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Experimental Investigation of Energy Harvesting by Employing Piezoelectric Element and Metallic Cantilever Beam

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ABSTRACT

In this paper, in response to the worldwide energy crisis, a piezoelectric element (0.2*35*50) mounted on a host metallic cantilever beam (0.8*37*220) will be presented as a unique contribution to power generation via the micro-electrical mechanical system. It's made out of aluminium and low carbon steel, both of which have a Young modulus of elasticity of 6.8 and 196 GPa, respectively. In order to take advantage of the engine's vibration as an exciting external force to collect energy in the aforementioned piezoelectric device, the whole rig has been coupled to a diesel engine 5kw 3000 rpm (50 Hz). The average power generated by the aluminium beam was 943 microWatts, while the power generated by the low carbon steel beam was 335 microWatts, an increase of 256%. In addition, for both scenarios, (45) mm from the cantilever beam's fixed point was where the engaged piezoelectric element performed best. The used two metals have different stiffnesses, and this accounts for the obtained difference between the induced powers; increasing the stiffness will result in relatively more power created, and vice versa.

1. Introduction

In the last decade highly an increase in research on energy harvesting (EH), it can be classified into two terms macro-scale and micro-scale; each one has many types of energy harvesting; as Figure 1, EH is the extraction of small amounts of energy from one or more energy sources. Conserving them for future use, piezoelectric energy harvesting (PEH), converting the wasted mechanical vibration energy into valuable electrical energy, depends on the piezoelectric effect, [1] with increasing IoT applications and microelectromechanical systems (MEMS) that work on independent power sources like a battery where it should be replaced at the end of battery life ends. In some cases of operation, it's difficult or costly and PEH with cantilever module promising solution for self-power application [2].

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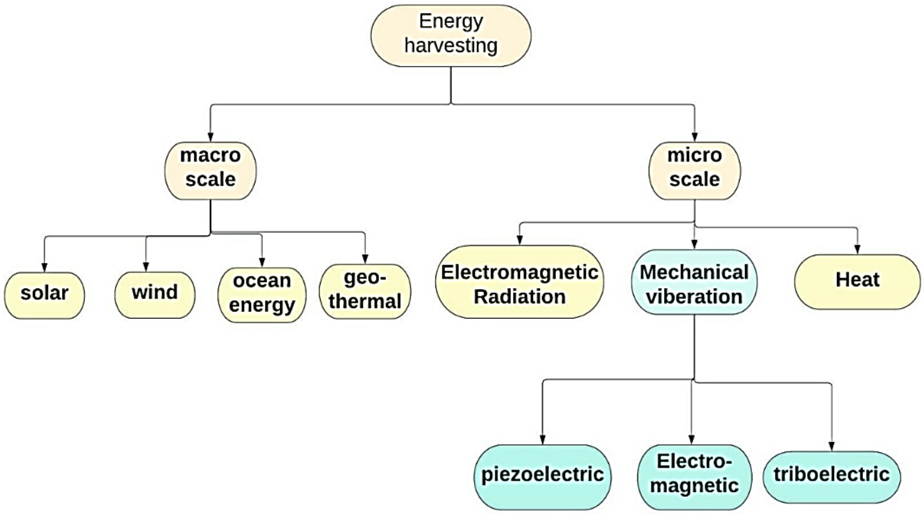


Fig. 1. Energy harvesting classification

The proliferation of "smart" cities, "wearable" electronics, and "in-car" electronics has skyrocketed in recent years. However, the growth of long-lasting, integrated, and miniaturised wireless sensor network nodes as well as portable electronic gadgets poses new issues to their energy supply units. Energy supply units now need to meet stricter criteria due to the additional issues that have arisen. These criteria include, but are not limited to, being compact, having a long lifespan, having a high output power density, being easy to integrate monolithically, and being failsafe under extreme conditions. Reliable and long-lasting power for work nodes and portable electronic devices can be provided by harvesting energy from the surrounding microenvironment. They are constantly converting the kinetic energy of vibrations in the surrounding medium into electrical power. This vitality is essentially ubiquitous. Energy harvesting technology has shifted its research focus to concentrate on developing this technology due to its obvious benefits, such as the lack of electromagnetic interference, good MEMS process compatibility, high output power density, high reliability, and mass manufacturing. There has been a lot of research done recently on the theoretical models, materials, and structures of MEMS PVEHs.

