UNIVERSITI PUTRA MALAYSIA

HARVESTING ENERGY FROM PLANETARY GEAR USING PIEZOELECTRIC MATERIAL

CHILABI HAIDER JAAFAR HUSSEIN

HARVESTING ENERGY FROM PLANETARY GEAR USING PIEZOELECTRIC MATERIAL

By

CHILABI HAIDER JAAFAR HUSSEIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

November 2019

DEDICATION

To My dear wounded country **IRAQ** and my marvellous family,

My dearest great father Dr. Jaafar Chilabi,

and **my beloved great mother Mrs. May al-Moussely**,

My lovely small family; **my gorgeous wife Dr. Hiba and my Sons Ahmed and Ameer**

My dear brothers Ahmed and Hassan and my lovely sister Muhaj

All **my family-in-law members Dr. Murtadha, Mrs. Ekhlas, Dr. Zainab, Dr. Mohammed, and Ali**

All **my relatives; uncles, aunties and all my friends**

All the people who were there for me

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November 2019

Chairman : Associate Professor Eris Elianddy bin Supeni, PhD
Faculty : Engineering

In this study, a rotational piezoelectric (PZT) energy harvester has been fabricated and tested. The prototype can enhance output power by frequency up-conversion and provide the desired output power range from a fixed input rotational speed by increasing the interchangeable planet cover numbers which is the novelty of this work. The prototype ability to harvest energy has been evaluated with four experiments, which determine the effect of rotational speed, interchangeable planet cover numbers, the distance between PZTs, and PZT number. Increasing rotational speed shows that it can increase output power. However, increasing planet cover numbers can increase the output power without the need to increase speed or any excitation element. With the usage of one, two, and four planet cover numbers, the prototype is able to harvest output power of 0.414 mW, 0.672 mW, and 1.566 mW, respectively, at 50 kΩ with 1500 rpm, and 6.25 Hz bending frequency of the PZT. Moreover, when three cantilevers are used with 35 kΩ loads, the output power is 6.007 mW, and the power density of piezoelectric material is 9.59 mW/cm3. It was concluded that the model could work for frequency up-conversion and provide the desired output power range from a fixed input rotational speed and may result in a longer lifetime of the PZT.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

MENUAI TENAGA DARI GEAR PLANET MENGGUNAKAN BAHAN PIEZOELEKTRIK

Oleh

CHILABI HAIDER JAAFAR HUSSEIN

November 2019

Pengerusi : Profesor Madya Eris Elianddy bin Supeni, PhD
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Dalam kajian ini, penuaian tenaga putaran piezoelektrik (PZT) telah direka dan diuji. Prototaip ini dapat meningkatkan daya output melalui kekerapan penukaran semula dan menyediakan julat kuasa output yang dikehendaki dari kelajuan putaran input tetap dengan meningkatkan nombor penutup planet yang dapat ditukar ganti yang merupakan suatu pembaharuan dalam kajian ini. Keupayaan prototaip untuk menghasilkan tenaga telah dinilai berdasarkan empat eksperimen, yang menentukan kesan kelajuan putaran, nombor penutup planet yang boleh ditukar ganti, jarak antara PZT dan nombor PZT. Peningkatan kelajuan putaran menunjukkan bahawa ia dapat meningkatkan kuasa output. Walau bagaimanapun, peningkatan jumlah penutup planet boleh meningkatkan kuasa output tanpa perlu meningkatkan kelajuan atau sebarang unsur pengujaan. Dengan menggunakan satu, dua dan empat bilangan nombor penutup bumi, prototaip mampu menghasilkan kuasa output 0.414 mW, masing-masing sebanyak 0.672 mW dan 1.566 mW, pada 50 kΩ dengan 1500 rpm, dan frekuensi lenturan 6.25 Hz PZT. Tambahan pula, apabila tiga julur digunakan dengan beban 35 kΩ, kuasa output adalah sebanyak 6.007 mW, dan ketumpatan kuasa bahan piezoelektrik ialah 9.59 mW / cm3. Dapat disimpulkan bahawa model ini dapat bekerja mengikut kekerapan penukaran tinggi dan menyediakan kadar tenaga output yang diperlukan daripada kelajuan putaran yang tetap seterusnya dapat menghasilkan PZT yang lebih lama jangka hayatnya.

