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MAXIMIZING OUTPUT VOLTAGE OF A PIEZOELECTRIC ENERGY HARVESTER VIA BEAM DEFLECTION METHOD FOR LOW-FREQUENCY INPUTS

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ABSTRACT: In micro-scale energy harvesting, piezoelectric (PZT) energy harvesters can adequately convert kinetic energy from ambient vibration to electrical energy. However, due to the random motion and frequency of human motion, the piezoelectric beam cannot efficiently harvest energy from ambient sources. This research highlights the ability of piezoelectric energy harvester constructed using a PZT-5H cantilever beam to generate voltage at any input frequency from human motion. An eccentric mass is used to convert the linear motion of human movement to angular motion. Then, using a magnetic plucking technique, the piezoelectric beam is deflected to its maximum possible deflection each time the eccentric mass oscillates past the beam, ensuring the highest stress is induced and hence the highest current is generated. For testing purposes, the frequency of oscillation of the eccentric mass is controlled using an Arduino Uno microcontroller. In this work, it is found that when given any input frequencies, the energy harvester produced a consistent AC voltage peak around 5.8 Vac. On the other hand, the DC voltage produced varies with respect to the input frequency due to the number of times the peak AC signal is generated. The highest DC voltage produced in this work is 3.7 Vdc, at 5 Hz, which is within the frequency range of human motion. This research demonstrated that energy can still be effectively harvested at any given low-frequency input, in the condition that the piezoelectric beam is being deflected at its maximum.

ABSTRAK: Piezoelektrik dapat mengubah tenaga kinetik daripada getaran persekitaran kepada tenaga elektrik melalui penjanaan tenaga berskala mikro. Namun, PZT tidak dapat menjana tenaga dengan berkesan dari sumber persekitaran kerana pergerakan dan kekerapan pergerakan manusia adalah rawak. Kajian ini adalah mengenai keupayaan penuai tenaga piezoelektrik menggunakan bilah kantilever PZT-5H bagi menjana voltan pada sebarang frekuensi menerusi gerakan manusia. Jisim eksentrik digunakan bagi menukar gerakan linear manusia kepada gerakan putaran. Kemudian, teknik penjanaan piezoelektrik secara magnetik digunakan bagi memesongkan bilah piezoelektrik ke tahap maksimum. Bagi memastikan tenaga tertinggi dihasilkan, jisim eksentrik perlu berayun melepasi bilah PZT. Ayunan frekuensi jisim eksentrik ini dikawal melalui kawalan mikro Arduino Uno. Dapatan kajian menunjukkan bagi setiap frekuensi input, PZT ini dapat menghasilkan voltan AC yang konsisten, iaitu sekitar 5.8 Vac. Namun, voltan DC maksimum yang terhasil adalah berbeza-beza bagi setiap frekuensi input, iaitu berdasarkan bilangan kekerapan maksimum isyarat AC yang terhasil. Voltan DC tertinggi ialah 3.7 Vdc, pada 5 Hz, iaitu pada kadar frekuensi gerakan manusia. Ini menunjukkan bahawa tenaga masih dapat dihasilkan secara berkesan pada frekuensi rendah, dengan syarat bilah piezoelektrik terpesong pada tahap maksimum.

KEY WORDS: *Energy harvesting, piezoelectric, magnetic plucking, random frequency*

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1. INTRODUCTION

The miniaturization of electronics components such as sensors has been rapidly developed for wearable and portable devices. These sensors have a variety of uses on the human body, including heart monitoring sensors, glucose level sensors, blood pressure and oxygenation sensors, and medication administration systems [1]. The sensors' diminutive size enables them to be comfortably fastened to a human body part. Additionally, the size reduction resulted in a reduction in power usage. By and large, most electronic gadgets use a conventional battery that has a finite life and requires replacement. This increases the attractiveness of alternatives to batteries as a power source. Batteries are the single largest source of electronic waste on a global scale. These conventional batteries contain hazardous elements that can be lethal to human health and the environment if not disposed of correctly [2].

One viable solution is to build self-powered gadgets capable of generating their own electricity, a process commonly known as energy harvesting. Energy harvesting can be used to harvest energy from a variety of sources, such as vibration, wind, sound, and human motion [3]–[5]. Numerous studies have been conducted on energy harvesting from human motion, which is the conversion of kinetic (vibration) energy to electrical energy. Motion from human limbs can be exploited as an input to the energy harvester, which will be used as a power supply to the wearable device. Human motion typically has a vibration frequency of between 0.1 to 25 Hz [6], which is quite low in comparison to the resonance frequency of the numerous varieties of piezoelectric materials.

Piezoelectric energy harvesters can have high output voltage from vibration as compared to other conversion mechanisms such as electromagnetic and electrostatic energy harvesters [7]. Additionally, it has been demonstrated that PZT-5H can generate a greater voltage than Polyvinylidene Difluoride (PVDF), Aluminum Nitride (AIN), and Barium Sodium Niobate (Ba2NaNb5O15) [2]. Traditionally, the piezoelectric energy harvester is designed as a linear resonator and only works effectively within a narrow bandwidth of frequency. The range of frequency bandwidth was around 5 Hz. For example, a PZT-5H beam has an optimum frequency range between 48 Hz and 53 Hz, while a PVDF beam has an effective frequency range between 250 Hz to 255 Hz. [8]–[10]. Outside of a specified frequency range, the effectiveness of energy harvesting decreases tremendously.

Numerous solutions have been proposed to address the issue. One of the approaches is the plucking technique. Regardless of the frequency of the input, the energy harvester will always operate at its most efficient state. This technique is capable of matching the low frequency of human motion, such as an arm swinging forwards and backwards in a walking motion, which occurs at approximately 0.9 Hz [11], or running motion which occurs at 1.9 Hz [12]. This plucking technique can be categorized into two types: contact or non-contact. Contact methods, also known as impact types, have been demonstrated by Gu and Livermore [13]. The piezoelectric was struck by plucking it with another beam with a low resonance frequency.

