Micro Power Harvesting using Flexible Thermoelectric and Electromagnetic Vibration-based Power Generators

by

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ABSTRACT

Micro Power Harvesting using Flexible Thermoelectric and Electromagnetic Vibration-based Power Generators

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MASc, University of Guelph, 2016

Advisors:
Dr. Bill Van Heyst
Dr. Shohel Mahmud

The area of micro power generation has been developing significantly in the field of microelectromechanical systems and wireless sensor platforms over the last two decades. This thesis presents two different micro power harvesting techniques using flexible thermoelectric power generator (FTEG) and electromagnetic vibration-based power generator (EVMPG). The design, modeling, development, and analyses of a FTEG and a low-frequency vibration based T-shaped cantilever type EVMPGs are detailed in this thesis. A manual dispenser printing-based fabrication technique was developed and applied to manufacture and characterize two flexible FTEG prototypes, having open circuit voltages and power outputs of 22.1 mV and 2.21 nW and 23.9 mV and 3.107 nW, respectively, at $\Delta T=22.5 \, ^\circ\text{C}$. In addition, four different configurations of EVMPGs were designed and manufactured and subsequently characterized using detailed experimental and analytical techniques. A small portable EVMPG prototype was developed based on the maximum voltage output of the optimal EVMPG configuration. The developed EVMPG prototype was capable of harvesting power of 0.22 nW at a voltage of 35.2 mV using a frequency of 7 Hz with 5.6 $\Omega$ resistance for a base acceleration of 0.8 ms$^{-2}$. 
Dedication

At first I would like to give my sincerest and humble thank to the Almighty, the most gracious and the most merciful

To my beloved parent, sisters and brother
To all my teachers
Acknowledgement

I would like to express my humble and sincere thanks to the advisor Dr. Bill Van Heyst and Dr. Shohel Mahmud for their endless effort, guidance and support to successfully complete my thesis. Their kind concern and encouragement of thinking new ideas and to implement it practically helped me to finish my graduate studies and research work. Their motivation and recommendation helped me to go one step ahead towards PhD program.

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I would like to also thank the Dr. Yu-Chih Tseng (CanMET materials lab, Natural Resources Canada) for his help and support to find out the thermoelectric material properties for my experimental work. I also thank the Department of Food Science for their support in order to perform the Scanning Electron Microscopy (SEM) test.

Finally, I am extremely thankful my family members for their unconditional love, support and blessings throughout my life.
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<th>Description</th>
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<td>ACT</td>
<td>Active Carbon Textile</td>
</tr>
<tr>
<td>ALN</td>
<td>Aluminum Nitride</td>
</tr>
<tr>
<td>BW</td>
<td>Band Width</td>
</tr>
<tr>
<td>CDS</td>
<td>Cadmium Sulfide</td>
</tr>
<tr>
<td>CIP</td>
<td>Cold Isostatic Pressing</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon Nano-Tube</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DRIE</td>
<td>Deep Reactive Ion Etching</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiography</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromotive Force</td>
</tr>
<tr>
<td>EVMPG</td>
<td>Electromagnetic Vibration-based Micro Power Generator</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FR-4</td>
<td>Flame Resistant</td>
</tr>
<tr>
<td>FTEG</td>
<td>Flexible Thermoelectric Generator</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium Arsenide</td>
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<tr>
<td>IDE</td>
<td>Interdigital Electrode</td>
</tr>
<tr>
<td>IMD</td>
<td>Implantable Medical Device</td>
</tr>
<tr>
<td>MEMS</td>
<td>Microelectromechanical System</td>
</tr>
<tr>
<td>MLCC</td>
<td>Multilayer Ceramic Capacitor</td>
</tr>
<tr>
<td>MPG</td>
<td>Micro Power Generator</td>
</tr>
<tr>
<td>NI DAQ</td>
<td>National Instrument Data Acquisition</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PDMS</td>
<td>Polydimethylsiloxane</td>
</tr>
<tr>
<td>PEN</td>
<td>Polyethylene Naphthalate</td>
</tr>
<tr>
<td>PFIG</td>
<td>Parametric Frequency-Increased Generator</td>
</tr>
<tr>
<td>PLD</td>
<td>Pulsed Laser Deposition</td>
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<tr>
<td>PVDF</td>
<td>Polyvinylidinefluoride</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>PZT</td>
<td>Lead Zirconate Titanate</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>SEM</td>
<td>Scanning Electronic Microscopy</td>
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<tr>
<td>TE</td>
<td>Thermoelectric</td>
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<td>TEG</td>
<td>Thermoelectric Generator</td>
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<tr>
<td>TG</td>
<td>Triboelectric Generator</td>
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<tr>
<td>VMPG</td>
<td>Vibration Based Micro Power Generator</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
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<tr>
<td>WTEG</td>
<td>Wearable Thermoelectric Generator</td>
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</table>
Co-Authorship Statement

The research described within this thesis was developed collaboratively by Abu Raihan Mohammad Siddique, Dr. Shohel Mahmud, and Dr. Bill Van Heyst. The research contained within the six chapters was developed to address two different micro power harvesting technologies i.e., thermoelectric and electromagnetic vibration based power generator. All the data gathered throughout this study was analyzed by Siddique with assistance from Mahmud and Van Heyst. All initial drafts of the manuscripts prepared for this thesis were prepared by Siddique and were later reviewed by Mahmud and Van Heyst.
Chapter 1

Introduction

1.1 Background

Over the last two decades, developments in miniaturization of electronic devices have made the power demands in the range of mili (mW) to micro (µW) watts level for wireless sensor networks (WSN) [1, 2]. In the field of mobile electronics and handheld devices, batteries are one of the most common power supply sources. These chemical-batteries, however, will typically fail and need replacement after a finite time thus requiring new batteries and extra labor for replacement [3, 4]. Researchers have been working on alternative power sources using renewable energy such as generating electrical energy from kinetic energy and thermal energy.

Power generators that generate power in the mili to microscale range are referred to as micro power generators or MPGs. MPGs, which use structural vibration (a common form of kinetic energy) as an input to generate electricity, are known as vibration based MPG or VMPG. Electromagnetic VMPGs (or EVMPG) use Faraday’s law of electromagnetic induction to convert vibration energy into electricity. According to Faraday’s law, an electromagnetic force (emf) is induced when a coil moves between magnets or vice versa and this emf causes a current flow in the load circuit. On the other hand, a thermoelectric generator or TEG is a solid-state heat engine which consists of a number of p-type and n-type thermoelectric (TE) legs. TE legs are interconnected with electrically conductive wires and covered with thermally conductive but electrically insulated rigid substrate (i.e. rigid heat absorber and rigid heat sink plate) at the top and bottom surfaces. A TEG is referred to as a flexible thermoelectric generator (FTEG) when the rigid substrate is replaced by a flexible substrate (e.g. thin films or fabrics).
The energy harvested by EVMPG and FTEG varies from mili to micro watt range [5]. This amount of energy is suitable for the low-powered autonomous operation of the portable electronic devices as shown in Table 1.1.

<table>
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<th>Electronic devices</th>
<th>Power consumption</th>
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<tr>
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<td>100 µW</td>
</tr>
<tr>
<td>Hand watch (Quartz)</td>
<td>5 µW</td>
</tr>
<tr>
<td>Hearing machine</td>
<td>1 mW</td>
</tr>
<tr>
<td>Digital smart watches</td>
<td>&lt; 1.5 mW</td>
</tr>
<tr>
<td>Radio-frequency identification (RFID) locator</td>
<td>&lt; 1.5 mW</td>
</tr>
<tr>
<td>FM radio</td>
<td>30 mW</td>
</tr>
<tr>
<td>GPS tracking system</td>
<td>1.5 mW – 10 mW</td>
</tr>
<tr>
<td>Smart Cell phones (stand by)</td>
<td>35 mW</td>
</tr>
<tr>
<td>MP3 music player</td>
<td>50 mW</td>
</tr>
</tbody>
</table>

This thesis presents two different micro power harvesting technologies: harvesting power from low potential thermal energy (i.e. body heat) and from kinetic energy (i.e. structural vibration). In order for the energy to be harvested or usable, it is then converted into electrical energy using FTEGs and EVMPGs, respectively. A state of the art literature survey on both TEG and VMPG is presented prior to detailing the design, modeling, fabrication process, and characterization of an FTEG prototype and a T-shaped cantilever-based EVMPG prototype.

1.2 Motivation and Objectives

The motivation of this thesis was to design and develop micro power harvesting systems using electromagnetic VMPG and flexible TEG which can potentially replace the traditional small scale power supply system (e.g., battery, capacitor) from the wearable, portable, and handheld low-powered electronic devices (i.e., human and livestock health monitoring and tracking system). The overall objectives behind this research work include:
i) Conducting a comprehensive literature review on TEG and electromagnetic and piezoelectric VMPG system.

ii) Developing a flexible thermoelectric generator using a simple, less expensive, and manual dispenser printing technology. Sub-objectives include:
   a. Characterizing the fabricated FTEG prototype by theoretical investigations and experimental tests.
   b. Studying the properties of the fabricated TE legs (n-type and p-type) (i.e. Seebeck coefficient, electrical resistivity, and thermal conductivity.
   c. Visualizing the microstructure of the freshly fractured surface of TE legs.
   d. Conducting experimental tests to check the compatibility of the developed FTEG prototype.

iii) Modeling, developing, and investigating of a T-shaped cantilever type electromagnetic vibration-based micro power generator for low frequency vibration sources. Sub-objectives include:
   a. Characterizing the developed EVMPG configurations by experimental and theoretical analyses.

iv) Testing the designed EVMPG prototype using different human movement conditions (i.e. normal walking, quick walking and running).

1.3 Scope of this Research

The research work is divided into four chapters based on the overall objectives. An overview of each of the chapter follows.

Chapter 2: A review of the state of the science on wearable thermoelectric power generators (TEGs) and their existing challenges.

Thermoelectric generators are solid state energy harvesters which can convert thermal energy into electrical energy in a reliable and renewable manner. Over the last decade, the human body has been considered as a good source of heat to harvest electrical energy through wearable thermoelectric generators and may eventually become an alternative power generation technique. Wearable thermoelectric generators have the potential to generate sufficient energy for any
wireless sensor node (typical power requirements < mW). In this chapter, a survey of thermoelectric generators has been comprehensively presented with a specific focus given to the rigid and flexible types of thermoelectric generators. The basic principal of thermoelectric power generator, applications, and some existing challenges have also been discussed.

Chapter 3: Thermal energy harvesting from the human body using flexible thermoelectric generator fabricated by a dispenser printing technique.

In this paper, a manual dispenser printing-based fabrication technique has been developed to synthesize a flexible thermoelectric generator (FTEG). Fabricated FTEGs, printed on polyester fiber clothe, convert the thermal energy from the human body into electrical energy using the Seebeck effect. Two flexible prototypes (prototype A and prototype B) were fabricated using a manual dispenser printing technique with \( n \)-type \((0.98\text{Bi},0.02\text{Sb})_2(0.9\text{Te},0.1\text{Se})_3\) and \( p \)-type \((0.25\text{Bi},0.75\text{Sb})_2(0.95\text{Te},0.05\text{Se})_3\) thermoelectric (TE) materials. The fabricated prototypes consisted of 12 pairs of \( n \)-type and \( p \)-type legs connected by silver conductive threads. The experimental investigations were conducted to determine the characteristics and the electrical outputs of the fabricated prototypes. The open circuit voltage and power output of prototype A and prototype B were 22.1 mV and 2.21 nW, and 23.9 mV and 3.107 nW, respectively, at 22.5 °C temperature difference. The fabricated prototypes were also tested on the human body at different body conditions and were found to be very flexible, twistable, and durable with the substrate as well as conforming well to the human body.

Chapter 4: A comprehensive review on vibration based micro power generators using electromagnetic and piezoelectric transducer mechanisms.

The area of micro power generation has developed significantly over the last two decades in the field of microelectromechanical systems, self-powered wireless sensor nodes, and mobile platforms. Batteries are the main power source of such systems but have some limitations which include a finite life time, periodic replacement, and environmental pollution. Therefore, electrochemical battery systems are not a suitable fit for all wireless self-powered electronic devices. Energy harvesting through renewable energy such as mechanical vibration can be an attractive alternative solution to replace or widen the lifespan of the traditional battery system. A good number of investigations have been conducted on vibration based micro power generation
to support the microelectromechanical systems. Electromagnetic, piezoelectric, and electrostatic transducers have all been used to convert kinetic energy (i.e. mechanical vibration) into electrical energy. A comprehensive literature review has been presented on vibration based micro power generation using two most common transducer mechanisms: electromagnetic and piezoelectric transduction systems.

Chapter 5: Energy harvesting by ‘T-shaped’ cantilever type electromagnetic vibration based micro power generator from low frequency vibration sources.

The design, development, and analyses of low-frequency vibration based T-shaped cantilever type electromagnetic micro power generators (EVMPGs) are presented in this chapter. Four different configurations (Configurations A to D) of EVMPGs were designed and manufactured and subsequently characterized using detailed experimental and limited analytical techniques. Configuration A and B consisted of a single and a double cylindrical moving magnets (NdFeB), respectively, while Configuration C consisted of four rectangular moving magnets with respect to a fixed copper coil. In contrast, Configuration D used a moving coil between four rectangular magnets with a back-iron bar. The open circuit RMS voltage output was observed to be a maximum for Configuration D (98.2 mV at 6.29 Hz) with a base vibration acceleration of 0.8 ms$^{-2}$. Therefore, Configuration D was selected for further experimental investigations, which included changing the back-iron bar thickness, changing the base acceleration level, and changing the air gap separation between the magnets in order to optimize this configuration. The maximum load RMS voltage and power outputs of Configuration D were 105.4 mV and 1.35 mW at 6.29 Hz for load resistance 8.2 Ω and a base acceleration of 0.8 ms$^{-2}$ with a 4.2 mm back-iron bar when the air gap between the magnets was 20 mm. Finally, a small portable EVMPG prototype was developed based on the Configuration D and was tested at different human movement conditions (i.e., walking, quick walking, and running). The developed EVMPG prototype was capable of harvesting 35.2 mV and 0.22 mW at 7 Hz with load resistance 5.6 Ω for a base acceleration of 0.8 ms$^{-2}$. 
1.4 Publication from Present Research Work

The work presented in this thesis is based on submitted or published papers submitted to the respective field of peer-reviewed international journals. Chapter 4 has been published and Chapters 2 and 3 are under review, and Chapter 5 is under preparation.

i) Abu Raihan Mohammad Siddique, Bill Van Heyst, Shohel Mahmud, “A review of the state of the science on wearable thermoelectric power generators (TEGs) and their existing challenges,” Renewable & Sustainable Energy Reviews (Elsevier), 2015 (under review, Ms. Ref. No.: RSER-D-15-01995). (Chapter 2)

ii) Abu Raihan Mohammad Siddique, Ronil Rabari, Shohel Mahmud, Bill Van Heyst, “Thermal energy harvesting from the human body using flexible thermoelectric generator fabricated by a dispenser printing technique,” Energy (Elsevier), 2016 (under review, EGY-D-16-00911). (Chapter 3)


Chapter 2

A Review of the State of the Science on Wearable Thermoelectric Power Generators (TEGs) and Their Existing Challenges

“A version of this chapter has been submitted: Abu Raihan Mohammad Siddique, Bill Van Heyst, Shohel Mahmud, “A review of the state of the science on wearable thermoelectric power generators (TEGs) and their existing challenges,” Renewable & Sustainable Energy Reviews (Elsevier), 2015 (Ms. Ref. No.: RSER-D-15-01995).”

2.1 Introduction

Sources of renewable energy are a major global concern for researchers. The rising cost of fossil fuel and their associated global environmental impact has led researchers to develop methods of replacing the use of fossil fuels with alternative renewable and sustainable energy sources [11–14]. Increasing use of natural gas, coal, and chemical batteries, used to keep pace with the world’s population increases and technological advances, continues to release greenhouse gases and cause environmental degradation [15, 16]. Efficient sources of renewable energy (e.g., solar, wind, wave, tide, acoustic, geothermal, heat, and kinetic energy) are therefore being explored and being developed as alternative solutions to many current and future energy problems. In recent years, among the various renewable energy based technologies, thermoelectric power generation from waste heat has appeared as a green and clean energy competitor [17].

In the field of mobile electronics and handheld devices, batteries are one of the most common power supply sources. Over the last two decades, developments in microelectromechanical systems (MEMS) and miniaturization of electronic devices have made the power demands in the range of mili (mW) to micro (µW) watts level for wireless sensor networks (WSN) [18, 19]. These chemical batteries, however, will typically fail and need replacement after a finite time thus requiring new batteries and extra labour for replacement [20]. To overcome this limitation
of batteries, researchers are developing novel power supply methods adopting renewable energy sources. However, the traditional renewable energy sources are not always suitable for wireless and portable electronic equipment because of their operating mechanism, cost, and size. Therefore, thermoelectric power generation techniques are receiving considerable attention by researchers both in academia and industry.

Wearable renewable energy generators or harvesters are an attractive alternate to battery-based systems and can generate power up to a few watts [21] for portable electronic equipment. However, the power generation using wearable harvesters depends on the type of the source, size, and generator efficiency. The human body is a great source of thermal energy and it is responsible for continuously generating heat through metabolic functions [22]. Approximately 100 to 525 W of heat is released from the human body, which can be converted to electrical power [23] using proper energy conversion techniques. A wearable thermoelectric power generator is therefore a logical fit to harvest power from the thermal energy of the body and use the harvested power to operate portable electrical systems [24]. This field of wearable thermoelectric power generators is fast becoming a new platform for powering wireless and portable devices.

The main objective of this paper is to comprehensively review the research which has been conducted on wearable thermoelectric generators (WTEG) to assess the state of the science in this field. The review entails WTEGs that are both flexible and flat-rigid based on the substrate type which is used for fabricating the thermoelectric elements. Existing challenges and possible future trends of wearable TEGs are also discussed.

2.2 Thermoelectric Generator

Thermoelectric generators (TEGs) are solid state static devices that produce electrical energy from temperature differences applied across the TEG. This generation technology was first introduced by Thomas Johann Seebeck in 1821 [25]. Seebeck reported that a thermoelectric potential energy could be developed in the presence of a temperature difference across two different materials or vice versa. Consequently, this phenomenon was termed the “Seebeck
Various types of TEGs have been developed for different purposes, depending on the magnitude of the power needed to be generated [26], and are summarized in Table 2.1.

**Table 2.1:** Summary of the size ranges for thermoelectric generators (TEGs) [26].

<table>
<thead>
<tr>
<th>TEG Type</th>
<th>Order of Magnitude of Power Generated</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large TEGs</td>
<td>&gt; W</td>
<td>Bulk usages for industrial purposes [27]</td>
</tr>
<tr>
<td>Small TEGs</td>
<td>≈ mW</td>
<td>GPS, tracking devices, biosensors</td>
</tr>
<tr>
<td>Micro TEGs</td>
<td>&lt; mW to µW</td>
<td>Microelectromechanical (MEMS) devices</td>
</tr>
<tr>
<td>Thin Film TEGs</td>
<td>≈ µW</td>
<td>Combines flexible substrate with micro scale generation</td>
</tr>
</tbody>
</table>

Advantages of TEGs include [28-32]: longer life spans than other generation systems, no moving parts, no emissions of harmful pollutants during operation, no operating and maintenance costs, no chemical reactions with environment i.e., environment friendly, reliable operation, solid-state operation, use of low potential of thermal energy.

### 2.2.1 Basic Principal

The fundamental principle of TEGs is based on the concept of the Seebeck effect of thermoelectric materials [25] where the generated voltage \( V \) is directly proportional to the temperature gradient.

\[
V = \alpha \Delta T
\]  

where \( \alpha \) is the Seebeck coefficient \( (V \text{ K}^{-1}) \) of the thermoelectric (TE) materials and \( \Delta T \) is temperature difference between two surfaces of the generator in K.

TEG systems consist of \( p \) and \( n \) type semiconductors where the \( p \) type has surplus holes and the \( n \) type has surplus electrons to carry the electrical current (see Fig. 2.1). When heat flows from the hot surface to the cold surface through the thermoelectric material, free charges...
(electrons and holes) of the semiconductors are also in movement. This charge movement converts the thermal energy into DC electrical energy. A typical value of the Seebeck coefficient for commercially available $n$-type bismuth telluride (Bi$_2$Te$_3$) is $-150 \times 10^{-6}$ V K$^{-1}$ while for a $p$-type antimony telluride (Sb$_2$Te$_3$) is $101-161 \times 10^{-6}$ V K$^{-1}$ at room temperature [33, 34].

Typically, a large number of TE elements are connected electrically in series and thermally in parallel to increase output power of the TEG. The standard sizes of TEG modules varies from 4 mm $\times$ 4 mm $\times$ 3 mm to 50 mm $\times$ 50 mm $\times$ 50 mm [35]. For flexible TEGs, the thickness varies from 10-500 µm [36]. Standard TEG modules typically use titanium (Ti), bismuth (Bi), antimony (Sb) or selenium (Se) to form the basis of the TE system [37]. Bismuth telluride (Bi$_2$Te$_3$) and antimony telluride (Sb$_2$Te$_3$) alloys are the most commonly used TE materials because of their high efficiency at room temperature. Moreover, these materials are also easily deposited in thin films to make the module flexible [24].

**Figure 2.1:** Single thermoelectric pair comprising of $n$ type and $p$ type materials. Heat is flow from hot side to top side ($Q_H \rightarrow Q_C$) and electrical current ($I$) is flowing from $n$-type to $p$-type material due to temperature gradient ($\Delta T = T_{Hs} - T_{Cs}$).
2.2.2 Wearable Thermoelectric Generators

Wearable power generators are one of the more recent technological advances in the field of portable electronics. Wearable TEGs use the temperature difference between any living body and surrounding environment to harvest energy and convert it to useful electrical output [38]. The core temperature of a human body varies from 28 °C to 37 °C with a change in the room temperature from 0 °C to 35 °C [23]. Moreover, the heat flow varies from 50 to 150 Wm$^{-2}$ during regular activities of the body [10]. Wearable TEGs can theoretically generate a maximum of 180 µWcm$^{-2}$ power from skin (considered skin temperature and heat flow are 34 °C and 20 mWcm$^{-2}$, respectively) at 22 °C ambient temperature [39]. Table 2.2 presents the power generation capabilities of different parts of the human body.

Table 2.2: Possible capabilities of harvesting power from human body parts [10]

<table>
<thead>
<tr>
<th>Body part</th>
<th>Power generation (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forehead</td>
<td>2.3-27.6</td>
</tr>
<tr>
<td>Chest</td>
<td>3.1-36.6</td>
</tr>
<tr>
<td>Arm</td>
<td>1.7-20.2</td>
</tr>
<tr>
<td>Forearm</td>
<td>1.3-16.1</td>
</tr>
<tr>
<td>Abdomen</td>
<td>3.1-36.6</td>
</tr>
<tr>
<td>Thigh</td>
<td>2.4-28.8</td>
</tr>
<tr>
<td>Foot</td>
<td>2.1-25.2</td>
</tr>
</tbody>
</table>

2.2.3 Power Calculations

For a typical TEG configuration (see Fig. 2.1), the difference between the rate of heat energy entering the hot side ($\dot{Q}_h$, W) and that leaving the cold side of the thermoelectric pair ($\dot{Q}_c$, W) is equal to the amount of power generated ($P$, W) by the system as given by:

$$P = n(\dot{Q}_h - \dot{Q}_c)$$

(2.2)
In the above equation, \( n \) is the number of couples in one module, and \( \dot{Q}_H \) and \( \dot{Q}_C \) are given by:

\[
\dot{Q}_H = \alpha I T_{Hn} + K(T_{Hn} - T_{Cs}) - 0.5I^2 R \\
\dot{Q}_C = \alpha I T_{Cs} + K(T_{Hn} - T_{Cs}) + 0.5I^2 R
\]  

(2.3)  

(2.4)

In Equations (2.3) and (2.4), \( \alpha = (\alpha_n + \alpha_p) \) (V K\(^{-1}\)) where \( \alpha_n \) and \( \alpha_p \) are the Seebeck coefficients of the \( n \) and \( p \) type materials, respectively, \( I \) is the load current (A), \( K \) is the thermal conductance (W K\(^{-1}\)) of the materials, and \( R \) is the load resistance (\( \Omega \)). Thermal conductance can be expressed as:

\[
K = k_n\gamma_n + k_p\gamma_p = k_n\left(\frac{A}{l}\right)_n + k_p\left(\frac{A}{l}\right)_p \quad (2.5)
\]

\[
\gamma = \frac{A}{l} \quad (2.6)
\]

where, \( k_n \) and \( k_p \) are the thermal conductivity (Wm\(^{-1}\)K\(^{-1}\)) of the materials, \( A \) is the cross-sectional area (m\(^2\)), \( l \) is the length (m) of the leg, and \( \gamma \) is the effective length (m) of the leg.

### 2.2.4 Important Parameters of Power Generation

The thermal efficiency of any thermoelectric material depends on many parameters; however, the most important parameter is the dimensionless figure of merit \( (ZT) \) [40]. Typical values of \( ZT \) is \( \sim 1 \) for most materials [24], while for Bi\(_2\)Te\(_3\), it is 0.8 at room temperature [41]. This figure of merit can be expressed as:

\[
Z = \frac{\alpha^2}{\rho k} \quad (2.7)
\]

where \( \alpha \) is the Seebeck coefficient for both the \( n \) type and \( p \) type material, \( \rho \) is electrical resistivity (\( \Omega \)), and \( k \) is thermal conductivity of the thermoelectric materials. Power generation
from a thermoelectric module also depends on geometry of TEG including the cross-sectional area \( (A) \) and the length of the leg \( (l) \), as well as the hot \( (T_{hs}) \) and the cold \( (T_{cs}) \) surface temperature of TEG module, the internal electrical resistance of the materials \( (R_{in}) \), and the number of couples \( (n) \) in one module. The effect of changing area and length on power generation of thermoelectric materials is very sensitive. In order to show this effect, \( n \)-type \( \text{Bi}_2\text{Te}_3 \) and \( p \)-type \( \text{Sb}_2\text{Te}_3 \) have been chosen for a numerical analysis. Using the material properties, as given in Table 2.3, the effect of area and length on modeled power generation \( (P, \text{W}) \), surface power density (surface power density refers to power per unit cross-sectional area of the leg, \( \text{W cm}^{-2} \)), and current \( (I, \text{A}) \) are illustrated in Fig. 2.2. The calculation has been done by numerically using equations (2)-(7).

Table 2.3: Material properties used for numerical analysis [42]

<table>
<thead>
<tr>
<th></th>
<th>( n )-type: ( \text{Bi}_2\text{Te}_3 )</th>
<th>( p )-type: ( \text{Sb}_2\text{Te}_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_n )</td>
<td>(-195 \times 10^{-6} \text{ V K}^{-1} )</td>
<td>( 230 \times 10^{-6} \text{ V K}^{-1} )</td>
</tr>
<tr>
<td>( \rho_n )</td>
<td>( 1.35 \times 10^{-3} \text{ ohm cm} )</td>
<td>( 1.75 \times 10^{-3} \text{ ohm cm} )</td>
</tr>
<tr>
<td>( Z_n )</td>
<td>( 2.05 \times 10^{-3} \text{ K}^{-1} )</td>
<td>( 2.5 \times 10^{-3} \text{ K}^{-1} )</td>
</tr>
</tbody>
</table>
Figure 2.2: (a) Effect of area; (b) effect of length on generated power, surface power density, and current of a typical thermoelectric generator using the given parameters from Table 2.3.
These graphs illustrate that, if cross-sectional area increases, power generation and current also increases but surface power density becomes almost constant; whereas, if the length of the legs of the elements increase, the surface power density and current rapidly decreases but after a certain length of the legs, power generation becomes nearly constant. Similar results have been previously reported in the literature [43].

