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Experimental Analysis of Multiple Modes and Nonlinear Behavior in Electromagnetic Type Vibration Energy Harvesters

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Keywords： Energy harvesting, Electromagnetic, Multiple modes, Nonlinear behavior, Planar movable coil.

ABSTRACT

Experimental analysis of multiple modes and nonlinear behavior in electromagnetic type vibration energy harvester (EV-EH) has been investigated in this paper. The EV-EH fabricated in this research is composed of planar movable coils (PMC) which is fabricated from printed circuit board sheet using Computer Numerical Control milling machine, neodymium (NdFeB) magnets residing on latex membrane and acrylic spacers. The EV-EH can harvest energy from multi modes sinusoidal and random vibrations. The multiple modes of the prototype have been found using various techniques like Fast Fourier Transform (FFT) and Power Spectral Density (PSD). The developed prototype has three resonant frequencies at 60 Hz, 139 Hz and 278 Hz. The nonlinear behavior of the EV-EH has also been discussed in this paper using bifurcation diagrams. At higher acceleration level, the resonant frequencies of EV-EH are shifting from those at low acceleration level. At different acceleration level, the EV-EH shows sharp jump and sharp fall phenomenon which is due to the nonlinear behavior of the device. The EV-EH is also able to generate a 12 mV open circuit voltage at 3 g acceleration level.

INTRODUCTION

Vibration is present almost everywhere and different techniques are available to convert mechanical vibrations into useful electrical energy (Khan and Ahmad 2015).

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A desktop PC during normal operation has a vibration of 0.021 g with a frequency of 543 Hz, however, its frequency reduces to 154 Hz when CD ROM is running (Kok, White et al. 2008). A microwave oven has a vibration of 0.068 g and of 100 Hz (Kok, White et al. 2008). Washing machine and refrigerator has a vibration of 0.31 and 0.017 g with a frequency of 85 and 58.7 Hz (Reilly, Miller et al. 2009) respectively. Electrostatic (Khan and Qadir 2016), piezoelectric (Shakthivel and Burela 2016) and electromagnetic (Khan and Ahmad 2014) are the three main approaches used to convert mechanical vibration into useful electrical energy. Most of the developed vibration energy harvesters are single mode having single resonant frequency (Liao and Sodano 2008, Khan, Sassani et al. 2010). Single mode energy harvesters have very narrow frequency bandwidth (Sari, Balkan et al. 2008). A single mode energy harvester is when excited at a frequency other than its resonance frequency; the generated energy would be considerably reduced. However, a limited research is available on multi-mode energy harvesters having several resonant frequencies. Multi-modes energy harvesters can scavenge energy at multiple resonance points and hence increase the band of frequencies. The bandwidth of the electromagnetic type vibration energy harvesters (EV-EH) can be enhanced utilizing the nonlinear behavior of the membrane (Khan, Sassani et al. 2014). An array of electromagnetic energy harvester with multiple modes has been reported in (Liu, Chen et al. 2015). For the three energy harvesters nine resonance frequencies have been found in the range of 158-614 Hz. The open circuit output voltages at the three resonances are varying from 0.01 to 0.13 mV. The authors claim that the device can be further optimized in the design and dimensional parameters to achieve maximum output. However, the authors have not verified the multiple modes experimentally. A piezoelectric and electromagnetic hybrid multi-frequency energy harvester has been presented in (Xu, Shan et al. 2016). Numerical simulation of the device has also been done in this research and the numerical natural frequencies have been found as 22 and 26 Hz for the magnetic and piezoelectric oscillators respectively, while, the experimental modes verification has not been seen. Piezoelectric energy harvester capable of generating a voltage of 1000 mV and a power of 0.136 μW is designed, fabricated and characterized for its first three natural frequencies in (Rezaeisaray. M et al. 2015). Another piezoelectric energy harvester (Dhote S et al. 2015), is designed with a unique geometry for multiple modes and low-frequency environment. Finite element analyses of the four-leaf clover resonant assembly type piezoelectric device have been illustrated in (Iannacci. J et al. 2014). Moreover, the prototype is able to generate 150 mV open circuit voltage (OCV) and 0.2 μW load power. Furthermore, an electromagnetic type energy harvester for multi-frequency vibration has been investigated in (Yang. B et al. 2009). The device has been characterized by its three natural frequencies of 369, 938 and 1184 Hz and a power of 3.2 μW has been achieved. Another electromagnetic type energy harvester (Liu. H et al. 2013), with multiple frequencies has been presented. The device is able to generate OCV at its three modes; mode-I, mode-II/III and mode-IV/V correspond to its high resonant frequencies (840, 1070 and 1490 Hz).

