# DEVELOPMENT OF LOW FREQUENCY ELECTROMAGNETIC VIBRATION ENERGY HARVESTER

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# DEVELOPMENT OF LOW FREQUENCY ELECTROMAGNETIC VIBRATION ENERGY HARVESTER

**by**

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## TABLE OF CONTENTS

CHAPTER 3 - METHODOLOGY

## LIST OF TABLES

# LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | Alternating Current |
| CAD | Computational Aided Design |
| DC | Direct Current |
| DDHO | Driven Damped Harmonic Oscillation |
| EM | Electromagnetic |
| EMF | Electromotive force |
| FFT | Fast Fourier Transform |
| FRF | Frequency Response Function |
| mFCUP | Micro mechanical frequency up conversion |
| MEMs | Micro electro mechanicals |
| NDFeB | Neodymium magnets |
| PFIG | Parametric frequency increased generator |
| PZT | Material of zirconatetitanate of piezoeletric |
| PVDF | Polyvinylidinefluoride |
| RF | Radio energy |
| TPMS | Tire pressure monitoring systems |
| VCA | Voice coil actuator |
| VEH | Vibration Energy Harvesting |
| VEMF | Back electromotive voltage |
| WSN | Wireless Sensor Network |

# LIST OF SYMBOLS

| | |
|---|---|
| $A$ | Surface Area of the coil |
| $A(\omega)$ | Calculated acceleration (radian per second) |
| $B$ | Magnetic field |
| $c_T$ | Total Damping coefficient |
| $c_e$ | Electrical damping coefficient |
| $c_m$ | Mechanical damping coefficient |
| $f$ | Frequency |
| $F$ | Force |
| $F_{lorentz}$ | Lorentz force |
| $i$ | Electrical Current |
| $k$ | Stiffness spring |
| $K_f$ | Force constant parameter |
| $K_b$ | The back electromotive force parameter |
| $l$ | Length |
| $L_{coil}$ | Inductance of coil |
| $n$ | Number of the turns in the coil |
| $\Phi$ | Magnetic flux |
| $P_{mean}$ | Mean power |
| $R_{coil}$ | Internal coil resistance |

| | |
|---|---|
| $R_{load}$ | Load Resistance |
| $V_{emf,back}$ | Electromotive force voltage |
| $\dot{x}$ | Velocity |
| $w$ | width |
| $\omega$ | Base excitation frequency |
| $\omega_n$ | Natural frequency |
| $\zeta$ | Damping ratio |

**PEMBANGUNAN PENJANA TENAGA ELEKTROMAGNET GETARAN BERFREKUENSI RENDAH**

## ABSTRAK

Tesis ini membentangkan pembangunan penjana tenaga getaran berdasarkan sistem elektromagnet yang menjana tenaga getaran yang berfrekuensi rendah pada struktur jambatan. Tujuan kajian ini adalah untuk menjana tenaga bagi penderia tanpa wayar. Penjana elektromagnet difabrikasi menggunakan empat unit penggerak gegelung suara yang dibuat daripada magnet Neodymium dan gegelung tembaga. Voltan maksimum 2.6 V dan kuasa maksimum 25 mW telah dihasilkan oleh penjana elektromagnet pada frekuensi 10 Hz dan pecutan 0.35g. Model penjana dibina dengan menggabungkan sistem mekanikal jisim-pegas-peredam dan sistem elektromagnetik yang menghasilkan arus akibat gerakan mekanikal gegelung. Keputusan simulasi menunjukkan perbandingan yang baik dengan eksperimen pada julat frekuensi 4Hz - 10 Hz untuk satu unit penjana mempunyai perbezaan sebanyak 4.3%. Sumbangan utama dalam kajian ini adalah pembinaan prototaip sistem penjana tenaga getaran yang rendah dan pembangunan model simulasi dalam Simulink. Ketumpatan kuasa system penjana adalah 602 µW/g.cm$^3$ dan 1308.2 µW/g.cm$^3$ pada 4 Hz dan 10 Hz dan cukup berupaya untuk menghidupkan peranti penderia tanpa wayar.

# DEVELOPMENT OF LOW FREQUENCY ELECTROMAGNETIC VIBRATION ENERGY HARVESTER

## ABSTRACT

This thesis presents the development of an energy harvester based on electromagnetic system to harvest energy from the low frequency vibration in particular structural vibration of the bridge. The eventual intended application is to power up a wireless sensor node that can be used to monitor structural integrity of a bridge. The electromagnetic vibration energy harvester is developed with four units of voice coil actuators using Neodymium magnets and copper coils. An open circuit voltage of 2.6 V and maximum output power of 25 mW were generated at 10 Hz under constant acceleration of 0.35g respectively. A model of the harvester is made by combining the mechanical of mass-spring-damper system with the electromagnetic resistance and inductance where the velocity of the moving coil from the mechanical system will produce current in the system. The simulation model showed a good agreement with the experimental results at 4 - 10 Hz for one cell harvester with 4.3% difference. The main contribution of this research is the prototype construction of low vibration energy harvester system and development of the energy harvester model using Simulink. The power density of the harvester system is 602 µW/g.cm$^3$ and 1308.2 µW/g.cm$^3$ at 4 Hz and 10 Hz respectively and enough to power up the wireless sensor network device.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background on energy harvesting

Energy harvesting is the process of acquiring the energy from environment and converting into usable electrical energy to provide power for electronic devices (Roundy et al. 2003). It has been developed and widely used by many researchers in this decade due to the environmental and economic reasons.

There are several energy sources which are widely used including kinetic energy (waves, wind, gravity and vibration), electromagnetic energy (radio frequency (RF), photovoltaic), thermal energy (solar indoor and outdoor, temperature differential, combustion), biological and chemical energy (biofuels, biomass) or nuclear energy (radioactive decay) (Sari et al. 2009 and Matiko et al. 2014).

Energy can be harvested from the ambient environment using several transducers. Transducer is a device that converts ambient energy into electrical energy. Three transducers most widely reported in vibration energy harvesting are piezoelectric which is a special materials that can be produce electricity when subjected to load, electrostatic which is based on the variable capacitors to extract the energy and electromagnetic which is based on the electromagnetic induction to produce the voltage from the motion of coil and magnet.

