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Piezoelectric Pre-Stressed Bending Mechanism for Impact-Driven Energy Harvester

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Piezoelectric Pre-Stressed Bending Mechanism for Impact-Driven Energy Harvester

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Abstract. This paper experimentally demonstrates and evaluates a piezoelectric power generator bending mechanism based on pre-stressed condition whereby the piezoelectric transducer being bended and remained in the stressed condition before applying a force on the piezoelectric bending structure, which increase the stress on the piezoelectric surface and hence increase the generated electrical charges. An impact force is being exerted onto bending the piezoelectric beam and hence generating electrical power across an external resistive load. The proposed bending mechanism prototype has been manufactured by employing 3D printer technology in order to conduct the evaluation. A free fall test has been conducted as the evaluation method with varying force using a series of different masses and different fall heights. A rectangular piezoelectric harvester beam with the size of 32mm in width, 70mm in length, and 0.55mm in thickness is used to demonstrate the experiment. It can be seen from the experiment that the instantaneous peak to peak AC volt output measured at open-circuit is increasing and saturated at about of 70V when an impact force of about 80N is being applied. It is also found that a maximum power of about 53mW is generated at an impact force of 50N when it is connected to an external resistive load of 0.7KΩ. The reported mechanism is a promising candidate in the application of energy harvesting for powering various wireless sensor nodes (WSN) which is the core of Internet of Things (IoT).

1. Introduction

Recently, Microelectromechanical systems (MEMS), wireless sensors network (WSN), as well as internet-of-thing (IoT) has grabbed the attention of many researchers worldwide, and particularly on microactuators, microsensors, together with microsystems that achieved by merge micromechanical devices with microelectronic for many-sided purposes. Precisely, impact-based energy harvesting (IBEH), which are capable of converting ambient mechanical impact energy into usable electrical energy, are attracting majority of researchers attention for the sake of increasing demand of self-powered WSN for IoT applications [1][2], in which many of this WSN are embedded in the stand alone structure or remote spatial environments whereby there will be a huge numbers of wireless sensors and smart objects surrounding our living space in the “IoT” era, where it will lead to make our living space being smarter, green, and for better quality of lives [3]. Up-to-date IBEHs are facing the trade-off among the impact force, impact velocity, and the output power, whereby the applied impact parameters will affect the stress on the piezoelectric surface which lead to change to output power [4].

As aforementioned, IBEH is one of the attractive approaches that proposed to be used for powering up low power portable autonomous microsystems, due to the fact that, mechanical impact energy resources are available in abundance and ubiquitous surrounding us, starting from human beings activities (walking, dancing, exercising), ending to the industries environment whereby all the machines are generates a noticeable and almost continues amount mechanical impacting energy, whereby all that impacts energy has been dissipated and wasted to the ground or into the impact absorbents. Therefore, this research paper presents a new pre-stressed bending mechanism along with laboratory testing which allocated for harvesting that wasted mechanical impact energy. Moreover the proposed method employs an off the shelf piezoelectric cantilever harvester element due to its high electrical output density contrast with the piezoelectric ceramic disc.

1.1. Piezoelectricity

Piezoelectricity is the electrical charge that accumulates in certain crystal in corresponding to applied mechanical stress. In another word, the word piezoelectricity means electricity that generated from pressure. This piezoelectricity effect is considered a reversible effect, whereby this type of crystal has the ability to behave as an actuator (the shape of the piezoelectric crystal will deform) in according to an AC signal supplied with a certain frequency connects to its terminals [5]. Brothers Pierre, Curie, and Jacques are the researchers who discovered this effect in 1880 [6]. Whereby they found that a certain crystals have the ability of producing dual polarities charges when mechanical stress was applied on it. Subsequent and in 1881, Lippmann has been mathematically deduced the inverse piezoelectricity from fundamental thermodynamic principles, and has been confirmed later on by Curies [7].

The piezoelectric element crystal is addressed by a constitutive equation, which is by merging the electrical induction *D*, electric field *E*, strain *S*, and the stress *T*. Moreover, according to the principle of energy conservation at low frequency we have:

$$D = dT + \mathcal{E}^T E \tag{1}$$

$$S = S^E T - d' E \tag{2}$$

Where: $\mathcal{E}^T$: Permittivity at constant stress.
S^E: Compliance at constant electric field.
d: Piezoelectric charge coefficient.

