ANALYSIS OF OUTPUT VOLTAGE PROFILE OF RAINDROP IMPACT USING PIEZEOLECTRIC-BRIDGE STRUCTURE FOR ENERGY HARVESTING

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ANALYSIS OF OUTPUT VOLTAGE PROFILE OF RAINDROP IMPACT USING PIEZOELECTRIC-BRIDGE STRUCTURE FOR ENERGY HARVESTING

By

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ANALISIS KESAN TITISAN HUJAN TERHADAP PROFIL VOLTAN KELUARAN MENGGUNAKAN KEADAH JAMBATAN PIEZOELEKTRIK UNTUK MENGHASILKAN TENAGA

ABSTRAK

Kajian ini memfokuskan kepada profil voltan keluaran yang dijana daripada struktur jambatan–piezoelektrik menggunakan setitik air dan titisan air yang berterusan. Dalam kajian ini, titisan air bersaiz 5.6 mm telah digunakan untuk bertindak ke atas bahan PVDF (*polyvinylidene fluoride*) yand berdimensi 30 mm x 4 mm x 25 µm pada ketinggian 0.3 m hingga 1.2 m. Kesan tindakan setitik air telah menghasilkan profil voltan keluaran berbentuk voltan sinusoidal manakala kesan titisan air yang berterusan pula tidak menunjukkan profil voltan keluaran yang jelas dan puncak voltan berubah-ubah. Keputusan kajian menunjukkan tindakan setitik air boleh menjana voltan puncak ke puncak yang lebih tinggi berbanding tindakan titisan air yang berterusan di mana nilai maksimum adalah 10.08 V berbanding 2.38 V. Walau bagaimanapun, dalam kedua-dua kajian, voltan puncak ke puncak bertambah dengan peningkatan ketinggian. Dalam kajian ini, kadar pereputan profil voltan keluaran telah dilaporkan bagi kesan tindakan setitik air sahaja kerana bentuk profil voltan keluaran bagi titisan air berterusan adalah tidak jelas. Kadar pereputan voltan dilihat berkurangan dengan penurunan ketinggian. Kehilangan tenaga boleh dikurangkan pada kelajuan yang lebih rendah kerana titisan hujan jatuh tanpa percikan. Ini menyebabkan getaran yang lebih besar pada bahan piezoelektrik, yang menghasilkan voltan yang lebih tinggi. Kesimpulannya, perbandingan kajian analisis antara hasil kajian dan kajian sebelumnya telah dilakukan dengan membandingkan nilai voltan keluaran dan kadar pereputan voltan yang berlaku.

ANALYSIS OF OUTPUT VOLTAGE PROFILE OF RAINDROP IMPACT USING PIEZOELECTRIC-BRIDGE STRUCTURE FOR ENERGY HARVESTING

ABSTRACT

This research focuses on the output voltage profile generated from the piezoelectric-bridge structure for a single drop and continuous drop. In this study, a 5.6 mm of water droplet was used to impact the PVDF material (polyvinylidene fluoride) of 30 mm x 4 mm x 25 µm at different heights ranging from 0.3 m to 1.2 m. The output voltage profile for a single drop has shown a sinusoidal voltage whereas for continuous drop has shown no pattern as the voltage peaks were fluctuated. The experimental results show that a single drop generated higher peak-to-peak voltage compared with continuous drops, reaching a maximum of 10.08 V compared to 2.38 V. For both cases the peak-to-peak voltage increases as the height increase. In this study, the rate of decay of the output voltage profile was focused only on a single drop case due to the inconsistency of the output voltage profile for continuous drops. It can be seen that, the rate of decay decreases as the height decrease. The energy loss can be reduced at lower impact velocities as the raindrop impacted without splashes. It causes larger vibration on the piezoelectric material, which generates higher voltage. Finally, a comparison of analytical study between the experimental results and previous research findings has been done to compare the output voltage and the rate of decay of the output voltage.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

With technology advancements over the last few decades, portable electronic devices such as smart phone, tablet, mp4 player and digital watch have become normal parts for human daily life. Some portable devices are even used to monitor human's health through smart applications, such as alarm system, security network system and other applications which operate in low power energy. However, as the technology for portable and wireless devices has grown greatly, battery and energy storage still in slow updating stage. Ultra-low power portable electronics and wireless sensors used conventional batteries as their power sources, but the life of the battery is limited and very short compared to the working life of the devices (Kim et al., 2011). Lacking of batteries' lifespan certainly causes the process of replacement or recharging of the battery.

The replacement or recharging of the battery is problematic because the electronics could die at any time and this could become a very expensive task for microelectronic and wireless sensor devices (Sodano, Inman & Park, 2004). In the case of wireless sensors that are to be placed in distant areas, the sensor must be simply reachable or a disposable nature to let the device to function over extended periods of time. Thus, to overcome this critical problem, the researchers started exploring the best method of getting electrical energy from the ambient energy surrounding the device (Anton & Sodano, 2007).