There are two main categories that can be used to categorise the theoretical models: those with lumped parameters (LP) and those with distributed parameters (DP) [3, 4]. Substrate materials by Pourashraf *et al.,* [5], doping optimisation by Yao *et al.,* [6], alteration and innovative piezoelectric materials by Lim *et al.,* [7] and He *et al,* [8] are currently the key areas of focus in the field of material research. Doping modification of the aluminium nitride (AlN) piezoelectric film has become a focus of research because of its importance as an energy-trapping film for the microelectromechanical systems piezoelectric energy harvester (MEMS PVEH) [9]. The structural design is mostly focused on enhancing the functionality of existing structures while also offering proposals for new ones. Cantilever designs are the most popular and have garnered the most study. Based on the previous studies, stress optimisation by Safaei *et al,* [10], geometric form optimisation by Serhane *et al.,* [11], electrode optimisation by Abdullah *et al.,* [12], topology optimisation by Hassan *et al.,* [13], and frequency band expansion by Arifin *et al.,* [14] are among the primary areas of research for cantilever beam-based PVEHs. These research focuses exclusively on the rectangular cantilever beam despite the tremendous advancement of MEMS PVEHs in theoretical models, materials, and designs. The bending stress on a rectangular cantilever beam is highest at the fixed end and decreases to zero at the free end due to the linear distribution of the bending force throughout the beam's length. This can lead to problems with the rectangular cantilever beam PVEH, such as fatigue and stress accumulation at the fixed end and subpar performance from the piezoelectric material surrounding the free tip. In recent years, researchers have started investigating into piezoelectric energy harvesters that are based on variable cross-section cantilever beams (VCSCB). Jin *et al.,* [15] reported that by linearly adjusting the beam's cross-section along its length, the energy harvesters' output power density can be increased by as much as 30%.

The output energy from this type is affected by many factors, such as the geometry dimension of the cantilever, fundamentals frequency, vibration displacement, and materials specification. A comparison of different EH was made by Liu *et al.,* [16] where they discovered that piezoelectric transduction is the most efficient mode of EH. A review of EH from vibrations utilizing piezoelectric materials is discussed by Kamaruzzaman *et al.,* [17]. The capacity of piezoelectric materials to convert mechanical energy into electric energy via a piezoelectric effect, such as sensors, and vice versa by an inverse piezoelectric effect, such as electric actuators, is their distinguishing feature. Sharaf *et al.,* [18] studied the impact of geometry parameter of rectangular shape cantilever with PEH to harvest mechanical vibration energy from ambient and effect of fundamental natural frequency, arbitrary shape beam [19]. This paper focuses on PEH generated from vibration of one piston four stock engine5kw speed 3000 rpm; an attempt is made to increase the charge created by using a piezoelectric cantilever-based energy harvester. Two types of metallic cantilever beams (aluminium and low carbon steel) were selected as host beams to make experimental validation.

2. Methodology

2.1 Coupling Equations for Piezoelectric Generator

When piezoelectric materials are affected by mechanical action like compressive, vibration or force, they produce electrical energy by direct piezoelectric effect anther ward act as a sensor, while if electric current applied on the terminal of the piezoelectric element, it have mechanical displacement refers to the inverse piezoelectric effect [7] to harvest energy from engine vibration as electrical energy, a cantilever beam mounted with piezoelectric material fixed on the engine body. By using newton's second law of motion and Euler's theory for continuous system cantilever beam vibration

$$EI\frac{\partial^4 V(x.t)}{\partial x^4} = -\rho A(x)\frac{\partial^2 V}{\partial t^2} \tag{1}$$

Where E is Young modulus, I the second-moment inertia of area V is a sheer force along x- the direction of the beam, ρ material density, A cross-section area

$V(x.t) = X(x)F(t)$. Using separation of variables yields

$$\frac{EI}{\rho A}\frac{X(x)''''}{X(x)} = -\left[\frac{\ddot{F}(t)}{F(t)}\right] = \omega_n^2 \tag{2}$$

Where ω_n is a natural frequency. Take the first part, the position analysis

$$\frac{X''''(x)}{X(x)} = K_n^4 \tag{3}$$

$$K_n = \sqrt[4]{\frac{\rho A}{EI} * \omega_n^2} \tag{4}$$

Apply boundary conditions on the cantilever beam as it continues the system at x= 0 and x= L for Eq. (4) and solves the equation to find routs, yields

$$\mathrm{X_n(x)} = \mathrm{C_2}\left\{\left[\{\cos(\mathrm{K_n} * \mathrm{X}) - \cosh(\mathrm{K_n} * \mathrm{X})\} + \frac{-\cos(\mathrm{K_n} * \mathrm{L}) - \cosh(\mathrm{K_n} * \mathrm{L})}{\sin(\mathrm{K_n} * \mathrm{L}) - \sinh(\mathrm{K_n} * \mathrm{L})}\right] * [\sin(\mathrm{K_n} * \mathrm{L}) - \sinh(\mathrm{K_n} * \mathrm{L})]\right\} \tag{5}$$

