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Design of Piezoelectric Energy Harvester Single Cantilever Beam for IoT applications and Micro-electronic devices

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ABSTRACT

A few years back the power requirement of electronic devices was very high. But with the technological developments in the field of internet-based systems, the design of low-powered microelectronic devices, WSN and IoT devices became necessary. In these systems the size and the power requirement are low and in most situations the replacement of batteries is challenging. For these microelectronic and IoT devices the abundant energy harvester is very useful. Among different abundant energy resources, vibrational energy harvesting with piezoelectric cantilever beam energy harvesters is of interest. This research work presents the design and analysis of an energy harvester (EH) which contains a single piezoelectric cantilever beam that captures the vibrational energy of the suspension bridge. This approach ties the two things together by framing piezoelectric energy harvesting as a solution to the power challenges faced by low-powered devices, making the transition feel more natural and connected. The main challenge in the design was matching the resonance frequency of the bridge with a piezo EH which is around 2.5Hz to extract maximum power. To overcome this problem Eigen frequency analysis in COMSOL Multiphysics is done. The 3D geometry of single beam piezo EH is designed and analyzed in COMSOL Multiphysics solid works. In this research work a relationship is established between the geometrical parameters of the single beam piezo EH and Eigen frequency based on the first six Eigen frequency analyses in COMSOL Multiphysics. For finite element analysis (FEA) a piezo single beam harvester is vibrated by application of force which is equal to the vibrational force (0.98m/s2) in the suspension bridge. The force of (0.98 m/s²) is chosen because it avoids resonating with critical system components. The output from the harvester is achieved at a resonance frequency of 2.5Hz. The output from the piezo is very low 800 milli volts at 2.5Hz. The output results of piezo EH are also compared with a cantilever beam with a single-branch structure.

Keywords: Energy harvesting; vibration; IoT; WSN; micro-devices

INTRODUCTION

In the quest for sustainable and renewable energy sources, one promising solution is harvesting energy from ambient sources, such as vibrations, heat, and light. Among these, vibrational energy harvesting (EH) has garnered significant attention due to its potential to convert mechanical vibrations into usable electrical energy. Electrical energy is so important in our daily lives that we completely depend on it. Electricity is making lives easier and faster, with fast industrial manufacturing, transportation, and communication (Caetano and Savi 2022). These factors have enhanced our lives' demand for low-cost energy (Riaz 2021). Nowadays, microelectronic devices are making our lives faster, easier and more comfortable. As a result of advancement in this field, traditional electronic devices transformed into portable electronic devices, IoT and wireless sensor networks (WSNs) (Sarker 2024)(Mazunga and Nechibvute 2021). The energy required for these networks has also decreased significantly with the development of low-powered circuits. The micro energy harvesting (EH) can be utilized to power low-power electronic devices (Sarker 2021)(Sun 2018). Despite the advancements in the size and energy consumption of microelectronic devices, traditional batteries are still employed as power storage devices. However, in the majority of industrial applications, the replacement might not even be practical or cost-effective. Many wireless sensors and microelectronic devices operate in limited areas where weight and size are important (Angwech 2022)(Wu 2018). There's a chance that conventional battery technologies, like lithium-ion or alkaline batteries, won't be able to meet these devices' long-term power needs with enough energy density. It is still difficult to extend the cycle life of batteries so they can withstand multiple charge-discharge cycles without experiencing significant decline. Improved durability is essential to batteries' long-term reliability. Future research must focus on the research gaps of battery power density enhancement, fast charging and discharging, cost, production and disposal of batteries that affect the environment (Khan 2024)(Sarker 2022).

Vibrational EH could be a good choice for providing power to the IoT, microelectronic devices and WSN. Conventional batteries are used to power IoT devices (Tavana 2022)(Usman Tahir 2023). But so many drawbacks associated with them like short lifespan, environmental degradation, and the necessity for frequent replacement, make them unfit. Therefore, researchers are carefully examining environmental energy using new techniques to generate self-sustaining IoT and WSN systems for different applications like bridge monitoring, weather forecasting and security surveillance (Ball 2018).

