Impact-Driven Energy Harvesting: Effect of Stress on Piezoelectric Bender

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***Abstract*— This research is experimentally characterized and evaluates the effect of stress on a piezoelectric transducer by employing different bending mechanism. Three forms of bender: flat, unstressed, and pre-stressed are being investigated for their maximum electrical charge generation subjected to the applied stress. These mechanisms were fabricated using 3D printer where the piezoelectric beam can be inserted in to maximize the applied stress onto it. Variable impact forces are being exerted to bend the piezoelectric transducer for generating an electrical power across its terminals when connecting to an external load. In this respect, a rectangular shaped piezoelectric transducer with the size of (70X32X0.55) mm manufactured by Piezo System utilized to empirically study the relation between the impact force and the electrical output from the proposed piezoelectric bender. From the experimental results, the instantaneous AC volt output at open-circuit improved gradually and reached saturation of 10VAC, 50 VAC, and 70 VAC for flat, unstressed, and pre-stressed piezoelectric bender respectively. It is also found that the output power increases from 4mW of that recovered by using a flat mechanism to a double when using that an unstressed bending mechanism, while under the condition of pre-stressed, the electrical power further increases to 53mW at the same impact force.**

***Index Terms*— Bending force; Energy harvesting; Impact to electrical energy transformer; Piezoelectric transducer application; Stress effect.**

I. INTRODUCTION

Energy harvesting refers to the procedure of recovering the electrical energy from the ambient resources such as temperature, vibration, light, air flow, etc. Converting the available raw energy from the environment allows a self-sufficient energy supply for small, low power electronic gadgets like Wireless Sensor Network (WSN) nodes or Internet of Thing (IoT) sensors. This is of particular interest whenever a power supply via cable is not possible and the use of batteries and the associated maintenance expenditure are not desired. Moreover, it's expected that in the near future there will be huge numbers of this self-powered autonomous wireless devices and smart devices surrounding our living space in the "IoT" era. Whereby these self-powered autonomous wireless devices will help to enhance our living style by making it green, smart, and better quality of lives [1].

Recently, most of the researchers around the globe have been paying attention to the impact-based energy harvesting (IBEH) due to the high demand for the self-powered mobile autonomous devices [2][3]. Where IBEH is capable of recovering a fair amount of electrical power from the wasted mechanical impact energy. Even though there are plenty of mechanical impacts energy sources that almost everywhere in our daily life, for instance, while walking, dancing, and exercising etc. Moreover, can find it so obvious in the industrial environments since almost all the machines are generating continuous noticeable amount mechanical impacting energy. However, this freely available raw energy is being wasted and dissipated into the ground in case of human activities or into the impact of absorbents in case of the industrial machinery.

Usually, IBEHs performance is subjected to three main factors, which are the force of the impact, the velocity of the impact, and the harvested power. Whereby, from the previous work [4] has proven that the piezoelectric transducer output power is dependent on the applied impact parameters (force and velocity). Accordingly, this research proposed a novel piezoelectric transducer bending mechanisms designed for recovering the wasted impact energy from both human and industrial environments. These mechanisms utilized a ready-made piezoelectric transducer cantilever rather than a piezoelectric transducer ceramic disc by cause of the high electrical output density. Furthermore, presents the way to increase the recovered energy by manipulating the magnitude of the piezoelectric stress with different binding mechanisms.

II. LITERATURE AND RELATED WORK

In this section piezoelectric transducer principal, free falling impact force, and a brief literature review will be presented accordingly as follow:

A. Piezoelectric Principles

Kinetic energy can be converted into useful electrical energy by means of the piezoelectric effect: Piezoelectric elements convert the kinetic energy from vibrations or shocks (impact) into electrical energy. Mechanically deforming a piezoelectric crystal with tension or pressure generates electrical charges that can be measured as a voltage on the electrodes of the piezoelectric element [5]. This phenomenon is discovered by the Brothers Pierre, Curie, and Jacques in 1880 [6]. Posterior, Lippmann mathematically deduced the inverse piezoelectricity phenomena from the fundamental thermodynamic principles and it was confirmed later on by the Curies in 1881 [7]. These piezoelectric crystals are assessed by the constitutive equations, in which by merging the strain *S,* electrical induction *D,* stress *T,* and the electric field *E*. Furthermore, and according to the energy conservation concept of low frequency can get:

$$D = dT + \mathcal{E}^T E \quad (1)$$
$$S = S^E T - d' E \quad (2)$$

where: $\mathcal{E}^T$: Permittivity at constant stress.