On the other hand, non-contact types use a magnet to pluck the piezoelectric beam, such as in a knee joint harvester [14]. This energy harvester is worn on the knee. By using the motion of the knee while walking or running, the piezoelectric cantilever beams are plucked by the magnets and generate up to 3.3 V of electricity. Other research using the same mechanical plucking include impulse excited energy harvester for human body excitation [6] and design and simulation of bistable piezoceramic cantilever for energy harvesting from slow swinging movement [15].

Although the piezoelectric energy harvester can convert kinetic energy to electrical energy, it could not properly harvest energy from ambient sources due to the unpredictable motion and

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periodicity of human movements. Thus, this paper will highlight the capability of the proposed beam deflection method in addressing the limitation. In this method, by utilizing magnetic force, the piezoelectric beam in the energy harvester device can be bent to its maximum deflection regardless of the input frequencies. The relationship between maximum deflection and applied voltage will be demonstrated by simulation. The findings will be further validated with a prototype to investigate the amount of energy harvested at various frequencies of motion.

2. RESEARCH METHOD

2.1. System Design

The principle of using a piezoelectric bimorph beam for energy harvesting based on magnetic plucking motion is demonstrated in this paper. Fig. 1 shows an assembly of an eccentric mass that was used to convert linear motion into rotational motion. This configuration made it suitable for the piezoelectric beam to be magnetically plucked due to excitation by low frequency or random human motion. The piezoelectric beam used for this research is the PZT-5H piezoelectric bimorph beam with a dimension of 40 mm x 10 mm x 0.5 mm. The magnet used is a Neodymium magnet with a diameter of 12 mm and height of 3 mm. This piezoelectric beam consists of a layer of copper sandwiched between two layers of lead zirconate titanate (PZT).

The PZT-5H beam was chosen because it has demonstrated a higher capability for voltage generation than other piezoelectric materials such as polyvinylidene difluoride (PVDF), aluminum nitride (AIN), and barium sodium niobate ($Ba_2NaNb_5O_{15}$) [16]–[19]. Additionally, according to Table 1, PZT-5H has the greatest piezoelectric strain coefficient, d_{33} value, indicating that it can generate a comparatively greater charge under normal stress applied due to transverse vibration.

Table 1: Comparison of strain coefficients, d_{33} for different types of piezoelectric materials

Material	d_{33} (m/V)
PZT-5H	600×10^{-12}
PVDF	30×10^{-12}
AIN	5.1×10^{-12}
Barium Sodium Niobate	319×10^{-12}

The parameters of the piezoelectric energy harvester assembly are listed in Table 2.

Table 2: Parameters of the piezoelectric energy harvester assembly

Material	Length/Mass
Diameter eccentric mass	80 mm
Circular magnet at the tip of the beam (proof mass)	12 mm (diameter), 3 mm (height)
Mass of the magnet at the tip of the beam (proof mass)	4.64 g
Rectangular magnet to bend the beam	10 mm x 10 mm x 3 mm
Piezoelectric beam	40 mm x 10 mm x 0.5 mm

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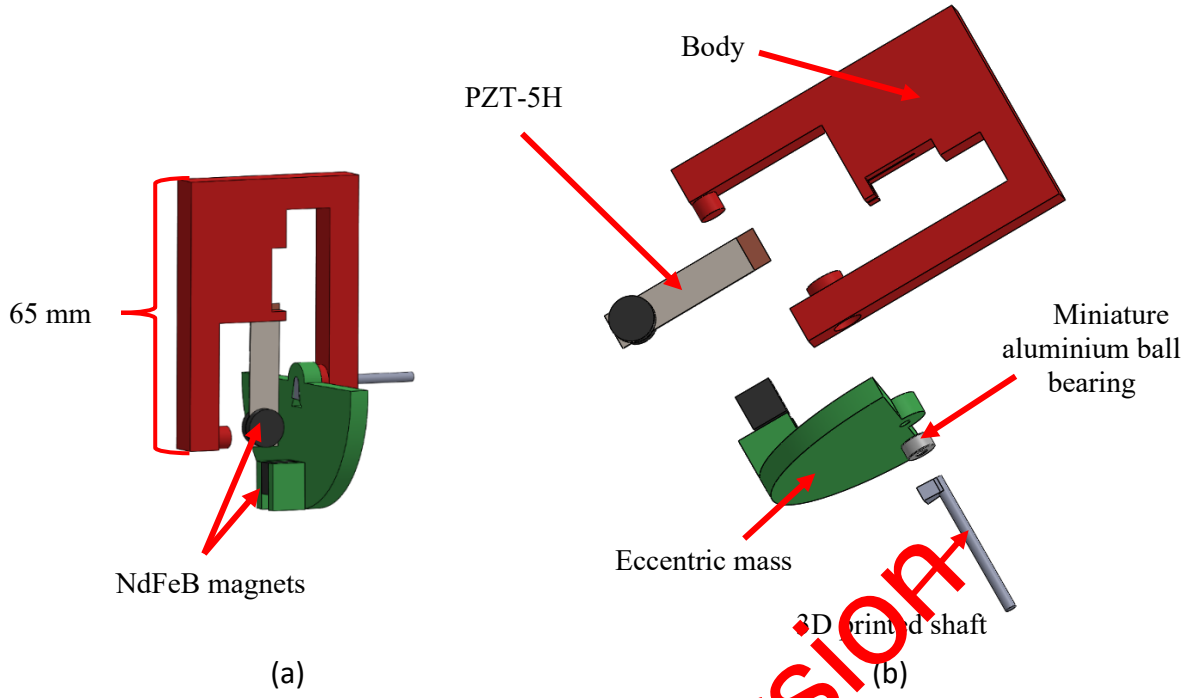

Fig. 1. (a) The design of the piezoelectric energy harvester utilizing beam deflection method (b) Exploded View of the Design.

Referring to Fig. 1, the design consists of an 80-mm diameter fabricated eccentric mass (green) with 65-mm length body (red), a PZT-5H piezoelectric bimorph beam, 6-mm diameter of neodymium (NdFeB) magnets, 10-mm length of rectangular NdFeB magnets and a miniature aluminum ball bearing with 8 mm outer diameter and 3 mm inner diameter. The circular neodymium magnet is mounted at the tips of the piezoelectric beam and the rectangular neodymium magnet is placed at the end of the eccentric mass, as shown in Fig. 1.