Several studies on piezo energy harvester (PEH) cantilever beam (CB) from ambient resources have been done in recent years (Jagiela and Kulik 2018)(Wang 2017). The quantity of power generated by PEH is substantially influenced by several parameters, including the applied load, vibration frequency, geometry, material characteristics, and boundary conditions (Mohamed 2016)(Zhang 2023). The harvesting system resonates to produce efficient energy when the frequency of the vibrational source coincides with the resonance frequency of the PEH. The output of the vibrational PEH is only maximum at a resonance frequency (Jiang 2014). In the case of a suspension bridge, the vibrational PEH is only maximum when the resonance frequency of the single beam CB matches the resonance frequency of the bridge (Gaglione 2018).

This research paper proposes an ultra-low frequency vibrational PEH system based on a single CB structure. This designed PEH will be ideal for scavenging and converting ambient low-vibration energy of suspension bridges into electrical energy for IoT sensors and WSNs. The major goal of this study is to develop PEH that collects energy from bridge vibrations caused by passing automobiles and transforms this energy into electric power by the single CB energy harvester (Fan 2020). The FEA analysis of the single CB is done in COMSOL Multiphysics (Wang 2019). The vibrational energy of the suspension bridge is below 10Hz. The bridge vehicle vibrations are in the range of 1.5Hz to 4Hz. To match the resonance frequency of a single CB energy harvester that of a suspension bridge, proof masses are connected to the tip of the free ends of each beam. A lower resonance frequency of 2.5Hz was obtained with the highest output voltage of 600 mV.

RESONANCE FREQUENCY AS FUNCTION OF BEAM'S LENGTH

The resonance frequency is important in the design of a single CB energy harvester (Sarker et al. 2017)(Wang et al. 2021). To get maximum output the resonance frequency should be equal to the frequency of the vibrational source (Sarker et al. 2016). When a cantilever beam is accelerated in the z-direction, the beam deflects upward or downward, causing a voltage to be induced due to the induced strain or stresses in the beam. To calculate the resonance frequency first we will find the radius of curvature of the beam. The inverse of the radius of curvature (*r*) can be stated as when a concentrated force F, acting perpendicular to the surface of the main cantilever beam, the radius of the curvature (*R*) is given as:

$$\frac{1}{R} = \frac{d^2H(x)}{dx^2} = \frac{M(x)}{WD} = -\frac{F}{\omega D}[L - x] \tag{1}$$

L is the total length of beam and value of x is $0 \leq x \leq L$, $H(x)$ and $M(x)$ are the cantilever beam axial displacement and bending moment at a distance x from the fixed end and D is the bending modulus of the cantilever beam per section per unit width and R is radius of curvature. The bending modulus per unit width are calculated as follows:

$$D = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{2}$$

The tip displacement of the cantilever beam with branches is calculated by the application of the boundary conditions. At the fixed end *H(x)* and *d(x)* are zero and mathematically expressed as:

$$H_{x=0} = 0 \tag{3}$$

$$\frac{dH}{dx} = 0 \tag{4}$$

The value of the axial displacement *H(x)* can be calculated by putting the boundary conditions to Eq. (1):

$$\frac{1}{R} = \frac{d^2H(x)}{dx^2} = \frac{M(x)}{WD} = \frac{F(L-x)}{WD} \tag{5}$$

The integration of Eq. (5) gives:

$$\frac{dH}{dx} = \int_0^x \frac{F}{WD}[L-x]dx \tag{6}$$

$$\frac{dH}{dx} = -\frac{F}{WD}\left[Lx - \frac{x^2}{2}\right] + K_1 \tag{7}$$

By the application of boundary conditions, the value of K_1 becomes zero. By further integrating the results of Eq. (7) and putting the value of $K_1=0$, the value of axial displacement *H(x)* becomes:

$$H(x) = -\frac{F}{WD}\left[\frac{Lx^2}{2} - \frac{x^3}{6}\right] + K_2 \tag{8}$$

