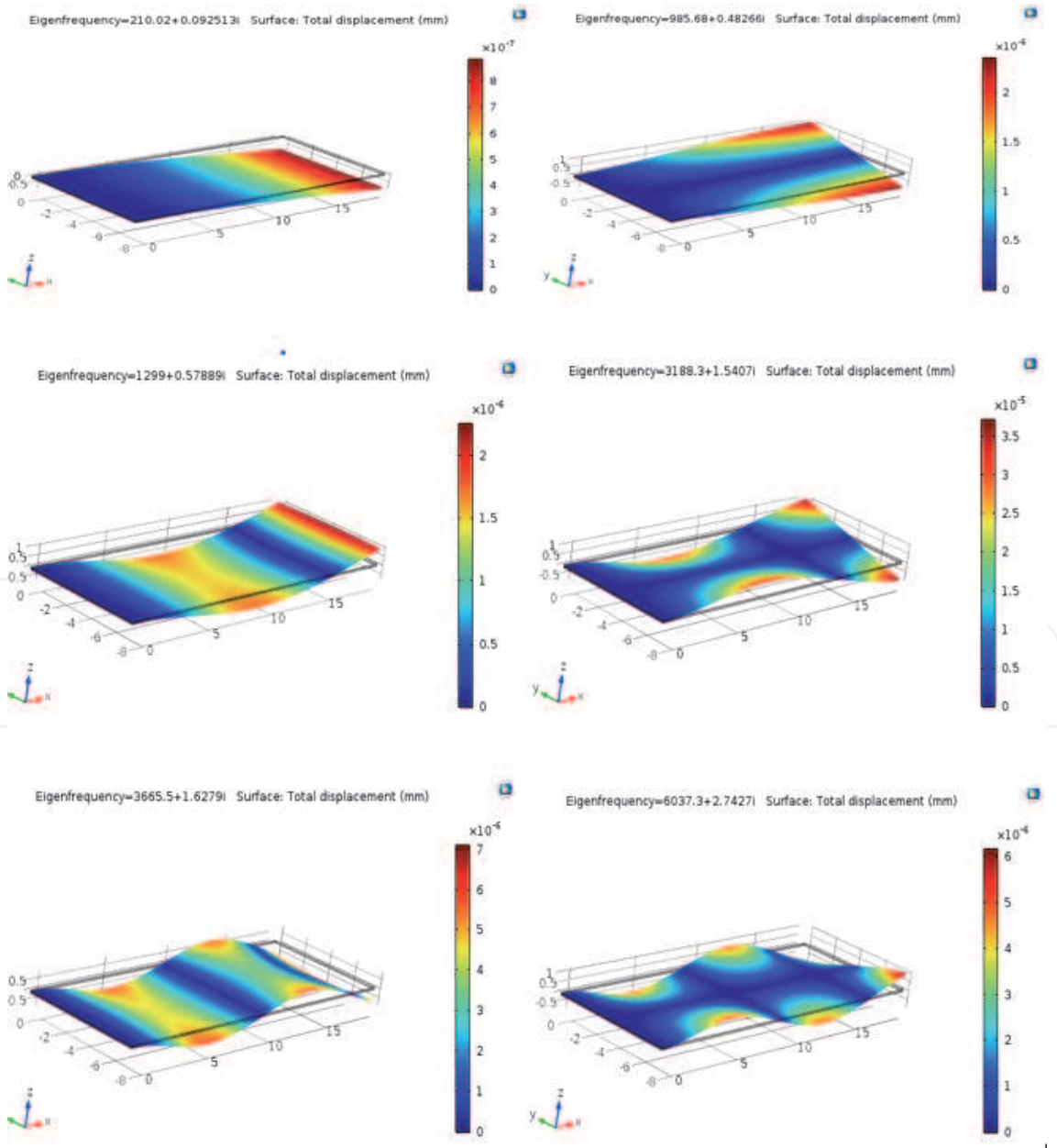


Figure 2.
Six eigenfrequencies of a piezoelectric cantilever bimorph without proof mass.

is a mechanical device which is fixed at one end. In the case of beam, two ends are fixed. The material used in these mechanical devices is silicon. Designs have been simulated in COMSOL Multiphysics.