Consequently, and compared to a non-piezoelectric material, there will be always a strain due to the applied electrical field, and vice versa, an electrical charges will be deduced due to the mechanical stress (electrical charges that displaced inside the material are inducing the opposite polarity surface charges on the plates). When the surface area does not deformed under the applied stress (which is impossible in polymers), then (d=d'). When solving Equation (1) for *E*, and equation (2) for *T*, we will get:

$$E = \frac{D}{\mathcal{E}^T} - \frac{Td}{\mathcal{E}^T} = \frac{D}{\mathcal{E}^T} - gT \tag{3}$$

$$T = -\frac{d}{S^E}E + \frac{1}{S^E} = C^E S - eE \tag{4}$$

Furthermore, while stressing the piezoelectric materials by applying an external force F_3 in the direction as shown in Figure 1, which bend the structure downward, stressing the piezoelectric materials and building up electric charges Q_3=D_3A_3 on the surfaces of area A_3 to yield a voltage V_3=Q_3/C_3. The electric charge density is $D_3 = d_{33}T_1$, whereby T_1=$d_{33}F_1/A_1$ and $C_3 = \mathcal{E}_{33}^T A_3/h$. Hence, the output voltage generated by applying a corresponding amount of force can be calculated from:

$$V_3 = d_{33}F_3\left(\frac{1}{A_3}\frac{h}{\mathcal{E}_{33}^T}\right) \tag{5}$$

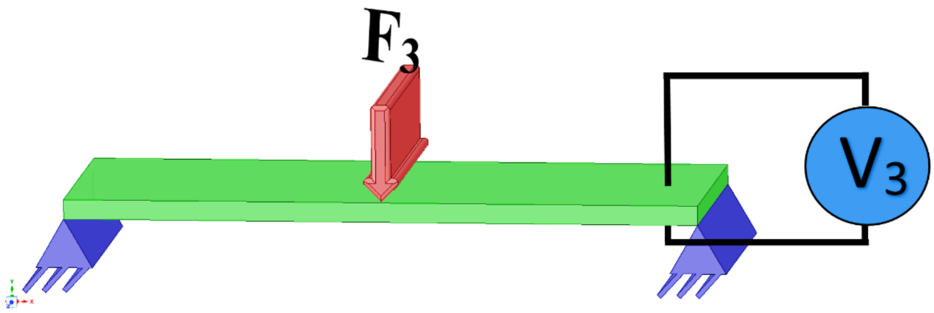

Figure 1. Open circuit voltage measurement of a piezoelectric module while applying external force.

Obviously it can be concluded from Equation (5) that the output voltage *V3* which generated at the piezoelectric transducer terminals is directly proportional to the applied force F_3, by assuming that the other variables are constants. A general piezoelectric energy harvester equivalent circuit can be illustrated as shown in Figure 2, which consisting of mechanical domain clarifies the direct effect of the piezoelectric materials, where *m* representing the mass of the harvester, *d* the damping factor, *k* the mechanical stiffness, α the piezoelectric coupling coefficient and σ_{in} represent the applied force, while the electrical domain consisting of *v* represents the output voltage, *Cp* and *RL* are representing the inner capacity and external resistive load respectively. Whenever an external force is being applied to deform the piezoelectric structure, the voltage output would be generated according to the responses of the force changes over the time [8][9].

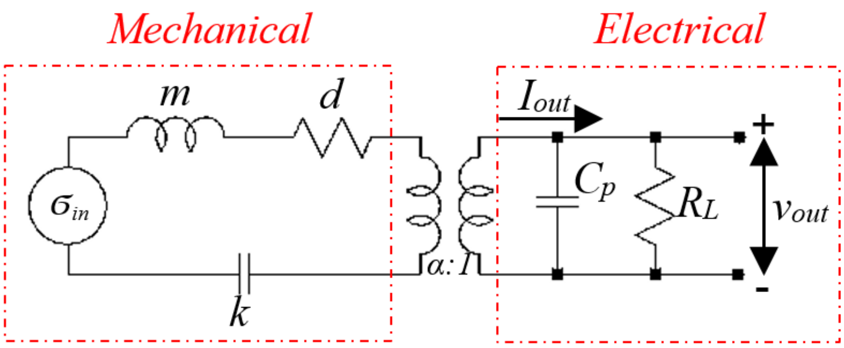

Figure 2. The equivalent circuit of the piezoelectric harvester.