## 1.2 Energy harvesting from bridge structures

Wireless monitoring of civil engineering structures such as bridges and overpasses has gained a lot of interest in the recent years (Ntotsis et al. 2009).The application of sensor node has been extensively used for the measurement of the vibrations in order to generate the appropriate power. In order to monitor the structural damage to the bridge, the strain level must be measured and recorded typically using wireless sensor.Wired connection system is generally used for monitoring the bridge vibration (Wang et al., 2006). However, this wiring involves considerable cost, maintenance and difficulty of installation of the sensor (Lynch et al. 2003). In California, the total cost for the bridge is $300 000 for 60 accelerometers where $5000 is spent for each the installed sensor (Li et al. 2011). The batteries are used to power the wireless system. However, these have to be replaced and scheduled frequently (Arroyo et al. 2012).

The researchers consider another solution for the battery alternative for powering of wireless sensor nodes which is based on harvesting the available vibration energy and converting it into electric power.

Vibration harvesting was the focus of this study because the standard operating conditions of bridge structure often produced a low level vibration spectrum. The typical structures have basic vibration level that occur at frequencies less than 5Hz (Beeby et al. 2006) and had input acceleration (peak less than $\pm$ 0.2g).Therefore, there is a need to develop vibration energy harvester to work in the frequency range of fundamental structure of models.

## 1.3 Problem Statement

The bridge structures have to be monitored periodically to ensure structural integrity. Several techniques exist to monitor an infrastructure, for example a conventional resistive strain gauging, embedded or attached optical fibre sensors, accelerometers and linear variable displacement transducer (Coolins et al., 2014). It is very challenging to harvest since the bridge vibration has low amplitude and frequencies. Application of the Wireless sensor network is more preferable because the wired sensors are weak, expensive to install and to maintain. However, the main issue of implementing wireless sensor is the limited battery life. The battery used need to be replaced, difficult to dispose and less energy capacity lifetime (Galchev et al., 2011). An alternative approach to the battery for powering the monitoring system of the structure system is by harvesting the vibration energy from the bridge structures.

There are many different designs of harvester and it is difficult to select the optimal design for vibration energy harvesting. This is because the vibration source is often nondeterministic in nature and contains impulse and other non-uniformity (Spreeman et al., 2008). In addition, most harvesters in the literature operate at frequencies of more than 30Hz, including many harvesters based on piezoelectric, electrostatics and electromagnetic energy conversion (Gu and Livermore, 2011). The aim of this research is to develop vibration energy harvester frequency of low frequency at range of 10Hz and below which is to provide perpetual power for wireless sensor network on the bridge structures.

## 1.4 Objectives

The main objectives of this work are

- To develop an energy harvester based on electromagnetic system in order to harvest energy at low frequency at range 4 to 10 Hz.
- To construct the model based on the governing equations of electromagnetic system and simulated in Matlab Simulink in order to characterize the energy harvester system.
- To determine the generating of voltage and power on different frequencies, vibration amplitudes and load resistors.

## 1.5 Research Contributions

The first contribution of this research is the model construction of low vibration energy harvester system which can be expanded for a higher power system. A second contribution is the development of simulation model of low frequency vibration energy harvester using Matlab Simulink.

## 1.6 Scope

This research is focused on the modelling and experiments for electromagnetic vibration energy harvester for low vibration energy harvester for frequency of 10Hz and below. The study is limited to the construction of vibration energy harvester consisting of four cells. The experiments also limited until the load power only. The range of low frequency is 4Hz to 10Hz and only employ for the bridge structure application.

## 1.7 Thesis Outlines

The following is a brief overview of each chapter of this thesis, which illustrates the sequence of tasks required to develop the vibration energy harvester for the bridge.

**Chapter 1** presents consists of brief introduction of the thesis, problem statement, objectives, contribution and scope of the research. The background information on energy harvesting and WSN technologies, technical benefits, and bridge applications is described.

**Chapter 2** describes comprehensive literatures on the vibration energy harvesting device. Piezoelectric, electromagnetic and electrostatic energy harvesters developed by researchers are discussed in depth. This section summarized the application and characterization of the low frequency vibration energy harvesting technologies.

**Chapter 3** fully describes the proposed electromagnetic vibration energy harvester system. It explains the concepts and development by analytical modelling, prototyping, fabrication and experimentation of energy harvester system. This chapter ends with the summary of the performance for the proposed electromagnetic vibration energy harvester.

**Chapter 4** describes the model development of the electromagnetic vibration energy harvester in Simulink software.

**Chapter 5** explains the result and discussion of the proposed electromagnetic vibration energy harvester system.

**Chapter 6** contains a summary of the work and conclusion as well as future work.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter covers the literature review on vibration energy harvesting and the different approaches in development of the system. The low frequency electromagnetic vibration energy harvesters of the bridge application from previous researcher are also discussed. It includes the principle of operations, architecture and design consideration. The application and issues related to electromagnetic vibration energy harvesting are also included.

## 2.2 Vibration Energy Harvesting

Vibration is one of the most accessible ambient energies. Ambient vibrations can only generate very small power for each system and application. Examples of energy harvesting is intermittent radio frequency identification (RFID) transmission (Shenck and Paradiso 2001), wireless sensors of humidity and temperature monitoring (Arms et al.,2005) and industrial and machinery monitoring (Discenzo et al.,2006).

Vibration energy harvesting uses vibration and converts it to useful electrical energy (Roundy et al., 2003). Basically, these vibration energy harvesters are inertial micro generators which consists of proof mass supported by spring. The mass oscillates when subjected to vibration. The oscillation of the mass is affected by the mechanical and electrical damping produced due to electromechanical transduction. This system has been utilized in a variety of applications for energy harvesting in electrical motors, turbines, and compressors and bridge structures (Elvin et al., 2006). It also has the potential to replace the standard chemical battery as energy sources for powering the wireless system (Dahari et al., 2011). Recently, this has been used as autonomous tire pressure monitoring systems (TPMS) in car and aircraft (Leng et al., 2007).

## 2.3 Vibration Energy Harvesting Mechanism

There are several energy harvesting mechanisms which can be used to convert vibrations into electrical energy. These include: (1) Piezoelectric, (2) Electrostatic, and (3) Electromagnetic. The following subchapter will discuss briefly on three common mechanism of energy harvesting approaches.

### 2.3.1 Piezoelectric

A piezoelectric energy harvester uses piezoelectric material, which deformed under applied stress and will produce electric field and voltage (Zhang 2010). The piezoelectric materials are affected by the vibration and develop voltage to produce the power. Most of the researchers used cantilever and diaphragm as the general shape in designing to harvest mechanical energy from vibration and turn into electrical energy.

