International Journal of Materials Science and Engineering Vol. 1, No. 2 December 2013

An Electromagnetic Micro Power Generator Based on Mechanical Frequency Up-Conversion

Vida Pashaei and Manouchehr Bahrami
University of Tabriz/Electrical and Computer Engineering Department, Tabriz, Iran
Email: v.pashaei90@ms.tabrizu.ac.ir, mbahrami@tabrizu.ac.ir

***Abstract*—This paper presents a novel inertial electromagnetic micro power generator. The proposed generator utilizes mechanical frequency up-conversion technique to improve the level of power generated in low environmental frequencies in order to make device more efficient. Power transduction is done by means of electromagnetic induction. The generator's structure consists of two main parts; first part contains of a planar spring with two magnets and a mechanical barrier placed between magnets to up-convert external frequency, and second part is made from four cantilever beams with copper coil deposited on them. The simulation results show 67.4mV and 46.6µW RMS voltage and average power respectively from a single beam by up-converting 75Hz external frequency to 5.9kHz. The total power density gained from four beams is 145.6µW/cm^3 with device internal volume of 0.64cm^3.**

***Index Terms*—electromagnetic power generation, energy harvesting, frequency up-conversion, inertial, power density**

I. INTRODUCTION

The great advances in development of wireless sensor networks and portable electronics have been accomplished with the fast growing of MEMS technology. These two have resulted in miniaturized sensors and electronic devices which have been used widely in both industrial and medical applications. In most cases they have to been implanted or embedded in human body or out of reach industrial places. Considering low power need and inaccessibility of them some efforts have been started to replace their finite energy supplies (electrochemical batteries) with infinite sources. Scavenging energy from environmental power resources like solar energy, heat, acoustic waves, electromagnetic radiation and ambient vibrations are the most applicable and attractive solutions. Among them, using ambient vibrations is appropriate in most cases because of its abundance and cleanness. There are three concepts to convert mechanical vibration into electrical energy; piezoelectric, electrostatic and electromagnetic. In all of the mentioned concepts the induced power is proportional to the external frequency which is mostly in the range of a few hertz to a few hundreds. According to this fact the most efficient way to increase the power level is to raise the frequency. Another problem with classic inertial generators is that they are designed to work in one specified frequency and with a little variation in it, the generated power decreases rapidly. Most of the electromagnetic micro harvesters, designed up to now, are working in high frequencies to achieve more power and are appropriate for one specified frequency. Wang et al.2009 designed a magnet attached to planar spring which moves against the coil and delivers 0.7µW in 94.5 Hz and 14µm amplitude [1], Beeby et al.2007 reported another classic micro harvester which was optimized to deliver 46µW in 52Hz [2]. In order to widen the bandwidth, sari et al.2007 used a series of cantilever beams with different resonance frequencies , although the bandwidth raised up to 800Hz, the generated power was very low[3]. The frequency up-conversion technique has been used by Kulah et al.2008 to produce the peak power of 3.97µW in the frequency range of 10-100Hz, but it had used additional magnets, caused to both complicated fabrication process and increased device volume [4]. Another similar method reported by Kulah in 2011 used a mechanical barrier to trigger a cantilever beam, the power density of 184µW/cm^3 has been reported but as it was noninertial generator it could be used just in special applications where two platform move against each other which limits its use [5], [6].

In this paper a novel inertial electromagnetic micro generator has been designed and simulated. This generator solves both problems of low power in low frequencies and limited bandwidth, while widens the application of device because of the inertial characteristic of it. The utilized generator benefits from the mechanical frequency up-conversion technique to increase the induced power in a specified bandwidth. Several simulations of different parts of the generator have been done with COMSOL 3.5a.