1.2. Impact Force of Object in Free Fall

A free fall is a special type of motion in which the only force acting upon a falling object is the gravity assume that there is no drag force of air. Likewise, when an object with mass equal to *m* is freely fall from h_1 height, and lets presume its velocity is *v* upon the impact, therefore its energy equation can be written as the following equation (6):

$$mgh_1 = \frac{1}{2}mv^2 \tag{6}$$

Where *g* is the gravity acceleration. When the free fall height h_1 is known, subsequently the impact velocity of the falling object can be calculated from:

$$v = \sqrt{2gh_1} \tag{7}$$

The impact force for a falling object is dependent on the impact depth, h_2 before it comes to a totally stop, which can be written as follow:

$$F = \frac{E_k}{h_2} = \frac{mv^2}{2h_2} \tag{8}$$

Where E_k is the kinetic energy. From equation (8) can tell that the falling object force upon the impact is inversely proportional to the penetrated distance h_2 or knowing as bending offset. Therefore and in order to increase the piezoelectric electrical charge generation, and from the stress equation bellow:

$$T = 6 * S \tag{9}$$

Where: T: Stress
σ: Young's Modulus
S: Strain

So from equation (8) and equation (9) can say that h_2 need to be enlarged so that the strain S, and the stress T will be increased accordingly. Consequently, the voltage output is proportional to the stress (Equation 5). Thus a pre-stress bending mechanism has been designed to enlarge the bending offset h_2, and hence maximizing the piezoelectric power generation as mentioned earlier rather than the unstressed bending mechanism, as clear in Figure 3.

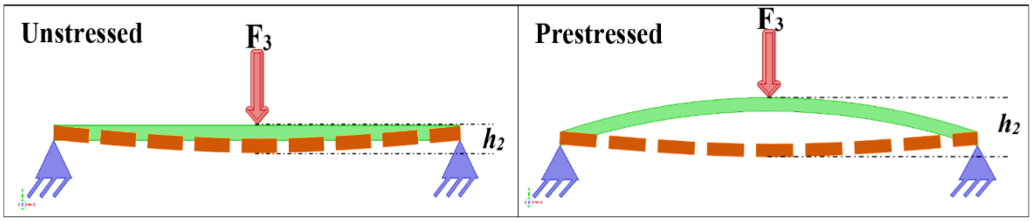

Figure 3. Unstressed vs prestressed bending offset h_2.

This mechanism is designed to house the piezoelectric, pre-stress it, and then stress it according to the applied force. The bending offset h_2 was set to be at a maximum of ≈ 5mm according to the used piezoelectric elasticity properties before it cracked.

A falling object is expected to be bouncing back and forth several times until its momentum reduced to zero and then its impact force can be written as follow:

$$F = \frac{dp}{dt} = m(\frac{dv}{dt}) \tag{10}$$

Where: p: is the momentum.

The maximum electrical power P_{out} generation is fully relying on the impact force F, impact velocity v, as well as the external resistive load R_L, where $P_{out} = V^2/ R_L$.

2. Related Work

Mechanical impact energy to electrical power conversion by employing the piezoelectric effect has received a considerable research attention around the globe in order to develop real-world applications. At present, most studies focus on using a single piezoelectric module. However researchers like M. Renaud and his team [10] have developed a prototype for utilizing the human beings foot strikes to impact piezoelectric beams. Their experimental results showed 600μW harvested from 10Hz frequency and 10cm amplitude linear motion. M. Ferrari et al [11] moved a step forward by presenting a prototype of an autonomous battery-less sensor module. An electrical power of 35mW was harvested from their module and successfully power up the sensor module and send the data within a range of 25m in a laboratory environment. S. Ju and C.-H. Ji in [12] presented a prototype of an impact based piezoelectric cantilever element for harvesting vibration energy by employing free movable metal spheres as a proof mass and an MFC (Macro Fiber Composite) beam as a piezoelectric cantilever, their design have the form factor of a conventional wristwatch in order to harvest energy from low frequency human-body-induced vibrations. When the device was mounted on a wristwatch and shaken manually they achieved a maximum peak-to-peak open circuit voltage of 54V and 621μW of output power have been measured at resistive load 1KΩ. Kyoo N. C. and Hee H. R. [13] presented a novel impact based piezoelectric harvester mechanism. The authors succeeded to harvest a continuous electricity by applying a continuous impact on the piezoelectric surface from wind flow. And they tried to increase efficiency by increasing the impact duty cycle with a spring retention action has been used to increase the frequency. In this prototype they had cascaded five elements of piezoelectric harvesters connected in series and four piezoelectric harvesters connected in parallel and it was able deliver about 16mW with optimum resistive load of 1KΩ.