Ambient energy sources involve of solar energy, wind, thermal energy, hydroelectricity and vibration energy. Generally, all these sources have already used by human beings. However, among these energy harvesting sources, mechanical vibration has received great attention by researchers over the last decade (Erturk, 2009). A review has been done to convince that the mechanical vibration is the best practical method since it is abundant enough to be used, easily accessible through microelectromechanical systems (MEMS) technology for conversion to electric energy, and is abundant in applications ranging from small domestic appliances to large infrastructures (Roundy et al., 2005). There are three basic vibration-to-electric energy conversion mechanisms which are electromagnetic, electrostatic and piezoelectric. In this study, the energy harvesting is limited to the vibration through raindrop impact on piezoelectric material.

A piezoelectric material is able to generate an electric charge when the material subjected to mechanical stress. Since piezoelectric material can convert mechanical vibration into electrical energy with very simple structure, piezoelectric energy harvesting is used as a self-power source of portable electronic devices (Sodano et al., 2004). There are many materials such as quartz and tourmaline crystals that exhibit this piezoelectric effect. The piezoelectric material can be found in various forms, including single crystal, piezoeceramic, thin film, screen-printable thick film using piezoeceramic powder, and polymeric material (Beeby, 2006). The material used for vibration energy harvesting plays a huge influence in efficiency and performance of the harvester. The most common types of piezoelectric material being used are polyvinylidene fluoride (PVDF) and lead zirconate titanate (PZT).

Vatansever et al., 2011, reported PZT is a ceramic-based piezoelectric material which produces a higher voltage than PVDF based piezoelectric. However, in the raindrop application, the PZT material generated a relatively lower peak voltage compared with PVDF due to the mass of the water drop, which was insufficient to activate the PZT material. Therefore, the piezoelectric material selected for this study is PVDF transducers because they generate high power, have a lower cost and are not toxic when compared to PZT transducers.

There are two common structures of the raindrop piezoelectric energy harvester being used in the researches which are a bridge and cantilever structure. The types of structure used in the raindrop energy harvesting play an important role to determine the impact mechanisms of a water droplet falling onto the piezoelectric material. The impact mechanism of a raindrop can be divided into three categories which are bouncing, spreading and splashing. Various studies show that the dominant impact mechanism of a raindrop is splashing mode (Perera et al., 2011). The splashing mode leads to significant energy loss.

In the previous research conducted by Wong et al., 2015, the result had shown that the bridge structure was able to generate higher voltage compared to cantilever structure when a single drop impacts on a 30 mm x 4 mm x 25 µm of PVDF material. This is due to the design of cantilever was embedded at one end, but the bridge was supported at both ends, being more stable than cantilever structure. It was observed that the droplet pass through the cantilever structure and splash on the ground whereas on the bridge structure the droplets impact and splash on the beam, thus absorbing more energy. The details of the structures of energy harvester were presented in Chapter 2.

The capability of a raindrop energy harvesting to generate higher voltage was also depends on other parameters of raindrop such as size, fall velocity, impact type and kinetic energy of a droplet. Theoretically, the raindrops falling from high altitudes have a significant kinetic energy, which is stored while them falling. The considerable kinetic energy if utilized can be used to power household appliances or sensors which may reduce stress on conventional energy sources. The amount of electrical energy can be extracted from such a system as shown in Figure 1.1.

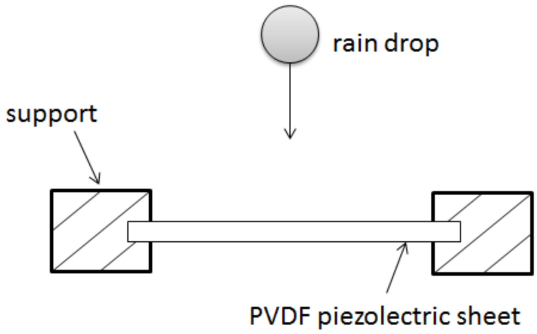


Figure 1.1: System of raindrop energy harvesting

According to Grinspan and Gnanamoorthy (2010), the height of water droplet released to impact on a piezoelectric material was strongly influenced the output voltage generated because the higher position of water released will lead to higher impact velocity. Vatansever et al., 2011, also reported that the peak voltages generated from the raindrop energy harvesting was affected by different parameters such as wind speed, water droplet weight and releasing height. This research only reported the output voltage generated based on the impact of a single droplet. However, for the output voltage of continuous dropss impact on the bridge piezoelectric have not been published in the literature before.

Another research reported on the output voltage generated from raindrop energy harvesting was conducted by Ilyas & Swingler, 2015. In their research, they reported on the detail investigation of the output voltage features such as the impact stage and decay stage. A PVDF film was used as a piezoelectric material. The results show that during the decay stage, the voltage oscillations decay away as time increases. However, the rates of decay of each output voltage generated from different heights have shown no significant difference.

1.2 Problem Statement

One of the current issues to be considered for developing a raindrop energy harvesting device is the ability of the device to supply energy at a constant rate over long periods of time. However, the existing of raindrop energy harvesters today can only produce electrical energy when subjected to stress or strain. An addition of an electrical storage device such as a battery or super capacitor is required but still the generated output voltage must therefore be investigated before it is delivered to the load. Previous studies have shown that the only one research investigated on the output voltage profile was conducted by Ilyas and Swingler, 2015. They performed the experiment by using a single drop impact on the PVDF material with the cantilever structure. There was no research reported on the output voltage profile generated from the bridge structure. Hence, in this project, a study was conducted to characterize the output voltage profile when subjected to piezoelectric material by varying the height of water released for a single drop and was expanded for continuous drops using a bridge structure.