One of the most common design architecture in piezoelectric energy harvesters is the cantilever beam consists of several thin layers of piezoelectric material which made of zirconatetitanate (PZT)(Khaligh et al., 2010). The tip of the beam is used to tune the frequency of the harvester. There are two designs of energy harvester using cantilever beam ;(a) unimorph piezoelectric (b) bimorph piezoelectric harvesters. Erturk (2008) developed a cantilever beam using piezoelectric ceramic layers based on the unimorph design. Meanwhile, Zhu et al., (2007) developed an energy harvester by using piezoelectric bimorph plate with a variable width and the theoretical study and the computational results showed that the output power is increases monotonically then decreases with increasing impedance. This shows the importance of having suitable impedance.

Rammohan et al., (2014) studied a bimorph piezoelectric resonator with polyvinylidinefluoride (PVDF) cantilevers and used this for maximizing the power generated from low frequency vibrations. They utilized 55μm thick of PVDF film harvester to harvester vibration energy between 30 to 40Hz and continued with 50μm thick copper foil between two similar poled PVDF layers, which generated power of 2.8μW, at 33Hz with acceleration 0.8g. Figure 2.1 shows the schematic diagram of a bimorph piezoelectric in series. In this figure, P indicates the direction of rod pole and the electric field (E) in z direction while power from vibrating bimorph is delivered across the load resistance $R_l$. The arrow of P indicate the direction up and down applied from the stress while the arrow of E is described as the direction of the current flow from the motion of piezoelectric beam and pass through the load resistance $R_l$.

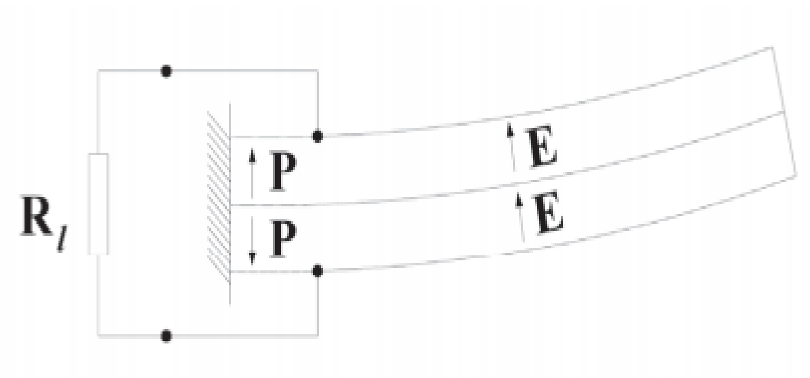


Figure 2.1: Schematic diagram of piezoelectric method (Rammohan et al., 2014)

This method is widely applied for the low power range and no external voltage source. The ability of this energy harvester is to generate high voltage levels (2 - 10V) and can be used for AC to DC conversion during rectification circuits. The configuration of using piezoelectric is compact, compatible with MEMS and high coupling in single crystals. The drawbacks of this approach are the electromechanical coupling coefficients are relatively small, brittleness of shock vibration and electrical conversion efficiency is low (Khan, 2011).

### 2.3.2 Electrostatic

An electrostatic energy harvester usually known as capacitive energy harvester based on the variable gap capacitor. It consists of a variable capacitor structure to induce charges from a relative motion of two parallel conductive plates. The operation condition is based on the change of capacitance between the parallel plates.

The common architectures employed for electrostatic energy harvesters is the out of plane gap varying type (Lee et al., 2009),in plane overlap (Yang et al.,2010) and the in plane gap varying type (Roundy et al.,2002). The out of plane varying type is the capacitance changes due to adjustment of the gap between two parallel plates. The top plate is the suspended by beams meanwhile the bottom plate is the substrate layer. Meninger et al., (2001) developed MEMS vibration energy harvesting by using electrostatic technique using in plane overlap electrostatic converter as a device. The result shows the predicted value of power is 8.6μW meanwhile in close loop the approximate useable power is 5.6μW. It can be seen that the maximum energy can be produced by moving strained process to increase the voltage.

Torres et al., (2006) used variable capacitor which acts like a current source that can power an electrical circuit by using vibration source by to varying the capacitance of an initially charged capacitor. Toshiro et al., (2002) developed pacemaker that can harvest the power from heartbeats. The output power of this prototype driven by on the heart of a goat was 58µW. In 2005, Despesse et al., developed a macroscopic device which can harvest 1mW for a vibration of 0.2g at 50Hz.

The schematic of basic concept of electrostatic method is shown in figure 2.2. In this figure, a variable capacitor structure is used. Both electrodes move in and out to generate the voltage. The charge ($Q$) from the movement of two electrode induced the current and voltage when pass through the load resistance $R$. This harvester can be integrated with the MEMS fabrication technology for building of low cost systems. The reduction of size also increases the capacitances (Boisseau et al., 2012) and generating the high voltage levels (>1V). However, there are limitations in this method such as low capacitances, need to control the µm dimensions and there is no direct conversion from mechanical to electrical for electrets free converters. The basic equation of this method is

$$C = \frac{Q}{V} \qquad (2.1)$$

Where $C$ is the capacitance of a capacitor (in Farads), $Q$ is the magnitude of the charge (coulombs) on two electrode and $V$ is voltage (volts).

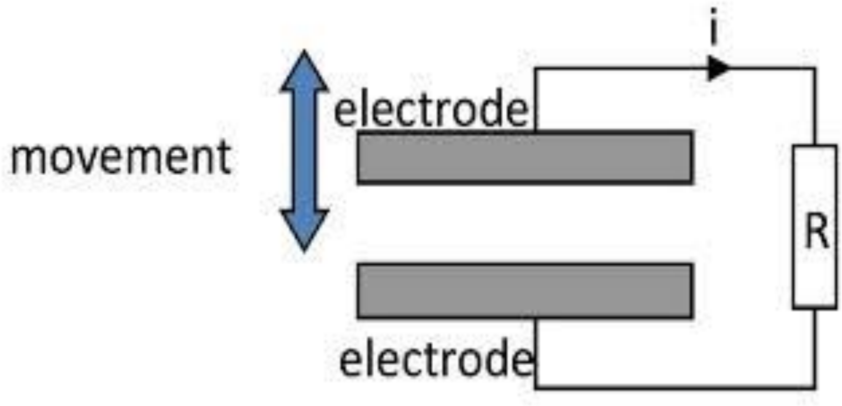


Figure 2.2: Schematic of electrostatic method (Boisseau et al., 2012)

### 2.3.3 Electromagnetic

An electromagnetic energy harvester uses the relative motion of a permanent magnet to induce a voltage across the terminals of a coil of wire thus converting mechanical energy to electrical energy (Amirtharajah et al., 1998).The working principle is based on Faradays Law of electromagnetism.