The value of *x* varies from *0* to l for the piezoelectric element and for the main cantilever beam varies from *0* to *L*. At the initial point $H=0$, $x=0$ and hence $K_2=0$. The tip displacement of the main cantilever beam is calculated by putting the value of *x* equal to *L* in Eq. (8).

$$H = -\frac{F}{WD}\left[\frac{L^2}{3}\right] \tag{9}$$

The load *F* is represented in Newton. Because the beam's stiffness constant (*K*) is defined as the force necessary per unit tip displacement, it can be calculated using Eqs given as:

$$K = \frac{F}{H} = \frac{3DW}{L^3} \tag{10}$$

The CB has a structure with a proof mass which is distributed load at the tip. Therefore, it is treated as a concentrated point load at a distance of $L_m/2$ from the tip end. As a result, the effective beam length is written as:

$$L_{effective} = \left[L - \frac{L_m}{2}\right] \tag{11}$$

As a result, the effective spring constant becomes

$$K_{effective} = K\left[\frac{L}{L_{effective}}\right]^{-3} \tag{12}$$

DESIGNED SINGLE CANTILEVER BEAM ENERGY HARVESTER IN COMSOL MULTIPHYSICS

A piezoelectric element is attached to the rectangular CB to utilize the stress more efficiently (Ismail et al. 2021). The model simulated a model in COMSOL Multiphysics to get maximum output and to understand the effect of length, width and thickness on the output of the CB. In Figure 1 the proposed model of CB is presented. The power generated by the CB not only depends upon the geometry, frequency of vibration, and displacement of the tip of the free end. The output voltage versus frequency is used to observe the frequency response of CB in COMSOL. The average output power of the CB is

$$P_{av} = \frac{V_{RMS}^2}{R_L} \tag{13}$$

Here, V_{RMS} is the root mean square voltage, P_{av} is the average output power, R_L is the resistance of the load.

$$R_L = \frac{1}{\omega C_P} \tag{14}$$

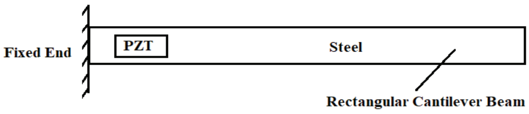

FIGURE 1. Proposed single cantilever beam energy harvester

TABLE 1. Optimized dimensions of single cantilever beam energy harvester

Geometry of Piezoelectric element PZT-5H (LDT1-028K Piezo Sensor)		Geometry of Rectangular Beam steel	
Length (mm)	30	Length (mm)	85
Width (mm)	16.26	Width (mm)	20
Thickness (mm)	0.5	Thickness (mm)	1
Material Parameters		Material Parameters	
Young's Modulus (GPa)	64	Young's Modulus (GPa)	190

SIMULATION RESULTS OF PROPOSED CANTILEVER BEAM PIEZO ENERGY

To observe the effect of the geometrical parameters i.e. length, width and thickness of the main and branched beams, Frequency analysis is done in COMSOL and explained below. Length is an important parameter of geometry and to analyze its effect on the output of CB, frequency analysis is done. Based on the frequency analysis, it is clear that the frequency reduces with the increase of the length of the beam as explained below in the simulation outcomes.

SIMULATION RESULTS OF SINGLE CANTILEVER BEAN PIEZO ENERGY HARVESTER WITH DIFFERENT LENGTHS

In Figures 2 and Figure 3, the length of the beam is varied and different Eigen's frequencies are obtained. When a length is 85mm, the 3rd Eigen's frequency is 3.01Hz, with a length of 105mm the 2nd Eigen's frequency is 2.89Hz.

