PERFORMANCE ENHANCEMENT OF VIBRATION-BASED ELECTROMAGNETIC ENERGY HARVESTER DUE TO REDUCED AIR DAMPING

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ABSTRACT

This work presents on the performance enhancement of vibration-based electromagnetic energy harvesters (EMEH's) due to reduced air damping. Fabrication and characterization of Copper foil-type EMEH-1 and polydimethylsiloxane (PDMS) membrane type EMEH-2 under vacuum and without vacuum pressures are reported. The harvesters are subjected to harmonic excitation with constant acceleration frequency-sweeps. In the developed energy harvesters, the air damping is decreased by generating vacuum pressure in the cavity where the magnets are oscillating. Under a pressure of -93 kPa and when excited at an acceleration of 13.5 g and resonant frequency of 371 Hz, in EMEH-1, the load voltage and load power delivered to a load resistance of 100 Ω increases from 46.3 to 79.4 mV and from 10.9 to 24.1 μW respectively. However, at optimum load condition (7.5 Ω) and at resonant frequency, 48.6 % and 122 % improvement in load voltage and load power respectively is obtained. With and without vacuum pressures, EMEH-2 exhibits nonlinear behaviour at 3 g acceleration level. When connected to 100 Ω load and excited at 3 g acceleration, under vacuum pressure the EMEH-2 produces 37.6 mV more load voltage and 39 μW more load power. Moreover, at optimum load condition (10.1 Ω) and under vacuum pressure, the harvester produces a maximum load voltage of 68 mV and load power of 231 μW. The reduced air damping provides a maximum improvement of 124 % and 107.6 % in power densities for EMEH-1 and EMEH-2 respectively.

KEYWORDS: *Air damping, Electromagnetic, Energy harvester, harmonic excitation, micro-fabricated, vibration-based*

INTRODUCTION

For autonomous sensor nodes development, the viable solution is the integration of micro energy harvesters (MEH's) with wireless micro sensors. The autonomous micro sensor nodes would perform for longer times in remote, embedded or hazardous environment, without the requirement of maintenance for battery replacement or charging. Energy harvesters are transducers that transform the energy present in the sensor environment into electrical energy for the usage in sensor nodes. A number of energies are available in the ambient of sensor node, such as solar, thermal, wind, acoustic, and vibration energy. Several vibration-based MEH's have been developed based on different working principles[1], the more popular among these are piezoelectric[2,3], electrostatic[4,5,6] and electromagnetic[7] MEH's. Most of them are resonators and therefore, the voltage or power generation by these MEH's is maximum at the resonant frequencies. Moreover, the voltage or power production is highly dependent on the damping in harvesters. The power generation of a resonant MPG's could be increased considerably by decreasing the damping in MEH's[8,9,10].

The electromagnetic energy harvester (EMEH) operates on the principle of Faraday's law of electromagnetism and normally comprises of a permanent magnet and a coil. The relative motion between the magnet and coil induced due to ambient vibration, actually produce the voltage cross the ends of the coil. During oscillation, the mass (magnet or coil) motion is restrained by the total damping in the harvester. The total damping[7,11,12], in EMEH, comprises of mechanical damping and electrical damping. Mechanical damping is the result of air (squeeze film or air compression) damping, structural damping and material damping[13]. However, the electrical damping is due to the Lorentz' force that acts on the current flowing in the coil, when the coil is connected to the load resistance. The squeeze film damping effects the performance of micro resonators[14,15,16,17]. In EMEH, the power could be increased by reducing or by eliminating the harvester's mechanical damping. Since, the air damping in the harvester is due to the presence of air. The removal of device air or by reducing the air pressure in the harvester, the air damping component of the harvester could be reduced in the total damping of the harvester.

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This work reports on the performance enhancement of vibration-based EMEH's due to reduced air damping. The copper foil type, linear EMEH-1 and PDMS membrane type, nonlinear EMEH-2 developed by the author in his previous work[18,19] are structurally amended and characterized under vacuum and without vacuum pressures.

PROTOTYPE ARCHITECTURE AND WORKING PRINCIPLE

The cross-section view of a copper foil type vibration-based EMEH-2 developed by the author in previous work[18] is shown in Figure 1. The harvester comprises of permanent magnets mounted on a planar spring and two planar coils separated by plastic spacers. Two tubes are connected to the harvester. One tube is connected to vacuum pump to remove air from inside the device and the second tube is connected to the pressure sensor to measure the inside pressure of the harvester.