Figure 2.3 shows the electromagnetic conversion device. In this figure, the device includes of a mass (*m*) that attached to a spring *(k).* A wire coil, *l* is attached to the oscillating mass through a magnetic field that established by a stationary permanent magnet *(B)* to produce electric energy. The coil is moving through a different level of magnetic flux and induced the voltage.

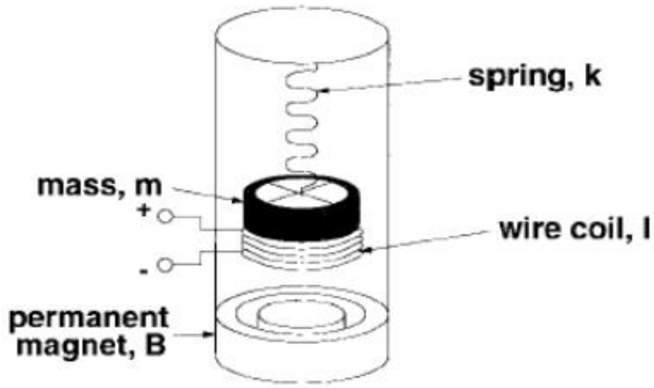


Figure 2.3: Electromagnetic conversion device (Amirtharajah et al., 1998)

Many researcher used moving magnet type to generate the power (El-Hami et al.,2001; Ching et al., 2000, Glynne et al.,2004, Yuen et al., 2007), moving coil type (Amirtharajah et al., 1998, Beeby et al., 2006, Sari et al.,2008), wound coil type (Park et al 2010), planar coil type (Kim et al., 2008), cantilever beam type (Torah et al., 2006), planar spring type (Ching et al., 2002) and the polymeric membrane type (Wang and Arnold 2009).

Williams and Yates (1996) developed a simple linear electromagnetic generator that consists of a mass attached to a rigid structure using a spring. Figure 2.4 shows a schematic diagram of the generator. The size of the electromagnetic generator is 5mm× 5mm×1mm. The mass (*m*) moves out of the time with the generator during the generator vibrated and net movement *z(t)* is produced between the mass and the housing.They predicted the power generated is 1µW at 70 Hz and 1mW at 330 Hz for a typical device.

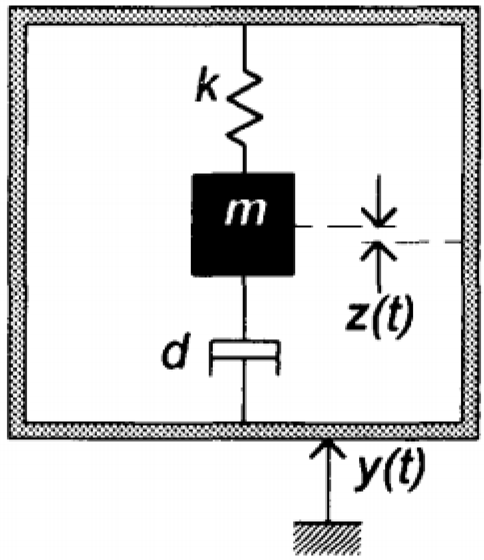


Figure 2.4: A schematic diagram of the linear electromagnetic generator (William et al. 1996)

Linear electromagnetic generators can also be used to generate low powers. Harb (2011) presented a brief history of energy harvesting: the techniques of conversion and management power, and batteries charging. The linear generators could be used to, for example, extend the lifetime of human implants (Morgad et al., 2012), to generate power from human body motion (Saha et al., 2008), to create an inertial generator (Rahimi et al., 2012) and (Stanton et al. 2010), to create a linear alternator in loudspeakers (Saha et al., 2012), to harvest energy from low frequencies (Foisal et al., 2012, Hatipoglu, et al., 2009), or to harvest energy from the DDHO (Driven Damped Harmonic Oscillation) in the backpack (Elmes et al. 2007).

The main advantage of electromagnetic harvesters is their high output current, long lifetime proven and flexibility of different design to suit the multiple circumstances. The limitation is that the voltage output and efficiency in low frequencies and small size harvester is very low.

### 2.3.4 Hybrid energy harvesting

Hybrid energy harvesting combines energy harvesting techniques on a single platform (Basagni et al., 2013). Yang et al (2010) developed a hybrid energy harvester that integrates the piezoelectric and electromagnetic energy harvesting mechanisms by using piezoelectric cantilever, permanent magnets and substrate of two coils. The maximum output voltage and power from the PZT cantilever of the device are 0.84 V and 176 μW respectively under the 2.5g acceleration at 310 Hz with maximum output voltage and power of 0.78 mV and 0.19 μW respectively. The value of power densities from the piezoelectric and electromagnetic components are 790 $\mu W/cm^3$ and 0.85 $\mu W/cm^3$.

Salim et al., (2012) developed the hybrid energy harvester of piezoelectric (PZT bimorph cantilever beam) and electromagnetic generator. It is found that the hybrid generator can produced maximum power of 187 μW and power density of $63\mu W/cm^3$ at frequency of 33 Hz under acceleration 0.25g.

Rahman et al., (2013) developed a hybrid based energy harvester of piezoelectric and electromagnetic transducers consisting of a four pole magnets placed onto a piezoelectric cantilever beam. The result showed that the piezoelectric generated optimum power of 2.3 mW in a 60 Ω resistive load, while electromagnetic harvester generated 3.5 mW power for a 40 Ω resistive load at frequency of 15 Hz and vibration acceleration of 1g.

Shan et al., (2013) developed a combined of piezoelectric – electromagnetic energy harvester consisting of a primary PZT piezoelectric energy harvester and a suspension electromagnetic is placed on the free end of PZT beam. The experimental results showed that the peak power output of the hybrid harvester are 7.2 mW and 16.4 mW at the resonance frequencies of 8.5 Hz and 16 Hz, respectively

Zaman et al., (2014) uses the combination of solar and chemical cells and produces power of 48mW.

### 2.3.5 Comparison

The power density of different types of vibration energy harvesters are shown in figure 2.5. In this figure, the overall power density ranges from 0.2 to 1000µW/cm$^3$ with the resonant frequencies from 1 to 120 Hz. The electromagnetic harvesters are mostly found to operate at below 10 Hz compared with the piezoelectric harvester which operate above 100Hz. Electrostatic is not widely used for vibration energy harvesting. It shows that the electromagnetic is commonly used and capable of harvesting a high output current and power at low frequency.