In order to decide on the appropriate device, all the three devices having the same volume are simulated, and an equal amount of force is applied on each one of them (**Figure 1**). **Table 1** compares the total deformation and equivalent stress values obtained from the above FEM analysis. From **Table 1** it can be inferred that on the application of the same force on cantilever, diaphragm, and beam, a cantilever experiences 42 and 99% more deformation than a beam and a diaphragm, respectively. The stress developed on the cantilever is 25 times more than that on a diaphragm and 7 more than that on a beam. Hence, cantilever structure is mostly used to harvest ambient mechanical vibrations, as for some amount of force; it has the capability to produce a significant stress and displacement.

A piezoelectric cantilever bimorph having piezoelectric layer on top as well as at the bottom is simulated on COMSOL Multiphysics having dimensions as shown in **Table 2**. Eigenfrequencies of the design are plotted in **Figure 2**. Modifications to cantilever by slotting its length have been carried out showing that basic cantilever has the best performance [6, 7]. A broadband piezoelectric energy harvester able to capture ambient vibrations has been designed based on a seesaw cantilever structure [8, 9].

3. Device optimization

To obtain an optimized device, it is essential to select an appropriate substrate and piezoelectric material. Substrate material provides strength and elasticity to the design, while the piezoelectric material performs the conversion of ambient mechanical energy into electrical energy. A substrate material should be able to interact with energy harvesting circuitry as well as provide basic elasticity to the device.

3.1 Selection of substrate material

A cantilever with different substrate material is simulated and its eigenfrequencies are obtained. A comparison of eigenfrequencies for the various designs is shown in **Figure 3**. A cantilever is composed of different substrates having similar dimensions. Aluminum has the lowest first eigenfrequency at around 900 Hz as compared to copper, polyethylene, and structural steel. As the majority of ambient vibrations have lower frequency, hence it is essential for the harvester to have a lower first resonant frequency as then it can match the ambient vibration frequency to produce high power output.

3.2 Selection of piezoelectric material

Piezoelectric materials can be categorized into two types: lead-based and lead-free materials. Lead is a toxic element and has an adverse impact on the environment; hence, its usage is barred in most countries. In this context, scientists are working toward new materials with comparable or better performance than lead-based materials. **Table 3** lists the properties of the piezoelectric materials utilized in this work. Selection of piezoelectric material is equally important for energy harvesting. Piezoelectric material can be lead-based or non-lead-based. Lead-based material has better piezoelectric coefficient than non-lead-based material.