II. MODELING AND SIMULATION

A. Design

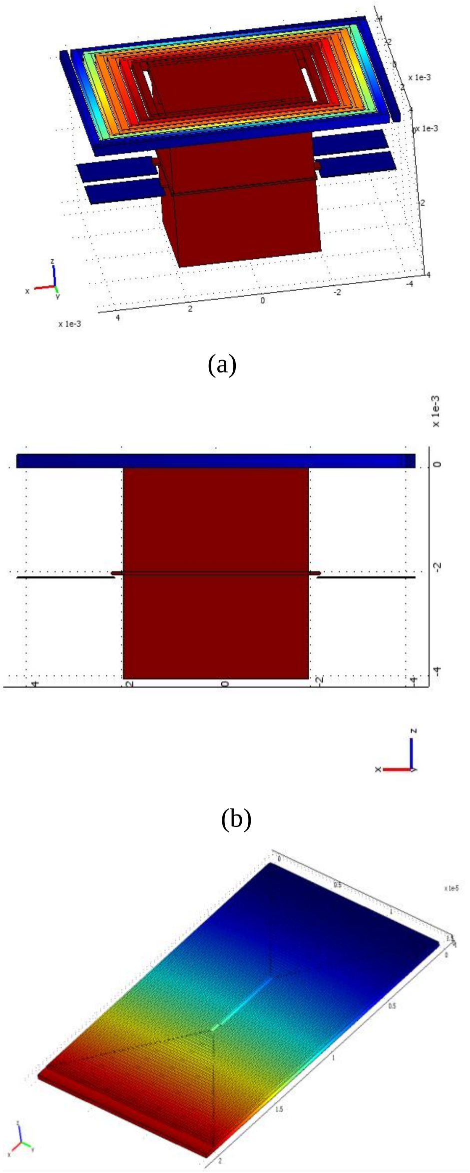
Fig. 1 shows the schematic view of proposed micro generator. As shown, device consists of two parts; (1) spring and magnets bonded on it with the barrier plate between two magnets, (2) cantilevers and deposited coils on them. The upper part of system has been designed to have a resonance frequency in the range of applied external vibrations (1-200Hz), while the resonance frequency of the cantilever and coil is much higher, and

---

Manuscript received July 1, 2013; revised Octomber 22, 2013

doi: 10.12720/ijmse.1.2.67-71

we can assume the upper plate stable in front of resonating beam. When ambient vibration is applied to the generator, produced inertial force causes magnets and barrier to move with respect to the housing. It contacts with beam and bends it. If the amplitude of magnets displacement with respect to housing and its energy which depends on the velocity and amount of mass be enough, it bends and releases the beam. It must be mentioned that the young modulus and thickness of mechanical barrier should be larger than beams to stay unaffected during contact, so we select tungsten as the mechanical barrier. The deformed and released beam starts to vibrate damply with its damped resonance frequency so the frequency up-conversion is done. The beam will be triggered twice (once in up-ward and other in down-ward movement) in each period of external frequency. As the coil resonates in the presence of magnetic field, generated from NdFeB permanent magnets, voltage will be induced on its terminals.



(a)

(b)

(c)

Figure 1. Proposed microgenerator structure.(a) 3-D view (b) Cross sectional view (c) Cantilever and coil view

B. Simulation and Disscussion

General model for vibration based generators which is used for both magnet-spring and cantilever-coil parts is mass-damper-spring system. Considering this fact and according to newton's second law of motion, when vibration $Y=Y_0\sin(wt)$ is applied on the system the dynamic equation of motion for each part before contact can be expressed as:

$$m_m\ddot{z}_1 + b_m\dot{z}_1 + k_m z_1 = -m_m\ddot{y} \quad (1)$$

$$z = x - y \quad (2)$$

$$m_c\ddot{z}_c + b_c\dot{z}_c + k_c z_c = -m_c\ddot{y} \quad (3)$$

where m_m, b_m and k_m are the mass, total damping and spring constants for magnet-spring respectively, and m_c, b_c and k_c are cantilever beams mass, damping and spring constant, while Z is displacement with respect to housing. Solving these equations results in[1]:

$$z_m(t) = Z_0\sin(\omega t - \varphi) = \frac{(\frac{\omega}{\omega_n})^2}{\sqrt{(1-(\frac{\omega}{\omega_n})^2)^2 + (2\zeta\frac{\omega}{\omega_n})^2}} \quad (4)$$
$$Y\sin(\omega t - \arctan\left(\frac{2\zeta\frac{\omega}{\omega_n}}{1-(\frac{\omega}{\omega_n})^2}\right))$$

In equation (4), ζ represents the total damping factor (including mechanical and electrical damping) ($\zeta = b_m/2mw_n$) and w_n is the natural resonance frequency of the magnet-spring. Calculation of ζ is given in Ref. [7] and Ref. [8].

