Multi-mode Vibration based Electromagnetic type Energy Harvester for Structural Health Monitoring

Iftikhar Ahmad Farid Ullah Khan

***Abstract*—A multi-mode vibration based electromagnetic type energy harvester has been illustrated in this work. The harvester consists of two planar movable coils (PMCs), acrylic spacers and permanent magnets placed on a membrane (latex). Fabrication and experimentation of the prototype is presented. The PMC and acrylic spacers are fabricated through computer numerical control (CNC) machine. The prototype is characterized at a frequency sweep of 5-200 Hz under various acceleration levels. The device has three resonant frequencies of 73 Hz, 100 Hz and 123 Hz at relatively higher acceleration level of 3 g. Single PMC of the prototype at resonant frequency (first) of 73 Hz and a vibration level of 3 g yields a voltage amplitude of 16.6 mV and output power of 65.24 μW.**

***Index Terms*—Electromagnetic, Energy harvesting, Multi-mode resonator, Planar movable coil, Vibration**

I. Introduction

Wireless sensor nodes (WSNs) are usually used for structural health monitoring (SHM) of civil infra-structure, such as, bridges, flyovers and high risers [1]. SHM of Stonecutters bridges in Hong Kong [2] are performed to ensure the bridges condition and safeguard the structure and human lives. 1723 sensors have been mounted on the bridge to measure the structural behavior of the bridge. However, these WSNs use battery as a sole power source. The limited shelf life of batteries, normally require regular replacement or recharging of these batteries which is a huge concern where large number of WSNs are deployed [3]. Various types of energies including, acoustic [5], solar [4], and vibration [6] are accessible in the vicinity of the deployed WSNs. These ambient energies can be renewed into beneficial electrical energy with energy harvesters. Vibration energy harvesters (VEHs) converts mechanical vibration energy into electrical energy [7]. The three main types of developed VEHs that is piezoelectric, electrostatic and electromagnetic have been discussed and reported in [7]. Based on the mode of vibration, VEHs are further classified into a single mode (single resonant frequency) and multi-mode (several resonant frequencies) VEHs. Usually, VEHs produces maximum power at resonance [8]. Therefore multi-mode VEHs generate power at multiple operational frequencies. In literature most of the research work related to multi-mode VEHs is based on piezoelectric transduction mechanism [9]. A multi-mode electrostatic energy harvester has been developed in [10] using silicon on insulator process. Different types of springs have been added to fishbone shaped inertial mass to achieve multi modal behavior. The developed prototype is able to generate a maximum power of 2.96 μW at 1272 Hz for a vibrational direction of 0 at 6 g acceleration level. Design, fabrication and testing of a multi modal piezoelectric VEH has been reported in [11]. Silicon and aluminum have been used as a structural material. Finite element method (FEM) has been used to model the device. For the developed harvester three resonant frequencies have been reported. A voltage of 1000 mV (open circuit voltage) and 136 nW of power is generated when a 2 MΩ load resistance is attached to the harvester. A piezoelectric VEH [12] with a distinctive geometry for the spring is developed. In the VEH a spring of distinctive geometry is able of having multiple resonant modes at a low excitation frequency. The three fixed guided beams of the harvester has a non-linear response when subjected to external vibration. The reported VEH has been studied through FEM and experiments. Multiples modes have been seen in the frequency response of the harvester. Moreover, a proof mass has been added to the springs to bring the vibration modes close to each other. In [13] an electromagnetic VEH for multiple resonant frequencies has been illustrated. The harvesters comprised of three magnets and three double sided PCB coils. However, the support structure for the VEH is made from acrylic sheet. The VEH has been characterized for its three natural frequencies (369, 938 and 1184 Hz). At second mode (938 Hz) and vibration amplitude of 14 um, a maximum voltage of 3.2 mV and a maximum power of 3.2 μW is generated. A multi degree of freedom electromagnetic VEH is reported in [14]. The VEH consisted of a suspension system and a cylindrical permanent magnet. Moreover, the suspension system has microfabricated metallic coils. The finite element analysis for the first five vibration modes is performed in Abaqus. The VEH is able to produce considerable voltage at three resonant frequencies (840, 1070 and 1490 Hz). In the literature most of the developed VEHs have higher resonance frequencies and low output power especially the electromagnetic VEHs. In this research a multi-mode VEH has been designed, fabricated and tested. The developed energy harvester consists of permanent magnets, membrane, planar movable coils (PMC) and acrylic spacers. The PMCs and the acrylic spacers have been produced through computer numerical control (CNC) milling machine from PCB sheet and acrylic sheet respectively. Two PMCs have been used in the device to increase the power generation.