2.2.5 Applications of TEG

The applications and the demand of TEGs are expected to increase dramatically in the near future because of the increasing demand of miniaturized electronic devices. The power demand of small electronic devices is decreasing gradually as shown in Table 2.4. In order to operate these increasingly small devices, TEGs are becoming the preferred power source instead of batteries.

Table 2.4: Power consumed by different battery driven electronic devices [10, 44, 45]

<table>
<thead>
<tr>
<th>Electronic Devices</th>
<th>Average power demand (operating time)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Android Mobile Phone (Talking/standby mode)</td>
<td>1W (5h) / 35 mW</td>
</tr>
<tr>
<td>Remote controller (TV/music player/air condition)</td>
<td>100 mW</td>
</tr>
<tr>
<td>Music player (MP3)</td>
<td>50 mW (15h)</td>
</tr>
<tr>
<td>FM radio (portable)</td>
<td>30 mW</td>
</tr>
<tr>
<td>Hearing aid</td>
<td>1 mW (5days)</td>
</tr>
<tr>
<td>Wrist watch (Quartz/digital)</td>
<td>5 µW (5years)</td>
</tr>
<tr>
<td>Pacemaker (Heart)</td>
<td>50 µW (7years)</td>
</tr>
<tr>
<td>Neurological stimulator</td>
<td>Several mW - 30 µW</td>
</tr>
<tr>
<td>RFID tracker</td>
<td>&lt; 1.5 mW</td>
</tr>
<tr>
<td>Wrist GPS</td>
<td>1.5-10 mW</td>
</tr>
<tr>
<td>Wireless sensors nodes</td>
<td>100 µW</td>
</tr>
</tbody>
</table>

TEGs are currently being used in many fields to harvest electrical energy, such as: automobile engines [46-50], aircrafts, biosensors, industrial areas, hot pipelines, [51-53], furnaces [54], internal combustion engines [55, 56] as a heat recovery device, biomedical devices
(e.g., health monitoring and tracking systems) using human body heat [10, 44], solar heating system [57, 58], telemetry systems [59-61], power plant exhaust heat, waste heat from industrial processes, on chip power generation in computers [62-68], micro self-powered wireless platforms [69, 70], aerospace [71] and space exploration investigation of NASA (Multi-Mission Radioisotope TEG) [72].

More recently, high-tech electrical equipment like e-paper smart watches, smart collars, and fitness trackers (GPS with health monitoring system) [73], Google glasses [74], and Zigbee wireless networks [75] are the most promising application fields of TEGs due to their low power requirement. In the near future, applications for monitoring, surveillance, and tracking for health will expanded very quickly and will need TEGs to power multiple sensors and wireless networks.

2.3 Literature Review

A significant amount of research has been conducted on wearable TEGs since 2001. This research includes investigation of rigid TEGs as well as flexible TEGs, which are more suited to generate power from body heat as they can conform to the shape of the body.

2.3.1 TEGs with Rigid Substrate

Rigid substrate TEGs have been extensively researched by Leonov and co-researchers who developed different types of TEGs using body heat [21, 22, 76-80]. Leonov et al. [76] designed a thermoelectric generator having a size of 6.7 mm × 8.4 mm × 1.8 mm with 128 thermocouples. Material used for the surface plates of the prototype was aluminium type 6063-T4. Researchers mentioned that thermal resistance of the hand is increased if the outside temperature drops to 8°C. A power conditioning circuit was used to provide sufficient power to the wireless sensor node (see Fig. 2.3(a)). The average output power of their prototype was observed to produce 250µW at day time. Concurrent to Leonov, Wang et al. [77] also investigated a surface micromachining fabrication process to develop a TEG using polycrystalline silicon germanium
as thermocouples. Their generator had an output power of 1-2 µW and had a voltage output of 1V.

Furthermore, to increase the output power of TEG, Leonov and Vullers [22] developed a hybrid TEG based on body heat and PV cell (see Fig. 2.3(b)). Their energy conversion efficiency of heat energy converted into electrical energy varied between 0.4 to 0.2% for outside temperatures ranging from 20 °C to 32 °C. Their prototype generated 7-30 µWcm⁻² from skin contact. In a later study, Leonov et al. [21] proposed a similar hybrid model having a size of 4 mm × 4 mm and discussed existing challenges of the thermopiles (e.g., lower aspect ratio and lower thermal resistance of the elements) to harvest a maximum amount of energy.

Leonov et al. [78] discussed the use of mathematical equations for thermal optimization where both temperature difference and heat flow were not constant to optimize the output power. Their results indicated that a heat source and a heat sink were two important factors for optimization of the power generation of the TEG. The length of the legs and the contact resistance of thermoelectric elements also played a significant role in generating maximum power. Subsequent studies detailed the optimization of the size and efficiency of the TEG [79, 80]. The authors discussed the general concept of wearable thermoelectric generators and optimized the generator to a size of 3 cm × 4 cm × 0.65 cm. This watch sized TEG, attached to the wrist, could generate 100-200 µW using a temperature difference ranging from 3.5-5 °C [79] (see Fig. 2.3(c)). Leonov [80] also investigated the relationship between the thermal properties of human skin and the performance of a TEG. It was reported that the thermal properties of the TEG affect the skin temperature as well as the ensuing heat flow through the element.
Figure 2.3: (a) Watch sized (38 mm × 34 mm) TEG for indoor usage having a large radiator with 32 thermocouples [76], (b) power generation from three TEGs (1) and photovoltaic (PV) cells (2), incorporated onto a shirt to power an electrocardiography (ECG) system [22], and (c) small TEG developed using BiTe thermopiles supported by thermally isolate plates with encapsulation layer [79, 80].

One growing area of application for TEGs is for powering biomedical devices using body heat. Mitcheson et al. [81] reported that a TEG is more suitable than a motion energy harvester for bio-sensors since the power density of a TEG harvester is 20 µWcm$^{-3}$ whereas, for motion energy harvester for walking and running, it is 10 µWcm$^{-3}$. Yang et al. [44] investigated the use of TEGs to power implantable medical device (IMD). Different thermal conditions of a patient (e.g. environmental and physical) were investigated and the results indicated that close to the skin surface is the best part of the human body to harvest power. In another application study, Ekuakille et al. [52] concluded that a TEG could be used to provide sufficient energy for a hearing aid device (see Fig. 2.4(a)). An additional power management circuit and battery were used as a back-up power source.

In the interest of improving the efficiency of a TEG at lower body temperatures, Udalagama et al. [82] used resonance and voltage set up techniques to increase the power harvesting capability of the system. A DC-DC boost converter was used as a set up transformer in the power management circuit (also used by Lossec et al. [83] in their power management circuit). A new parameter $Z_E$, which depends on the physical properties of materials, was used to optimize the power output of the TEG during poor thermal coupling [83]. An additional heat sink was attached to the TEG to increase the productivity of the TEG as shown in Fig. 2.4(b).
Figure 2.4: A hearing aid powered by a TEG [52]. (b) Fin was attached to the cold surface of the module (two TEG modules were connected in series) to harvest energy from hand [83].

Different thermoelectric materials (e.g. bismuth telluride), have been investigated by Funahashi et al. [84] who used Ni$_{0.9}$Mo$_{0.1}$ for the $n$ type and La$_{0.035}$Sr$_{0.965}$TiO$_3$ for the $p$ type for fabricating their prototype generator. A Y$_{0.03}$Zr$_{0.97}$O$_2$ insulator was placed between the $n$ type and the $p$ type elements. Multilayer co-fired ceramic technology was used for fabricating the generator. At a 10 °C temperature difference, the prototype (see Fig. 2.5(a)) produced 100 µW which is sufficient for powering a radio transmitter.

In order to increase the voltage output from the TEG, Settaluri et al. [39] discussed some current limitations of TEGs, such as small temperature difference across two surfaces of TEG, poor natural air cooling by convection, and suitable substrate material. To overcome one of these limitations, a 1 mm thick copper heat spreader was used as a heat sink with the TEG. A DC-DC converter was used in the external circuit to boost up the surface power density from 8.6 µW cm$^{-2}$ to 28.5 µW cm$^{-2}$. The resulting TEG configuration could generate 4.18 V when the thickness of heat sink was less than 5 mm (see Fig. 2.5(b)).
Figure 2.5: (a) Fabricated monolithic TEG using multilayer ceramic capacitor (MLCC) technology by Funahashi et al. [84]. (b) DC-DC converted integrated with a TEG. A heat spreader was also embedded within the TEG for cooling purposes [39].

More recently, Wahbah et al. [85] used a commercial TEG on wrist and found that the TEG could generate 20 µW at 22 °C. Their designed prototype (see Fig. 2.6) could harvest an open circuit voltage of 12 mV using a 0.5 °C temperature difference. In a subsequent study, Mahalakshmi et al. [36] proposed a new transmitter circuit with a traditional TEG system. This circuit (i.e. radio frequency (RF) transmitter) transmits the generated power to the implantable devices in human body by using a wireless communication system. For this purpose, a commercial TEG (TEP1-1264-1.5) was used that transferred the harvested energy into a 12 V battery for storage.

Figure 2.6: Wearable TEG having a size of 3 cm × 3 cm mounted onto a wrist. A heat sink was attached to the TEG for better heat dissipation from the cold surface of the TEG to maintain a temperature difference between two surfaces [85].
2.3.2 Flexible TEGs

Since the human body is not a flat surface, typical rigid TEGs are not the most suitable for skin applications. Research has been conducted on the ways to make TEGs flexible since 2001 [86]. Different fabrication techniques have been explored to enhance the flexibility while increasing the energy conversion efficiency of the TEG. Flexible TEGs have many advantages over rigid type TEGs such as: light weight, very thin profile, portability, easily attached onto clothes and curved surfaces, and they can cover a large surface area.

As early as 2001, Qu et al. [86] used foil lithography, embedding, electroplating, and chemical etching mechanisms for fabricating flexible TEGs. Figure 2.7 shows a flexible TEG composed of a 100 pairs of Sb-Bi thermoelectric elements with an overall size of 16 mm × 20 mm × 0.05 mm. The prototype produced 0.25 V at 30 °C temperature difference. Subsequently, a compound material alloy, Bi₂Te₃, was used in thermoelectric element to make it more efficient.

![Image of Sb–Bi thermopiles](image)

**Figure 2.7:** Sb–Bi thermopiles were fabricated on 50 μm thin copper sheet. Materials were connected by overlaying their ends with each other [86].

2.3.2.1 Lift-off Process

Hasebe et al. [87] used Ni-Cu thermopiles for fabricating a flexible TEG based on a lift-off process. A polyimide sheet was used (see Fig. 2.8) was used as both a heat absorber as well as a
heat sink. The dimension of the generator was 60 mm × 45 mm × 3 mm which could generate a Seebeck voltage of 15.4 µV K\(^{-1}\) with 78 thermoelectric elements.

**Figure 2.8:** Schematic diagram of flexible generator fabricated using Ni-Cu thermocouples on polyimide based thermopile sheets. Top polyimide sheet acts as a heat sink whereas the bottom one absorbs the heat [87].

A similar fabrication process as well as the same Ni-Cu material was used by Itoigawa et al. [88] to develop their flexible TEG which consisted of 38 pairs of thermopiles. A wavy flexible thermopile sheet and slits were used to make their generator flexible giving a bending radius of their prototype up to 9 mm (see Fig. 2.9). The designed prototype had an output voltage and power of approximately 16 µV K\(^{-1}\) and 4.1 pWK\(^{-2}\) per thermocouple, respectively.

**Figure 2.9:** Flexible TEG proposed by Itoigawa et al. [88] with a wavy structure of Ni used with Cu on flexible substrate with heat sink and heat absorber.

### 2.3.2.2 Flash Evaporation Method

Takashiria et al. [89] developed a thin film thermoelectric generator based on a \(p\) type Bi\(_{0.4}\)Te\(_3\)Sb\(_{1.6}\) and a \(n\) type Bi\(_2\)Te\(_{2.7}\)Se\(_{0.3}\) material. A flash evaporation method and hydrogen
annealing process were used for their fabrication process. The fabricated TEG had a dimension of 15 mm $\times$ 1 mm $\times$ 0.001 mm (see Fig. 2.10). Output voltage and power from 7 pairs of thermoelectric element were 83.3 mV and 0.21$\mu$W at 30 °C temperature difference, respectively.

**Figure 2.10:** (a) Schematic presentation of thin film thermoelectric generator which was fabricated using BiTe thermoelectric materials. (b) Al electrode was used for connecting the thermocouples [89].

Moreover, researchers conducted many experiments to improve the efficiency of the flexible generator at low temperature. Therefore, thermally evaporated thin film fabrication process (see Fig. 2.11) was adopted by Yadav et al. [90] for their flexible generator. At first silica fiber was used as a substrate and then polyamide was used to increase the output power of the prototype. The generator consisted of seven pairs of Ni-Ag in thin film which is fiber shaped. The voltage and power output of the prototype were 19.6 $\mu$VK$^{-1}$ per thermocouple and 2nW, respectively, at 6.6 K temperature difference under open circuit condition.
2.3.2.3 Photolithography and Etching Technique

Schwyter et al. [91] designed a flexible TEG based on photolithography and etching technology (see Fig. 2.12(a)). Bi\textsubscript{2+x}Te\textsubscript{3-x} was used in SU-8 mold for their micro generator fabrication. An electrochemical deposition method was used for thermoelectric materials deposition in a mold. Electroplating helped to increase the leg lengths of the generator. The prototype could generate 278 $\mu$Wcm\(^{-2}\) at 40 K temperature difference. In a later research, to optimize the design of generator, Glatz et al. [92] used electroplating technique for fabrication. Ni-Cu and Bi\textsubscript{2}Te\textsubscript{3} were individually used and reported that $2.6 \times 10^{-3}$ $\mu$Wcm\(^{-2}\)K\(^{-2}\) could be generated from Ni-Cu and 0.29 $\mu$W cm\(^{-2}\)K\(^{-2}\) from Bi\textsubscript{2}Te\textsubscript{3}, respectively. The prototype could bend up to 7.5 mm. In order to optimize the generator size, different arrangements of the TEG as well as heat flow were considered as illustrated in Fig. 2.13.

More recently, similar kind of approach (e.g., photolithography and etching technique) of fabrication was reported by Khan et al. [93]. Si micro wires were used with polydimethylsiloxane (PDMS) substrate for their flexible module. The lengths of Si wires were 5
mm. An array of 34 Si wires were used which had an open circuit voltage of 9.3 mV at $\Delta T = 54^\circ C$ as shown in Fig. 2.12(b).

**Figure 2.12:** Electroplated $\text{Bi}_{2+x}\text{Te}_{3-x}$ based flexible thin film using gold connector fabricated by Schwyter et al. [91], (b) Silicon micro wires were used on SOI wafer and after etching it was deposited on PET substrate to fabricate thin film TEG [93].

**Figure 2.13:** Different setups to optimize the design of generator presented by Glatz et al. [92]. (a) Heat flows laterally through laterally fabricated thermocouples. (b) Heat flows vertically through laterally fabricated thermocouples. (c) Heat flows vertically through vertically fabricated thermocouples.
2.3.2.4 Screen Printing and Dispenser Printing Methods

Navone et al. [94] used a screen printing technique, using polyethylene naphthalate (PEN) substrate, for their generator. Thermoelectric materials $p$ type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ and $n$ type $\text{Bi}_2\text{Se}_{0.3}\text{Te}_{2.7}$ were used to construct the generator. Screen printing mechanism consists of the elaboration of material powder, paste preparation, and printing process. The dimension of their generator was 0.8 cm × 1.2 cm × 0.008 cm (see Fig. 2.14(a)). Suemori et al. [36] also used similar substrate for their flexible generator. A light weighted and thinner (0.15 mm) TEG was developed on PEN substrate. Carbon nanotubes and polystyrene were used for their generator. The prototype generated approximately 55 mWm$^{-2}$ at $\Delta T=70$ °C (see Fig. 2.14(b)).

![Figure 2.14:](image)

(a) Flexible thermoelectric power generator on polymer substrate developed by (a) Navone et al. [94] and (b) Photographic representation of flexible thin TEG consists of 1985 thermoelectric couples, fabricated by Suemori et al. [36].

Besides, using similar screen printing technology, Lee et al. [95] developed a flexible TEG with Zn-Sb materials on SiO$_2$/Si substrate as shown in Fig. 2.15. A high temperature (580 °C) was used for annealing the film. Their generator had a power density of 0.22 mWcm$^{-2}$ with a temperature difference of 70 K.
Cao et al. [96] used a printable thermoelectric material paste (with $n$ type $\text{Bi}_2\text{Te}_3$ and $p$ type $\text{Sb}_2\text{Te}_3$) for fabrication process. Screen printing technique increases the electrical resistivity of the thermoelectric materials. Their prototype had an output voltage and power of 6 mV and 48 nW at 20 °C temperature difference, respectively (see Fig 2.16(a)). In another study, Cao et al. [97] introduced cold isostatic pressing (CIP) for lowering the resistivity of the thermoelectric materials. The size of their prototype was $20 \text{ mm} \times 2 \text{ mm} \times 0.0784 \text{ mm}$ with 8 thermopiles as shown in Fig. 2.16(b). The designed prototype produced 36.4 mV and 40.3 nW at $\Delta T=20$ °C.

Another simple and easy dispenser printing technique for fabricating the TEG was described by Kim et al. [98]. $\text{Be}_2\text{Ti}_3$ powder with a ceramic binder was used to make a paste. This paste was used to fill up the substrate’s (e.g., polymer based fabric) hole. The fabric was then sintered at 100° C for 2 hours. Their prototype could generate 178 nW at $\Delta T=27$ K as shown in Fig.
2.17(a). In a later research, Kim et al. [99] modified their structure using $p$ type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ and $n$ type $\text{Bi}_2\text{Se}_{0.3}\text{Te}_{2.7}$ instead of $\text{Be}_2\text{Ti}_3$ to increase the output power. Their modified prototype consisted of 12 thermopiles and could generate 224 nW at 15 K temperature (see Fig. 2.17(b)). Furthermore, using the same $p$ type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ materials, Madan et al. [100] developed a fixable TEG having single leg on epoxy composite thin film based on dispenser printing technology. Their designed generator produced 20.5 µW with a temperature difference of 20 K (see Fig. 2.17(c)).

**Figure 2.17:** (a) Flexible TEG with 20 thermocouples was fabricated using dispenser printing technology. It was flexible as well as bendable [98]. (b) Modified TEG with 12 thermocouples having a size of 25 mm × 6 mm [99]. (c) Single leg thermoelectric generator was deposited on flexible printed circuit board substrate [100].

Jo et al. [101] also used $\text{Be}_2\text{Ti}_3$ powder with PDMS thick substrate and used flexible printed electrical circuit boards for connecting the legs (see Fig. 18). The dimension of their fabricated prototype was 50 mm × 50 mm and could generate 2.1 µW from the body at 19 K temperature difference.

**Figure 2.18:** Flexible TEG with printed circuit boards proposed by Jo et al. [101].
A detailed presentation of fabricating TEG having Bi$_2$Te$_3$ and Sb$_2$Te$_3$ on glass fabric was described by Kim et al. [102]. Using a screen printing technique, the thickness of their generator became 500 µm and it was very light in weight as well (see Fig. 2.19). COMSOL was used for numerical simulation to observe the temperature distributions. The output power density of the module was 3.8 mW cm$^{-2}$ at $\Delta T = 50$ K. A similar kind of fabrication process using the same materials was reported by We et al. [103]. Researchers used an organic polymer composite and inorganic thermoelectric thick film for flexibility of the TEG. Materials Bi$_2$Te$_3$ and Sb$_2$Te$_3$ were used to make the paste and deposit it on PI substrate. 450°C temperature was used for annealing the fabrication process. The fabricated TEG had an output voltage of 85.2 mV at $\Delta T$=50 K (see Fig. 2.20).

**Figure 2.19:** Different steps of fabrication of flexible thermoelectric generator done by Kim et al. [102].

**Figure 2.20:** Prototype of flexible TEG developed by We et al. [103].
2.3.2.5 Sputtering Technique

Radio frequency (RF) magnetron co-sputtering method was used by Francioso et al. [24] for fabricating Be₂T₃ and Sb₂Te₃ material on kapton film (see Fig. 2.21(a)). 100 thermopiles were used for their generator. It has an overall power output of 4.18 nW at 15 K temperature difference. Francioso et al. [104] also used kapton film as a flexible substrate for their developed TEG. Mill-machined polycarbonate master was chosen for molding PDMS. Researchers reported that their prototype could recover almost 5 K temperature from the hot and cold junctions of thermoelectric elements with a temperature difference of 17 K between skin and surrounding. Voltage management circuit was also used for their TEG to boost the power output up to 1.2 V.

Sevilla et al. [105] considered physical vapor deposition technique using ultra low power (52 W) sputtering method for fabricating their TEG. Such deposition technique helped to make the generator 18µm thick as shown in Fig. 2.21(b). Surface power density of their prototype was 0.139 mWcm⁻² at 20 K temperature difference. More recently, a new approach of supporting technique i.e., DC magnetic sputtering technique reported by Fan et al. [106] for their fabrication process on kapton substrate. 10 pairs of n type Al doped ZnO and p type Zn-Sb were used as thermoelectric materials (see Fig. 2.21(c)). The substrate was 0.15 mm thick. The generator could produce 246.3 µW at ΔT =180 K.

![Figure 2.21:](a) Photographic presentation of flexible TEGs using katon substrate [24]. (b) Flexible 18µm thin TEG having 63 thermocouples on SiO₂ wafer [105]. (c) Developed TEG by Fan et al. [106].
2.3.2.6 Thermal Evaporation

Hsiao et al. [107] used thermal evaporation technique to increase the efficiency of their fabricated TEG. Bismuth-telluride based alloy was used to make n type and p type materials by doping with antimony and selenium. The prototype looks like a fan shaped flexible generator using polyamide film (see Fig. 2.22).

![Figure 2.22: p-type and n-type materials are connected by Al connector on PI substrate. Flexible TEG proposed by Hsiao et al. [107].](image)

2.3.2.7 Using Nano-Materials

Delaizira et al. [108] prepared Bi$_2$(Te$_{0.9}$Se$_{0.1}$)$_3$ and (Bi$_{0.245}$Sb$_{0.755}$)$_2$Te$_3$ materials based TEG system from n type and p type Be$_2$Te$_3$ nano powder. Spark plasma sintering technique was used for fabricating the TEG on kapton flexible substrate. The fabricated TEG generated 51 mV at 14 K from 17 couples (see Fig. 2.23(a)). Besides, Yang et al. [109] used another nano materials i.e., Te-nanowire/poly (3-hexyl thiophene) (P3HT) polymer composite for their prototype. Their generator produced 38 mV at 55 K temperature difference. Fabricated TEG was also used as a temperature sensor having a good sensing capability as shown in Fig. 2.23(b).
Figure 2.23: (a) TEG was fabricated using nano-materials in polymer matrix presented by Delaizira et al. [108]. (b) Flexible TEG was developed using Te nanowire on kapton film by Yang et al. [109].

In a later study, nano materials (e.g., carbon nano tubes) were used for TEG fabrication industry. Such fabrication process of TEG was described by Im et al. [110]. Carbon nano-tubes (CNTs) coated with active carbon textile (ACT) electrode was used in their fabrication. These thermoelectric cells were used in the T-shirt to charge up a capacitor (see Fig. 2.24(a)). The structure of the capacitor was identical to the thermocell which was embedded in the T-shirt. The capacitor could store up to 1.2 mV. Their fabricated thermo cell has a thickness of 600 µm with a good flexibility. The maximum power density of their TEG was 0.46 mWm$^{-2}$. More recently, Suemori et al. [111] described direct dispersion of carbon nanotube (CNT) without degradation which was more useful for fabricating the TEG. Researchers presented planetary ball milling-based dispersion mechanism to fabricate their TEG. CNT with bundles were directly distributed in polystyrene composite. The power factor of their fabricated TEG was 413 µWK$^{-2}$m$^{-1}$ (see Fig. 2.24(b)).

Figure 2.24: Carbon nano-tube coated with ACT thermo cells developed by (a) Im et al. [110], (b) Suemori et al. [111].
Furthermore, Chen et al. [112] fabricated a flexible thermoelectric module where organic materials were used. Researchers reported that poly (3, 4-ethylenedioxythiophene) (PEDOT) has a high electrical conductivity as well as a low internal thermal conductivity. It was also reported that it is necessary to control the doping process to make PEDOT highly conductive.

Since 2012, researchers have been paying more attention to the flexible TEG as well as trying to develop new fabrication techniques with new materials to improve the TEG efficiency. A summary of literature review of flexible thermoelectric generator that is discussed in section 2.3.2 is given in Table 2.5.

<table>
<thead>
<tr>
<th>Reference, year</th>
<th>Materials</th>
<th>No. of pairs</th>
<th>Tem. (K)</th>
<th>Fabrication Technology</th>
<th>Voltage</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qu et al. [86], 2001</td>
<td>Sb-Bi</td>
<td>100</td>
<td>30</td>
<td>Foil lithography</td>
<td>0.25V</td>
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<td>Hasebe et al. [87], 2003</td>
<td>Ni-Cu</td>
<td>78</td>
<td></td>
<td>Lift-off process</td>
<td>15.4µVK⁻¹ per couple</td>
<td></td>
</tr>
<tr>
<td>Itoigawa et al. [88], 2005</td>
<td>Ni-Cu</td>
<td>38</td>
<td></td>
<td>Lift-off process</td>
<td>16µVK⁻¹ per couple</td>
<td>4.1pW K⁻² per couple</td>
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<tr>
<td>Takashiria et al. [89], 2007</td>
<td>Bi₀.₄Te₃₀Sb₁.₆ and Bi₂₀Te₂₇Se₀.₃</td>
<td>7</td>
<td>30</td>
<td>Flash evaporation</td>
<td>83.3 mV</td>
<td>0.21µW</td>
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<td>Yadav et al. [90], 2008</td>
<td>Ni-Ag</td>
<td>7</td>
<td>6.6</td>
<td>Evaporation thin film</td>
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<td>2nW</td>
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<td>photolithography and etching</td>
<td>278µWcm⁻²</td>
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<td>Glatz et al. [92], 2009</td>
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<td></td>
<td>2.6×10⁻³µWcm⁻²K⁻²</td>
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<tr>
<td></td>
<td>Be₂T₃</td>
<td></td>
<td></td>
<td></td>
<td>0.29µWcm⁻²K⁻²</td>
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<td>Composition</td>
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<td>Power</td>
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<tr>
<td>Navone et al. [94], 2010</td>
<td>Bi&lt;sub&gt;0.5&lt;/sub&gt;Sb&lt;sub&gt;1.5&lt;/sub&gt;Te&lt;sub&gt;3&lt;/sub&gt; and Bi&lt;sub&gt;2&lt;/sub&gt;Se&lt;sub&gt;0.3&lt;/sub&gt;Te&lt;sub&gt;2.7&lt;/sub&gt;</td>
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<td>0.06 μW cm&lt;sup&gt;-2&lt;/sup&gt;</td>
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<td>Lee et al. [95], 2011</td>
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<td>Screen-printing</td>
<td>70 mV</td>
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<td>Francioso et al. [24], 2011</td>
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<td>Sputtering</td>
<td>160 mV</td>
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<td>Dispenser printing</td>
<td>7 mV</td>
<td>2.1 μW</td>
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<td>55 mV</td>
<td>38 mV</td>
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<td>Delaizira et al. [108], 2012</td>
<td>Bi&lt;sub&gt;2&lt;/sub&gt;(Te&lt;sub&gt;0.9&lt;/sub&gt;Se&lt;sub&gt;0.1&lt;/sub&gt;)&lt;sub&gt;1.3&lt;/sub&gt; and (Bi&lt;sub&gt;0.245&lt;/sub&gt;Sb&lt;sub&gt;0.755&lt;/sub&gt;)&lt;sub&gt;2&lt;/sub&gt;T&lt;sub&gt;e&lt;/sub&gt;&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Spark plasma sintering technique</td>
<td>51 mV</td>
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<td>Madan et al. [100], 2013</td>
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<td>130 mV</td>
<td>20.5 μW</td>
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<td>Cao et al. [96], 2013</td>
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<td>Screen-printing</td>
<td>6 mV per couple</td>
<td>48 nW</td>
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<td>Kim et al. [98], 2013</td>
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<td>Dispenser printing</td>
<td>2.1 mV</td>
<td>15 nW</td>
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<td>Suemori et al. [111], 2013</td>
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<td>70</td>
<td>55 mW m&lt;sup&gt;-2&lt;/sup&gt;</td>
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<tr>
<td>Sevilla et al. [105], 2013</td>
<td>Bi&lt;sub&gt;2&lt;/sub&gt;Te&lt;sub&gt;3&lt;/sub&gt; and Sb&lt;sub&gt;2&lt;/sub&gt;Te&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Sputtering</td>
<td>0.139 mW cm&lt;sup&gt;-2&lt;/sup&gt;</td>
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<tr>
<td>Cao et al. [97], 2014</td>
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<td>40.3 nW</td>
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<td>Kim et al. [99], 2014</td>
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<td>Dispenser printing</td>
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<td>1.2 mW cm&lt;sup&gt;-2&lt;/sup&gt;</td>
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<td>Im et al. [110], 2014</td>
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<td>36</td>
<td>0.46 mW m&lt;sup&gt;-2&lt;/sup&gt;</td>
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2.4 Existing Challenges

Most of the wearable TEGs generate power in the micro watt range or less. It therefore becomes a challenge to generate sufficient amounts of energy from body heat to power more energy intensive devices. Some of the existing challenges of wearable TEGs are discussed in the following sections.

