Fabrication and Investigation of a Millimeter-Scale Electromagnetic Generator for Large-Amplitude Impact Motions

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Environment vibrations are an important source of energy, often occurring at very low frequencies, but with large amplitude. The possibility to use the large amplitude of the motions is important to enhance the energy harvester's output power. In this paper, an electromagnetic energy harvester is designed and fabricated to produce electricity from low-frequency high amplitude impact motions using an elastic polyurethane cylinder. This millimeter-scale electromagnetic generator (MS-EMG) includes a movable magnet attached to a free sliding mass, a fixed coil, and a polyurethane holding chamber. Polyurethane is a very stable elastic polymer that provides continuous large-amplitude movement for the magnet and plays an effective role in impact capability. Therefore, the effect of impact excitation and the polyurethane foam was investigated simultaneously. The performance of the device was studied, experimentally, for the environment vibrations in the range of 1 to 10 Hz. The impact motions were applied using a simulator that was fabricated for this work. The fabricated MS-EMG with a volume of 1.07 cm^3 and a mass of 8.74 g show the capability of producing a voltage of 44.41 mV and power of 10.48 μW over a 100 Ωresistive load, using a 6 Hz frequency impact motion. Finally, an analytical model is used to simulate the device performance which showed a good agreement with the experimental results.

Keywords: *MS-EMG, Impact, Polyurethane, Large-Amplitude Motions, Energy Harvester, Environment Vibrations.*

1. INTRODUCTION

One major purpose of environmental energy harvesting is to provide free and steady electric power to supply wireless systems and sensors without batteries. Rechargeable and non-rechargeable batteries as the most common power supply for such systems have lots of limitations in terms of their performance and the environmental effect. To overcome the disadvantages of the batteries such as limited lifetime, high volume, high costs, and chemical pollution, harvesting energy from the environment has been suggested as a reliable and cost-effective solution [1]. Among them, vibration is the most abundant source of energy in an environment which is considered by various researchers on developing energy harvester devices [2-5]. Usually, human movements, vehicles, or ambient noise produce random displacements, vibrations, or forces in the environment. This abundant energy resource can be used to generate clean electricity by designing proper devices for the considered application. Fabricated devices based on vibrations produce high energy densities, which are used in wireless sensors and systems [6 and 7], automobiles [8], intelligent clothes [9], etc. Among them, electromagnetic micro-generators are developed to harvest the energy of low and high-frequency environment vibrations [10, 11]. The advantages of the electromagnetic generators are simple in design and fabrication and its high output power, concerning input energy, and reliability.

The first electromagnetic vibration energy generator was founded by Williams and Yates in 1996 [12]. The proposed generator produced a power of about 1 μW at a frequency of 70 Hz and a power of 0.1 mW at a frequency of 330 Hz. Further, Galchev et al designed a device that converted non-periodic and low-amplitude vibrations on bridges into usable electrical energy [13]. This device produced an average power of 2.3 μW at an input acceleration of 0.54 m/s^2 and a frequency of 2 Hz.

Sari et al proposed a structure to increase the power density of the device in a low-frequency environment, the device has been improved by a frequency amplification method [14]. Environment frequencies, such as human movement, are in the range of 1 to 100 Hz. However, the resonant frequency of most devices is higher than 100 Hz. Therefore, mechanical frequencies should have been converted to higher resonant frequencies. For this purpose, in the upper part of the microgenerator, a diaphragm with a resonant frequency of 10 Hz has been used. Which excited the low structure (coil located on the bases) at its resonant frequency (11.4 kHz). The fabricated micro-generator produced a power of 0.25 nW from the environment with a

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frequency range of 70-150 Hz [14]. Zarlou et al proposed a design that included two diaphragms [15]. The magnet is located on the diaphragm with the lower resonant frequency and the coil is located on the diaphragm with the higher resonant frequency. This generator produced a power of 1.2 nW and an effective voltage of 6.94 mV at a frequency of 10 Hz and an amplitude of 3 mm. Some electromagnetic energy harvesters have been designed to be used at very low frequencies, using a cylindrical structure. In a recent study, a magnet has been attached to a spring located inside a cylindrical device and aligning pin and guide have been used to move the magnet [16]. However, the manufacturing process of such a device is complex and its volume is relatively large. Most other studies have focused on the use of flexible diaphragms [14, 15] and sinusoidal excitation [17, 18, and 19]. In a flexible diaphragm, the movements are limited and so, it cannot be employed for a large amplitude excitation.