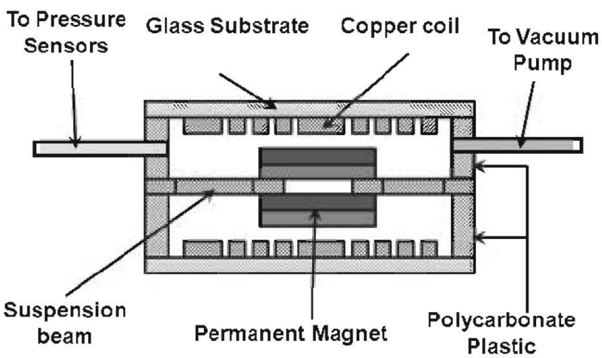

Figure 1: Cross-sectional view of a copper foil type EMEH-1.

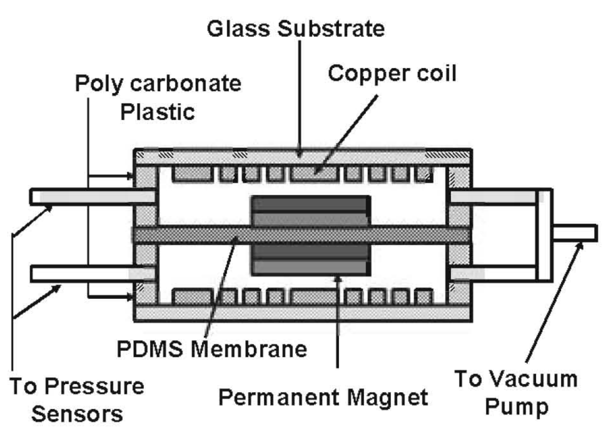

Figure 2: Cross-sectional view of a membrane type EMEH-2.

Figure 2 shows the cross-section view of the membrane type vibration-based EMEH-2 developed in our work[19]. For energy harvesting from low vibration environment more flexible membrane is used instead of planar spring. Tubes are connected through spacers in the device on either side of the membrane. Two tubes are connected to vacuum pump to produce negative pressure inside the harvester and the remaining two tubes are connected to pressure sensor to record the pressure inside the harvester cavity.

The energy harvesters when subjected to the base vibration, the magnets oscillate relative to the planar coils. Due to the relative motion, the planar coils see the change in magnetic flux and voltage is induced across the electrical pads of the coil according to Faraday's law of electromagnetism. The induced voltage[18]

$$V_G(t) = S\frac{dB}{dz}\dot{Z} \tag{1}$$

depends on magnetic flux density gradient $\frac{dB}{dz}$,

relative velocity between the magnets and planar coil $\dot{Z}$ and the area sum S of individual turns. With lumped parameter modeling of the harvesters, at resonance the load voltage amplitude[18]

$$V_L = \left(\frac{R_L}{R_L + R_C}\right) S \frac{dB}{dz} \frac{A}{2\omega_n(\zeta_m + \zeta_e)} \tag{2}$$

and average power[18]

$$P_L = \frac{V_L^2}{2R_L}$$

$$= \frac{R_L}{2(R_L + R_C)^2} S^2 \left(\frac{dB}{dz}\right)^2 \frac{A^2}{4\omega_n^2(\zeta_m + \zeta_e)^2} \tag{3}$$

can be written as function of coil resistance R_C, load resistance R_L, undamped natural frequency ω_n, base acceleration A, mechanical damping ratio ζ_m and electrical damping ratio ζ_e of the harvester.

FABRICATION OF AMENDED PROTOTYPES

To check the vacuum production in harvester cavity and investigate the mechanical behaviour of EMEH1 under vacuum, a test prototype, based on the micro-fabricated parts of EMEH-1 is fabricated and is shown in

Figure 3. The planar spring, having the mounted permanent magnets is bonded to the polycarbonate spacers on top and bottom. Then two glass slides are bonded on the either sides to produce the similar cavity for the magnets vibration as present in the original EMEH-1. The gap between the magnet and glass substrate is 500 µm. Two tubes are connected to the drilled holes in polycarbonate spacers by epoxy. One tube of the test-prototype is connected to vacuum pump and second one to the pressure sensor, Figure 3 (a). DC voltage source is used to power the pressure sensor and oscilloscope read the pressure signal from the sensor, Figure 4 (b). A vacuum pressure of -93 kPa is successfully produced in the energy harvester prototype cavity. The test-prototype is then bonded to the Teflon block on the vibration shaker and vibrometer is used to measure the relative displacement of the magnets when the prototype is subjected to frequency sweep. Due to the vacuum pressure of -93 kPa in the cavity the relative displacement of the magnets showed an increase of 76 µm at 13.5 g acceleration and resonant frequency of 371 Hz. In the test prototype, the increase in displacement magnification indicates the reduction in air damping and thus forth the improvement in the performance of the energy harvesters is expected.