S^E: Compliance at constant electric field.
d : Piezoelectric charge coefficient.

Thus, there will be always a strain in the piezoelectric material in relating to the supplied electrical field, and contrariwise, the piezoelectric material will generate electrical charges in case of mechanical stress is applied to its surfaces. The altered signals appear on the piezoelectric terminals is because of the electrical charges that displaced inside the Piezo crystals. Moreover, in case that the piezo crystal does not deform in according to the supplied electrical field which is considered an impossible thing in the polymers, then ($d=d'$), so by solving Equation (1) for E, and also Equation (2) for T, then will have:

$$E = \frac{D}{\varepsilon^T} - \frac{Td}{\varepsilon^T} = \frac{D}{\varepsilon^T} - gT \quad (3)$$

$$T = -\frac{d}{s^E}E + \frac{1}{s^E} = C^E S - eE \quad (4)$$

Moreover, by Appling an external vertical force F_3 as demonstrated in Figure 1, which bend and stress the piezoelectric structure downward. This force will lead to building up electrical charges $Q_3=D_3A_3$ on the surface of area A_3 to generate a $V_3=Q_3/C_3$ voltage. The electric charge density is $D_3=d_{33}T_1$, whereby $T_1=d_{33}F_1/A_1$ and $C_3 = \varepsilon_{33}^T A_3/h$.

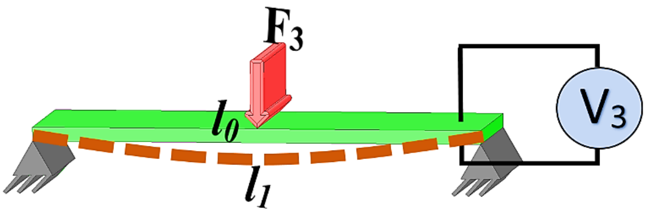

Figure 1: Appling F_3 will lead to stress the piezoelectric material by l_1 and generate an electrical signal V_3.

Thence, can calculate the output voltage that generated by stressing the piezoelectric material by applying a corresponding amount of force by:

$$V_3 = d_{33}F_3\left(\frac{1}{A_3}\frac{h}{\varepsilon_{33}^T}\right) \quad (5)$$

Since the strain is $S = \frac{\Delta l}{l_0}$, and the stress is $T = \Upsilon S$, where Υ is representing young's modulus. Then can rewrite the stress as follows:

$$\begin{aligned} T &= \Upsilon\frac{\Delta l}{l} \\ &= \Upsilon\left(\frac{l_1 - l_0}{l_0}\right) \\ &= \Upsilon\frac{1}{l_0}(l_1 - l_0) \end{aligned}$$

where l_0 representing the initial length of the piezoelectric beam before applying the force F_3, and l_1 representing the final length of the piezoelectric beam after applying the force F_3 as illustrated in Figure 1. Furthermore, stress also can be found by $T = F/A$ therefore can rewrite it into:

$$F = A\left[\Upsilon\frac{1}{l_0}(l_1 - l_0)\right] \quad (6)$$

Apparently, from Equation (6) and Figure 1 above can notice that the force is directionally proportional to the value of elongation Δl. Consequently, from Equation (5) increasing the force F_3 on the piezo structure will lead to increase the recovered voltage V_3 that generates at the piezo terminals, "with assuming that the other variables are constants". Accordingly, this paper will focus on presenting different bending mechanisms to manipulate and engage the l value by pre-stressing the piezoelectric transducer and hence maximizing the harvested power.

B. *Free-Fall Object Impact Force*

In accord to Newtonian physics, free-fall is an object motion whereby gravity is the only force acting upon it with neglecting the drag force of air. Accordingly, the energy equation of an object that is freely falling from a certain height can be addressed in the following:

$$mgh_1 = \frac{1}{2}mv^2 \quad (7)$$

where: g: gravity acceleration.
m: free falling object's mass.
h_1: free falling object height.
v: free falling object velocity.

By knowing the free-fall height h_1, the impact velocity v of the free-falling object can be computed as:

$$v = \sqrt{2gh_1} \quad (8)$$

Finally, the impact force F of the free falling object is depending on h_2 which representing the penetrating height before the object reached to a total stop, which can be composed as

$$F = \frac{E_k}{h_2} = \frac{mv^2}{2h_2} \quad (9)$$

where E_k is representing the kinetic energy. According to Equation (9) can observe that the force of the falling object is proportional to the infiltrated distance h_2 in an inverse manner. Moreover, the free-falling object is likewise anticipated that would be ricocheting forward and backward for a few times until its momentum reaches zero. In this case the impact force can be addressed as:

$$F = \frac{dp}{dt} = m\left(\frac{dv}{dt}\right) \quad (10)$$

where: p: is the momentum.