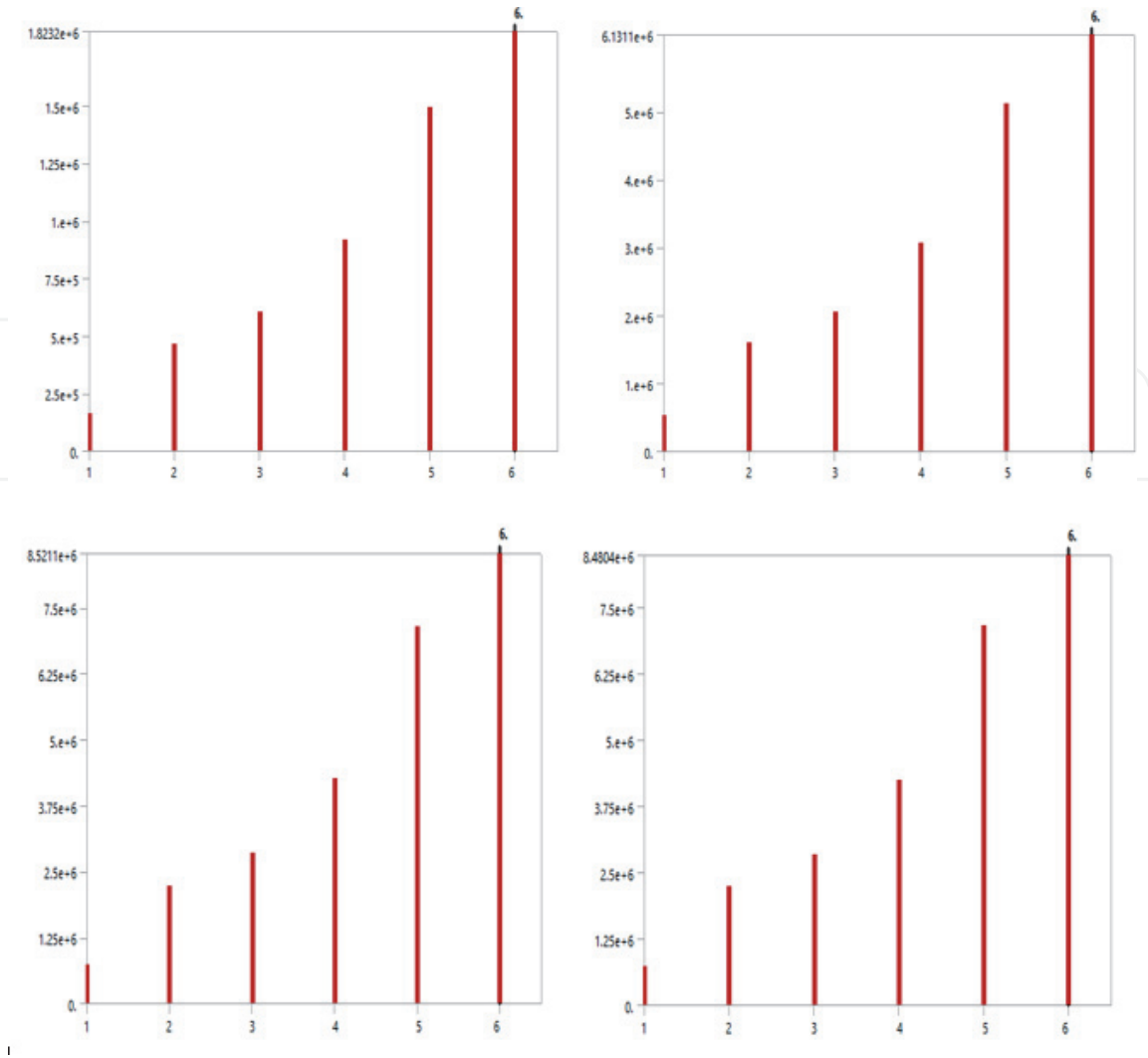


Figure 3. Six eigenfrequencies of a piezoelectric cantilever bimorph without proof mass using (a) copper, (b) aluminum, (c) polyethylene, and (d) structural steel.

Piezoelectric material	Young's modulus (E) GPa	Density (Kg/m ³)	Relative permittivity	Piezoelectric constants	
				e ₃₁ (C/m ²)	d ₃₁ (pC/N)
PZT 5H	127	7500	1433.6	−6.55	−274
PZT 5A	120	7750	826.6	−5.4	−171
PVDF	1.31	1780	7.3	0.0098	−13.6
AlN	149	3300	9	−0.58	−1.72
ZnO	105.3	5680	10.204	−0.56	−5.43

Table 3. Piezoelectric material properties.

For a dielectric material,

$$D = \varepsilon E \tag{1}$$

For an elastic material,

$$T = sS \tag{2}$$

For a piezoelectric material,

$$D = \epsilon E + P \quad \text{and} \quad T = sS + P \quad (3)$$

The value of P for direct piezoelectric effect is

$$P = d_{31}S \quad (4)$$

And for inverse piezoelectric effect is

$$P = d_{31}E \quad (5)$$

So, constitutive equations for direct and inverse piezoelectric effects are given by

$$D = \epsilon E + d_{31}S \quad (6)$$

$$T = sS + d_{31}E \quad (7)$$

where D and E are the dielectric displacement and electric field, respectively. T and S are strain and stress on the material. ϵ and s are electrical permittivity and compliance which is reciprocal to Young's modulus. Piezoelectric cantilever made only with piezoelectric material PZT 5A, PVDF, and zinc oxide is simulated on COMSOL Multiphysics. Results depicted in **Figure 4** show that PVDF has the lowest first eigenfrequency and generates the highest voltage. PVDF has a significantly low Young's modulus, causing it to break easily on application of a very low force. Hence, zinc oxide is selected as piezoelectric material as it is not poisonous and has a significant piezoelectric constant.