For under vacuum pressure characterization of the copper foiled type EMEH-1 developed by the author in research work[18], few amendments are performed. Two 0.85 mm diameter tubes are connected into the drilled holes at the sides of the polycarbonate spacers as shown in Figure 4. Epoxy is used to bond the tubes into the drilled holes and the device is tested for any air leakage into the prototype cavity by connecting one tube to the vacuum line (through the valve) and the second one to the pressure sensor. No rise of pressure in the cavity confirmed a well sealed harvester ready for further characterization.

However to characterize the membrane type EMEH-2 (developed by the author[19]) under vacuum pressure, the 3mm thick, slotted polycarbonate spacers are replaced by solid polycarbonate spacers. Two 1.5 mm holes are drilled in the sides of each spacer and 1.45 mm diameter plastic tubes are bonded to these holes, as shown in Figure 5(a) and Figure 5(b). Epoxy is used for connecting and sealing the gap between the tube and the drilled hole. Using the glass fixture, the PDMS membrane having the magnets is sandwiched between the polycarbonate spacers with epoxy, Figure 5(c) and then the two glass

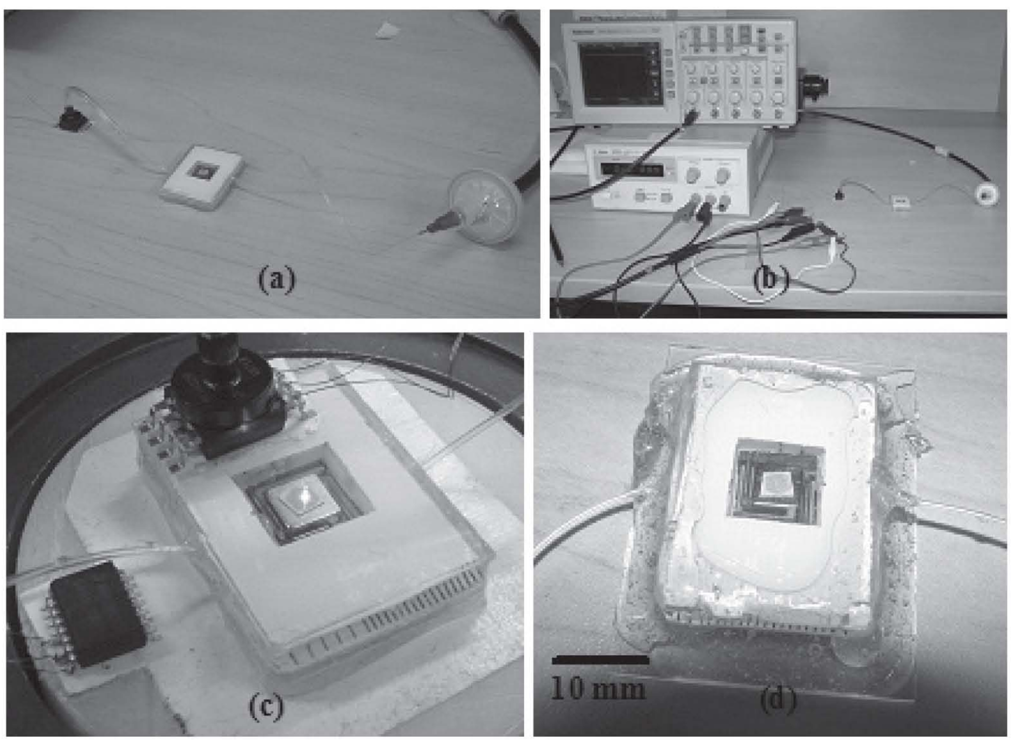

Figure 3: Test device (EMEH-1) for initial experimentation: (a) and (b) Test device connected to pressure sensor and vacuum pump, (c) Test device and accelerometer mounted on vibration shaker, (d) Test device sealed by epoxy.