In the present paper, a millimeter scale-electro–magnetic generator (MS-EMG) with a vertical hollow cylinder is fabricated and its performance is investigated. To remove the limitation of the diaphragm displacement, a cylindrical case is used and filled with elastic polyurethane (PU). Excitation of the device is done by impact movements. The impact between two masses allows momentum to be transferred from a heavier mass (a magnet attached to the screen) to a lighter mass (elastic PU), thereby amplifying the velocity. The device outputs are measured for various input frequencies and a range of external loads. Analytical modeling is used to simulate the device performance and a comparison is made between the experimental and analytical results.

2. MATERIALS AND METHODS

To successfully design an energy harvester device, a wide range of factors must be considered, such as frequency range and amplitude of the excitation source and the device volume, weight, and cost. In this section, an electromagnetic energy harvester is designed and fabricated to produce electrical energy from low-frequency high amplitude impact motions that are presented in the environment due to humans walking and running, pushing the bottoms of various instruments, etc. Following, the fabrication and characterization methods are described in detail.

The energy harvester device is an MS-EMG, where an impact motion is considered as the input energy resource. The elastic property of PU is used to remove the limitation of low diaphragm displacement and provide the restoring force. PU has a high degree of elasticity, so it is appropriate to create high displacement for the magnet. The magnet is located in the upper part of the device and moves up and down under the influence of external force. As a result, voltage is induced in the coil. To provide the magnetic field, a boron iron neodymium cylindrical magnet (NdFeB), grade 42, was used. The magnet is attached to a circular screen with a diameter of 10 mm. The screen is made of poly-methylmethacrylate (PMMA). Movable mass includes magnet and screen mass. A PU polymeric material is placed in a Teflon cylindrical case of the device supporting the reciprocating motion of the magnet. Figure 1 shows a schematic of the device with its different parts including NdFeB magnet, PMMA plate, a fixed copper coil, and PU foam which is located inside a hollow Teflon cylinder. The magnet is attached to a screen that distributes the applied force, evenly, and protects the magnet from the degradation effect of the impact force. The movement of the magnet is reciprocating in the vertical direction. Elastic PU is used to increase impact capability and magnet displacement. It has good elasticity, low stiffness, is lightweight, good resistance to impact, easy synthesis and recycling procedure, and relatively low price [20-21]. This poly-meric material has superior degradation stability compa-red to natural rubber and also, it has higher mechanical stability comparing the vastly used silicone rubber.

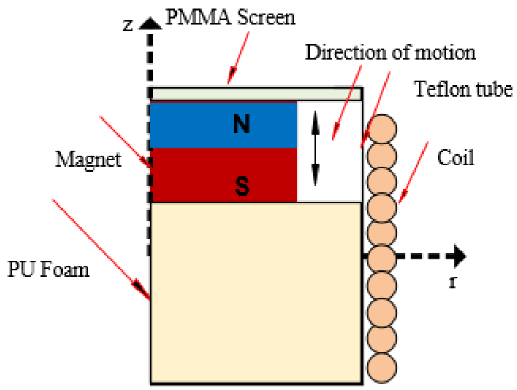


Figure 1. Schematic of a fabricated electromagnetic generator

The coil is made of copper wire with a diameter of 10 micrometers and 600 turns. The whole resistance of the coil is 92 Ωand its inductance is 7 mH. The dimen-sional parameters of the device are given in table 1.

