



## DESIGN AND ANALYSIS OF VIBRATION ENERGY EXTRACTION SYSTEM

Arun Bhosale<sup>1</sup>, A. Anderson<sup>2</sup>, Suhas P. Deshmukh<sup>3</sup> and Sharad Ambad<sup>3</sup>

<sup>1</sup>Mechanical Engineering Department, Sathyabama University, Chennai, Tamilnadu, India

<sup>2</sup>Sathyabama University, Chennai, Tamilnadu, India

<sup>3</sup>Sinhgad Academy of Engineering, Pune, Maharashtra, India

E-Mail: [arunbhosale@rediffmail.com](mailto:arunbhosale@rediffmail.com)

### ABSTRACT

Advancement in Micro-Electro Mechanical System (MEMS) and the devices which required low power are very popular and these are used in many applications but there is major problem for the actuation of these devices because they requires very small amount of power, also many times these devices are not in physical contact with surrounding environment so it is very difficult to supply power to these devices. Many times it is not suitable to supply power using batteries. This paper presents the design of power supplying devices to MEMS and low power devices. This power supplying devices generate power from vibration which are common in many household application and industrial operations, these vibrations can be converted into electrical energy and can be used for actuation of MEMS devices. This paper presents study of different vibration energy conversion systems like electromagnetic, piezoelectric and electrostatic conversion system. By comparing these systems it is observed that electromagnetic conversion system produce large amount of output power. The system is designed in Catia V5 and which consist of three magnets and four coils. Then static, modal, harmonic analysis were carried out at different boundary conditions. Induced voltage is validated with the help of Electromagnetic analysis carried out in Ansys Maxwell. During experimentation, if this system is vibrated at about 11.5 Hz vibration frequency, then each coil produce output voltage of about 8.5 V i.e. it will produce nearly 24.65 mW of power and total power of 98.6 mW.

**Keywords:** electromagnetic, electrostatic, micro-electro mechanical system, piezoelectric, modal analysis, harmonic analysis.

### INTRODUCTION

The recent use of wireless sensors in many applications and the development of low power consumption devices have been driving research on micro energy generators converting vibration energy into electrical energy to replace batteries. Harvesting ambient vibration energy to supply appears to be a key technology to develop lightweight, compact and energy autonomous devices [1]. It is observed that mechanical vibrations which are available in many application domains (e.g. appliances, industrial environment or operations, transportation systems and even the human body) can produce large amount of vibrations which may be converted into electrical energy by using different conversion system and it can produce potentially sufficient power density [2,3]. Mechanical energy from ambient vibrations can be converted into electrical energy is performed by a different conversion system. Its conversion efficiency depends on the operating conditions and applications of implementation. Among different vibration energy conversion systems, piezoelectric and electromagnetic conversion systems present the advantages of harvesting high power levels with simple implementations. Piezoelectric conversion system (PECS) generally consists of a cantilever beam and can be used in force and impact-coupled harvesting applications. Electromagnetic conversion system (EMCS) consists of one or more permanent magnet and one or several coils assembled in proper manner in simple geometry [4].

They systems have been widely studied and MEMS have been developed. MEMS usually consist of planar coils and planar springs with permanent magnets

moving or vibrating in stationary coils in electromagnetic conversion system [5, 6]. Electromagnetic conversion system are placed in environments with tens or hundreds hertz frequency of vibration and is suitable for micro-systems with modest power requirement and the power produced by such conversion devices is proportional to the cube of frequency of vibration [7].

### STUDY OF DIFFERENT CONVERSION SYSTEM

There are three basic mechanisms vibrations energy can be converted to electrical energy:

- a) Electrostatic
- b) Electro-magnetic
- c) Piezoelectric

In the first case, Electrostatic generation system consists of two conductors separated by a dielectric (i.e. a capacitor), which move relative to one another. When the conductors move, the energy stored in the capacitor changes, thus providing the mechanism for mechanical energy to electrical energy conversion.[8,9] Primary disadvantage of electrostatic conversion system is that they require a separate power source to start the conversion system.[10] So that the separate convertor is require to step down the potential for electrostatic convertors.