1.3 Research Objectives

This project involves detailed investigation on raindrop impacts for energy harvesting. There are three objectives to be accomplished at the end of this project.

i. To characterize the output voltage profile when raindrop is hitting the PVDF material at different heights for a single drop and continuous drops.

ii. To determine the rate of decay of each output voltage at different heights for a single drop and continuous drops.

iii. To perform comparison analytical study between experimental results and the previous research findings.

1.4 Significant of Study

A brief experiment was conducted to study the characteristics of the output voltage profile from the raindrop energy by varying the parameters of height released of water droplet for a single droplet and continuous drops. The outcome of this study can be used for developing a stable raindrop energy harvesting device by taking consideration on parameter of height as well as the size of water droplet and dimension of piezoelectric material.

Besides that it also can be a comparative result if another research performed with different approaches like using other materials and structure of energy harvesting device. Besides that, the study of the output voltage profile will lead to prove that the impact mechanism of splashing as the factors of the amount of energy losses in surrounding.

1.5 Scope of Study

The scope of this study was limited on the PVDF material as a piezoelectric transducer to generate electrical energy when impacted by a water droplet. In this study, the dimension of PVDF used was 30 mm x 4 mm x 25 µm. In order to characterize the output voltage profile, the height of water released was set from 0.3 m to 1.2 m. This study also focused on the impact of a single drop and continuous drops by using bridge structure.

1.6 Organisation of Thesis

The first chapter covered the three main objectives to be accomplished at the end of this research. The objectives of the research consist of to characterize the output voltage profile when raindrop is hitting the PVDF material at different heights for a single drop and continuous drops, to determine the rate of decay of each output voltage at different heights for a single drop and to perform comparison analytical study between experimental results and the previous research findings.

The second chapter of this dissertation reviews the background knowledge of raindrop energy harvesting. This chapter emphasized the principle of a raindrop energy harvesting, the ability of a bridge structure and PVDF piezoelectric material as a transducer to convert electrical energy into mechanical energy and what related equation can be observed from the output voltage and power output.

The third chapter presents the research methodology of the research. It discussed the details description of experiments carried out. The apparatus set up were explained with the help of some illustrated figures. The analysis data has been done using MATLAB version R2014a to obtain the maximum peak voltage value as well as to measure the rate of decay of the output voltage. Some mathematical expressions have been presented to calculate a few of important parameters of raindrop.

The fourth chapter consists of results obtained from the experiment. The results were divided to three parts which consist of characterization of the output voltage profile for a single drop and continuous drops at different heights. The detail explanation of the findings was also discussed in this chapter.

Finally, Chapter 5 summarizes the findings of this study and conclusions have been drawn through the entire chapters.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this section, the literature on on-going researches of raindrop energy harvesting has been presented. A subset of literature has been selected based on its relevance point in order to understand the concept of piezoelectric transducers and some effort to enhance the raindrop energy harvesting device.

2.2 Conceptual Background of Piezoelectric Energy Harvester

The use of piezoelectric materials as transducers over electromagnetic and electrostatic mechanism seems to be one of the best methods to fulfill the demands for sustainable and remote energy power supplies in applications such as portable devices and wireless sensor network (Viola et al., 2015). The basic idea is to convert the mechanical energy into electrical energy. However, a complete characterization on the probability of harvesting energy and gather information in different scenarios is difficult to be provided, since novel approach and innovative idea are persistently being developed. Different scenarios have been considered. Moro and Benasciutti (2010) studied the possibility of harvest energy from vibrating shoe-mounted piezoelectric cantilevers, such system can also be used to monitor weight distribution on the sole of the foot: Xiang et al., (2013) proposed the harvesting of energy induced from the deformation of pavements due to moving vehicles: but also Van den Ende et al., (2011) discussed the harvesting from automotive tires; and finally Hobeck and Inman (2012) proposed an innovative piezoelectric grass energy harvester.

Recent advances in low-power electronic design and fabrication have opened the possibility of self-powered micro sensors and communication nodes (Chandrakasan et al., 1998). The awareness among researchers on the need to power remote system or embedded devices independently has led many research efforts harvesting electric energy from ambient sources (Roundy et al., 2004).

Energy harvesting sources can be categorized into two categories: ambient sources and external sources. Ambient sources readily exist in the environment and also known as natural resources. On the other hand, external sources are deployed explicitly in the environments for energy harvesting purposes (Shaikh & Zeadally, 2016). These categories are further divided as shown in Figure 2.1 below.