$X(x)$ = transceiver displacement of a vibration cantilever beam for (x = L); this term is essential in calculating the energy harvesting equation.

$$\mathrm{Ux} = -\mathrm{z}\frac{\partial \mathrm{x(x\,.\,t)}}{\partial \mathrm{x}} \tag{6}$$

Ux is displacement along x – direction in the continence system, z is the initial position of the node point in the z-direction, and the strain along the x-direction due to bending can be written as

$$\varepsilon_\mathrm{x} = \frac{\partial \mathrm{u_x}}{\partial \mathrm{x}} = -\mathrm{Z}\frac{\partial^2 \mathrm{x}}{\partial \mathrm{x}^2} \tag{7}$$

Refer to direct piezoelectric effect

$$\mathrm{Dz} = \mathrm{e_{31}}\varepsilon_\mathrm{x} + \mathrm{e_{33}}\mathrm{E_z} \tag{8}$$

$$Ez = -\frac{\partial v}{\partial z} = -\frac{v}{\nabla} \tag{9}$$

$\mathrm{e_{31}}$, $\mathrm{e_{33}}$ are dielectric constants in 31 and 33 directions Dz is the dielectric displacement in the z-direction, Ez is an electric field in the z-direction, ∇ is the thickness of piezoelectric materials. v voltage difference on poles the integration of area determinant of surface charge density represents total charge Q and can be written as

$$\mathrm{Q} = -b\int_{l^\circ}^{l1} \mathrm{e_{31}} * \frac{h}{2} * \frac{\partial 2y}{\partial x2}\, dx + b\int_{l^\circ}^{l1} \mathrm{e_{33}}\; Ez\, dz \tag{10}$$

$$\mathrm{Q} = \frac{bh(\mathrm{e_{31}})}{2}\,[\emptyset(l^\circ) - \emptyset(l1)] - \frac{bl(\mathrm{e_{33}}\,)v}{\nabla} \tag{11}$$

Where $\emptyset(x\;\; t) = \frac{\partial X(x.t)}{\partial x}$ is the slop of beam $\emptyset(l^\circ)\; and\; \emptyset(l1)$ specifies the beginning edge and end edge of the piezoelectric strip, h thickness of the host cantilever beam, L is the length of the piezoelectric element,b width of the piezoelectric element. The current flow from electrodes can be written as

$I = \omega Q$. Also $I = \frac{V}{R}$. The time average output power is calculated as

$$\bar{P} = \frac{Vm}{\sqrt{2}} * \frac{Im}{\sqrt{2}} = \omega^2 \, b^2 \, h^2 e_{31}^2 A^2 \, R * \frac{1}{4\left(1 + ble_{33} \ \frac{\omega R}{\nabla}\right)^2} \tag{12}$$

Where A = X(x) at x = L, ω vibration frequency rad/sec depend on speed of engine, R piezoelectric resistance, l length of piezoelectric element.

2.2 Experimental Proposed Harvesting Model

Block diagram Figure 2 shows the utilization of piezoelectric element as E.H. to convert mechanical vibration into electrical energy and storage in the accumulator (battery or supercapacitor).

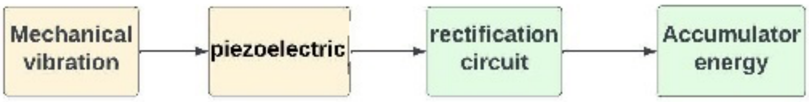


Fig. 2. Block diagram of energy harvesting

2.3 Host Beam at a Glance

Figure 3 shows the suggested dimension of the beam for two metallic (aluminium and low carbon steel) [8].