Motivation

In summary, there are few major motivations for the work presented in this research paper. First, the existing vibration energy harvesters majorly rely on its single mode, which is not enough to harvest real vibration that exhibit multiple natural frequencies. Second, most of the work considering multi-modes energy harvesters only emphases on simulated modes but does not majorly concern the experimental validation of modes. Third, the experimental analysis of the nonlinear behavior of the electromagnetic type vibration energy harvester (EV-EH) is also a major motivation. Finally, the multiple planar movable coils (PMCs) can be added to increase the number of natural frequencies and output power.

Statement of contribution

In this article, we study the experimental analysis of multiple modes and nonlinear behavior in EV-EH. A prototype of EV-EH is conceptualized, designed, fabricated and characterized for its multiple modes and nonlinear behavior. The contributions can be seen in twofold:

- The EV-EH, capable of delivering decent output voltage at multi-frequency vibration levels is designed and fabricated. The prototype has novelty in terms of its multiple natural frequencies below 300 Hz. Unlike, the conventional vibration energy harvester, PMC adds to the resonant frequencies along the moving magnet.
- The device has been fabricated through conventional machining. In-lab characterization has been performed. Multiples modes of the device have been verified with two different techniques; Fast Fourier Transform (FFT) and Power Spectral Density (PSD). The device has also been characterized at random vibration and the nonlinear behavior of the prototype has been analyzed in this work.

ARCHITECTURE AND FABRICATION

Device Configuration

The cross sectional and exploded view of EV-EH has been shown in the figure 1 (a) and (b) respectively. Two planar movable coil (PMC) have been used in EV-EH; each coil is like a spiral spring which is able to move up and down. A single PMC has 4 numbers of turns and has a volume of 1.5 x 1.5 x 0.1 cm3. The PMC is supported by the acrylic spacers which has a square slot of 1.5 cm2, and a height of 0.4 cm. Another acrylic spacer of 0.2 cm height is placed on top of each PMC to allow room for the coil movement. Two neodymium (NdFeB) magnets each having volume of 0.3 cm3 residing on latex membrane have been used. The overall volume of the prototype is 5.41 cm^3.

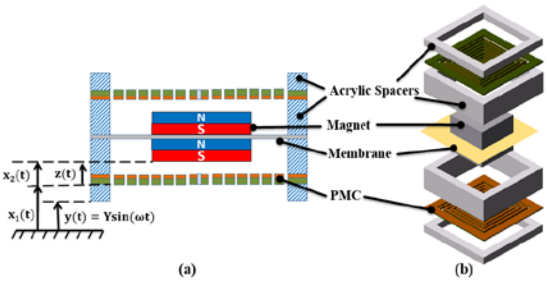


Fig. 1. EV-EH (a) cross sectional view (b) exploded view.

Due to base excitation, y (t) the suspended components, like, the PMC and magnet-membrane assembly moves with $x_1(t)$ and $x_2(t)$ respectively. The magnets-membrane assembly is expected to have low resonant frequency due to lumped mass of magnet. Then the PMC and both the suspended components moves with different velocity. The magnet and PMC moves relative to each other, due to which a voltage is induced in the PMC based on Faraday's law of electromagnetic induction. The voltage induced in the PMC depends on the relative velocity, z (t) between magnets and the PMC, acceleration level, residual flux density of the magnet and the gap between PMC and magnet.

