

Design and Analysis of Vibration Energy Extraction System



#¹Sharad P. Ambad , #²Suhas P. Deshmukh , #³ Arun V. Bhosale

¹ sharadambad@gmail.com

² suhas.deshmukh@gmail.com

³ arunbhosale@rediffmail.com

#¹PG scholar, Mechanical Department, SAOE, Pune, Savitribai Phule Pune University, Pune

#² Professor, Mechanical Department, SAOE, Pune, Savitribai Phule Pune University, Pune

Assistant Professor, Mechanical Department, SAOE, Pune, Savitribai Phule Pune University, Pune

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 producing devices, 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. Design and analysis of electromagnetic conversion system is represented. Also we find equilibrium position of magnet inside the coil so that the maximum flux to be cut by coils and it will produce maximum output power.

Keywords— Electromagnetic, Electrostatic, Micro-Electro Mechanical System, Piezoelectric, Vibration energy

ARTICLE INFO

Article History

Received : 18th November 2015

Received in revised form :

19th November 2015

Accepted : 21st November , 2015

Published online :

22nd November 2015

I. INTRODUCTION

The recent expansion of wireless sensors networks in many applications and the development of low power consumption devices have been driving research on microgenerators converting vibration energy into electricity to replace batteries that require costly maintenance. Harvesting ambient energy to supply appears to be a key technology to develop compact, lightweight and energy autonomous devices [1]. It has been shown that mechanical vibrations are available in many application domains (e.g. home appliances, industrial environment or operations,

transportation systems or even the human body) can produce large amount of vibrations which can be converted into electrical energy by using different conversion system and it can produce potentially sufficient power density [2]. Converting the mechanical energy from ambient vibrations into electrical energy is performed by a different conversion system. The conversion efficiency depends on the operating conditions and applications of implementation. Among different vibration energy conversion systems, piezoelectric and electromagnetic generators 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 and Electromagnetic conversion system consist of one or permanent magnet and one or several coils assembled in proper manner in simple geometry [4].

They systems have been widely studied and MEMS structures have been develop. 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 (EMCS) are placed in environments with tens or hundreds hertz frequency of vibration and is suitable for microsystems with modest power requirement and the power produced by such conversion devices is proportional to the cube of frequency of vibration [7].

A. Power Generation Capacities of Different Sources

The results of a broad survey of potential energy sources for wireless sensor nodes, both power scavenging sources and fixed energy sources such as batteries, are shown in Table 1. The top part of the table contains fixed level of power generation sources and the bottom part of the table contains sources with fixed amount of energy storage.

Solar cells provide excellent power density in direct sunlight. However, in dim office lighting, or areas with no light, they are inadequate. Power produced from thermal gradients is also substantial enough to be of interest if the necessary thermal gradients are available. The hydrocarbon fuels produces very high amount of power but they are not easily switch off so that we have to run these for long time storage system is require to store this energy so that it minimizes it advances.

A variety vibrations have been measured which are commonly occurring in order to investigate the nature of vibrations available. Most of the vibrations measured were from commonly occurring sources like household appliances, industrial operations, vehicle engine vibrations these vibration cannot avoided so that these vibrations could be used for power generation.

TABLE 1
COMPARISON OF ENERGY SOURCES AND POWER
SCAVENGING

Source	Power density (mW/cm ³)
Solar (outdoors condition)	15,000 in Direct sun, 150 in Cloudy day
Solar (indoors condition)	6 on Office desk
Vibrations (electromagnetic or conversion)	250
Vibrations (electrostatic conversion)	50
Temperature gradient	15 at 10° C gradient
Batteries (non-rechargeable lithium)	47

Batteries (rechargeable lithium)	7
Hydrocarbon fuel (micro heat engine)	333

II. STUDY OF DIFFERENT CONVERSION SYSTEM

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

- i. Electrostatic
- ii. Electro-magnetic
- iii. Piezoelectric

In the first case, Electrostatic generation consists of two conductors separated by a dielectric (i.e. a capacitor), which move relative to one another. As the conductors move the energy stored in the capacitor changes, thus providing the mechanism for mechanical to electrical energy conversion. The primary disadvantage of electrostatic converters is that they require a separate voltage source to initiate the conversion system. 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 magnetic field. The conductor typically is in the form of a coil and the electricity is generated by either the relative movement of the coil and magnet, or because of changes in the 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. This voltage generated in the coil is determined by Faraday's Law.