2.4.1 Figure of Merit of Thermoelectric Materials

The available TEGs that are used in industrial and commercial purposes can generate moderate power at high temperature difference because of the high figure of merit \( (Z) \) [113, 114]. For wearable TEGs, thermoelectric materials must have good material properties (i.e., Seebeck coefficient, electrical resistivity, thermal conductivity) as well as a good figure of merit to work at low temperature differences. Researchers have been making efforts to investigate alternative thermoelectric materials and to modify the material’s properties by mixing other semiconductor or nano materials to increase the value of \( Z \).

Recently researchers are using nano as well as organic materials to improve the efficiency of the TEGs. Researchers found that dimensionless figure of merit \( (ZT) \) of for nano materials is 3 at 300 °C whereas it varies from 0.4 to 1.1 at low temperature of 27 °C [115]. \( ZT \) is typically 0.8 at temperatures less than 150 °C for commercially available materials such as \( n \) type \( \text{Bi}_2\text{Te}_3 \) and \( p \) type \( \text{Sb}_2\text{Te}_3 \) [40]. For low temperature applications, it is still problematic to achieve higher figures of merit using thermoelectric materials.

<table>
<thead>
<tr>
<th></th>
<th>Material</th>
<th>Temperature</th>
<th>Methodology</th>
<th>Voltage</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kim et al. [102], 2014</td>
<td>( \text{Bi}_2\text{Te}_3 ) and ( \text{Sb}_2\text{Te}_3 )</td>
<td>50</td>
<td>Screen-printing</td>
<td>90mV</td>
<td>3.8mWcm(^2)</td>
</tr>
<tr>
<td>Fan et al. [106], 2015</td>
<td>Al-doped ZnO and Zn-Sb</td>
<td>10</td>
<td>180 Direct current (DC) magnetic sputtering</td>
<td>460mV</td>
<td>246.3(\mu)W</td>
</tr>
<tr>
<td>Suemori et al. [111], 2015</td>
<td>Carbon nanotube</td>
<td></td>
<td></td>
<td></td>
<td>413(\mu)Wk/(m^2)</td>
</tr>
</tbody>
</table>
2.4.2 Cost of Materials

The high cost of thermoelectric materials is one of the main limitations in developing thermoelectric technology. The cost of bismuth telluride is much higher than other available thermoelectric materials (e.g., the cost of Mg$_2$Si$_{0.6}$Sn$_{0.4}$ is $4.04$/kg whereas $125$/kg for Bi$_{0.52}$Sb$_{1.48}$Te$_3$) [115]. A report states that recent thermoelectric materials costing ($7$ to $42$ per Watt) with comparatively low efficiency (6-8%) [116].

2.4.3 Flexibility

Flexibility of TEG is an additional challenge that requires further investigation for wide scale adoption. Wearable TEGs are designed in such a way that they can be used with the human body as a heat source. As the human body is not a flat surface, most of the commercially available TEGs with rigid plates are not suitable. Much of the research on TEGs now focuses on their flexibility while maintaining good power generation. The current limitation in TEG thickness needed to balance good power performance as well as flexibility is at least 100 µm [36]. Several fabrication methods are reported in the literature to make TEG flexible, however, most of these techniques are complex to execute, require elevated operational temperatures, and are expensive [36].

2.4.4 Low Thermal Resistance

Low thermal resistance of the TEG is another major limitation to generate optimum power. The temperature difference between the two sides becomes almost the same after prolonged operation which, in turn, reduces the voltage generation. Wang et al. [77] conducted a study specifically about the thermal resistance of the TEG and its effect on power generation. The TEG was composed of a polycrystalline silicon germanium material fabricated using surface micro machining technology. Their aim was to increase the thermal resistance of the module, which is very low compared to the human body and natural air. Wang et al. [77] designed and modeled the thermoelectric module in such a way that, in a natural convection process, output voltage and power were 53 mV K$^{-1}$ cm$^2$ and 1-2 µW, respectively. Therefore, to increase the output voltage,
one possible solution was to increase the thermal resistance of the TEG using suitable fabrication techniques with high efficient materials (e.g. nano materials, organic composite materials, and materials that have a high $Z$). The schematic diagram of the thermal model is illustrated in Fig. 2.25 and the equivalent thermal circuit model is showed in Fig. 2.26.

![Schematic diagram of thermal model of wearable TEG.](image)

**Figure 2.25:** Schematic diagram of thermal model of wearable TEG.
Figure 2.26: Equivalent electrical circuit of thermal system.

In Fig. 28, $R_{in}$ (i.e., $R_{in} = R_{U\text{connector}} + \left( R_n || R_p \right) + R_{L\text{connector}}$) is very low compared to the body ($R_{body} = R_{bodycore} + R_{skin}$) and the ambient resistance. Therefore, the cold surface temperature quickly approaches the temperature of the hot surface.

2.4.5 Other Limitations

Other limitations that exist in the TEG research field include:

(a) Maximum efficiency of the TEG is currently around 5% -10% primarily due to the low figure of merit ($ZT$ less than 1) [117];

(b) The practical temperature differences between the human body and the atmosphere is very low ($\Delta T=5-15$ °C) [40];

(c) Small size and flexibility do not allow for the addition of practical heat sinks (fins) for cooling purposes; and

(d) Matching load (internal and external load of the TEG) is another problem to harvest the optimum power from the TEG. If the external load does not match with the TEG’s internal load then generated power output becomes low [52, 118].
2.5 Conclusion

Researchers have been conducting a state of the art research on WTEG since 2001. Therefore, the objective of this paper is to survey a comprehensive literature review on wearable thermoelectric generators (WTEGs). Since wearable thermoelectric generator converts body heat into electrical energy; therefore, researchers have given maximum priority on flexible thermoelectric generator over rigid ones because of human body structure. With regards to TEG, different fabrication techniques with deferent materials have been used in research which gives a general idea of the regular advancement in TEG industry. Moreover, most of the fabrication methods: sputtering, thermal evaporation, chemical deposition, photolithography and etching technique all use high temperature and the overall process is complex as well as costly. Therefore, flexible thermoelectric generator is not available in the market yet. Nevertheless, screen and dispenser printing fabrication techniques are now becoming popular in the TEG industry; it is easy to implement and the overall process is very simple compared to others.

2.6 Nomenclature

\( A \) \hspace{1cm} \text{Cross-sectional area (m}^2) \\
\( K \) \hspace{1cm} \text{Thermal conductance (W K}^{-1}) \\
\( I \) \hspace{1cm} \text{Load current (A)} \\
\( k_n \) \hspace{1cm} \text{Thermal conductivity the n-type materials (Wm}^{-1}\text{K}^{-1}) \\
\( k_p \) \hspace{1cm} \text{Thermal conductivity the p-type materials (Wm}^{-1}\text{K}^{-1}) \\
\( l \) \hspace{1cm} \text{Length (m) of the leg} \\
\( n \) \hspace{1cm} \text{Number of couples} \\
\( P \) \hspace{1cm} \text{Generated power (W)} \\
\( \dot{Q}_H \) \hspace{1cm} \text{Rate of heat energy entering the hot side (W)} \\
\( \dot{Q}_C \) \hspace{1cm} \text{Cold side of the thermoelectric pair (W)}
Load resistance ($\Omega$)

Internal electrical resistance of the materials

Temperature difference (k)

Hot surface temperature (k)

Cold surface temperature (k)

Generated voltage (Volt)

Figure of merit

dimensionless figure of merit

Greek Symbols

Seebeck coefficient (V K$^{-1}$)

Seebeck coefficients of the n-type materials (V K$^{-1}$)

Seebeck coefficients of the p-type materials (V K$^{-1}$)

Effective length of the leg (m)

Electrical resistivity of the TE materials ($\Omega$)
Chapter 3

Thermal Energy Harvesting From the Human Body Using Flexible Thermoelectric Generator Fabricated By a Dispenser Printing Technique

“A version of this chapter has been submitted: Abu Raihan Mohammad Siddique, Ronil Rabari, Shohel Mahmud, Bill Van Heyst, “Thermal energy harvesting from the human body using flexible thermoelectric generator fabricated by a dispenser printing technique,” Energy (Elsevier), 2016 (EGY-D-16-00911).”

3.1 Introduction

Microelectromechanical systems (MEMS) have made self-powered portable electronic devices (e.g., tracking devices [69], biosensors [52], smart wrist watches, hearing aids, and Google glasses [119]) more practical and convenient in terms of power consumption. Over the last two decades, developments in MEMS and the miniaturization of electronic devices have reduced the power demand in the range of mW to µW level for the wireless sensor networks (WSN) [120, 121]. This small amount of power requirement is usually fulfilled by traditional electrochemical batteries [3, 5]. However, the traditional batteries need to be changed on a regular basis and are toxic to the environment [4, 20]. Thermoelectric (TE) power harvesting using thermal energy from the human body, however, can be one of the attractive alternative solutions to conventional batteries. The environmentally friendly thermoelectric generator (TEG) is a solid state compact device that can convert thermal energy into electrical energy [122, 123]. TEGs are capable of harvesting energy from waste thermal energy sources; for example, solar heat, thermal energy from the human body, and any other kind of waste heat from machinery. TEGs have many advantages over many traditional small-scale power generation systems in that they are compact, easy to fabricate, easy to conform to the human body, less costly to implement, silent in operation, have longer operational time, and it has no moving parts [103, 124]. Therefore, such characteristics of TEG make them environmentally friendly. In order to have the best use of the TEG on the human body for energy harvesting, it should be wearable and flexible.
Recent advancement in the small scale thermoelectric system manufacturing techniques makes flexible TEG (FTEG) more advantageous for self-powered portable electronic devices.

Since 2001, FTEG has been a very active research area using different fabrication techniques [86]. These fabrication techniques include dispenser printing [101], evaporation [90], lift off process [87], lithography and etching [125], screen printing [95], and sputtering [70]. Yadav et al. [90] used a thin film evaporative technique to fabricate the FTEG with Ni-Ag materials of 7 pairs of $n$-type and $p$-type TE legs with a power output of the prototype of 2 nW at a temperature difference of 6.6 K. Hasebe et al. [87] designed a FTEG using lift-off process with Ni-Cu on polyimide sheet which had a voltage output of 15.4 $\mu$VK$^{-1}$ using 78 couples of $n$-type and $p$-type TE legs. Francioso et al. [70] used RF-magnetron co-sputtering method for integrating 100 TE couples for their FTEG prototype with a generated power output of 4 nW at 15 K. Navone et al. [95] and Suemori et al. [36] used screen printing technology for fabricating an FTEG with 5 and 108 pairs of $p$-type Bi$_{0.5}$Sb$_{1.5}$Te$_3$ and $n$-type Bi$_2$Se$_{0.3}$Te$_{2.7}$, carbon nanotubes and polystyrene material, respectively on the polyethylene naphthalate (PEN) substrate. The power density of the fabricated prototype was 55 mWm$^{-2}$ [36].

Most of the printing fabrication techniques (e.g., chemical vapor deposition, lithography and etching, screen printing, sputtering, etc.) are complex and expensive which require very high curing temperature (300-600 °C) and highly configured electronic equipment for fabrication (e.g., hot press machine, controlled dispenser, sputtering machine, printed circuit board, thin film etc.) [36, 70, 87, 90, 95, 101, 125]. In contrast, the dispenser printing technology is simple, less expensive, and it does not require any thin film mechanism. Moreover, it requires low curing temperatures in the range of 100-200 °C. Recently, the dispenser printing technique has been used for fabricating FTEGs for various applications [98-101]. Jo et al. [101] fabricated a FTEG with 8 TE couples of $n$-type and $p$-type Bi$_2$Te$_3$ on on polydimethylsiloxane (PDMS) thick substrate. The power output of their prototype was 2.1 $\mu$W at 19 K. Madan et al. [100], using similar technology, developed an FTEG with an epoxy composite thin film by integrating 60 thermoelectric (TE) elements which had a power output of 20.5 $\mu$W at 20 K. More recently, Kim et al. [99, 98] used 12 and 20 pairs of $n$-type and $p$-type Bi$_2$Te$_3$, respectively on polymer fabric as
a substrate to fabricate their TEG prototype. A maximum output power of 178 nW at $\Delta T=27$ K \[99\] and 224 nW at 15 K \[98\] was measured from their designed FTEG prototypes.

From the literature reviewed on the dispenser printing fabrication technique, it is apparent that the reported dispenser printing techniques are still a costly and complex process \[19, 25\] for widespread practical use due to the requirement of appropriate substrates (e.g., high heat resistive, thin, and flexible substrates), controlled dispensing equipment, and high curing temperature. In the current research, a simple and easy way to conduct the dispenser printing technique compared to other dispenser printing techniques has been demonstrated to fabricate FTEGs. The complete fabrication process, except the curing step, is performed manually (e.g., preparing substrate, sewing process to connect $n$-leg and $p$-leg, filling up the holes with TE paste). This fabrication technique provides wearability and flexibility to FTEG for thermal energy harvesting from the human body. The FTEG comprises of polyester fabric, silver thread, $n$-type and $p$-type bismuth telluride powder, liquid binder, and Kapton thin film for insulation between the TEG and the skin.

### 3.2 Flexible Thermoelectric Generator

Typically, a TEG is a solid-state heat engine which consists of a number of $n$-type and $p$-type TE legs. TE legs are interconnected with conductive wires and covered with thermally conductive but electrically insulated rigid substrates at the top and bottom surfaces. A TEG can be referred to as a FTEG when the rigid substrate is replaced by a flexible substrate (e.g., thin film, fabric clothes). FTEGs are compliant to curved surfaces such as human body. Figure 3.1 schematically represents the magnified version of a unit cell of a FTEG.
A typical FTEG is made up of multiple unit cells similar to Fig. 3.1. These cells are connected electrically in series and thermally in parallel. According to the Seebeck effect, an electric potential is established when two dissimilar TE materials are connected together with an applied temperature difference across the junctions [26]. The generated electric potential is directly proportional to the temperature gradient between the hot and cold surfaces of the FTEG which can be expressed as:

\[ V = n\alpha \Delta T_{TEG} \]  

(3.1)

where, \( V \) is the electric potential, \( n \) is the number of TE legs, \( \alpha \) is the Seebeck coefficient, and \( \Delta T_{TEG} \) is the temperature difference across the FTEG surfaces. The FTEG can harvest the maximum thermal energy from the human body when the total internal electrical resistance (\( R_{in} \)) is equal to the load resistance (\( R_L \)). The maximum power output (\( P_{max} \)) can be calculated as:
\[ P_{\text{max}} = VI_l = \frac{V^2}{(R_l + R_m)^2} \times R_l = \frac{V^2}{4R_m} = \frac{1}{4R_m} (n \alpha \Delta T_{\text{TEG}})^2 \]  

(3.2)

where, \( I_l \) is the electrical load current output. The voltage output of the FTEG depends on the temperature gradient, TE materials properties (i.e., Seebeck coefficient, thermal conductivity, and electrical conductivity), and the geometric design of the legs [27]-[29].

Flexibility is an important criterion of an FTEG to harvest thermal energy from the human body due to the curved surfaces encountered. In order to make an FTEG, it is very important to select a proper flexible substrate which can provide elasticity to the substrate. A schematic diagram of a FTEG is shown in Fig. 3.2.

![Diagram of a FTEG](image)

**Figure 3.2:** (a) Schematic presentation of the FTEG designed for the human body. (b) Characteristics of the FTEG module.

### 3.3 Materials Specifications and Fabrication Process

#### 3.3.1 Material Specifications

The prototype FTEG includes a substrate, \( p \)-type and \( n \)-type TE materials, an adhesive binder material, Kapton film, and silver thread to connect TE legs. The substrate of the prototype consists of polyester based fabric (supplier: A-B Thermal Technologies) which can withstand temperature up to 593 °C. \( p \)-type \((0.25\text{Bi},0.75\text{Sb})_2(0.95\text{Te},0.05\text{Se})_3\) powder and \( n \)-type \((0.98\text{Bi},0.02\text{Sb})_2(0.9\text{Te},0.1\text{Se})_3\) powder are used as TE materials (supplier: Hi-Z Technology
Inc.). TE powder materials are mixed with an adhesive binder (Durabond-950, supplier: iS-Connect) which is a combination of powder and the liquid thinner refractory ceramic colloid. Silver connective thread with an electrical resistance of 0.65 $\Omega \text{cm}^{-1}$ (supplier: Lame lifesaver) is used to connect $p$-type and $n$-type TE legs. Additionally, a polymer based Kapton (supplier: Cole-Parmer) film is used to create isolation between human skin and FTEG.

### 3.3.2 FTEG Fabrication Steps

Figure 3.3 illustrates a step-by-step procedure to fabricate the FTEG prototypes. A flexible substrate is prepared using the polyester fabric with holes in it. The polyester fabric substrate hole was created manually with a hole size of 5 mm (± 0.2 mm). The dimension of each hole is 5 mm × 5 mm, whereas the thickness is approximately 2.5 mm for Prototype A and 1.4 mm for Prototype B. A 5 mm gap is maintained between two consecutive holes as shown in Fig. 3.3(a). A hand sewing process is performed with a silver thread to connect holes which will be filled with $n$-type and $p$-type TE materials. Schematic diagrams of the top and the bottom views of connection between $n$-type and $p$-type legs are shown in Fig. 3.3(b). To make the printable paste initially, 80-82 wt% of $n$-type and 80-82 wt% of $p$-type TE materials powder are mixed manually with 18-20 wt% of Durabond-950 binder powder. Next, 18-20 wt% of Durabond-950 binder liquid is mixed with the composite mixer of TE materials and binder powder to make the printable paste (see Fig. 3.3(c)). The holes of the fabric substrate are then filled alternatively with prepared $n$-type and $p$-type paste (see Fig. 3.3(d)). The fabric substrate, filled with $n$-type and $p$-type paste, is kept at the room temperature for 24 hours for initial curing. Subsequent curing is performed in a furnace chamber at 100 °C for 2 hours (see Fig 3.3(e)). After curing at 100 °C, it is recommended to cure the FTEG further at a higher temperature of 200-250 °C for 2 hours to get good material bonding [128]. However, the developed FTEG system was cured further at 160 °C for 2 hours to avoid damaging the silver connective thread. Lastly, a Kapton film was attached to one side of the FTEG and this side will be attached to the skin for power generation (see Fig. 3.3(f)).
(a) Preparing the polyester fabric as a substrate for FTEG

(b) Connection between $n$-type and $p$-type legs using silver thread

(c) Preparation of TE materials pastes using binder powder and liquid

(d) Fill up the holes with liquid paste with dispenser (manually)
(e) Curing inside the furnace chamber

(f) Attached polyimide film at the bottom side of the fabricated FTEG

**Figure 3.3:** (a)-(f) Fabrication steps for current fabricated FTEG prototypes using dispenser printing method.

Figure 3.4 shows two images of the fabricated FTEG prototype. The prototype had excellent bonding between the $n$-type and the $p$-type TE materials, binder material and the fabric substrate. Moreover, the fabricated prototypes were very flexible, twistable, and bendable.

**Figure 3.4:** (a) Fabricated FTEG prototype. (b) Bending capability of the prototype.
3.4 Characteristics of The FTEG Prototypes

The characteristics of the fabricated FTEG prototypes includes: geometric and material characteristics of TE legs, theoretical analysis of temperature distribution profile, output voltage and power, and microscopic structure of TE legs. Table 3.1 lists the geometric characteristics of the two fabricated prototypes (average size was considered for all dimensions), with the main difference being the thickness of the prototypes. The dimensions were measured by electronic caliper (supplier: Mastercraft) which had an accuracy of ± 0.002 mm.

<table>
<thead>
<tr>
<th>Description</th>
<th>Prototype A</th>
<th>Prototype B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of single leg ((a \times b \times l))</td>
<td>5 mm \times 5 mm \times 2.5 mm</td>
<td>5 mm \times 5 mm \times 1.4 mm</td>
</tr>
<tr>
<td>Size of the fabricated module</td>
<td>95 mm \times 65 mm</td>
<td>65 mm \times 50 mm</td>
</tr>
<tr>
<td>Thickness or height of TE leg ((l))</td>
<td>2.5 mm</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>Gap between two legs</td>
<td>5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Number of thermoelectric pairs</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Initial measured resistance ((R_{in}))</td>
<td>272 k(\Omega)</td>
<td>135 k(\Omega)</td>
</tr>
</tbody>
</table>

Figure 3.5 shows the fabricated TE materials (\(n\)-type and \(p\)-type legs) properties (i.e., Seebeck coefficient, electrical resistivity, and thermal conductivity). These properties were measured at the CanmetMATERIALS Laboratory (Natural Resources, Hamilton, Canada). ZEM-3 equipment (supplier: Ulvac, Inc.) was used to measure the Seebeck coefficient and electrical resistivity while LF457 equipment (supplier: Netzsch, Inc.) was used to measure the thermal diffusivity of fabricated TE legs. The specific heat capacity of prepared TE legs was measured based on the hot disk method using TPS 500 (supplier: Thermttest, Inc.). Additionally, the density of the sample was measured based on the Archimedes’ principle by MDS-300. (supplier: Alfa Mirage). The Seebeck coefficient and thermal conductivity of both \(n\)-type and \(p\)-type materials, and electrical resistivity of \(n\)-type material increase whereas electrical resistivity of \(p\)-type material decreases with increasing temperature. The properties of the fabricated \(n\)-type and \(p\)-type TE legs are extrapolated from the Fig. 5 for subsequent theoretical analysis of designed FTEGs.
**Figure 3.5:** Seebeck coefficient, electrical resistivity and thermal conductivity of the fabricated TE legs.

Figure 3.6 shows numerical thermal fields and heat flow lines inside the TE legs of the FTEG prototype generated using the FlexPDE software. The constant temperature ($T_{Hs}$ and $T_{Cs}$) at the hot and cold surface of the TE legs and adiabatic process were considered for this numerical simulation of the temperature distribution profile. The hot surface temperature of the TE element was set relatively close to the human skin temperature assuming the very good contact between the skin and the FTEG. The simulated result shows that the temperature difference between two surfaces ($\Delta T_{TEG}$) of the TE leg is around 0.3 °C ($T_{Hs} = 31.9$ °C and $T_{Cs} = 31.6$ °C) at $\Delta T = 10$ °C between hot side ($T_H = 32$ °C, skin temperature varies from 32-35 °C [129]) and surrounding temperature (assuming $T_C = 22$ °C). Due to this low-temperature difference, the power output becomes lower than expected.
Figure 3.6: Temperature profile of one pair of TE legs in the FTEG. The arrows represent the heat flow profile from hot side to cold side.

Applying the method proposed in reference [130], voltage and power output of the fabricated FTEG prototypes were calculated analytically using the fabricated TE materials properties. One dimensional heat transfer model (see Eqs. (3.3)-(3.5) below), applicable to the FTEG, was solved to calculate the voltage and power output with respect to temperature difference and load current [130-132]. Figure 3.7 shows the analytical results of the fabricated FTEG. In Fig. 3.7(a), the power output of both prototypes is plotted as a function of temperature difference. The plot shows that the power output increases non-linearly as temperature difference increases from 0 °C to 25 °C. Moreover, the plot also shows that power output of the prototype A remains lower than the prototype B because of higher internal resistance. Internal resistance is affected by the thickness of TE leg which is higher for the prototype A than the prototype B. Figure 3.7(b) shows the voltage and power output as a function of current when the temperature difference is 10 °C. Figure 3.7(b) also shows that voltage output of the prototypes decreases linearly with increasing current flow. The power output can be calculated from:
\[ P = n(\dot{Q}_H - \dot{Q}_C) \]  

(3.3)

where, \( P \), \( n \), \( \dot{Q}_H \), and \( \dot{Q}_C \) are the output power, number of TE pairs, the rate of heat entering to the hot side of the TE system, and the rate of heat leaving from the cold side of the TE system, respectively. \( \dot{Q}_H \) and \( \dot{Q}_C \) can be expressed as [130-132]:

\[ \dot{Q}_H = \alpha I T_{Hs} + K(T_{Hs} - T_{Cs}) - 0.5I^2R \]  

(3.4)

and

\[ \dot{Q}_C = \alpha I T_{Cs} + K(T_{Hs} - T_{Cs}) + 0.5I^2R \]  

(3.5)

where, \( \alpha = \alpha_n + \alpha_p \) is the Seebeck coefficient of the TE legs, \( I_L \) is the electrical load current, \( T_{Hs} \) is the hot surface temperature, \( T_{Cs} \) is the cold surface temperature, \( K \) is the thermal conductance, and \( R_{in} \) is the internal resistance of the FTEG prototype [130-132].
Figure 3.7: Analytical results of fabricated FTEG (a) Output power against temperature difference. (b) Output voltage and power with respect to current at \( \Delta T = 10 \, ^{\circ}\text{C} \).
The power output curve shows the rise in output power with the rise in electric current. However, after a certain rise in electric current, power output decreases due to the dominance of the irreversible Joule effect. Equations (3.4) and (3.5) present the heat input to and heat output from the TE system. Each equation has three terms: (i) Peltier heat (first term), (ii) Fourier heat conduction (second term), and (iii) heat generation or Joule heat (third term). Substituting Eqs. (3.4) and (3.5) into Eq. (3.3), the power output \( P \) can be expressed as
\[
\frac{n\alpha L(T_{Hs} - T_{Cs}) - nI_C^2R_m}{L}\frac{\Delta T}{\Delta T}.
\]
For given number of modules \( n \), constant temperature difference \( T_{Hs} - T_{Cs} \), and known properties \( \alpha \) and \( R_m \) the magnitude of power output depends on the produced electric current. The Peltier power generation term is always positive and varies linearly with the current. However, the heat generation term (i.e., \( nI_C^2R_m \)), which varies quadratically with current, possess a negative effect on the net power generation and varies. Therefore, power generation is zero when current is zero and in case of \( n\alpha L(T_{Hs} - T_{Cs}) = nI_C^2R_m \) which can be observed from Fig. 3.7(b). However, between these two limiting cases of zero power generation there is an optimum value of electric current \( \left( \frac{\alpha \Delta T}{R_m} \right) \) which maximizes the net power output. This optimum value of current depends on \( \alpha \), \( R_m \), and \( \Delta T \). Any current larger than this optimum value causes the reduction of the net power output from its peak value. The peak values in Fig. 3.7(b) show that the power output is maximum at one specific electric current value for a given temperature difference condition provided that the geometric and thermophysical properties are constant.