In second the electric current is generated in a conductor which is located within a changing magnetic field.[11,12] The conductor typically is in the form of a coil and the electricity is generated by either the relative movement between magnet and coil, or because of



changes in magnetic field. The amount of electricity generated mainly depends upon the strength of the magnetic field, the number of turns of the coil and the velocity of the relative motion.[13-15] This voltage generated in the coil is determined by Faraday's Law.

In last case, if mechanical strain is applied to certain crystals, they became electrically polarized. The degree of polarization is proportional to the strain applied. Conversely, these materials get deformed when exposed to an electric field.

### GENERAL MATHEMATICAL MODEL

Electromagnetic generators are usually modelled by essentially a second-order simple mass-spring damper system, in which the damper embodies the energy harvesting process and mechanical losses. This model does not consider the electrical parasitic losses. So we can formulate a general mathematical model for the conversion of the kinetic energy (KE) of a vibrating body to electrical power. This conversion based on linear system theory without specifying the mechanism through which the conversion takes place. Figure-1 shows a general example of such a system which is based on a vibrating mass 'm' on a spring with stiffness 'k'. Energy losses in the system are given by the coefficient of damping  $c_t$ . These losses consists of parasitic losses  $c_p$  (e.g. air damping) and electrical energy dissipated through the transduction mechanism  $c_e$ . These generators are designed to operate at its natural frequency, given by  $\omega_n = \sqrt{k/m}$ , and should be designed in such a way that this coincides with the frequency of vibrations present in that environment. The theory of inertial-based generators is studied [10,16] and will only be briefly covered here. Assuming the generator is excited by external vibrations are in the form  $y(t) = Y \sin(\omega t)$ , at resonance, it will vibrate out of phase with the mass. This results in a net displacement  $z(t)$  between the mass and the frame.

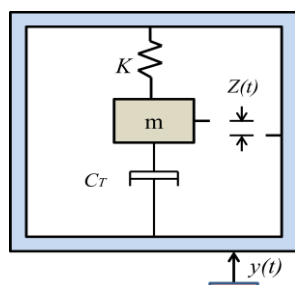


Figure-1. Linear, inertial generator model.

Assuming that the mass of the vibration source is significantly higher than that of the seismic mass and therefore it is not affected by its presence, then the differential equation of motion is represented as: The dynamic equation of the mass spring damper system can be written as

$$m\ddot{z}(t) + c\dot{z}(t) + kz(t) = -m\ddot{y}(t) \quad (1)$$

Since energy is extracted due to relative movement between the inertial frame and the mass, the following equations apply.[17] The steady state solution for the mass displacement is given by:

$$z(t) = \frac{\omega^2 Y \sin(\omega t - \phi)}{\sqrt{\left(\frac{k}{m} - \omega^2\right)^2 + \left(\frac{c_t \omega}{m}\right)^2}} \quad (2)$$

Where  $c_t$  the total damping factor and  $\phi$  is the phase angle given by:

$$\phi = \tan^{-1} \left( \frac{c_t \omega}{(k - \omega^2 m)} \right) \quad (3)$$

The power dissipated within the damper (i.e. extracted by the parasitic damping mechanism and transduction mechanisms) is given by:

$$P_d = \frac{m \xi_t Y^2 \left( \frac{\omega}{\omega_n} \right)^3 \omega^3}{\left[ 1 - \left( \frac{\omega}{\omega_n} \right)^2 \right]^2 + \left[ 2 \xi_t \left( \frac{\omega}{\omega_n} \right) \right]^2} \quad (4)$$

Where  $\xi_t$  is the total damping ratio given by

$$\xi_t = \frac{c_t}{2m\omega_n} \quad (5)$$

Maximum power occurs when the device is excited at  $\omega_n$  and in this case the theoretical maximum power stored in the system is given by:

$$P = \frac{m Y^2 \omega_n^3}{4 \xi_t} \quad (6)$$

Where,  $Y$  is the vibration magnitude of input vibrations. Note in Equation. (4) that the power obtained is inversely proportional to frequency. Power is linearly proportional to mass. So, the converter should have the maximum proof mass that is possible while staying within the available space.

