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Research Article

Novel Structure for Electromagnetic Micro-Power Harvester

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Abstract: Energy harvester could supply electronic devices such as implantable biomedical systems. Among the different methods of energy harvesting, the mechanical approach with the electromagnetic transduction method converts mechanical vibrations into output electrical power. In this research, an electromagnetic micro-generator is designed. The proposed device consists of a spring and a planar coil, designed using the Micro-electromechanical Systems (MEMS) technology, and also, a magnet and magnetic core. Different configurations are proposed to optimize the output power of the micro-generator. An innovative structure for the magnetic core is used to maximize the output power. The results show that the output power is increased up to 1.0344 µW and the power density is 2.94 µW/cm^3. The attained output power is higher than that reported in the literature. The proposed energy harvester is a suitable replacement for limited lifetime supplies.

***Keywords*:** energy harvester, mechanical vibrations, electrical power, magnetic core, MEMS

1. Introduction

Implantable biomedical devices have low electrical power consumption [1]-[3]. An energy harvester could supply these devices [4]-[6]. Energy harvesting techniques could be used to supply these applications with their nearly infinite lifetime [7], [8].

Different methods of energy harvesting are available: photovoltaic, micro-fuel cells, and electromechanical methods. Electromechanical energy generation includes electromagnetic [9]-[12], piezoelectric [13], [14], and electrostatic [15], [16]. The electrostatic method requires initial energy to produce electrical energy. The piezoelectric method produces a relatively lower electrical current than the electromagnetic method and has more output impedance. Due to these advantages, electromagnetic power generation is used. A new magnetic core is proposed to maximize the output electrical power density [17].

The magnetic core improves the magnetic flux path in electrical machines. Consequently, flux loss is minimized and the major part of the electromagnetic field is passed through the coil cross-section. Utilizing the magnetic core, the magnetic field path is corrected and the output power density is maximized [18]-[20].

In this work, an innovative electromagnetic micro-generator is proposed to scavenge environmental mechanical vibrations such as walking, arms moving, and especially heartbeat energy, and convert it into electrical energy [21]. Using the proposed micro-generator, energy harvesting from the cardiovascular system in the frequency range of 1-3 Hz

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is possible.

The micro-generator is composed of a magnet, planar coil, suspension system, and magnetic core. Mechanical vibrations oscillate the magnet. The changing magnetic flux, passing through the coil cross-section, generates electrical power at the output terminals of the coil. Also, a magnetic core improves the power density.

The design and implementation of planar coil and spring as suspension systems require high precision. For this purpose, MEMS technology is utilized. MEMS fabrication is planar or two-dimensional, where the designed micro-generator could be built using planar technology. For this purpose, the coil and suspension system is designed in a planar form. Hence, accurate fabrication is possible and different shapes could be implemented. The final device is an innovative design of micro-generator with high output performance.

Different optimizations are performed to increase the output power and output power density. For this purpose, the effect of vibration direction is investigated; different steady-state position for the magnet is assigned; finally, a new structure for the magnetic core is proposed. This new structure improves the efficiency of the micro-generator and results in high output power, subsequently, the output power density is optimized.

A new structure with four folded beams is proposed as a suspension system to scavenge low-frequency mechanical vibration and convert it into electrical power. The resonant frequency of the suspension system could be varied to match the frequency of input mechanical vibrations; hence, the output power and performance are maximized. For the optimum design, generator operation is simulated and the results are collected.

The remainder of the paper is organized as follows: In section 2, mechanical modeling and equivalent circuit of the micro-generator are described. Section 3 discusses the design and simulation of the micro-generator. Comparison of results and discussions are demonstrated and tabulated in section 4. Finally, conclusions are given in section 5.

2. Mechanical modeling and equivalent circuits

According to the direction of motion, two types of the generator are designed: linear and rotational. Linear generators are driven by linear motion. Rotational generators are excited by fluent sources of energy such as wind or fluid. There are two configurations for linear generators: resonant mode and imposed motion. Resonant mode devices have a specific resonant frequency and bandwidth [1]-[3]. Input vibration frequency should be limited to power generation bandwidth. A resonant generator could be used for every vibration source and the installation is easy. For imposed motion devices, the position of the vibration mass is constrained by input mechanical vibration. As shown in Figure 1, for the imposed motion micro-generator, there should be two vibrating mechanical parts, one for the coil and one for the magnet, which is not completely practical. For different situations of excitation (vibration direction as mentioned in Figure 1), the generator should be redesigned and then implemented. Out-of-vibration axis excitation (vibration direction as mentioned in Figure 1), is harmful and could damage imposed motion generators, although, resonant mode generators, could partially convert out-of-axis mechanical vibration to electrical power.