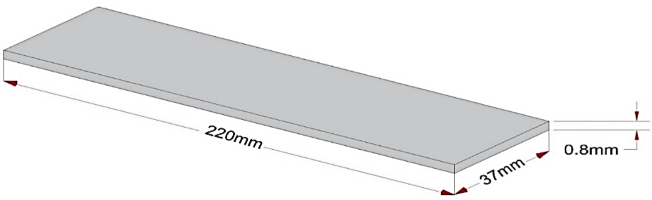


Fig. 3. Dimension of (aluminium and low carbon steel) beam

2.4 Piezoelectric Elements at a Glance

Piezoelectric element (PZT5A) and terminals of electric connections are shown in Figure 4, together with their corresponding dimensions and technical characteristics, which can be found in Table 1 [9, 10]. One of the connecting wires had been soldered on the outer surface layer of the piezoelectric as a terminal, and the other had been connected on the substrate layer as a ground. Soldering had been reinforced with covering silicone, and high adhesive epoxy was used to mount the piezoelectric element on the host beam. During this process, the cantilever at the shifted location was cleaned by removing old epoxy, and the piezoelectric element was re-instilled in the next position.

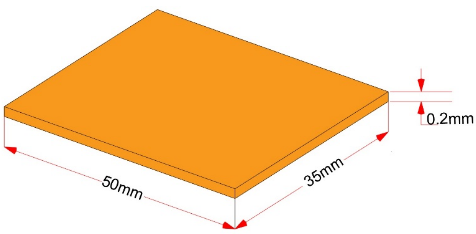


Fig. 4. Piezoelectric element dimension

Table 1
Piezoelectric element material properties from piezo system

No	Parameter	Values
1	Young modulus (Gpa)	50
2	Poisson ratio	0.3
3	Density(kg/m^3)	7500
4	D33	680
5	Coupling coefficient	0.65
6	Thickness*width*length(mm)	0.2*35*50

2.5 Assembly of the piezoelectric element and host beam

The piezoelectric element and the cantilever beam are shown assembled in Figure 5, which is an illustration of the process.

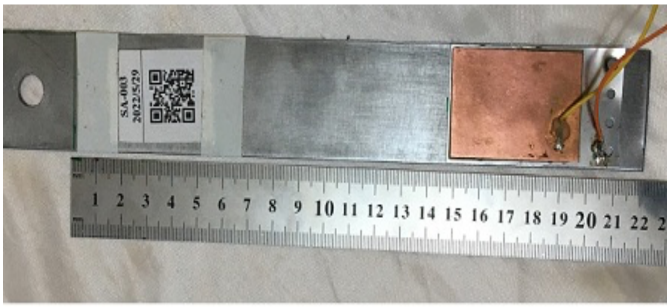


Fig. 5. Piezoelectric Element and the Host Beam

2.6 The Suggested Rig

Assembly models have been connected to the body of the diesel engine as in Figure 6, which converts mechanical vibration into electric energy and acts as MEMS; the technical specification of the engine is shown in Table 2.

Fig. 6. Suggested rig

Table 2
Technical specification of the engine

Engine model	KM186FA
Rated rotation speed(rpm)	3000
Engine type	Single cylinder, 4-stroke, direct injection
Rated output power [Kw/rpm]	5/3000

3. Results and discussion

3.1 Aluminium Host Beam Experimental

Figure 7 depicts the placement of the piezoelectric element L_0, which represents the distance from the fixed point to the commencing edge. This experimental test was performed twice to determine the variation reading for both models. As can be seen in Table 3, there are several parameters whose values remain the same across all the different experimental runs. These involve the computation of electrical power by monitoring changes in voltage and current.

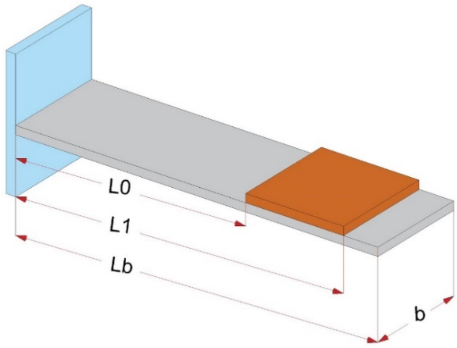


Fig. 7. Schematic representation of piezoelectric energy harvesting model

Table 3
Constant parameter of experimenters

Parameter	Value	Unit
Length of host beam (L_b)	220	mm
Width of host beam (b)	37	mm
thickness of host beam (h)	0.8	mm
vibration frequency (ω)	296	rad/sec
Young modules aluminium (E)	6.8	Gpa
Young modules low carbon steel (E)	196	Gpa
Second area moment (I)	1.5786*10^{-12}	m^4

The experimental portion of this paper demonstrated, as shown in Table 4 and Figure 8, that the maximum output power is 2500 uW when the cantilever is positioned 45 mm away from a fixed point, and the minimum value is 36 uW when the cantilever is positioned 3 mm away. This variation is associated by a curvature that depends on the mode of vibration in other ward related by the modulus of elasticity of metallic of the beam. In other words, this variation is related by the modulus of elasticity of metallic.