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LIST OF ABBREVIATIONS

DADR	Dual Attraction in Dual Repulsion
DASR	Dual Attraction in Single Repulsion
MEMS	Micro Electro Mechanical Systems
PZT	Piezoelectric Cantilever
SASR	Single Attraction in Single Repulsion
TPMS	Tire Pressure Monitoring System
U-VPEH	U-Shaped Vibration-Based Piezoelectric Energy Harvester
VMPGS	Vibration Micro Power Generation System
WSN	Wireless Sensor Networks

LIST OF SYMBOLS

c	internal capacitance of the PZT prototype
c_1	sun and planet gear one central distance
c_2	sun and planet gear two central distance
D	electric displacement (density of charge)
d	the piezoelectric direct effect matrices
d_p	planet gear tip diameter
d_t	the piezoelectric reverse effect matrices, where the superscript t is the transposed matrix
E	electric field
f	bend per second (frequency)
F_r	Radial force of the gear that acts in the direction of the y-axis
F_t	Tangential force of the gear that acts in the direction of the x-axis
F_x	Axial force of the gear that acts in the direction of the z-axis
n	number of planets
Nc	carrier teeth Numbers
Np	Planet gear teeth Numbers
Nr	Ring gear teeth Numbers
Ns	Sun gear teeth Numbers
R_L	External Resistance from the resistance box
R_S	Internal Resistance of the Prototype
S	Mechanical Strain
T	Mechanical Stress
$T_{(planet)}$	Torque of planet gear

$T_{(sun)}$	Torque of Sun gear
V	voltage measured by the oscilloscope
ωc	angular velocities of the carrier gear
ωp	angular velocities of the planet gear
ωr	angular velocities of the ring gear
ωs	angular velocities of the sun gear,
Ω	The ohm is the SI derived unit of electrical resistance,
β	gear helix angle
s^E	compliance under an electric field of a zero or constant
α	gear pressure angle
ε^T	the permittivity of dielectric under a stress of zero or constant
η	stands for efficiency
θ	A plane angle in geometry
ω	Angular velocity
π	is a mathematical constant, approximately equal 3.142
c	internal capacitance of the PZT prototype
c_1	sun and planet gear one central distance
c_2	sun and planet gear two central distance
D	electric displacement (density of charge)

CHAPTER 1

INTRODUCTION

1.1 Research background

Converting mechanical energy such as kinetic energy, vibration or distortion energy into electrical energy is known as energy harvesting. The fast development of wireless sensor networks (WSNs) and the solution of storage power better efficacy will, ultimately, increase the devices that use self-power in an automotive application, monitoring of the environment, and health-care (Yang et al., 2018). However, the limitation of the power source of WSNs is one of the significant problems in this technology. Further, there are issues such as volume, weight, and short lifetime of batteries, which is much shorter than the WSN life, and batteries must be changed frequently. Consequently, researchers must find an alternative power source by focusing more attention on energy-harvesting technology (Kherbeet et al., 2015; Wu et al., 2014).

An energy harvester for powering WSNs and microdevices is a feasible approach in our environment, due to its low power consumption, small size, and special working environment. Piezoelectric energy harvesting is one of the novel approaches that has been developed to harvest power for these devices using different types of mechanical sources (Elahi et al., 2018). Depending on the application, different types of harvesting energies, as well as the handiness of the mechanical power sources, are available most of the time. Mechanical energies such as airflow, vibration, pressing, rotational machine, and human motion are variable frequencies and amplitude energies, which can be called random energies that are available everywhere (Kumar and Kim, 2012).

Rotational mechanical energy is one of the important power sources for piezoelectric energy harvesting. Different types of rotational power sources have been used in the past decades for piezoelectric energy harvestings, such as rotational machines (Dannier et al., 2019; Fu and Yeatman, 2019; Khameneifar et al., 2011; Wu et al., 2018; Zou et al., 2017), human motion (Fan et al., 2017; Li et al., 2018), vehicle tires (Fu and Yeatman, 2017; Wang et al., 2019; Xie et al., 2018; Yu-Jen et al., 2017; Zhang and Jin, 2019), and even air, wind and fluids (An et al., 2018; Gong et al., 2019; Kyoo and Rho, 2015; Nezami et al., 2019; Ramírez et al., 2019; Stamatellou and Kalfas, 2018; Yang et al., 2014). They have been applied in different applications such as WSNs in any rotary machine (Khameneifar et al., 2011; Li et al., 2011), tire pressure-monitoring systems (TPMSs) (Guan and Liao, 2016; 2016; Zhu et al., 2017), wearable devices, and medical implants (Choi et al., 2017; Kuang et al., 2016; Mohamad Hanif et al., 2018; Pillatsch et al., 2016).