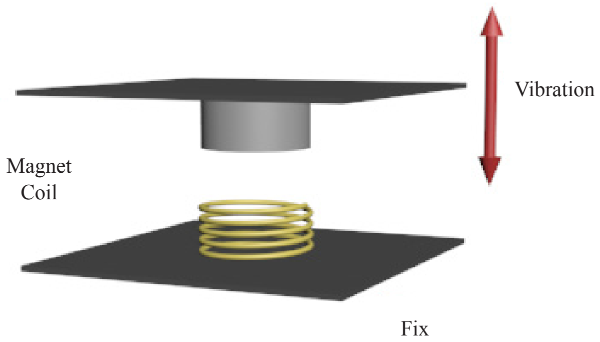

Figure 1. Imposed motion electromagnetic micro-generator

This article aims to design a micro-generator to scavenge mechanical vibrations such as heart motion, human walking, etc. Hence, linear devices are preferred against rotational devices to harvest human body motions. The most interesting configuration for linear generators, which is studied in the literature, is resonant mode systems. Whereas, imposed motion linear generators are difficult to design, package, and install. Although the resonant mode generators have limited bandwidth, in this study, a linear micro-generator with a specific resonant frequency is designed and a novel structure is proposed. A linear resonant electromagnetic micro-power harvester is developed to convert heartbeat mechanical vibrations into output electrical power. The proposed device is utilized as an electrical power source and cardiac monitoring system.

A typical resonant mode micro-generator is shown in Figure 2. The generator consists of a spring as a suspension system, magnet, housing, and coil. Mechanical vibrations shake the housing, so the magnet is vibrated and the flux passing through the coil cross-section is changed. Consequently, the output electrical power is generated at the coil terminals.

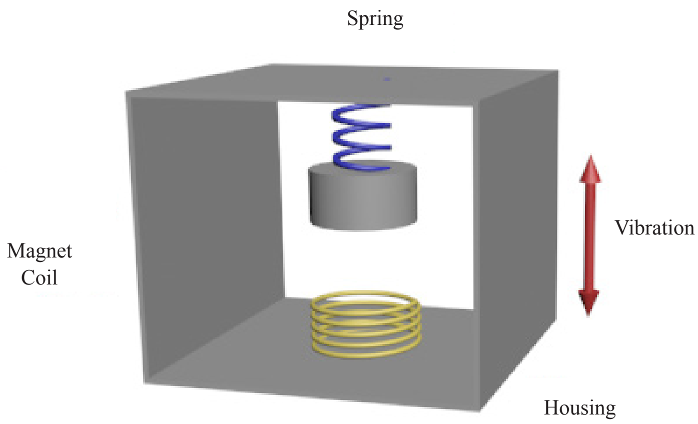

Figure 2. Resonant mode electromagnetic micro-generator

A resonant mode mechanical vibration system consists of mass *m*, spring with a stiffness coefficient of *k*, and damper with coefficient of *d*, moving within a frame. When the housing is exposed to external vibration, the suspended mass has experienced a vibration that can be modeled with equations. Figure 3 shows the vibration system model [22]. Where the relative displacement of mass to the frame is $z(t)$, the displacement of the frame is denoted as $y(t)$, therefore, the displacement of mass is $x(t) = y(t) + z(t)$. The input vibration is assumed to be $y(t) = Y_0 cos(\omega t)$.

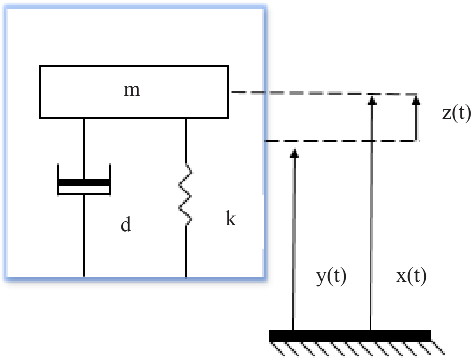

Figure 3. Vibration system with mass, spring, and damper

The differential equation which models the system is given by:

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

Assume, the resonant frequency of the system is $\omega_n = \sqrt{k/m}$, where $\omega_c = \omega/\omega_n$ and the damping factor is $\xi = d/2m\omega_n$. The transfer function of the relative displacement of mass to the displacement of frame is:

$$\frac{Z(s)}{Y(s)} = \frac{-ms^2}{ms^2 + ds + k} = \frac{-s^2}{s^2 + 2\xi\omega_n s + \omega_n{}^2} \tag{2}$$

Assume that all of the dampings are caused by the electrical damping factor. Hence, the dissipated energy in one period of motion, which is converted to electrical energy is:

$$Energy = \int 2d\dot{z}\, dz \tag{3}$$

So the output power could be calculated as [23]:

$$P = \frac{\xi\omega_c^3 Y_0^2 \omega^3 m}{[1-\omega_c^2]^2 + [2\xi\omega_c]^2} \tag{4}$$

The equivalent electric circuit for the generator is shown in Figure 4.