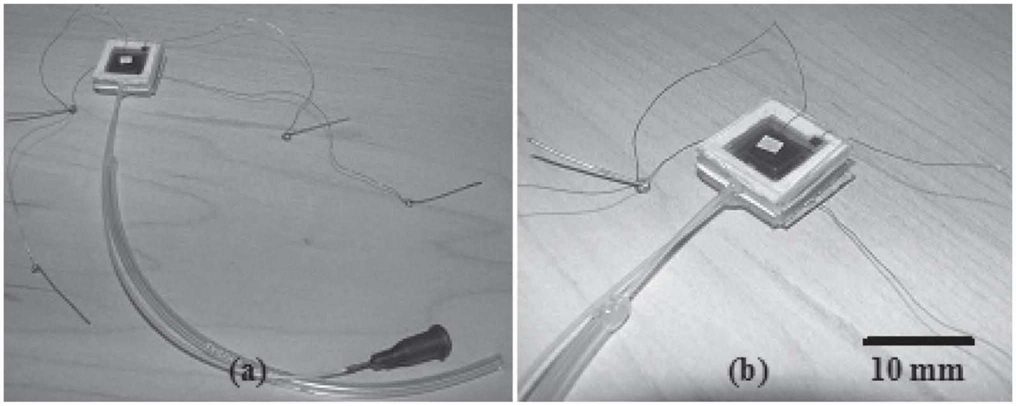

Figure 4: Tubes connected to the EMEH-1.

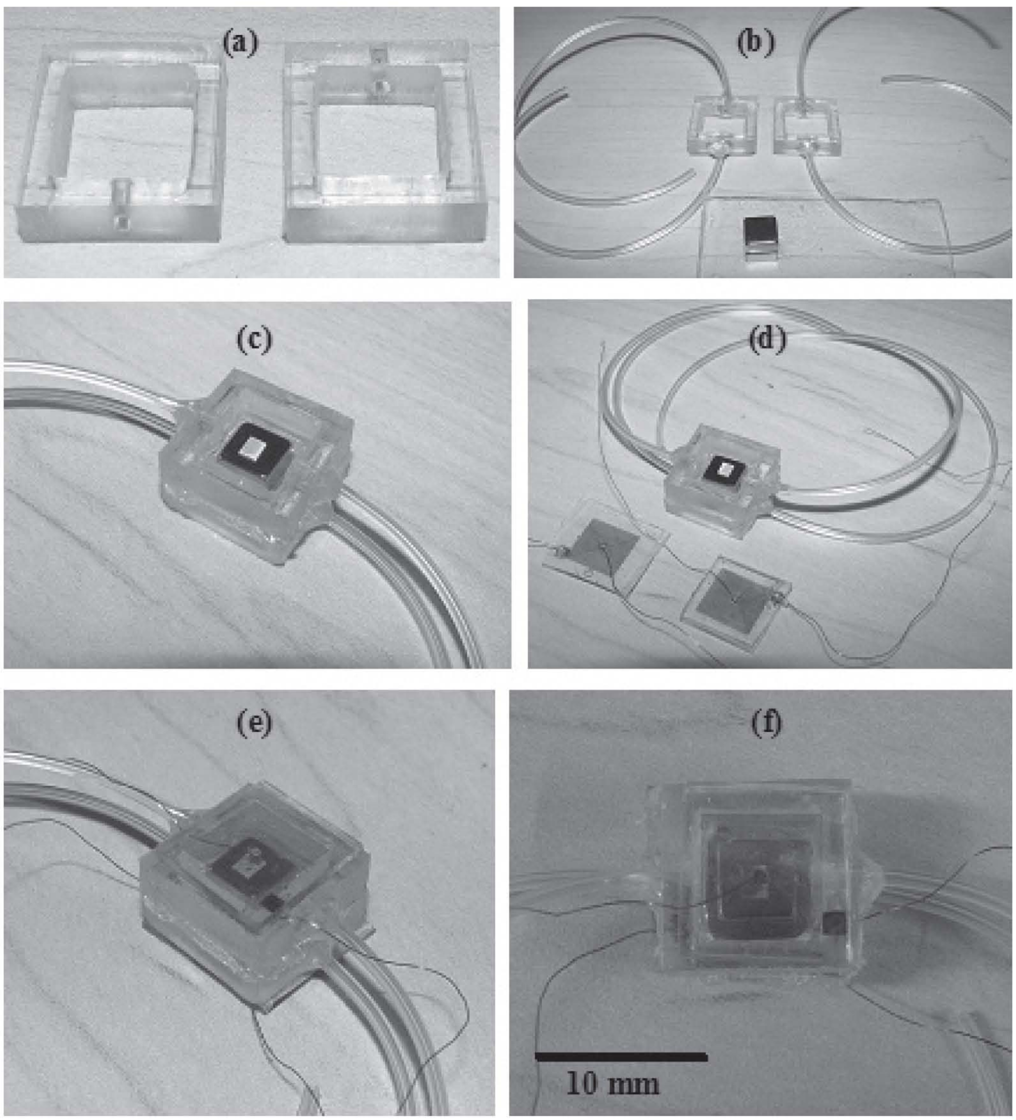

Figure 5: Photographic images of EMEH-2 during assembling: (a) Polycarbonate spacers with drilled holes at the sides, (b) Polycarbonate spacers with tubes connected and magnets on PDMS membrane, (c) PDMS membrane and spacers bonded altogether, (d) Harvester's sub-assembly along planar copper coils, (e) Planar copper coils bonded to the top of spacers, (f) Top view of the assembled Energy harvester.