3. Impact based experiment setup for piezoelectric power generator

For the sake of proving the concept that the prestressed piezoelectric mechanism can further improve and maximize the output wattage generated by the piezoelectric comparing to the unstressed piezoelectric bending mechanism as mentioned in Figure 3 previously. In consequence, a free fall experiment was conducted to evaluate the piezoelectric transducer performance (in term of the electrical power generated via the conversion of impact force) that seated into the prestressed bending mechanism as shown in Figure 4, which is designed to maximize the piezoelectric transducer output from a single impact.

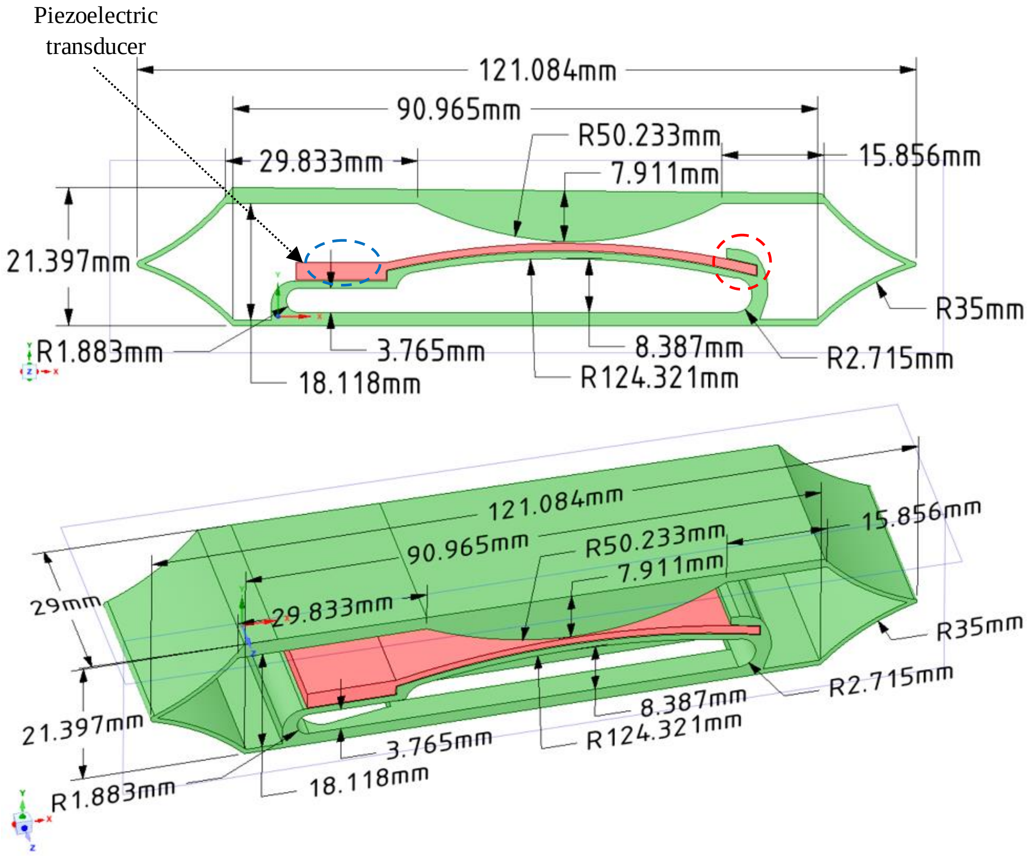

Figure 4. 3D model of the proposed piezoelectric prestressed bending mechanism.

The first task of this piezoelectric housing mechanism is to upward stress (in a concave manner) the piezoelectric by 3mm. The upper lip of the mechanism is convex oppositely to the piezoelectric, where it has the ability to press down on the top of the piezoelectric and strained it. And then when the impact force F_3 being applied on the top of the mechanism (upper lip) the concave piezoelectric will gradually flatten and then becomes convex due to the magnitude of the applied force. The bending offset h_2 for this mechanism was set to be at a maximum of ≈ 5mm according to the used piezoelectric elasticity properties before it cracked. An off-the-shelf rectangle shaped piezoelectric transducer manufactured by “Piezo Systems, Inc” is used to conduct the experiment as shown in Figure 5. Table 1 illustrates the dimensions of the used piezoelectric transducer and the overall dimension of the proposed bending mechanism including the piezoelectric transduce.