Where i is current, L is coil inductance, R_{Coil} is coil internal resistance, R_{Load} is load resistance, N is coil turns, A is coil cross-section area, $\acute{B} = dB/dz$, B is the magnetic field, and $z(\acute{t})$ is derivative of relative displacement of mass to the frame.

The voltage induced in the coil (Electro Motive Force) is $\varepsilon = NA\acute{B}z(\acute{t})$. Assuming $R = R_{Coil} + R_{Load}$, the damping factor could be calculated as:

$$d = (NA\acute{B})^2 / (R + Ls) \tag{5}$$

The transfer function could be rewritten as follows:

$$\frac{Z(s)}{Y(s)} = \frac{-ms^2}{ms^2 + \frac{(NA\acute{B})^2}{R+Ls}s + k} \tag{6}$$

The dissipated power in the resistor R is:

$$P = \frac{(NA\acute{B}V_0)^2}{2R} = \frac{m^2\omega^6 Y_0^2 (NA\acute{B})^2 R / 2\omega_n^4}{R^2(1-\omega_c^2)^2 m^2 + \omega^2\left[(NA\acute{B}/\omega_n)^2 + mL(1-\omega_c^2)\right]^2} \tag{7}$$

where the maximum velocity of the motion $z(t)$ is V_0.

Assuming $\xi_t = \xi_e + \xi_p$ (Total damping factor = Electrical damping factor + Mechanical damping factor), the generated power can be rewritten as [22]:

$$P = \frac{\xi_e \omega_c^3 Y_0^2 \omega^3 m}{[1-\omega_c^2]^2 + [2\xi_t \omega_c]^2} \tag{8}$$

The generated output electrical power, which is calculated using equation 8, is illustrated in Figure 5. As shown, at a resonant frequency, the output power is maximum. Also, the reduction of the mechanical damping factor increases the output power.