The maximum electrical power P_{out} recovered is depending on the impact force F stress, impact velocity v, likewise the external resistive load R_L, where $P_{out} = V^2/R_L$.

C. *Related Work*

The recovery of the electrical power from mechanical impact energy by utilizing the piezoelectricity effect has gotten a significant consideration from the researchers around the globe. So far, most of the researchers are focusing on vibration based energy harvesting like [8][9]. However, some of them have decided to work with low-frequency vibration or by other word impact based, like Jeong Hun Kim and his colleagues were they developed a prototype to harvest the energy from the human beings foot strike. They relied on their work on the vibration generated via the impact, where it will generate a low amount of voltage but with a longer span. Where they succeeded to harvest a maximum of 18.44V peak by hitting and vibrating four piezoelectric cantilevers beams while there is a motion of the proposed device [10]. Moreover, Le Van Minhand his fellows [11] also proposed a microenergy harvester based on impact to vibration conversation. They vibrated a piezoelectric cantilever at a low frequency of <200H_z by utilizing a metal ball. A 34.6nW only was harvested by their prototype. Others follow suit like [12-

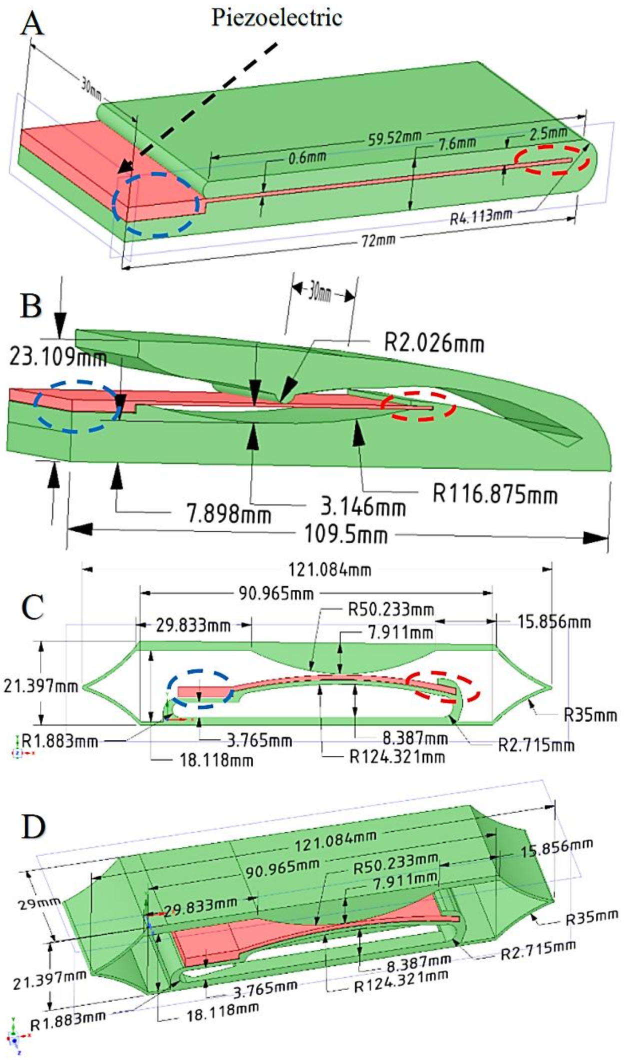

Figure 2: 3D models of the proposed piezoelectric bending mechanisms where, A: Flat Mechanism, B: Unstressed Mechanism, C and D: Pre-stressed mechanism.

14]. Whereas few researchers have proposed a direct impact based on piezoelectric energy harvesting such as Monika Jain et al [15] reported a prototype of directly impacting the piezoelectric transducer with the human weight without vibration. They embedded the piezoelectric polymer transducer inside a shoe. By utilizing this method they were able to harvest about 130V. Chan Ho Yang and his fellows [16] have gone a step further by developing a harvester prototype utilized to harvest the car's tiers impact on the road. 625mW was the peak power harvested. G. Yesner et al. [17] also developed an energy harvester based on vehicle tire's impact. B. Andò et al. [18] have proposed a hybrid energy harvester. The harvester is combining piezoelectric with electromagnetic techniques. They utilized a piece of magnet slides inside a tube terminated with a piezoelectric transducer at each side. The magnate was impacting the piezoelectric whenever there was a movement.