The scanning electronic microscopy (SEM) method was used to visualize the microstructure of the freshly fractured surface of TE legs as well as the connection between the silver thread and the substrate to the TE legs. The microstructure was obtained by using Hitachi S-570 Scanning Electron Microscope (supplier: Hitachi High-Technologies, Tokyo, Japan). Figure 3.8 illustrates different SEM images of the fabricated FTEG legs. Figure 3.8 (a) and 3.8 (c) provide SEM surface images of \( p \)-type and \( n \)-type legs, respectively which indicate that the surface is not very smooth at a magnification of 15 \( \mu m \). In some space bonding of TE materials with the binder is quite good whereas some portion is not bonded well with each other. Figures 3.8 (b) and 3.8 (d) provide a cross-sectional view of freshly fractured \( p \)-type and \( n \)-type legs, respectively, at a
magnification of 30 μm. These cross-sectional SEM images show that the grains are randomly oriented and there are some void spaces between the solid structures. A possible reason for this may be the lack of additional pressure applied to the substrate during the fabrication process. Figures 3.8 (e) and 3.8 (f) show the bonding condition between TE materials and the substrate, and connection of silver thread (circled area) to the TE legs, respectively. From Fig. 3.8, it can be said that the electrical resistivity is very high due to some void spaces. Therefore, the overall current output decreases and subsequently power output decreases.

Figure 3.8: (a) and (c) provide SEM surface images of p-type and n-type legs, respectively. (b) and (d) provide a cross-sectional view of freshly fractured p-type and n-type legs, respectively, (e) and (f) show the bonding condition between TE materials and the substrate.
3.5 Experimental Tests and Results

Experimental tests were performed on the two fabricated FTEG prototypes to measure output voltage and power in a controlled lab environment. Additionally, the performance of the FTEGs was tested by attaching them to the arm of the human body while under different body conditions (e.g., standing, sitting, walking, and running).

3.5.1 Lab Test

Figure 3.9 illustrates the schematic diagram of the experimental setup developed to measure the voltage and current output of the fabricated FTEG prototypes. The experimental setup includes two thermo-regulators to create a controlled temperature environment, two heat exchangers, thermometer with a k-type thermocouple, and multimeter. Cold temperature was maintained by one thermo-regulator (supplier: Cole-Parmer; model number: polystat CR250WU re-circulator) with a temperature range from 0 °C to 80 °C and temperature stability of ± 0.1 °C (Thermo-regulator 1 in Fig. 3.9). The high temperature was maintained by a second thermo-regulator (supplier: Omega; model number: HCTB 3020) with a working temperature range of ambient to 120 °C and temperature stability of ± 0.1 °C (Thermo-regulator 2 in Fig. 3.9). Thermo-regulator 1 was used to supply water at low temperatures to a plate and tube heat exchanger while thermo-regulator 2 supplied hot water to a second plate and tube heat exchanger (supplier: Lytron Inc.). The hot-side heat exchanger was used to mimic the human body with a temperature of 32 °C while the cold-side heat exchanger was used to mimic the ambient temperature condition ranging from 9.5 °C to 31 °C. Temperatures at the hot and cold surfaces of the FTEG were monitored using the Omega-HH374 thermometer. A digital multi-meter (supplier: Amprobe; model: 37XR-A) was used to measure the electric voltage and the current generated by the prototypes.
Figure 3.10 illustrates the variation in the open circuit output voltages generated by the FTEG prototypes with respect to time. Study of such transient behavior is significant to identify the performance characteristics of FTEG prototypes over the duration of use. This test was carried out multiple times inside the lab environment by applying a constant temperature difference (i.e., $\Delta T_{\text{TEG}} = 10 ^\circ \text{C}$) between the hot surface ($T_{\text{Hs}} = 32 ^\circ \text{C}$) and cold surface ($T_{\text{Cs}} = 22 ^\circ \text{C}$) of the FTEG systems. Figure 3.10 illustrates that the voltage output for both prototypes decreased with increasing time and reached a steady-state value after a certain time. The error bar represents the range of the open circuit output voltages generated during each tests by prototype A and prototype B. At the beginning, both prototypes generate their maximum voltage due to the largest temperature difference between the two surfaces. However, as time advances, the irreversible internal heat transfer mechanism raises the cold surface temperature and consequently reduces the temperature difference between two surfaces. Therefore, the output voltage reduces as time advances. The low thermal resistance and low heat dissipation rate from the cold surface can be the reasons for degrading the voltage over the course of time.
Figure 3.10: Voltage output of FTEG prototypes with respect to time at a temperature difference of 10 °C.

Figures 3.11(a) and 3.11(b) show the open circuit voltage and power output of the FTEG as a function of temperature difference (i.e., cold surface temperature varies from 9.5 °C to 31 °C and the hot surface is fixed at 32 °C). The data were recorded when the output voltage became stable (approximately 10-15 minutes after of each temperature difference was applied). Results obtained from both prototypes are presented in Fig. 3.11 for a comparison purpose and indicate that the trend in the voltage and power output remain similar for both prototypes. Prototype B, however, generated more voltage and more power than prototype A at a given temperature difference. This can be attributed to the lower thickness of prototype B compared to prototype A. The internal resistance ($R_{in} = \rho l/A$) of the TE legs decreases with decreasing thickness ($l$) and, according to Eq. (3.2), power output will be increased. Therefore, prototype B can generate more power than prototype A. Table 3.2 shows the maximum open circuit output voltage and power of the prototypes at open circuit condition at $\Delta T_{TEG} = 5$ °C and $\Delta T_{TEG} = 22.5$ °C.
Figure 3.11: (a) Open circuit voltage output and (b) power output with respect to the temperature difference between two surfaces for two fabricated FTEGs.
Table 3.2: Harvested energy from the experimental results of Prototype A and Prototype B

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Hot surface temperature (°C)</th>
<th>Cold surface temperature (°C)</th>
<th>Voltage (mV)</th>
<th>Power (nW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>32</td>
<td>27</td>
<td>2.1</td>
<td>0.105</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>9.5</td>
<td>22.1</td>
<td>2.21</td>
</tr>
<tr>
<td>B</td>
<td>32</td>
<td>27</td>
<td>4.2</td>
<td>0.294</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>9.5</td>
<td>23.9</td>
<td>3.107</td>
</tr>
</tbody>
</table>

The output voltage of the fabricated FTEG prototypes is suitable to power a range of portable electronic devices (e.g., active RFID locators, wireless heart rate monitors, wireless pedometers, wireless oximeter, digital watches, etc.) which require very small power (< mW) [10]. However, the lower current output of FTEG prototypes results in a lower power output. Potential causes for lower power output are discussed:

(a) The $p$-type and $n$-type legs are surrounded by polyester fabric which is not a good thermal insulator. Therefore, heat loss occurs from the side wall surfaces of the FTEG system to the surrounding environment through the polyester fabric. Such heat loss lowers the direct energy conversion from body heat to electricity and consequently reduces the efficiency of the FTEG [131].

(b) The relatively higher thickness of the FTEG prototype compared to the prototypes reported in the literature results in a higher internal electrical resistance, which is responsible for lower power output as can be verified by Eq. (3.2).

3.5.2 Test on Human Body

The fabricated FTEG prototypes were attached to a human arm and tested for the power output capability (see Fig. 3.12). Table 3.3 presents the open circuit voltage and power output from the prototypes at different test conditions. The temperature difference across FTEG varies depending on the location of the FTEG on the human body. Both prototypes harvest maximum voltage and power at maximum temperature difference which is in the cold environment. Prototypes generate maximum power during running condition compared to walking condition due to the temperature drop at the outer surface of the FTEG because of increasing rate of
convection. Moreover, FTEGs generate minimum voltage and power at sitting and standing condition compared to other conditions.

![Fabricated TEG was attached to the human arm.](image)

**Figure 3.12:** Fabricated TEG was attached to the human arm.

**Table 3.3:** Voltage and power output at different test conditions

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Temperature difference between body and ambient (°C)</th>
<th>Temperature difference between the two surfaces of the FTEG (°C)</th>
<th>Prototype</th>
<th>Output Voltage (mV)</th>
<th>Power (nW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitting inside the lab, FTEG is horizontally placed with respect to ground</td>
<td>10.9</td>
<td>2.3</td>
<td>A</td>
<td>1.3</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>2.1</td>
<td>0.063</td>
</tr>
<tr>
<td>Standing inside the lab, FTEG is vertically placed with respect to ground</td>
<td>10.9</td>
<td>2.3</td>
<td>A</td>
<td>1.2</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>1.9</td>
<td>0.057</td>
</tr>
<tr>
<td>Walking</td>
<td>11.4</td>
<td>2.4</td>
<td>A</td>
<td>1.6</td>
<td>0.032</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>2.4</td>
<td>0.072</td>
</tr>
<tr>
<td>Running</td>
<td>11.9</td>
<td>2.9</td>
<td>A</td>
<td>1.7</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>2.6</td>
<td>0.078</td>
</tr>
<tr>
<td>Cold environment</td>
<td>32.9</td>
<td>11.9</td>
<td>A</td>
<td>9.1</td>
<td>0.182</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>B</td>
<td>11.3</td>
<td>0.339</td>
</tr>
</tbody>
</table>
3.5.3 Uncertainty Analysis of The Experimental Results

The experimental results have different uncertainties pertaining to the test equipment. It is clear from experimental results that the voltage and power output of the fabricated FTEGs are highly influenced by the temperature difference between the surfaces of the FTEG. Therefore, thermometer and multi-meter were considered in order to determine the uncertainty of the experimental results of FTEGs. The uncertainty analysis was accomplished using the root-sum-squared (RSS) method [133]. The uncertainty of the statistical data analysis is assumed 95% confidence interval for each calculated variable. Table 3.4 represents the uncertainty of the measured variables by thermometer and multi-meter that were used in the experiment. The analysis is completed for a specific temperature difference i.e., $\Delta T_{TEG} = 10^\circ$C for prototype A.

Table 3.4: Uncertainty analysis of the experimental results for $\Delta T_{TEG} = 10^\circ$C of Prototype A.

<table>
<thead>
<tr>
<th>Sensors and Equipment</th>
<th>Accuracy, $U_C$</th>
<th>Measured value $(x)$</th>
<th>Relative uncertainty $(U_C/x)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermometer</td>
<td>±0.1% [°C]</td>
<td>$T_H = 32$ °C</td>
<td>±0.0031%</td>
</tr>
<tr>
<td></td>
<td>$T_C = 22$ °C</td>
<td></td>
<td>±0.0045%</td>
</tr>
<tr>
<td>Multi-meter</td>
<td>±0.1% [mV]</td>
<td>$V = 7.8$ mV</td>
<td>±0.013%</td>
</tr>
<tr>
<td></td>
<td>±0.5% [$\mu$A]</td>
<td>$I = 0.06$ $\mu$A</td>
<td>±8.33%</td>
</tr>
<tr>
<td></td>
<td>±0.5% [kΩ]</td>
<td>$R = 272$ kΩ</td>
<td>±0.0018%</td>
</tr>
</tbody>
</table>

Using the value of $V$ and $I$ from Table 3.4, the relative uncertainty of the harvested power for the current fabricated FTEGs can be calculated by:

$$ U_p = \sqrt{\left(\frac{U_V}{x_V}\right)^2 + \left(\frac{U_I}{x_I}\right)^2} $$  (3.6)

where, $U_p$ is the relative uncertainty of output power, $U_V$ and $U_I$ are the accuracy of the measuring instrument for voltage and current, respectively, and $x_V$ and $x_I$ are the measured value of voltage and current, respectively of the system. According to Eq. (3.6), the relative uncertainty of the power output of the Prototype A is around ±8.33 % and for Prototype B, it is approximately ±6.25 % at $\Delta T_{TEG} = 10^\circ$C. Figure 3.13 presents the relative uncertainty of the
power generation by FTEG prototype A and prototype B at temperature difference ranging from 0 °C to 25 °C.

![Graph showing output power vs. temperature difference for prototypes A and B.](image)

**Figure 3.13:** Uncertainty analysis of power output for both prototype A and prototype B.

### 3.6 Conclusion

In this research work, a complete manual fabrication process for a FTEG is presented. The FTEG can be used as an alternative power source for self-powered portable electronic devices. The FTEG prototypes were fabricated with a simple dispenser printing method using a polyester based, high heat resistive fabric and using *n*-type \((0.98\text{Bi}, 0.02\text{Sb})_2(0.9\text{Te}, 0.1\text{Se})_3\) and *p*-type \((0.25\text{Bi}, 0.75\text{Sb})_2(0.95\text{Te}, 0.05\text{Se})_3\) TE materials. The prototypes had high flexibility and durability and were well suited for human body applications.

The fabricated prototypes were characterized in terms of material properties and structure, one-dimensional theoretical analysis, and experimental results. SEM images were obtained to determine the surface and cross-sectional structures of the fabricated *n*-type and *p*-type legs. A
maximum open circuit voltage and power output of Prototype A (5 mm × 5 mm × 2.5 mm) and Prototype B (5 mm × 5 mm × 1.4 mm), were 22.1 mV and 2.21 nW and 23.9 mV and 3.107 nW, respectively, at a 22.5 °C temperature difference. Moreover, the experimental results were fair with the theoretical analysis regarding maximum power and voltage output (according to Figs. 3.7(a) and 3.11(b)). Uncertainty analysis of fabricated prototypes was also performed. The fabricated prototypes were tested under different body conditions at different temperatures to assess the variation of the output voltage and power under real environment conditions.

### 3.7 Nomenclature

- \(a\) Length of the TE leg (mm)
- \(A\) Cross sectional area of TE leg (mm\(^2\))
- \(b\) Width of the TE leg (mm)
- \(I_L\) Electrical load current output (A)
- \(K\) Thermal conductance (W/°C)
- \(k\) Thermal conductivity (W/m°C)
- \(l\) Thickness or height of the TE leg (mm)
- \(n\) Number of TE legs
- \(P\) Instantaneous power output (W)
- \(P_{max}\) Maximum power output (W)
- \(\dot{Q}_H\) Rate of heat entering to the hot side of the TE system (W)
- \(\dot{Q}_C\) Rate of heat leaving from the cold side of the TE system (W)
- \(R_{in}\) Internal electrical resistance (Ω)
- \(R_L\) Load resistance (Ω)
- \(T_H\) Hot body temperature (°C)
- \(T_{Hs}\) Hot surface temperature of FTEG (°C)
- \(T_C\) Cold side temperature (°C)
- \(T_{Cs}\) Cold surface temperature of FTEG (°C)
- \(\Delta T\) Temperature difference between hot side and ambient (°C)
- \(\Delta T_{TEG}\) Temperature difference between FTEG surfaces (°C)
- \(U_p\) Relative uncertainty of output power
$U_V$ Accuracy of the measuring instrument for voltage
$U_I$ Accuracy of the measuring instrument for current
$V$ Electric potential (V)
$x_V$ Measured value of voltage by multimeter
$x_I$ Measured value of current by multimeter

**Greek letters**

$\alpha$ Seebeck coefficient ($\mu$VkJ$^{-1}$)
$\rho$ Electrical resistivity (Ωm)

**Subscripts**

TEG Thermoelectric generator
C Cold
Cs Cold surface of FTEG
H Hot body
Hs Hot surface of FTEG
I Current
in Internal
L Load
max Maximum
n $n$-type TE material/leg
P Power
p $p$-type TE material/leg
V Voltage
Chapter 4

A comprehensive review on vibration based micro power generators using electromagnetic and piezoelectric transducer mechanisms

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4.1 Introduction

Over the last two decades, miniaturizing the transducer systems is one of the technological advancements in the microelectromechanical systems (MEMS) [1]. Therefore, the power consumption has been made in the order of mW to µW scale for MEMS devices [2]. This effort has reviled a new and attractive research area which is one of the suitable alternatives to replace the traditional energy resources (e.g. fossil fuels) and store this energy in a convenient way rather than using battery system [134]. Conventional batteries have a limited life time [135], needs regular replacement, labor cost and also have hazardous environmental impact (e.g., it releases chemical substances to the environment) [136]. Recently, researchers are very much concerned about the increasing global warming [11] because of using conventional fossil fuels [12] and electrochemical batteries [13]. Researchers have been working on various alternative renewable energy resources like solar, ocean wave, rain, sound, wind, acoustics, thermal vibration etc. [137]. These sources are clean, renewable as well as have tentatively infinite lifetime compared to batteries [138]. Among these sources solar, ocean wave, sound, and wind energy have already been massively used in industrial, commercial as well as residential area as a power source which has a huge initial setup cost and requires arrangements [139]. Hence, researchers have been trying to propose some energy sources which are unexplored verily yet such as generating electrical energy from kinetic energy and thermal gradient for modern MEMS industry [140].
Providing green and efficient renewable energy is a challenge for microelectronic equipment that requires micro to macro level energy for operation [141]. Vibration based micro power generator (VMPG) is one of the leading research fields for engineers for developing an energy efficient micro generation system for MEMS devices [142]. With the omnipresent availability of mechanical vibration energy, VMPG can be a suitable alternative energy source for self-powered wireless sensor network (WSN) [143] and mobile electronic platforms [144]. A transducer is required in order to convert the mechanical vibration energy into electrical energy. Three common transduction mechanisms: electromagnetic, piezoelectric, and electrostatic, are considered to be the most promising for VMPGs.

The objective of this research article is to represent a comprehensive survey of the rapid development in the area of VMPGs using electromagnetic and piezoelectric transducer mechanisms. In this review paper, hybrid micro power generators (e.g., electromagnetic with piezoelectric or electromagnetic with thermoelectric or any combination of vibration based energy source with other energy source) have also been presented. A summary of the literature review has been illustrated in a tabular form in the review section starting from 1996 to date.

4.2 Micro Power Generators (MPGs)

Micro power generators (MPGs) refer to the generators that are small in size (mili (m) to micro (µ) range) and use available surrounding energy sources to convert into electrical energy. The surrounding environment is a bank of different types of energy sources which can be tapped for harvesting and converted into electrical energy. Table 4.1 shows some natural energy sources that can be used for harvesting energy by MPGs.
Table 4.1: Energy sources available in the surrounding for harvesting electricity [145]

<table>
<thead>
<tr>
<th>Main sources</th>
<th>Type of sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>Solar, wind, tide, temperature gradient, acoustic wave, sound, thundering, radioactive materials</td>
</tr>
<tr>
<td>Human body</td>
<td>Blood pressure, body temperature, walking, running arm, leg, finger motion and breathing</td>
</tr>
<tr>
<td>Vehicles</td>
<td>Automobiles, aircraft, trains, turbines, tires, ships</td>
</tr>
<tr>
<td>Structure</td>
<td>Building, bridges, roads, MEMS) control switch</td>
</tr>
<tr>
<td>Industrial</td>
<td>Motors, generators, compressors, fans, pumps, switch-gates</td>
</tr>
</tbody>
</table>

4.2.1 Vibration based MPG (VMPG)

Recently, vibration, which is one of the forms of kinetic energy, is widely used by MPGs to harvest electrical energy [146]. VMPG can be defined as harvesting the available mechanical vibration from the surroundings and converting it into electrical energy. Vibration based energy sources are available in our surroundings: different types of commercial and industrial machines, vehicles, buildings, various structures (bridges, railways), household appliances, and human body movements. Table 4.2 represents the magnitude of vibration sources measured with respect to frequency and acceleration of the fundamental vibration.

Table 4.2: Acceleration and average frequency of different sources [9]

<table>
<thead>
<tr>
<th>Vibration based energy sources</th>
<th>Acceleration (m/s²)</th>
<th>Peak frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Walking</td>
<td>0.4</td>
<td>2</td>
</tr>
<tr>
<td>Passenger automobile engine</td>
<td>12</td>
<td>200</td>
</tr>
<tr>
<td>Base of 3-axis machine tool</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>After closing the door</td>
<td>3</td>
<td>125</td>
</tr>
<tr>
<td>Blender machine</td>
<td>6.4</td>
<td>121</td>
</tr>
<tr>
<td>Vibration based energy sources</td>
<td>Acceleration (m/s²)</td>
<td>Peak frequency (Hz)</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>---------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Washing and drying machine</td>
<td>3.5</td>
<td>121</td>
</tr>
<tr>
<td>Instrumental panel of car</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>HVAC vents in commercial buildings</td>
<td>0.2-1.5</td>
<td>60</td>
</tr>
<tr>
<td>Microwave oven</td>
<td>2.5</td>
<td>121</td>
</tr>
<tr>
<td>Windows beside busy street</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>Footbridge</td>
<td>-</td>
<td>0.9-1</td>
</tr>
</tbody>
</table>

VMPG is usually designed in such a way so that the natural frequency matches with the excitation frequency. VMPGs consist of a mechanical oscillator system, energy conversion device i.e., a transducer, and power management circuit. The schematic diagram of vibration based micro power generation system is illustrated in Fig. 4.1. The electromechanical system consists of two main systems. One is mechanical (mass-spring-damper) system and the other one is electrical system (the load resistance and inductance and internal resistance of the coil) as shown in Fig. 4.2.

**Figure 4.1:** Schematic diagram of vibration-based energy harvesting system.
Figure 4.2: (a) Spring-mass system vibration based MPG model and (b) electromechanical representation of the system.

The system showed in Fig. 4.2(a) consists of a proof mass \((m, \text{Kg})\) which is attached to one end of the spring. This spring \((k\) is the spring constant\) is attached to the system which will vibrate due to the external vibration. The dashpot has a total damping of \(b_t\) which consists of electrical and mechanical damping represented by \(b_m\) and \(b_e\), respectively. When the system is subjected to a vibration the mass moves with the generating housing where \(y(t)\) and \(x(t)\) are the displacement of frame and relative displacement of mass and frame, respectively. The electromechanical system presented in Fig. 4.2(b) is used to get the transfer function. It includes electromagnetic transducer system to convert the vibrational energy into electrical energy. Here, \(L\) is coil inductance (H); \(R_c\) and \(R_L\) are the internal coil resistance (Ω) and the load resistance (Ω), respectively, and \(V\) is load voltage (V). The power \((P, \text{W})\) can be calculated from spring-mass system which is dissipated from electrical damping given by [139].

\[
P = \frac{Y_{\text{max}}^2 \zeta \omega_c^4 \left(\frac{\omega_c}{\omega_n}\right)^3}{1 - \left(\frac{\omega_c}{\omega_n}\right)^2 + \left(\frac{2 \zeta \omega_c}{\omega_n}\right)^2}
\]

\[\text{(4.1)}\]
4.2.2 Different Types of VMPGs

A transducer mechanism must be introduced to convert the vibration energy into electrical energy. There are different types of transduction mechanism such as electromagnetic, piezoelectric, electrostatic, and combination of any of two i.e. hybrid. But among these, electromagnetic and piezoelectric are mostly used in VMPGs systems.

4.2.2.1 Electromagnetic VMPGs

According to the Farady's law of electromagnetic induction, electromagnetic force arises for the relative movement of magnetic field and electric current carrying conductor. In electromagnetic VMPGs, this basic principle is followed to generate the electrical energy from mechanical energy. Vibration is used as a means of mechanical energy to vibrate the coil to the magnetic field or vice versa. Therefore, it generates electromotive force (EMF) which causes a current flow in the load circuit.

4.2.2.2 Piezoelectric VMPGs

Piezoelectric generators are used to produce voltage using piezoelectric materials which generate electrical charges when it experiences a mechanically stressed. In piezoelectric transducers, kinetic energy i.e., vibrations is used to produce potential difference between piezoelectric materials thereby generating voltage. In 1880, Curie and Curie were the first to introduce the piezoelectric effect and they observed that if certain piezoelectric material (e.g., crystal) was subjected to stress, they became electrically polarized. Various forms of piezoelectric materials are available including: aluminum nitride (AlN) [147], cadmium sulfide (CdS), gallium arsenide (GaAs), barium sodium niobate [148], lead zirconate titanate (PZT) [149], natural crystal (e.g. lead titanate- PbTiO₃, quartz-SiO₂), piezo ceramic materials and powders [150], synthetic ceramics (BaTiO₃, ZnO, ZnS) [151], sputtered zinc oxide, and polymeric materials (PVDF) [152].
4.2.2.3 Electrostatic VMPGs

Electrostatic transducer is another type of transformation process of translating mechanical energy into electrical energy. This conversion process is done by the electric forces and work is done using the relative movement of isolated capacitor plates which are already electrically charged. The work done against the force between two electrically charged plates delivers static electricity. According to the movements of the plate, battery-based electrostatic transducers are categorized as: plane overlap, in-plane closing gap, and out-of-plane closing gap [153]. Table 4.3 presents the advantages and disadvantages with average energy storage density of these three different transduction mechanisms.

<table>
<thead>
<tr>
<th>Type</th>
<th>Practical maximum Energy Storage density (mJ/cm³)</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelectric</td>
<td>35.4</td>
<td>Simple structure, easy to fabricate, high output voltage levels (&gt;5V), easy to voltage rectifying, large piezoelectric coefficient and dielectric constant.</td>
<td>Low output current (nA to µA), high output impedance (&gt;100k).</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>24.8</td>
<td>A number of positions or designs are available for device architecture, relatively low output impedance, high output current (µAmp to m Amp), tuning is possible to low,</td>
<td>Low output voltage (typically &lt;1V), difficult to rectify the voltage, too small vibration amplitudes, low electromechanical coupling coefficient.</td>
</tr>
</tbody>
</table>
medium, high g vibration levels.

| Electrostatic | 4 | Very high output voltage (>100V), easy to voltage rectifying and frequency tuning. | Switching circuit required for operation, requires voltage source for initial charge, high resonant frequency, high output impedance, low output current. |

Therefore, most of the researchers consider piezoelectric and electromagnetic transduction mechanisms to be the best ones suitable for vibration based micro power generation because of their advantages over electrostatic mechanism.

### 4.2.3 Applications of VMPGs

VMPG is a relatively new technology used in MEMS industries. The use of VMPG is growing faster for newer and newer applications. The main objective of the vibration based energy harvester is to provide small power to those devices which require mili to micro power. VMPGs have potential to replace small scale battery system or to increase the life time of the battery. Some applications include advanced wireless data transmission protocol Zigbee system [156] and picoradio system [157, 158], aerospace and deep sea applications [45], mining field [62], nuclear power station (e.g., sensors inside the reactor) [63], implantable bio-sensing application (i.e., pace makers and cochlear implants) [159], controlling industrial monitoring systems (e.g., different sensors which are located in dark and dirty remote environments) [160], controlling and monitoring the automobile sensors (e.g., vehicles speed sensor, air flow sensor, cruise control, engine heat sensor etc.) and recharge small batteries using potential energy of engine vibrations [161], wireless communication systems (e.g., IEEE 801.15.4 wireless sensor protocol) [162], sensors in institutional and commercial buildings [163], tracking the movement of the livestock as well as their health condition [164], sensors in active end of service life
indicator (AESLI) [165], low powered communication devices (e.g., pagers, two way communicators etc.) from human heel strike [166], wireless sensor networks (e.g., WiseNET introduced by Swiss Centre for Electronics and Micro technology) [167].