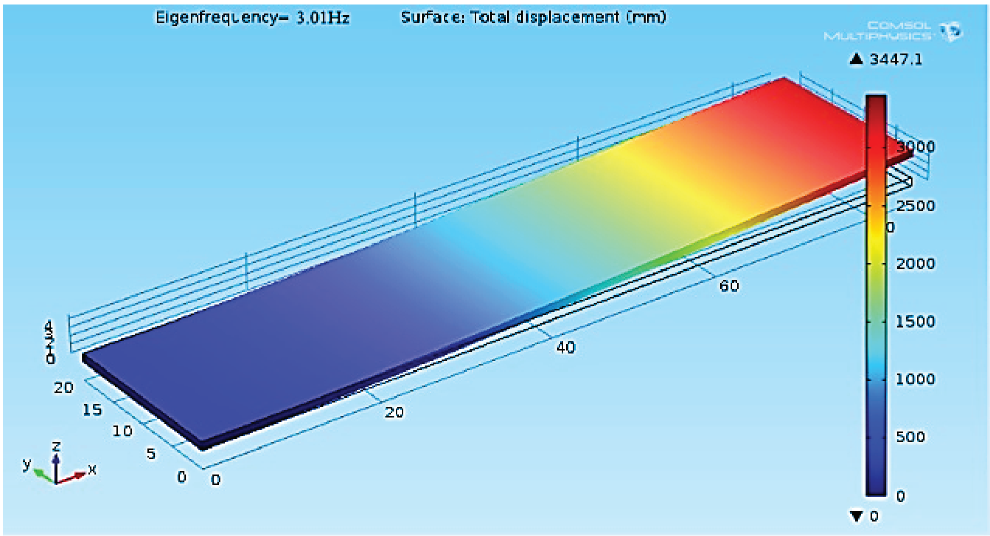

FIGURE 2. Single cantilever beam Piezo energy harvester, COMSOL simulation with 3rd Eigen Frequency 3.01Hz, beam length 85mm, width 20mm and thickness 1mm.

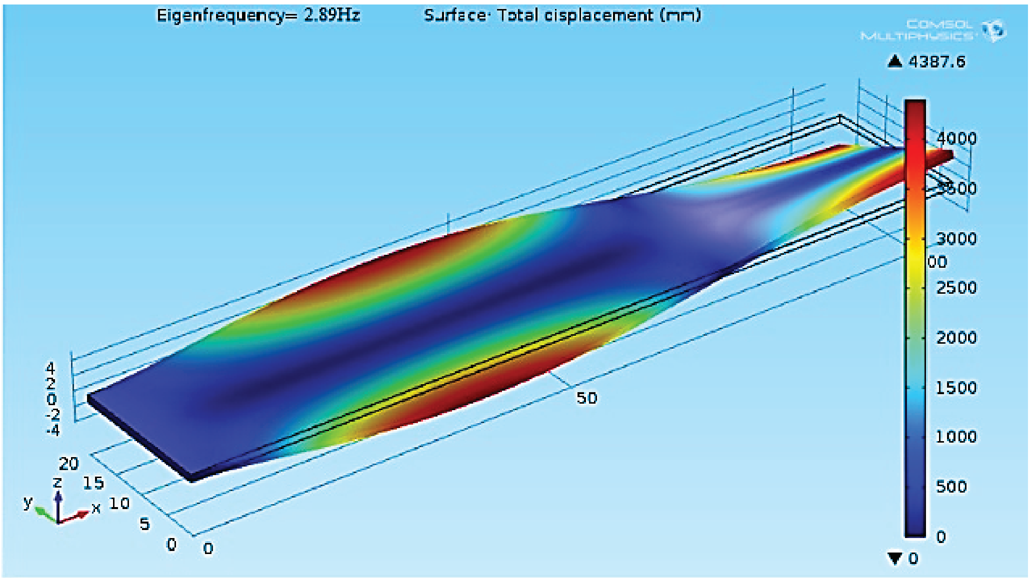

FIGURE 3. Single beam piezo energy harvester, COMSOL simulation with 2nd Eigen Frequency 2.89Hz, beam length 105mm, width 20mm and thickness 1mm.