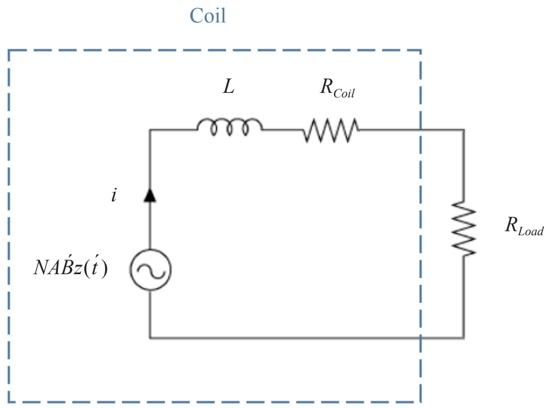

Figure 4. Equivalent circuit of the proposed electromagnetic micro-generator

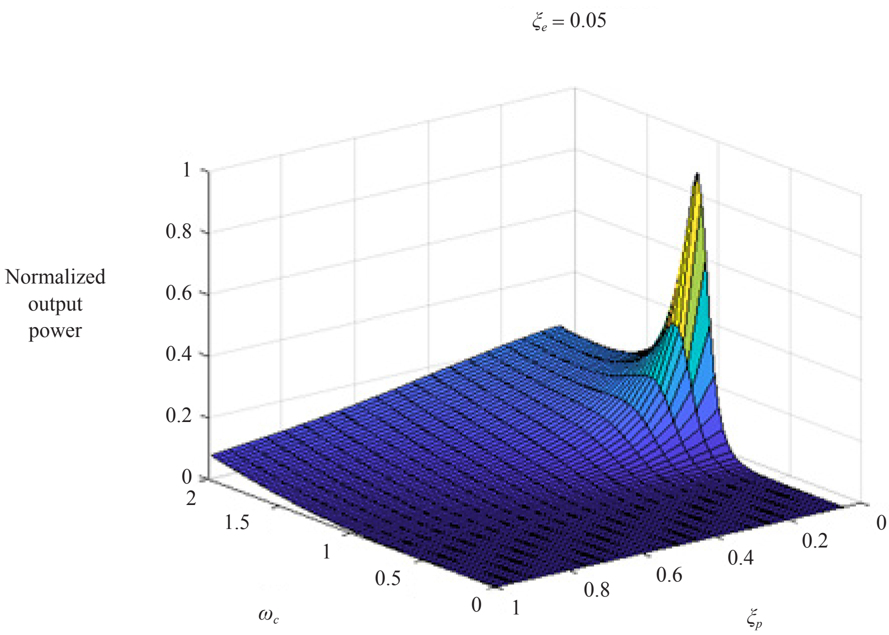

Figure 5. Output power according to damping factors and vibration frequency

3. Design and simulations

Different structures for the electromagnetic micro-generator are presented in the literature. In [24], Shearwood et al. presented a simple membrane-based electromagnetic micro-generator. At a vibration frequency of 3.9 kHz, a maximum output power of 0.3 μW is achieved. There is a slight change in bandwidth for different amplitudes of vibration. Using a membrane as the suspension system reduces the maximum vibration amplitude and low resonant frequencies are unattainable. For the proposed device, we attempt to design a novel suspension system to achieve high vibration amplitude at low mechanical frequency. Wang et al. presented a micro-generator with the folded beam as a suspension system with a planar coil [25]. The maximum attainable power is reported to be 0.7 μW at an input vibration frequency of 94.5 Hz. In the proposed work, a novel configuration is recommended to achieve high output power for a low vibration frequency of 1-3 Hz. In [2], Podder et al. reported an electromagnetic micro-power harvester with a planar copper coil and folded beams to suspend the magnet. At an input acceleration of 0.1 g, the output power is 0.68 μW. For a low input mechanical frequency (1-3 Hz), a relatively high vibration amplitude is required. So the designed device uses a spacer to achieve this purpose. Mallick et al. presented a micro-generator with a flexible suspension system for the magnet [26], so a different resonant frequency is achieved. The maximum output power reported is 0.43 μW at a few hundred Hz. In this study, a new structure for the magnetic core is recommended to improve the output power for 1-3 Hz input mechanical vibration.

In the proposed work, we used folded beams as a suspension system to have a high range of linear vibration with specific stiffness and resonant frequency. To achieve high vibration amplitude, the magnet is attached to the planar coil with a spacer. Using the spacer, a high mechanical vibration amplitude of about a few millimeters is attainable. Different positions for magnet and coil are assigned to maximize the output power. A magnetic core with a novel configuration is used to intensify magnetic flux passing through the coil area. Hence, high output power and power density are achieved.

The proposed micro-generator is composed of mechanical and electromagnetic parts. In this design, a vibration amplitude of about a few millimeters for the magnet is required. Consequently, the mechanical part is designed with four folded beams as a suspension system which will be oscillated due to environmental vibrations. The suspension system satisfies the linear motion of the magnet with a few millimeter vibration amplitudes. A spacer connects the spring to the magnet. Subsequently, maximum vibration amplitude is limited by spacer height. The electromagnetic part consists of a magnet, magnetic core, and planar coil. The output terminals of the planar coil are plugged into a resistive load. By means of mechanical vibrations, the voltage is induced at the coil, and output electrical power is generated.

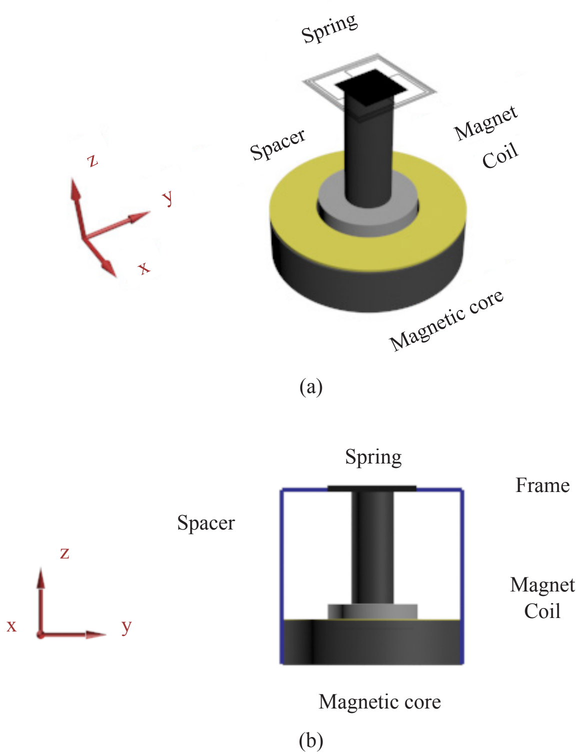

Figure 6. (a) The proposed structure of the micro-generator; (b) Cross-section view with frame

The optimization of the recommended system is demonstrated in section 2. Firstly, an initial design for the micro-generator is proposed. With five steps, the micro-generator structure is optimized as mentioned in section 2 and the final optimum design is performed. For the optimum design, the mechanical suspension system is designed as illustrated in section 1. The optimum structure of the micro-generator is shown in Figure 6.

The design of the proposed micro-generator is using the Finite Element Analysis (FEA) Software. Where, mechanical, electromagnetic, and electrical simulation results are obtained with high accuracy, and the practical results converge with FEA results. MEMS technology could be used to fabricate a micro-power harvester with high precision.