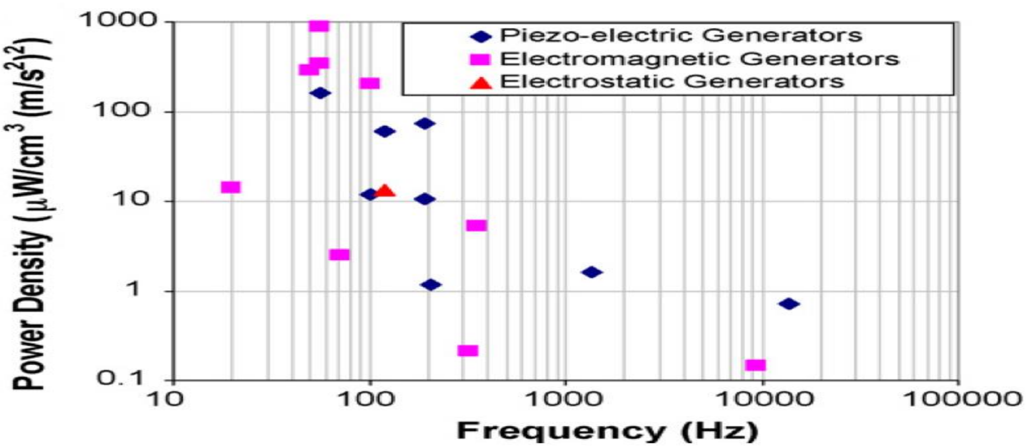


Figure 2.5: The power density comparison of the three different harvesters versus frequencies (Mathúna et al., 2008).

## 2.4 Principles of electromagnetic harvester

Electromagnetic harvester utilized Faraday's Law to produce the voltage in a coil with moving magnet. The law states that the back electromotive force (EMF) is proportional to the rate of change of magnetic flux linkage around a closed path (Sadiku, 2007). Figure 2.6 shows a schematic diagram of electromagnetic vibration energy harvester and the relation of the model is represented in equation (2.2 - 2.6). The harvester consists of an inertial mass, m hanging with a spring constant (*k*) and *d* is damping coefficient.

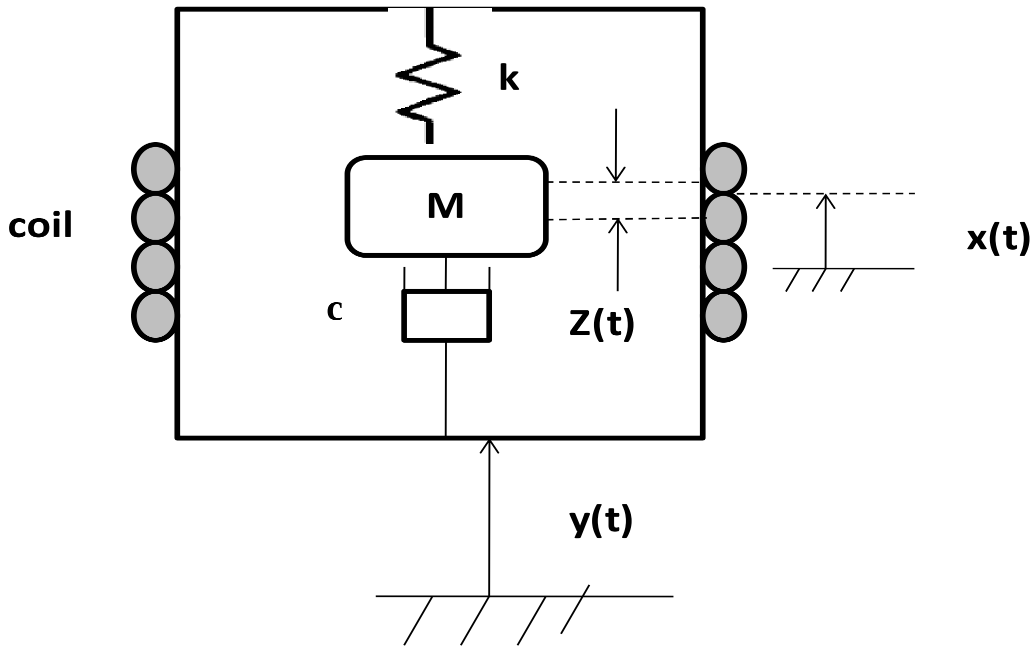


Figure 2.6: Schematic diagram of an electromagnetic vibration energy harvester (Munaz et al., 2012).

According to the Faradays Law, when a magnet oscillates, the coil cuts the flux line of the magnet, producing the back electromotive voltage ($V_{emf,back}$) as shown in equation 2.2.

$$V_{emf,back} = -n\frac{d\Phi}{dt} \tag{2.2}$$

Where $V_{emf,back}$ is the back electromotive force in volts, $n$ is the number of turns of wire and $d\Phi$ is the magnetic flux linkage through each turn. *B* is a magnetic field strength and *A* is surface area of coil. The flux is given as:

$$\Phi = \int_A BdA \tag{2.3}$$

When considering the Lenz's Law, the induced $V_{emf}$ will be in a direction such that the induced current magnetic field opposes the original magnetic flux change in the magnetic field (Sadiku 2007). By substituting equation 2.3 into equation 2.2, the equation 2.4 is obtained as below,

$$V_{emf,back} = -n\frac{d\Phi}{dt} = -n\frac{d}{dt}\int_A BdA \tag{2.4}$$

Equation 2.4, it shows that a time-varying condition between electric and magnetic fields are correlated and *dA* is according to right hand rule as well as Kevin-Stokes's theorem (Sadiku 2007).

Figure 2.7 shows a closed loop wire of rectangular shape loop in xy plane. The motion between the coil and magnet is in single direction. Assuming the coil moves along the y direction at velocity, $\dot{x}$ where $\dot{x} = \frac{dy}{dt}$. The rectangular wire loops has a length, *l* in x direction while width *w* in y direction. The magnetic field, *B* can be classified into two side; upper side $B = y + \frac{w}{2}$ and lower side is $B = y - \frac{w}{2}$. Equation 2.5 expresses the back emf as proportional to *n* times, velocity ($\dot{x}$) and magnetic flux ($\Phi$).

$$V_{emf,back} = -\frac{d\Phi}{dy}\frac{dy}{dt} = -n\frac{d\Phi}{dy}\frac{dy}{dt} \tag{2.5}$$

Faradays law used the magnetic flux Φ through an integral area of coil, $dA$.