TABLE 2

COMPARISON OF DIFFERENT CONVERSION SYSTEMS

	Advantages	Disadvantages
Electro-magnetic	No voltage source required	Easy to design, fabricate, Easy to install
Piezoelectric	No voltage source required	More difficult to integrate in Microsystems
Electrostatic	Easier to integrate in Microsystem	• Separate voltage source is required • Practical difficulties are available

Electromagnetic and Piezoelectric conversion system do not require a separate voltage source, but piezoelectric system are not as easily integrated into a micro fabrication process. The main comparative points are represented in table 2. While it is true that piezoelectric thin films can be integrated into MEMS processing, the piezoelectric coupling is greatly reduced. Therefore here we will compare only Electromagnetic and Piezoelectric conversion systems.

A. Comparison between Piezoelectric and Electromagnetic Conversion systems [1]

Comparative points between electromagnetic and piezoelectric conversion system are as follow

- i. The harvested power has been measured for both generators as a function of the load resistance.

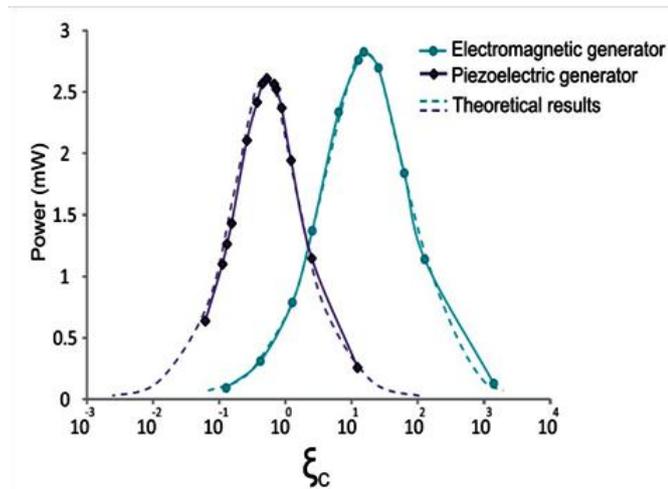


Fig. 1 Power as a function of the load coefficient, for the PEG and the EMG

- ii. EMGs has much higher coupling coefficient values than PEGs ones, which partially compensates the high losses induced by the coil resistance loss, it leading to extract the same power as PEGs.
- iii. For the PEG, for an optimal load value of 23.5 kΩ at 2 g and 127 Hz, a maximum power of 2.6 mW has been reached, corresponding to 30% of the limit power.
- iv. For the EMG, 2.9 mW have been harvested on a load value of 1.1 kΩ at 135 Hz, which also corresponds to approximately 30% of the limit power.
- v. The lowest losses coefficient or the highest coupling coefficients leads to the highest normalized power.
- vi. That the power density of an electromagnetic generator does not decrease proportionately with its volume.

From above comparison we conclude that the electromagnetic conversion system is more efficient than piezoelectric conversion system, hence we can implement electromagnetic conversion system for electricity generation from vibration energy.

III. GENERAL MATHEMATICAL MODEL

EMCS and PECS are usually modeled by a simple mass-spring damper system, in which the damper embodies the energy harvesting process and mechanical intrinsic losses. However, in this model does not consider the electrical parasitic losses. So one can formulate a general model for the conversion of the kinetic energy of a vibrating mass to electrical power based on linear system theory without specifying the mechanism by which the conversion takes place. A simple model based on the schematic in Fig. 2. This system is described by Eq. (1).