Machining

PMCs of EV-EH have been manufactured using computer numerical control (CNC) milling machine. The 3D drawing of the coil has been made in PTC Creo® software and automatic CNC code has been generated using the same software. The final code has been uploaded to CNC milling machine and a coil has been manufactured. Electrical connections have been made to the coil through soldering process. Using the same milling process inner and outer acrylic spacers have been manufactured. All these components have been assembled in an order as shown in the exploded view of the prototype in figure 1 (b). The fabricated parts and the assembled prototype has been shown in figure 2.

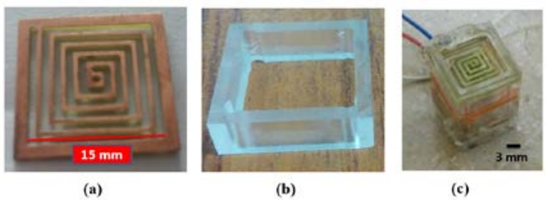


Fig. 2. EV-EH (a) Fabricated PMC (b) Fabricated acrylic spacer (C) Assembled prototype

CHARACTERIZATION

The developed EV-EH has been tested on the experimental setup shown in figure 3. The experimental setup consists of a power amplifier, shaker table, accelerometer, Data Acquisition (DAQ) Card and a PC to acquire data through USB port. DAQ card generate a signal and power amplifier pass the amplified version of that signal to the shaker table. Accelerometer is used to measure the vibration level of the shaker table. The output signal of the EV-EH has been analyzed in PC through DAQ card.

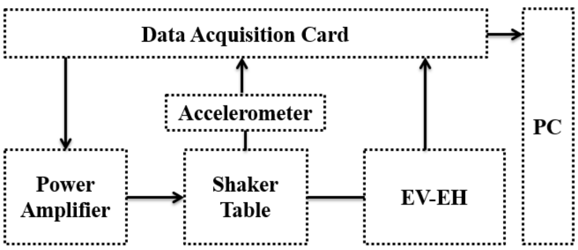
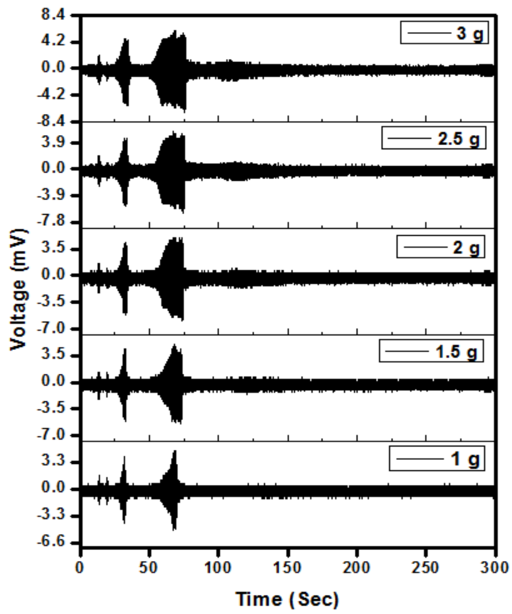


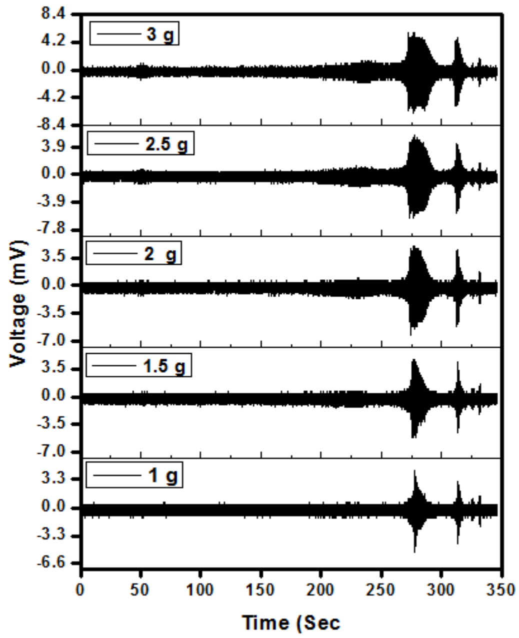
Fig 3.Schematic diagram of the experimental setup