Due to the identical polarity of the magnets at the piezoelectric beam tip and eccentric mass, the piezoelectric beam will bend when the eccentric mass rotates, causing the magnets to push against one another. As the magnets move away from each other, stress is induced in the piezoelectric beam and output voltage is generated. The distance between the two magnets can be adjusted to ensure that the PZT-5H piezoelectric beam always bends at its 2 mm deflection. According to the product datasheet [20], the maximum deflection of the PZT-5H was 2 mm.

$$Ymax = -\frac{Fl^3}{3EI} \tag{1}$$

The cantilever beam formula, Eq. (1), was used to calculate the magnetic forces required to deflect the beam at 2mm. The term Y_{max} is maximum deflection, F is force, l is length of the beam, E refers to modulus elasticity of the beam and I refers to moment of inertia. From the calculation, the required force was 0.0344 N. Before each experiment began, the deflection was also measured using a Vernier scale. This is referred to as the mechanical plucking technique. It is well suited to human motion, which is predominantly random and low in frequency. It is capable of converting low-frequency movements into higher-frequency vibrations.

2.2. Simulation Study Using MATLAB Software

When a piezoelectric material experiences mechanical strain, some amount of voltage is generated at its terminal (known as sensor mode), and if a voltage is applied to the piezoelectric

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material, this will cause it to deform (actuator mode). Here, a simulation study was carried out to investigate the relationship between the deflection produced by the piezoelectric cantilever beam with the amount of voltage applied to the beam. The amount of voltage applied to the PZT beam in this study is made equal to the voltage generated when it vibrates at its resonance in sensor mode. MATLAB software was used to conduct the simulation.

The equations used in this paper have been discussed [21]. The typical constitutive equations for piezoelectric material are:

$$\{S\} = [s^E]\{T\} + [d]^T\{E\} \tag{2}$$

$$\{D\} = [d]\{T\} + [\varepsilon^T]\{E\} \tag{3}$$

In Eq. (2) and (3), constant *{S}* refers to the deformation vector, *{D}* is the electric displacement vector, *{E}* is the electric field vector, *[ε]* is the dielectric constant matrix, *[s]* and *[d]* are the elasticity and piezoelectric constant matrices whereas *{T}* refers to the stress vector. Based on the constitutive equations above, the state space equations are derived.

$$\begin{Bmatrix} S_{11} \\ S_{22} \\ S_{33} \\ S_{23} \\ S_{13} \\ S_{12} \end{Bmatrix} = \underbrace{\begin{bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 \\ s_{12} & s_{22} & s_{23} & 0 & 0 & 0 \\ s_{13} & s_{23} & s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66} \end{bmatrix}}_{\text{Coupling}} \begin{Bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{23} \\ T_{13} \\ T_{12} \end{Bmatrix} + \underbrace{\begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}}_{\text{Permitivity}} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix} \tag{4}$$

Piezoelectric coupling matrices have a few non-zero elements due to the crystal symmetries as shown in Eq. (4), and the design of the sensing and actuation device is dictated by the available coupling modes. There are two state-space formulas which are for actuation and sensing mode. However, the actuation mode state-space formula is only used because only the actuation mode will be simulated. The piezoelectric material that will be used is PZT-5H. Therefore, PZT coupling matrices are shown below.

$$[d]_{PZT} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix} \tag{5}$$

In this simulation, the electric field will be applied perpendicularly to the poling direction, resulting in transverse displacement, as shown in Fig. 5. In order to obtain the bending action, thin PZT materials are bonded on the structure. The geometrical arrangement causes d_{31} to dominate the design, and the useful direction of expansion is normal to that of the electric field. By solving Eq. (3) and (4), a deflection for the bimorph PZT can be found based on Eq. (6) [21].

$$Deflection = -\frac{3}{2}\frac{d_{33}\emptyset}{h^2}L^2 \tag{6}$$

In Eq. (6), d_{33} refers to the piezoelectric strain coefficient at the z-axis direction, Ø denotes the electrical potential, *h* and *L* are the height and length of the piezoelectric beam, respectively.

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The design of the piezoelectric beam is illustrated in Fig. 2. Here, the beam material used is PZT-5H in bimorph configuration.

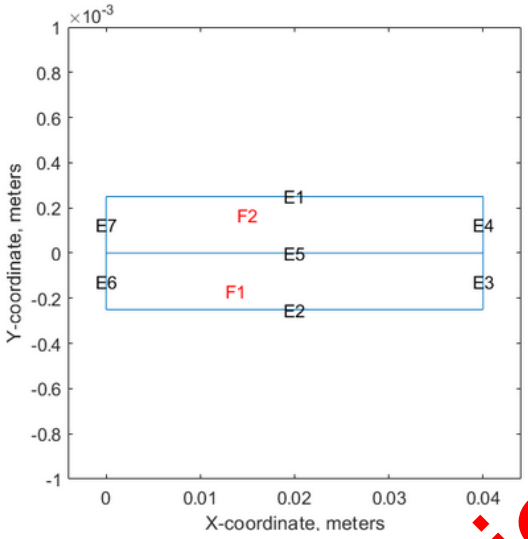

Fig. 2. Piezoelectric beam with a dimension of 40 mm x 10 mm x 0.5 mm.

Based on Fig. 2, *E1, E2*, and *E5* are the length of the PZT-5H beam, which is 40 mm, *E7, E6, E4,* and *E3* are the height of the beam, which is 5 mm. The PZT-5H is a bimorph beam, therefore, the total height is 10 mm. Table 3 shows the parameters that are set in the MATLAB software based on the selected PZT-5H beam according to the datasheet [20].