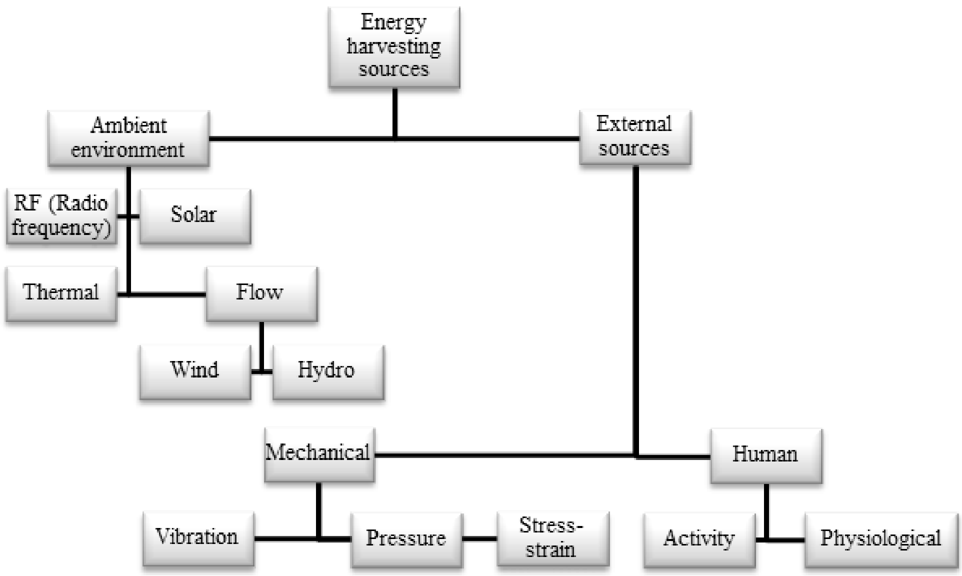


Figure 2.1: Taxonomy of energy harvesting sources

Piezoelectric transducer which converts vibration energy to electricity has gained a lot of attention because of the advantages such as having a high electrochemical coupling, without requiring external voltage source and are particularly attractive for use in micro electrochemical systems (MEMS) (Jeon et al., 2005). Piezoelectric energy harvesting devices can be used to capture vibration, motion or acoustic noise, to be converted into electrical output. These are normally used for application with low power requirements like powering sensor equipment from ambient vibrations, MEMS, wireless sensor and military applications (Reilly et al., 2011).

Piezoelectricity is a form of coupling between the mechanical and electrical behaviours of certain materials. The materials exhibiting the piezoelectric effect are called the piezoelectric materials. The piezoelectric effect is usually divided into two parts as the direct and the converse piezoelectric materials. In this study, when a raindrop is hitting on a piezoelectric material, it will vibrate and subsequently creates a charge, Q. This generated charge is then collected by two electrode plates. Lastly a voltage, U is generated through the electrode plates in relation to

$$U = Q/C_{piezo} \tag{2.1}$$

where the capacitance $C_{piezo} = \varepsilon_r \varepsilon_0 A/t$, ε_r is the relative permittivity of the medium between the electrode plates, ε_0 is the electrical permittivity in vacuum, A is the electrode area, and t is the separation of the electrode plates. Thus, the generated power can be calculated as

$$P = E/T \tag{2.2}$$

where the stored energy $E = C_{piezo}U^2/2$ and T is the period of water droplet impact on the piezoelectric structure.

However, the output power generated from the energy harvesting device is normally affected by a few factors. The drop, while centering fully the piezoelectric film, is not able to transfer maximum energy as it subject to the phenomenon of splashing: the collision is not complete since the impact are separated some small drops. It must therefore associate an efficiency of a collision (Guan and Liao, 2007).

In other word, during the impact, not all energy has been transferred as the energy loss due to heat dissipation. Consequently, the output power can be derived as below

$$P_{out} = \eta_{impact}\, \eta_{piezoelectric}\, \eta_{rectify}\, P_{max} \qquad (2.3)$$

where P_{max} and P_{out} are the output power with and without consideration of energy loss, η_{impact}, $\eta_{rectify}$ and $\eta_{piezoelectric}$ are the efficiencies of the collision, the power conversion and the piezoelectric mechanism, respectively

. Miceli et al., 2014 stated that the piezoelectric energy harvesting devices can be reflected as a charge generator or a voltage generator. The inside charges are produced during the piezoelectric material is subjected to a pressure due to the droplet which gives rise to an electric field. The electrodes that are set close to the surface are affected by this field and collect a quantity of charge on their surfaces proportional to pressure. The function of the transducer will be different depending on the type of load that is connected at its ends: if the piezoelectricity material is connected to a high-impedance load, the charges remain confined on the faces of the sensor thus keeping the electric field unchanged, as in voltage generator.

However, if the load has low input impedance, the charges that accumulate on the electrodes are poured entirely on it, similar to a charge generator. A suitable equivalent electrical model can be that of a voltage source in series with a capacitor or the equivalent Norton's one. In addition, a resistance R_e that connects the two ends of the active component can be used to refine the model, so introducing the electrical loss. Figure 2.2 shows the equivalent electro-mechanical scheme so that the behaviour of the electromechanical transducer can be defined.