It is clear from Figure 2, Figure 3 and Table 2 that the length of the single beam and Eigen frequency of the beam has an inverse relationship, as the length increases the Eigen frequency decreases. It is clear from Table 2 that as the length increases from 15mm to 130mm the 1st Eigen frequency decreases from 15.19Hz to 2.99Hz, 2nd Eigen frequency decreases from 14.12Hz to 1.57Hz, 3rd Eigen frequency decreases from 12.90Hz to 1.42Hz, 4th Eigen frequency decreases from 9.16Hz to 1.36Hz, 5th Eigen frequency decreases from 7.81Hz to 1.14Hz and 6th Eigen frequency decreases from 6.98Hz to 1.10Hz.

The relationship between the length of the single beam PEH and the associated Eigen frequency is also explained in Figure 4. It is visible with the help of this figure that the Eigen frequency is inversely proportional to the cantilever beam's length. The Eigen Frequency is on the Y-axis and the length of the beam is on the X-axis, different colours are used to display the Eigen frequencies at different lengths.

TABLE 2. Different lengths of single cantilever beam piezo energy harvester and associated Eigen Frequencies

Length (mm)	1st Eigen Frequency(Hz)	2nd Eigen Frequency(Hz)	3rd Eigen Frequency(Hz)	4th Eigen Frequency(Hz)	5th Eigen Frequency(Hz)	6th Eigen Frequency(Hz)
15	15.19	14.12	12.90	9.16	7.81	6.98
30	10.26	8.22	7.62	6.90	5.19	5.03
45	9.21	7.65	6.80	5.77	4.95	3.11
65	8.63	6.95	5.44	4.97	3.25	2.65
85	5.98	4.34	3.01	2.50	2.14	1.76
95	4.56	3.98	3.78	2.19	1.56	1.89
105	3.15	2..89	1.98	1.61	1.43	1.15
130	2.99	1.57	1.42	1.36	1.14	1.10

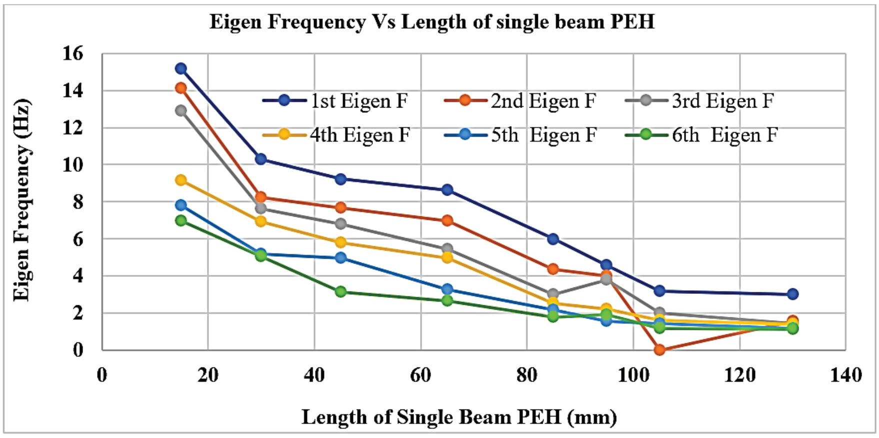

FIGURE 4. Eigen Frequency vs beam's length characteristics of single beam piezo energy harvester

SIMULATION RESULTS OF SINGLE BEAM PIEZO ENERGY HARVESTER WITH DIFFERENT WIDTHS

Now to analyze the effect of width on the Eigen frequency of single beam PEH, a series of simulations was performed with a constant length 85mm and thickness of 1mm but the width is increased gradually. The width of the beam is varied and different Eigen's frequencies are obtained.