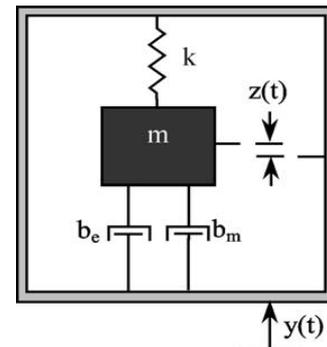


Fig. 2: Schematic of generic vibration converter

$$m\ddot{z} + (b_e + b_m)\dot{z} + kz = -m\ddot{y} \tag{1}$$

Where, z is the spring deflection, y is the input displacement, m is the mass, b_e is the electrically induced damping coefficient, b_m is the mechanical damping coefficient and k is the spring constant. The term b_e represents an electrically induced damping coefficient. The primary idea behind this model is that the conversion of energy from the oscillating mass to electricity looks like a linear damper to the spring mass system. This is a fairly accurate model for certain types of electro-magnetic converters. For other types of converters (electrostatic and piezoelectric), this model must be changed somewhat. First, the effect of the electrical system on the mechanical system is not necessarily linear, and it is not necessarily proportional to velocity. The conversion will always constitute a loss of mechanical kinetic energy, which can broadly be looked at as ‘damping’. The power converted to the electrical system is equal to the power removed from the mechanical system by b_e , the electrically induced damping. The electrically induced force is $b_e \dot{z}$. Power is the product of force and velocity, and therefore, the power converted is given by Eq. (2).

$$P = \frac{1}{2} b_e \dot{z}^2 \tag{2}$$

Eqs. (1) and (2) can be used to derive the following analytical expression for power converted.

$$|P| = \frac{m \zeta_e \omega_n \omega^2 \left(\frac{\omega}{\omega_n}\right) Y^2}{\left(2\zeta_T \frac{\omega}{\omega_n}\right) + \left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2} \tag{3}$$

Where, $|P|$ is the magnitude of output power, Y the displacement magnitude of input vibrations, ζ_e the electrical damping ratio ($b_e = 2m\zeta_e\omega$), ζ_T the combined damping ratio ($\zeta_T = \zeta_e + \zeta_1$), the input frequency and ω_n is the natural frequency of spring mass system. If it is assumed that the resonant frequency of the spring mass system matches the input frequency, Eq. (3) can be reduced to the equivalent expressions in Eqs. (4) and (5).

$$|P| = \frac{m \zeta_e \omega^3 Y^2}{4\zeta_T^2} \tag{4}$$

$$|P| = \frac{m \zeta_e A^2}{4\omega \zeta_T^2} \tag{5}$$

Where, A is the acceleration magnitude of input vibrations. Note in Eq. (5) that the power is inversely proportional to frequency. Therefore the acceleration magnitude of the vibrations is constant or decreasing with frequency. Power is linearly proportional to mass. Therefore, the converter should have the largest proof mass that is possible while staying within the space constraints.

IV. DESIGN OF ELECTROMAGNETIC EXTRACTION SYSTEM

The EMCS (device) consist of flexural spring, coil windings, magnet, spacer block, spacer plate, end plate, middle plate etc.

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 Fig. 3.

- i. First the magnets are press fit into the aluminum pipe at center and ends.
- ii. The spring-magnet system (flexure spring and the magnet) is fixed on the Aluminum-housing with optimal dimensions.
- iii. The wound-wire coil is glued on the assembled end plates and at mid plate.
- iv. Finally the end plates, spacer block, spacer plate, mid plate and flexure spring and magnets are fixed together using studs.
- v. Connections from the coil are taken out of assembly to measure output of Energy Harvester.

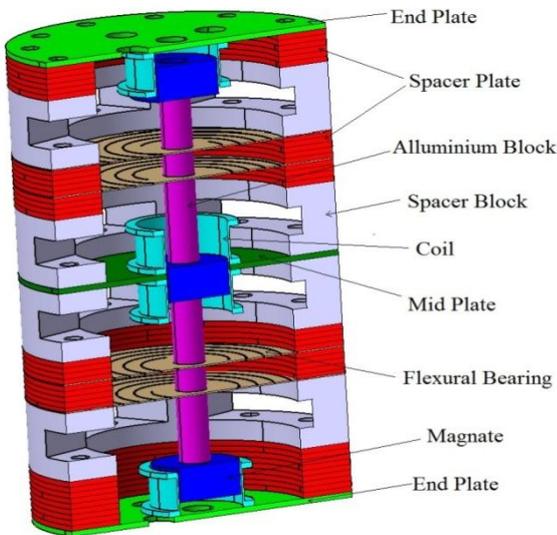


Fig. 3 Sectional view of CAD model of electromagnetic conversion system

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- 30,000 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 20Hz. So to calculate stiffness of the spring by the formula:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{6}$$

The CAD model of spring is designed in Catia V5 R19 and it is shown in Fig. 4(a) and the analysis if this model is done with the help of Ansys 13 workbench. The meshed model is shown in Fig. 4(b). When apply force of 10 N and apply remaining boundary conditions observed the deformation and equivalent stresses by using FEA software it is observed that it will produce deformation of 45.02 mm and it is shown in Fig. 5. Also the stresses are developed in coil due to these loading are shown in Fig. 6.