Time domain analysis

Time signal of the EV-EH has been acquired for a single PMC at forward and reverse frequency sweep. The EV-EH has been excited at various vibration levels (1 g, 1.5 g, 2 g, 2.5 g and 3 g) and a frequency sweep of 0-350 Hz. The corresponding output time signal of a single PMC at forward frequency sweep is shown in figure 4 (a). Single PMC of EV-EH produces a peak to peak voltage of 12 mV at forward frequency sweep at 3 g acceleration level. The device has also been characterized at a reverse frequency sweep of 350-0 Hz at the same acceleration level of 1 g, 1.5 g, 2 g, 2.5 g and 3 g. Time response of a single PMC at reverse frequency sweep is shown in figure 4 (b).



(a)



(b)

Fig 4. Time response of a single planar movable coil at (a) forward (b) reverse frequency sweep

Frequency Domain Analysis

Frequency analysis has been performed to find out the different modes of EV-EH. Two different approaches FFT and PSD analysis have been used to find the modes of the device. Time response of a single PMC at 3 g acceleration level at forward and reverse frequency sweep has been taken for the FFT analysis in MATLAB. The FFT result obtained are shown in the figure 5. FFT graph of the PMC shows three peaks (60 Hz, 139 Hz and 278 Hz) at forward and reverse frequency sweep which clearly shows the three modes of the EV-EH.

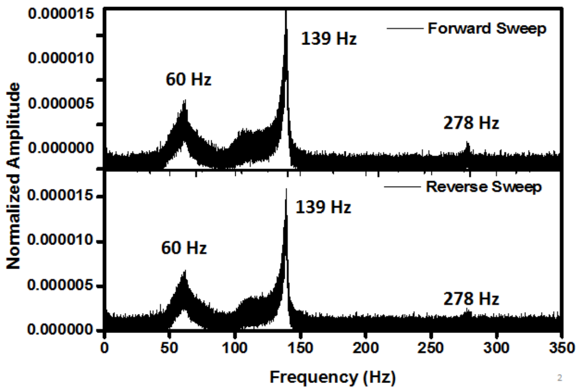


Fig 5. Fast Fourier Transform of a single planar movable coil at 3 g

PSD analysis has also been performed to validate the FFT results. The same experimental setup has been used to acquire the PSD signal. The device has been placed on the shaker table and a PSD signal has been acquired through DAQ card under sinusoidal vibration of different levels. PSD plot of a single PMC has been shown in figure 6. It can be clearly seen from the PSD plot that the device has three modes (60 Hz, 140 Hz and 280 Hz) at 1 g. From figure 6 it can be clearly seen that the resonance frequencies in second mode are increasing as the acceleration level increases which is due to the nonlinear behavior of the device.

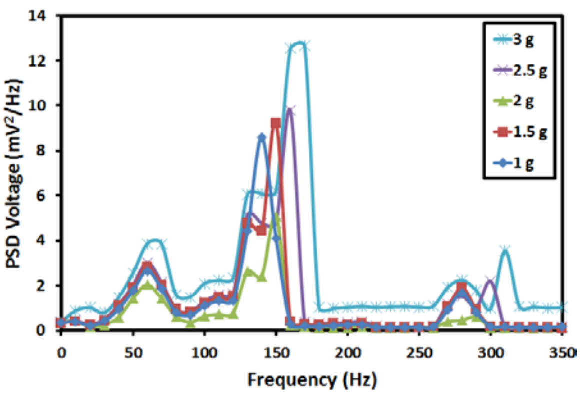


Fig 6. Power spectral density of a single planar movable coil

Random Vibration Characterization

The results in section 3.3 have been achieved using sinusoidal vibrations. However most of the real vibrations exhibit random oscillation consisting of various frequencies and amplitudes. The EV-EH has been characterized under random vibrations. The time signals at random vibration of a single PMC has been shown in figure 7. Time signal of the PMC at random vibration shows a maximum peak to peak voltage of 12 mV.