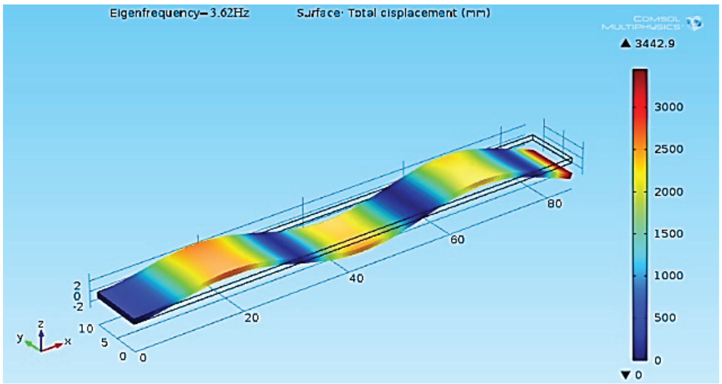

FIGURE 5. Single beam piezo energy harvester, COMSOL simulation with 3rd Eigen Frequency 3.62Hz, beam length 85mm, width 10mm and thickness 1mm

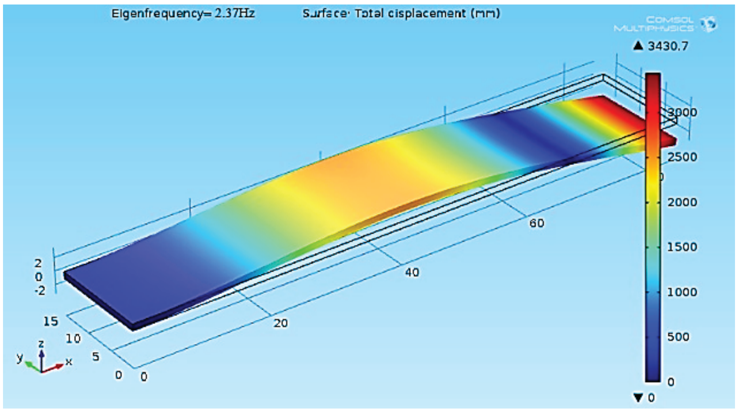

FIGURE 6. Single beam piezo energy harvester, COMSOL simulation with 1st Eigen Frequency 2.37Hz, Beam length 85mm, width 15mm and thickness 1mm

It is clear from Figure 5, Figure 6 and Table 3 that the width of the beam and Eigen frequency of the beam has a linear relationship, as the width increases the Eigen frequency also increases. It is also visible from Table 3 that when the width increases from 2mm to 8mm the 1st Eigen frequency changes from 3.65Hz to 6.85Hz, 2nd Eigen frequency from 4.78Hz to 7.15Hz, 3rd Eigen frequency from 5.69Hz to 8.86Hz, 4th Eigen frequency from 6.88Hz to 8.96Hz, 5th Eigen frequency from 7.53Hz to 9.43Hz and 6th Eigen frequency from 9.38Hz to 12.48Hz. When the width is further increased above 8mm the six Eigen frequencies are reduced.

The relationship between the width of the beam and the Eigen frequency is also explained in Figure 7. In Fig 8 the Eigen Frequency is on Y-axis and the width of the beam is on X-axis, different colors are used to display the Eigen frequencies at different widths. It is visible with the help of this figure that the relationship between the width of the main beam and the Eigen frequency is linear.

TABLE 3. Different widths of Single beam piezo energy harvester and associated Eigen Frequencies.

Width (mm)	1st Eigen Frequency(Hz)	2nd Eigen Frequency(Hz)	3rd Eigen Frequency(Hz)	4th Eigen Frequency(Hz)	5th Eigen Frequency(Hz)	6th Eigen Frequency(Hz)
2	3.65	4.78	5.69	6.88	7.53	9.38
4	4.14	5.79	6.98	7.69	8.94	10.32
6	5.62	5.97	7.35	7.80	9.10	10.56
8	6.85	7.15	8.86	8.96	9.43	12.48
10	1.96	2.19	3.62	3.69	4.23	5.19
15	2.37	3.77	4.86	5.98	6.69	7.78
20	3.01	3.98	4.93	6.93	7.13	8.73

