Impact Based Piezoelectric Energy Harvesting: Effect of Single Step's Force and Velocity

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***Abstract*—This paper reports an impact driven energy harvesting via employing a piezoelectric ceramic disc, in which a usable alternating electrical energy has been harvested via the mechanical impact of the human weight on the surface of a piezoelectric plate transducer. A prototype of a single human step piezoelectric plate impact driven harvester consisting of a piezoelectric transducer disc was tested on a hydraulic pressing machine with variable forces and impact velocities. In this experiment, a piezoelectric ceramic disc with a size of pallet 44mm in diameter and 10mm in thickness was able to transform the mechanical impact into an average output power of up to 14.5µW across a resistive load of 500kΩ, when a force of 0.75 kN with a velocity of 600mm/min is applied on it.**

***Index Terms*—Piezoceramic Application; Energy Scavenging; Impact To Electrical Energy Transformer.**

I. INTRODUCTION

Energy harvesting is the procedure of converting raw ambient energy resources into a limited magnitude of electrical energy (but useful), in which this harvested electricity can be used to power small portable low power embedded devices. The raw ambient energy resources can be found as heat sources, ambient light, vibration and impacting (mechanical sources), and ambient radio frequency signals generated via antennas. The energy harvesting using piezoelectric transducer has attracted many attentions as harvesting the vibration energy sources is considered as a means of abundance of available energy for low power embedded devices[1][2]. This type of energy can be an added feature for the designed embedded systems, in which the replacement/maintenance of the batteries is a challenge due to the system's limited lifetime. Kinetic energies derived from either vibrations or impacts are ubiquitous from the ambient environment and industrial environment, which can easily be found from available energy resources, such as transportations, machines, household appliances, and human life activities. Within the past few years, the ubiquity of these energies has resulted in the rapid development of energy harvesters that transform the mechanical vibration/impact raw energy into a useable electric energy. Energy harvesting approaches can be classified according to the hierarchy chart, as shown in Figure 1. This paper focuses on the piezoelectric transducer motion/impact harvesting technique.