4.3 Literature Review

VMPGs are becoming attractive gradually because of their generating mechanism without any turbine or engine (prime mover). The research on vibration based energy harvesting has started since the 1980s. Possibly the first energy generating system was made by Hausler and Stein in 1984 [168]. As a consequence in the late 1990s, the first energy-harvesting devices were fabricated by the Media Lab at MIT (e.g. using three different vibration energy generators in shoes [169] and using piezoceramic converter in shoes [170]). After that Williams and Yates introduced the main concept of vibration based energy harvesting in 1996 [139]. A state of the art review on vibration based electromagnetic, piezoelectric, and hybrid power generators has been presented in this section.

4.3.1 Electromagnetic VMPGs

Electromagnetic is the widely used transducer technique in energy conversion process of VMPGs. A beam is used to vibrate along with coil or magnet and according to the Faraday’s law it generates electrical energy. Different shapes of cantilever beam (e.g., rectangular shape, cylindrical shape and other different shapes) and different magnets with different coil size are being used for conversion process.

4.3.1.1 Using Rectangular Shaped Cantilever

As early as 1996, William and Yates [139] analytically investigated an electromagnetic vibration based energy harvester having a size of 5×5×1mm³. Silicon diaphragm was used for analytical calculation. It was noted that power output is directly proportional to the cube of the vibration frequency. The power output of their generator is 1µW and 0.1mW at 70 Hz and at 330Hz, respectively, with vibrating amplitude of 50µm from their designed prototype.
A similar kind of approach of energy harvesting from mechanical vibration was described theoretically and experimentally by El-hami et al. [171]. Permanent magnet (e.g., samarium-cobalt, neodymium-iron-boron (NdFeB)) was used in C-shaped core. The size of their prototype is 240mm$^3$ with a power output of 0.53mW at 322Hz. The research of El-hami was further investigated by Glynne-J et al. [172] who designed two prototypes with NdFeB magnets. Prototype A consists of two magnets having a size of 0.84cm$^3$, whereas prototype B consists of four magnets having a size of 3.15cm$^3$ (see Fig. 4.3). The power output of prototype A and B are 37µW at 0.6Ω load and 157µW, respectively.

![Figure 4.3](image)

(a) (b)

**Figure 4.3:** Micro generator (a) prototype A, (b) prototype B developed by Glynne-J et al. [172]

Mizuno and Chetwynd [173] also used permanent magnet NdFeB with an array of cantilever beams to increase the efficiency of the generator. The size of the beam is 500×100×20µm$^3$. Researchers reported that their designed micro generator can generate 1.4mV and 6nW at 58 KHz with an amplitude of 100nm. Kulah and Najafi et al. [174] also conducted research on the array of cantilever beam for designing a micro scale generator. Frequency up-conversion technique was used to boost up the low frequency. Their prototype generates 2.5µW and 150mV at 100 KHz resonant frequency.

A detailed description of design, modeling, and fabrication process vibration based electromagnetic generator was explained by Beeby et al. [175]. The simulated results show that voltage output is 0.38V at 6.4 KHz with a maximum amplitude of 0.14mm. Research work of Beeby et al. [175] was further extended by Koukharenko et al. [176] and Kulkarni et al. [177, 178]. Using numerical and experimental techniques, Koukharenko et al. [177] presented a micro
energy harvester. Silicon micromachining technology was used to fabricate the prototype. ANSYS was used for optimizing the design of the prototype. The size of prototype is 100mm$^3$ (see Fig. 4.4(a)). Simulated results show that power and voltage output are 0.11mW and 0.7 V at 1.6 KHz, and 3.35mW and 4.15V at 9.5 KHz, respectively, with an amplitude of 240µm. Besides, Kulkarni et al. [177] designed a similar micro generator using the same technology, having a size of 30mm$^3$. The voltage and power output from the prototype are 55mV and 70µW at 7.4 KHz with an acceleration of 1.1ms$^{-2}$. In a later research, Kulkarni et al. [178] developed three different prototypes to improve the design of the previous study. Prototype A and prototype B (see Fig. 4.4(b)), and prototype C (see Fig. 3.4(c)) generate 148nW, 23nW, and 586nW at 8.08 KHz, 9.83 KHz, and 60 Hz, respectively. It is reported that the size of prototype B is 0.1cm$^3$, which was the smallest generator using silicon micromachining technology at that time.

![Figure 4.4: Silicon micromachining technology based generator developed by (a) Koukharenko et al. [176], (b) and (c) Kulkarni et al. [178].](image)

P´erez-Rodr´iguez et al. [179] also used ANSYS to design and optimize the generating power from electromagnetic VMPG based on Si technology. Fixed coil with moveable magnet was used on a vibrating membrane for their developed VMPG. The designed converter can generate up to 385µW at 120Hz with an amplitude of 2.5ms$^{-2}$. Besides, Spreemann et al. [180] described a new frequency conversion technique (non-resonant technique) with some advantages: it can convert low frequency; it has the ability to convert high and low frequency simultaneously; and it has a wide frequency range. The size of their prototype is 1cm$^3$ as shown in Fig. 4.5(a). Their proposed generator has a power output of 0.4-3mW at 30 to 80Hz.
Additionally, to improve the conversion efficiency (magnetic energy into electrical energy) of the generator, Torah et al. [181] developed a novel cantilever beam based electromagnetic energy harvester. The size of their designed generator is 150mm$^3$ using NdFeB magnet. The measured power output of the prototype is 17.8µW at 60 Hz having a load resistance of 150Ω. The research was continued by Beeby et al. [182] who optimized the coil properties as well as magnet size to improve the power generation of system. The dimension of the generator is 0.15cm$^3$ (see Fig. 4.5(b)). Maximum power output of their modified generator is 46µW at 52Hz having a load resistance of 4KΩ. It was measured that 30% of the converted power can be delivered to the load from their developed generator. In a similar research, Zhu et al. [143] continued the work of Beeby et al. [182] where Zhu et al. [143] presented a frequency tunable generator (see Fig. 4.5(c)). Axial tensile force was applied to the generator to tune the frequency. It was observed that their designed generator can be tuned in the frequency ranging from 67.6 to 98 Hz with power output between 61.6-156.6µW.

![Figure 4.5: (a) Non-resonant vibration based transducer developed by Spreemann et al. [180]. (b) Schematic diagram of micro generator designed by Beeby et al. [182] and (c) tunable micro generator developed by Zhu et al. [143].](image)

In a later study, Sari et al. [183] investigated to broaden the frequency range of the VMPG using different lengths of cantilevers array. Cantilevers are connected in series. NdFeB was used in their designed generator having a size of 14×12.5×8mm$^3$ (see Fig. 4.6). Both numerical simulation and experiments were conducted to validate their design. A detailed explanation of the fabrication process was presented using five masks with SiO$_2$ substrate. The voltage and power output of the prototype were 10mV and 0.4µW, respectively, over a frequency range from 3.5 to 4.5 KHz. In a subsequent study, Sari et al. [134] described similar fabrication process with
mathematical modeling. Optimization of the size of generator was also included in their new study with an array of 20 cantilevers. Their modified generator size is $9.5 \times 8 \times 6 \text{mm}^3$ having a power output of $56\text{pW}$ per cantilever at 3.4 KHz. In order to improve the efficiency, frequency up-conversion mechanism was used by Sari et al. [184] in their modified design. The size of the generator is $8.5 \times 7 \times 2.5 \text{mm}^3$ having a power output of $0.25\text{nW}$ per cantilever at 50-200Hz.

![Image](image.png)

**Figure 4.6:** An array of 40 cantilevers was used to develop a vibration based power generator by Sari et al. [183].

In order to improve the generated power, Soilman et al. [185] investigated two important parameters, i.e. the coil configuration and electrical damping coefficient, of their developed prototype. A maximum power of $190\mu\text{W}$ was obtained at $2\Omega$ load resistance. It is reported that the maximum electrical efficiency becomes 94% if the number of coil is infinity.

Zorlu et al. [186] also used frequency up conversion technique. Non resonant vibration (e.g., using low frequency with low vibration amplitude) based energy harvester using NdFeB was proposed. The dimension of the generator is $2.5 \times 2.5 \times 0.5 \text{mm}^3$. An optimum rms voltage and power of $2.1\text{mV}$ and $18.5\text{nW}$, respectively, were obtained under 10Hz. The fabricated prototype was attached to the Printed circuit board (PCB) for harvesting power (see Fig. 4.7(a)). Besides, using frequency up-conversion technique, Zorlu et al. [187] proposed a novel electromagnetic vibrator structure having single diaphragm with single coil instead of a number of coils. Their designed prototype was the modified version of Sari et al. [134]. The size of the prototype is $10.4 \times 8.8 \times 5 \text{mm}^3$. The prototype has a maximum voltage and a power output of $12-18\text{mV}$ and $3.6-8.1\text{nW}$ at 5-10Hz with a vibration amplitude of 3mm. It was reported that increasing the
number coil turns as well as effective coil area improves the performance of the micro energy harvester.

Pashaei and Bahrami [188] also described frequency up-conversion method in order to improve the generated power from low frequency based electromagnetic micro generator. To increase the ambient low frequency, planer spring with two magnets and four cantilever beams were used to construct the structure of the generator. The voltage and power output from their developed prototype are 67.4mV and 46.6µW, respectively, at 75Hz (after up conversion frequency becomes 5.9 KHz). Another method to improve the frequency range of the energy harvester is to use double resonant method which allows both magnets and coils to vibrate at an additive phase angle. Ooia and Gilbert [189] used double resonant technique to widen the frequency band of their designed generator (see Fig 4.7(b)). MATAB was used to simulate the numerical model analysis. From experimental results, it was obtained that their prototype has a voltage of 259.5mV at 21.3 Hz with 0.8ms$^{-2}$ acceleration.

![Figure 4.7:](a) Picture of micro energy generator chip designed by Zorlu et al. [186] attached to the PCB with NdFeB magnet and barrier arms. (b) Dual resonator generator developed by Ooia, and Gilbert [189].

In another study, Sato et al. [190] presented an analytical method to describe the motion, circuit, and Maxwell equations using the coupled analysis technique to develop the VMPG. From the coupled analysis method it was noticed that vibration based energy harvester has linear and chaotic oscillations at a large coil radius. In a subsequent study, Sato et al. [191] developed a prototype to validate their previous research. Their designed generator has a power output of 0.1mW at 30 Hz from numerical and experiment tests.
A different type of material (FR4) was used to fabricate a nonlinear bistable electromagnetic transducer by Podder et al. [192]. A detailed explanation of design, modeling, and fabrication was presented to describe their prototype and validate their results. Two oppositely oriented NdFeB magnets were used for introducing the bi-stable state (see Fig. 4.8). Experimental results show that the generator harvests 22µW at 35 Hz with a resistive load of 1KΩ. More recently, in order to operate and tune the electromagnetic generator in a high frequency range, Mallick and Roy [193] also reported bidirectional FR4 based energy harvester using capacitive and inductive load. Four different spring configurations were discussed at different frequencies using laser micromachining technology. A maximum power of 468.17µW, 348.2µW, 4.31µW, and 6.54µW was obtained from prototype P1, P2, P3, and P4 at 58.6Hz, 83.8Hz, 162.9Hz, and 42.9Hz, respectively (see Fig. 4.9).

**Figure 4.8:** Fabricated bistable micro power generator developed by Podder et al. [68].

**Figure 4.9:** (a)-(d) Four different spring configurations fabricated on FR4 developed by Mallick and Roy [193].
4.3.1.2 Using Different Shapes of Cantilever

Besides using rectangular shaped cantilever, researchers also studied other shapes (e.g., T shape, U shape, S shape, spring type, etc.) of cantilever to investigate the efficiency improvement of the generator. Starting from 2000, Li et al. [194] researched ways to design, analyze, and experimentally test of VMPG having a size of ~1 cm³. To optimize the size of the prototype, laser micro-machined spring was used as a resonator. A voltage quadrupler circuit was used for rectifying generated ac voltage into dc. The prototype can generate 10 μW and 2 V DC at 64 Hz with an amplitude of 100 μm. Similar to Li et al. [194], Ching et al. [195] fabricated a prototype with NdFeB to harvest power to drive the inferred transmitter at different vibration modes. It is observed that the voltage and power output of the prototype were 4.4 V_{p-p} and ~830 μW at a frequency range between 60 to 110 Hz with approximately 200 μm vibration amplitude.

A detailed description of design methodology and fabrication process of liner micro energy harvester was explained by Williams et al. [196]. Permanent magnet samarium-cobalt was attached to the flexible GaAs polyimide membrane. The developed prototype was tested in various environment conditions (e.g., air and vacuum). A maximum power of 0.3 μW was obtained at 4 MHz. In a subsequent research, similar spring type vibrator was fabricated by Wang et al. [197] using MEMS technique. ANSYS was used to determine the resonant frequency and different modes of the system. Permanent magnet NdFeB and two layer of copper coil were used for their prototype as shown in Fig 4.10(a). Their prototype generates a maximum of 60 mV_{ac} at 121.25 Hz with 1.5 g acceleration. In a later study, Wang et al. [198] presented a fabrication process of micro power generator using resin-bonded NdFeB magnet powder. The magnet powder was used to make different sizes of magnet discs (see Fig. 4.10(b)) using micro patterning process.
Figure 4.10: (a) Schematic architecture and (b) fabricated electromagnetic generator developed by Wang et al. [197, 198]

Rather than using the copper spring type resonator, Lu and Hwang [199] used silicon helical micro-spring in their developed generator. Ferroplatinum permanent magnet membrane, copper coil and two glass pieces were used to fabricate their prototype (see Fig. 4.11). A maximum voltage and power of 44.2mV and 114.5µW was measured at 60Hz with a vibration amplitude of 0.03mm. The output power becomes 4.2 times greater at 0.05mm vibration amplitude than uncontrolled vibration amplitude.

Figure 4.11: Schematic representation of electromagnetic micro energy harvester designed by Lu and Hwang [199].

Another novel approach to improve the efficiency of the micro electromagnetic energy harvester is to use three dimensional excitations at different modes with corresponding frequencies. Liu et al. [200] fabricated a novel power generator chip which consists of double
layer three sets of aluminum coils, circular type spring with magnet and supporting beam. Different modeling (e.g., mechanical, dynamic, and electro-mechanical modeling) and simulations were conducted to finalize the design of the prototype. Plasma-enhanced chemical vapor deposition (PECVD) technology was used to fabricate the energy harvester. The prototype generates 0.016µW, 0.0087 µW, and 0.0045 µW at 1285Hz, 1470Hz, and 1550Hz, respectively. In a later research, Liu et al. [201] minimized the distance between magnet and energy harvester chip to achieve better performance of the generator. Besides, Wang et al. [202] designed a flow induced vibration based electromagnetic VMPG. The vibration was induced from kármán vortex street which allows the magnet to move under the coil. The size of the harvester is 37.9cm³. Their fabricated energy harvester can generate 20mVpp and 1.77µW at 62 Hz.

Arafa [203] used a trapezoidal plate energy harvester as shown in Fig. 4.12(a) for their developed VMPG prototype. Such trapezoidal plate design helps to obtain a close gap between two consecutive modal frequencies to achieve a wide bandwidth of the harvester. It was seen that the frequency ratio of mode I and II is 1.7 (19 Hz and 32 Hz). A dynamic model was described to anticipate the performance of the system using 30 Ω, 100 Ω, and 1000 Ω load resistance. El-Hebeary et al. [204] continued the research conducted by Arafa [203] by changing the geometry of the plate (see Fig. 4.12(b)) to widen the frequency bandwidth more. The modified geometry becomes V-shaped. It is noticed that their designed harvester can generate voltage at three different modes using three different resonance frequencies (e.g., 8 Hz, 11.8 Hz, and 19.2 Hz).

![Figure 4.12: V-shape multimodal energy harvester developed by (a) Arafa [203] and (b) El-Hebeary et al. [204].](image)
In a later study, Khan and Ahmed [205] developed a novel electromagnetic power generator having two permanent magnets with planar and wound coils. A latex membrane was placed between two magnets and coils were fabricated by PCB technology. Teflon spacers were used to create gap between magnets and coils. The dimension of the developed prototype is $18 \times 18 \times 18 \text{ mm}^3$. The open circuit voltage and load power are 15.7 mV and 11.05 mV, and 1.8 $\mu$W and 2.1 $\mu$W, respectively at a frequency range between 10 to 80 Hz at 0.3 g acceleration. Besides, Khan et al. [206] developed similar electromagnetic power generator using PDMS membrane. Slotted polycarbonate plastic was used as a spacer instead of Teflon spacer. The modified size of the prototype was $15 \times 15 \times 10 \text{ mm}^3$ (see Fig. 4.13(a)). A maximum voltage and power of 88.8mV and 39.4$\mu$W was measured at 108.4Hz under 0.1-3g acceleration.

In a subsequent research, Yang et al. [207] used circular type elastic rod for their electromagnetic power generator to harvest energy at a wide frequency range. Ansoft’s Maxwell 3D was used to obtain the maximum performance of the prototype (see Fig. 4.13(b)). The prototype generates a maximum power of 13.4mW at 5.7Hz with an acceleration of 0.6g.

![Image](image_url)

**Figure 4.13:** (a) Polydimethylsiloxane membrane type energy harvester developed by khan et al. [206]. (b) Vibration based electromagnetic energy harvester using cylinder type rod developed by Yang et al. [207].

### 4.3.1.3 Using Cylinder Shaped Structure

Besides, using different shapes of cantilever (e.g., rectangular, spring type, V shape, circular rod etc.), researchers also considered cylindrical shape structure for vibration based electromagnetic energy harvesters. Buren and Troster [208] designed a tubular shape VMPG using translational motion of the magnets. Translator bearing was also used in the generator.
architecture. In order to optimize the generator size, stator and translator parameter, load resistance, and resonant frequency were optimized. The size of the combined stator and translator is 0.25 cm$^3$ (see Fig. 4.14). The prototype can generate 2-25 µW based on different position of the human body.

![Figure 4.14: (a) Schematic diagram of 3D model of tubular stator with translator (0.25 cm$^3$). (b) Cross-sectional view of the generator [208].](image)

Saha et al. [209] developed similar tubular type electromagnetic power generator for human usage. Their generator consists of 3 sets of oppositely polarized permanent magnets placed in a Teflon tube. Top and bottom magnets are fixed whereas the middle magnet moves vertically. 1000 turns of coil was used outside of the tube for electromagnetic induction purpose. The developed prototype has a maximum power 0.30mW and 1.86mW at 8Hz with matched load (800 Ω). In a subsequent research, Foisal et al. [210] used similar magnet configuration to fabricate the electromagnetic energy harvester. Two different configurations with an array of four electromagnetic generators were developed. The total volume of prototype A and B were 108.11 cm$^3$ and 40.18 cm$^3$. A maximum power of 2.37 mW and 2.09 mW was measured at 7-10Hz from prototype A and B, respectively. The power density of prototype B is found more than prototype A.

Munaz et al. [211] extended the research by Foisal et al. [210] using multi-pole magnets in their designed energy harvester. Similar cylindrical tube (acrylic glass), copper coil, NdFeB were used to develop the generator. MATLAB was used to measure the open circuit voltage which was 6600 mV. Prototype can generate 4.84mW at 6Hz with an acceleration of 0.5g. Similar
battery type electromagnetic generator was proposed by Cepnik et al. [212]. A simple equation was derived to directly calculate the induced voltage and electromechanical damping of the electromagnetic vibration generator. The calculation takes 50% less time than conventional calculation system using their developed electromagnetic coupling equations and optimization method. Optimized prototype can generate an average power of 20.6 mW at 50Hz with 1g acceleration. In a later study, a novel approach to calculate the electromagnetic properties of the electromagnetic vibration power generator was presented by Elvin and Elvin [213]. Rare earth magnet i.e., neodymium was attached to a spring inside a tubular structure (see Fig. 4.15(a)). Two different coil configurations were used. First configuration was with one layer of copper coil with 23 turns and second one was with two layers. A normalized power of $1.7\text{mW}/[(\text{m/s}^2)^2\text{cm}^3]$ was obtained at 112.25 Hz.

Besides, a new approach of harvesting energy from low frequency and non-periodic vibration using Parametric Frequency-Increased Generator (PFIG) was presented by Galchev et al. [214]. PFIG has three magnetically tied structures. The internal displacement of the structure is fixed which allows it to oscillate at high frequency. The total size of the generator is 3.75cm$^3$. The maximum power output of designed prototype is $163\mu\text{W}$ at 10 Hz which can generate power up to 60Hz. Lee et al. [215] also used spring (flame resistant (FR-4)) inside the Taflon tube for moving the magnets in their proposed vibration generator. Two thin FR4 spring, NdFeB magnet, and copper coil were used to construct the prototype (see Fig. 4.15(b)). The bottom and top FR4 springs were used to decrease the stress on the springs and also to get a linear movement of the magnets. A maximum power of $1.52\text{mW}$ was obtained at 16Hz with 0.2g acceleration. It was reported that their designed prototype can generate 2.4mW from car engine.
Figure 4.15: (a) Magnet with spring and cylindrical structure with coil are the two parts of proposed electromagnetic vibration energy harvester [213]. (b) Prototype designed by Lee et al. [215]. NdFeB magnet was placed inside the Teflon tube between top and bottom FR4 springs. Copper coil was warped around the tube. A rectifier circuit was also attached to the top of the generator for ac-dc conversion.

Additionally, Delnavaz and Voix [216] developed an electromagnetic energy scavenger using human breath pressure. In order to use the breath, a breath mask was used with connecting tubes which was connected to the electromagnetic module. Copper coil was warped outside of the tube. Two magnets were placed: one at the top and another one at the bottom position of the tube. The third magnet moves between two magnets inside the tube which is surrounded by coil. The prototype can generate 25 mV and 3.1 µW. More recently, the research of Morgadoa et al. [217] focused on mathematical modeling of the cylindrical shape electromagnetic VMPG. The mathematical modeling is based on Newton’s second law. However, a nonlinear mathematical expression has been used for the consequential magnetic force. It is reported that magnets size, gap between these magnets, number of coil windings are responsible to optimize the power generation of this cylindrical type electromagnetic energy harvesters.

4.3.1.4 Using Power Conditioning Circuit

In order to improve the efficiency of the vibration based electromagnetic generator, different power management circuits were incorporated with prototype. Starting from 1998, Rajeevan and Chandrakasan [218] designed a self-powered digital signal processing electromagnetic transducer implemented by CMOS technology. Their designed chip consists of an ultra-low power controller and DSP load circuit. To construct a self-powered system, an integrated circuit
which consists of a DC-DC converter and a FIR filter were introduced. The electromagnetic transducer can harvest 400µW at 500 KHz.

In a later study, Hadas et al. [219] used a power management circuit in their designed power generator to rectify as well as stabilize the generated voltage. A maximum power voltage output of 3-6µW and 2.5V was measured at 34Hz with amplitude of 50-150µm. Schottky barrier diodes and 220µF capacitor were used in the generator circuit for rectifying and stabilizing the purpose. Further research on power management circuit conducted by Dayal et al. [220] presented a micro power generator integrated with a single stage AC-DC boost converter. Single stage AC-DC boost converter was used for power processing of their prototype. A detailed description of numerical and experimental work was presented to verify the functionality of the designed system. The voltage output of the prototype is 0.45V at 108Hz.

More recently, Bowden et al. [221] researched ways to overcome the frequency limitation of the vibration based micro power generator using electrical tuning method. A voltage-source-converter was used as an AC-DC boost converter for rectifying the generated power and a static converter was integrated for power factor correction. A full H-bridge circuit of MOSFET was used to run the full operation of the converters. Experimental results indicate that switch-mode converter used in the tuning circuit increases the -3dB power bandwidth of the generator 3 times more than the untuned one. A summary of literature review on vibration based electromagnetic micro power generators has been listed in Table 4.4.
**Table 4.4:** Summary of literature review of vibration based electromagnetic micro power generators.