Voltage generated in direct piezoelectric effect across a material having t_s thickness is given by

$$V = t_s E \quad (8)$$

The charge on a material is given by

$$Q = AD \quad (9)$$

Charge is integral of current over a period 't'

$$I = DAt \quad (10)$$

Put value of D from (6) to (10):

$$I = At(\epsilon E + d_{31}S) \quad (11)$$

Piezoelectric capacitance is given by

$$C = \frac{\epsilon A}{t_s} \quad (12)$$

Using (8) and (12) in (11) we get:

$$I = CtV + At d_{31}S \quad (13)$$

For open circuit condition $I = 0$. Hence, (13) solves to

$$V = -\frac{Ad_{31}S}{C} \quad (14)$$

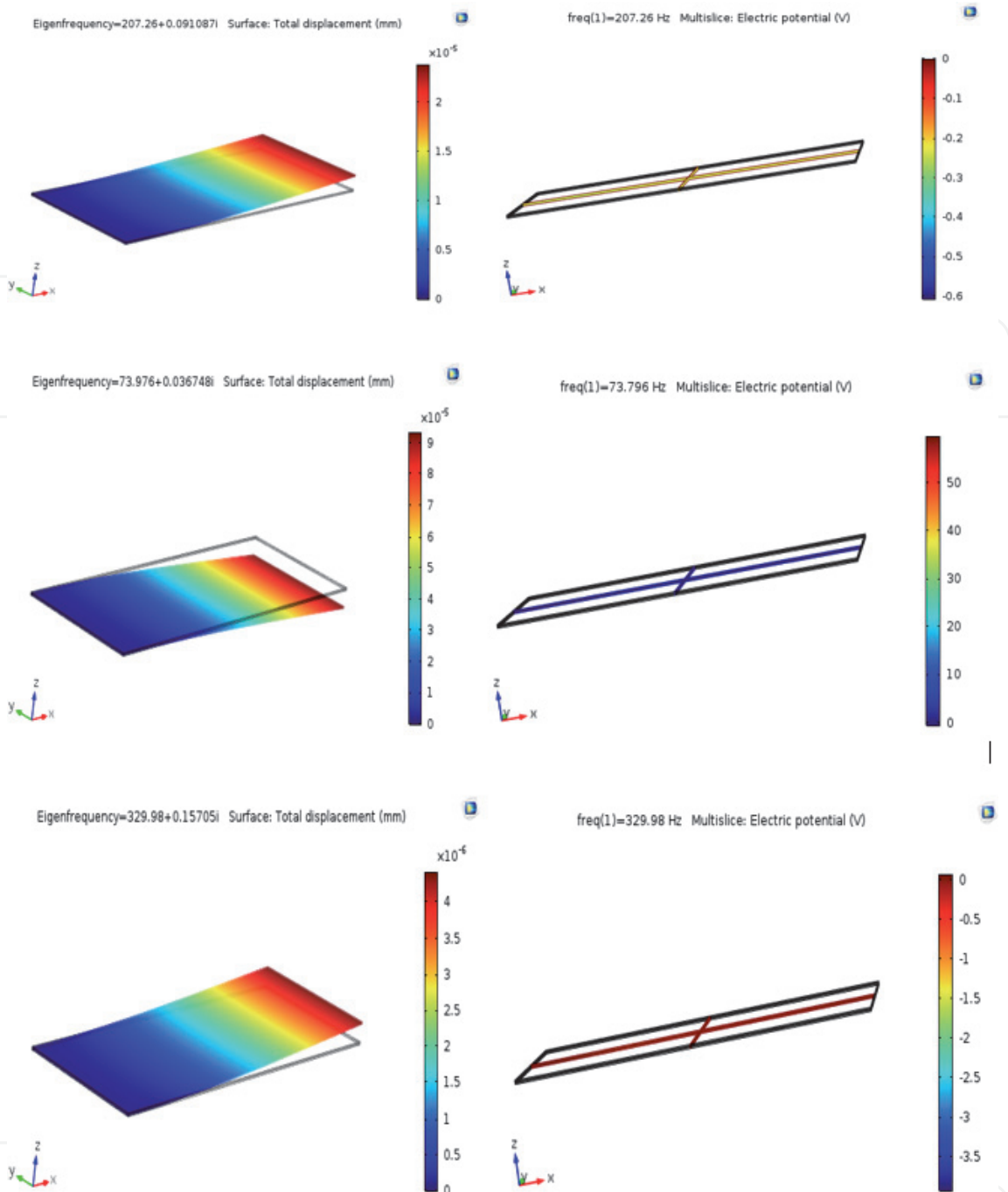


Figure 4. Eigenfrequencies of a piezoelectric cantilever bimorph without proof mass using (a) PZT 5A, (b) PVDF, and (c) zinc oxide.