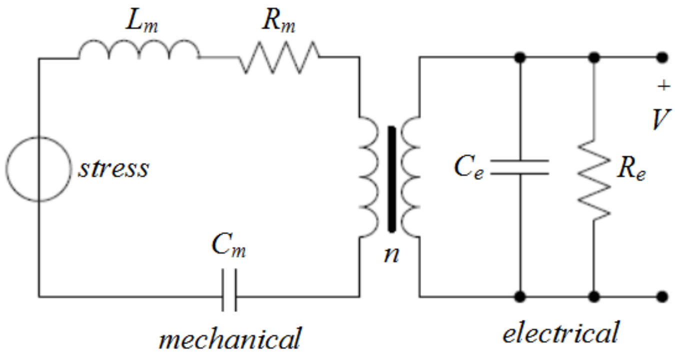


Figure 2.2: The equivalent electro-mechanical scheme

In the mechanical, part the inductor L_m represents the equivalent mass and inertia of the piezoelectric generator, R_m represents the mechanical losses, C_m represents the mechanical stiffness, stress generator is caused by mechanical vibration, *n* is the transformation ratio of the equivalent transformer, an element that relates the physical quantities with those electrical (Brusa et al., 2009). C_e represents the capacitance of the piezoelectric element and *V* is the voltage across the piezoelectric transducer. The mechanical and electrical parameters depend on the shape of the piezoelectric transducer.

Viola et al., 2014 stated that the piezoelectric transducers were able to generate tens of volts, but the results still not sufficient enough to discover the character of power generators. Dissimilar performances caused by inconstant drop dimension (mass) and impact point make it hard to model the phenomenon. An equivalent average voltage has to be defined because the voltage has a peak waveform, not a continuous voltage. For a power system the equivalent average current can be obtained by using a bridge rectifier and a smoothing capacity: for the theoretical initially this approach has been not considered.

2.2.1 Overview of the Energy Flow in the Piezoelectric Energy Harvester

Figure 2.3 below provides an overview of three forms of energy involved in the piezoelectric energy harvesting devices. These three forms are mechanical, electrical and thermal. The mechanical and electrical forms are linked by the bi-directional piezoelectric transducer. At the same time, either mechanical or electrical energy can be converted into thermal energy by dissipative elements such as mechanical dampers or electrical resistors. Once the energy is dissipated, for example transforms into heat, it will not be recovered in the devices. Therefore dissipative transformation is uni-directional (Liang and Liao, 2010).

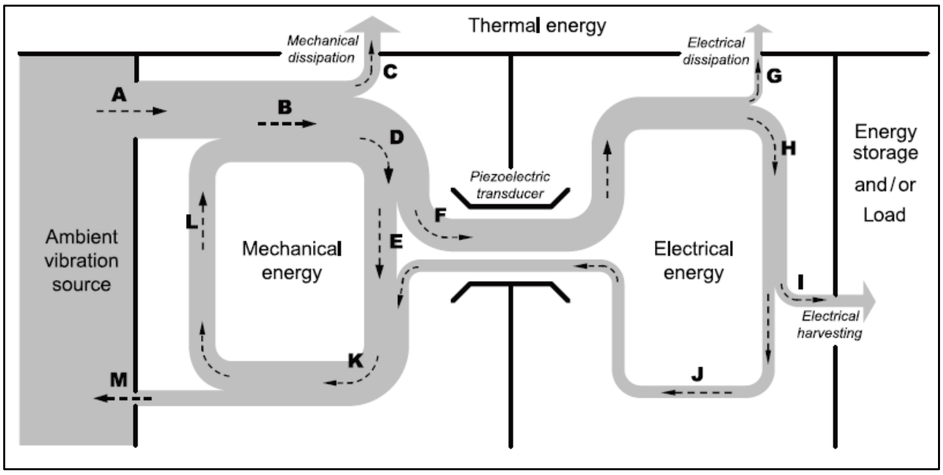


Figure 2.3: Energy flow chart in general piezoelectric energy harvesting devices

The energy flow chart provides an intuitive way to indicate the directions of different branches of flow in energy vibration cycle. During each cycle, the ambient excitation source inputs energy into the system in mechanical form (branch A). A portion of the energy keeps cycling in the mechanical domain as the vibratory energy (loop B-D-E-K-L-B). Accompanied by the vibration, some mechanical energy is dissipated, i.e., converted into thermal energy (branch C), while some is converted into electrical energy (branch F) with the electrochemical coupling characteristic of the piezoelectric transducer. In the electrical domain, without the circuit connected, i.e., under open circuit condition, the electrical energy is temporarily stored in the piezoelectric capacitance and then all returns to the mechanical part; however, with different interface circuits connected, this electrical energy may have different destinations. Generally, there are three possible ways; (a) being converted into thermal energy (branch G), i.e., dissipated, (b) being stored in energy storage devices and/or used to power the load (branch I), i.e., harvested, (c) returning to the mechanical domain (branch J). If the total mechanical impedance of the piezoelectric device does not match the source impedance, some energy will return to the source (branch M).

2.3 Important Parameters for Raindrop Energy Harvesting

The focus of this study is to investigate on raindrop impacts by means of piezoelectric as transducers. According to Ilyas and Swingler (2015) the potential of raindrop energy harvesting is still not fully revealed. Therefore, a good understanding on raindrop energy harvesting is needed by reviewing a few of important parameters such as, height, size, terminal velocity, impact type mechanism and kinetic energy of a droplet (Abd Elbasit et al., 2011).

2.3.1 Terminal Velocity of Raindrop

A raindrop which is falling vertically with free-fall towards the ground experiences two forces; namely force acting upwards and force acting downwards. The force acting upward is also known as the drag force whereas the force acting downward acted as the gravitational force resulting in the weight of droplet. The forces acting on the droplet are illustrated in Figure 2.4.