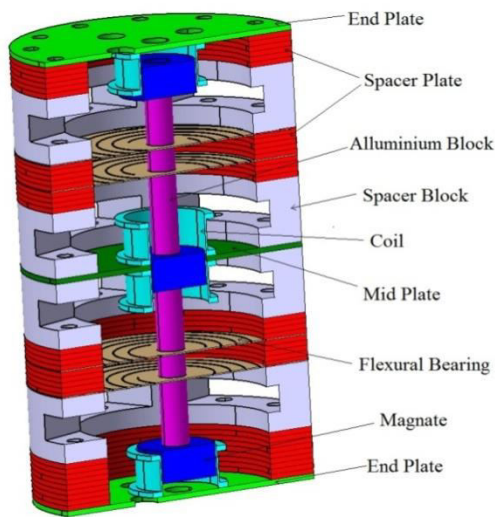
### DESIGN OF ELECTROMAGNETIC EXTRACTION SYSTEM

The EMCS (device) consist of flexural spring, coil windings, magnet, spacer block, spacer plate, end plate, middle plate, stud etc. Out of these components spacer block, spacer plate, end plate and middle plate are made up of Aluminium material except Flexural spring and coil windings. Flexural spring is made up of Beryllium copper and coil windings are of copper wire. Three Neodymium magnets were used in this work. Neodymium has strongest magnetic field strength in the rare earth family because of the Neodymium, Iron and Boron.[18,19]

The Electromagnetic device is composed of spring-magnet system and wire-wound coil. The order of



assembly is as follow and Section view of CAD model of assembly is shown in Figure-2.



**Figure-2.** Sectional view of CAD model of electromagnetic conversion device.

- Flexural spring and magnet assembly is placed at proper position.
- Finally flexural springs are glued to aluminium pipe to enhance input vibration amplitude so that magnet will vibrate with greater amplitude.
- Connections from the coil are taken out of assembly to measure output of Energy Harvester.

Flexure suspension system forms an important part of the electromagnetic device. Design of the flexure suspension system will ensure friction less and wear free, movement of the magnet and coil. Therefore, flexure spring play crucial role in the long life and maintenance free operation of the electromagnetic device. So we are going to design flexural spring as follow. Each spring is in the form of a thin flat metal disc having three spiral slots, yielding three spiral arms which bear the axial and radial loads.

#### A. Calculations for stiffness of flexure spring

Selected parameters are as follows:-

Magnet:-

Dimensions- 28 mm dia. x 12.5 mm thick x 10 mm dia. hole

Mass-50 gm

Magnetic Field Density- 3,000 gauss

From study it is observed that natural resonating frequency of the structure has to match the dominating frequency of the mounting surface. From the study it is found that dominating frequency of such objects lie between 10 to 20 Hz. So to calculate stiffness of the spring by the formula:

$$\omega_n = \sqrt{\frac{k}{m}} \quad (7)$$

The CAD model of spring is designed in Catia V5 R19 and it is shown in Figure-3(a) and the analysis if this model is done with the help of Ansys 15 workbench. The meshed model is shown in Figure-3(b). When force of 10 N and remaining boundary conditions were applied then observe the deformation and equivalent stresses by using FEA software, it will produce deformation of 30.78 mm