Table 1: Dimensions and parameters of developed EMEH's.

Description	EMEH-1	EMEH-2
Harvester size	12 mm x 12 mm x 7 mm	15 mm x 15 mm x 10 mm
Magnet (NdFeB), Br	1.32 T	1.32 T
Magnet dimensions	6 mm x 6 mm x 1.5 mm	6 mm x 6 mm x 3 mm
Mass of each magnet	0.465 g	0.93 g
Suspension system	Planar spring	PDMS membrane
Planar spring thickness	350 μm	-
Membrane thickness	-	200 μm
Coil type	Planar	Planar
Coil size	8 mm x 8 mm	8 mm x 8 mm
No. of turns of coil	21	25
Resistance of coil	7.5 Ω	10.1 Ω
Gap between magnet and coil	500 μm	1000 μm

substrates having the planar copper coil are glued to the other side of the polycarbonate spacers, Figure 5(e), Figure (f). The fabricated harvester is then checked for any leakage by connected it to the vacuum line and to pressure sensor. The summary of the dimensions and important parameters of developed EMEH's is shown is Table 1.

EXPERIMENTATION AND DISCUSSIONS

The experimental setup for the characterization of EMEH-1 and EMEH-2 under vacuum pressure is shown in Figure 6. The function generator (Agilent, Model: 33220A) and power amplifier (Bruel and Kjaer, Model: 2719) are used to control the frequency and amplitude of the input vibration from a vibration shaker (Bruel and Kjaer, Model: 4809). Laser head and vibrometer (Polytech Inc. Model: OFV501) measured the amplitude of the mass and base (Teflon block) during vibration. Pressure sensor/s (Freescale Semiconductor, Model: MPXV4115V) measured the vacuum pressure in the cavity in which magnets are oscillating. The EMEH and accelerometer (Freescale Semiconductor, Model: MMA1200) are bonded to the Teflon block by a double-sided adhesive tape. LabView software and data acquisition card (DAQ) (National Instruments, Model: NI USB-6212) read the signals from vibrometer, output from the EMEH, accelerometer and pressure sensor. Vacuum pump is used to produce the desired vacuum pressure in the cavity.

Characterization of EMEH-1

A load of R_L = 100 Ω is connected to the EMEH-1 and is subjected to a frequency sweep from 150 to 800 Hz. The acceleration 13.5 g is kept constant during the

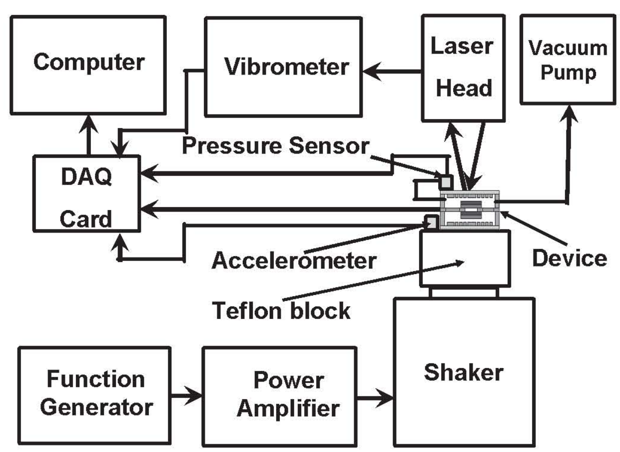

Figure 6: Block diagram of the experimental setup.

frequency sweep and harvester's output load voltage is measured without any vacuum pressure in the harvester's cavity and under vacuum pressure of -93 kPa. The load voltage and the average power delivered to the load as function of frequency at 13.5 g is shown in Figure 7 and Figure 8 respectively. Due to the reduced air damping in the harvester's cavity an improvement in the load voltage and average load power is obtained. At resonant frequency an increase from 46.3 mV to 79.4 mV is obtained in the load voltage, which corresponds to an improvement of 13.2 μW (from 10.9 to 24.1 μW) in load power.