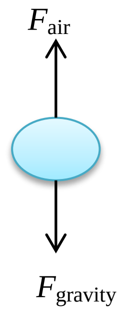


Figure 2.4: Forces acting on a falling droplet

The drag force on the droplet can be expressed in Equation 2.4, where ρ_a is the density of air, A is the projectile frontal area of the droplet, V is the velocity of the droplet and C is the coefficient of drag.

$$F_{air} = \frac{1}{2}\rho_a A C v^2 \tag{2.4}$$

The weight of the droplet,

$$F_{gravity} = \frac{4}{3}\pi r^3 \rho_w g \tag{2.5}$$

where ρ_w is the density of water droplet, r is the radius of the droplet and g is the acceleration of the droplet due to gravity. When these two forces are in equilibrium, constant velocity of motion is called as terminal velocity, v_T. The expression for terminal velocity is of the form

$$v_T = \sqrt{\frac{8 r \rho_w g}{3 \rho_a C}} \tag{2.6}$$

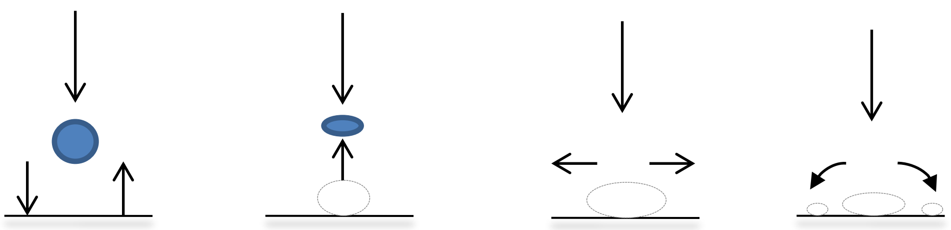
Perera et al., 2014 stated that the formula for the terminal velocity is valid if the prediction of spherical shape of the raindrop is accurate. If the raindrop falls from a higher height, the fall velocity will increase, while the fall velocity will decrease for droplets dropped from lower height (Grinspan & Gnanamoorthy, 2010).

However, the shape of the droplet is normally not consistent due to air resistance. A few studies have been investigated on this part. Partovi and Aston

(1989) reported a raindrop falling through the mist is generalized to experience air resistance and changing in shape.

2.3.2 Raindrop Impact Mechanism

The impact mechanism is another factor which contributes to the energy transfer function of the energy harvesting device and its output power. Studies have shown that there are three different types of droplet impact mechanism on solid surfaces; bouncing, spreading and splashing (Rein, 2002). The water droplet can either fully bounce leaving no water residue on the solid surface, which is depicted in Fig. 2.5a, or partially bounce leaving water residue, as depicted in Fig. 2.5b. The second type of the droplet impact is called as spreading when the water adheres to the surface at impact as depicted in Fig. 2.5c. The third one is splashing when the droplet breaks into many parts and adheres to the surface. The droplet will then be distributed on the surface as depicted in Fig. 2.5d. The impact of a droplet on an energy harvesting device is assumed to demonstrate all or a combination of these mechanisms (Rein, 2002).



a) Rebound b) Partial rebound c) Spreading d) Splashing

Figure 2.5: Water droplet impact on solid surface

According to Perera et al., (2014) most of the researches conducted showing that the water droplet experience splashing when impact on the surface. Marengo et al., (2011) reported in their studies, the air resistance, shape of the droplet and a drop inclination angle will affect the impact type and kinetic energy of the water droplet. Various sizes of raindrop will generate different types of impact behaviour. During impact on the piezoelectric material surface, the water droplet possesses kinetic energy and converted to surface energy. In order to measure the ratio of the kinetic energy and surface tension of the water droplet, the Weber number can be used as follows

$$We = \frac{\rho_w v^2 d_0}{\sigma} \tag{2.7}$$

where ρ_w is the density of water, v^2 is the velocity at impact, d_0 is the drop diameter before impact and σ is the surface tension (Durickovic &Varland, 2005).

At very low impact velocities, i.e., $We \ll 1$, the flow is controlled by capillarity forces. At higher speeds, i.e., $We \gg 1$, a deposition mode (creation of a liquid film on the surface) takes over. Durikovic & Varland (2005) stated that the splashing phenomenon happens at even higher impact velocities. Another finding from Guigon et al., (2008a) also reported that a splash mode is normally happening in even higher impact velocities. The recoverable energy during the impact of a droplet is very useful to be estimated because this energy will establish the output power generated from this method. The splash mode leads to significant energy loss. In addition to that, the more raindrop impact without splashing causes more vibration of the membrane. Therefore, a greater amount of electrical energy can be produced (Guigon et al., 2008a).