Table 1. Dimensional parameters of MS-EMG

parameters	Value (mm)
Diameter of device	12
Height of device	31
Diameter of magnet	7
Height of magnet	4
Inner diameter of the coil	12
Outer diameter of the coil	15
Coil height	28
Diameter of PU	10
length of PU	26

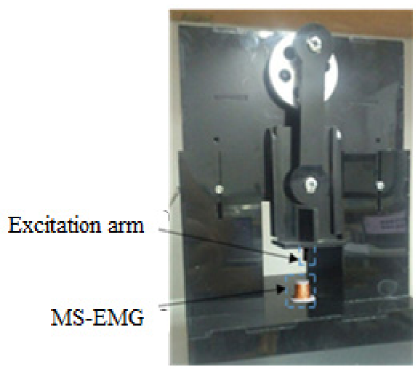


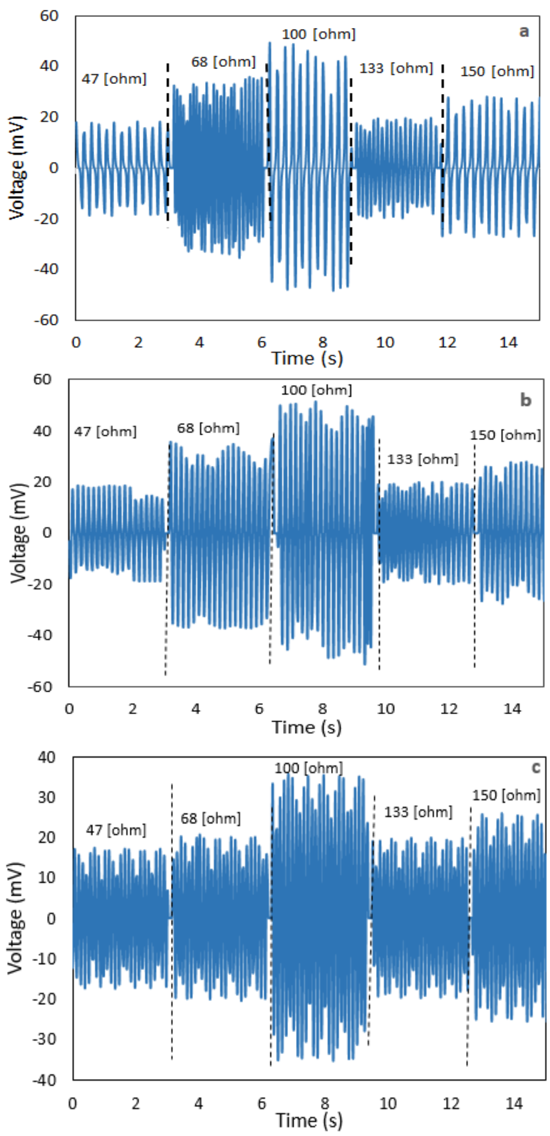
Figure 2. Fabricated Instrument for applying impact forces to MS-EMG device

The impact forces were applied to the device using an instrument that was fabricated for this work. The instrument and the fabricated MS-EMG device are shown in figure 2. The output currents and voltages were measured using a GDM-8261A double digital multimeter and the magnetic flux density of the magnet was measured using an EMF-827 electromagnetic field meter.

3. RESULTS AND DISCUSSION

The experiments are performed by changing the frequency from 1 to 10 Hz. Figure 3 shows the output voltage waveform with the frequency of impacts. Resistance loads in the range of 40-150 Ωare connected to the coil.

Maximum voltage values are obtained at resonant frequencies. At 4 and 6 Hz, the maximum voltage instantaneous values are 47.9 and 50.8 mV, respectively. Figure 4 shows the corresponding voltage frequency response using the FFT (fast Fourier transform) at these two frequencies. Three voltage peaks are obtained at the resonance frequencies of 4, 6, and 8.12 Hz. These three frequencies correspond to the frequency of impacts at 4 and 6 Hz and the PU frequency at 8.12 Hz.



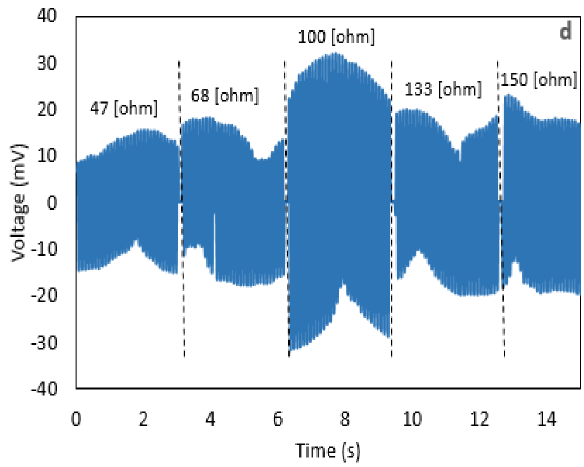


Figure 3. Time history for voltage as the load resistance is swept from 40-150 Ω at frequencies a. 4 Hz, b. 6 Hz, c. 8 Hz, d. 10 Hz