III. PIEZOELECTRIC IMPACT BASED EXPERIMENTAL SETUP

In respect of proving the concept that the amount of recovered power is in a directly proportional manner to the amount of applied stress on the piezoelectric transducer as shown in Equation 5 and 6. Accordingly, three types of bending mechanism being designed (flat, unstressed, and pre-stressed mechanism) so can study the effect of the stress parameter in the piezoelectric output. Figure 2 illustrates the design along with the measurements for each bending mechanism.

Figure 2 shows the piezoelectric being mounted in three different bending mechanisms each with different stress. The first bending mechanism is flat whereby the piezoelectric transducer is mounted on a flat surface, then the force will be applied on the top of it. In this case, there will be not much stress in the piezoelectric transducer due to the rigidity of the mechanism base. Following to the next unstressed bending

Figure 3: Piezoelectric transducer.

mechanism, in this mechanism, the piezoelectric transducer will be mounted from the two ends only as can its clear in Figure 2B. The transducer will mount from its ends with a cavity beneath the middle. The cavity height is about 3mm. This concave base will allow the used piezoelectric transducer to bend downward with the help of the notch in the upper lip. Whereby after applying a certain force on the top surface of the mechanism, the upper lip will gently move downward stressing the transducer until it matches the concave based. Pursuing to the last design in this research. Where this mechanism is much different from the previous mechanisms. This mechanism is exploiting the pre-stressed approach, whereby the piezo cantilever being stressed upward “in a convex manner” before driving the force as shown in Figure 2C, and D. In this mechanism the used transducer will be pre-stressed by about 8.3mm in the normal state. Since this bending mechanism has an upper lip convex opposite to the piezoelectric, therefore, it is able to depress on the top surface of the piezoelectric and stressed it further. The convex piezoelectric will gradually flatten first and then turns into a concave shape according to the mechanism shape with the help of the force applied. 5mm is the maximum curvature offset in this mechanism due to the elastic properties of the utilized piezoelectric before it damaged. The proposed bending mechanisms were experimentally evaluated by utilizing rectangle ready-made piezoelectric transducer produced by “Piezo Systems, Inc” as shown in Figure 3.

Table 1
Mechanical measurements of the piezo cantilever and the proposed bending mechanisms.

Criterion	*Piezo.*	*Bending Mechanism*		
		Flat	*Unstressed*	*Pre-stressed*
Width	29mm	30mm	30mm	29mm
Length	70mm	72mm	109.5mm	121mm
Thickness	0.55mm	7.6mm	23mm	21.4mm

The mechanical measurements of the utilized piezo cantilever as well as the final measurements of the proposed bending mechanisms are shown in Table 1.

The bending mechanisms designed to have a rigid platform to fix the piezoelectric transducer. Two screws used to rigidly mount down the piezoelectric transducer at the left end “blue ring in Figure 2”, meanwhile, the second right end was freely lying inside a slit “red ring in Figure 2”. The right end is seated inside a sit due to the fact that the transducer will be elongated by a few millimeters with regard to the applied impact force. 3D printer exploited to fabricate the proposed designs by utilizing (Acrylonitrile-Butadiene-Styrene) ABS material as shown in Figure 4.

Afterward, the manufactured mechanisms were impacted by different forces, the forces were generated via freely fall objects having different masses, from different heights. A guiding duct was exploited to ensure that the free falling object is precisely impacting the assigned surface of the bending mechanism as illustrated in Figure 5. Meanwhile, the maximum alternate voltage recovered by the piezo cantilever was simultaneously measured via a digital storage oscilloscope DSO.