<table>
<thead>
<tr>
<th>Reference, year</th>
<th>Magnet</th>
<th>Size</th>
<th>Reson. Frequency (Hz)</th>
<th>Amplitude</th>
<th>Power</th>
<th>Volt.</th>
<th>Load Resistance (Ω)</th>
<th>Accel. (g=9.81 ms⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Williams and Yates [139], 1996</td>
<td></td>
<td>25mm³</td>
<td>70</td>
<td>50µm</td>
<td>1µW</td>
<td>0.1 mW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li et al.[194], 2000</td>
<td></td>
<td>1cm³</td>
<td>64</td>
<td>100µm</td>
<td>10µW</td>
<td>2V</td>
<td></td>
<td>1.69g</td>
</tr>
<tr>
<td>Willium et al. [196], 2001</td>
<td>Samariu m-cobalt</td>
<td>4×10⁶</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El-hami et al.[171], 2001</td>
<td>NdFeB and samariu m-cobalt</td>
<td>240mm³</td>
<td>322</td>
<td>25µm</td>
<td>0.53m W</td>
<td>14mV</td>
<td></td>
<td>0.28</td>
</tr>
<tr>
<td>Ching et al.[195], 2002</td>
<td>NdFeB</td>
<td>1cm³</td>
<td>60-110</td>
<td>200µm</td>
<td>830µW</td>
<td>4.4V_p_p</td>
<td>1000</td>
<td>9.7g</td>
</tr>
<tr>
<td>Mizuno et al. [173], 2003</td>
<td>NdFeB</td>
<td>500×100×2 0 mm³</td>
<td>58000</td>
<td>100nm</td>
<td>6 nW</td>
<td>1.4mV</td>
<td></td>
<td>82</td>
</tr>
<tr>
<td>Glynne-J et al.[172], 2004</td>
<td>NdFeB</td>
<td>A: 0.84cm³</td>
<td>322</td>
<td>0.36mm</td>
<td>37µW</td>
<td>0.6</td>
<td></td>
<td>0.26g</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B: 3.15 cm³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kulah et al. [174] 2004</td>
<td>NdFeB</td>
<td>400×30×10 µm³</td>
<td>11400</td>
<td>2.5 µW</td>
<td>150mV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P’erez- Rodríguez et al. [179], 2005</td>
<td>NdFeB</td>
<td></td>
<td>120</td>
<td>385µW</td>
<td>0.5-0.9 V</td>
<td>0.25g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beeby et al. [175], 2005</td>
<td></td>
<td></td>
<td>6400</td>
<td>0.14mm</td>
<td>0.38V</td>
<td>77</td>
<td></td>
<td>0.196g</td>
</tr>
<tr>
<td>Torah et al. [181], 2006</td>
<td>NdFeB</td>
<td>150mm³</td>
<td>56.6</td>
<td>17.8µW</td>
<td>52mV</td>
<td>150</td>
<td></td>
<td>60mg</td>
</tr>
<tr>
<td>Spreemann et al. [180], 2006</td>
<td></td>
<td>1.5cm³</td>
<td>30-80</td>
<td>100µm</td>
<td>0.4-3mW</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koukharenko et al. [177], 2006</td>
<td>NdFeB</td>
<td>100mm³</td>
<td>1615 &amp; 9500</td>
<td>240 µm</td>
<td>0.11 &amp; 3.35mW</td>
<td>0.7 &amp; 4.15 V</td>
<td>2000</td>
<td>0.4g</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Description</td>
<td>Volume</td>
<td>Length</td>
<td>Diameter</td>
<td>Area</td>
<td>Power</td>
<td>Voltage</td>
<td>Force</td>
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<tr>
<td>Kulkarni et al. [178], 2006</td>
<td>30mm³</td>
<td>7500</td>
<td>240µm</td>
<td>75µW</td>
<td>55mV</td>
<td>37.5</td>
<td>0.11g</td>
<td></td>
</tr>
<tr>
<td>Beeby et al. [182], 2007</td>
<td>52</td>
<td>46µW</td>
<td>428mV</td>
<td>4000</td>
<td>60mg</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Hadas et al. [219], 2007</td>
<td>NdFeB</td>
<td>50×32×28mm³</td>
<td>34</td>
<td>50-150µm</td>
<td>3-6mW</td>
<td>2.5V</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Wang et al. [197], 2007</td>
<td>NdFeB</td>
<td>0.18mm³</td>
<td>121.25</td>
<td>738µm</td>
<td>60mV</td>
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</tr>
<tr>
<td>Kulkarni et al. [178], 2008</td>
<td>A-NdFeB</td>
<td>106mm³</td>
<td>8080</td>
<td>148nW</td>
<td>52700</td>
<td>0.398g</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B-NdFeB</td>
<td>106mm³</td>
<td>9840</td>
<td>23nW</td>
<td>52</td>
<td>1g</td>
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<tr>
<td></td>
<td>C-NdFeB</td>
<td>150mm³</td>
<td>60</td>
<td>1.5 mm</td>
<td>586nW</td>
<td>23.5 mV</td>
<td>110</td>
<td>0.9g</td>
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<tr>
<td>Saha et al. [209], 2008</td>
<td></td>
<td>12.48cm³</td>
<td>8</td>
<td>0.3-2.46 mW</td>
<td>800</td>
<td>0.5g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sari et al. [183], 2008</td>
<td>NdFeB</td>
<td>14×12.5×8mm³</td>
<td>4200-5000</td>
<td>1µm</td>
<td>0.4µW</td>
<td>10mV</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Sari et al. [134], 2009</td>
<td>NdFeB</td>
<td>9.5×8×6mm³</td>
<td>3400</td>
<td>56pW/cantilever</td>
<td>0.67mV</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sari et al. [184], 2010</td>
<td>NdFeB</td>
<td>8.7×7×2.5mm³</td>
<td>70-150</td>
<td>0.44-2mm</td>
<td>6.6 nW/cantilever</td>
<td>13.5 mV</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Solaiman et al. [185], 2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>190µW</td>
<td>0.021V</td>
<td>2</td>
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</tr>
<tr>
<td>Zhu et al. [143], 2010</td>
<td>NdFeB</td>
<td>67.6-98</td>
<td>61.6-156.6µW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lu et al. [199], 2011</td>
<td>Ferroplatinum magnet</td>
<td>60</td>
<td>0.03mm</td>
<td>114.5µW</td>
<td>44.2mV</td>
<td>10.6</td>
<td>0.45g</td>
<td></td>
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<tr>
<td>Dayal et al. [220], 2011</td>
<td>NdFeB</td>
<td>108</td>
<td>2mm</td>
<td></td>
<td></td>
<td>0.45V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galchev et al. [214], 2011</td>
<td>NdFeB</td>
<td>3.75cm³</td>
<td>10</td>
<td>13.6µW</td>
<td></td>
<td>1g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>Year</td>
<td>NdFeB</td>
<td>Volume</td>
<td>Width</td>
<td>Height</td>
<td>Power</td>
<td>Voltage</td>
<td>Length</td>
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<tr>
<td>Cepnik et al. [212], 2011</td>
<td></td>
<td></td>
<td>50</td>
<td>100µm</td>
<td>20.6m</td>
<td>W</td>
<td></td>
<td>1g</td>
</tr>
<tr>
<td>Wang et al. [202], 2012</td>
<td></td>
<td></td>
<td>37.9cm²</td>
<td>62</td>
<td>1.77uW</td>
<td>20mV</td>
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<tr>
<td>Lee et al. [215], 2012</td>
<td>NdFeB</td>
<td></td>
<td>16</td>
<td>1.52mW</td>
<td>4.8V</td>
<td>5460</td>
<td>0.2g</td>
<td></td>
</tr>
<tr>
<td>Foisal et al. [210], 2012</td>
<td>NdFeB</td>
<td></td>
<td></td>
<td></td>
<td>2.23mW</td>
<td>3.326–5.770V</td>
<td>0.5g</td>
<td></td>
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<tr>
<td>Delnavaz et al. [216], 2012</td>
<td></td>
<td></td>
<td>40 mm</td>
<td>3.1 µW</td>
<td>20mV</td>
<td>214</td>
<td></td>
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<tr>
<td>Liu et al. [200], 2012</td>
<td>NdFeB</td>
<td>10×8×0.45 mm³</td>
<td>1285</td>
<td>0.016µW</td>
<td>3.6mV</td>
<td>1800</td>
<td>1g</td>
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</tr>
<tr>
<td>Žorlu &amp; Külah [186], 2013</td>
<td>NdFeB</td>
<td>2.5<em>2.5</em>5 mm³</td>
<td>10</td>
<td>5 mm</td>
<td>18.5nW</td>
<td>2.1 mV</td>
<td>1g</td>
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</tr>
<tr>
<td>Pashaei &amp; Bahrami [188], 2013</td>
<td>NdFeB</td>
<td>0.64cm³</td>
<td>5900</td>
<td>46.6µW</td>
<td>67.4 mV</td>
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<tr>
<td>Liu et al. [201], 2013</td>
<td>NdFeB</td>
<td>0.035 cm³</td>
<td>840</td>
<td>5.5nW</td>
<td>626</td>
<td>1g</td>
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<tr>
<td>Žorlu et al. [186], 2013</td>
<td>NdFeB</td>
<td>10.4×8.8×5 mm³</td>
<td>10</td>
<td>3 mm</td>
<td>1.2nW</td>
<td>6.94mV</td>
<td>0.6g</td>
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<tr>
<td>Munaz et al. [87], 2013</td>
<td>NdFeB(N35)</td>
<td>9.043cm³</td>
<td>6</td>
<td>4.84mW</td>
<td>6600mV</td>
<td>1000</td>
<td>0.5g</td>
<td></td>
</tr>
<tr>
<td>Ooi &amp; Gilbert [189], 2014</td>
<td>NdFeB(N35)</td>
<td>21.3</td>
<td></td>
<td>259.5 mV</td>
<td></td>
<td></td>
<td>0.08g</td>
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</tr>
<tr>
<td>Yang et al. [207], 2014</td>
<td></td>
<td></td>
<td>5.7</td>
<td>13.4mW</td>
<td>110</td>
<td>0.6g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khan &amp; Ahmad [205], 2014</td>
<td></td>
<td></td>
<td>18×18×18 mm³</td>
<td>10-80</td>
<td>1.8µW &amp;2.1µW</td>
<td>15.7 &amp;11.05 mV</td>
<td>3g</td>
<td></td>
</tr>
<tr>
<td>Khan et al. [206], 2014</td>
<td>NdFeB</td>
<td>15×15×10 mm³</td>
<td>108.4</td>
<td>68µW</td>
<td>48.5–88.8 mV</td>
<td>3 g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Authors</td>
<td>Material</td>
<td>Area (mm²)</td>
<td>Power (µW)</td>
<td>Voltage (mV)</td>
<td>Frequency (Hz)</td>
<td>Mass (g)</td>
<td></td>
<td></td>
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<tr>
<td>Podde et al. [192], 2014</td>
<td>NdFeB</td>
<td>35</td>
<td>22</td>
<td>150</td>
<td>1000</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sato &amp; Igarashi [191], 2015</td>
<td>NdFeB</td>
<td>30</td>
<td>0.1</td>
<td>&gt;0.1</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mallick &amp; Roy [193], 2015</td>
<td>NdFeB</td>
<td>P1-2.5×2.5</td>
<td>468.17</td>
<td>1.06</td>
<td>2400</td>
<td>0.3</td>
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<tr>
<td></td>
<td></td>
<td>P2-8.3</td>
<td>348.2</td>
<td>0.89</td>
<td>2100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P3-2.2×2.2</td>
<td>4.31</td>
<td>0.058</td>
<td>780</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>P4-42.9</td>
<td>16.54</td>
<td>0.122</td>
<td>900</td>
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</tr>
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</table>

**4.3.2 Piezoelectric VMPGs**

Piezoelectric is another common transducer mechanism which has been used in VMPGs. Different piezoelectric materials (e.g., PZT, PVDF, AlN etc.) with different structures were used to fabricate the VMPGs. A list of literature review has been presented in this subsection based on different materials and different geometry shapes.

**4.3.2.1 Using Different Piezoelectric Materials**

Using footsteps of human beings, Kymissis et al. [169] presented three different configurations to convert vibration energy into electrical energy. Among them two are piezoelectric and one is electromagnetic in nature. PZT and PVDF were used in piezoelectric energy harvester. Piezoelectric harvester was identified more suitable than electromagnetic one. A peak power of 80µW was measured at 1Hz from piezoelectric harvester attached to the shoe. This generated power was transmitted through a radio frequency (RF) transmitter. Similar research was continued by Shenck et al [222] by using the same material and procedure. The prototype has a power of 1.3mW and 8.4mW at 0.9Hz using PZT and PVDF, respectively. It was observed that electromechanical efficiency of the generator using PVDF is 0.5% and 20% with PZT generator. Additionally, a forward switching power conditioning circuit was designed and included with the harvester.
Similar material PZT was used by Glynne-Jones et al. [223] and White et al. [224] for developing their designed piezoelectric energy harvester based on thick film piezoelectric mechanism. A detailed fabrication process was illustrated using thick film piezoelectric technology. The developed piezoelectric generator can generate $3\mu W$ at 80.1 Hz under 0.8mm vibration amplitude [223] while the other similar generator can generate $2\mu W$ under 09mm amplitude at same frequency [224].

In a subsequent research, Roundy et al. [9] and Roundy and Wright [154] investigated the piezoelectric energy harvester performance using PZT bimorph on a cantilever beam. A literature review on low power generation using vibration was presented by Roundy et al. [9] and based on the literature, an experimental work was conducted. The developed generator has a power output of $250 \mu W$ at 120Hz under $2.25 \text{ms}^{-2}$ acceleration. Furthermore, Roundy and Wright [154] conducted a similar research on modeling, design, and optimization using PZT-5H for the electrostatic generator. Their proposed electrostatic generator has two layers of bending elements. The size of their generator is $1\text{cm}^3$ with an output power of $375\mu W$ at 120 Hz (see Fig. 4.16).

![Figure 4.16:](image)

(a) Designed prototype using two layer of PZT-5A, (b) optimized prototype (constraint length is 1.5cm) developed by Roundy and Wright [154].

Rather than using general PZT for piezoelectric energy harvester, Lu et al. [225] used modified PZT-PIC255 and single crystal PZN-8%PT for developing a generator. The experimental results showed that the power output varied at different load resistances at same frequency (2939.8Hz). The optimum power output is $0.66mW$ at 68$\Omega$ and $0.571mW$ at 215$\Omega$. 
from PZT-PIC255 and PZN-8%PT, respectively. PZT-PIC255 is found sensitive to load resistance whereas PZN-8%PT is sensitive to resonance frequency. Besides, Bayrashev et al. [226] proposed a new technique for low frequency vibration based piezoelectric power generator using PZT with Terbium Dysprosium Iron alloy (Terfenol-D) as shown in Fig. 4.17(a). Terfenol-D is a good magnetostrictive element and it has a good electrical conductivity. PZT was placed between two Terfenol-D layers to increase the voltage generation. The results show that the power output varies from 10 to 80 µW at 1-30Hz.

A complete mathematical model of the piezoelectric power generator model was presented by Sodano et al. [227] using PZT. Quick pack model QP40N was used to validate the model. The QP40N consists of complex PZT layer and a beam. The model was tested at various mechanical conditions including damping effect. Another piezoelectric material, Aluminium Nitride (AlN), was used with PZT to fabricate the micro piezoelectric generator [228]. Marzencki et al. [228] presented detailed fabrication process of AlN using SiO$_2$ with Si layers. It was reported that the prototype can generate 60nW from AlN layer whereas using typical PZT it can generate 600nW. In a subsequent study, the work is continued by Muralt et al. [229] who fabricated and tested a thin film piezoelectric micro power generator (see Fig. 4.17(b)). PZT was deposited on the thermal oxide layer ID electrode in fabrication steps. The voltage and power output are 1.6V and 1.4µW at 870Hz under maximum load impedance.

**Figure 4.17:** (a) Developed piezoelectric generator using PZT with two Terfenol-D layers [226]. (b) Schematic presentation of fabricated thin film PZT energy harvester attached to the cantilever beam with tip mass [229]. The PZT film is 2µm thin which is deposited on the SOI wafer.
In a later research, Jeon et al. [230] also described the fabrication process of thin film piezoelectric generator using three photo mask processes. Sol–gel-spin coated PZT with top Pt/Ti electrode was used to fabricate the device (see Fig. 4.18(a)). It was reported that their designed $d_{33}$ mode generates more voltage than $d_{31}$ mode. A maximum voltage and power of 2.4 V$_{dc}$ and 1 µW was measured at 13.9 KHz across 5.2 MΩ resistance. The energy density of the developed prototype is 0.74 mW h/cm$^2$. Thin film Sol–gel-spin coated PZT was also used by Duggirala et al. [231] to fabricate the radioactive micro piezoelectric generator. Kinetic energy of radioactive $\beta$ particle was stored as a mechanical energy in the piezoelectric materials. Then mechanical energy was transformed into electrical energy. The fabricated prototype can generate 1.13 µW at 38 Hz with a conversion efficiency of 37%.

Micromachining technology was used to fabricate the micro piezoelectric power generator using same Pi/Te electrodes with same Sol–gel coated PZT on silicon substrate by Fang et al. [232]. The developed prototype (see Fig. 4.18(b)) has a voltage and power output of 898mV and 2.16µW at 608 Hz across 21.4 KΩ load resistance. Leland and Wright [233] proposed a new approach (e.g., compressive axially preload) to harvest energy at low frequency from vibration. Such technique is used to compress the piezoelectric bimorph for making its resonance frequency lower. It was obtained that axial preload also increases the piezoelectric coupling coefficient. The designed generator can harvest 300-400µW at a frequency range from 200 to 250 Hz. In order to tune the resonance frequency, Eichhorn et al. [234] also used the axial preload technique. It was reported that resonance frequency was tunable from 292Hz to 380Hz.

**Figure 4.18:** (a) Fabricated piezoelectric thin film micro power generator. SiO$_2$ wafer, buffer layer of ZrO$_2$, PZT layer, seismic mass of SU-8, and Pi/Te electrode were used to fabricate the piezoelectric cantilever structure [230]. (b) Schematic diagram of cross sectional view of fabricated piezoelectric energy harvester [232].
Additionally, Wu et al. [235] used frequency tuning mechanism by changing the positioning of the center of gravity of mass to adjust the resonance frequency of the generator. The results show that the developed prototype has a frequency range between 130Hz to 180Hz depending on the position of the mass. Besides, Challa et al. [236] also used frequency adjustment technique by introducing a novel approach of magnetic force technique. A prototype was developed and experimentally tested by using this magnetic force technique to adjust the frequency. It was reported that this technique allows tuning the resonant frequency to ± 20% from untuned one. The results show that the prototype can generate 240-280µW at a frequency range between 22-32Hz. In another study, the frequency range varies from 3.19 to 12 Hz based on attractive magnetic force effect using PVDF as a piezoelectric material [237].

Aktakka et al. [238-240] further focused on the thinned film piezoelectric micro power generator on silicon substrate using batch mode, mask, and micromachining fabrication technology. Thinned PZT was deposited on SOI wafer with silicon mass. The results show that the designed prototype can generate 10.2µW at 252Hz under 2g acceleration [239] and 205 µW at 154Hz under 1.5g [240]. Jambunathan et al. [241] focused on comparatively new fabrication technique (e.g., pulsed laser Deposition (PLD)). The fabrication process includes top-down with deep reactive ion etching (DRIE). Different resonant frequencies with different size of the devices were tested to find out the optimum configuration. It was measured that fabricated prototype can generate maximum 51.4µW at 615 Hz under 0.9g acceleration. In order to make a micro or miniature device, mechanical and electrical design, which includes natural axis, resonant frequency, and load resistance, plays an important role [242]. Leong et al. [242] investigated the mechanical and electrical design of the piezoelectric beam to fabricate a micro PZT energy harvester. It was reported that optimum deflection of the cantilever beam is important than stress. The developed prototype generates 4.5µW and 960mV at 80KΩ under 10ms^{-2} acceleration.

Kim et al. [243] researched ways to characterize the d_{31} and d_{33} modes of piezoelectric energy harvester and compare their output results. Interdigital electrode (IDE) was used to fabricate the d_{33} mode. The power output from d_{31} mode is 2.15µW and 2.33µW whereas from d_{33} mode it ranges from 0.62 µW to 1.71 µW, depending on the size of the IDE, at 243Hz. It was
obtained that $d_{33}$ with IDE has higher efficiency than $d_{31}$ mode of PZT. Besides, Kim et al. [244] developed a dual PZT cantilevers with silicon mass using micrelectromechanical system (MEMS). First, numerical analysis was carried out using finite element analysis with parametric analysis. The prototype generates a maximum voltage and power output of 118.5mW and 0.34 µW at 78.7Hz under 0.5g acceleration. Another recently developed piezoelectric material is single crystal piezoelectric material $(1-x)\text{Pb(Mg1/3Nb2/3)O}_3-x\text{PbTiO}_3$ (PMN-PT) which has a high piezoelectric and electromagnetic coupling coefficient. Tang et al. [245] also used $d_{33}$ mode single crystal PMN-PZT with IDE. The fabricated thick film PZT energy harvester can generate 5.36V and 7.182µW at 406Hz under acceleration of 1.5g.

A detailed analysis with experimental results has been conducted using different configurations (e.g., bi-stable single beam and magnetically coupled multiple beams). Trigona et al. [246] studied to compare different configurations using PbTiO$_3$ materials with NdFeB magnet at the tip of the cantilever. A maximum power output of ~5.5µW was obtained at 450Hz with 2.5g excitation. Additionally, Cho et al. [247] investigated the relationship between control variables (e.g., material properties, geometry, and active and inactive layers) and structural performance of the generator. A detailed description of layers (see Fig. 4.19(a)) of the beam was discussed and mathematically presented. PZT: PSI-5A4E was used as a piezoelectric material to fabricate the prototype. The prototype can generate 52.5mW at 30Hz using 6.9ms$^{-2}$ excitation. More recently, Prušáková et al. [248] developed a piezoelectric energy harvester (see Fig. 4.19(b)) using zinc oxide (ZnO) as a sandwich between Al$_2$O$_3$ layers on Si substrate with RF and DC magnetron supporting technique. A maximum power and voltage of ~20µW and 0.975V was obtained from at ~595Hz across ~10KΩ.

**Figure 4.19:** (a) Schematic representation of different layers of a piezoelectric cantilever [247]. (b) Fabricated thin film piezoelectric micro power generator using ZnO layer on silicon substrate [248].
Jaafar and Salleh [249] designed a novel piezoelectric power generator modifying the cantilever structure using silicon rubber on the tip of the beam. PSI-5H4E piezoelectric ceramic was used to develop the prototype. It was reported that adding extra rubber with the cantilever beam widens the frequency bandwidth by 115%. The experimental results show that the prototype has a power output of 38.1µW at 52 Hz across 110.3KΩ load resistance.

4.3.2.2 Using Different Geometry of PZT Cantilever Beam

Deepak and Vikas [147] researched ways to improve the power output from vibration based piezoelectric energy harvester using different shapes (e.g., rectangular shape, U-shaped, T-shaped) of cantilever. ANSYS 10 was used to design the cantilever shapes in order to decrease the resonant frequency of the system. COMSOL 3.5, PZT-5A piezoelectric layer was used to design a unimorph having a size of 30×10×0.4mm³. The designed cantilever has a voltage output of 2.7V at 147 Hz. In a later research, using finite element analysis (FEA) in COMSOL multi-physics, Reddy and Kumar [250] also studied different shapes (e.g., rectangular, triangle, T, π shaped) of cantilever to find out the sensitivity of the beams. It was reported that triangle shaped beam has a high sensitivity than other shapes of beam. It was obtained from the numerical simulation that displacement of triangular shaped beam is 9.7901×10⁴ µm at 0.5N/m² applied force.

Additionally, Basari et al. [251] suggested that triangular shaped lead zirconate titanate piezoelectric (PZT) energy harvester is more efficient than normal rectangular PZT under matching impedance condition. It was stated that the efficiency of PZT generator depends on geometry of the cantilever beam, proof mass, matching impedance and vibration force. Triangular PZT device has a regeneration efficiency of fixed 5% under changing load mass. Rather than using rectangular shape cantilever, Saadon, and Sidek [252] designed an E-shaped cantilever to extract energy using piezoelectric vibration generator. Silicon and lead zirconate titanate (PZT) were used to design the cantilever. The designed harvester generates 1 W at 2KΩ resistive load under first mode resonant frequency of 15 Hz. Similar to the research conducted on E shaped beam, Saadon, and Sidek [253] presented a T shaped beam for piezoelectric energy
harvester. The designed prototype generates 2.4µW at 11 Hz across 5KΩ load resistance under 1g acceleration.

In a subsequent study, Tufekcioglu and Dogan [254] described a parametric study of the design of piezoelectric energy harvester (PEH) and effect of stacking on the device performance. Cymbals with single-layer (C-PZT1) and two-layer-stacked (C-PZT2) disks were used as transducers to develop PEH. A maximum power of 141.61µW and 104.04 µW were obtained at 153Hz and 166 Hz across 40KΩ and 80 KΩ from C-PZT2 transducer (BPZT-2) and C-PZT1 transducer (BPZT-1), respectively. After experiment it was obtained that stacked PZT generator harvests more energy than single layer C-PZT1 transducer. Ali et al. [255] focused on fabricating a micro piezoelectric power generator using silicon micromachining technology. Aluminium nitride (AlN) was used as a piezoelectric material between the top and bottom electrode. Four Schottky diodes were used in the external driving circuit to rectify the generated voltage. A maximum power output of 34.78µW was measured at 572Hz under 2g acceleration.

Besides using ployvinylidene fluoride (PVDF) piezoelectric material, Wen et al. [256] designed and tested a spiral shaped cantilever for harvesting energy at low frequency. In order to decrease the resonant frequency, cantilever length was increased and two different proof masses (e.g., silicon and copper) were used on both ends. The developed prototype has a voltage and power output of 1.8V_{peak} and 8.1nW at 0.2g acceleration across 100 MΩ load resistance. More recently, using screen print technology, Debéda et al. [257] demonstrated a piezoelectric thick film sacrificial layer process. Gold (Au), zirconate titanate piezoelectric (PZT), and gold (Au), (Au/PZT/Au) bridge was fabricated using screen print method as shown in Fig 4.20. It was noted that the printed piezoelectric harvester is more suitable at higher frequency with in-plane d_{31} mode.
In order to widen the frequency band of the piezoelectric power generator, Zhang et al. [258] designed a cylindrical shaped nonlinear power generator using magnet levitation. Four doubled piezoelectric layers were used to develop the structure of the generator where the top and bottom magnets were fixed but the middle one was movable along the tube. It was obtained that the designed prototype has a frequency range from 0.1 to 30Hz. More recently, Fan et al. [142] developed a beam-roller piezoelectric power generator which can harvest energy from multimode vibration (e.g., sway and bi-directional vibration). Frequency up-conversion technique was also used to operate the system in a wide frequency range. A maximum open circuit voltage output of 13 V was obtained at resonant frequency 32 Hz from z-direct vibration of the prototype (see Fig. 4.21). A summary of literature review on piezoelectric transducer based micro energy harvesters has been presented in Table 4.5.

**Figure 4.20**: Fabricated Au/PZT/Au piezoelectric cantilever using SrCO$_3$-based sacrificial layer (a) before firing and (b) after firing [257].