In Figure 6, the material utilized for the suspension system is silicon. The type of magnet is NdFeB (an alloy of neodymium, iron, and boron) with a grade of N42. Also, a magnetic core is used to improve the efficiency and performance of the micro-generator. In follow, mechanical and electromagnetic simulations are presented.

3.1 *Mechanical simulations*

The mechanical part of the micro-generator, as shown in Figure 7, consists of four folded beams and a membrane with a spacer attached to it. The design procedure of the suspension system is discussed as follows. Firstly, a beam with quarter stiffness of the final suspension system is designed. Then, to achieve the minimum volume of spring, a folded beam is constructed. To attain high linear vibration amplitude, desired stiffness, and required resonant frequency, four folded beams are connected to build a suspension system. A membrane is attached to the folded beams to operate as a plate, so a spacer could be established on the membrane. The magnet is connected to the end of the spacer. The spacer creates adequate space for the magnet vibration. The maximum attainable vibration amplitude is equal to the spacer height. Finally, the resonant frequency of the system is predicted to be 2 Hz.

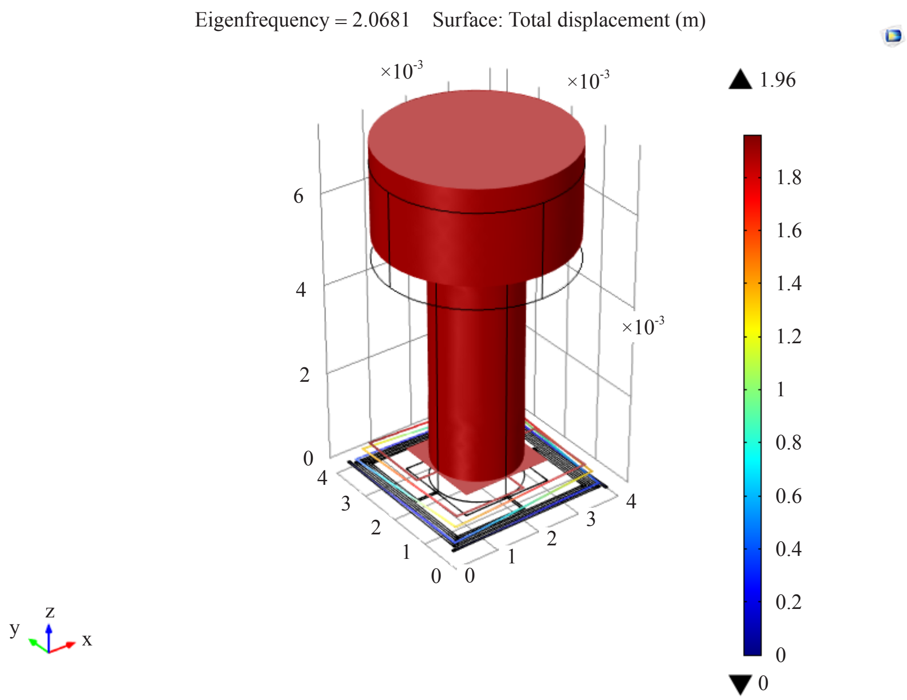

Figure 7. Resonant frequency of the suspension system

The estimation of resonant frequency is essential to determine the output performance. The maximum output power is generated at a mechanical resonant frequency of the system. Using COMSOL software [27], the resonant frequency of the practical device is achieved. The resonant frequency is 2.0681 Hz, as shown in Figure 7. The dimensions could be changed to maintain the resonant frequency between 1-3 Hz. Hence, heartbeat energy could be scavenged and converted to electrical power. The top view of the planar spring is shown in Figure 8. The dimensions as mentioned in Figures 7-8 are as follows: beam width and spacing is 50 µm, beam and membrane thickness is 7.5 µm, membrane width and length is 2 mm, spacer radius is 950 µm, spacer length is 5 mm, magnet radius is 2 mm, and magnet height is 2 mm.