$$\text{Applied force} = F$$

$$= 10 \text{ N}$$

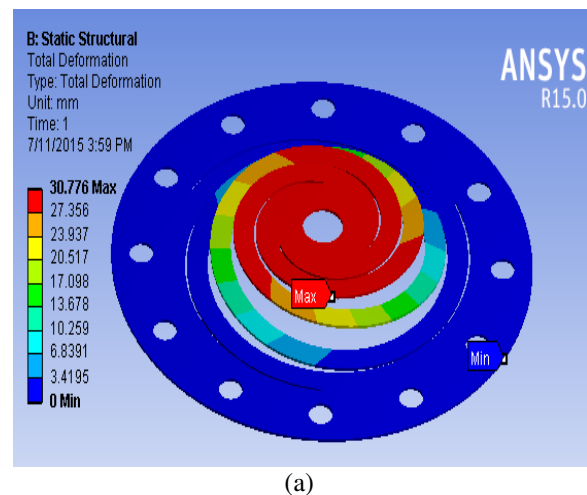
$$\text{Deformation} = \delta = 30.78 \text{ mm} = 30.78 \times 10^{-3} \text{ m}$$

$$F = k\delta$$

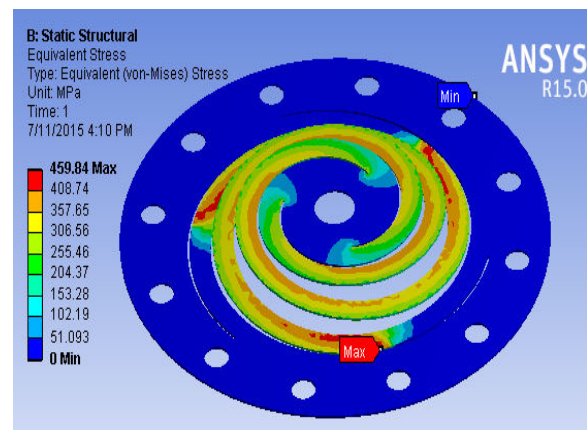
$$k = 325 \text{ N/m}$$

(8)

Spring have been designed which having dimensions as Thickness = 0.5 mm, Number of grooves = 3, Spiral angle = 540°, width of cut = 0.5 mm, Starting & ending radius = 12.5 mm & 38 mm.



(a)



(b)

**Figure-3.** (a) Total deformation and (b) Equivalent stresses in flexure spring.



### B. Design calculations of extraction system

When boundary condition are applied to electromagnetic device i.e. 10 N force is applied on first magnet in downward direction and centre hole of bottom end plate is fixed then it will shows deformation of 7.42 mm by considering standard gravity, this is shown in Figure-3(a). The stress produced on device due to the load applied is shown in Figure-3(b). This deformation result is used to calculate the stiffness and natural frequency of extraction system.[21,22]

### C. Calculations to find natural frequency of device

Mass of 3 magnet and 2 aluminium pipes = 170 gm

Applied force =  $F = 10\text{ N}$

Deformation =  $\delta = 7.42\text{ mm} = 7.42 \times 10^{-3}\text{ m}$

$F = k\delta$

$k = 1347.7\text{ N/m}$

$$\omega_n = 2\pi f_n = \sqrt{\frac{k}{m}} ; f_n = 14.17\text{ Hz}$$

From calculated natural frequency of 14.17 Hz, when we give excitations of 14.17 Hz resonance will happened. At resonance condition magnet will vibrate with maximum amplitude and it will generate large output voltage.