**Figure 4.21**: Developed beam roller piezoelectric power generator prototype for (a) vibration and (b) sway experiment. The constructed beam was made of brass substrate and PZT-5H, single crystal chip. NdFeB magnet was attached to the free end of the beam [142].
<table>
<thead>
<tr>
<th>Reference, year</th>
<th>Material</th>
<th>Resonant Frequency (Hz)</th>
<th>Power</th>
<th>Volt</th>
<th>Load Resistance</th>
<th>Acceleration (g=9.81ms⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kymissis et al. [169], 1998</td>
<td>PZT, PVDF</td>
<td>1</td>
<td>80µW</td>
<td>150V_p</td>
<td>10Ω</td>
<td></td>
</tr>
<tr>
<td>Shenk [170], 2001</td>
<td>PZT &amp; PVDF</td>
<td>0.9</td>
<td>1.3mW &amp; 8.4mW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glynne-Jones et al. [223], 2001</td>
<td>PZT-5H</td>
<td>80.1</td>
<td>3µW</td>
<td></td>
<td>333K Ω</td>
<td></td>
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<tr>
<td>White et al. [224], 2001</td>
<td>PZT-5H</td>
<td>80</td>
<td>2µW</td>
<td>1.2V</td>
<td>333K Ω</td>
<td></td>
</tr>
<tr>
<td>Roundy et al. [9], 2003</td>
<td>PZT &amp; PVDF</td>
<td>120</td>
<td>252 µW</td>
<td></td>
<td></td>
<td>0.25g</td>
</tr>
<tr>
<td>Bayrashev et al. [226], 2004</td>
<td>PZT</td>
<td>5</td>
<td>10-80µW</td>
<td>&gt;1V_p-p</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lu et al. [225], 2004</td>
<td>PZT-PIC255 &amp; PZN-8% PT</td>
<td>2939</td>
<td>0.66 mW &amp; 0.571 mW</td>
<td></td>
<td>68 k Ω &amp; 215 KΩ</td>
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<tr>
<td>Roundy &amp; Wright [154], 2004</td>
<td>PZT-5A</td>
<td>120</td>
<td>375 µW</td>
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<td></td>
<td>0.25g</td>
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<tr>
<td>Marzencki et al. [228], 2005</td>
<td>PZT / AlN</td>
<td>900</td>
<td>0.6 µW</td>
<td></td>
<td>1.02g</td>
<td></td>
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<tr>
<td>Jeon et al. [230], 2005</td>
<td>Sol–gel-spin coated PZT</td>
<td>13900</td>
<td>1µW</td>
<td>2.4V_dc</td>
<td>5.2M Ω</td>
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<tr>
<td>Duggirala et al. [231], 2006</td>
<td>PZT, radioactive thin film</td>
<td>38</td>
<td>1.13µW</td>
<td>350mV</td>
<td>90K Ω</td>
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<tr>
<td>Leland et al. [233], 2006</td>
<td>Brass center shim coated PZT</td>
<td>200-250</td>
<td>300-400 µW</td>
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<td>1g</td>
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<td>Fang et al. [234], 2006</td>
<td>Sol–gel coated PZT</td>
<td>608</td>
<td>2.16µW</td>
<td>0.89V</td>
<td>21.4 K Ω</td>
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<tr>
<td>Challa et al. [236], 2008</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Muralt, et al. [229]</td>
<td>Thin film PZT</td>
<td>870</td>
<td>1.4 µW</td>
<td>1.6V</td>
<td>2g</td>
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101
<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Material/Method</th>
<th>Power</th>
<th>Voltage</th>
<th>Resistance</th>
<th>Weight</th>
</tr>
</thead>
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<tr>
<td>2009</td>
<td>Aktakka et al. [239], 2010</td>
<td>Thinned PZT</td>
<td>252</td>
<td>10.2 µW</td>
<td></td>
<td>2g</td>
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<tr>
<td></td>
<td>Aktakka et al. [240], 2011</td>
<td>Thinned PZT-5A</td>
<td>154</td>
<td>205 µW</td>
<td></td>
<td>1.5g</td>
</tr>
<tr>
<td></td>
<td>Jambunathan et al. [241], 2012</td>
<td>PLD- PZT</td>
<td>615</td>
<td>51 µW</td>
<td></td>
<td>0.93g</td>
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<tr>
<td></td>
<td>Leong et al. [242], 2012</td>
<td>PZT</td>
<td></td>
<td>4.5 µW</td>
<td>960mV</td>
<td>80k Ω</td>
</tr>
<tr>
<td></td>
<td>Deepak &amp; Vikas [147], 2013</td>
<td>PZT-5A</td>
<td>147</td>
<td></td>
<td>2.7V</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kim et al. [243], 2013</td>
<td>PZT-31 &amp; 33 mode</td>
<td>243</td>
<td>2.5 µW &amp; 062-1.71 µW</td>
<td></td>
<td>1.02g</td>
</tr>
<tr>
<td></td>
<td>Saadon &amp; Sidek [252], 2013</td>
<td>Si &amp; PZT</td>
<td>15</td>
<td>1 W</td>
<td>0.1 V&lt;sub&gt;pp&lt;/sub&gt;</td>
<td>2K Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25mW - simulated</td>
<td>0.45 V - simulated</td>
<td>5k Ω - simulated</td>
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<tr>
<td></td>
<td>Kim et al. [244], 2013</td>
<td>PZT-31 mode</td>
<td>78.7</td>
<td>0.34 µW</td>
<td>118.5mV</td>
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<tr>
<td></td>
<td>Tang et al. [245], 2014</td>
<td>Single crystal PMN-PZT</td>
<td>406</td>
<td>7.182 µW</td>
<td>5.36 V&lt;sub&gt;p-p&lt;/sub&gt;</td>
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<tr>
<td></td>
<td>Trigona et al. [246], 2014</td>
<td>PZT- PbTiO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>450</td>
<td>~5.5 µW</td>
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<td></td>
<td>Cho et al. [247], 2014</td>
<td>PZT: PSI-5A4E</td>
<td>30</td>
<td>52.5mW</td>
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<td></td>
<td>Wen et al. [133], 2014</td>
<td>PVDF</td>
<td>15-50</td>
<td>8.1 nW</td>
<td>1.8 V&lt;sub&gt;p&lt;/sub&gt;</td>
<td>100 M Ω</td>
</tr>
<tr>
<td></td>
<td>Tufekcioglu et al. [254], 2014</td>
<td>PZT-5H</td>
<td>153</td>
<td>C-PZT-2</td>
<td>2380 mV</td>
<td>40 K Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>141.61µW</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>166</td>
<td>C-PZT-1</td>
<td>2885 mV</td>
<td>80K Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>104.04µW</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Saadon &amp; Sidek [253], 2014</td>
<td>PZT</td>
<td>11</td>
<td>2.4 µW</td>
<td>0.12V</td>
<td>5 K Ω</td>
</tr>
<tr>
<td></td>
<td>Ali et al. [255], 2014</td>
<td>Aluminium nitride (AlN)</td>
<td>572</td>
<td>34.78 µW</td>
<td></td>
<td>495 kΩ</td>
</tr>
<tr>
<td>Source</td>
<td>Material</td>
<td>Voltage (V)</td>
<td>Power Output (W)</td>
<td>Resistance (Ω)</td>
<td>Acceleration (g)</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>----------------</td>
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<td>------------------</td>
<td>----------------</td>
<td>------------------</td>
<td></td>
</tr>
<tr>
<td>Prušáková et al. [248], 2015</td>
<td>Thin-film ZnO</td>
<td>0.98</td>
<td>~20μW</td>
<td>~10K Ω</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaafar and Salleh [249], 2015</td>
<td>PZT: PSI-5A4E</td>
<td>1.02</td>
<td>38.1μW</td>
<td>110.3K Ω</td>
<td>0.25g</td>
<td></td>
</tr>
</tbody>
</table>

### 4.3.3 Hybrid VMPGs

Recently, there is an increasing trend to use hybrid energy sources to improve the energy production from one generator. Different combinations of energy sources especially electromagnetic and piezoelectric, and electromagnetic and thermoelectric are being used to widely optimize the efficiency.

A detailed explanation of theoretical and experimental work of hybrid vibration power generator consists of electromagnetic and piezoelectric transducer mechanism which was presented by Tadesse et al. [259]. Pb(Zn$_{1/3}$Nb$_{2/3}$)O$_3$-PbTiO$_3$(PZN-PT) single crystals was used as a piezoelectric plate ($d_{31}$ mode) on the cantilever beam with magnet. The size of their designed prototype is 25×30×125 mm$^3$ as shown in Fig. 4.22(a). It was reported that electromagnetic transducer is suitable for low frequency whereas piezoelectric is fit for high frequency. The power output from electromagnetic piezoelectric systems is 0.25W and 0.25mW, respectively at 20Hz with an acceleration of 35g. In a later study, Sang et al. [260] also designed a hybrid power generator using piezoelectric and electromagnetic energy conversion system. An analytical model was developed and experimentally tested in order to study the nonlinear behavior of the vibration and performance of the system. The voltage and power output of the prototype (see Fig. 4.22(b)) were 0.71 V and 10.7mW, respectively at 50Hz with a load resistance of 50 Ω. It was stated that hybrid generator can harvest 81.4% more power than an individual generator.
Figure 4.22: (a) Schematic presentation of cross sectional view multimodal energy harvester (electromagnetic with piezoelectric system). T shape cantilever was used as a resonator [259]. (b) Hybrid power generator prototype combined with piezoelectric and electromagnetic system. Two piezoelectric plates were used with the cantilever substrate. A bridge rectifier circuit was used to convert the generated ac signal to dc [260].

More recently, Li et al. [261] studied ways to harvest power effectively from multi-source (e.g., electromagnetic and piezoelectric system) power generator using wide random vibration (see Fig. 3.23(a)). The study includes modeling, simulation, experimental tests. Dimensionless parameters were developed for mean power and spectral density calculation to make the system more effective in random excitation. It was reported that maximum power can be achieved when load resistance of the hybrid system becomes equal to the matching impedance at resonant frequency. It was also observed that coupling strength greatly affects the frequency band width (e.g., if the coupling strength becomes high then the frequency bandwidth becomes wide as well as mean power and power density of the system).

Additionally, Yu et al. [262] researched ways to improve the efficiency of the hybrid (e.g., piezoelectric and electromagnetic) power generator using a power conditioning circuit. MEMS piezoelectric cantilever with Si proof mass and NdFeB were used to build the hybrid power generator. PCB technology was used for micromachining the coil fabrication on the bottom surface of the harvester. PCB consists of AC-DC rectifier with dc-dc buck converter to regulate the generated voltage. The maximum voltage and power of 3.6V and 40.62 µW was obtained at 55.9 Hz from the designed prototype (see Fig. 4.23(b)).
Figure 4.23: (a) Schematic illustration of hybrid power generator [261]. (b) Developed hybrid power generator with power management circuit. Number of cantilever is 5 having a size of $5 \times 2.4 \times 0.05 \text{ mm}^3$ [262].

Another effective approach to generate power from the combination of thermoelectric and electromagnetic energy harvester was presented by Toreyin et al. [263]. Thermoelectric materials Cr-Al and permanent magnet NdFeB were used in the cantilever based hybrid power generator. Ambient temperature was used as a heat source for thermoelectric module. The dimension of their designed prototype is $9.5 \times 8 \times 6\text{ mm}^3$ (see Fig. 4.24). A maximum voltage and power of 16.7mV and 1.91nW (from thermoelectric 0.79nW and electromagnetic 1.12nW) was measured, respectively at 3.45 kHz.

Figure 4.24: (a) Schematic diagram of multi-source vibration based micro power generator. (b) Paylene C was use for cantilever structure and Si was used as a heat sink for thermoelectric module [263].

Zhang et al. [264] studied a new vibration based hybrid generator combined with triboelectric nano-generator and an electromagnetic generator. Triboelectric generator (TG) is a new technology which converts low frequency vibration into electrical energy. The conversion principal of triboelectric generator is the combination of triboelectrification and electrostatic
induction. The size of the hybrid generator is $5 \times 5 \times 25 \text{ cm}^3$. The maximum power output from triboelectric nano-generator and an electromagnetic generator are 4.9mW and 3.5mW under 6MΩ and 2KΩ, respectively. A summary of literature review on hybrid micro energy harvesters is given in Table 4.6.

### Table 4.6: Summary of literature review of vibration based hybrid power generator.

<table>
<thead>
<tr>
<th>Reference, year</th>
<th>Mechanism</th>
<th>Materials</th>
<th>Reson. Frequency (Hz)</th>
<th>Power</th>
<th>Voltage</th>
<th>Load Resistance (Ω)</th>
<th>Accela. (g=9.81 ms$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tadesse et al. [259], 2009</td>
<td>Piezoelectric &amp; Electromagnetic</td>
<td>PZN (PT)</td>
<td>20</td>
<td>0.25 W &amp; 0.25mW</td>
<td>120</td>
<td>35g</td>
<td></td>
</tr>
<tr>
<td>Toreyin et al. [263], 2010</td>
<td>Thermoelectric &amp; Electromagnetic</td>
<td>Cr/Al &amp; NdFeB</td>
<td>3450</td>
<td>1.91 nW</td>
<td>16.7mV</td>
<td>680</td>
<td></td>
</tr>
<tr>
<td>Sang et al. [260], 2012</td>
<td>Piezoelectric &amp; Electromagnetic</td>
<td>PZT-51 &amp; NdFeB</td>
<td>50</td>
<td>10.7mW</td>
<td>0.71 V</td>
<td>50</td>
<td>0.4g</td>
</tr>
<tr>
<td>Yu et al. [262], 2015</td>
<td>Piezoelectric &amp; Electromagnetic</td>
<td>PZT &amp; NdFeB</td>
<td>55.9</td>
<td>40.62µW</td>
<td>3.6V</td>
<td>0.2g</td>
<td></td>
</tr>
<tr>
<td>Zhang et al. [264], 2015</td>
<td>Triboelectric nano-generator &amp; Electromagnetic</td>
<td></td>
<td></td>
<td>4.9mW &amp; 3.5mW</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.4 Conclusion

Significant development of MEMS has made the micro power generators more demandable in the area of WSNs in recent years. Vibration based MPGs can be one of the best fits for the self-powered WSNs. This review paper presents the research headway of VMPGs. VMPG systems (i.e., electromagnetic, piezoelectric, and hybrid system) require external vibration sources to operate. However, vibration produced by real life sources is typically intermittent in nature which restricts harvesting power at constant rate using VMPGs. Nevertheless, due to the wide range of application potential and several inherent advantages, VMPGs can be suitable alternatives to fulfill the energy requirement at many small scale applications.
From the research conducted on VMPGs, it is noted that researchers have been facing some challenges to achieved required energy from the system. According to Eq. (3.1), the maximum power depends on vibration frequency (where natural frequency equals the system vibrational frequency) and maximum amplitude of the external vibration force. But due to small size of the devices, the resonant frequency is high which is difficult to achieve [139]. Another problem is the narrow operating bandwidth [264-266]. It is known that the frequency of the environmental vibration is not predetermined as well as not stable which is low in amplitude and random. Thus, this is hard to extract energy from such environment with VMPGs. In most of the research papers, rectangular shaped cantilevers were used in piezoelectric or electromagnetic type VMPG because of their simple design, easy constructor or ease of fabrication. But the main disadvantage of using such shape is that it has a very poor average strain [267]. Low power density is (power/volume^3) another big problem. Many MPGs have been designed and built but most of them suffer low power density problem.

4.5 Nomenclature

\begin{align*}
  b_e & \quad \text{Electrical damping} \\
  b_m & \quad \text{Mechanical damping} \\
  b_t & \quad \text{Total damping} \\
  k & \quad \text{Spring constant} \\
  L & \quad \text{Coil inductance} \\
  m & \quad \text{Proof mass} \\
  P & \quad \text{Power output} \\
  R_C & \quad \text{Internal coil resistance} \\
  R_L & \quad \text{Load resistance} \\
  V & \quad \text{Load voltage}
\end{align*}
Chapter 5

Energy harvesting by ‘T-shaped’ cantilever type electromagnetic vibration based micro power generator from low frequency vibration sources

“A version of this chapter has been submitted: Abu Raihan Mohammad Siddique, Shohel Mahmud, Bill Van Heyst, “Energy harvesting by ‘T-shaped’ cantilever type electromagnetic vibration based micro power generator from low frequency vibration sources,” Sensors & Actuators: A. Physical (Elsevier), 2016.”

5.1 Introduction

Over the last two decades, a considerable amount of research has been conducted to identify and characterize different transduction techniques to convert energy from structural vibration sources into electricity [268, 269]. The major objective behind such research works is to power the autonomous function of the self-powered electronic systems including microelectromechanical systems (MEMS) [270] and wireless sensors networks (WSN) [18]. In the next decade, wireless sensors networks and portable/wearable small electronic devices are expected to establish a new era of smart wearable technologies that have a reduced environmental footprint and thus more eco-friendly. The technological advancement of MEMS enables the size reduction of small electronic devices from mili to micro/nanoscale with a power consumption ranging from miliwatt (mW) to microwatt (µW) [271]. The finite lifetime of traditional batteries that have been used to run a large number of such electronic devices [3] has presented limitation and the periodic replacement of such batteries can be labor intensive and costly in the case of high population applications (e.g., human and livestock health monitoring and tracking systems). The vibration-based micro power generator (VMPG) is an attractive alternate to fulfill the power requirement for the portable electronic devices [272, 273].

Any power generator that generates power at mili to microscale range is referred to the micro power generator or MPG. MPGs which use structural vibration (a common form of kinetic
energy) as an input to generate electricity are known as vibration based MPG or VMPG. VMPGs have some advantages over other MPG systems that use solar, wind, waste heat, acoustic etc. as input energy sources, including comparatively high power densities and less maintenance costs [5]. A schematic is presented in Fig. 5.1 to illustrate the energy conversion process from vibration energy into electrical energy through a transducer. There are three major types of transduction mechanisms used for MPG: electromagnetic, piezoelectric, and electrostatic. Electromagnetic and piezoelectric are the widely used conversion techniques for VMPGs due to their high power harvesting capability and power density [9]. Nevertheless, the electromagnetic system is preferable for VMPGs due to its high current output, low output impedance, and tunable frequency mechanism over the piezoelectric and the electrostatic transducer mechanisms [206].

![Schematic diagram of a transduction mechanism for low-frequency vibrational based energy harvesting system using electromagnetic induction technique.](image)

**Figure 5.1:** Schematic diagram of a transduction mechanism for low-frequency vibrational based energy harvesting system using electromagnetic induction technique.

Since 1996, a considerable amount of research have been reported in the literature on low-frequency vibration based electromagnetic VMPG (or EVMPG). Williams and Yates [139] were the first to design an energy harvester capable of generating power from 1 µW to 0.1 mW in the frequency range from 1 to 100 Hz. Subsequently, different researchers have investigated cylindrical EVMPG using frequencies ranging from 6 Hz to 10 Hz and with power output ranging from 1.2 nW to 4.84 mW [186, 187, 209-211, 274]. More recently, Yang et al. [275] designed a cylindrical EVMPG with a maximum power output of 13.4 mW at 5.7 Hz.
In addition to cylindrical and rectangular shaped EVMPGs, researchers have been trying to use other designs of cantilever beams, such as T’, ‘U’, ‘A’, and spring shaped cantilevers to obtain low natural frequency for the EVMPGs [147, 276-278]. T-shaped cantilevers have advantages over other shapes including easy to design, construct, high power output, maximum displacement, and low natural frequency [276, 279]. Most of the research previously reported on T-shaped cantilever type energy harvesters is based on a piezoelectric transducer mechanism. For example, O’Keeffe et al. [280] designed a piezoelectric T-shaped beam type VMPG capable of producing a power output of 0.45 µW at 110 Hz. Deepak and Vikas [147] developed a similar VMPG using a T-shaped beam that could generate 2.68 V at 147 Hz. In later studies, Akin-Ponnle et al. [281] and Tufekcioğlu and Dogan [282] designed T-shaped VMPGs capable of generating 48 nW at 100 Hz and 141.61 µW power at 153 Hz, respectively. The resonant frequencies, however, of the reported VMPGs [281, 282] were high and the power generation was too low for practical applications. To address these drawbacks of the piezoelectric transducer, an electromagnetic transduction mechanism can be used instead for the T-shaped cantilever beam type VMPG system to improve the performance.

In this work, a T-shaped cantilever type EVMPG using an electromagnetic transduction mechanism has been proposed to harvest energy from low frequency mechanical vibrations (i.e., less than 10 Hz) from sources such as the movement of humans and cattle, vibration in automobile dashboard or instrument panels, and vibrations in bridges due to pedestrians [5, 8]. A T-shaped cantilever beam was designed and tested which had a natural frequency less than 10 Hz. Both theoretical analysis and experimental tests were conducted to validate the output results of proposed configuration from four different EVMPG configuration designs. Furthermore, additional experimental investigations were carried out on the proposed configuration for further characterization of the harvester. Finally, a small portable EVMPG prototype was developed and was tested at different conditions using human movement.

5.2 The Basic Principle of Electromagnetic VMPG

Electromagnetic VMPGs (or EVMPG) use Faraday’s law of electromagnetic induction to convert vibration energy into electricity. According to Faraday’s law, an electromagnetic force
(emf) is induced when a coil moves between magnets or vice versa and this emf causes a current flow in the load circuit. EVMPG can be approximated by a mechanical spring-mass-damper system as shown in Fig. 5.2(a), while the equivalent electromechanical model of the EVMPG system is shown in Fig. 5.2(b).

Figure 5.2: (a) Spring-mass system representation of EVMPG model. (b) Electromechanical representation of the system [9].

In Fig. 5.2(a), a displacement motion $y(t)$ is considered acting on a seismic mass ($m$) of the generator frame which results in a displacement $x(t)$ between the mass and the fixed frame. Therefore, two different forces are introduced in this system: a damping force whose damping coefficient is $b_t$ ($b_t = b_e + b_m$, where $b_e$ is the electrical and $b_m$ is the mechanical damping coefficients, respectively) and a spring force where the stiffness of the spring system is $k$. In Fig. 5.2(b), $L$ is the coil inductance, $R_C$ is the coil resistance, and $V$ is the root-mean-square (RMS) voltage output across the load resistance $R_L$ of the EVMPG, which is given by [5]:

\[
V = \frac{1}{\sqrt{2}} \frac{B_l \omega_y Y_{\text{max}} \left( \frac{\omega_c}{\omega_n} \right)^2}{\left( 1 - \left( \frac{\omega_c}{\omega_n} \right)^2 \right)^{\frac{1}{2}} + \left( \frac{2 \zeta \omega_c}{\omega_n} \right)} \times \frac{R_L}{R_L + R_C} \quad \quad (5.1)
\]
where $B$ is the magnetic flux density, $l$ is the length of the coil, $Y_{\text{max}}$ is the maximum displacement of the beam, $\omega_e$ and $\omega_n$ are the excitation and the natural frequency of the system, respectively, and $\zeta_t$ is the total damping factor ($\zeta_t = \zeta_e + \zeta_m$, where $\zeta_e$ is the electrical damping factor and $\zeta_m$ is the mechanical damping factor, respectively). The instantaneous power output ($P$) of the EVMPG can then be written as:

$$P = \frac{V^2}{R_L}$$  \hfill (5.2)

### 5.3 Design of a T-Shaped Cantilever Beam

VMPGs generate a large amount of power at or near their resonant frequencies. The natural frequencies of a cantilever beam can be varied by adjusting their geometric profiles (i.e. shape, length, width, and thickness), using different materials, using different masses mounted on the beam, and changing the center of the gravity of the masses [283, 204]. Many sources produce vibration in a relatively wide range of natural frequencies which results in larger frequency ratios. For the effective utilization of the vibration energy from such sources and widen the bandwidth of the power generation, the cantilever type VMPGs are expected to have closely spaced natural frequencies (i.e. lower frequency ratios) those fall within the frequency range of sources.

Typically, rectangular-shaped cantilever beams, operating at their lower natural frequencies, are used to design EVMPGs [5]. As a baseline EVMPG, a brass rectangular beam, with dimension of 10 cm × 1.5 cm × 0.06 cm, was used in this paper with first three natural frequencies of 33.69 Hz ($= \omega_1$), 210.94 Hz ($= \omega_2$), and 433.48 Hz ($= \omega_3$), respectively. The corresponding frequency ratios are 6.26 ($= \omega_2 / \omega_1$) and 12.87 ($= \omega_3 / \omega_1$), respectively. Brass was selected for its excellent non-magnetic properties.

In order to manipulate the natural frequency and obtain a smaller frequency ratio, a T-shaped cantilever beam was developed by incorporating an additional arm to the tip of the rectangular
beam (see Fig. 5.3). The mode shapes of the T-shaped beam at the first three natural frequencies were obtained by using finite element analysis (FEA) in SolidWorks [284] and are illustrated in Fig. 5.4. Further FEA was performed to determine the first and second natural frequencies of the T-shaped cantilever beam by varying the length ($L$) and the width ($W$) of the additional arm. Figures 5.5(a) and 5.5(b) present the variations in the first natural frequency ($f_1$), second natural frequency ($f_2$), and the frequency ratio ($f_2/f_1$) with $W$ and of $L$, respectively. It should be noted that no magnet mass was added to the beam during this analysis.

**Figure 5.3:** The left image is for the baseline rectangular-shaped cantilever beam while the right images are for the T-shaped beam.

**Figure 5.4:** (a) 1$^{\text{st}}$ mode, (b) 2$^{\text{nd}}$ mode, and (d) 3$^{\text{rd}}$ mode of the freely vibrating T-shaped beam at their respective natural frequencies.
Figure 5.5: (a) Natural frequencies and frequency ratios with respect to different widths. (b) The frequency ratio at different lengths of the additional arm.
The reason behind the variations in the natural frequencies is that the inertial mass \((m)\) and the stiffness \((k)\) of the cantilever beam changes with changing geometric and material properties [28]. Figure 5.5(a) shows that 1\(^{\text{st}}\) natural frequency \((f_1)\) gradually decreases while 2\(^{\text{nd}}\) natural frequency \((f_2)\) and frequency ratio \((f_2/f_1)\) rapidly decreases with increasing \(W\) of the beam. However, it must be considered that a magnet mass will be added later that will again decrease the natural frequencies of the beam (< 10 Hz). Therefore, 7 cm of beam width \((W)\) is compromised for further investigation. Figure 5.5(b) illustrates that the frequency ratio \(f_2/f_1\) fluctuates whereas 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) natural frequencies decrease with increasing \(L\). It was observed that the frequency ratio \(f_2/f_1\) becomes minimum (i.e., 4.16) when \(L\) is 2 cm (where, \(f_1 = 15.08 \text{ Hz}\)). Therefore, the final geometry of the additional arm of the T-shaped beam was fixed at 2 cm \(\times\) 7 cm \(\times\) 0.06 cm (where, \(L = 2\) cm, \(W = 7\) cm, and thickness is 0.06 cm) in the following study.

5.4 Experimental Work and Theoretical Validation

5.4.1 Experimental Set-Up, Tests, and Results

The experimental setup, as depicted in Fig. 5.6, consisted of a function generator, a shaker, an accelerometer, an oscilloscope, a multimeter, and an NI DAQ system. The function generator (GFG-8020H, supplier: GW Instek) was used to excite the shaker (SF9324, supplier: Pasco Scientific) at a given frequency and acceleration. The accelerometer (SHGLVM024, supplier: Shimana) was used to measure the base acceleration of the system vibration so that the supplied acceleration could be controlled. The output signal of the EVMPG was measured using a two-channel digital real time oscilloscope (TDS 210, supplier: Tektronix). A digital multimeter (Fluke 116 series) was used to measure the load resistance and RMS voltage output of the EVMPG. The data recorder (NI USB-6221, supplier: National Instruments) was used to record the output data on a computer for further processing.
For the experimental test, EVMPGs with four different configurations were manufactured with proposed T-shaped cantilever as shown in Fig. 5.7. The same analytical approach, discussed in Section 3, was applied to analyze the following four possible configurations before manufacturing to ensure low natural frequencies. It was found from the FEA of these four configurations that the natural frequency with the attached magnet mass was less than 10 Hz. Therefore, these four configurations were considered further for experimental test in order to finalize one configuration for EVMPG prototype.

**Figure 5.7:** Four different T-shaped beam configurations used for the experimental test to finalize the EVMPG prototype.
• Configuration A (Fig. 5.7(a)) consisted of a cylindrical magnet (NdFeB-N42, supplier: Indigo Instruments) mounted firmly on the top surface of the beam so that the magnet moved through the electrical coil;
• Configuration B (Fig. 5.7(b)) consisted of two cylindrical magnets mounted on the top and the bottom surfaces which moved through two electrical coils at the top and bottom, respectively;
• Configuration C (Fig. 5.7(c)) consisted of four rectangular magnets (NdFeB-N42) mounted sidewise on the top and bottom surfaces of the beam with a small portion from the middle of the beam removed so that the electrical coil was kept fix between the moving magnets; and
• Configuration D (Fig. 5.7(d)) consisted of an electrical coil which was attached to the middle of the vibrating beam. In this configuration, as the beam vibrates, it passes the coil between two pairs of fixed magnet supported with a back-iron bar in order to make a closed path for the magnetic field.

Table 5.1 shows the cantilever beam, magnet, and electrical coil properties used for the subsequent frequency analysis and designing of different EVMPG configurations. The proposed experimental setup was used to record the output data from all configurations.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension of the rectangular beam</td>
<td>10 cm × 1.5 cm × 0.06 cm</td>
</tr>
<tr>
<td>Dimension of the additional arm</td>
<td>2 cm × 7 cm × 0.06 cm</td>
</tr>
<tr>
<td>Elastic modulus of brass</td>
<td>$1 \times 10^{11}$ N/m²</td>
</tr>
<tr>
<td>Poisson’s ratio of brass</td>
<td>0.33</td>
</tr>
<tr>
<td>Mass density of brass</td>
<td>8500 kg/m³</td>
</tr>
<tr>
<td>Coil length (l)</td>
<td>552 cm</td>
</tr>
<tr>
<td>Coil diameter</td>
<td>2.55 cm</td>
</tr>
<tr>
<td>Thickness of the coil</td>
<td>0.65 cm</td>
</tr>
<tr>
<td>Properties</td>
<td>Unit</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Weight of the coil</td>
<td>13.75 g</td>
</tr>
<tr>
<td>Coil resistance ($R_C$)</td>
<td>1.4 Ω</td>
</tr>
<tr>
<td>Air gap between coil and magnet</td>
<td>0.425 cm</td>
</tr>
<tr>
<td>Air gap between two side magnets</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>Magnet</td>
<td>NdFeB (N42)</td>
</tr>
<tr>
<td>Magnetic flux density ($B$) [285]</td>
<td>1.3 T</td>
</tr>
<tr>
<td>Magnetization field ($M$)</td>
<td>1050.4 KA/m</td>
</tr>
<tr>
<td>Mass of the cylindrical magnet ($h=12.7 \text{ mm}, d=6.4 \text{ mm}$)</td>
<td>7.51 g</td>
</tr>
<tr>
<td>Mass of the rectangular magnet ($20 \text{ mm} \times 10 \text{ mm} \times 5 \text{ mm}$)</td>
<td>3.17 g</td>
</tr>
<tr>
<td>Thickness of the back-iron bar</td>
<td>0.07 cm</td>
</tr>
</tbody>
</table>

The open circuit RMS voltage output generated by the four configurations of EVMPGs is presented in Fig. 5.8. The output voltage increases with increasing frequency of the vibration source and reaches a maximum value at the resonant frequency. The RMS voltage output at the resonant frequency was observed to be a maximum for Configuration D (98.2 mV at 6.29 Hz) and a minimum for Configuration A (39.9 mV at 8 Hz) with a base vibration acceleration of 0.8 ms$^{-2}$. Therefore, Configuration D was selected for additional analysis, characterization, and optimization. Besides, Fig. 5.9 presents the variation in the generated voltage for Configuration D only with respect to time. The generated voltage shows periodic variation within a range of 150 mV to 150 mV when the frequency is 6.29 Hz.
Figure 5.8: Open circuit RMS voltage with varying frequencies for the four different EVMPG configurations.