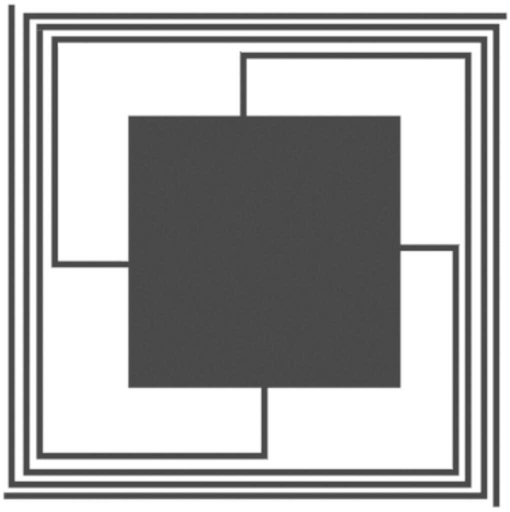

Figure 8. Planar spring

The planar spring is designed to achieve a specific resonant frequency between 1-3 Hz. Also, four folded beams are used to have linear motion and high vibration amplitude of about 5 mm. The stiffness coefficient of the proposed suspension system is estimated to be 0.0363 N/m. The parameters, which are assumed in this section to evaluate the resonant frequency and stiffness of the beam, could be varied. These parameters are beam width, beam length, beam thickness, utilized materials, dimension of the magnet, the position of the magnet, and other properties. The parameters should be adjusted to achieve a specific or optimum resonant frequency and stiffness. To generate maximum electrical output power, the input mechanical vibration frequency should be adjusted to the resonant frequency of the suspension. Also, there is a limited bandwidth of spring suspension, where the output power is available. Therefore, the resonant frequency should be aligned with the input vibration frequency. Altering different parts of the mechanical structure could adjust the resonant frequency and vibration frequency. Using Finite Element Analysis (FEA), the suspension resonant frequency is designed precisely.

3.2 *Electromagnetic simulations*

In this section, electromagnetic analysis of the micro-power harvester is performed. Together with, the generator operation of the device is described. Stimulation of micro-generators with mechanical vibrations in two directions is studied. Also, the effect of different structures on output power is discussed. Finally, an innovative configuration is proposed to achieve high output power and power density. Due to the low frequency and inductance of the planar coil, the imaginary part of coil impedance is neglected.

The device is analyzed for generator setup. During the generator operation, transient analysis in one period of magnet motion is performed to estimate the output voltage and power for different configurations. Different optimizations are performed to achieve a higher output power and power density. These optimizations include magnet vibration direction, variation of the steady-state position of the magnet, and attachment of magnetic core to the micro-generator structure.

The micro-generator requires a magnetic source that generates electrical current when the magnetic flux passing through the coil cross-section varies. So, a NdFeB permanent magnet with a grade of N42 is utilized. The remanence of the magnet practically is measured to be 1.28 T.

Optimizations are performed to improve the performance of the proposed micro-generator. Different optimizations are as follows.

3.2.1 *Stimulation in the x-axis direction*

Initially, mechanical vibration is applied in the x-axis direction. Hence, the magnet oscillates in parallel with the planar coil. For calculation of the output power, an initial position is assigned to the magnet and then the magnet is released to vibrate freely. The vibration amplitude of the magnet to frame is equal to the initial position. The output power is estimated using Flux software [28]. The simulated output power is 4.8695 nW, which is improved in the next sections. The design parameters are as follows: coil radius is 4 mm, coil turn is 40, magnet radius is 1 mm, magnet height is 2 mm, the air gap is maintained to be 0.1 mm, vibration amplitude is 3 mm, load resistance and internal resistance of the planar coil is 5 Ω, therefore, maximum power is delivered to load. The load resistance is assumed to be 5 Ω. Therefore, to deliver maximum output power to load, internal resistance is designed to be equal to the output load. Where the imaginary part of coil impedance is neglected due to low vibration frequency and low coil inductance ($\omega L \ll R_{Coil} + R_{Load}$). Also, for higher coil impedance, an RLC network could be designed to deliver maximum electrical power to the load. The copper planar coil is deposited on the silicon substrate. For planar coil: track width and space width is 50 µm, and track height is 34 µm. Dimensions of the planar coil are demonstrated in Figure 9. The proposed structure for stimulation in the x-axis direction is shown in Figure 10(a).

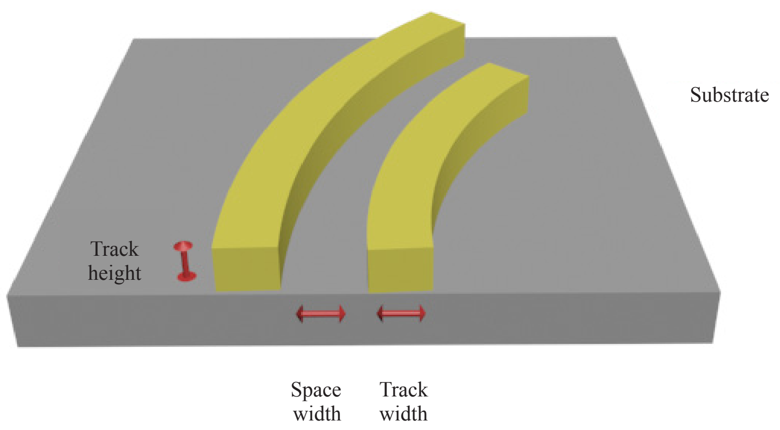

Figure 9. Planar coil dimensions

3.2.2 *Stimulation in the x-axis direction with additional disk shape magnetic core*