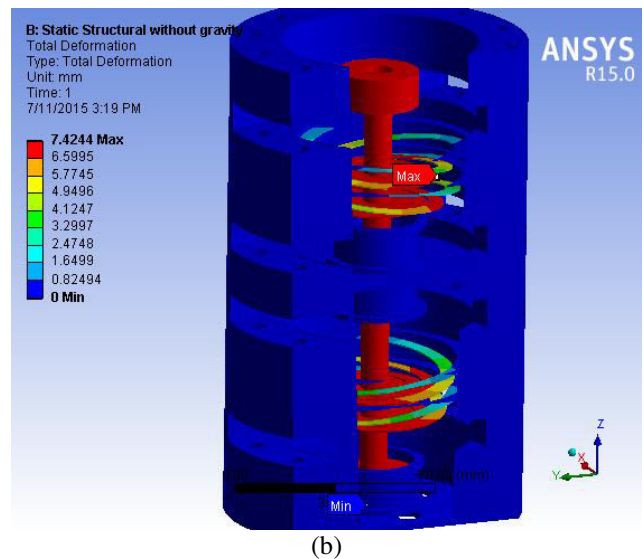
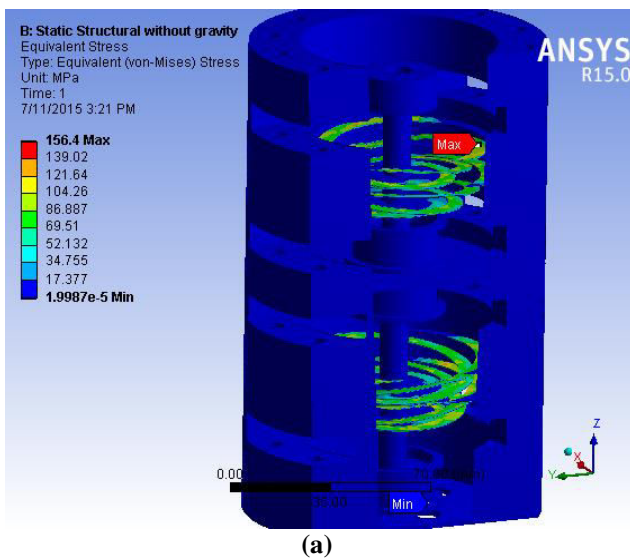


Figure-4. a) Equivalent stresses b) Deformation in electromagnetic device.

Also we perform the modal analysis of electromagnetic device and obtained first three modes of vibration these modes are at different frequencies of vibration. These three modal frequencies are 13.56, 66.99, 67.2 Hz respectively. Among these three modes, first mode of vibration is important because we are considering only low frequency vibrations only and this mode is shown in Figure-5.

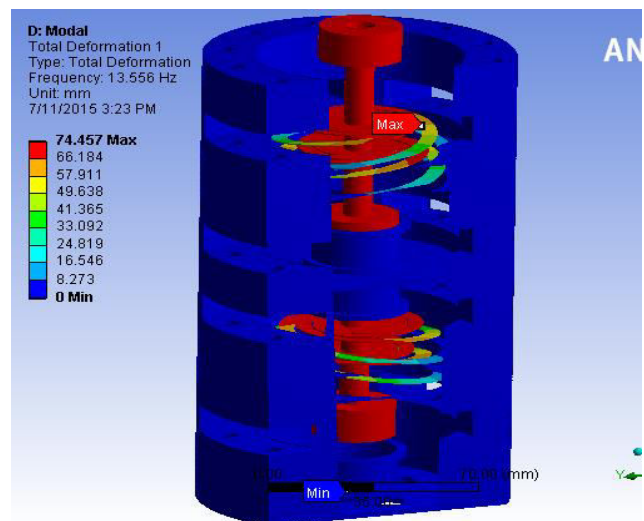


Figure-5. First mode of vibration if electromagnetic device.

### Experimental setup

Vibration testing system is used to measure output characteristics (voltage and displacement) of Electromagnetic energy harvester. A block diagram of the experimental setup for EMH system is shown in Figure-6. The components of this system are power amplifier, vibration exciter, electromagnetic device, dSPACE software or an oscilloscope, LVDT and DC power supply. The vibration signal is generated from the signal generator





and these are amplified by using power amplifier and these signals are utilized to control the vibration amplitude and frequency of the exciter. Electromagnetic energy harvester device is mounted on the vibration exciter by using supporting frame and base plate. Accordingly, due to excitations the electromagnetic device will undergo excitations and it will generate output voltage signal, these are recorded by the oscilloscope or dSPACE software. Displacement is measured by using LVDT and it displayed on the computer monitor. The photo of experimental setup for testing the Electromagnetic Energy Harvester is shown in Figure-7.