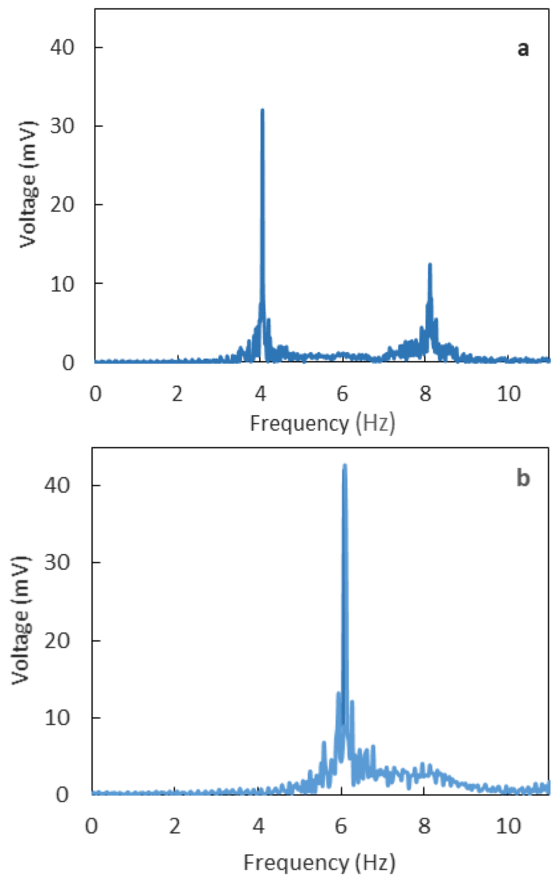


Figure *4.* Results of FFT analysis a. 4 Hz, b. 6 Hz

To find the optimal resistance, in the mentioned frequencies, effective voltage and current changes are investigated in figure 5.

The effective power variations with load resistance in different frequencies are shown in figure 6. In all modes, the maximum effective power is obtained at a resistance of 100 Ω, which is close to the resistance of the coil, 92 Ω.

The output power of electromagnetic harvester is maximum in the following conditions: at the resonant frequency, load resistance equals the coil resistance, and electrical damping compared to mechanical damping is negligible [22].In this study, all three conditions occur.

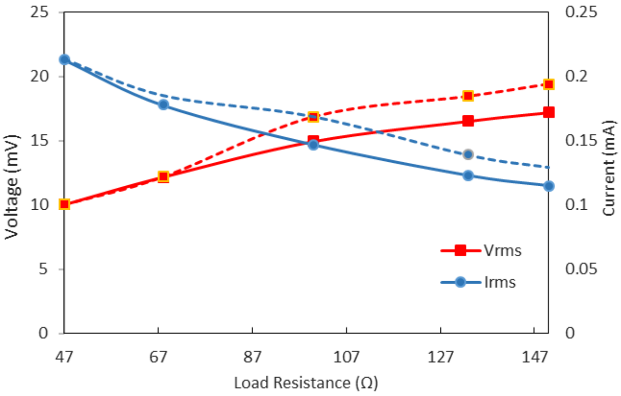


Figure 5. Variation of the effective voltage and current infrequency modes 4Hz (solid line), 6 Hz (dash line)

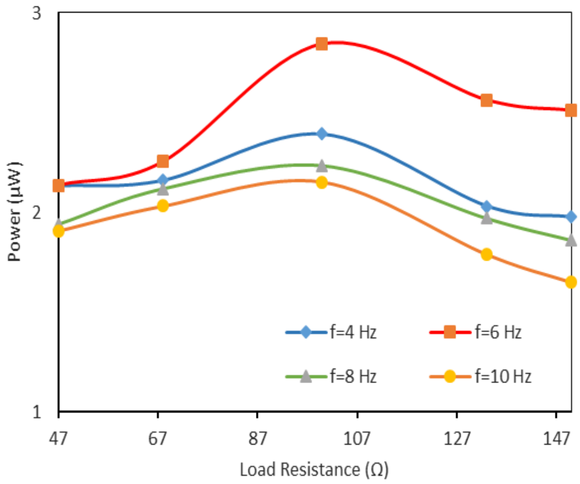


Figure 6. Variation of effective power with load resistance in different modes.