In this section, mechanical vibration is applied in the x-axis direction as in section 3.2.1. Also, a new configuration is proposed for an additional magnetic core. A disk shape magnetic core is attached to the planar coil. Consequently, the flux concentration passing through the coil cross section is improved. This phenomenon approximately improves the output power as twice in comparison with section 3.2.1. The estimated output power is 10.471 nW. The design parameters are as follows: coil radius is 4 mm, coil turn is 40, magnet radius is 1 mm, magnet height is 2 mm, the air gap is maintained to be 0.1 mm, vibration amplitude is 3 mm, load resistance and internal resistance of the planar coil is 5 Ω, hence, maximum power is delivered to load. Track width and space width is 50 µm, track height is 34 µm, magnetic core radius is 4 mm, magnetic core height is 1 mm, the relative permeability of magnetic core is 600, and the magnetic flux saturation of magnetic core is 1.6 T. The proposed structure for stimulation in the x-axis direction with additional magnetic core is shown in Figure 10(b).

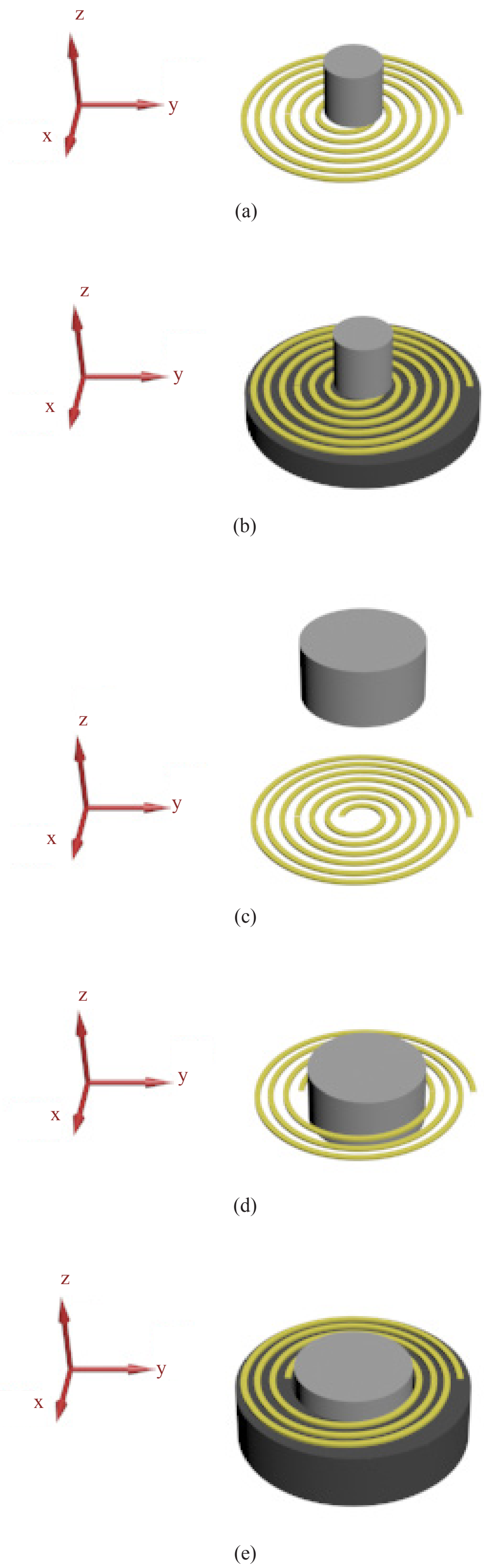

Figure 10. Structure of micro-generator for: (a) stimulation in the x-axis direction. (b) stimulation in the x-axis direction with disk shape magnetic core. (c) stimulation in the z-axis direction. (d) aligned position of magnet in center of planar coil. (e) Optimum structure of the micro-generator with additional ring shape magnetic core

3.2.3 *Stimulation in the z-axis direction*

In this step, mechanical vibration is applied in the z-axis direction; hence, magnet is oscillated orthogonal to planar coil surface. An initial displacement of 5 mm is assigned to the magnet in the z-axis direction. Then the magnet is released to vibrate freely. For one period of magnet vibration, the output power is calculated. The achieved output power is 27.959 nW. The results illustrate that the stimulation in the z-axis direction significantly improves the output power. The design parameters are as follows: coil radius is 4 mm, coil turn is 40, magnet radius is 2 mm, magnet height is 2 mm, vibration amplitude is 5 mm, load resistance and internal resistance of the planar coil is 5 Ω, track width and space width is 50 µm, and track height is 34 µm. The proposed structure for stimulation in the z-axis direction is shown in Figure 10(c).