$$\Phi = l \int_{y-\frac{w}{2}}^{y+\frac{w}{2}} B dy \tag{2.6}$$

$$V_{emf,back} = \frac{d\Phi}{dt} = (-)\dot{x}l \,[B\left(y+\frac{w}{2}\right) - B\left(y-\frac{w}{2}\right)] \tag{2.7}$$

The coil also consist the N loops, so the total induced $V_{emf,back}$ would be *n* times,

$$V_{emf,back} = -n\frac{d\Phi}{dt} = nBl\dot{x} \tag{2.8}$$

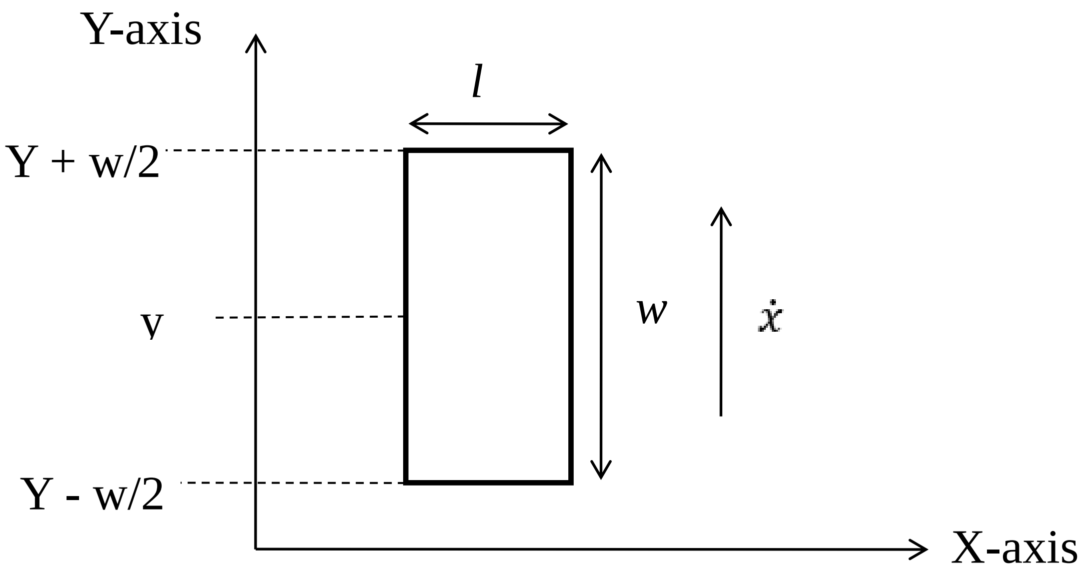


Figure 2.7: A close loop wire of rectangular shape

## 2.5 Vibration energy harvesting at low frequency vibration

Most harvesters in the literature focused at frequencies of more than 30Hz, which cover; piezoelectric (Beeby et al., 2007), electrostatic (Mictheson et al., 2008) and electromagnetic induction (Sardini et al., 2011; Amirtharajah et al., 1998) and human motion (Saha et al., 2008).

Electromagnetic vibration harvesting approach has been used by many researchers to harvest energy at low frequency. For example, the electromagnetic power micro generator prototype device developed by Beeby et al., (2007). Figure 2.8 shows this tunable electromagnetic micro harvester. In this figure, the tuning magnet is fixed at the end of cantilever beam. The copper coil is attached at the centre of the two magnets and fixed with steel keeper. The resonator frequency of the harvester is 45Hz and generated 200µW power at acceleration of $0.588ms^{-2}$.

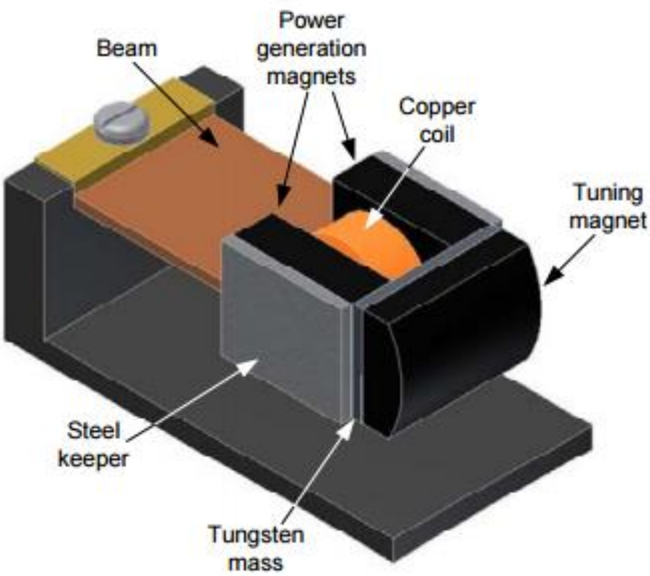


Figure 2.8: A tunable electromagnetic micro harvester (Beeby et al., 2007)

Saha et al., (2008) and Dayal et al., (2011) applied two repulsively magnets in electromagnetic harvester to harvest energy. Figure 2.10shows a schematic diagram of magnetic spring generator structure. In this figure, the magnetic spring generator is placed vertically inside a tube with the magnet facing each other with similar polarization so that the magnets repel one another. The two magnets are fixed at the top and below of the generator tube housing. A centre magnet is separated by soft magnetic pole and was free to move. A coil is wrapped around the outer surface of the tube. The middle magnets vibrated up and down when the tube is excited, inducing voltage. This assembly system is related to the patent of magnetic power torch (Luzy, 1923).

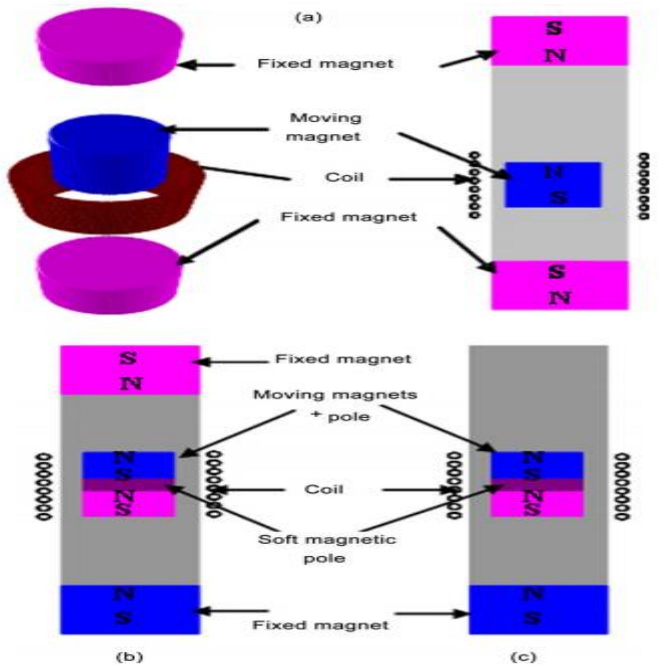


Figure 2.9: Repulsively magnet attached in electromagnetic harvester (Saha et al., 2008).