A summary of the experimental results is given in table 2, in the frequency range of 1-10 Hz and the optimum resistance of 100 Ω. The quality factor is calculated using the logarithmic decrement method from the equation $Q=\frac{\pi f_0 \Delta t}{\ln\left(\frac{V_1}{V_2}\right)}$ [23]. Where f_0 is frequency, $V_1$and V_2, are the voltage ranges in the time interval Δt.

4. ANALYTICAL MODELING

To validate the experimental results, analysis of voltage, power, and quality factor parameters is performed.

The fabricated electromagnetic generator can be modeled with a mass-spring-damper system. The mechanical acceleration produced by the vibrations leads to the oscillation of the mass and its displacement in the direction of the oscillations. This relative displacement creates damping and frictional forces opposite to the motion of the mass. The mechanical model of the generator is shown in figure 7.

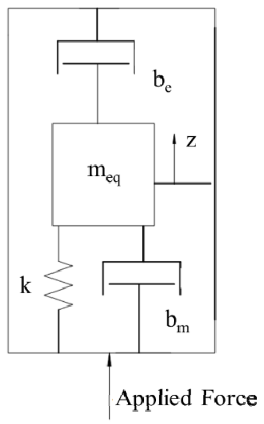


Figure 7. Mechanical model for electromagnetic energy harvester

Input to the system is an impact function. One of the advantages of this type of excitation is the transmission of force in a very short time. The dynamics of an impact system with displacement amplitude of $Z$is are expressed by equation (1).

$$m_{ea}\ddot{z}+\left(b_m+b_e\right)\dot{z}+kz=Z\delta\left(t\right) \tag{1}$$

In equation (1), z is the relative displacement, which represents the difference between the displacement of the moving mass and the displacement caused by the excitation of the environment vibrations. b_m and b_e are mechanical and electrical damping, respectively and k is the elastic constant of PU.

In an electromagnetic harvester, the energy of the mechanical vibrations of the mass is converted into a change in the magnetic field. As a result, electrical current is induced in the coil, which opposes the change in the magnetic field. A circuit is formed by connecting the load resistance to the output ends of the coil and an inductive current flows in the output. L_c and Rc are the inductance and resistance of the coil, respectively, and R_L is the load resistance. Electrical damping is caused by the electromagnetic force between a moving magnet and a coil [24]. In equation (2), l is the effective length of the coil, B is the magnetic flux density, and ω is the frequency of the vibrations.

$$b_e=\frac{\left(Bl\right)^2}{R_L+R_C+j\omega L_C} \tag{2}$$

Mechanical damping is known as mechanical loss and can include losses of air resistance, surface friction, and material hysteresis losses [25]. In equation (3), μ_e is the effective air viscosity, A is the mass surface and g is the air gap distance between the moving masses and the micro-coil.

Table 2. Comparison of experimental results in different modes

Frequency (Hz)	Quality factor	Voltage (mV_{rms})	Power (μW_{rms})	Max. voltage (mV)	Max. power (µW)
4	65.5	14.93	1.16	41.81	9.28
6	86.13	15.86	1.31	44.41	10.48
8	88.16	14.82	1.14	41.49	9.12
10	92.87	14.66	1.12	41.04	8.96

$$b_m = \mu_e \frac{A}{g} \tag{3}$$

Mechanical and electrical damping values are calculated at 0.003 and 0.0004 N.s / m, respectively.

The response of the system to the impact excitation is expressed by equation (4) [26]:

$$z(t) = \frac{e^{-\xi \omega_n t}}{m_{eq}\omega_d} \sin \omega_d t \tag{4}$$

In equation (4), $\omega_d = \omega_n \sqrt{1-\xi^2}$, is the damping frequency of the system and $\xi = \frac{b_m + b_e}{2m_{eq}\omega_n}$ is the total damping ratio.