3.2.4 *Steady-state position of the magnet in the center of a planar coil*

In this step, steady-state position of magnet is aligned to the center of the planar coil. Subsequently, the results of section 3.2.3 are improved. The estimated output power is 0.30568 µW, where it's improved considerably in comparison with the prior step. The design parameters are as follows: coil inner radius is 2.1 mm, coil outer radius is 4 mm, coil turn is 40, magnet radius is 2 mm, so air gap is maintained at 0.1 mm, magnet height is 2 mm, vibration amplitude is 5 mm, load resistance and internal resistance of the planar coil is 5 Ω, track width and space width is 25 µm, and track height is 102 µm. The proposed structure for the aligned position of the magnet in the center of a planar coil is demonstrated in Figure 10(d).

3.2.5 *Additional ring shape magnetic core*

For further improvement of the results of section 3.2.4, an additional ring shape magnetic core is attached to the planar coil. The achieved optimum output power is 1.0344 µW, which illustrates approximately three times the improvement of output power in comparison with air core. Ring shape magnetic core concentrates the magnetic flux passing through the planar coil cross-section. Consequently, the flux deviation, Electromotive Force (EMF), and output power are improved. The design parameters are as follows: coil inner radius is 2.1 mm, coil outer radius is 4 mm, coil turn is 40, magnet radius is 2 mm, so air gap is maintained at 0.1 mm, magnet height is 2 mm, vibration amplitude is 5 mm, load resistance and internal resistance of the planar coil is 5 Ω, track width and space width is 25 µm, track height is 102 µm, magnetic core inner radius is 2.1 mm, magnetic core outer radius is 4 mm, magnetic core height is 2 mm, the relative permeability of magnetic core is 600, and the magnetic flux saturation of magnetic core is 1.6 T. The proposed structure for an additional ring shape magnetic core is illustrated in Figure 10(e).

4. Comparisons and discussions of the prior studies

Several surveys and literature searches have been performed during 1997-2017. Content of 4 prior research studies and articles were investigated in this study and results are tabulated in Table 1.

Where, in Table 1, Shearwood et al. [24] presented a simple membrane-based electromagnetic micro-generator with a low output power in comparison with the proposed study. The proposed work has a higher output power in comparison with the research work of Wang et al. [25]. The proposed method exhibits higher output power in comparison with Podder et al. [2] work. Also, in comparison with the work of Mallick et al. [26], the proposed work has higher output power.

The micro-generator is a cylinder shape with a height of 7 mm and a diameter of 8 mm. The micro-power harvester is designed to be biocompatible and used for implantable biomedical applications.

Referring to Table 1, the advantages of the proposed method are compared with prior works. The optimized output power of the proposed method is about 1.0344 µW, which could supply wireless sensor networks, implantable biomedical devices, etc. Also, the proposed energy harvester could be excited in two directions, the x- and z-axis directions, which improves the capability of the proposed device for scavenging random mechanical vibrations in different directions. In conclusion, the optimization procedure in this study and the new proposed structure and configuration lead to achieving higher output power in comparison with the articles in the literature search.

Table 1. Results of prior and proposed studies

Author	Year	Size	Frequency	Acceleration	Voltage	Power	Power density
Shearwood et al. [24]	1997	2 mm dia.				0.3 μW	
Wang et al. [25]	2009		94.5 Hz	4.94 m/s^2	42.6 mV p-p	0.7 μW	
Podder et al. [2]	2015			0.1 g		0.68 μW	3.5 $kg \cdot s/m^3$
Mallick et al. [26]	2017			0.5 g		0.43 μW	
The proposed method	2022	7 mm × 8 mm dia.	2 Hz		8.72 mV	1.0344 μW	2.94 $\mu W/cm^3$

5. Conclusion

In this research work, a new configuration for energy harvesting is proposed. The proposed device is composed of four folded beams as suspension system, magnet, magnetic core, and planar coil. The electromagnetic energy harvester converts mechanical vibrations into electrical power. Due to the flexible structure design, the micro-generator could convert environmental vibrations to electrical power in two orthogonal directions, which is studied in this work. Moreover, different structures and configurations are proposed to increase the output voltage, output power, and output power density. The obtained results indicate that a lower air gap and utilization of a new configuration magnetic core will increase output power and power density. Finally, the optimized micro-generator is designed and simulated. Hence, electronic devices could be supplied with the energy harvester; consequently, the proposed micro-generator could be an appropriate replacement for limited lifetime power supplies.

Conflict of interest

There is no conflict of interest.

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