Figure 2.10 shows the experiment setup of micro generator from Dayal et al., (2011). In this figure, the generator is mounted on the shaker. The cylindrical two magnets are axially attached to the spring while the coil is clamped to the generator frame. The shaker is operated at resonance frequency of 108Hz and they managed to get the power output of 4.5mW at 1g.

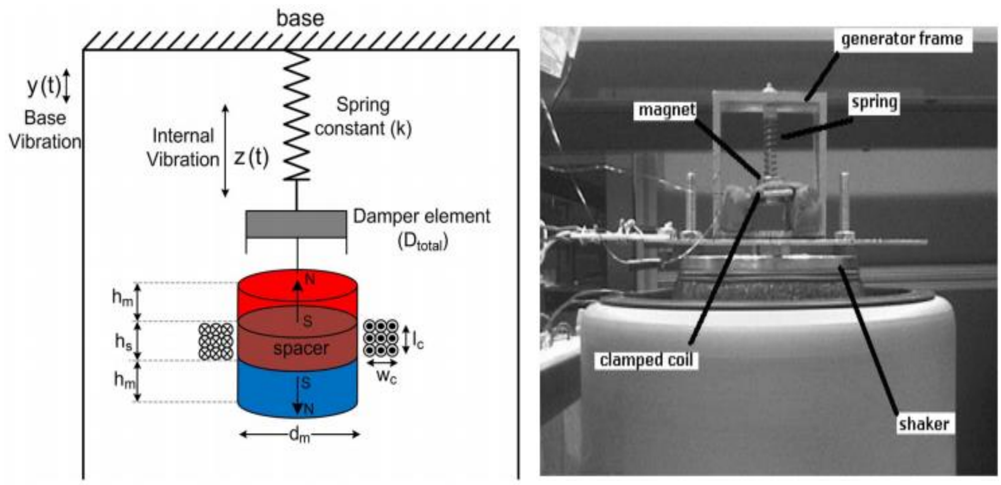


Figure 2.10: Experiment setup of micro generator (Dayal et al., 2011).

Figure 2.11 shows the schematic and prototype a four pole generator. In this figure, the sliding translator contains four individual NdFEB magnets (0.32cm x 2.5cm x 0.64cm) with alternating the S and N pole magnetizations were used in this harvester. A 300 turn coil is wrapped and mounted on the stator with a gap 1mm. A ball bearing was used as a slider in this harvester to constrain the motion in one degree of freedom. At 0.8g acceleration and frequency of 9.25 Hz the power generated is 0.55 mW at 400 Ω of load resistance.

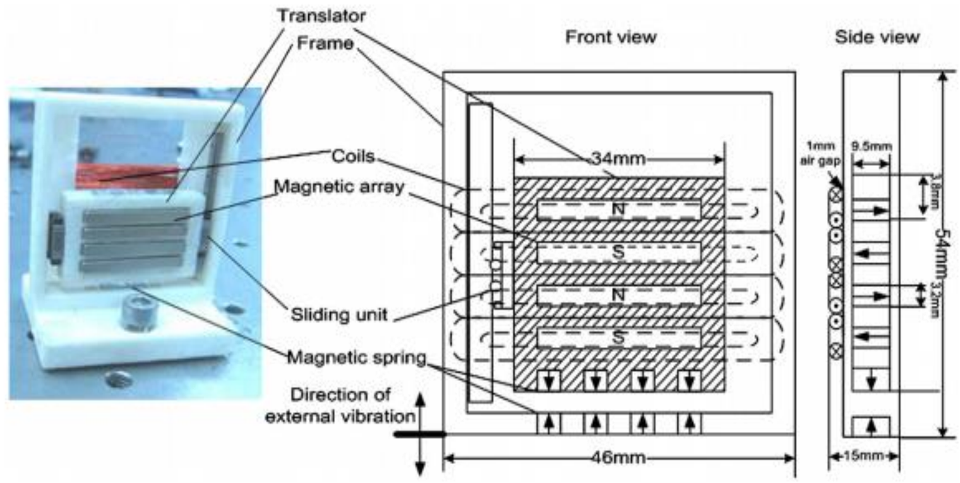


Figure 2.11: Schematic of the prototype four pole generator (Cheng et al., 2008)

Figure 2.12 shows an electromagnetic harvester using FR-4 spring. In this figure, two FR-4 springs are used and placed at the top and bottom of the harvester. The two FR-4 springs are used to reduce the stress and to achieve linear movement of the moving magnet. The prototype device produced output power of 1.52 mW at 16 Hz with a load resistance of 5.4 kΩ and acceleration of 0.2 g.

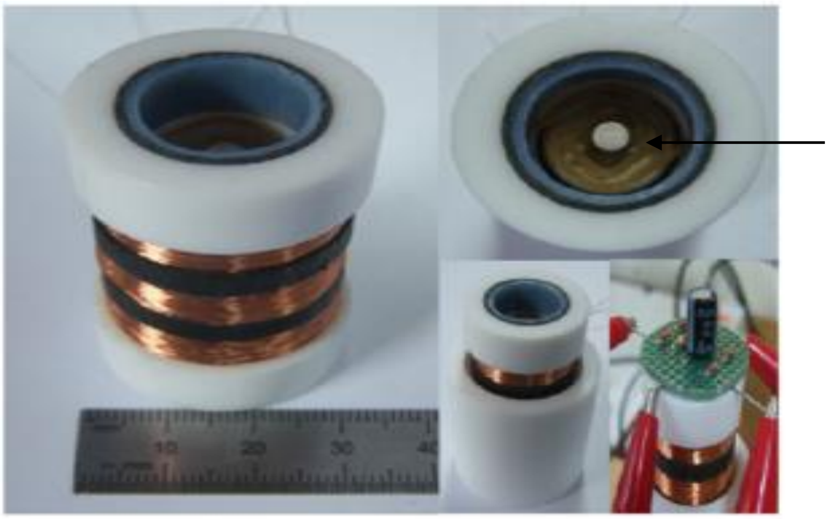


Figure 2.12: Electromagnetic harvester by using FR-4 spring (Lee et al., 2012)

Figure 2.13 shows the assembly of FR4 energy harvester studied by Hatipoglu (2010). In this figure, the FR4 spring is glue on the pickup coil (bobbin) which acts as mechanical stopper. This energy harvester is tested on different type of application such as on the shaker, human running and tire. In shaker experiment, this prototype manages to get the Vrms of 530mV and 320mV at 22Hz for simulation and experiment on open loop system respectively. In human running, they predicted 39.5μW and 34μW rms power at 2.75Hz for both simulation and experiment. The real operation, the power is 1mW at 3g which is sufficient to power the wireless tire sensors.