Table 3: Parameters of PZT-5H Piezoelectric Beam

Parameter	Value
Elastic modulus	7.2 x 10^{10} N/m^2
Poisson ratio	0.31
Shear modulus	4.6 x 10^{10} N/m^2
Piezoelectric constant d_{31}	-270 x 10^{-12} m/v
Piezoelectric constant d_{33}	600 x 10^{-12} m/v
Maximum deflection	2 mm

The amount of voltage that needs to be applied to the beam (actuator mode) in this study is determined via experiment by investigating the maximum voltage produced when the PZT beam vibrates at its resonant frequency (in sensor mode). In accordance with prior work [22], a digital signal analyzer (DSA HP-35670A) was used to provide base excitation to the same piezo cantilever beam over a frequency sweep from 0 Hz until 100 Hz. The result of this study is shown in Fig. 3. At its resonant frequency of 18.33 Hz, the PZT beam produced 4.55 V with a proof mass of 2.3 g and 4.01 V without proof mass. Although the resonant frequency was within the range of frequency of human motion (1 Hz - 25 Hz)[23], it is observed that the frequency bandwidth was quite narrow. This means that the PZT beam can only efficiently harvest energy at 18.33 Hz but will tremendously degrade when there is a slight change in the frequency of vibration. From this study, the voltage 4.55V will be taken as input to the simulation study, as shown in Fig. 2. The result will be discussed in a later section.

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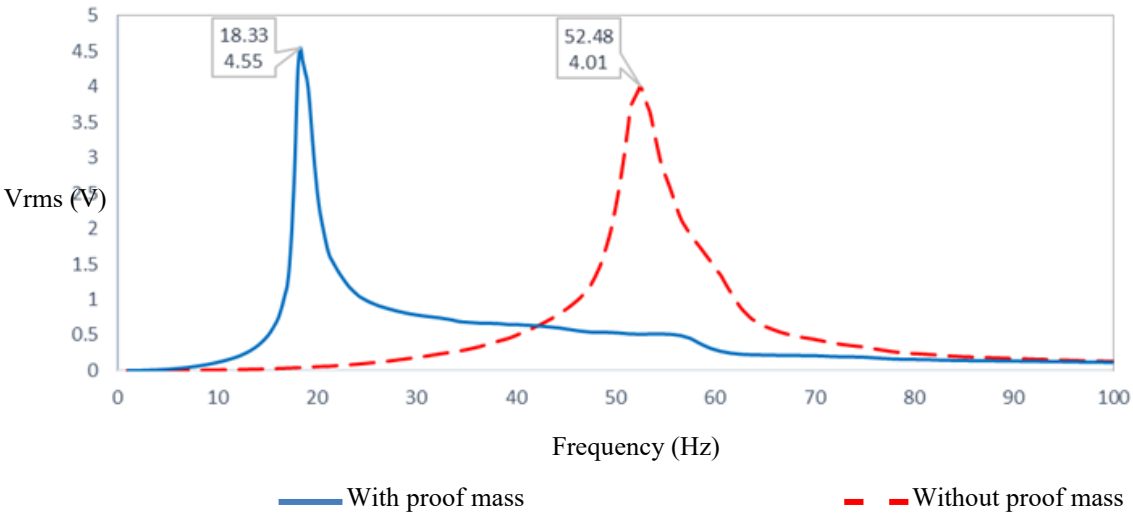

Fig. 3. Frequency sweep of PZT-5H piezoelectric beam. The peaks show the resonant frequencies of the beam with and without proof mass [22].

2.3. Measurement of Output Voltage from Beam Deflection

An experimental setup for the whole assembly of the fabricated energy harvester in measuring the output voltage is shown in Fig 4. The apparatus for the experiment includes an Arduino Uno microcontroller to control the servo motor, a servo motor to oscillate the eccentric mass and imitate the average frequency of a human hand swinging forward and backward while walking and running, and a data acquisition board (National Instruments cDAQ-9171) to acquire the output signals from the piezoelectric beam to send to a computer with LabView software. The fabricated prototype was held using a tripod stand.

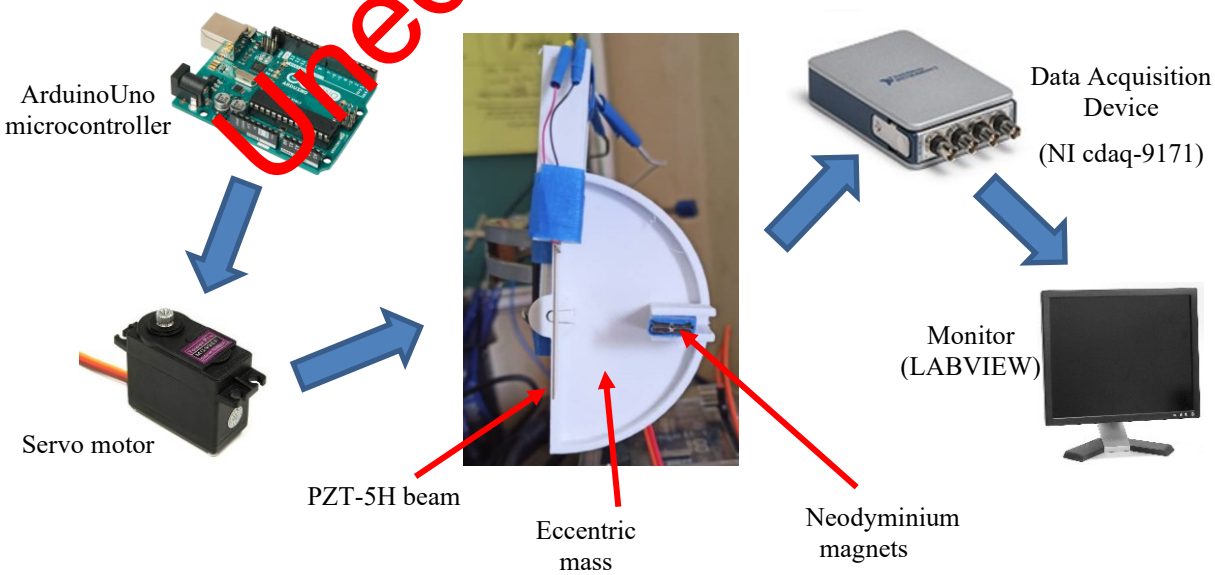

Fig. 4. Experimental Setup

The Arduino Uno was programmed to oscillate the servo motor at specific frequencies (0.9 Hz (walking) [11] and 2 Hz (running) [12]) to show that the peak AC voltage will always

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be the same, regardless of the input frequencies. Additionally, four more frequencies (1.5 Hz, 2.5 Hz, 3.0 Hz, and 5 Hz) were also tested to observe the capability of the proposed design at other frequencies, as shown in Table 4. The frequency of oscillation for the eccentric mass was measured using a tachometer during the experiment.