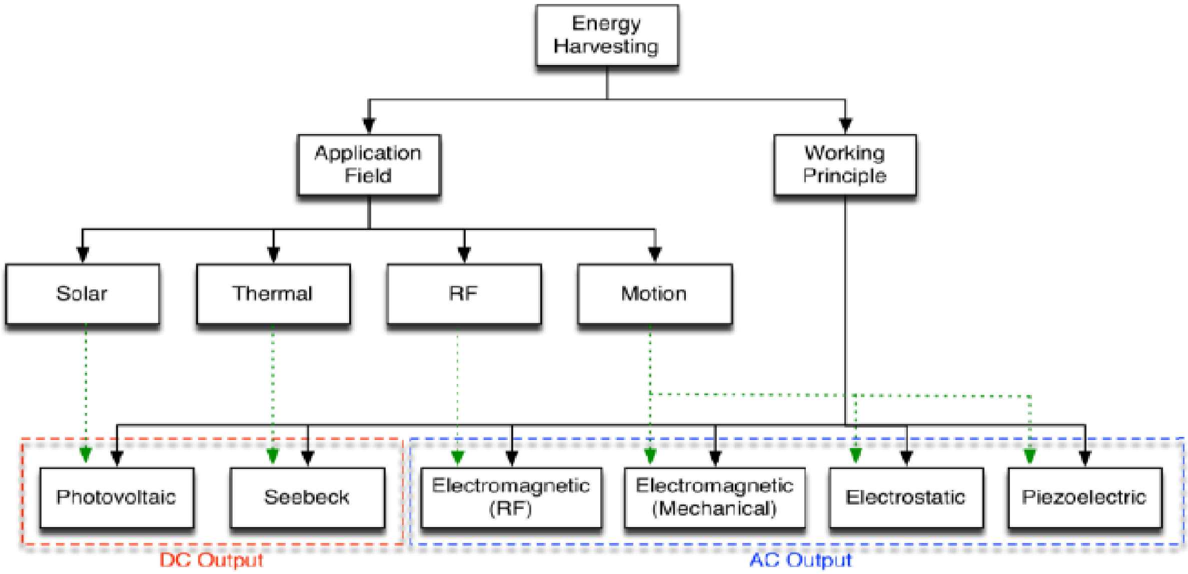

Figure 1: Hierarchy chart of the ambient energy resources approaches

Studies of the potentialities and the efficacy of converting the human daily activities into a useful electrical energy have been conducted more than two decades ago [3]. The basic principle is that as long as there is movement obtained from the human limbs activates (the movements of the hands and the legs), fingers movements while typing, air motion while breathing, and the energy of walking [4][5], a continuous energy can be derived into useful electrical power. Commonly, there are many types of transduction mechanisms suitable for mechanical vibrations and impact energy harvesting, such as the Piezoelectric transducers, electromagnetic, thermoelectric and many others. Roundy et al. state that "piezoelectric transduction" is able to provide higher power densities in contrast to an "electrostatic transduction" for the mechanical movements based harvesters [6]. The current state-of-the-art "microfabrication & nanofabrication" process is considered as another evidence in favour of piezoelectric transduction approach. It is considered as a better solution for MEMS implementations rather than the electromagnetic ones because of the limitations in magnets miniaturization [7], and the straightforward simple structures and mass manufacturability [8]. Additionally, Piezoelectric materials are considered as good harvesters approaches for the industrial environment monitoring applications, whereby sensors could be embedded inside the machines that can be located in the dark or dirty environments [9][10]. It also demonstrates as useful applications to convert human powered devices into useable electrical power, such as foot strikes while walking, knee bends and backpacks strips during hiking [11][12][13].

However, compared to the mechanical vibration or resonance type piezoelectric generation mechanism, the mechanical impact type is not broadly available due to its low interaction chances with external impact, hence generating less averaging electrical power. Therefore, this paper aims to evaluate the performance of a piezoelectric ceramic disc when an average human weight is applied on the device.

II. Literature Review and Related Work

A. Piezoelectric Fundamentals

The principle of the piezoelectric effect (piezoelectricity) is to convert the mechanical stress energy into useful electrical energy [14][15]. This phenomena mainly depends on the fundamental structure of the crystalline. Whenever this kind of crystalline is disturbed or excited via an outsider mechanical deformation atop the mesh crystal, the energy will be conveyed by the electric charge carriers, leading to the generation of a current in the crystalline. On the other hand, whenever an external electrical charge is applied as an input to the crystalline terminals due to the imbalance state in the neutral charge, a mechanical deformation in the crystalline shape will happen. Moreover, when applying a continuous AC signal, this material will be vibrating at the same frequency as the applied AC duty cycles [16]. For a unidimensional piezoelectric material, it is managed by a constitutive equation, which is by combining the electrical induction D, electric field E, strain S, and the stress T. Further, according to the principle of energy conservation, at low frequency we have:

$$D = dT + \varepsilon^T E \quad (1)$$

$$S = S^E T - d^{'} E \quad (2)$$

where: ε^T = the permittivity at constant stress.
S^E = the compliance at constant electric field.
d = the piezoelectric charge coefficient.

Therefore, when compared to a non-piezoelectric material, there is also a strain due to the electric field, and an electric charge due to the mechanical stress (charges displaced inside the material induce the opposite polarity surface charges on the plates). When the surface area does not change under the applied stress (which is not true in polymers), then $(d = d^{'})$. When solving Equation (1) for E, and equation (2) for T, we will get:

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

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

Moreover, when stressing the piezoelectric materials (applying an external force) while measuring the output voltage at the piezoelectric terminals, as shown in Figure 2, it leads to the accumulation of an electric charge $Q_3 = D_3 A_3$ on the electrodes 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 $C_3 = \varepsilon_{33}^T A_3/h$. Therefore, voltage output when applying a certain force can be calculated from:

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

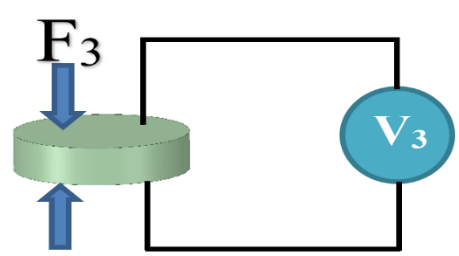

Figure 2: Open circuit voltage measurement set up of a piezoelectric sample when applying external mechanical force

From Equation 5, it can be concluded that the output voltage generated at the piezoelectric materials terminals V_{33} is directly proportional to the applied force F, by assuming the other superscripts are constants.