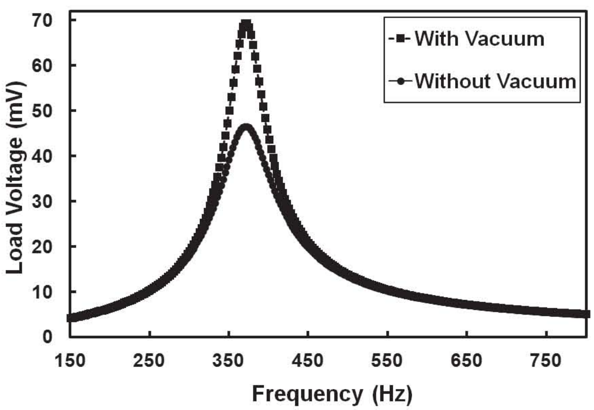

Figure 7: Load voltage at a base acceleration of 13.5 g and load resistance of 100 Ω.

The mechanical damping ratio obtained for the harvester by the method of logarithmic decrement[13] decreases from 0.09 to 0.06 due to the vacuum pressure. The reduction in the mechanical damping ratio, actually contributed to the voltage and power enhancement of the harvester. Slight shift in the resonant frequency from 371 to 370.4 Hz is also observed, which is attributed to the reduced damping in the harvester.

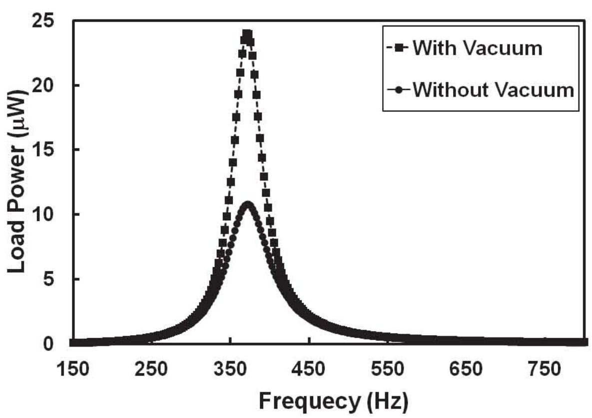

Figure 8: Load average power at a base acceleration of 13.5 g and load resistance of 100 Ω.

Figure 9 and Figure 10 show the load voltage and load average power as a function of load resistance. The harvester is provided oscillation at the resonant frequency and acceleration level of 13.5 g. The experiments are performed under vacuum pressure of -93 kPa and without vacuum pressure. The measurement shows an improvement in load voltage and load power. A maximum power is obtained at the load matching condition, when the load resistance connected to the harvester is equal to the coil resistance R_C = 7.5 Ω.

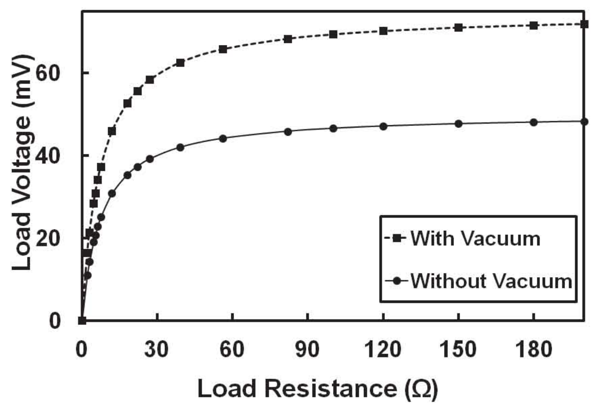

Figure 9: Load voltage at resonant frequency and a base acceleration of 13.5 g.

At optimum load condition, an improvement of 12.3 mV (from 25.1 mV to 37.4 mV) in load voltage

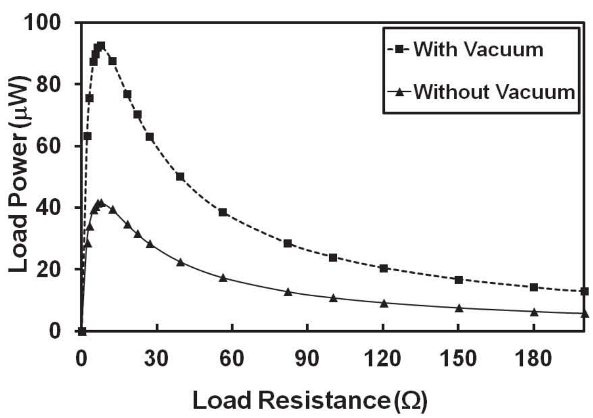

Figure 10: Load average power at resonant frequency and a base acceleration of 13.5 g.