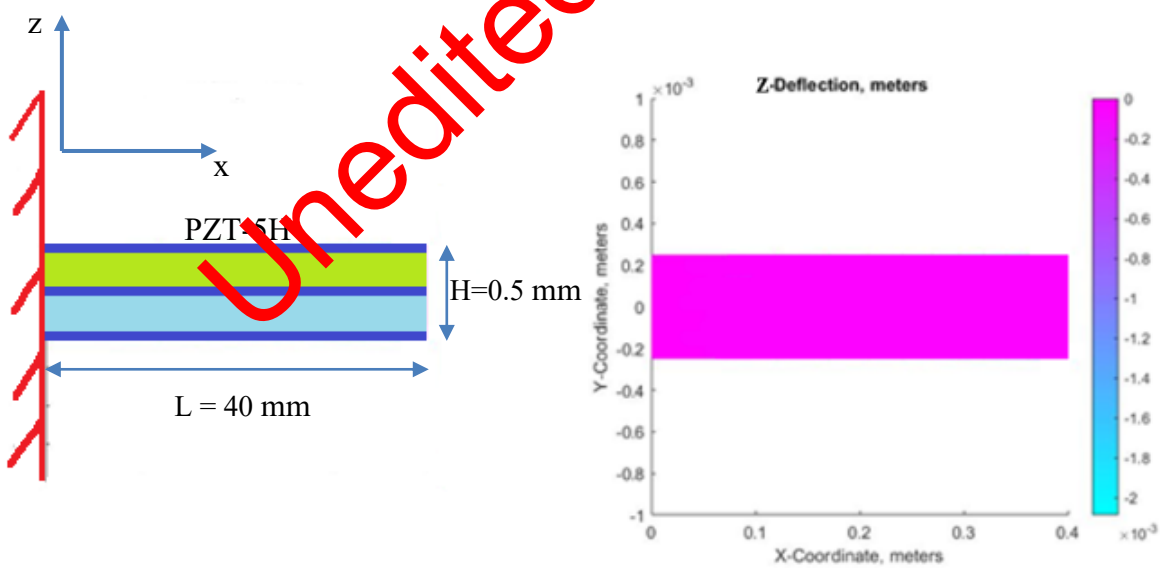
Table 4: Frequency of the human limb motion when walking, running, and randomly pick frequencies.

Test	Frequency of arm swing forward and backward (Hz)
Walk	0.9
Run	2.0
Test 1	1.5
Test 2	2.5
Test 3	3.0
Test 4	5

3. RESULT AND ANALYSIS

3.1. MATLAB Software Simulation Results

The simulation research results stated in Section 2.2 will be discussed in this section. At the resonant frequency, the beam vibrates vigorously, resulting in greater deflection than at other frequencies, allowing for more voltage generation. To verify this, identical voltage is applied to the PZT beam and its resulting deflection is recorded. According to Fig. 3 (shown in the preceding section), the voltage generated when it vibrates at its initial resonance frequency is 4.55 V. Figs. 5(a) and 5(b) illustrate the initial condition of the beam before any voltage is applied, during which no deflection occurs. When 4.55 V is supplied, the tip of the beam deflects 1.56 mm in the y-direction as seen in Fig. 5(c) and 5(d).



(a) (b)

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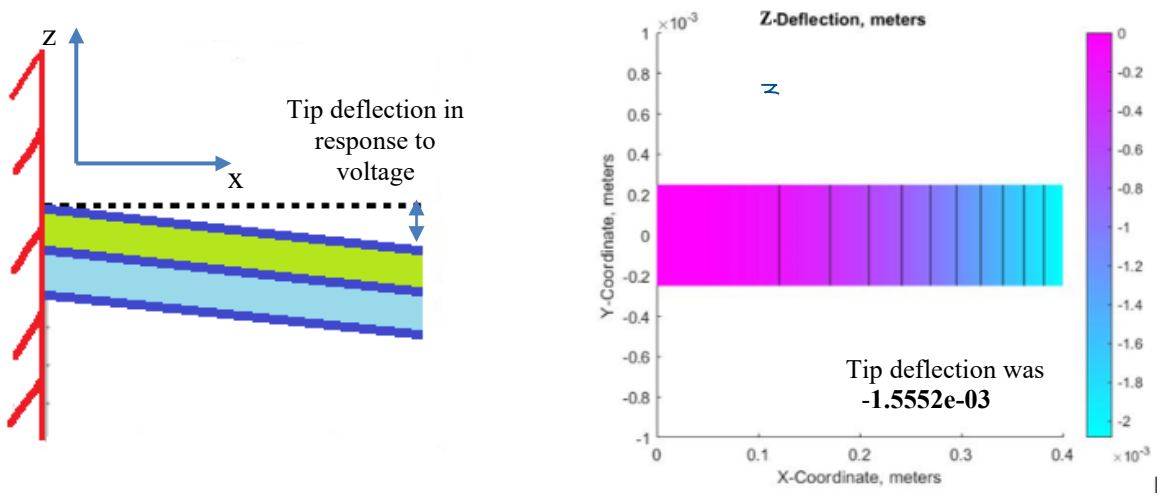

(c) (d)

Fig. 5 (a) Initial shape of PZT-5H beam (b) Deflection of PZT-5H beam in the z-direction during initial condition (c) Shape of PZT-5H beam after a deflection in response to voltage (d)Deflection of PZT-5H beam in the z-direction in response to voltage

According to this investigation, the tip deflection of the beam generated by applying 4.55V to its terminal is 1.56mm, but the maximum deflection specified in the datasheet is 2mm (Table 3), a difference of almost 22%. The following section will show experiments conducted to demonstrate that by ensuring the piezo beam deflects maximally via the plucking approach, the same maximum output voltage, Vac, can be generated regardless of the frequency.