II. DESIGN AND ARCHITECTURE

The cross sectional view of the multi-mode VEH is displayed in fig. 1.The prototype is composed of two neodymium (NdFeB) magnets placed on a membrane (Latex). PMC have been placed on the acrylic spacer. These spacers have been used to support the PMC and furthermore to provide gap for the coils and magnets movement. Moreover, on outer side of each PMC a mini acrylic spacer is also attached to offer gap for the open-air movement of coils.

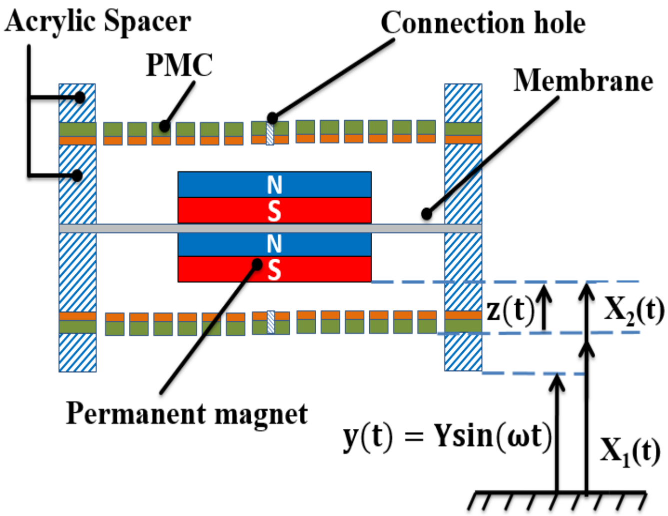

Fig. 1: Cross sectional view of developed VEH

The suspended components, like, PMC and magnet & membrane assembly moves with x1(t) and x2(t) respectively due to base excitation, y(t). The magnets & membrane assembly is expected to have low resonant frequency than the PMC due to heavy mass of the magnet. The magnet and PMC moves relative to each other, and a voltage is induced in the PMC due to this relative motion based on Faradays law of electromagnetic induction. The voltage induced in the PMC depends on the relative velocity z (t) between PMC and the magnets, residual flux density of the magnet, acceleration level and the gap between magnet and PMC.

III. FABRICATION

The multi-mode VEH has been developed using traditional machining processes. The PMC has been fabricated in the form of a spiral spring that it can oscillate with the base excitation. A single sided FR4, PCB sheet is used and a through whole machining is performed with CNC milling machine to fabricate the planar coil in the form of a spiral spring. The coil has a dimension of 15 mm x 15 mm. The spacers are also fabricated through CNC milling machine from the acrylic sheet. Four spacers two inner and two outer have been used. The inner spacers have a height of 6 mm and a 19 mm x 19 mm of external dimension, however, the outer spacers have the same dimension as that of the inner but the only change is of height which is 2 mm. The fabricated PMC and the acrylic spacers are shown in fig. 2 (a) & (b) respectively.

All the fabricated components are assembled with adhesive epoxy. Electrical wires are connected in the central electrical pad and to the outer pad of PMC. The magnets are first mounted on the stretched membrane which is then glued to

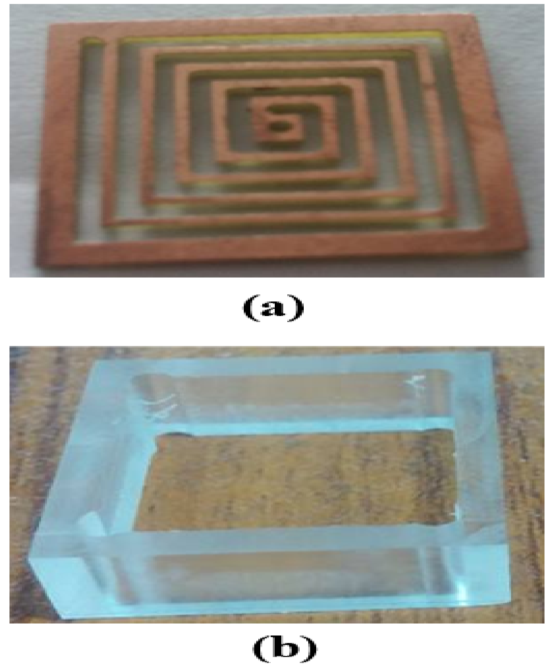

Fig. 2: Fabricated components of the harvester: (a) Planar movable coil, (b) Acrylic spacer

the spacers. The PMC is attached to the inner acrylic spacer. Afterward, the outer small spacer is placed on the top of the PMC so that to provide space for the outward movement of the coil. The assembled prototype is shown in fig. 3 and dimensions of the developed prototype are given in table 1.