Putting the value of C back from (12), we get

$$V = -\frac{d_{31}S t_p}{\epsilon} \tag{15}$$

Hence, on application of S stress on a piezoelectric material of thickness t_p having piezoelectric constant d_{31} and permittivity ϵ , the voltage generated is given by Eq. (15).

3.3 Effect of proof mass

Proof mass is added to a piezoelectric cantilever to reduce its eigenfrequency. The dimensions of the proof mass added to the cantilever are given in **Table 4**.

S. no.	Parameter name	Parameter symbol	Parameter value [units]
1.	Length of proof mass	l_m	10 [mm]
2.	Width of proof mass	w_m	8 [mm]
3.	Height of proof mass	t_m	5 [mm]

Table 4.
Dimensions of proof mass.

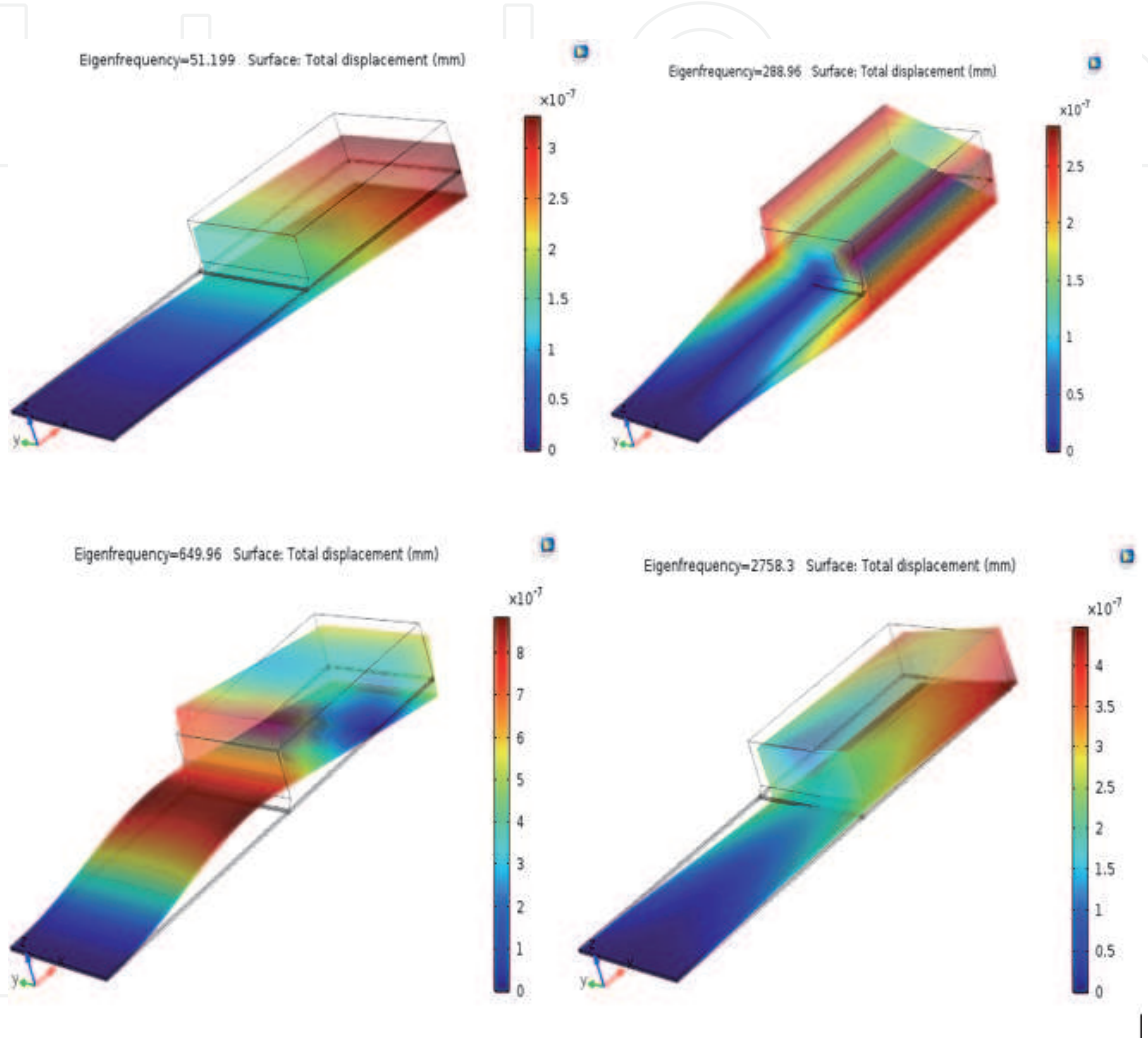


Figure 5.
First four eigenfrequencies of a piezoelectric cantilever bimorph with proof mass.