As the resonance frequency of cantilever beam is much higher than applied frequency its relative displacement to the housing has been assumed to be zero.

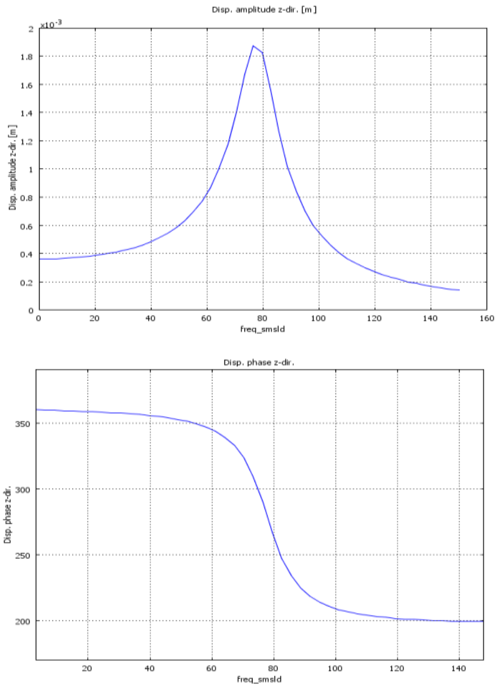


Figure 2. Frequency response of spring-magnet system

Fig. 2 illustrates the frequency-response amplitude and phase of the magnet-spring part for Y_0=400 µm.

Table I represents the physical characteristics of the designed generator.

TABLE I. SIMULATION PARAMETERS

Parameter	Designed model
Spring width(µm)	200
Spring thickness(µm)	200
spring gap(µm)	100
central platform(mm^2)	4×4
spring material	Silicon
barrier length(µm)	200
barrier width(µm)	500
barrier thickness(µm)	50
barrier overlap(µm)	60
magnets size(mm^3)	3.9×3.9×2
magnet material	NdFeB(1.3T)
natural frequency of magnet-spring	78hz
cantilever size(μm^3)	2060×1500×20
cantilever resonance frequency	5968hz
coil area(mm^2)	1.98×1.48
coil thickness(µm)	10
coil linewidth(µm)	10
coil turns	36
coil resistance(Ω)	24.36

When the mechanical barrier contacts with beam two parts move together (beam corresponds to 4 beams) as a single system, so the equation of motion in this situation is determined by:

$$\begin{aligned}&(m_m+4m_c)\ddot{z}+(b_m+4b_c)\dot{z}+(4k_{beam}+k_m)z\\&=-(m_m+4m_c)\ddot{y}\end{aligned} \tag{5}$$

Both equivalent mass and damping of beam are small enough to be neglected, but the spring constant of the cantilever beam is added as a parallel spring as shown in Fig. 3 and also the energy loss caused by contact friction is neglected:

$$m_m\ddot{z}+b_m\dot{z}+(4k_{beam}+k_m)z=-m_m\ddot{y} \tag{6}$$

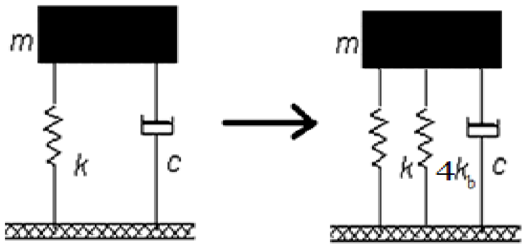


Figure 3. Equivalent schematic diagram of system during contact

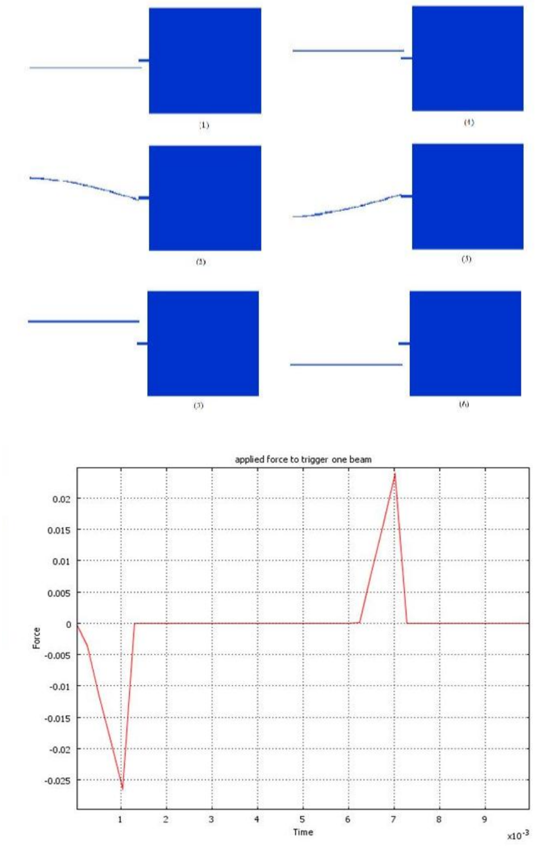


Figure 4. (a) Contact simulation results (b) Applied force to trigger one beam.

Fig. 4 shows the contact simulation results and maximum amplitude of Z_0, applied to the beam, measured 400 µm. Increase of Z_0 by increasing the overlap between mechanical barrier and cantilevers tip points is possible but it should be considered that initial deflection of beam can't be more than a third of its length [4]. The spring force applied to mechanical barrier during deflection is defined by equation (7) and has been illustrated in Fig. 4.

$$F=kx \tag{7}$$

By multiplying the spring force shown in Fig. 4 in four and adding it to the vibrating magnet spring system as a damping force, relative motion of mass in 75Hz has been illustrated in Fig. 5 (the initial distance between beam and barrier is assumed to be zero), the minimum frequency needed to trigger all of the beams is 75Hz and the designed generator can work efficiently in higher frequency until the relative displacement of mechanical barrier be enough to release the beams which means a broad range of vibrations and no need to match external frequency to devices resonance frequency.

After beam is released, it starts to resonate damply, Fig. 6:

$$\begin{aligned}z(t)=e^{-\xi\omega_n t}(&\frac{\zeta Z_0}{\sqrt{1-\zeta^2}}\sin(\sqrt{1-\zeta^2}\,\omega_n t)\\&+Z_0\cos\sqrt{1-\zeta^2}\,\omega_n)\end{aligned} \tag{8}$$

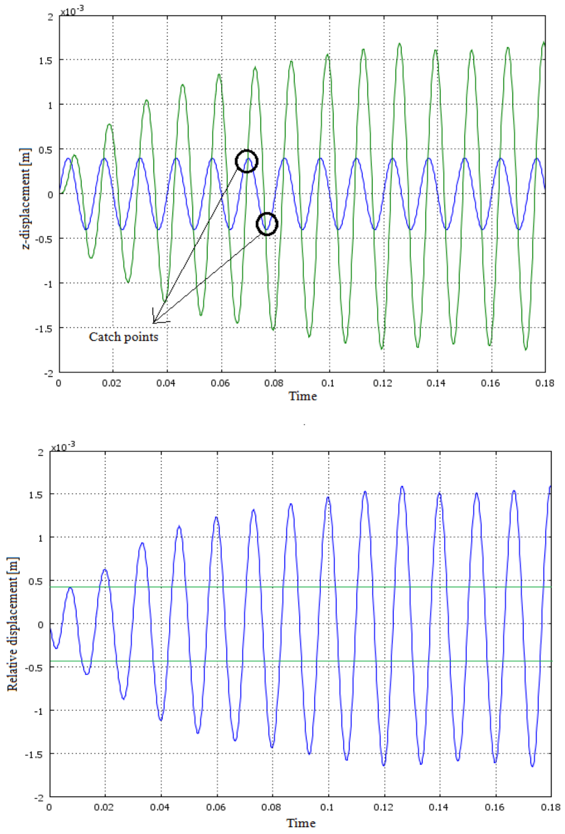


Figure 5. Z-displacement of magnet and housing and relative displacement of magnet after applying force.