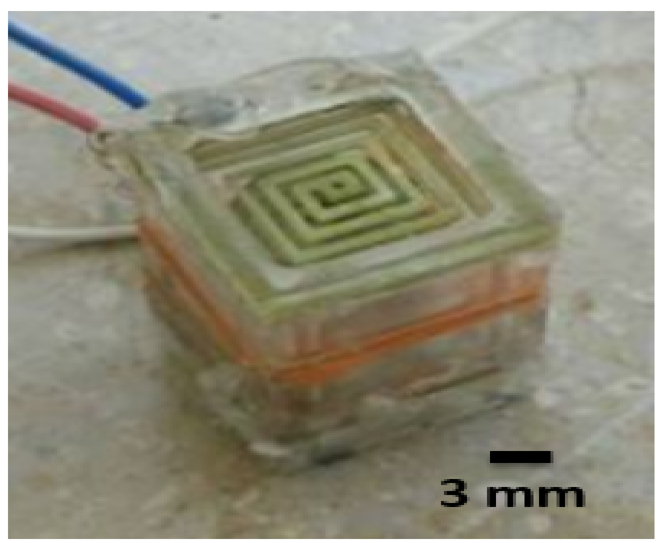

Fig. 3: Isomeric view of the assembled prototype

IV. EXPERIMENTATION

The experimental setup has been developed for the characterization of the multi-mode VEH; schematic of which is displayed in fig. 4. The experimental setup comprises of a

TABLE I. PARAMETERS AND DIMENSIONS OF PROTOTYPE

Description with Unit	Values
Harvester's overall dimensions (mm)	19 x 19 x 19
Magnet's dimension (mm)	10 x 10 x 5
Mass of each magnet (g)	4
Suspended portion of PMC (mm)	15 x 15
Resistance of PMC (Ω)	1.2
Inner acrylic spacer height (mm)	6
Outer acrylic spacer height (mm)	2
Gap between PMC and magnet (mm)	1

vibration shaker, power supply and power amplifier. The KENWOOD desktop speaker of model number of KFC-W3010 is used as a shaker table. A Teflon block has been placed on the speaker diaphragm and is fixed with an adhesive material (polychloroprene). This Teflon block has been used as a platform for the multi-mode VEH. An accelerometer (ADXL-335) is attached with the Teflon block to measure the vibration level continuously. A power amplifier of ROCKMARS^{TM} is used to regulate amplitude of the shaker table. Moreover, a signal generator of GW-INSTEK^{TM} with a model number of GFG-8020H is used to generate a sinusoidal signal and regulate the frequency of operation. The output voltage of the harvester is analyzed with an oscilloscope of GW-INSTEKTM.

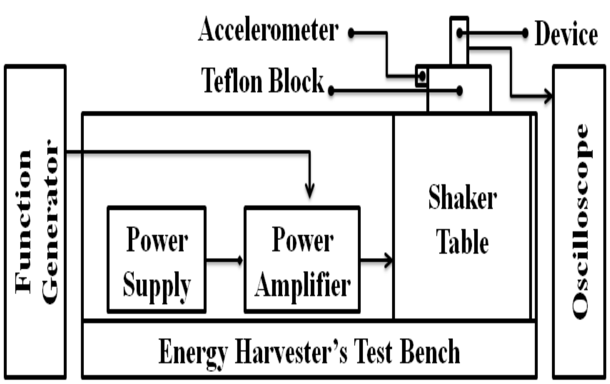

Fig. 4: Schematic diagram of the experimental setup

The multi-mode VEH was excited at a frequency sweep of 5 to 200 Hz with a vibration levels of 1, 2 and 3 g. It has been noted that the energy harvester exhibits three resonant frequencies 73 Hz (magnet and membrane suspension), 100 Hz (PMC) and 123 Hz (PMC) at higher acceleration level. Fig. 5 shows the open circuit voltage of a single PMC. At acceleration amplitude of 1, 2 and 3 g, a voltage amplitude of 3.5, 10.3 and 16.6 mV is respectively generated by the device at fundamental frequency (73 Hz).