Figure 5. Piezoelectric transducer.

Table 1. Dimensions of the piezoelectric transducer and the proposed mechanical housing.

Parameter	*Piezoelectric transducer*	*Mechanical housing*
Width	29mm	29mm
Length	70mm	121mm
Thickness	0.55mm	21.4mm

The piezoelectric transducer shows in Figure 5 above is being rigidly fixed by two screws at the left end (blue circle in Figure 2), whereas the second right end it was freely lying into a slot (red circle in Figure 2). Since the piezoelectric transducer will be bend by 5mm due to the impact force F_3 so it is obviously the transducer be elongates by about 1mm so here the usefulness of this slot comes to allow the transducer to elongates and shrieks during the bending phase and returned back to the original length after the bending force vanish. The 3D printer used to manufacture the proposed design using ABS material as shown in Figure 6.

Figure 6. 3D printed prototype that used for conducting the experiment.

Next, can start the evaluation experiment by applying different magnitudes of forces on the top of the manufactured prototype by impacting it with different objects have a different mass, freely falls from different heights. And simultaneously measure the maximum harvested AC voltage by using a digital storage oscilloscope. A guiding tube was used so that can produce a consistent result. And also to guarantee that the free falling object is precisely impact on the designated surface of the bending mechanism as shown in Figure 7.

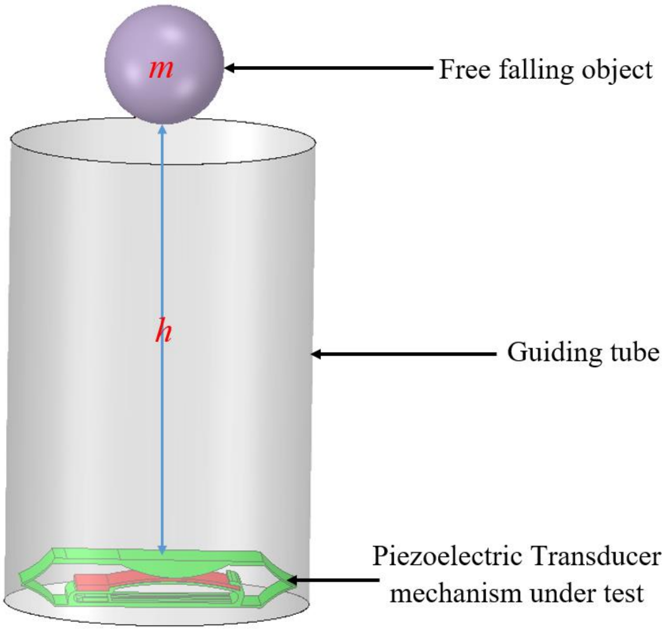

Figure 7. Drop test experiment set-up.

4. Experimental results and discussion

In pursuance of proving the concept of the proposed prestressed bending mechanism, the output AC voltage harvested by the piezoelectric has been measured with the aid of digital storage oscilloscope DSO while the mechanism was impacted by several forces. During the free fall test, and according to the fact of that the manufactured (3D printed) mechanism's surface is very compact (more solid) comparing to the falling object, in consequence, the free fall object will follow the guide tube and precisely impact the mechanism's top surface at its full momentum generating the highest AC peak voltage. And thereafter it will bounce forth and back generating smaller AC peaks until its momentum becomes zero. Figure 8 shows these two peaks.