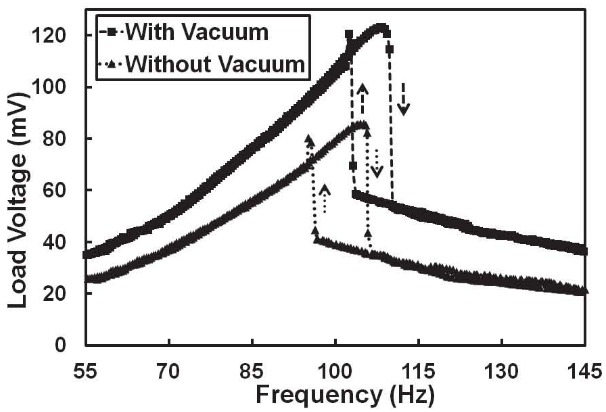

Figure 11: Load voltage at a base acceleration of 3 g and load resistance of 100 Ω.

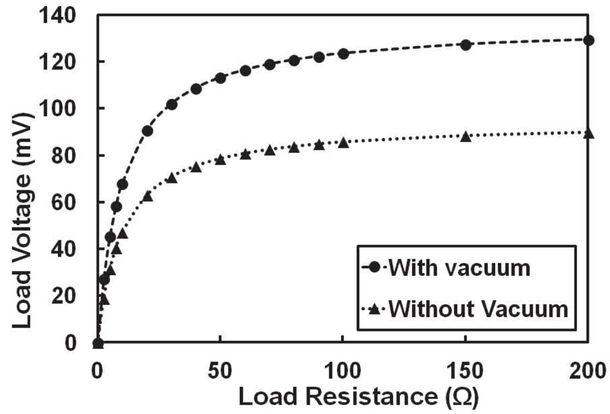

Figure 13: Load voltage at resonant frequency and a base acceleration of 3 g.

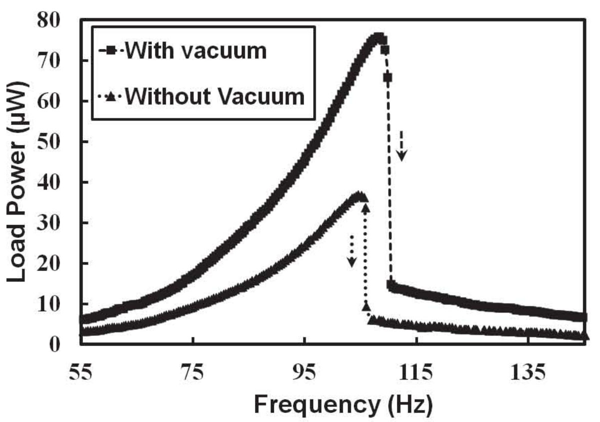

Figure 12: Load average power at a base acceleration of 3 g and load resistance of 100 Ω.

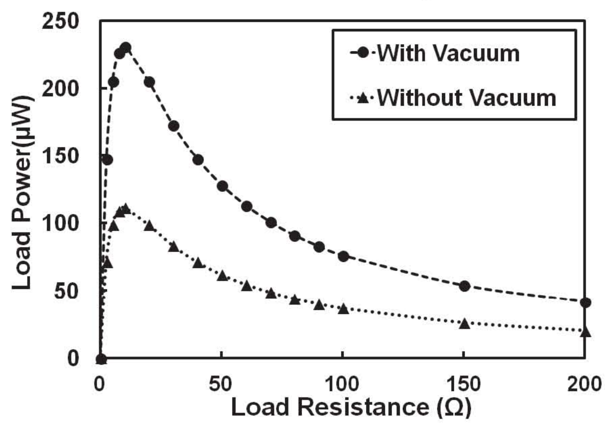

Figure 14: Load average power at resonant frequency and a base acceleration of 3 g.

and 50.9 μW (from 41.8 μW to 92.7 μW) in load power is obtained. This corresponds to 49.2 % and 122 % increase in load voltage and load power respectively due to reduction in damping of the harvester.

Characterization of EMEH-2

With the nonlinear PDMS membrane type EMEH-2 a load resistance of 100 Ω is connected and is subjected to harmonic excitation at acceleration level of 3 g. The harvester is subjected to increasing frequency sweep (IFS) as well as decreasing frequency sweep (DFS). Figure 11 shows the load voltage as a function of frequency at Vacuum pressure (-93kPa) and without vacuum pressure. The frequency response curve of the harvester is non-symmetric. Sudden jump down and jump up characteristics are obtained during IFS and DFS respectively. Moreover, the shift in resonant frequency of the harvester is also obtained. The behaviour of the harvester at 3 g harmonic excitation is nonlinear. Such response of the harvester is due to the nonlinear stiffness of the membrane. The membrane upon increasing deflection stretches more, which results in increasing tensile stresses in membrane. The membrane's tensile stresses contribute to the increasing stiffness and resonant frequency of the harvester[19]. The energy harvester during the operation exhibits membrane hardening due to which the frequency response curve o f the harvester is tilted towards the higher frequency side during IFS. For the harvester, an improvement in the load voltage is obtained which is attributed to reduce air damping. Due to vacuum pressure, during the IFS, the load voltage increases from 86 to 123.3 mV, whereas the resonant frequency shifts from 104.5 to 108.9 Hz. However, during the DFS the shift in the resonant frequency is 95.1 from to 102.4 Hz and the load voltage changes from 80.5 to 120.8 mV. An overshoot is also obtained during DFS.