As far as it is concerned, the general piezoelectric energy harvester could be described in Figure 3, which illustrates the direct effect of piezoelectric materials, where *m* is the mass of the harvester, *d* is the damping, *k* is the mechanical stiffness, *α* is the piezoelectric coupling coefficient, *F* and *v* represents the applied force and output voltage separately, C_p and R_L represent the inner capacity and external resistive load respectively. Considering that the harvester generates a sinusoidal voltage, thus whenever applying an external forces in an attempt to deform the piezoelectric shape, the output should be equivalent as the output of the constant voltage source [17].

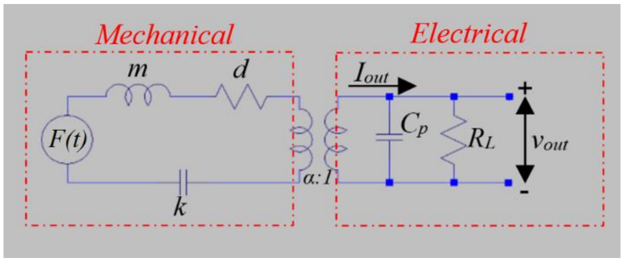

Figure 3: The equivalent circuitry of the piezoelectric harvester.

B. Related Work

Mechanical to electrical energy conversion technique based on step impact has been presented in [18], whereby multi piezoelectric beams were been periodically impacted to power up autonomous sensors. The harvester operates at low frequency (i.e. < 25 Hz), and it consists of a submissive consistent solid driving beam, in which it is sandwiched between two parallel piezoelectric beams with an equal gap. An extra proof of masses was added on the free tips of the piezoelectric beams so they can tune up the resonant frequencies. These two piezoelectric cantilevers will be periodically excited by the effect of impaction of the solid driving beam.

Amat and Bunji[19] moved a step forward by presenting a study of a mechanical impact driven piezoelectric transducer power generator, and evaluating the effects of two mechanical impact parameters (velocity and mass). They have proven that the instantaneous output voltage is proportional to the impact velocity, and the output power is in a straight line in relation to the same parameter. They stated that "the momentum of the object with higher impact velocity generates higher instantaneous peak output power than the object with the same momentum but heavier". Another research as reported in [20] presented a harvester mechanism to harvest the low frequency vibration by using multi piezoelectric beam energy harvester, which makes use of the impact. They used the harvested electrical energy to power up an autonomous sensor device. Their solution was to exploit the impact between the derived energy and the two piezoelectric beams.

Janphuang et al. [21] succeeded to harvest an average output power of 1.26uW with resistive load of 2.7MΩ by developing a novel concept of MEMS impact base energy harvester. Using piezoelectric MEMS scavenger, constructed from a thick flat PZT layer bonded on a silicon AFM like cantilever, the energy harvesting was developed from a spinning gear. This spinning gear has 16 teeth, and it was rotating by about 25 rpm to generate an impact on the free tip of MEMS piezoelectric transducer.

Ju and Ji in [22] also showed an improvement by designing a wearable device with the volume of 4.59cm3. Their prototype was able to generate about 54 AC volta at open circuit and output power equals to 621 μW. Their wearable device consist of metal spheres, which are able to freely move in two parallel trenches, in which the moving of the device leads to the movement of the metal spheres and the impact with trenches walls causes a vibration in the piezoelectric cantilever located between the trenches.

III. EXPERIMENT SET-UP

For the experiment, a human single step piezoelectric generator prototype is designed as illustrated in Figure 4.