Table 4
Experimental attempts result for aluminium host beam

Item	L_0 (m)	L_1 (m)	First attempt			Second attempt			Average
			Volt (V)	Amp (mA)	Power (uW)	Volt (V)	Amp (mA)	Power (uW)	Power (uW)
1	0.145	0.195	2.75	0.295	811	2.79	0.312	870	840
2	0.095	0.145	2	0.208	416	1.8	0.209	376	396
3	0.045	0.095	4.8	0.51	2448	4.9	0.522	2550	2500
4	0.003	0.053	2	0.022	44	1.8	0.016	28	36

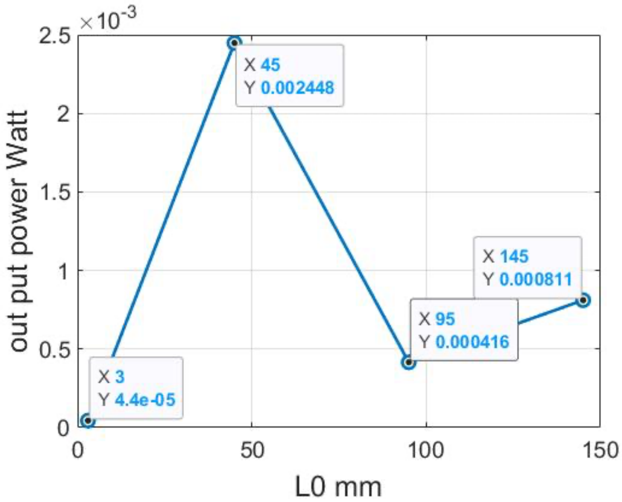


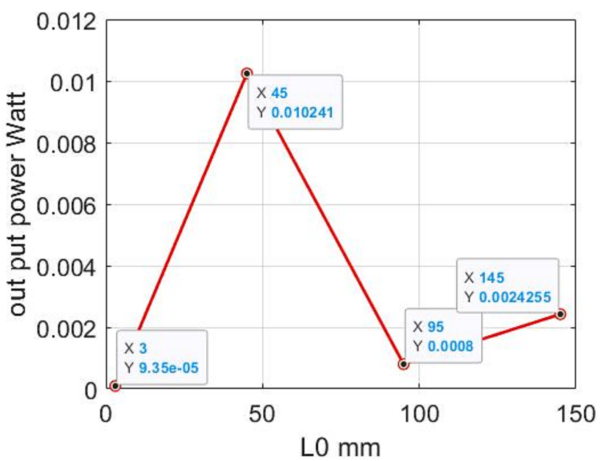
Fig. 8. First attempt for aluminium

3.2 Low Carbon Steel Host Beam Experimental

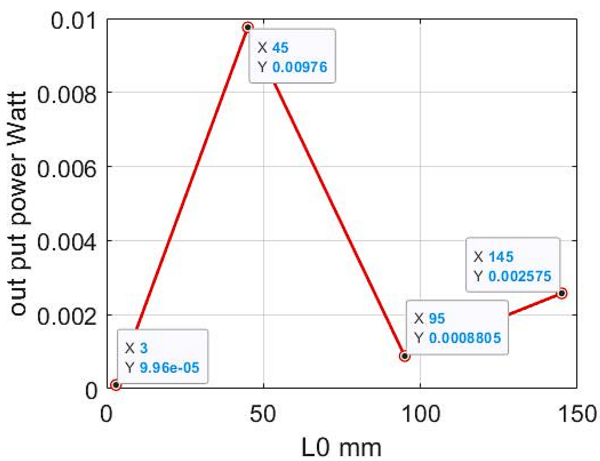
The results of the experiments presented in Table 5 and Figure 9 showed that the maximum output power is 10000 uW when measured from a fixed point on the cantilever at 45 mm, while the minimum value measured at 3 mm is 96 uW. This indicates a considerable variance in the amount of power generated owing to variations in the modulus of elasticity.