Table 2: Summary of EMEH's characterization.

			Under vacuum			Without vacuum		
Harvester	**Acceleration (g)**	**Rload (Ω)**	**Max. Vload (mV)**	**Max. Pload (µW)**	**Max. Power density (µW/cm3)**	**Max. Vload (mV)**	**Max. Pload (µW)**	**Max. Power density (µW/cm3)**
EMEH-1 (1.008 cm3)	13.5	100	79.4	24.1	23.91	46.3	10.9	10.8
		7.5	37.4	92.7	91.97	25.1	41.8	41.47
EMEH-2 (2.25 cm3)	3	100	123.3	76.0	33.8	85.7	36.97	16.31
		10.1	68	231	102.7	47.2	111.3	49.5

Figure 12 shows the average power delivered to a load resistance of 100 Ω during IFS and the harvester is characterized under vacuum and without vacuum pressure. The reduction in air damping caused the load power to increase from 37 to 76 µW, which corresponds to an improvement 105 % in load power for the harvester.

Figure 13 and Figure 14 show the load voltage and load power as the function of load resistance at a base acceleration of 3 g. Variable load resistance is connected to the coils and the harvester is oscillated at the corresponding resonant frequency during IFS.

The plots indicate the enhancement in both load voltage and load power as result of decreasing the air damping. At the optimum load operation, the load voltage improved from 47.2 mV to 68 mV. In Figure 14, maximum power is delivered at the load matching condition ($R_L = R_C$ = 10.1 Ω). Under such optimum load operation and due to reduced air damping in the harvester, the load power increases from 111.3 to 231 µW. This corresponds to an improvement of 107.6 % in load power.

The summary of characterization of EMEH-1 and EMEH-2 under vacuum and without vacuum pressure is shown in Table 2. Optimum power is obtained under vacuum and at optimum load condition ($R_L = R_C$). EMEH-1 produced the maximum power density of 92.7 µW/cm³ at -93 kPa pressure and 7.5 Ω load resistance. Moreover, at a load resistance of 100 and 7.5 Ω, the increase in power density due to vacuum pressure is 121 % and 124 % respectively. However, the maximum power density obtained for EMEH-2 is 102.7 µW/cm³ at optimum load of 10.1 Ω and under vacuum. For EMEH-2, the vacuum pressure resulted in an improvement of 107.2 % and 107.6 % in power densities at 100 and 10.1 Ω respectively. Comparatively, EMEH-2 generated more power density than EMEH-1 and this is due more coil turns, bigger size magnet and larger displacement magnification in EMEH-2. Moreover, EMEH-2 operates at much lower acceleration level than EMEH-2.

CONLUSIONS

The characterization of micro-fabricated vibration-based electromagnetic energy harvesters (EMEH's) under vacuum pressure and without vacuum is performed in this work. The performance enhancement for vibration-based copper foil type electromagnet energy harvester (EMEH-1) and non-linear PDMS membrane type electromagnet energy harvester (EMEH-2) is obtained by reducing air damping in the cavity where the mass (magnets) are oscillating.

At 100 Ω load, in EMEH-1, the reduced air damping at vacuum pressure of -93 kPa resulted in the load voltage and load power increase of 33.1 mV and 13.2 µW respectively at a harmonic excitation of 13.5 g acceleration. However, at optimum load condition a maximum of 92.7 µW power is obtained under vacuum pressure, which corresponds to an improvement of 50.5 µW (122 %) in load power.

The EMEH-2, when subjected to a harmonic excitation of acceleration level of 3 g, under vacuum, improvement in both load voltage and load power is obtained. Maximum power enhancement is obtained under vacuum and at load matching condition. Under such operation a load power of 231 µW is produced at the resonant frequency and base acceleration of 3 g. An improvement of about (119.7 µW) 107.6 % in load power is obtained for EMEH-2 due to reduced air damping. Operating at vacuum pressure, maximum power densities of 91.97 and 102.7 $\mu W/cm^3$ are obtained with EMEH-1 and EMEH-2 respectively. The load voltage, load power and power density produced by the reported energy harvesters are quiet comparable with the energy harvesters developed world wide.

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