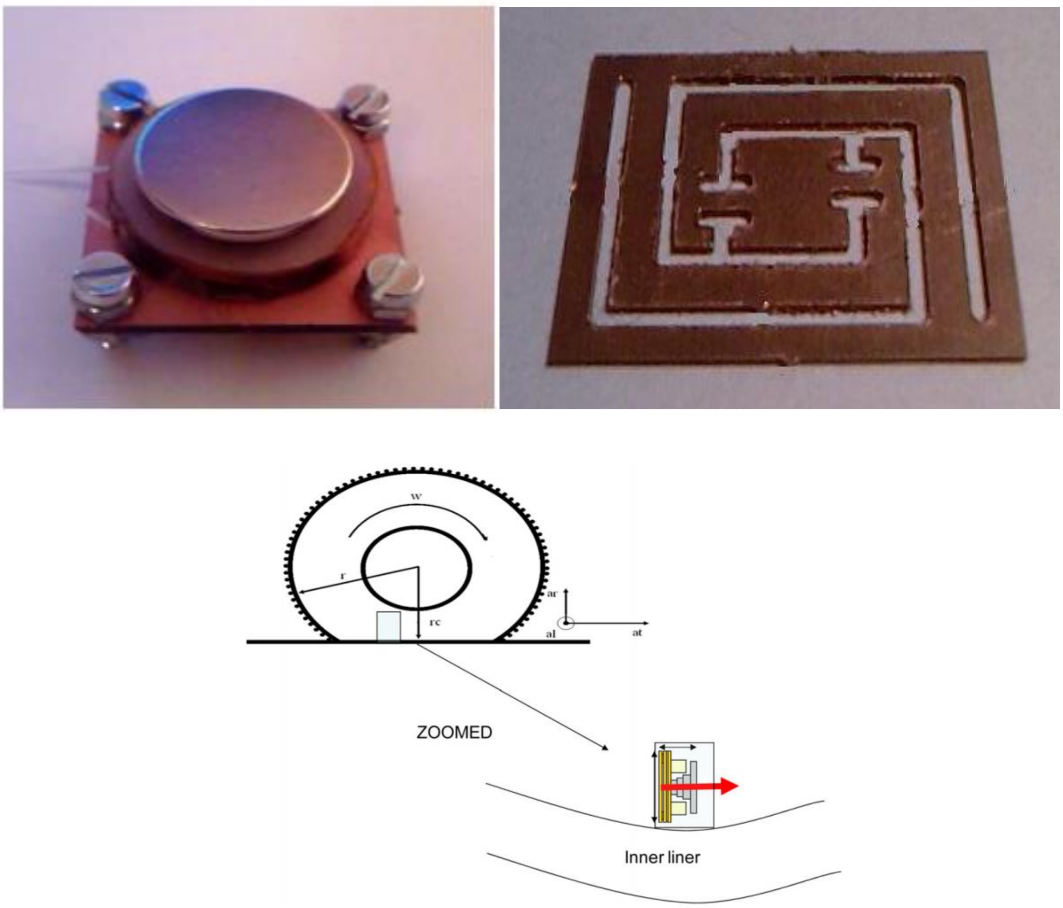


Figure 2.13: Energy harvester by using FR-4 spring (Hatipoglu et al., 2010)

Kulah et al., (2008) used frequency up conversion for wireless sensor network sensor under low frequency applications. Figure 2.14 shows the prototype and test setup structure of the assembly harvester by using frequency up conversion method. In this figure, the miniature frequency up converter is built and placed on the resonating cantilever beam. There are two vibrating system absorbing energy from ambient motion, converting the mechanical energy into electrical energy. The power is generated by using electromagnetic induction of the magnet and coils with a maximum power of 170nW and voltage of 6mV. In vacuum, the MEMS the maximum power and voltagesgenerated are 3.97uW and 76mV respectively. Without increasing the area of assembly generator, the generated power can be maximized by a series of connected cantilevers.

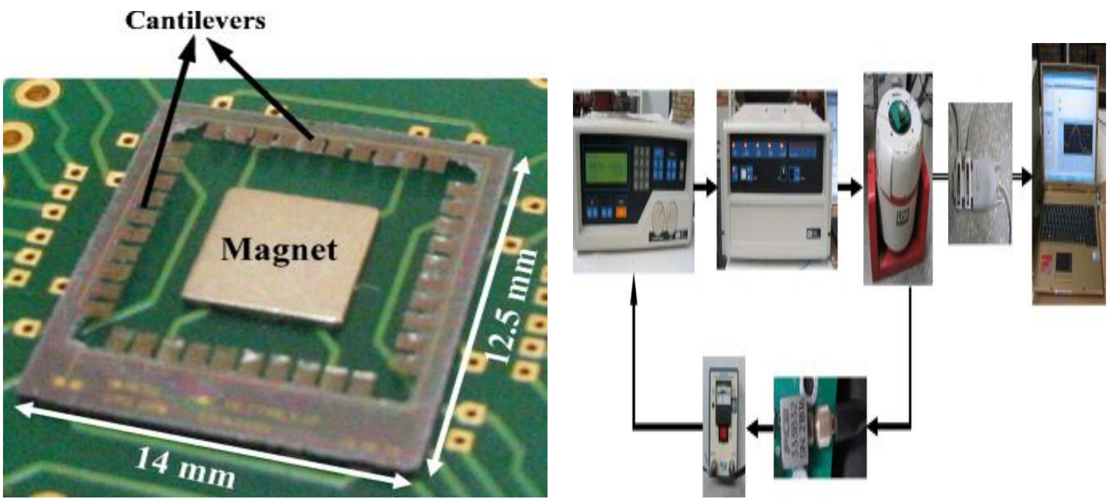


Figure 2.14: The prototype and test setup structure (Kulah et al., 2008)

Zorlu et al., (2009) proposed a similar mechanism with two cantilevers where the tips are overlapping. The low frequency cantilever has a permanent magnet which is the proof mass and resonated with the external vibration and actuates the high frequency cantilever. The electrical energy is harvested by the motion of coil