Applied force = F = 10 N

Deformation = $\delta = 45.02 \text{ mm} = 45.02 \times 10^{-3} \text{ m}$

F = k δ (7)

k = 221.24 kg/m

Mass of 3magnet and 2 aluminium pipes is 170 gm

And there are four springs

$$\omega_n = 2\pi f_n = \sqrt{\frac{k}{m}} ; f_n = 11.48 \text{ Hz}$$

By considering spring stiffness 221.24 N/m design the spring having dimensions as Thickness = 0.5mm, Number of grooves = 3, Spiral angle = 540°, width of cut = 0.5 mm, Starting & ending radius = 12.5 mm & 38 mm.

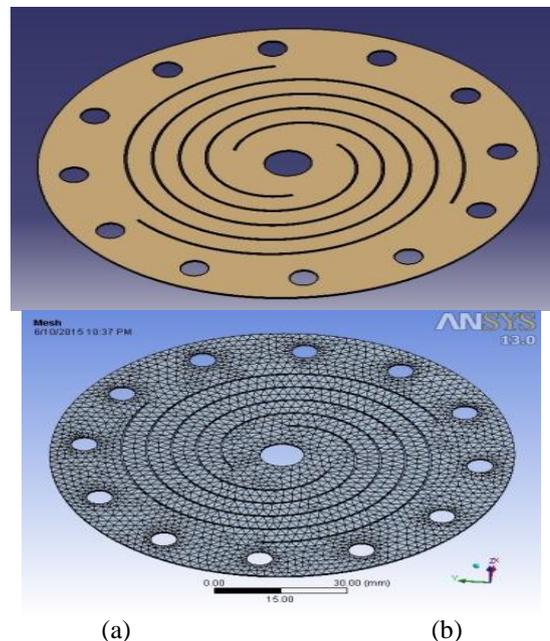


Fig. 4 (a) CAD model of flexural spring, (b) Mesh model of flexural spring

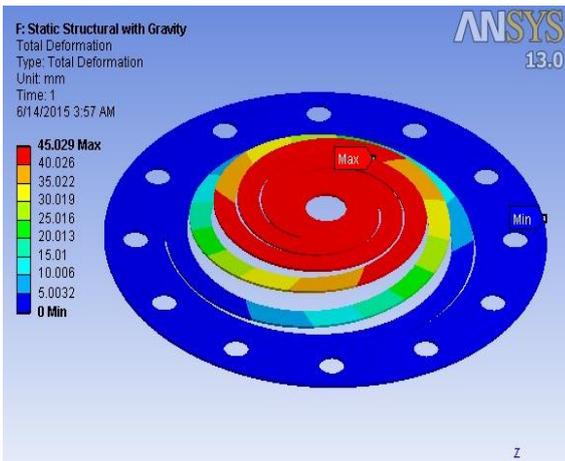


Fig. 5 Total deformation of flexure spring

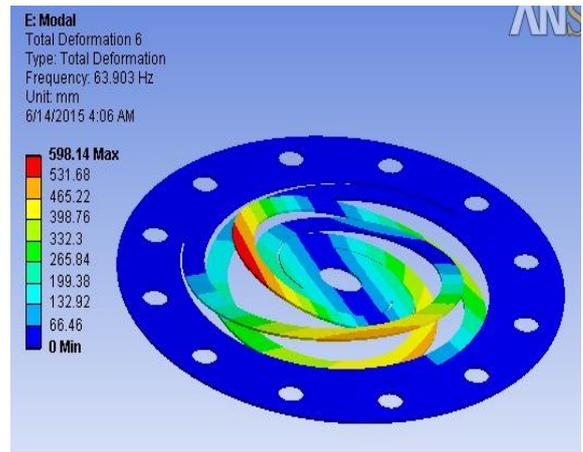


Fig. 8 Sixth mode of vibration of spring

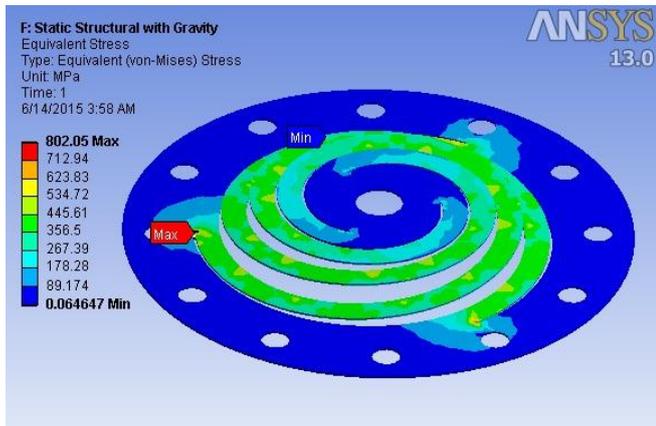


Fig. 6 Equivalent stresses in flexure spring