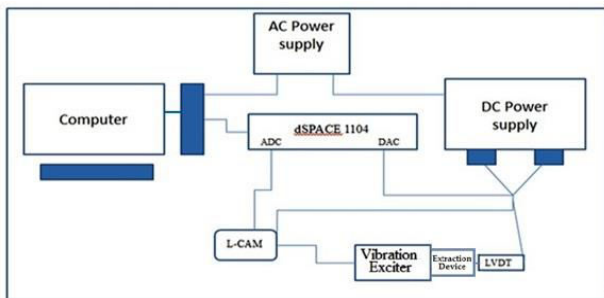


Figure-6. Block diagram of experimental setup.

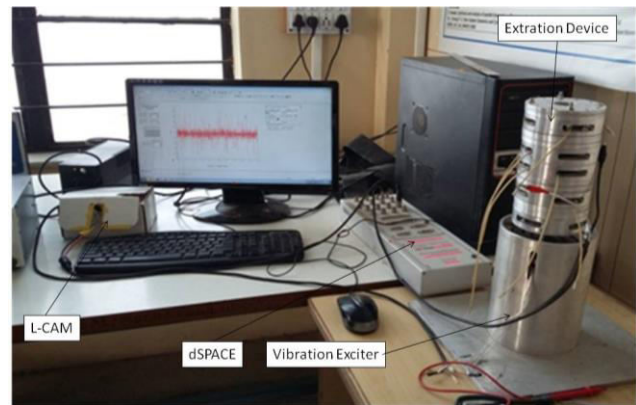


Figure-7. Photo of experimental testing setup.

## EXPERIMENTAL RESULTS

When we mount the extraction device on exciter for testing it at different vibration frequencies and it will show the graph of induced voltage v/s time. During testing we were increase the frequency of vibration and due to this there is increase in induced voltage. During this procedure it is observed that at input frequency is 13 Hz the device gives maximum voltage of 8.5 V for coil 3 and after this voltage goes on decreasing. The first and fourth coil will show same output voltage so here voltage graph of three springs are shown below.

Table-1. Induced voltage readings of coil.

Input voltage to exciter (V)	0.5	1	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Frequency (Hz)	12.5	12.5	10.5	11.5	12	12.5	13	13.5	14.5
Induced Voltage (V) Coil1	4.0	6.2	4.8	6.5	7.1	7.8	8.0	7.7	7.0
Induced Voltage (V) Coil2	3.7	6.4	6.3	7.3	7.7	8.3	8.5	8.0	7.1
Induced Voltage (V) Coil3	3.8	6.4	6.2	7.3	7.8	8.3	8.5	8.1	7.1

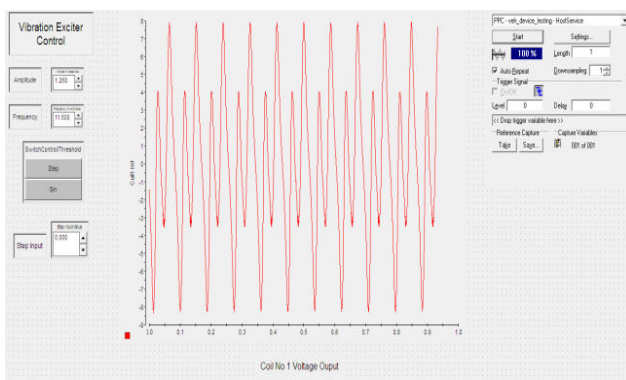


Figure-8. Induced voltage of coil 1 at exciter amplitude of 1.25 V and frequency of 13 Hz.