2.3.3 Kinetic Energy of Raindrop

Another important parameter of raindrop energy harvesting to be investigated in this study is the kinetic energy of water droplet that will be converted into electrical energy. This kinetic energy depends on two variables; size and fall velocity of water droplet. The greater the size of the droplet, the faster it falls (Biswas et al., 2009). As the droplet is released from standstill it accelerated along a path increasing in velocity. Therefore, the kinetic energy of the droplet can be calculated using the equation below:

$$E_k = \frac{1}{2}mv^2 \tag{2.8}$$

where *m* is the mass of a water droplet, $m = \rho_w V = \rho_w \left(4/3\pi \left(D_{drop}/2\right)^3\right)$, V is the volume of the droplet, D_{drop} is the droplet diameter, ρ_w is the density of water, and *v* is the terminal velocity of the droplet. Then the Equation 2.9 can be expressed as;

$$E_k = \frac{1}{2}\rho_w \left(\frac{4}{3}\pi \left(\frac{D_{drop}}{2}\right)^3\right) v^2 \tag{2.9}$$

In equation 2.9, the shape of the droplet is considered as spherical and the volume is constant while falling.

2.3.4 Rain Fall Rate

Generally, there are four types of rains reported by NASA website. It consists of light stratiform rain (LSR), moderate stratiform rain (MSR), heavy thurderstorms (HT) and violent. Table 2.1 below shows the raindrop sizes, meteorological experimental terminal velocities (Horstmeyer, 2011).

Table 2.1: Rain fall rate per hour of different types of storms

Type of Storm	Rate	Largest diameter of a raindrop (mm)	Terminal velocity (ms^{-1})
Light rain	2-4 mm/hr	2.0	6.49
Moderate rain	5-9 mm/hr	2.6	7.57
Heavy rain	10-40 mm/hr	5.0	9.09 or 10
Violent	› 50 mm/hr	N/A	N/A

*1 mm rainfall equals 1 litre or water per an area of one m^2

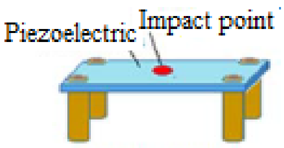
Al Ahmad, 2014, has proposed the five-layer PZT clamped-free cantilever energy harvester, the dimension of the cantilever was 25 mm x 3 mm x 0.58 mm. The experiment was conducted with two different drop intensity, namely one at 75 drop/s drop intensity and the other one was at 200 drop/s. The mass of a water drop was 0.23 g with drop speed of 3.43 m/s. It was reported that at 75 drop/s drop intensity, 0.3 µJ of energy was harvested whereas at moderate intensity of 200 drop/s, the energy output of the harvester yield a total energy of 400 µJ.

Another research investigated on different rain fall rate was conducted by Wong, Ho and Yap (2015), have studied the impact of different rate of droplet on a PZT cantilever with dimension of 46 mm x 3 mm x 127 µm. They utilized six syringes connected to six solenoid valves to produce 4.5 mm diameter water drops. The water drops were produced one by one at a controlled rain rate to impact different surface locations of the cantilever beam as shown in Figure 2.6c.

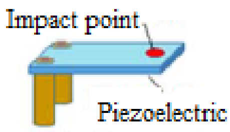
The rate of flow was set to light stratiform rate (LSR), moderate stratiform rate (MSR) and heavy rain (HR). The voltage produced was largest when the water drops was impacted close to the free end of the cantilever and was lowest when the impact location located near the fix end of the cantilever. This is because larger strain was produced when water drop impacted locations close to the free end of the cantilever and hence more energy was converted. The average power for three different rain rates, LSR, MSR and HR were 0.52 µW, 1.01 µW AND 1.84 µW.

2.4 Types of Raindrop Energy Harvesters

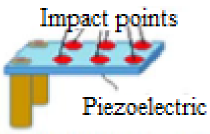
The most common structures have been developed by researchers were bridge and cantilever structures. Chua et al., 2016 have summarized the different types of raindrop piezoelectric harvesters as shown in Figure 2.6.



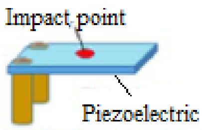
a) Bridge structure



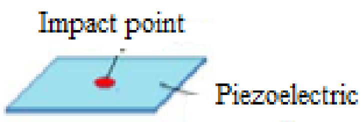
b) Cantilever structure with impact point near the free-end



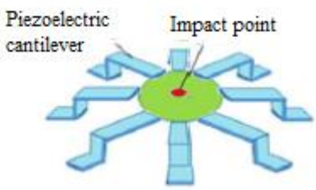
c) Cantilever structure with six impact point at the centre



d) Cantilever structure with impact point at the centre



e) PVDF membrane or PZT edge-anchored plate



f) Collecting diaphragm cantilevers

Figure 2.6: Different types of raindrop piezoelectric harvesters

The first raindrop piezoelectric harvester was proposed by Guigon et al., (2008a). They produced a system that recovers vibration energy from a piezoelectric material (PVDF) impacted by falling raindrop on the bridge structure as shown in

Figure 2.6a. The PVDF material was selected for its flexibility, smoothness and lead-free natures. A syringe pump was used in this experiment to create water droplets with diameter ranging from 1 mm to 5 mm. The droplet was set up at different drop heights ranging from 1 cm till 5 cm. The results showed that a single downpour raindrop of 5 mm in diameter was possible to recover up to 25 μJ and 12 mW from downpour drops.