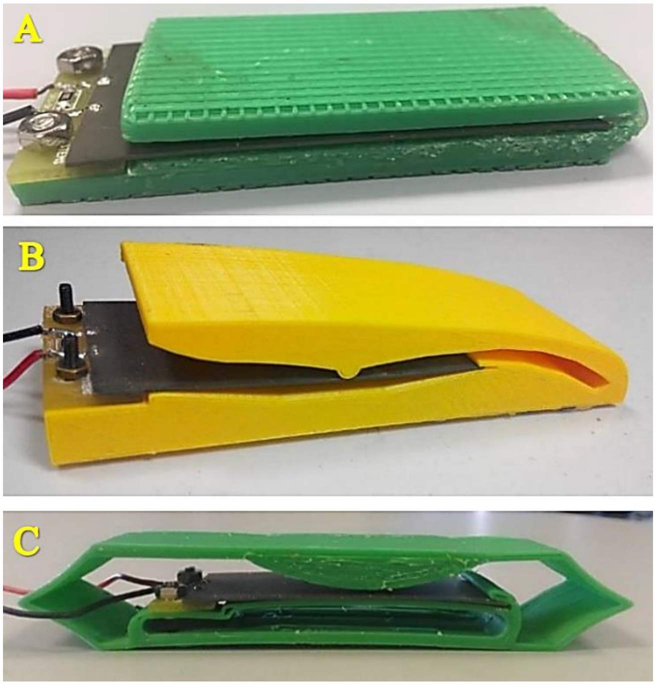

Figure 4: 3D printed prototypes that used to conduct the evaluation phase where, A: Flat Mechanism, B: Unstressed Mechanism, C: Pre-stressed mechanism.

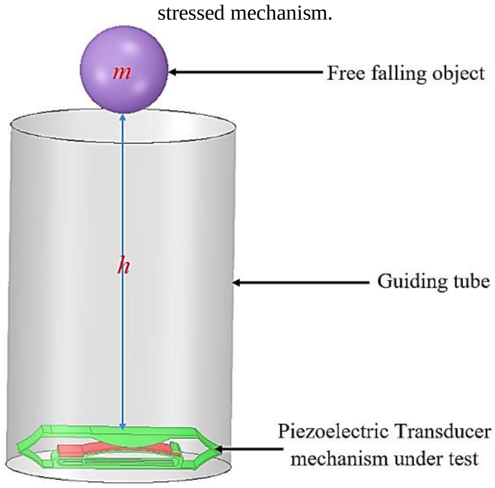

Figure 5: Drop test experiment set-up.

IV. Experimental Results and Discussion

Throughout the experimental test and because of the fabricated mechanism's surface is quite compact “more solid” a contrast to the free-falling object material, therefore, the free-fall object will precisely impacting the mechanism's top surface with the help of the guide duct at its full momentum. This high momentum of the falling object will lead to producing the highest alternate voltage peak. And then it will be bouncing back and forth leads to generate lower AC peaks before coming to a full stop. Figure 6 shows these peaks.

As depicted in Figure 6, that shows a screenshot of a DSO capturing a waveform of the piezo transducer while it’s been under impact with a specific force. It’s very obvious to notice and by reason of the high momentum of the free-falling object, a high peak AC signal will be generated at the first impact, as it’s seen in the left signal in Figure 6. Sequentially, the signal magnitude is gradually reduced while the object is losing its momentum and comes to a full stop. Consequently, the first highest peak of the recovered AC waveform will be considered in comparison to address the evaluation. Nonetheless, the remained lower pulses are still having an effect and can contribute to charge a storage element for such systems that exploiting the energy harvesting as a power source. The V_{AC} output of all the three mechanisms shows a logarithmic behavior. Furthermore, the output voltage also it is proportional to the used force until the V-out saturated at about 80N as clear in Figure 7. Figure 7 can see the enormous differences in the amounts of the harvested voltage among every bending mechanism. Whereby the flat bending mechanism can harvest a maximum of 10 V_{AC} comparing to the others, and it’s considered the lowest harvester. That due to the very low stress of the used piezoelectric transducer when utilizing this mechanism. Furthermore, when utilizing the unstressed bending mechanism can observe the prominent increment in the amount of the harvested voltage. Where it’s

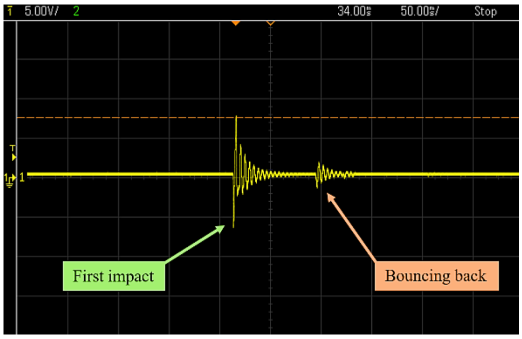

Figure 6: DSO screenshot capturing the piezo output voltage waveform at the open - circuit when it’s been impacted at specific force.