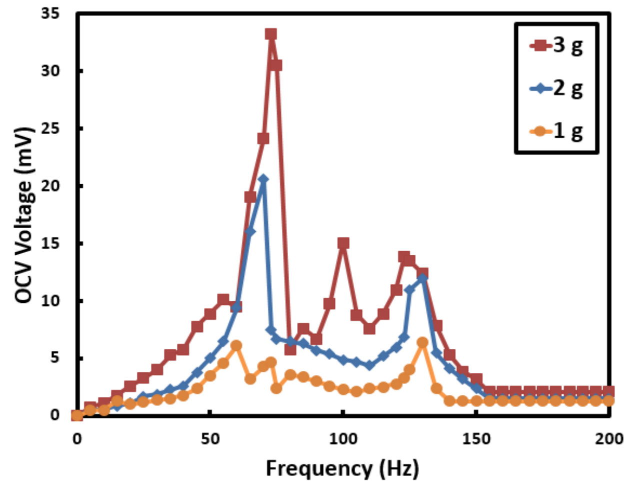

Fig. 5: OCV of a single PMC as a function of frequency at different acceleration levels

Output load voltage of a single PMC versus resistive load is shown in fig. 6. For the measurement the device is kept to oscillate at a frequency of 73 Hz and a variable resistor is used to change the load on the harvester. A voltage (max.) of 21.5 mV is generated at a 4.2 Ω resistance for a vibration of 3 g.

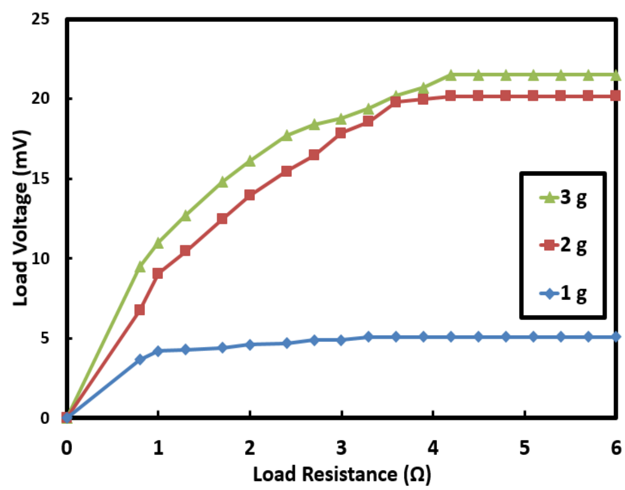

Fig. 6: Load voltage of a single PMC verses resistive load at different acceleration levels

The developed multi-mode VEH is compared with the reported multi-mode VEHs in table 2. The multi-mode VEH developed in this work can be compared by virtue of size, multi-mode frequencies, voltage produced, power generated and the power density. The device size of most of the reported energy harvesters is less than the multi-mode VEH developed in this work. This is because of the advance micro fabrication techniques used for the fabrication of the reported energy harvesters. The resonant frequencies of the multi-mode VEH developed in this work are at lower side when compared to the reported energy harvesters. The lower resonant frequencies of the devised VEH are due to the heavier magnet (proof

TABLE II. SUMMARY OF DIFFERENT MULTI-MODE VIBRATION BASED ENERGY HARVESTERS

Type	Size (cm^3)	Natural Frequencies (Hz)			Max. Output Voltage (mV)	Max. Output Power (μW)	Power density (μW/cm^3)	Ref.
		1st	2nd	3rd				
Electrostatic	0.0041	1272	-----	-----	5000 [a]	2.96	799.8*	[10]
Piezoelectric	1.08*	71.8	84.5	188.4	1000 [b]	0.136	0.12	[11]
Piezoelectric	38.46	101.04	108.16	134.4	3100 [a]	-----	-----	[12]
Electromagnetic	4.05	369	938	1184	3.2 [b]	3.2	0.79	[13]
Electromagnetic	0.035	840	1070	1490	3.7 [c]	0.0041	0.117	[14]
Electromagnetic	6.85	73	100	123	33.3 [a]	65.24	9.52	[This work]

*Estimated values
[a] At first mode [b] At second mode [c] At 3rd mode

mass) and the more flexible PMC. It can be clearly seen from the table that the developed VEH produced the highest power and moreover, the power density of the multi-mode VEH developed in this work is also better than the reported multi-mode VEHs. Overall VEHs [10-12] are producing more voltage than the developed VEH which is because of the electrostatic and piezoelectric transduction mechanism used in these harvesters. Among the electromagnetic multi-mode VEHs, the developed energy harvester is capable to generate higher voltage.

V. CONCLUSIONS

The development and in-lab characterization of the multi-mode vibration energy harvester (VEH) is reported in this work. Along the magnet & membrane suspension system, a planar movable coil (PMC) adds to the resonant frequencies of the device. The developed VEH is subjected to a sinusoidal vibration and analyzed under different acceleration of 1, 2 and 3 g with a frequency sweep from 5 to 200 Hz. The resonant frequencies of the harvester were found to be 73 Hz, 100 Hz and 123 Hz. The single PMC of the device produced the open circuit voltage amplitude of 16.6 mV and a power of 65.24 μW at fundamental frequency (73 Hz). The developed VEH is also compared with the reported multi-mode VEHs and it is found that it has better performance than most of the reported energy harvesters and is capable to generate enough power at all the three resonant frequencies.

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