We perform the modal analysis of spring and obtained first six modes at different frequencies of 24.18, 41.01, 41.02, 61.09, 63.89, 63.90 respectively and first and sixth modes of vibration are shown Fig. 7 and Fig. 8

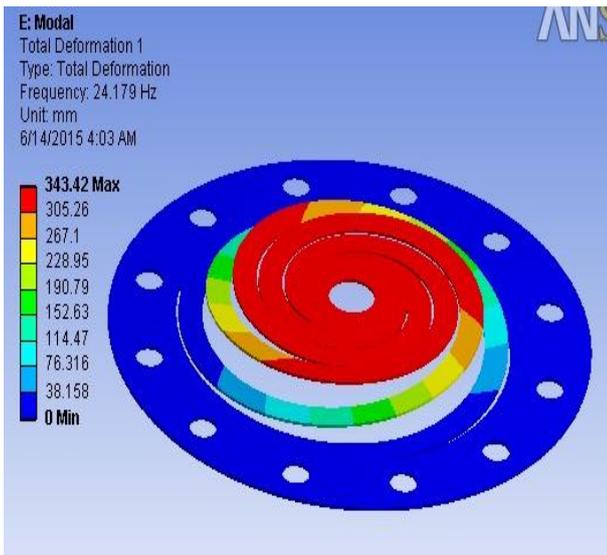


Fig. 7 First mode of vibration of spring

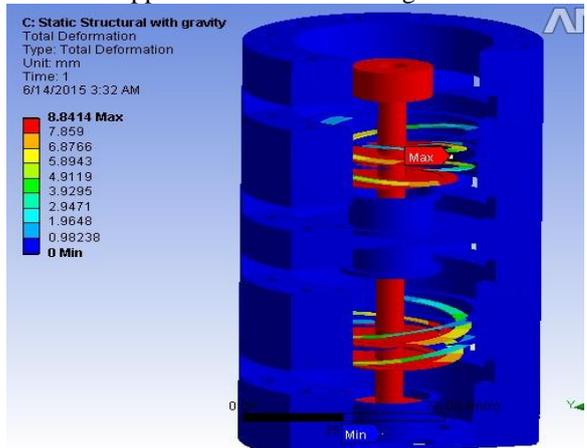


Fig. 9 Total deformation of electromagnetic device

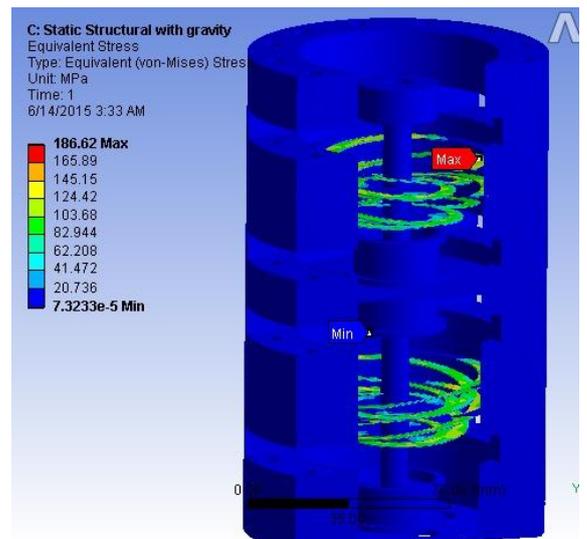


Fig. 10 Equivalent stresses in electromagnetic device

B. Design calculations of Extraction System

When boundary condition are applied to electromagnetic device i.e. 10N force is applied on first magnet in downward direction and centre hole of bottom end plate is fixed then it will shows deformation of 8.84 mm by considering standard gravity, this is shown in fig. 9. The stress produced on device due to applied load is shown in fig. 10.