3.2. Voltage Output from Beam Deflection

Fig. 6(a) illustrates the AC output voltage measured by the data acquisition device as the energy harvester device is swing back and forth at a 0.9 Hz input frequency. This motion is meant to mimic the frequency of hand gestures made by an average healthy human when walking. Magnetic repulsion occurs when the magnets on the beam have the same polarity as the eccentric mass, deflecting or bending the beam. The piezoelectric beam is pushed and operated to its maximum deflection of 2 mm before the magnet is pulled away from the tip mass and the repulsion force is released. Within a brief period of time, the beam will vibrate and dampen, bringing the magnets closer together once more.

A similar experiment was repeated at a frequency of 2 Hz, which is the average frequency of healthy human motion while running. Similarly, the peak voltage was produced when the piezoelectric beam was actuated, as shown in Figure 6(b). As shown in the graph, the highest output voltage produced was nearly identical, at 5.9 Vac. However, the frequency of the peak voltage produced in Fig.6(b) was greater than in Fig.6 (a). This is because the eccentric mass oscillates at a higher frequency.

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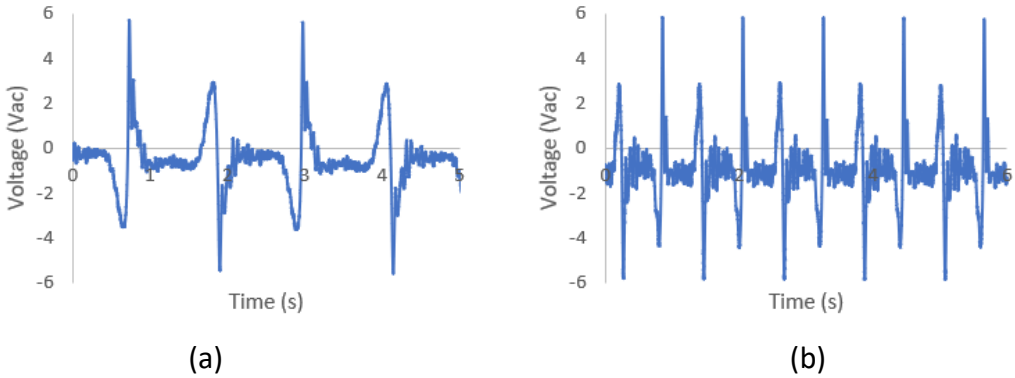

Fig. 6. Output voltage (a) during 0.9 Hz frequency excitation (b) during 2 Hz frequency excitation

As illustrated in Figure 6, when the plucking approach is used in the experiment, the peak output voltage does not significantly alter at the different excitation frequencies. This is because the piezoelectric beam always bends at its maximum deflection at the same amount of force every time the eccentric mass's magnet passes beneath it, resulting in the highest peak output AC voltage. However, the frequency of peak voltage is varied because the eccentric mass's frequency varies with the tested frequencies of motion. Figure 7 demonstrates that even when the frequency is altered up to 5 Hz, the output AC voltage remains constant.

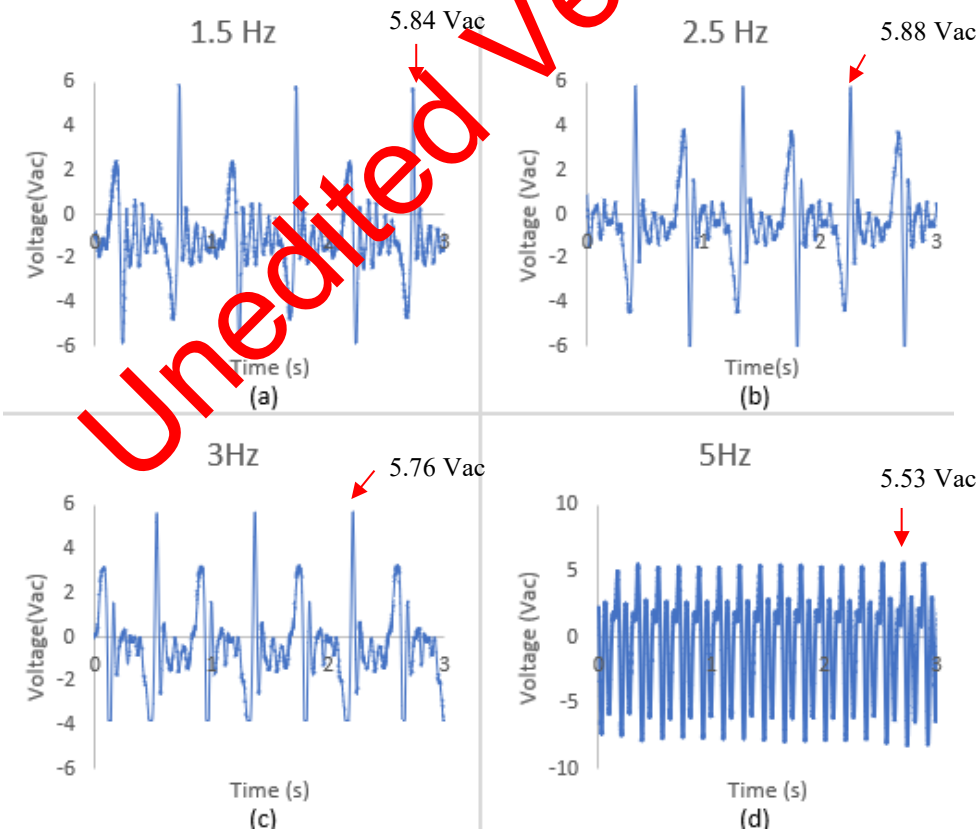

Fig. 7. Result for different tests for frequency (a) 1.5 Hz (b) 2.5 Hz (c) 3 Hz (d) 5 Hz

It can be observed from Fig. 7 that the peak voltages for all four different frequencies vary between 5.76 Vpeak (at 3 Hz) to 5.88 Vpeak at 2.5 Hz i.e. 2% difference. The distance between the two magnets is adjusted continuously to maintain the deflection of the piezo beam such that it will be at its maximum value i.e. 2 mm.