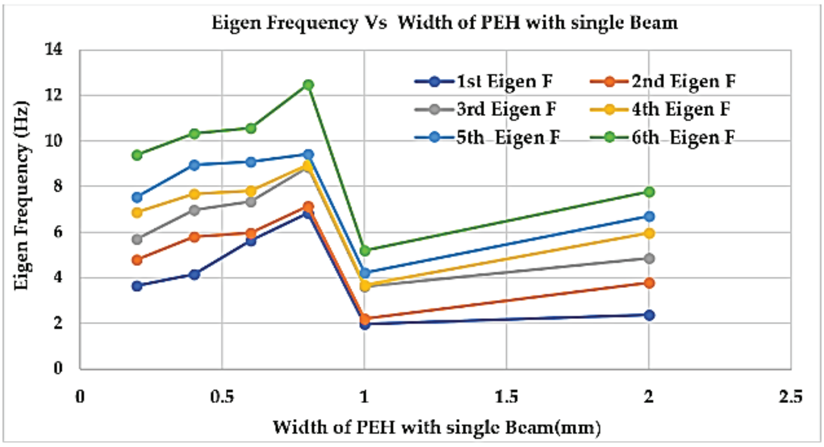

FIGURE 7. Eigen Frequency vs beam's width characteristics of single cantilever beam piezo energy harvester.

SIMULATION RESULTS OF SINGLE BEAM PIEZO ENERGY HARVESTER WITH DIFFERENT THICKNESSES

In order to study the relationship between the thickness and Eigen frequency, the thickness of the beam is varied from 0.2mm to 2mm and Eigen frequency analysis is done in COMSOL. Now to analyze the effect of thickness on the Eigen frequency of PEH with a single beam a series of simulations are performed. In Figure 8 and Figure 9, the thickness of the beam is varied and different Eigen's frequencies are obtained. When thickness is 0.6mm the 1st Eigen Frequency is 5.88Hz, with thickness 2mm the 2nd Eigen Frequency is 3.19Hz. To analyze the effect of thickness on frequency, the thickness of the beam is increased from 0.2mm to 2mm and its effect on Eigen frequencies is observed.

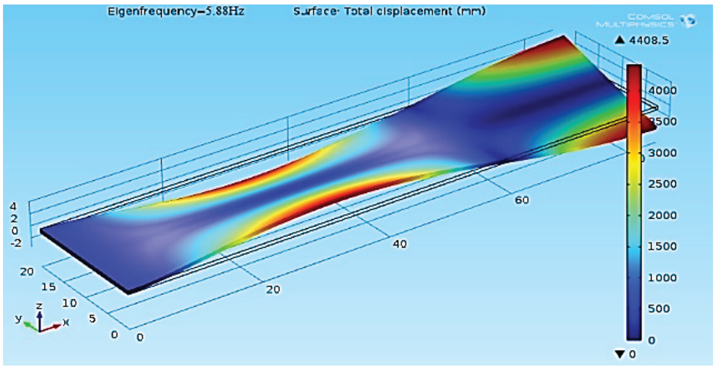

FIGURE 8. Single beam PEH, COMSOL simulation 1st Eigen Frequency 5.88Hz, beam length 85mm, width 20mm and thickness 0.6mm

It is clear from Figure 8, Figure 9 and Table 4 that the thickness of the beam and Eigen frequency of the beam has a linear relationship, as the thickness increases the Eigen frequency also increases. It is also visible from Table 5 when the thickness increases from 0.2mm to 0.8mm the 1st Eigen frequency changes from 3.54Hz to 5.96Hz, 2nd Eigen frequency from 4.97Hz to 7.28Hz, 3rd Eigen frequency from 5.97Hz to 8.19Hz, 4th Eigen frequency from 6.93Hz to 8.61Hz, 5th Eigen frequency from 7.27Hz to 9.20Hz and 6th Eigen frequency from 8.64Hz to 11.43Hz. When the thickness is further increased above 1mm the Eigen frequency is reduced and with a further increase in the thickness there is a minor increase in the Eigen frequency.