In their study, a comparison between the theoretical and experimental results of a thickness of 25 μm monostretched PVDF material with a piezoelectric strain coefficient d_{31} of 15 pCN^{-1} and a thickness of 9 μm of bistreched PVDF material with a piezoelectric strain coefficient d_{31} of 5 pCN^{-1} has been done. The finding showed a good correlation between theoretical and experimental results. However, the thickness of 25 μm of PVDF was much more effective than the thickness of 9 μm of PVDF material. They found that droplets dropped from a low height resulted in electrical energy proportional to the square of the drop's mechanical energy, whereas the voltage and mechanical energy were directly proportional to each other. The recoverable energy was influenced by directly on the size of the raindrop and its falling velocity.

Vatansever et al., (2011) relatively studied the voltage generated by using a cantilever structure. Two different piezoelectric transducers were used in their study, namely PVDF and PZT with dimensions of 16 mm x 4 mm x 0.2 mm. Both of the piezoelectric materials have been evaluated when subjected to different releasing heights and weight of water droplets as well as various wind speeds. In their experiment, water drop of mass 7.5 mg and 50 mg were released from height of 20 cm, 50 cm and 100 cm to obtain the effect of different parameters on the voltage generation ability of the piezoelectric samples. The results obtained from the raindrop experiment showed that the PVDF transducer was able to produce higher peak voltage compared to PZT when a 50 mg water droplet was set to fall at 100 cm. It was recorded that the PZT cantilever generated only 3 V while the PVDF cantilever was able to generate the maximum peak voltage of 12 V. Thus, the PVDF material is capable to utilize energy from raindrop impact. It was found that, the mass of water droplets was unsatisfactory to activate the PZT material. A previous study from Guigon et al., (2008) stated that PVDF materials afford several advantages for example being lead free, low-cost, easy to process, lightweight, flexible and smooth while the PZT materials were inflexible and breakable, which limits the range of their application.

Another research conducted by Miceli et al., (2014) compared the behaviour of the lead zirconate titanate (PZT) and polyvinylidene difluoride (PVDF) transducers impact to a real and simulated raindrop. An epoxy cantilever which sandwiched between electrodes was used to collect the generated power. There were two different transducer configurations that can be used in cantilever structures as shown in Figure 2.7.

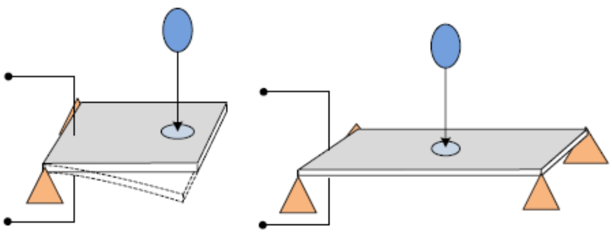
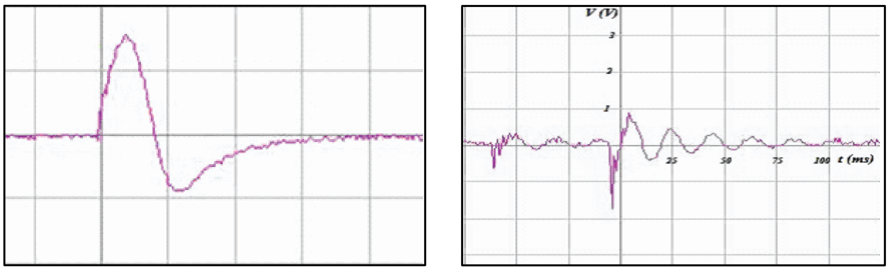


Figure 2.7: Piezoelectric cantilevers, one edge bound on the left, two edges on the right

The experiment was conducted at closed circuit for a single drop with loads ranging from 10 kΩ to 470 kΩ. Results showed that the PZT transducers bound to the both ends have generated waveforms more regular, in which a first larger pulse is followed by a second one, smaller and of opposite sign as shown in Figure 2.8a whereas for the PVDF transducer the output voltage has an oscillating behaviour, due to the presence of an under damped system as shown in Figure 2.8b.



a) b)

Figure 2.8: Signal acquired for a) PZT transducer; b) PVDF transducer

The results also showed that the PZT was able to generate the maximum of output power of $100 \times 10^{-7} W$ when connected to 100 kΩ whereas the PVDF produced the maximum of power output of $490 \times 10^{-6} W$ with 47 kΩ. This study has shown that the single transducer PVDF creates a much more power than PZT.

Since the PVDF material has been reported as a good transducer to generate higher voltage and output power, Viola et al., (2014), in their study, has performed a new design of piezoelectric transducers to harvest the energy. They have been focused on the PVDF material only. The design consists of a piezoelectric film on an epoxy cantilever sandwiched between the electrodes. In this work, the generated pulse is only considered by one end locked. Figure 2.9 below shows the schematic of the design under the piezoelectric transducer.

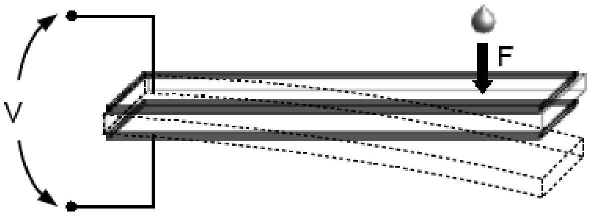


Figure 2.9: Schematic of the cantilever under the piezoelectric transducer.