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3.3. Signal Rectification

The AC signals of the generated voltage for all frequencies were converted to DC signals using the same full bridge rectifier circuit in the previous works [22], shown in Fig. 8. The rectified signals from the full bridge rectifier circuit were then stored inside a 100 µF capacitor.

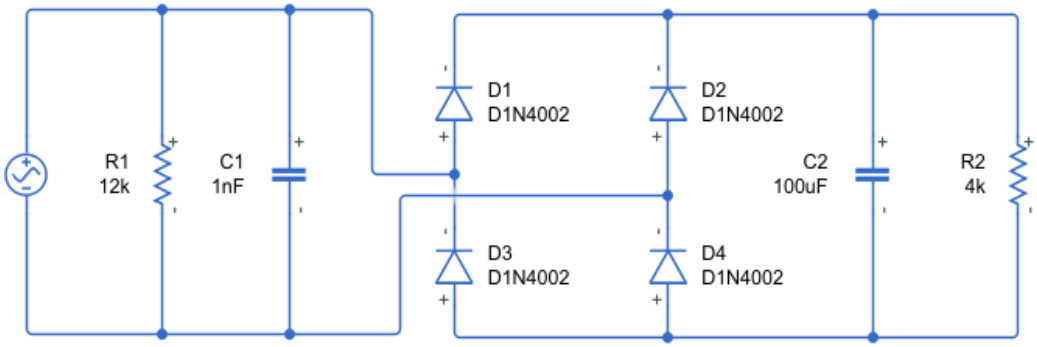

Fig. 8. Full-bridge rectifier circuit for the assembly [22]

For each frequency, the experiment was conducted for 5 minutes to allow the DC voltage to stabilize and reach steady state. During the initial stages, the DC voltage will continue to rise [24]. Fig. 9 shows that the voltage is the highest, 3.7 Vdc, when the energy harvester is excited by a 5 Hz frequency of motion. This is because its alternating current voltage has a higher peak value than others. As the frequency of the signal rises, the DC voltage stored inside the capacitor increases proportionately. Although the walking frequency of 0.9 Hz is the lowest due to the lower peak voltage in the AC Voltage, it can still generate an average of 1.5 Vdc over a 5-minute period, which is sufficient to drive low-powered electronic equipment.

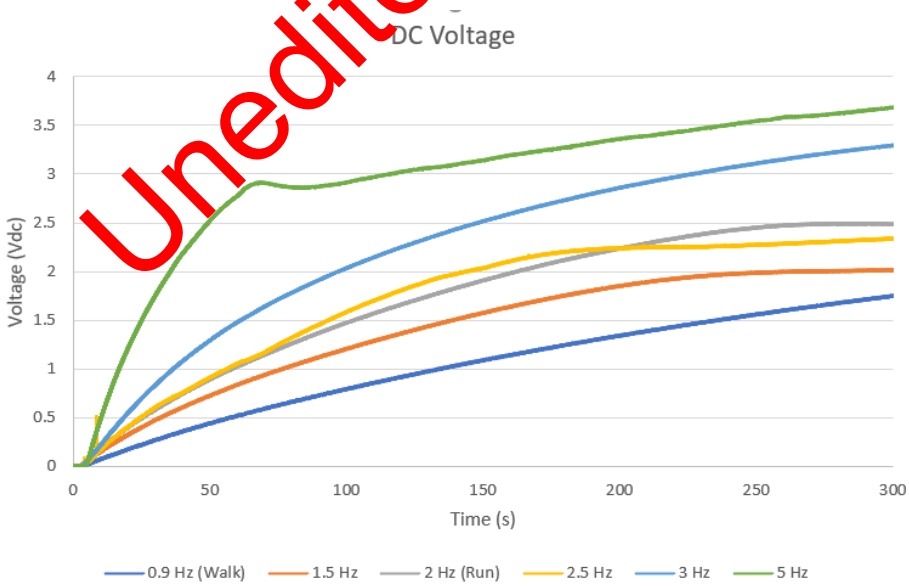

Fig. 9. Rectified voltage of the energy harvester at different frequencies

The generated voltage is summarized in Table 5 for various frequency settings both before and after rectification. As can be seen, the average AC output voltage across all frequencies is 5.77 V. However, the rectified signals changed in response to the amount of frequency excited by the harvester. A higher DC voltage is generated when the excitation frequency is increased, and vice versa. This is proven in another work; a 5 V output was produced by a PZT-5H

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piezoelectric beam under 50 microstrain loading, which is the ultimate strain limit, over 50 MΩ load resistance [25].

Table 5: Summary of the Generated Voltage

Frequency (Hz)	Voltage peak of AC voltage (V)	DC Voltage (V)
0.9 (Walking)	5.70	1.6
2.0 (Running)	5.90	2.5
1.5	5.84	2.0
2.5	5.88	2.3
3.0	5.76	3.3
5	5.53	3.7

4. CONCLUSION

When subjected to input frequencies ranging from 0.9 Hz to 5 Hz, the fabricated energy harvester device consistently produced peak AC output voltages of 5.5 – 5.8 Vac. This implies that the PZT beam always deflects in the same direction when the magnet on the eccentric mass passes below the PZT beam's tip. The results of the studies demonstrate the benefits of the suggested energy harvester for wearable devices using a magnetic plucking approach. As the eccentric mass in the proposed design can convert any directions of motion, it is less reliant on one-directional motion thus making it ideal for human applications with varying and random motion.

In the future, the efficiency of AC to DC conversion can be improved by employing alternative rectifiers such as voltage doubler rectifiers and synchronized switch harvesting on inductor rectifiers [26]. Apart from that, the size can be enhanced by making it more compact, allowing the gadget to be worn comfortably.

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REFERENCES

[1] Pillatsch P, Yeatman EM, Holmes AS. (2013). A wearable piezoelectric rotational energy harvester. In Proceedings of IEEE Internatinal Conference Body Sensor Networks: 6-9 May 2013; Cambridge; pp 1-6.

[2] Huda A, Noor Hazrin Hany MH, and Aliza Aini MR. (2019) Magnetically plucked piezoelectric energy harvester via hybrid kinetic motion. IIUM Engineering Journal, 20(1):245–257. doi: 10.31436/iiumej.v20i1.981.