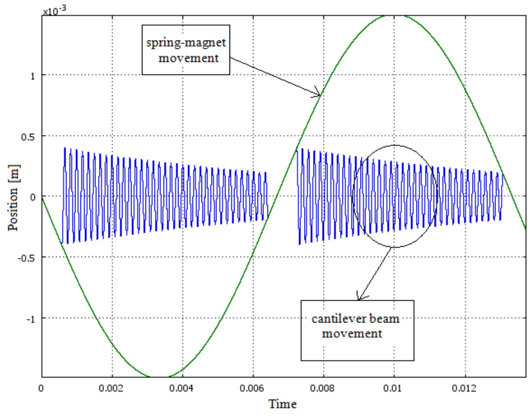


Figure 6. Movement of spring-magnet and cantilever beam with respect to each other.

Velocity of tip point of cantilever beam has been calculated as: [4]

$$\dot{z}(t) = -Z_0\omega_n \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}} \sin(\sqrt{1-\zeta^2}\,\omega_n t) \tag{9}$$

According to faraday's law of induction when a coil moves in a uniform magnetic field, voltage induces on its terminals. The induced open-circuit voltage is given by: [3], [8]

$$V_{oc} = BL\dot{z} \tag{10}$$

where L is coils length, $\dot{z}$ is the velocity of it, and B is the magnetic flux density. As it is shown in Fig. 7 magnetic flux is constant in z and y directions and it just depends on x (distance from magnet). As the velocity and B on different points of coil are different, equation (10) has to be calculated for each part of coil with length of dl and integrated along coil's length. Simulation result for the total induced voltage is shown in Fig. 8. The voltage induced in mixed movement of mass and beam is neglected.

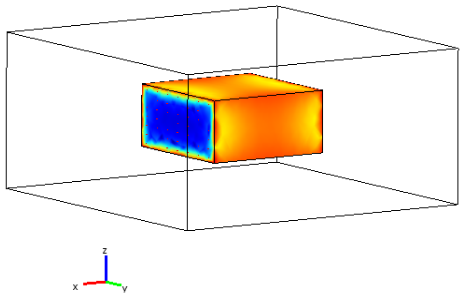


Figure 7. Magnetic flux density of NdFeB magnet

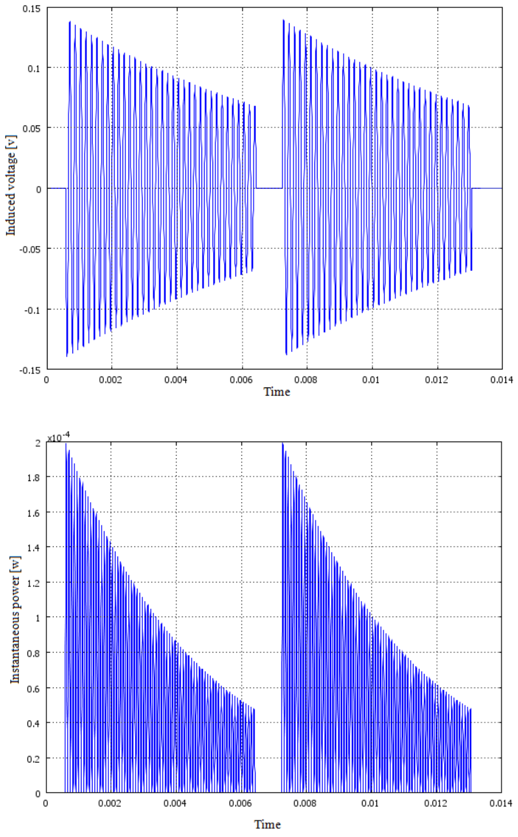


Figure 8. Simulated voltage and power for a single coil

Instantaneous power generated on load resistance is given in equation (11) according to Ref. [1]:

$$P = \left(\frac{V_{oc}}{R_{coil} + R_{load}}\right)^2 R_{load} \tag{11}$$

where R_{coil} is the resistance of coil and R_{load} is the resistance of external circuit. When R_{coil} is equal to R_{load} the maximum of the generated power can be derived from equation (12).

$$P_{\max} = \frac{{V_{oc}}^2}{4R_{coil}} \tag{12}$$

Table II indicates the generated average power for a single beam, thus resulted power density for the total of four beams is a considerable amount.