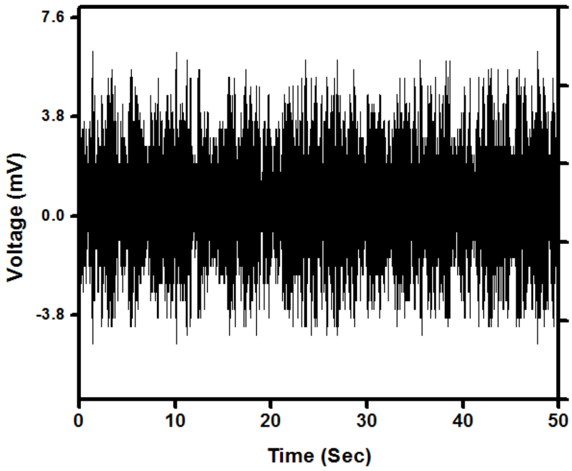


Fig 7. Time signal of a single planar movable coil at random vibration

The modes of the EV-EH have also been verified in random vibration characterization. A PSD analysis has been done on the available setup as shown in figure 8. PSD of the PMC shows three peaks (at 55 Hz, 135 Hz, and at 275 Hz) during this analysis. All the three peaks are comparable to the sinusoidal vibration analysis.

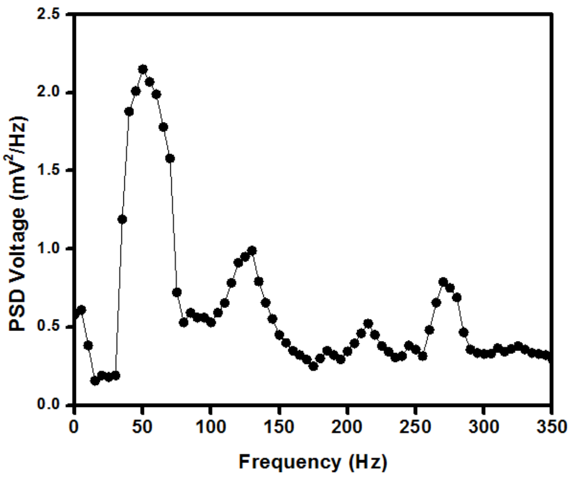


Fig 8. Power spectral density of a single planar movable coil at random vibration

Non-Linear behavior

The EV-EH consist of two suspensions structures the PMC and the magnet-membrane assembly. The membrane shows a nonlinear behavior which has been observed during the experimentation. The peaks in figure 4 (a) and (b) show the sharp drop and jump phenomenon which is due to the nonlinearity in membrane of the EV-EH. Similar phenomenon has also been observed in the FFT analysis. In figure 5 it can be clearly seen that the peaks at 139 Hz has sharp drop phenomenon. The nonlinearity of the membrane in the EV-EH has also been confirmed from the PSD analysis. The resonant frequencies have been seen in the increasing order with the increasing of acceleration level. The three resonant frequencies for the PMC have been plotted vs. acceleration level in figure 9. First and third resonances of the device show a little deviation from 60 Hz to 75 Hz and 280 Hz to 295 Hz respectively. However, the second resonance shows more deviation and the resonance frequency has been shifted from 140 Hz at 1 g to 170 Hz at 3 g which is due to the nonlinear behavior of the membrane.