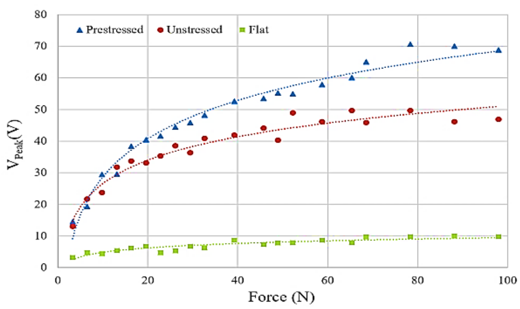

Figure 7: AC. V recovered via the piezoelectric transducer bending mechanisms that been impacted at varying forces.

succeeded to recover a maximum of 50 V_{AC}. The increment of the readings in the unstressed bending mechanism is due to the fact that the used piezoelectric transducer is being stressed downward according to the magnitude of the applied force. And this stress in the transducer is translated into an extra voltage. Moreover, and since the pre-stressed bending mechanism is pre-stressed the piezoelectric transducer before applying the force as clear in Figure 2C and D, where it leads to further increase the stress of the transducer which it will translate into an extra voltage. Therefore, can see from the previous Figure 7 that the pre-stressed bending mechanism has the highest voltage recovery among of the rest. Whereby it's capable of recovery a maximum of 70 V_{AC} per impact.

It's obvious from the aforesaid that the piezoelectric transducer has the ability to recover a very high amount of voltage from the mechanical impact. However, because of the piezo properties and the internal impedance the recovered alternating current is very small. And when the load impedance matches with the internal impedance of the piezo a maximum output current and hence the output power is attained. For the aim of power evaluation phase, the pre-stressed bending mechanism is chosen to be evaluated since it's capable of recovering the highest amount of voltages among the other mechanisms. Since the piezoelectric generates an AC form of signals, therefore, full-wave bridge rectifier based on four SMD Schottky diodes designed to rectify the AC signal. Schottky diodes were utilized because of their low forward voltage drop contrast to the conventional diodes. A capacitor of 0.1 µF utilized to filter out and smoothen the ripple in the output voltage. A resistor decade box exploited as a load. Figure 8 illustrates the recovered direct power and the direct voltage by the piezoelectric versus the resistive load. The pre-stress mechanism was exposed to the constant impact force of 80N while testing, at this force the piezoelectric can recover about 70 V_{AC} at open circuit. The piezo terminals were connected to a resistive load that varied from 0.5 KΩ up to 6 KΩ after the rectifier. Maximum power of 53mW is attained from the system load of 700Ω, as shown in Figure 8. That indicates that the piezoelectric internal impedance matches the load impedance and resulting in the maximum power out. By using power law $P=I*V$ at the load matching point with 6V DC. Measured, then will get about 9mA. These findings considered good enough to be exploited and stored in super capacitors or rechargeable batteries to power up an autonomous system. Since the continual battery replacement is not an economical solution. Therefore, this technology can be utilized to prolong the autonomous system's lifespan like WSN nodes or IoT applications.

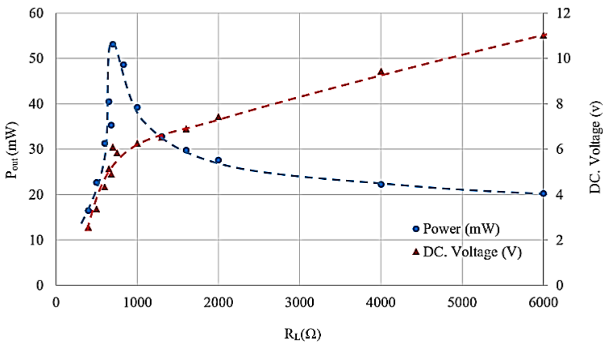

Figure 8: Direct power and voltage at varying load.

V. Conclusion

This research paper presented a piezoelectric bending mechanism that can maximize the amount of stress applied to it and hence the electrical power. A free fall test was utilized as the evaluation procedure. It was proven that the stress has a direct effect on the piezoelectric energy recovery, moreover the recovered voltage can increase by maximizing the stress of the piezoelectric transducer. The maximum recovered AC voltage was measured at about 70 V_{AC} by utilizing the pre-stressed bending mechanism, and generating a power of 53mW when connected to external resistive loads of 700Ω. This amount of electrical power can fulfill the minimum requirement of low power electronic devices such as those used in wireless sensor network nodes and IoT devices.

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