[3] Fan PMY, Wong OY, Chung MJ, Su TY, Zhang X, Chen PH. (2015) Energy harvesting techniques: energy sources, power management and conversion. In Proceedings of European Conference on Circuit Theory and Design: 24-26 August 2015;Trondeim; pp 1-6.

[4] Nguyen S, Amirtharajah R. (2018) A hybrid RF and vibration energy harvester for wearable devices. In proceedings of IEEE Applied Power Electronics Conference and Exposition: 4-8 March 2018; San Antonio no; pp. 1060–1064.

[5] Sang Y, Huang X, Liu H, Jin P. (2012) A vibration-based hybrid energy harvester for wireless sensor systems. IEEE Tranactions on Magnetics, 48(11): 4495–4498, doi: 10.1109/TMAG.2012.2201452.

[6] Pillatsch P, Yeatman EM, Holmes AS. (2012) A scalable piezoelectric impulse excited energy harvester for human body excitation. Smart Materials and Structures, 21(11): 1-9. doi: 10.1088/0964-1726/21/11/115018.

[7] Mohd Fauzi AR, Kok SL, Noraini MA, R. Affendi , and Khairul Azha AA. (2013) Hybrid vibration energy harvester based on piezoelectric and electromagnetic transduction mechanism. In Proceedings of the IEEE Conference Clean Energy Technology: 18-20 November 2013;Langkawi; pp 1–5.

[8] Fan K, Tan Q, Liu H, Zhu Y, Wang W, Zhang D. (2018) Hybrid piezoelectric-electromagnetic energy harvester for scavenging energy from low-frequency excitations. Smart Materials and Structures, 27(8): 1-28. doi: 10.1088/1361-665X/aaae92.

[9] Anton SR, Sodano HA. (2007) A review of power harvesting using piezoelectric materials (2003-2006). Smart Materials and Structures, 16(3): R1-R21. doi: 10.1088/0964-1726/16/3/R01.

[10] Haitao L, Weiyang Q, Chunbo L, Wangzheng D, Zhiyong Z. (2015) Dynamics and coherence resonance of tri-stable energy harvesting system. Smart Materials and Structures, 25(1):1-10. doi: 10.1088/0964-1726/25/1/015001.

[11] Quantification of Arm Swing during Walking in Healthy Adults and Parkinson ' s Disease Patients : and Validation [https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5685089/].

[12] Is the Relationship Between Stride Length , Frequency , and Velocity Influenced by Running on a Treadmill or Overground ? [https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5685089/].

[13] Gu L, Livermore C. (2011) Impact-driven, frequency up-converting coupled vibration energy harvesting device for low frequency operation. Smart Materials and Structures, 20(4):1-10. doi: 10.1088/0964-1726/20/4/045004.

[14] Pozzi M. (2016) Magnetic plucking of piezoelectric bimorphs for a wearable energy harvester. Smart Materials and Structures, 25(4):1-12. doi: 10.1088/0964-1726/25/4/045008.

[15] Rubes O, Hadas Z. (2018) Design and simulation of bistable piezoceramic cantilever for energy harvesting from slow swinging movement. In Proceedings of IEEE 18th International Conference Power Electronics and Motion Control: 26-30 August 2018; Budapest; pp 1-6.

[16] Noor Hazrin Hany MH, Ahmad Jazlan M, Huda A, Mas Ehsan R. (2018) Rotational piezoelectric energy harvester for wearable devices. Cogent Engineering, 5(1): 1–11. doi: 10.1080/23311916.2018.1430497.

[17] Cheng X, Wu J, Lou X, Wang X. (2014) Achieving both giant d_{33} and high T_C in patassium-sodium niobate ternary system. ACS Applied Materials and Interfaces, 6(2): 1–7. doi: 10.1021/am404793e

[18] Tian W, Ling Z, Yu W, Shi J. (2018) A review of MEMS scale piezoelectric energy harvester. Applied Sciences, 8(4): 1–20. doi: 10.3390/app8040645.

[19] Gao S, Ao H, Jiang H. (2019) Properties and performance of general piezoelectric materials on a novel cantilevered energy harvester. In Proceedings of 7th Annual International Conference on Materials Science and Engineering: 19-20 April 2019; Hubei; pp 1-8.

[20] Steminc Steriner & Martins Inc [https://www.steminc.com/PZT/en/piezo-ceramic-bimorph-40x10x05mm-2-khz].

[21] V. Piefort (2001) Finite element modelling of piezoelectric active structures. PhD thesis. Universit´e Libre de Bruxelles, Faculty of Applied Sciences.

[22] Mohamad Safiddin MT, Noor Hazrin Hany MH, Muhammad Hafizuddin CK. (2021) Performance measurement of piezoelectric energy harvester with permanent magnet assembly for wearable devices. In Proceedings of IEEE International Instrumentation and Measurement

Technology Conference: 17-20 May 2021;Glasgow; pp 1–5.

[23] Von Büren T, Mitcheson PD, Green TC, Yeatman EM, Holmes AS, Tröster G. (2006) Optimization of inertial micropower generators for human walking motion. IEEE Sensors Journal, 6(1): 28-38. doi: 10.1109/JSEN.2005.853595.

[24] Muhammad Aiman ZA, Noor Hazrin Hany MH, and Mohamad Safiddin MT. (2021) Energy storage system for dual energy harvester for wearable or portable devices. In Proceedings of 8th International Conference Computer and Communication Engineering: 22-23 June 2021; Kuala Lumpur; pp 135–139.

[25] M. Rhimi. (2013) Power management and damage assessment techniques for self-powered sensing based on piezoelectric. PhD Dissertation. University of Michigan, Civil Engineering Department.

[26] Vishnu Sidharthan P, Bhasker MU, Korla S, Chandrasekhar MS. (2018) Energy harvesting of synchronized switch harvesting on inductor. In Proceedings of International Conference Recent Innovations in Electrical Electronics and Commununicaton Engineering: 27-28 July 2018; Bhubaneswar; pp 2282-2887.