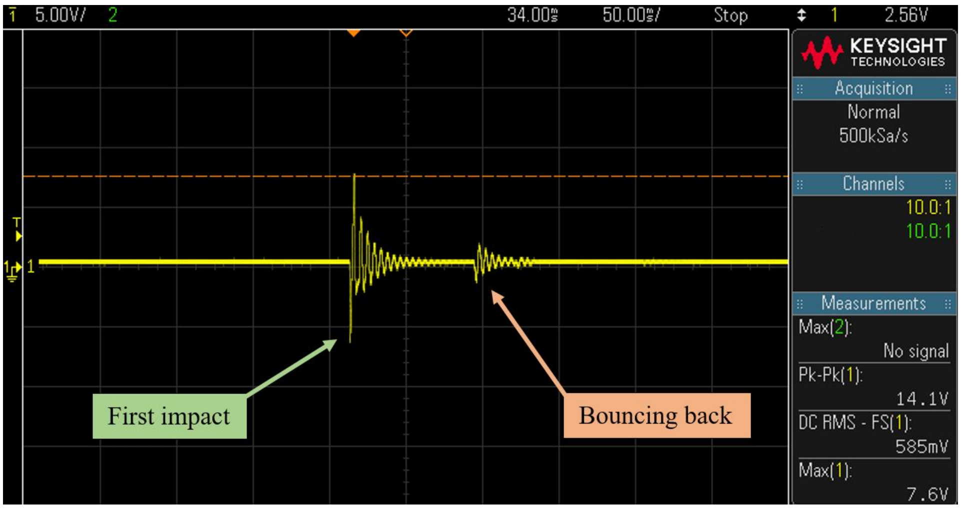

Figure 8. Screenshot of DSO measuring an open-circuit AC output voltage waveform of piezoelectric when it's been impacted at certain force.

From Figure 8, can observe that the first peak is a noticeably higher comparing to the rest of the signal, that's due to the high momentum of the free falling object at the first impact time, where its gradually losing its momentum until reach to the steady state zero. Accordingly with regard to the evaluation aim, only the peak of the first AC pulse will be considered and compared, however the other low signals are still considerably useful harvested signals where it have a small noticeable contribution of charging a storage device in case of energy harvesting powered system. As shown in Figure 8, which illustrates a screenshot of DSO measuring an open-circuit AC output voltage waveform of piezoelectric when it's been impacted at certain force. The AC.V output of this mechanism shows a logarithmic behaver where its starts from about 14.5 AC.V while impacted with a minimum of 3.3N, and gradually increases along with applied force. From Figure 9 can see that the AC.V out was saturated at 70 AC.V with 78.5N onwards, therefore there is no need of applying more amount of forces.

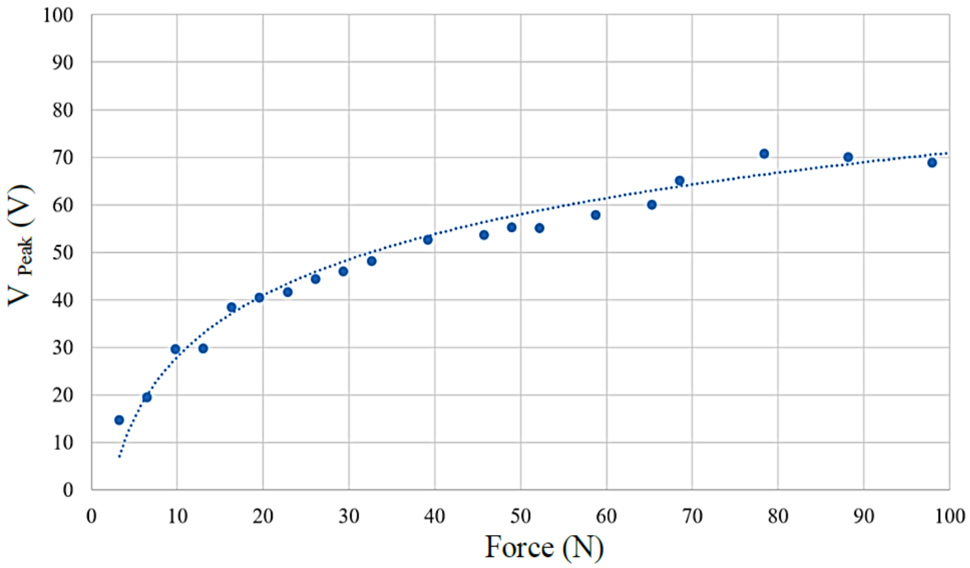

Figure 9. Peak AC. V harvested by piezoelectric transducer that prestressed and been impacted at varying forces.

Even though can get very high amount of harvested voltage from a single piezoelectric harvester, where on the other hand it generates very small amount of alternating current due to its properties and the internal impedance of the piezoelectric itself. Wherefore and in order to maximize the output current of piezoelectric and hence the power, the load impedance has to be matched with the value of the internal impedance where can attain the maximum power output.