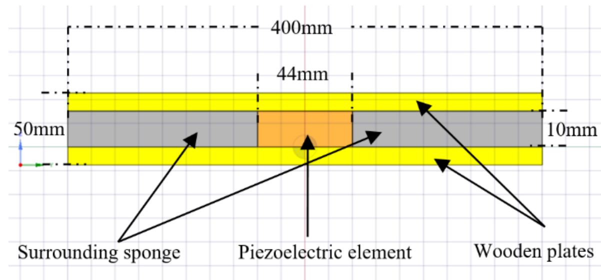

Figure 4: Schematic diagram of a human single step piezoelectric generator prototype

The construction of the human single step prototype consisted of a piezoelectric ceramic disc (diameter of 44 mm and thickness of 10 mm thick, which has a sensitivity of 5.8 V/kN) sandwiched between two wooden plates was surrounded by a sponge. The step prototype was then enclosed into a nylon cover in order to give it a nice appearance and make it more compact. It is also protected against excessive mechanical load. The finished step prototype has a diameter of 400 mm and a height of 50 mm. Various forces and velocities were generated by using AUTOGRAPH AG-I 100kN hydraulic pressing machine to simulate a single human step, as shown in Figure 5.

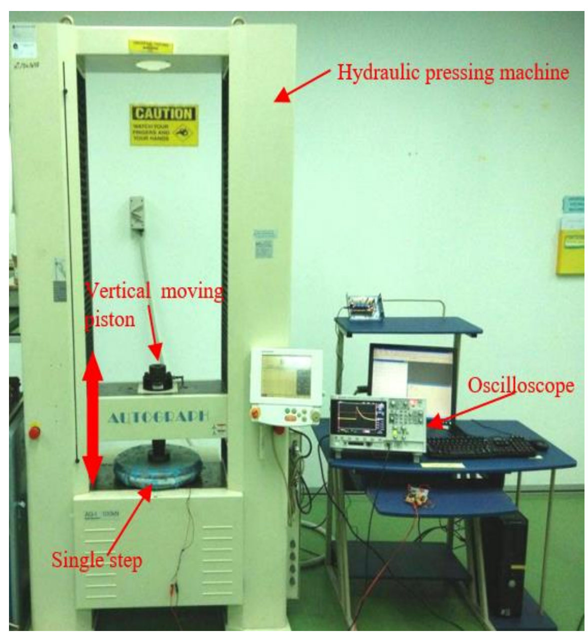

Figure 5: Experimental set-up to measure voltage generation of the single step piezoelectric generator prototype (labelled as 'single step')

As mentioned in the literature review section, the piezoelectric materials generate an alternating instantaneous electrical charge whenever there is a change of stress applied onto the materials surfaces. Thus, the output voltage and the power presented in the experiment results were measured at an instantaneous manner and the highest peak recorded via the DSO was taken for the evaluation and comparison. Figure 6 illustrates the instantaneous AC signal generated from the piezoelectric ceramic disc while being impacted during the experiment, which was captured via DSO.

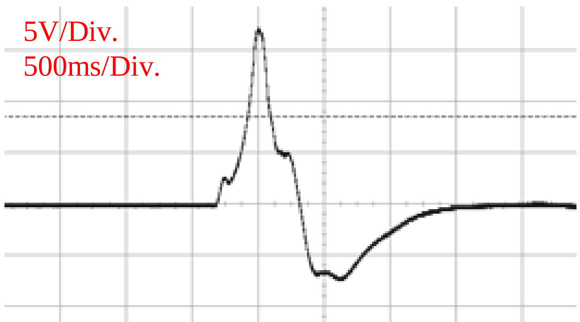

Figure 6: Instantaneous output AC voltage waveform of single step generator while been tested

IV. Experimental Results and Discussion

An AC voltage harvested from the single step prototype was measured with varying force from 0.25 kN up to 3 kN at a fixed velocity of 700 mm/min. In this experiment, the measured AC voltage showed a linear increment proportional to the applied forces starting from about 2 VAC at the minimum of 0.25 kN. It dramatically increased by a linear manner as the applied force was increasing, as shown in Figure 7. The measured AC voltage was recorded maximum about 16 V when 3 kN of force is being applied at the prototype.