TABLE II. GENERATOR RESULTS

Excitation frequency	Average output power of one beam	RMS voltage	Total power density
75Hz	46.6µW	67.4mV	145.6µW/cm^3

III. CONCLUSION

This paper presents design and simulation of an inertial electromagnetic micro energy harvester which is able to produce energy from low level environmental vibrations. The proposed device benefits from mechanical frequency up-conversion technique to improve amount of average generated power and systems efficiency, besides it can work over a range of frequencies since there is no need for resonance because of up-converting mechanism. The minimum frequency needed to trigger all of four beams is 75Hz and device works efficiently in higher frequencies as long as the relative displacement of barrier is enough to trigger beams. The average power resulted from each beam in excitation frequency of 75Hz is 46.6µW which means total power of 186.4µW and power density of 145.6µW/cm^3, where the internal size of device is 0.64cm^3. The Generated power will increase in higher external frequencies. In addition to works done in this study it is possible to make device appropriate for lower frequencies by changing spring and beam designs and materials. Also Power level can be increased by reducing the space between wires to reach more turns of coil or using wires with higher linewidth to decrease coil resistance.

REFERENCES

[1] P. Wang and K. Tanaka, “A micro electromagnetic low level vibration energy harvester based on MEMS technology,” *Microsyst Technol*, pp. 941–951, 2009.

[2] R. N. Torah, M. J. Tudor, P. Glynne-Jones, T. O’Donnell, C. R. Saha, and S. Roy S. P. Beeby, “A micro electromagnetic generator for vibration energy harvesting,” *J. Micromech. Microeng*, vol. 17, no. 7, pp. 1257–1265.

[3] T. Balkan, H. Külah, and I. Sarı, “An electromagnetic micro power generator for wideband environmental vibrations,” *Sensors and Actuators*, no. 145-146, pp. 405–413, July–August 2008.

[4] H. Külah and K. Najafi, “Energy scavenging from low-frequency vibrations by using frequency up-conversion for wireless sensor applications,” *IEEE Sensors J.*, vol. 8, no. 3, pp. 261-268, 2008.

[5] E. T. Topal, H. Külah, and Ö. Zorlu, “A vibration based electromagnetic energy harvester using mechanical frequency up-conversion method,” *IEEE Sensors Journal*, pp. 241-248, February 2011.

[6] E. T. Topal, H. Külah, and Ö. Zorlu, “A mechanical frequency up-conversion mechanism for vibration based energy harvesters,” *IEEE Sensors Journal*, vol. 11, no. 2, Februrary 2011.

[7] K. Itao, S. Kuroda, and H. Hosaka, “Evaluation of energy dissipation mechanism in vibrational microactuators,” *MEMS*, pp. 193–198, 1994.

Vida Pashaei was born in Tabriz, Iran, in 1988. She received the BSc and MSc degrees in electronics engineering from University of Tabriz, Tabriz, Iran, in 2010 and 2013, respectively. She has held several Teaching Assistance positions. Her research interests include Design, Analysis, and simulation of microelectromechanical systems with an emphasis on vibration based energy scavenging and MEMS sensors.

Manouchehr Bahrami received the BSc degree in electronics engineering from Iran University of Science & Technology, Tehran, Iran, in 1991 and his MSc degree in electronics engineering from Sharif University of Technology, Tehran, Iran in 1994. Then he obtained his PhD degree in MEMs from Southampton University, Southampton, United Kingdom. Currently he is an Assistant Professor of Department of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran. His research interests include Microelectromechanical Systems, sensor design, and RF circuits.