Therefore, in order to find the maximum power that can be harvested by the piezoelectric with the aid of this prestressed mechanism, four SMD schottky diodes are preferred to use as a full-wave bridge rectifier due to their low forward voltage drop comparing to a normal diodes. 0.1 μF smoothing filter capacitor used to smoothen the output voltage. A resistor decade box in the magnitude of 0Ω up to 10 KΩ used as a pure resistive load. From Figure 10 can observe the relation of the DC power and the DC voltage output verses the resistive load. The mechanism was impacted at fixed magnitude all the time of force of 80N (the open circuit voltage at this force is about 70AC.V). The load was varied from 0.5 KΩ up to 6 KΩ. Can realize from Figure 10 that the maximum power can be achieved is about 53mW when connecting a resistive load of 700Ω. That elucidates that the load impedance matches the internal impedance of the Piezoelectric therefore produce the maximum power out at this point. At this amount of load the measured DC voltage was about 6V and when applying power law $P = I * V$ will find that the output current is about 9mA.

These values considered more than enough and can play a noticeable role in charging a storage element, powering up, and as a result prolong an autonomous system's lifespan. Where it can be used for portable low-power devices such as wireless sensor network node (WSN) or an internet of thing (IoT) applications to substitute the conventional batteries where frequent changing batteries, economically not a good idea.

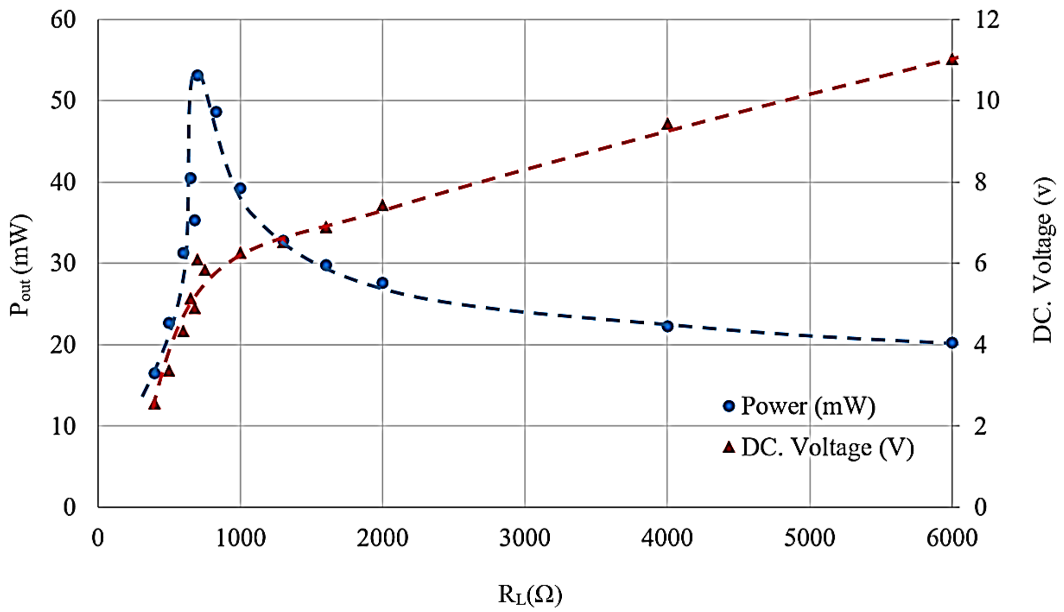

Figure 10. DC output power and voltage at varying external resistive.

5. Conclusion

A piezoelectric prestressed bending mechanism has been presented in this research paper. This mechanism improves the mechanical impact force into bending strain on the piezoelectric harvester and hence generating higher electrical energy compared to non-prestressed piezoelectric structure. Proof of concept along with the evaluation procedure was performed with the aid of a free fall test. The suggested mechanism was capable of harvesting 70 AC.V at open circuit measurement. After rectified it was able to deliver a maximum DC power of 53mW with a load of 700Ω. This amount of electrical power is considerably good enough to be stored and then power up low power portable devices, where this mechanism comes handy to be used for such devices where it’s not an easy choice to replace the battery, for instance, wireless sensor network nodes and IoT devices. This prestressed mechanism is meant to be used for harvesting human foot strike impact energy since it can be easily embedded inside the shoes or even built-in beneath the tiles. Furthermore, It also can be used in the industry environment to harvest the wasted impact/bending energy that generates from machines and automobile chassis (car wheel strut assembly) when driving on to undulating roads.

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