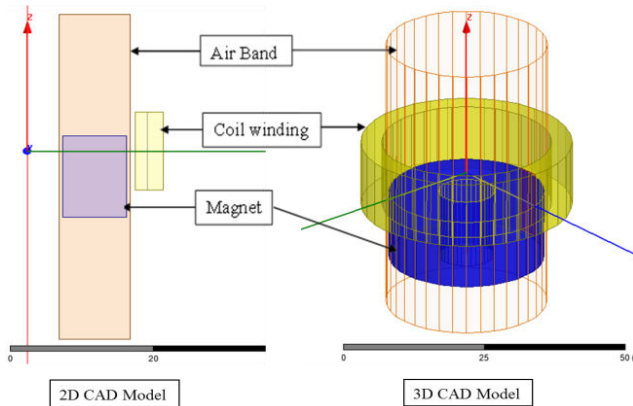
In this testing we are increasing the input amplitude of exciter so that three magnets were vibrates with different amplitude. The amplitude of vibration of magnet at input voltage (to the exciter) of 1 V is 9 mm and at 1.25 V it is 11 mm. This amplitude is measured by using LVDT.

These results can be validated by using Ansys Maxwell. First of all CAD model were prepared and apply material properties. Then apply actual loading conditions like translational motion, input velocity, assign windings and number of turns etc. and then solve the problem to find induced voltage v/s time graph, flux density, flux lines, current density etc. These results are shown in following figures.

Extraction device consist of three magnets interconnected with the help of aluminium pipe so all magnets



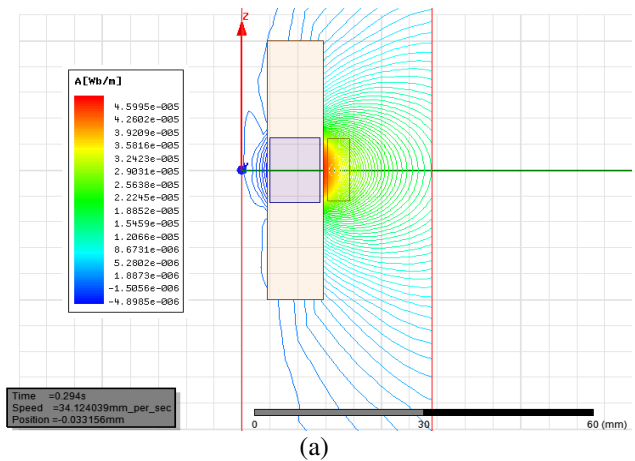
will oscillate with same amplitude. Here we consider only one pair of coil and magnet to complete simulation of device. We can complete simulation in 2D or 3D modelling. 2D and 3D CAD model is drawn in Ansys Maxwell with exact dimensions and it is shown in Figure-15.



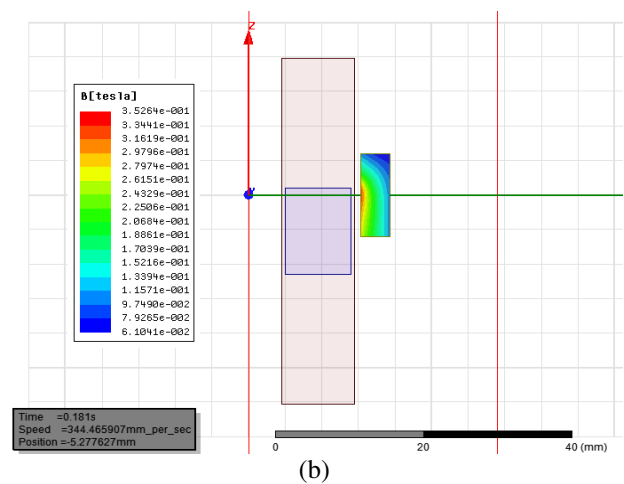
**Figure-9.** 2D and 3D CAD model of magnet and coil drawn in Ansys Maxwell.