C. Calculations to find natural frequency of device

Mass of 3 magnet and 2 aluminium pipes = 170 gm

$Applied\ force = F = 10\ N$

$Deformation = \delta = 8.84\ mm = 8.84 \times 10^{-3}\ m$

$F = k\delta$

$k = 1131.22\ kg/m$

$\omega_n = 2\pi f_n = \sqrt{\frac{k}{m}} ; f_n = 12.98\ Hz$

From calculated natural frequency of 12.98 Hz, when we give excitations of 12.98 Hz resonance will happened. At resonance condition magnet will vibrate with maximum amplitude and it will generate large output voltage.

Also we perform the modal analysis of electromagnetic device and obtained first six modes of vibration these modes are at different frequencies of vibration. These six modal frequencies are 13.56, 66.20, 67.61, 68.44 and 68.67 respectively. Among these six modes, first and sixth modes of vibration are shown in fig. 11 and fig. 12.

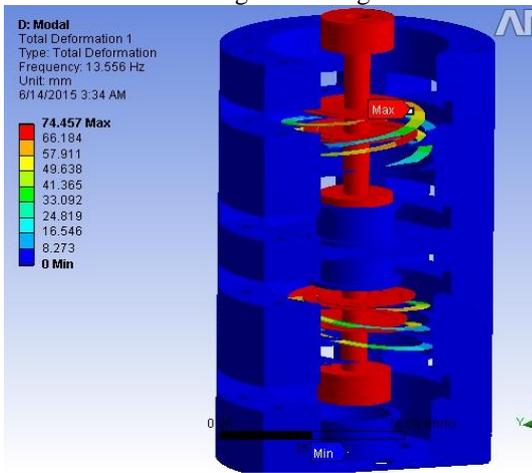


Fig. 11 First mode of vibration if electromagnetic device

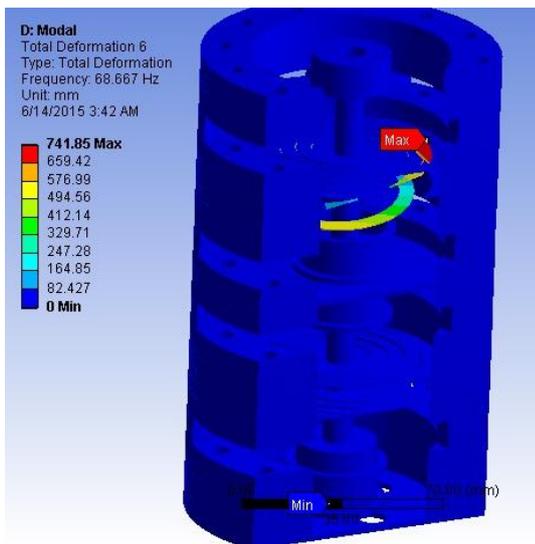


Fig. 12 Sixth mode of vibration of electromagnetic device

V. 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 Fig. 13. Its components 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 Fig. 14.