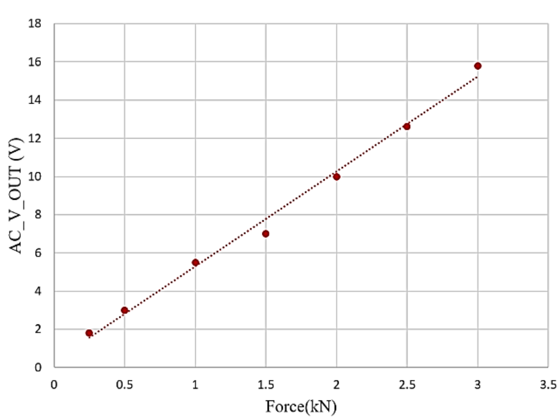

Figure 7: Instantaneous AC voltage generated at different step's forces (impact velocity = 700 mm/min)

The next experiment is to study the effect of varying the amount of velocity rather than the force to the output voltage. Here, the amount of velocity was varied from 100 mm/min up to 1000 mm/min, and a fixed amount of applied impact force of 0.5 kN. The AC voltage showed a linear increment starting from 1 VAC at minimum of 100 mm/min and dramatically increased by a linear manner as the velocity of the force is increased, as shown in Figure 8. An AC voltage of 27 V is recorded when the speed of the force is at 1000 mm/min.

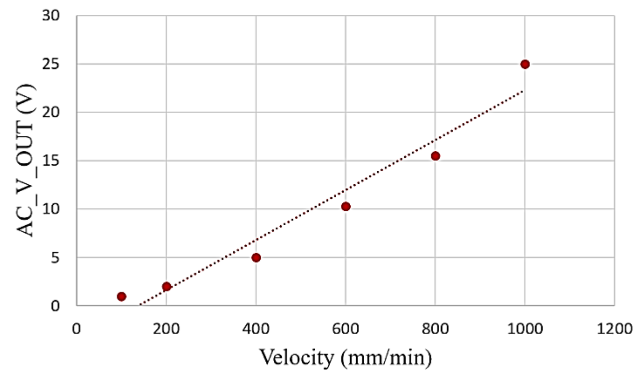

Figure 8: Instantaneous AC voltage generated at different step's velocities (impact force = 0.5 kN)

According to Equation (5), it can be seen that the V_out of piezoelectric is directly proportional to the applied force, as verified by the previous data at a linear function. However, the piezoelectric disc used in this prototype has the potential to break in case it is being subjected to a force more than 3kN. Therefore, this implies that the maximum force allowed onto the prototype is up to 3kN.

From Figure 9, we can see the electrical output power when a decade resistive load being connected as an external load to the step prototype. The force was fixed at 0.75 kN mimicking an average human weight. A maximum harvested output power of 14.5 μW is being measured across an external load of 500 kΩ. Even though the harvested power was in a magnitude of micro-watts, the DC. Voltage was always greater than 1.5V DC, when the external load exceeded 200kΩ. This means that the piezoelectric materials are able to deliver a noticeably high amount of voltages at the contrary of current.

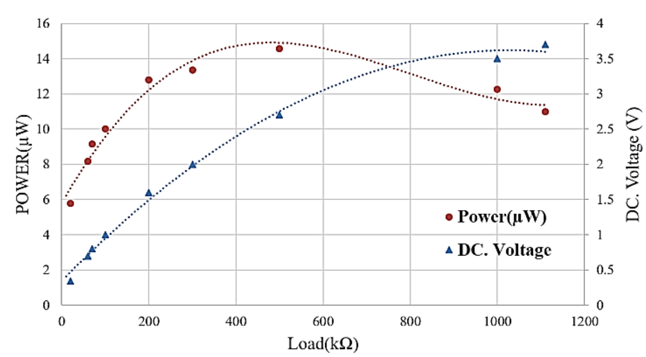

Figure 9: Instantaneous DC. power and voltage vs. external resistive load of the step prototype

From the harvested power graph showed in Figure 9, we can conclude that the proposed prototype is able to convert a single human step into a useful voltage and succeeds to harvest about 14.5 μW with an optimum load resistor 500 kΩ; hence, it matches the internal impedance of the piezoelectric element used.

V. Conclusion

A human single step prototype based on a piezoelectric powered device has been presented and tested at different range of forces and velocities. A hydraulic pressing machine to simulate a normal human step was used to measure the amount of electrical output. It shows a maximum harvested voltage of about 16V AC., which is due to the piezoelectric hardness. Moreover, it has the potential of powering low power and portable electrical devices with a power of 14.5 μW.

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