The principle of rotational piezoelectric energy harvesting operation is based on the PZT plucking for excitation, which results in PZT bending, vibration, or pressing, and thus voltage is generated. Researchers have used different excitation elements in rotational piezoelectric energy harvestings, such as mass (Mohamad Hanif et al., 2018; Zhu et al., 2017), magnetic (Çelik et al., 2017; Karami et al., 2013; Pozzi, 2018) centrifugal force

(Gu and Livermore, 2010a, 2012), gravitational force (Febbo et al., 2017; Hsu et al., 2014; Farbod Khameneifar et al., 2013), and gear teeth force (Park et al., 2012; Wei and Duan, 2015) or a compilation of these elements (Yeo, et al., 2018; Yunshun Zhang et al., 2018, 2016). They have also applied these elements to widen the broadband range (Bai et al., 2015; Fu and Yeatman, 2017; Rezaei-Hosseinabadi et al., 2015) or for frequency up-conversion (Fu and Yeatman, 2019; Pillatsch et al., 2014; Yeo, et al., 2018) and rotational frequency, which is considered to be low in some cases compared to piezoelectric resonant frequency. While these different methods for rotational piezoelectric energy harvesting offer many advantages, they have numerous challenges. These include harvesting the desired output power ranges from a fixed input rotational speed, finding new methods in frequency up-conversion with better results, less force on PZT and hence a longer lifetime, and avoiding using slip ring or any other extra device for power transfer. Using a new source power type, design or method that can achieve these challenges is still desirable.

Most of the previously published papers on rotational piezoelectric energy harvesting area focused on frequency up conversion; however, frequency up conversion methods continues to be enhanced. Hence, rotational power sources, especially for wind, human motion, some rotary machines, and some vehicle tires, are generally considered as low frequencies, compared to PZT frequency. In some cases, the wiring for output power transfer is still an issue because the PZT is rotating with the system and thus a slip ring or any other wireless transfer is needed, which makes the device more complicated (Guan and Liao, 2016; Larkin and Tadesse, 2013; Li et al., 2011; Ramírez et al., 2017; Resali and Salleh, 2017b; Wu et al., 2014). Also, the heavy and rapid repetitive bending or striking on the PZT with the direct excitation contact can be considered an issue because it will reduce its lifetime; however, this can be avoided in different ways (Çelik et al., 2017).

Using a gear as a rotational mechanical input for piezoelectric energy harvesting excitation has been considered a good and new method. Only a few works have been accomplished using the gear as input in rotational piezoelectric energy harvesting. Juil Park et al. (Park et al., 2012) proposed a design where the cantilever free tip was excited by any rotary motion of mechanical devices. Using a mouse gear as the rotary mechanical device, the frequency can be changed from 0 to 800 Hz according to the changes in rotational speed and gear teeth numbers. Further, the output voltage and power generated from the gear model frequency up-converted kinetic energy harvesting device have reached a level of interest for practical applications and could be easily increased using multiple cantilevers within a single gear (Janphuang et al., 2015). Energy harvesting is produced from an impact by using a piezoelectric Micro-Electro-Mechanical Systems (MEMS) scavenger. Useful electrical power is generated by the impact of the rotating gear on the MEMS piezoelectric transducer (PJanphuang et al., 2011). Moreover, Janphuang et al. 2011 (Janphuang et al., 2013) conducted an experiment where the results revealed that free vibrations of the harvester after plucking contributed significantly to the power efficiency. The efficiency and output energy can be greatly improved by adding a proof mass to the harvester. Yang et al. (Yang et al., 2019) proposed a gullwing-structural piezoelectric energy harvester that consists of two typical non-linear buckled-bridges to scavenge low-frequency rotational energy based on a gear mechanism induced oscillation. This design is promising for self-powered sensors, especially at changeable and low frequency, such as tire pressure monitoring. However, as far as the authors are concerned, no research has been done using the planetary gear. Also, the PZT lifetime, wiring, and getting the desired output power from a fixed input rotational speed have not been clearly studied.

The novelty of this work is to design, fabricate, and test a compact frequency up-conversion energy harvester that can harvest sustainable energy in broad range frequencies. This work is inspired from previous studies (that use normal gear), but with an enhanced gear design (planetary gear), which has less effect on the PZT and its primary system. The planetary gear design can harvest energy using a piezoelectric cantilever. The advantage of this study design over the previous designs that use a standard gear (Janphuang et al., 2011; Pattanaphong Janphuang et al., 2015, 2014; Park et al., 2012) is that it uses interchangeable planet covers so that it will have the ability to provide the desired output power range from a fixed input rotational speed, thus, by increasing the planet cover numbers without the need to increase the input speed, use of multiple PZT cantilevers, or increase the PZT pressing force. Moreover, it could be applied in any rotational machine such as a steam turbine with a pump for powering WSNs. Also, the PZT will be gently bent by the pressing of planet teeth gear, due to the way the planet gear moves in the planetary gear system, and this may result in a longer life-time for PZT. The wiring will not be an issue; there is no need for a slip ring or any other wireless device to transfer output power because the PZT will be fixed and will not rotate with the system.