When the proof mass is added, the first eigenfrequency reduces to 51.3 Hz as shown in **Figure 5**. The cantilever becomes bulkier. The material of proof mass is the same as that of the substrate. Proof mass also increases the overall mass of the device and hence, the displacement of the device from the neutral position.

4. Results and discussion

4.1 Frequency response

The frequency response of the piezoelectric cantilever obtained is plotted by varying the input vibration frequency (**Figures 6–8**). The frequency response depicts a peak when the frequency of vibration matches the first eigenfrequency.

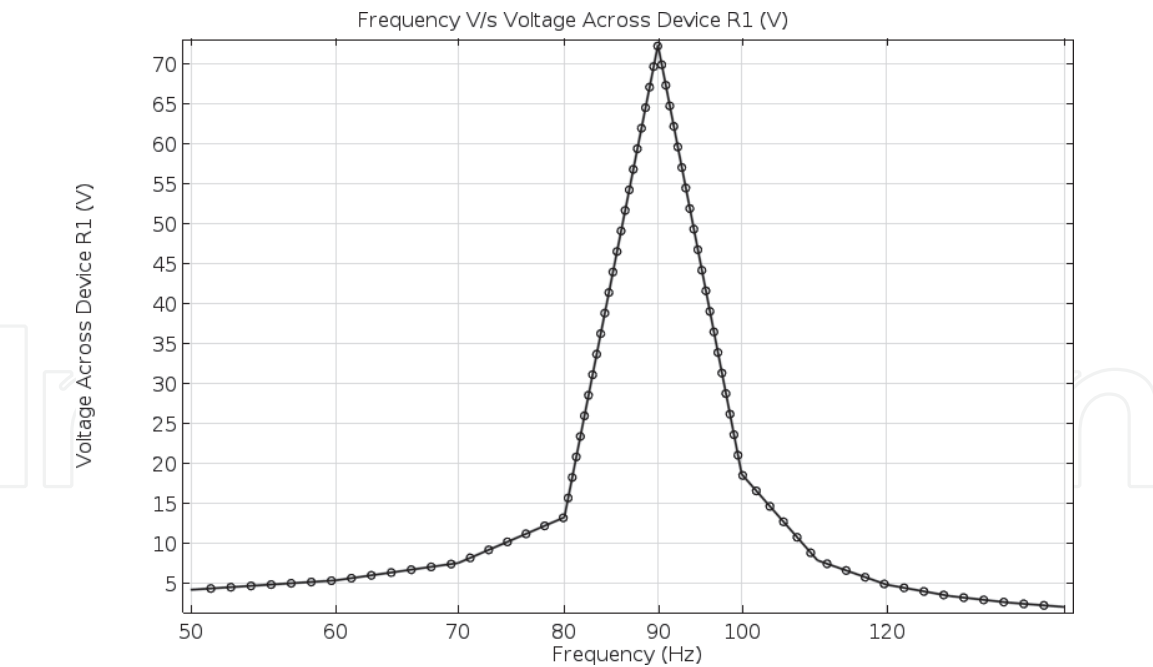


Figure 6.
Voltage generated on a frequency response of a piezoelectric cantilever bimorph.