In this problem, motion of magnet is unidirectional and it is along z direction. After number of trials it is observed that maximum voltage is at 13 Hz. In our CAD model cylindrical axis of coil matches with z-axis and x-axis is at middle of height coil. Initially magnet is at 5 mm below the x-axis (i.e. center of magnet is at 5 mm below the x-axis). The amplitude of displacement of magnet is about 5 mm up and down of initial position. Velocity of motion in mm per second is given by  $v = \omega \times \cos(\omega t) = 5 \times 2\pi \times 11 \times \cos(2\pi \times 11 \times \text{time}) = 345 \times \cos(69.15 \times \text{time}) \text{ mm/sec}$

All parameters mentioned above are assigned in motion setup dialog box then create coils windings with 3240 as number of turns. Copper coil has 30  $\Omega$  resistance and inductance of 13.3 mH. Then add solution setup in analysis. In solution setup add solution stopping time and time step then click on analyzes all to solve the simulation. Magnet oscillates with 5 mm amplitude in z direction and due to this motion of magnet magnetic lines are cut by coil, Figure-10(a) shows flux lines plot of magnet and Figure-10(b) shows flux density plot for 2D model.

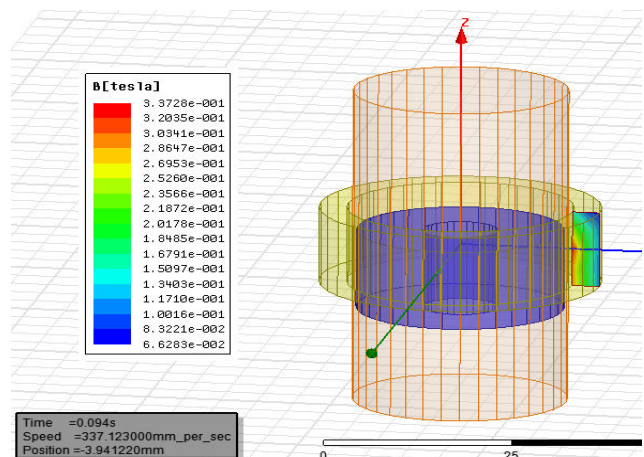


**Flux lines induced due to magnetic field in 2D model**



**Figure-10.** (a) Flux lines and (b) Flux density in 2D model.

When same problem is solved by using 3D model then we will get same results as that if 2D model simulation. The flux density plot of 3D simulation is shown in Figure-18.

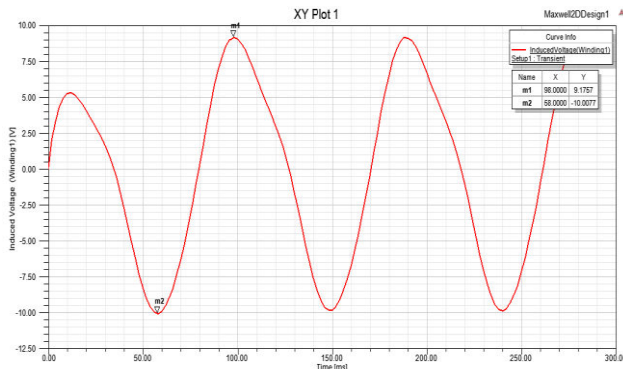


**Figure-11.** Flux density of 3D model.



### Voltage induced in simulation

After completion of simulation we get maximum voltage of about 9.18 and -10 V as shown in Figure-12. This induced voltage is nearly same as that of experimental voltage and it is about 8.5 volt.



**Figure-12.** Induced voltage v/s time plot of both 2D and 3D simulation.

### CONCLUSIONS

From the above results, it concludes that the spring with the stiffness of 325 N/m, has capability to sustain vibrations. This spring sustain the vibrations and support vibratory motion of magnet inside the coil, so that coil will generate output voltage due to magnetic flux cut by the coil.

The natural frequency of device is about 13.5 by simulation. Experimentally if this device is vibrated at about 13.0 Hz vibration frequency, then each coil has capability of producing output voltage about 8.5 V i.e. it will produce nearly 24.65 mW of power when we connect resistance of 2 k $\Omega$  across the terminals of coil. There are four coils used in extraction device, so device will produce total power of 98.6 mW.

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