Many applications can be suggested to apply this piezoelectric energy harvester prototype due to its properties, such as when it is connected to any rotational source that runs with variable speeds such as steam turbine or wind rotational source; moreover, it could be used in human motion energy harvesting with a more compact design.

1.2 Problem statement

Energy harvesting is the most effective way to respond to the energy shortage and to produce sustainable power source from the surrounding environment. In particular, rotational piezoelectric energy harvesting, which uses a direct energy conversion from any rotational mechanical input energy to the electrical energy, has been considered as an important type of harvesting (Elahi et al., 2018).. However, it is a challenge to harvest the energy at the desired output power range from a fixed input rotational speed. Frequency up conversion is still an issue for rotational power source, a lot of research has been done on frequency up conversion (Fu and Yeatman, 2019; Williams, et al., 2018) . However, new method are still desirable especially, most of the rotational power sources and their applications are considered as low frequency compared to high resonant frequency of piezoelectric (Febbo et al., 2017).

Only few works have been done on piezoelectric energy harvesting using gear, and there are lot of rooms to be filled with these kinds of design and enhance it (Janphuang et al., 2011; Janphuang et al., 2014; Park et al., 2012) . further, it has been found that no research has been done on piezoelectric energy harvesting using planetary gear. One of the issues in using gear for piezoelectric energy harvesting is that the gear teeth may damage the piezoelectric, due to the hard bending of the teeth, so, finding new contactless method or using less friction will enhance the output power (Janphuang et al., 2015).

However, it is the usage of planetary gear may increase the lifetime of piezoelectric cantilever, as the way the planet gear moving in the planetary gear system and thus, it bend the piezoelectric cantilever smoothly without damaging it. In addition, the wiring to transfer output power in rotational energy harvesting has also been considered as an issue because most of the time, the source of power rotates within the system and thus an extra device such as slip ring or Bluetooth will be needed for output power transfer (Guan and Liao, 2016; Lallart, 2017; Ramírez et al., 2017; Resali and Salleh, 2017b).

1.3 Objective of Research

The primary objective of this study is to design a rotational energy harvester model by using an interchangeable planetary gear cover that can harvest different ranges of output power from piezoelectric without changing the excitation pressure or rotational speed, and this can be done with the following secondary objectives.

1. To fabricate and test compact energy harvester using planetary gear.

2. To evaluate the performance of the prototype for frequency up conversion and test it with four experiment which is; effect of rotational speed, effect of planet cover numbers, effect of distances between PZT, and effect of PZT number, and prove its ability to provide the desired output power range from a fixed input rotational speed by increasing the planet covers numbers.

1.4 Hypothesis

Using planetary gear as energy harvester; the output power can be increased by increasing; rotational speed, choose the best angular distance between PZTs, and increasing PZTs numbers. However, increasing planet cover numbers can increase the output power without need to increase rotational speed or any other elements.

1.5 Contributions

It is clearly noted that no research has been done using planetary gear for piezoelectric energy harvesting. The ability to give different ranges of output power without increasing the frequency (rotational speed) or pressing on piezoelectric by simply plugging in more planet covers is the significance of this work. Moreover, the device was worked as a frequency up conversion, when more planet covers are used and in addition to that, the bending of piezoelectric cantilever is done smoothly because of the way that the planets gear move in the planetary gear. Consequently, this may increase the lifetime of piezoelectric.

1.6 Research Scope

1. Rotational speed range 300 rpm (5 Hz) to 1500 rpm (25 Hz), has been chosen according to the suggested application which is human motion applications to

wind turbine generator sensor. The frequency of gait motion is normally about 0.5–3 Hz which corresponds to a walking speed of 1.3–7.8 km/h, however human motion maximum frequency such as for walking is less than 10 Hz (Choi et al., 2017). The digital sensors rotating part that use to measure the rotational speed is mounted on wind turbine generator shaft with a typical speed range from 750 to 1500 rpm (Van Engelen and Kanev, 2010).

2. The sufficient output power is 100 µW which is enough for powering sensors. However, the Optimum power output that supposed to reach by this prototype is more than 1 mW (Adu-Manu et al., 2018; Grady and Jeff, 2019; M′boungui et al., 2015)(Grady and Jeff, 2019).