Table 5
Experimental attempts results for low carbon steel host beam

Item	L_0 (m)	L_1 (m)	First attempt			Second attempt			Average
			Volt (V)	Amp (m A)	Power (uW)	Volt (V)	Amp (m A)	Power (uW)	Power (uW)
1	0.145	0.195	4.9	0.495	2425	5	0.515	2575	2500
2	0.095	0.145	3.2	0.250	800	3	0.294	880	840
3	0.045	0.095	7.7	1.33	10241	8	1.22	9760	10000
4	0.003	0.053	1.1	0.085	93	1.2	0.083	99	96



(a)



(b)

Fig. 9. (a) First attempt for low carbon steel (b) Second attempt for low carbon steel

3.3 Overall Results of Host Beams

When compared, the results produced as an average reading of output electric power for both beams can be seen to be the low carbon steel cantilever beam has a high ability to transfer the mechanical vibration into piezoelectric as transient displacement, which yields significant harvesting energy via piezoelectric element Figure 10, the behaver of variation values of power produced along the beam is similar for both host beams. That belong to the similarity mode vibration in which the frequency is in the low range (50 Hz) at the rate, the first mode of vibration generated on beam, also the vibration frequency is a function of engine speed in which experimentally the rotational speed was measured by tachometer, and the reading was 296 rad/sec.

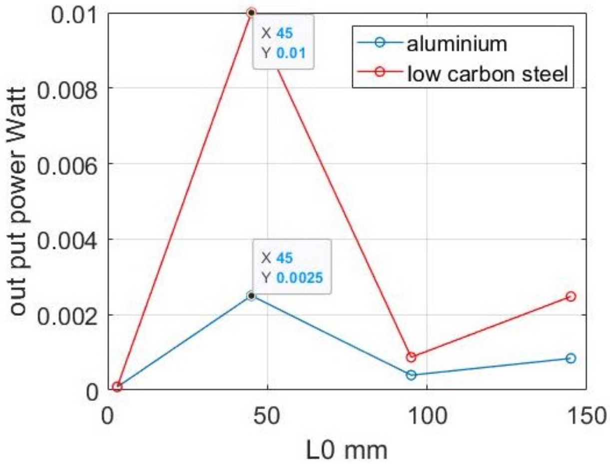


Fig. 10. Piezoelectric element average output power with (aluminium low carbon teel) host beam

As it is well-known, each experimental investigation has its own percentage error ratio, that is depending on many factors related to the nature and procedure of the practical part, so in this paper, the situation is a little bit complex, where a mixture of electrical and mechanical parts has been adopted to achieve the expected results. In the other ward, the deviation in the gained results will be attributed to the electric part and the other one related to the mechanical assembly, with a different ratio for each part. The following paragraphs explain in detail each one. There is no doubt that the employed piezoelectric element is facing fatigue stress due to the cyclic repetition of the applied periodic load, which means it will lose some of its accuracy, precision and resolution and consequently will give variation in the induced electric power as the time going on. The second main factor is how much the electrical power loose in the connection and soldering wires as a result of its internal electrical resistance, especially that the harvesting energy in terms of micro-Watt; therefore, it is better to use an excellent electric wire with minimum resistance to the electric current, supported by soldering connection to avoid bad contact between any two matting poles.

4. Conclusions

In conclusion, it has been discovered that when the modulus of elasticity (E) grows, the generated power will also dramatically increase, but only up to a certain point before reaching a limit. It is possible to consider that the energy harvesting is a function of the modulus of elasticity but to some specified limit, whereas the modulus of elasticity is in a continuous increment, this will transform the employed cantilever beam into a very efficient energy harvester. In other words, in the case of the aluminium cantilever beam (E = 6.8 GPa), the associated power generated was 943 Watt as a mean value. Meanwhile, the induced power was 3. In this study, the percentage increase in the amount of power that was created was 256 percent higher for the beam made of low carbon steel compared to the beam made of aluminium. The second primary concern is the question of where along the entire length of the host beam the piezoelectric element should be attached. Because there is no connection between the geometry of the cantilever beam and the metal used in its construction, the position of the beam must remain unchanged regardless of whether it is made of aluminium, low carbon, or some other sort of metal. The results of practical investigations showed that the maximum power generated was 2,500 and 10,000 Watt for aluminium and low carbon steel, respectively, at a distance of 45/220 mm from the fixed point along the whole length of the cantilever beam. Considering that the other values of the generated power with the other distances from the fixed point were less than the peak point value, it is abundantly clear that at that distinguished point the curvature of the cantilever beam was maximum in comparison with the other points also it is possible to say that the best power harvesting will occur by increasing the modulus of elasticity of the employed cantilever beam but with a definite limit and attaching the piezoelectric element at a distance of about 20% of the total length of the cantilever beam starting from the fixed point regardless of the metal type of the cantilever beam. This is true regardless of the fact that increasing the modulus of elasticity of the employed cantilever beam will result in the best power harvesting.

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