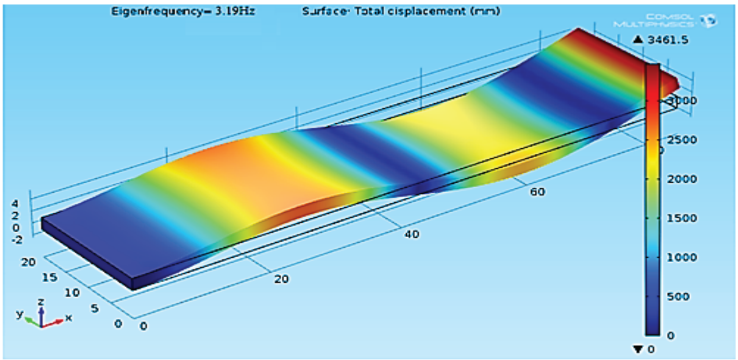

FIGURE 9. Single beam PEH, COMSOL simulation with 2nd Eigen Frequency 3.19Hz, beam length 85mm, width 20mm and thickness 2mm

The relationship between the thickness of the beam and the Eigen frequency of the single beam PEH is also explained in Figure 10. In Figure 10 the Eigen Frequency is on Y-axis and the thickness of the beam is on X-axis, different colours are used to display the Eigen frequencies at different thickness. It is visible with the help of this Figure 10 that the Eigen frequency increases with the increase in the thickness of the beam.

TABLE 4. Different Thickness of single beam piezo energy harvester associated with each Eigen Frequency.

Thickness (mm)	1st Eigen Frequency(Hz)	2nd Eigen Frequency(Hz)	3rd Eigen Frequency(Hz)	4th Eigen Frequency(Hz)	5th Eigen Frequency(Hz)	6th Eigen Frequency(Hz)
0.2	3.54	4.97	5.97	6.93	7.27	8.64
0.4	4.32	4.49	5.39	6.03	7.98	10.92
0.6	5.88	6.62	6.87	7.19	7.54	11.25
0.8	5.96	7.28	8.19	8.61	9.20	11.43
1	2.50	4.95	5.20	6.80	7.25	7.51
2	2.68	3.19	4.27	5.78	5.93	6.85

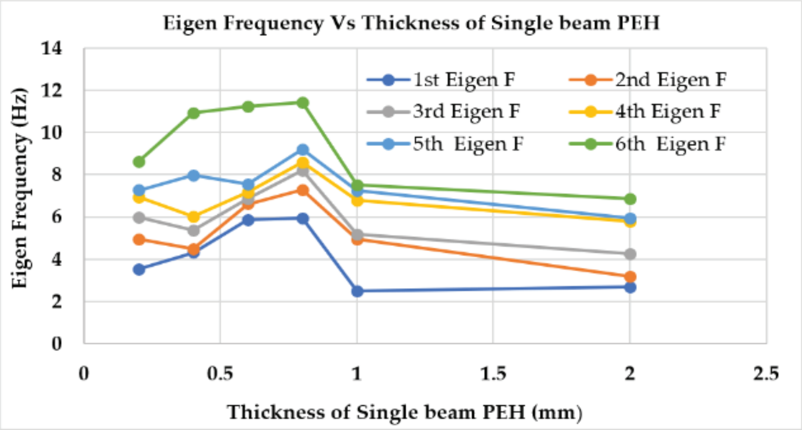

FIGURE 10. Eigen Frequency vs beam's thickness characteristics of single beam piezo energy harvester

CONCLUSION

The basic concept behind this research is the design of a signal branch CB harvester that utilizes the free energy of vibrations of the suspension bridge and the generation of stable output voltage. The main limitation of this work is capturing energy from the suspension bridge which is only possible when the frequency of vibration of the CB harvester matches the resonance frequency of the suspension bridge. To match the resonance frequency with that of harvester frequency the design of the harvester is very important. This study presents a finite element analysis of the CB multi-branch structure in COMSOL Multiphysics to enhance the output voltage. The output power of the CB harvester is the function of Eigen frequency and this Eigen frequency depends upon the geometry of the CB harvester.

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DECLARATION OF COMPETING INTEREST

None.

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