3. The PZT cantilever is 5H material, d_{31} parallel connection and a sealed type named (S234-H5FR-1803XB) from Mide technology company with a dimension of 71×10.4×0.84 mm. These type as stated by the manufacturer is sealed by using reinforcement laminated between the two piezoelectric layers that make it a rugged PZT (Mide Technology, 2019a).

4. The planetary gear type is chosen with 100 mm diameter to cope with the selected PZT dimension. The planet gear maximum numbers that can be fit in this size is four planets (Kohara Gear Industry Co., 2015) .

5. 3-dimension finite element method simulation using COMSOL Multiphysics program has been done to predict the performance of the harvester. According to the target applications and the size of the planetary gear, the simulation has been done to test these range of frequencies and planet cover numbers and with the using of 50% of the maximum allowable displacement of the PZT. The FE check whether the harvester with these elements were able to harvest the sufficient output power.

1.7 Thesis outline

First chapter of this study gives a background on energy harvesting, its piezoelectric rotational movement, problem statement, objective of the study and its outline. The literature review in the second chapter contains factors that affect output power energy, review, comparison of previous studies from different aspects with mechanical input which has been divided it into four parts; rotational from wind, vehicle tires, human motion and any rotary machine that include gear. Chapter three describes the methodology which includes planetary gear system, planetary gear components, fabrication of the prototype, experimental setup and procedures for four experiments which are the effect of rotational speed, effect of planets cover number, effect of distances between PZT, and increasing PZT number, effect on primary system, and modelling and simulation. Chapter four provides the experimental results and the discussions. Finally, chapter five draws the conclusion with the recommendations of future work.

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BIODATA OF STUDENT

Haider Jaafar Chilabi was born in June 24th 1986 in Baghdad, IRAQ. He is married since 2015 and has two kids. He has received his bachelor degree in mechanical engineering (2008 – 2009) Iraq -Baghdad-from Baghdad University. He was ranked as a Practitioner Engineer in Iraqi Engineers Union since 2009. He started his master degree in mechanical engineering (Energy Harvesting) at Universiti Putra Malaysia in 2017.

Professional experience:

From 23/11/2009 to 10/12/2012:

Work in al-Dora Refinery in Maintenance department "pumps & compressors section" as a Maintenance Engineer & that job include:

- Supervising & making maintenance for Pumps & Compressors in its different types.
- Supervising & making spare parts manufacturing for pumps& compressors in the machine shop.

From 10/12/2012 to 20/11/2013:

- Shaft formal in al-Dora Refinery. This job sharing with working as:
- Sales representative "part-time" Authorized Agent for MICHELIN tires-CASTROL oils- &VARTA Batteries.

From 20/11/2013 to 20/9/2015:

- Shift former in al-Dora Refinery. This job sharing with working as:
- A Sales Responsible "part-time" in Authorized Agent for MICHELIN tires-CASTROL oils- &VARTA Batteries.

From 20/10/2015 to 15/6/2016:

- Shift former in Rapiscan X-Ray machine Eagle P45 for Oil vehicle checkup in al-Dora Refinery. This job sharing with working as:
- A Sales Supervisor "part-time" in Authorized Agent for LEGRAND & PHILIPS.

From 29/3/2017 to 1/5/2017:

- Shift former in Rapiscan X-Ray machine Eagle P45 for Oil vehicle checkup in al-Dora Refinery. This job sharing with working as:
- Sales Supervisor in Authorized Agent for Braun drugs company.

From 15/5/2017 to 1/9/2017:

- Sales Manager in Authorized Agent for Cosmetics & Home cleaning European Brands.
- On leave from Al-Dora Refinery since 8-5-2017

From 15/9/2017 to Present day:

- Studying Master by research in Energy Harvesting /Mechanical and Manufacturing Engineering /UPM/Malaysia.

LIST OF PUBLICATIONS

Publications in Scientific Journals

Haider Jaafar Chilabi, Hanim Salleh, E. E. Supeni,*, Azizan B. As'arry, Khairil Anas Md Rezali, and Ahmed B. Atrah. Harvesting Energy from Planetary Gear Using Piezoelectric Material. Energies. **(ISI Q3, Accpted for Publication)**

Haider Jaafar Chilabi, Hanim Salleh, E. E. Supeni,*, Azizan B. As'arry, and Khairil Anas Md Rezali. Rotational Piezoelectric Energy Harvesting; Comparison of Design and Performance. (Submit review)

Haider Jaafar Chilabi, Hanim Salleh, E. E. Supeni,*, Azizan B. As'arry, and Khairil Anas Md Rezali. Piezoelectric Energy Harvesting using Planetary Gear with Interchangeable Planet Cover. (Submit patent)

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