Figure 5.9: Alternating open circuit voltage output waveform with respect to time recorded by NI DAC system for Configuration D.
5.4.2 Detailed Characterization of Configuration D

The arrangement of electric coil and the magnets for Configuration D is shown in Fig 5.10. Magnetic flux lines can be drawn from the north pole (N) to the south pole (S) through the air gap (see Fig. 5.10(a)). A portion of this magnetic flux lines goes back from to the south pole from the north pole and the remaining flux lines are leaked into the surrounding (see Fig. 5.10(b)). This flux line leakage can be reduced by adding an iron bar to the back of the magnets and making a closed path for the flux lines as shown in Fig. 5.10(c).

![Figure 5.10:](image-url)

**Figure 5.10:** (a) Schematic diagram of the configuration of four magnets and coil of Configuration D, (b) traveling direction of magnetic flux lines before adding an back-iron bar, and (c) closed circular path for the magnetic flux lines after adding an back-iron bar.
The effect of a back-iron thickness on the RMS voltage generated by Configuration D is presented in Fig. 5.11. In Fig. 5.11(a), peak open circuit RMS voltage is plotted for different thicknesses of the back-iron bar ranging from 0 mm (i.e. no back-iron) to 7 mm at the resonant frequency for Configuration D. At the resonant frequency, Configuration D generates a maximum voltage (160.1 mV at 6.29 Hz) for 4.2 mm iron thickness. However, the magnitude of the maximum voltage generated increased with increasing back-iron thickness until an asymptotic limit of approximately 160 mV is reached. Incorporation of the back-iron into the magnetic circuit reduces the magnetic flux leakage thus improving the magnetic flux density in the air gap until it gets saturated. Subsequently, it helps to improve the RMS voltage generated by Configuration D. Nevertheless, after reaching to the maximum voltage, the voltage generation remains almost constant because of saturated magnetic flux density in the air gap. Therefore, Configuration D with a back-iron thickness of 4.2 mm was selected for further experimental investigations. Figure 5.11(b) shows the fluctuation of RMS voltage output with varying frequency between 4 Hz and 8Hz for different back-iron thicknesses ranging from 0 mm to 4.2 mm as thickness greater than 4.2 mm generate the same maximum voltage as the 4.2 mm thickness beam.
Figure 5.11: (a) Peak open circuit RMS voltage with respect to different thicknesses of the back-iron at its resonant frequency and (b) RMS voltage output at different frequencies for Configuration D varying back-iron bar thickness between 0 mm and 4.2 mm.
The effect of base acceleration of vibration on the open circuit RMS voltage output at different frequencies was also investigated for Configuration D and is presented in Fig. 5.12. Vibrational acceleration is the velocity per unit time of the shaker machine on which the base of the T-shaped cantilever is attached. Figure 5.12 illustrates that, as the base acceleration increases, so too does the maximum output RMS voltage at resonant frequency. Moreover, the output voltage increased nearly linearly with increasing base acceleration. Increasing the base acceleration results in increasing coil moving speed which increases the tip amplitude of the cantilever beam. Therefore, the cantilever cuts off the magnetic flux more frequently thus increase the voltage output (maximum peak 160.1 mV at 6.29 Hz when it was excited at 0.8 ms$^{-2}$).

![Figure 5.12: Open circuit RMS voltage output against different frequencies for Configuration D.](image)

The effect of load resistance ($R_L$) at different base accelerations on the load voltage and load power output of Configuration D is illustrated in Fig. 5.13. The experiments were carried out by
increasing the load resistance for a fixed base acceleration (see Fig. 5.13(a)). The voltage output increased rapidly with increasing load resistance value. However, the variation in the load voltage was negligible when $R_L$ was much larger than the coil resistance ($R_C=1.4 \, \Omega$). This trend in the load voltage variation can be confirmed from Eq. (5.1) which shows that the RMS load voltage of the EVMPG is proportional to the resistance ratio, $R_L/(R_C + R_L)$. This ratio asymptotes and almost becomes independent of $R_C$ when $R_L >> R_C$. Figure 5.13(b) shows the power output for the cases shown in Fig. 5.13(a). It was observed that initially output power increases rapidly with increasing the load resistance ($R_L$), reaching a maximum near a load resistance of between 8.2 $\Omega$ and 10 $\Omega$, and then decreased gradually with further increases in the load resistance. According to Eq. (5.2), the load power output depends on the load voltage and $R_L$. Since the voltage output becomes nearly constant after a certain value of $R_L$, the power output therefore decreases after reaching the peak load voltage with further increases in $R_L$. Configuration D generated a maximum 1.35 mW at 8.2 $\Omega$ under the resonant frequency of 6.29 Hz and base acceleration of 0.8 ms$^{-2}$.
Figure 5.13: (a) RMS load voltage and (b) load power with respect to various load resistances for different base accelerations at the resonant frequency of 6.29 Hz with 4.2 mm back-iron for Configuration D.

The effect of the air-gap thickness between the magnet on peak RMS voltage and power production was also investigated with the results given in Fig. 5.14. The periodic movement of the electric coil in the air gap magnetic field produces an emf which, in turn, causes an electric current in the coil. For a given coil velocity, the magnitude of the produced emf is larger when the air gap magnetic flux density is higher. However, the produced electric current interacts with the magnetic field and results in a back emf which can suppress the coil movement. The strength of the magnetic field depends strongly on the air gap thickness. A stronger magnetic field is observed at the smaller gap thickness; however, the value of back emf can be significant when the gap thickness is small. Therefore, peak RMS voltage and power occur at a certain gap thickness as observed from Fig. 5.14. The air gap thickness was varied from 12 mm and 40 mm, which produced maximum power and voltage at a 20 mm thickness as illustrated in Fig. 5.14 (i.e. 1.35 mW and 105.1 mV at 6.29 Hz for 8.2 Ω). A smaller or larger than 20 mm air gap thickness resulted in smaller values of peak power and RMS voltage.
Figure 5.14: Load RMS voltage and load power at different air gaps between the magnets for Configuration D at 6.29 Hz using 8.2 Ω load resistance for 0.8 ms².

5.4.3 Theoretical Analysis

A theoretical analysis was performed in order to validate the experimental results obtained from Configuration D. The magnetic flux density \( (B) \), natural frequency \( (\omega_n) \), vibration amplitude \( (Y_{max}) \), stiffness of the beam \( (k) \), effective mass \( (m) \), and mechanical damping coefficient \( (b_m) \) were determined from the numerical simulations using SolidWorks and COMSOL Multiphysics [271, 284, 286]. Figure 5.15 shows the fluctuation of the magnetic flux density in the air gap along the length of the magnet faces. The magnetic flux density is non-linear in the air gap and acts in the opposite direction for the bottom and top magnets. From the numerical simulation, it can be seen that the average magnetic flux density \( (B) \) is calculated as 0.097 T.
The stiffness \((k)\) of the T-shaped cantilever beam was calculated using numerical simulations conducted in SolidWorks and found to be 50.89 N/m. The effective mass \((m)\) of the beam was calculated from \(m = \frac{k}{(2\pi f)^2} = 32.27\) g, where, the frequency of the beam was 6.29 Hz. The bandwidth of the half-power point \((BW)\) was obtained from the experimental results of power output as 0.38 Hz. The total damping factor was then calculated using [5]:

\[
\zeta_t = \frac{b_c + b_m}{2\sqrt{Km}} = \frac{(Bl)^2}{2\sqrt{Km}} + \frac{b_m}{2\sqrt{Km}} \tag{5.3}
\]

In Eq. (5.3), all parameters are known except for the mechanical damping coefficient \((b_m)\). The mechanical damping coefficient can be calculated from \(b_m = C_C \times \delta\), where \(C_C\) is the critical damping coefficient and \(\delta\) is the damping ratio, From experimental measurements, \(C_C = 2.55\)
N.s/m and $\delta = 0.00685$. A list of the parameter used in the analytical investigations of Configuration D is presented in Table 5.2. Based on these parameters and Eqs. (5.1) and (5.2), the theoretical RMS load voltages and load power output were calculated as given in Fig. 5.16 alongside the experimental results as a function of frequency when the system was excited at 0.8 ms$^{-2}$ with 8.2 $\Omega$. The agreement between the theoretical and experimental results are reasonable given the assumptions used to calculate some of the parameters such as magnetic flux density.

### Table 5.2: Parameter used for the analytical calculation of voltage and power.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic flux density ($B$)</td>
<td>0.097 T</td>
</tr>
<tr>
<td>Effective length of the coil ($l$)</td>
<td>5.5 m</td>
</tr>
<tr>
<td>Maximum vibration amplitude ($Y_{max}$)</td>
<td>1.695 mm</td>
</tr>
<tr>
<td>Stiffness of the beam ($k$)</td>
<td>50.89 N/m</td>
</tr>
<tr>
<td>Effective mass ($m$)</td>
<td>32.27 g</td>
</tr>
<tr>
<td>Load resistance ($R_L$)</td>
<td>8.2 $\Omega$</td>
</tr>
<tr>
<td>Coil resistance ($R_C$)</td>
<td>1.4 $\Omega$</td>
</tr>
<tr>
<td>Bandwidth of half-power point ($BW$)</td>
<td>0.38 Hz</td>
</tr>
<tr>
<td>Mechanical damping coefficient ($b_m$)</td>
<td>0.0175 Ns/m</td>
</tr>
<tr>
<td>Total damping factor ($\zeta_t$)</td>
<td>0.0185</td>
</tr>
</tbody>
</table>
5.4.4 EVMPG Prototype

A prototype of EVMPG (see, Fig. 5.17) based on the experimental and theoretical investigations on Configuration D was designed and tested for the practical applications. In order to use the EVMPG prototype for practical applications, the size of the Configuration D was reduced to nearly half of its geometry. The overall size of the prototype was 9 cm × 6.2 cm × 2.8 cm. The prototype was placed inside a container made of transparent Plexiglas having a size of 11 cm × 7.4 cm × 4 cm (see Fig. 5.17(c)). Table 5.3 gives the physical characteristics of the EVMPG prototype.
Figure 5.17: (a) T-shaped cantilever beam, (b) EVMPG with a wooden frame with 1.4 mm thick back-iron bar, and (c) EVMPG prototype covered by plexiglas.
Table 5.3: Physical characteristics of EVMPG prototype.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension of the rectangular beam</td>
<td>5 cm × 0.7 cm × 0.03 cm</td>
</tr>
<tr>
<td>Dimension of the additional arm</td>
<td>1.5 cm × 3.5 cm × 0.03 cm</td>
</tr>
<tr>
<td>Thickness of the brass plate</td>
<td>0.03 cm</td>
</tr>
<tr>
<td>Overall dimension of EVMPG</td>
<td>9 cm × 6.2 cm × 2.8 cm</td>
</tr>
<tr>
<td>Coil length</td>
<td>250 cm</td>
</tr>
<tr>
<td>Coil diameter</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>Coil thickness</td>
<td>0.5 cm</td>
</tr>
<tr>
<td>Coil resistance ($R_C$)</td>
<td>0.8 Ω</td>
</tr>
<tr>
<td>Load resistance ($R_L$)</td>
<td>5.6 Ω</td>
</tr>
<tr>
<td>Magnets (10 mm × 5 mm × 2.5 mm)</td>
<td>NdFeB (N42)</td>
</tr>
<tr>
<td>Back-iron bar thickness</td>
<td>0.14 cm</td>
</tr>
<tr>
<td>Air gap between magnets</td>
<td>1.5 cm</td>
</tr>
</tbody>
</table>

Figure 5.18 shows the generated open circuit RMS voltage by the EVMPG prototype as a function of vibration frequencies ranging from 2 Hz to 13 Hz. The EVMPG prototype generated a maximum open circuit voltage of 41.8 mV at 7 Hz for an acceleration of 0.8 ms$^{-2}$. Furthermore, the characterization of the prototype was determined at different load resistance ($R_L$) at the resonant frequency (see Fig. 5.19). The prototype generates a maximum power of 0.22 mW and RMS voltage of 35.2 mV at 5.6 Ω, 7 Hz, and 0.8 ms$^{-2}$.  

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Figure 5.18: Open circuit RMS voltage at different frequencies of EVMPG prototype at 0.8ms$^{-2}$.

Figure 5.19: Experimental results of load RMS voltage and power at various load resistance at 7 Hz resonant frequency of EVMPG prototype when it excited at 0.8 ms$^{-2}$. 
5.4.5 Experimental Tests with EVMPG Prototype in Real Scenario

The EVMPG prototype was tested using an experimental setup to simulate the motion of a human leg, as depicted in Fig. 5.20. The experimental setup included a voltage controller (1687B, supplier: BK Precision) and a DC motor (variable speed with the adjustable gearbox, 1-6 VDC, supplier: Plastruct Inc.). In addition, a wooden bar was attached to the motor shaft which was rotating and striking periodically a circular wooden disk which was mounted on an iron rod through a spring. A second wooden holder was connected at the bottom of the spring to assist the free movements (up and down) of the iron rod. From this experimental setup, the open circuit RMS voltage output of the EVMPG prototype was recorded at different speeds of the rotating wooden bar and is presented in Table 5.4.

![Figure 5.20: Schematic diagram of experimental setup with EVMPG prototype to simulate the human leg movements.](image)

The prototype was also attached to a human leg to get better real life application results (see Fig. 5.21). A comparison of output results at different moving conditions (i.e. normal walking, quick walking, and running) is presented in Table 5.4 between the experimental rig and the human leg. The results presented in Table 5.4 indicate that the average RMS voltage generated by both the experimental and the human leg tests were very similar for normal and quick walking. However, there is a much larger difference between the voltage output during running conditions which is likely the result of the entire mass of the human body striking through the heel while running which cannot be simulated with the current experimental set-up.
Figure 5.21: EVMPG prototype testing on the human leg at different conditions.

Table 5.4: The open circuit RMS voltage output at different movements.

<table>
<thead>
<tr>
<th>Test Conditions [287]</th>
<th>Testing duration (minutes)</th>
<th>Open circuit RMS voltage (peak voltage)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Experimental setup</td>
</tr>
<tr>
<td>Normal walking (120 steps)</td>
<td>5</td>
<td>5.3 (peak: 8.6)</td>
</tr>
<tr>
<td>Quick walking (150 steps)</td>
<td>5</td>
<td>9.6 (peak: 15.7)</td>
</tr>
<tr>
<td>Running (180 steps)</td>
<td>5</td>
<td>12.5 (peak: 19.6)</td>
</tr>
</tbody>
</table>

5.5 Uncertainty Analysis

The uncertainty regarding the sensors used during experimental tests was analyzed for the designed EVMPG prototype. Experimental data (i.e., resistance, voltage, and power output) were measured using a digital multimeter. Base acceleration of the vibration was measured by the accelerometer. The accuracy of the function generator was ±1 count (GFG-8020H, supplier: GW Instek). The overall uncertainty analysis of the prototype was accomplished by root-sum-squares (RSS) method [133] and was presented in Table 5.5. The relative uncertainty of generated power ($\delta_P$) of the EVMPG prototype can be calculated using Eqs. (5.4) and (5.5) [288].
Table 5.5: Uncertainty analysis of the final EVPG prototype

<table>
<thead>
<tr>
<th>Variables</th>
<th>Measured value, $x$</th>
<th>Uncertainty, $U_x$</th>
<th>Relative Uncertainty, $(U_x/x)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage, $V$</td>
<td>35.2 mV</td>
<td>± 0.5 % [mV]</td>
<td>± 0.014 %</td>
</tr>
<tr>
<td>Resistance, $R$</td>
<td>5.6 Ω</td>
<td>± 0.9 % [Ω]</td>
<td>± 0.16 %</td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.8 ms$^{-2}$</td>
<td>± 5 % [ms$^{-2}$]</td>
<td>± 6.25 %</td>
</tr>
<tr>
<td>Power, $P$</td>
<td>-</td>
<td>-</td>
<td>± 0.16 %</td>
</tr>
</tbody>
</table>

\[
P = \frac{V^2}{R} = V^2 \times R^{-1}
\]

\[
\delta_p = \frac{U_{x_P}}{x_p} = \left[ \frac{a_V \times U_V}{x_V} \right]^2 + \left[ \frac{a_R \times U_R}{x_R} \right]^2
\]

In Eq. (5.5), $a_V = 2$ and $a_R = -1$ (from Eq. (5.4)), therefore, the relative uncertainty was calculated to be ± 0.16 % for the designed EVMPG prototype.

5.6 Conclusion

In this work, a nonlinear T-shaped cantilever type EVMPG has been described for low-frequency applications. Four different configurations of T-shaped cantilever were considered for initial tests to select the EVMPG prototype. These four configurations were considered due to their low natural frequencies (less than 10 Hz). The Configuration D generated the largest maximum voltage and power output compared to other three configurations. The maximum load RMS voltage and power outputs of Configuration D were 105.4 mV and 1.35 mW at 6.29 Hz for 8.2 Ω and a base acceleration of 0.8ms$^{-2}$ with a 4.2 mm back-iron bar when air gap between the magnets was 20 mm. Further experimental investigations (i.e. changing the back-iron bar thickness, changing base acceleration level, changing air gap between the magnets) were performed to optimize Configuration D.

A EVMPG prototype was constructed based on the Configuration D. The constructed EVMPG prototype was capable of harvesting 35.2 mV and 0.22 mW at a resonant frequency of 7
Hz with 5.6 Ω for a base acceleration of 0.8 ms$^{-2}$. Such power is suitable for digital smart watches (< 1.5 mW), radio-frequency identification (RFID) locator (< 1.5 mW), quartz watches (5 µW), and wireless sensor nodes (100 µW) [9, 10, 145]. The prototype was experimentally tested at different conditions i.e., walking, quick walking, and running using experimental setup and on the human leg. Table 5.6 presents a comparison of the voltage and power output of T-shaped cantilever type VMPG system reported in the literature.

<table>
<thead>
<tr>
<th>Reference, year</th>
<th>Transduction method</th>
<th>Frequency (Hz)</th>
<th>Resistance</th>
<th>Acceleration (ms$^{-2}$)</th>
<th>Voltage and Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>O'Keeffe et al. [280], 2013</td>
<td>Piezoelectric</td>
<td>110</td>
<td>0.1 MΩ</td>
<td>9.8</td>
<td>1.74 V, 0.45 µW</td>
</tr>
<tr>
<td>Deepak and Vikas [147], 2013</td>
<td>Piezoelectric</td>
<td>147</td>
<td></td>
<td></td>
<td>2.68 V</td>
</tr>
<tr>
<td>Akin-Ponnle et al. [281], 2014</td>
<td>Piezoelectric</td>
<td>100</td>
<td>1 MΩ</td>
<td>30.2</td>
<td>48 nW</td>
</tr>
<tr>
<td>Tufekcioglu and Dogan [282], 2014</td>
<td>Piezoelectric</td>
<td>153</td>
<td>40 kΩ</td>
<td>20</td>
<td>141.61 µW</td>
</tr>
<tr>
<td>Current work (Configuration D</td>
<td>Electromagnetic</td>
<td>6.29</td>
<td>8.2 Ω</td>
<td>0.8</td>
<td>105.4 mV, 1.35 mW</td>
</tr>
<tr>
<td>and final prototype)</td>
<td></td>
<td>7</td>
<td>5.6 Ω</td>
<td>0.8</td>
<td>35.2 mV, 0.22 mW</td>
</tr>
</tbody>
</table>

5.7 Nomenclature

$B$ Magnetic flux density

$b_e$ Electrical damping coefficient

$b_m$ Mechanical damping coefficient

$b_t$ Damping coefficient

$C_C$ Critical damping coefficient
\( k \)  
Stiffness of the spring system

\( L \)  
Coil inductance

\( l \)  
Length of the coil

\( M \)  
Magnetization field

\( m \)  
Seismic mass

\( P \)  
Instantaneous power output

\( R_C \)  
Coil resistance

\( R_L \)  
Load resistance

\( V \)  
Root-mean-square (RMS) output voltage output

\( W \)  
Width of the additional arm

\( x(t) \)  
Displacement between the mass and the fixed frame

\( y(t) \)  
Displacement motion of the frame

\( Y_{max} \)  
Maximum displacement of the beam

**Greek Symbols**

\( \omega_e \)  
Excitation frequency

\( \omega_n \)  
Natural frequency

\( \zeta_t \)  
Total damping factor

\( \zeta_e \)  
Electrical damping factor

\( \delta \)  
Damping ratio
Chapter 6

Conclusions and Future Work

6.1 Conclusions

Details of the design, modeling, fabrication, and characterization for both a FTEG and an EVMPG prototype have been presented in this thesis. Each type of energy harvester has had an experimental component to ascertain the power generation along with a theoretical validation.

For the FTEG harvester, a complete manual fabrication process of FTEG has been described using a simple dispenser printing method using a polyester based, high heat resistive fabric and using $n$-type $(0.98\text{Bi,0.02Sb})_2(0.9\text{Te,0.1Se})_3$ and $p$-type $(0.25\text{Bi,0.75Sb})_2(0.95\text{Te,0.05Se})_3$ TE materials. The prototype had a high degree of flexibility and durability and was well suited for human body applications.

For the nonlinear T-shaped cantilever type EVMPG, four different configurations of the T-shaped cantilever were considered for initial tests to select the EVMPG prototype. Configuration D was found to generate the largest maximum voltage and power output compared to other three configurations. Further experimental investigations (i.e. changing the iron bar backing plate thickness, base acceleration level, and air gap distance between the magnets) were performed to optimize Configuration D. Finally, an EVMPG prototype was constructed based on the optimized Configuration D. The EVMPG prototype was experimentally tested at different conditions (i.e. walking, quick walking, and running) using an experimental setup on a human leg. Table 6.1 shows the overall contribution of this thesis.
### Table 6.1: Contribution of current work

<table>
<thead>
<tr>
<th>Findings from literature review</th>
<th>Research topics</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Research topics</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>TEG</strong></td>
<td></td>
</tr>
<tr>
<td>Most of the printing fabrication techniques are complex and expensive which require very high curing temperature and high configured electronic equipment for fabrication.</td>
<td>No research performing on T-shaped cantilever for electromagnetic VMPG system. Most of the cases, EVMPG uses rectangular shaped cantilever or cylindrical beam with a large natural frequency [5].</td>
<td>A manual dispenser printing technology has been demonstrated which is simple, less expensive, requires less curing temperature, and does not require any thin film mechanism. Fabricated TEG is very flexible, twistable, and durable with the substrate as well as conforming well to the human body.</td>
</tr>
<tr>
<td>Bending and twisting characteristics are limited.</td>
<td>A very few research has been conducted on low frequency (&lt; 10 Hz) based electromagnetic VMPG [5, 9].</td>
<td></td>
</tr>
<tr>
<td>Voltage output is very low.</td>
<td>Most of the cases, power output of T-shaped VMPG using piezoelectric transducer technique is from µW to nW scale [5].</td>
<td>The power output of the T-shaped EVMPG is in mW range.</td>
</tr>
</tbody>
</table>
The energy generated by the both FTEG prototype and T-shaped cantilever type EVMPG prototype can be used to operating most of portable electronic devices as listed in Table 1.1. The overall results from the both experimental tests include:

i) The maximum open circuit voltage and power output of FTEG prototype A (5 mm × 5 mm × 2.5 mm) and prototype B (5 mm × 5 mm × 1.4 mm), were 22.1 mV and 2.21 nW and 23.9 mV and 3.107 nW, respectively, at a 22.5 °C temperature difference.

ii) The maximum load RMS voltage and power outputs of Configuration D were 105.4 mV and 1.35 mW at 6.29 Hz for 8.2 Ω and a base acceleration of 0.8ms⁻² with a 4.2 mm iron bar backing plate thickness when the air gap between the magnets was 20 mm. However, the EVMPG prototype was capable of harvesting 35.2 mV and 0.22 mW at a resonant frequency of 7 Hz with 5.6 Ω for a base acceleration of 0.8 ms⁻².

6.2 Future Work

One common area of future research for both energy-harvesting systems is to focus on a power conditioning circuit (i.e. power rectification, power boost up, and energy storage system) to make more efficient and compact energy harvesters. Specific recommendations for each of the energy harvesting systems are given below.

6.2.1 FTEG

Future work on FTEG design need to be concerned with not only the flexibility, but also about increasing the power output from wearable thermoelectric generators. Some challenging research areas that are still to be improved include:

- Poor figure of merit of thermoelectric materials,
- Low thermal resistivity,
- Thickness of the substrate,
- Matching load, and
- Modifying power management circuit for steady state power output [289, 290].
Recently, researchers have been using nano and organic composite materials instead of typical thermoelectric materials to improve the efficiency of the generator as well as to make it flexible and thin. Future work will need to focus on the fabrication process using a thinner substrate with automated controlled dispenser machine so that the fabrication mechanism can be more precise. Moreover, different TE materials, proper insulation, printed circuit board, and optimization of geometrical structures should be investigated for the further developments in the field of FTEG.

6.2.2 EVMPG

Further research on such vibration based MPGs will accelerate the development of energy harvested from renewable resources and make the miniature electric devices more reliable and durable. Due to the many challenges and limitation, there are many areas where improvements are necessary to make the VMPGs efficient and more usable. Such improvements are:

- Developing new design and cantilever structure,
- Improving strain by maximizing the proof mass,
- Developing tuning circuit for achieve the resonant frequency,
- Designing a wide bandwidth generator,
- Implementing frequency up conversion technique,
- Applying nonlinear dynamical systems, and
- Improving piezoelectric material properties [291].

A large portion of the recent research has been conducted to modify the generator size, shape and to introduce a power conditioning circuit in order to widen the frequency bandwidth system and harvest maximum power from the vibration sources.
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The members of the University of Guelph Research Ethics Board have examined the protocol which describes the participation of the human participants in the above-named research project and considers the procedures, as described by the applicant, to conform to the University's ethical standards and the Tri-Council Policy Statement, 2nd Edition.

The REB requires that researchers:

- Adhere to the protocol as last reviewed and approved by the REB.
- Receive approval from the REB for any modifications before they can be implemented.
- Report any change in the source of funding.
- Report unexpected events or incidental findings to the REB as soon as possible with an indication of how these events affect, in the view of the Principal Investigator, the safety of the participants, and the continuation of the protocol.
- Are responsible for ascertaining and complying with all applicable legal and regulatory requirements with respect to consent and the protection of privacy of participants in the jurisdiction of the research project.

The Principal Investigator must:

- Ensure that the ethical guidelines and approvals of facilities or institutions involved in the research are obtained and filed with the REB prior to the initiation of any research protocols.
- Submit a Status Report to the REB upon completion of the project. If the research is a multi-year project, a status report must be submitted annually prior to the expiry date. Failure to submit an annual status report will lead to your study being suspended and potentially terminated.

The approval for this protocol terminates on the EXPIRY DATE, or the term of your appointment or employment at the University of Guelph whichever comes first.

Signature:               Date: April 22, 2016

A. Papdopoulos
Chair, Research Ethics Board-NPES

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<th>April 22, 2016</th>
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<td>April 22, 2017</td>
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