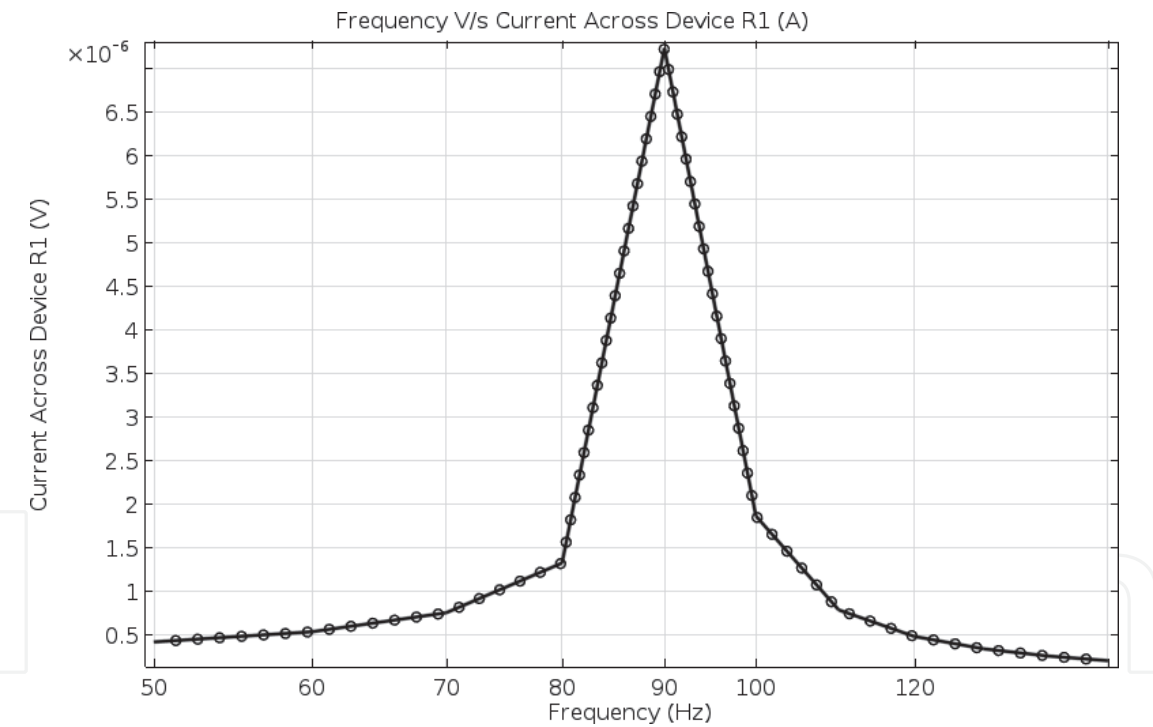


Figure 7.
Current generated on a frequency response of a piezoelectric cantilever bimorph.

The cantilever has two piezoelectric layer of zinc oxide and a substrate layer of aluminum. The cantilever energy harvester can generate a power of 0.47 mW across a 4 Mohm resistor. The current value is around 6.8 μ A. Generated power can be increased by integrating the harvester with energy harvesting circuitry [10, 11].

4.2 Electromechanical analysis

A significant part of the piezoelectric energy harvesting process is mechanical to electrical conversion. High power is generated on high amount of stress on the

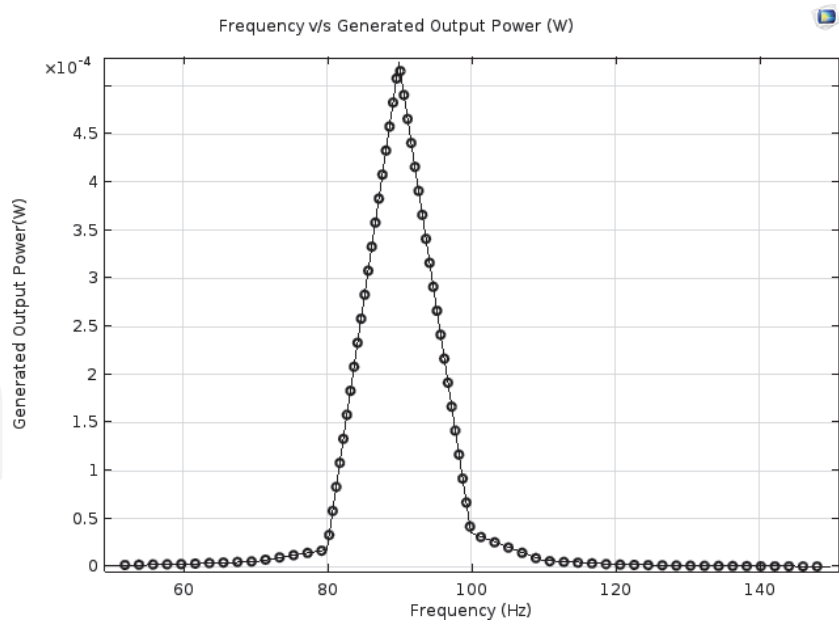


Figure 8.
Power generated on a frequency response of a piezoelectric cantilever bimorph.