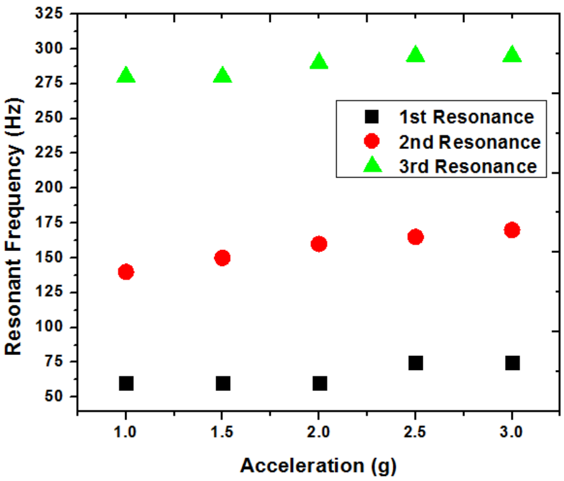
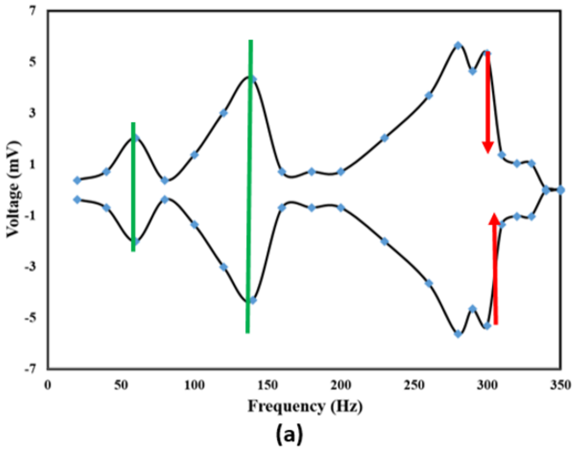


Fig 9. Resonant frequencies of EV-EH at different base acceleration

To analyze the changes in the time series of the EV-EH, a bifurcation diagrams were created at both forward and reverse frequency sweep at 3 g acceleration level. Figure 10 (a) shows the bifurcation diagram of the EV-EH at forward frequency sweep. It is clear from the figure that there is a change in voltage at three different points which show the three modes of the device, while the drastic sudden fall can be seen at a frequency around 278 Hz which shows the nonlinear mode of the device which is due to the membrane used in the device. Similarly figure 10 (b) shows the same phenomenon as the changes at frequency of 60 Hz and 140 Hz are symmetrical, showing linear behavior, while, that of 278 Hz is not symmetrical and a sharp jump phenomenon has been seen which is because of the nonlinear behavior at reverse frequency sweep.



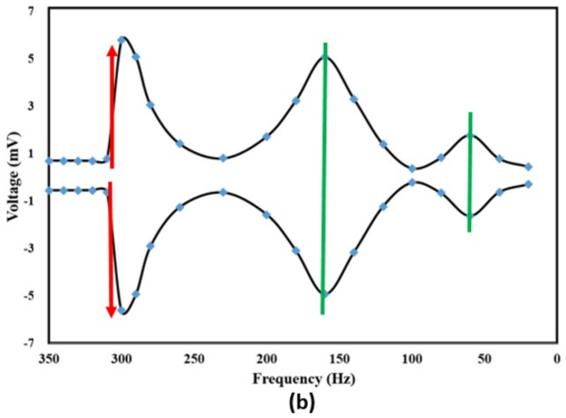


Fig 10. Figure 10.Bifurcation diagrams (a) at forward frequency sweep (b) at reverse frequency sweep

CONCLUSION

An EV-EH was developed and characterized in this research. The device has been characterized under sinusoidal and random vibrations. During characterization, it was founded that the device has three natural frequencies which have been verified using experimental analysis. The natural frequencies at different signal processing analysis have been summarized in table 1.

Table 1. Different resonance frequencies of EV-EH at different analysis.

Analysis	**1st Mode**	**2nd Mode**	**3rd Mode**
Power Spectral Density at Sinusoidal Vibration	60	140	280
Fast Fourier Transform	60	139	278
Power Spectral Density at random Vibration	55	135	275

Under sinusoidal vibration the time domain signal of single PMC has been acquired in forward and reverse frequency sweep. The open circuit voltage of the single PMC has been noted which was 12 mV. The same voltage has been achieved in random vibration characterization. The sharp drop & jump phenomenon has been seen in peaks during time and frequency domain analysis and in bifurcation diagrams which confirm the nonlinear behavior. The device can be tuned to different desired modes by changing the architecture of the PMC and the lump mass of the magnet.

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