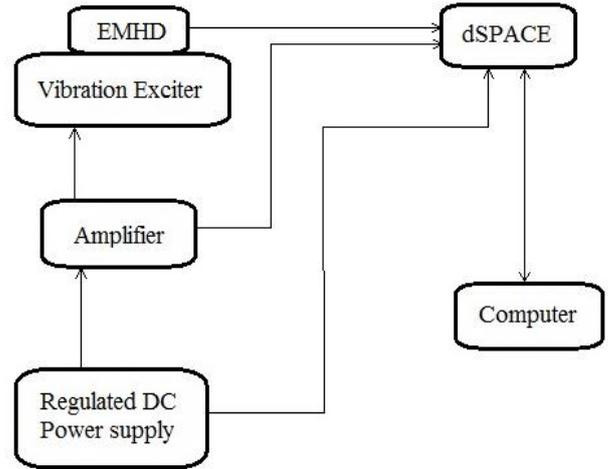


Fig 13 Block diagram of Experimental Setup

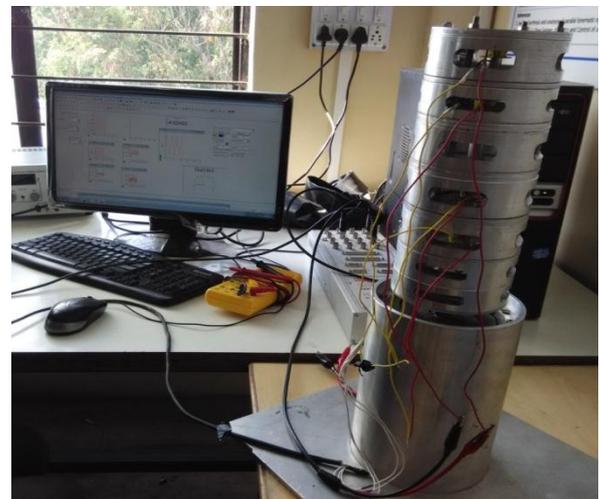


Fig.14 Photo of experimental testing setup

VI. CONCLUSIONS

From the above study it is conclude that the spring having stiffness 221.24 N/m has capability to sustain vibrations and produce the vibratory motion of magnate into the coil, so that coil will generate output voltage due to magnetic flux cut by the coil. If this device is vibrated with 13 Hz vibration then coil will deflect 12 mm and it has capability of producing output voltage about 6.2 V. It means that this system will produce nearly 3.2 mW power.

ACKNOWLEDGMENT

Thanks to BCUD and SPPU for funding this project. Also thanks to Dr. S. P. Deshmukh, Prof. A. V. Bhosale for his valuable guidance and contribution in developing the IJRSD article.

REFERENCES

- [1] E. Arroyo, A. Badel, F. Formosa, Y. Wu, J. Qiu, "Comparison of electromagnetic and piezoelectric vibration energy harvesters: Model and experiments", *Sensors and Actuators A* 183 (2012) 148–156
- [2] S. Roundy, P.K. Wright, J. Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes", *Solar Cells* 26 (2003) 1131–1144.
- [3] El-Hami M et al 2001 Design and fabrication of a new vibration-based electromechanical power generator *Sensors Actuators A* 92 335–42
- [4] P.-H. Wang, X.-H. Dai, D.-M. Fang, X.-L. Zhao, "Design, fabrication and performance of a new vibration-based electromagnetic micro power generator", *Microelectronics Journal* 38 (2007) 1175–1180.
- [5] S. Kulkarni, E. Koukharenko, R. Torah, J. Tudor, S. Beeby, T. O'Donnell, S. Roy, "Design, fabrication and test of integrated micro-scale vibration-based electromagnetic generator", *Sensors and Actuators A: Physical* 145–146 (2008) 336–342.
- [6] S.P. Beeby, R.N. Torah, M.J. Tudor, P. Glynn Jones, T. O'Donnell, C.R. Saha, S. Roy, "A micro electromagnetic generator for vibration energy harvesting", *Journal of Micromechanics and Microengineering* 17 (2007) 1257–1265.
- [7] C.B. Williams, R.B. Yates, "Analysis of a micro-electric generator for microsystems", *Sensors and Actuators A: Physical* 52 (2008) 8–11.
- [8] D. Spreemann, D. Hoffmann, B. Folkmer, Y. Manoli, Numerical optimization approach for resonant electromagnetic vibration transducer designed for random vibration, *Journal of Micromechanics and Microengineering* 18 (2008) 104001.
- [9] D. Zhu, S. Roberts, M. J. Tudor, S. P. Beeby, "Design and experimental characterization of a tunable vibration-based electromagnetic micro-generator", *Sensors and Actuators A* 158 (2010) 284–293.
- [10] W. L. Lu, Y. M. Hwang, C. T. Pan, S. C. Shen, "Analyses of electromagnetic vibration-based generators fabricated with LTCC multilayer and silver spring-inducer", *Microelectronics Reliability* 51 (2011) 610–620.