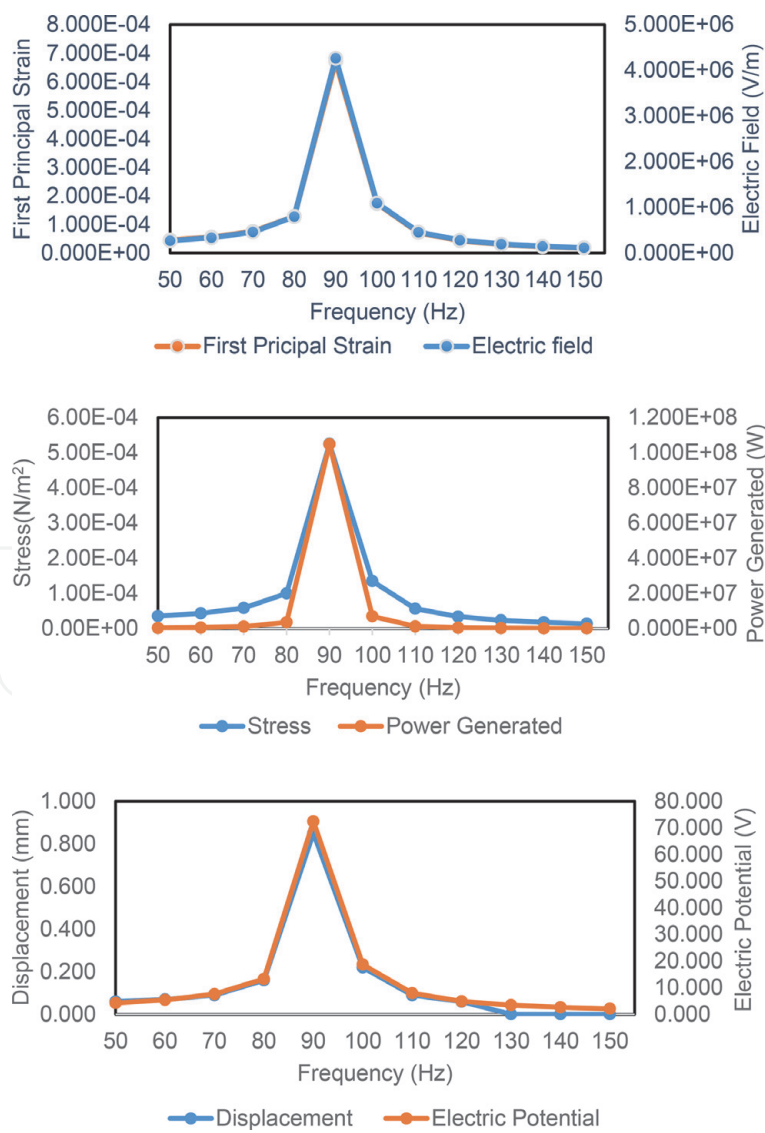


Figure 9.
Electromechanical conversion on a frequency response of a piezoelectric cantilever bimorph energy harvester for strain to electric field, stress to power generated, and displacement to electric field.

piezoelectric layer. Electromechanical coupling displays the conversion of stress on the piezo layer and equal conversion of electrical power by those layers. The more the stress, the larger is the displacement of the device which increases the quantity of accumulated charges and the higher is the potential developed on the layer.

Figure 9 shows electromechanical conversion from first principal strain to electric field, displacement to electric potential, and stress to generated output power.

A peak strain of 6.712×10^{-4} resulted in a peak electric field of 4.26×10^6 V/m with both occurring near the first resonant frequency. A peak stress of 1.05×10^8 Pa resulted in power generation of around 0.5 mW with both occurring near the first eigenfrequency. A peak displacement of 0.85 mm resulted in peak electric potential of 72.394 V, with both occurring near the first eigenfrequency.

5. Conclusions

A piezoelectric cantilever bimorph is simulated in this chapter. Optimizing the designing from the selection of substrate and piezoelectric material is described. A cantilever with aluminum substrate and zinc oxide is designed with a proof mass. Analytical model of generated voltage by the piezoelectric cantilever energy harvester is also described. Addition of proof mass reduces the resonant frequency of the device. Power frequency response functions and electromechanical analysis of the resultant structure are able to generate 0.47 mW power having 6.8 μ A current at 1 g input acceleration.

Author details

Prateek Asthana* and Gargi Khanna
National Institute of Technology, Hamirpur, Himachal Pradesh, India

*Address all correspondence to: prateekasthana1989@gmail.com

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