The relative motion between the coil and the magnet is used to induce a voltage in the coil. According to Faraday's law, the induced electromotive force is proportional to the negative rate of change of the coil's magnetic flux.

$$V = \left| -N \frac{d\varnothing}{dt} \right| \tag{5}$$

The expression of the output voltage, as a product of the flux gradient and velocity, is important for understanding the performance of the vibrating generator. In equation (5), N is the turns of the coil, $\varnothing = \iint B, dA$, the total magnetic flux passing through the coil and A is the surface of the coil located in the magnet field. According to figure 8, the magnetic flux density is calculated from equation (6) [27].

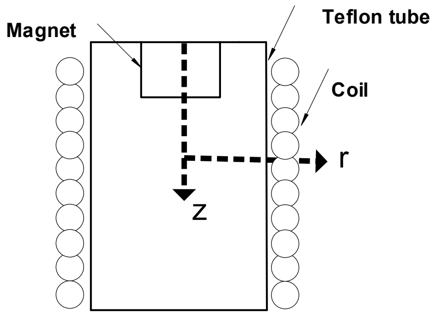


Figure 8. A cylindrical magnet at a distance r from the coil

$$B_r = \frac{3\mu_0 m_0}{4\pi} \frac{zr}{\left[z^2 + r^2\right]^{5/2}} \tag{6}$$

In equation (6), B_r is the flux density, μ_0 is the permeability of a vacuum (=$4\pi\times10^{-7}$ H/m), m_0 is the magnetic dipole moment of the magnet (m_0=MV, M=4.3×10^5 A/m, and V is the magnet volume), r is the distance from the center of the magnet to the coil and z is the displacement of the magnet. The radial distance r is constant and the z value is changed when the magnet is pushed vertically using the impact motion. The changes in magnetic flux density concerning magnet displacement are shown in figure 9.

For experimental measurements, the magnetic flux density along the longitudinal axis of the coil core, the Gauss meter is fixed at one point and the magnet is pushed vertically using an impact signal simulator. During the measurement, the probe should be tangential to the surface of the procedure. Initially, as the magnet approaches the probe, the magnetic flux density increases to a maximum of 11.41 mT at a distance of 3.8 mm. but the magnetic flux density goes to zero when the magnet and the magnetometer probe are at the same height. At larger displacements, the magnet covers a smaller area of the coil and the magnetic flux density will reduce to zero at the end of the device.

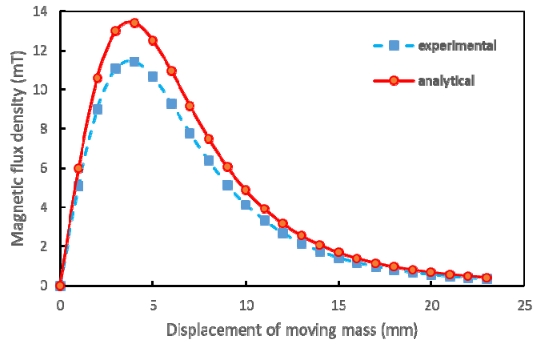


Figure 9. Variation of the magnetic flux density

The resonant frequency, f, can be calculated as [28]:

$$f = \frac{1}{2\pi} \frac{\alpha c}{l} \tag{7}$$

In equation (7), c is the acoustic velocity in the material ($c = \sqrt{\frac{E}{\rho}}$), where E is Young□ s modulus (= 18 kPa) and ρ is the density (=1.2 gr/cm^3). Furthermore, l is the length of the PU. For the first-order frequency mode, the value of α is calculated 0.4 by linear interpolation. The PU frequency was calculated to be 9.48 Hz which is close to the observed frequency (8.12 Hz) in figure 4.a.

By simplifying equation (5) and placing equation (4), the voltage for the impact motion is calculated from equation (8).

$$V = N\frac{d\varnothing}{dt} = N\frac{d\varnothing}{dz}\frac{dz}{dt} = \frac{NBl}{m\sqrt{1-\xi^2}} \left(-\xi \sin \omega_d t + \sqrt{1-\xi^2} \cos \omega_d t\right) e^{-\xi \omega_n t} \tag{8}$$

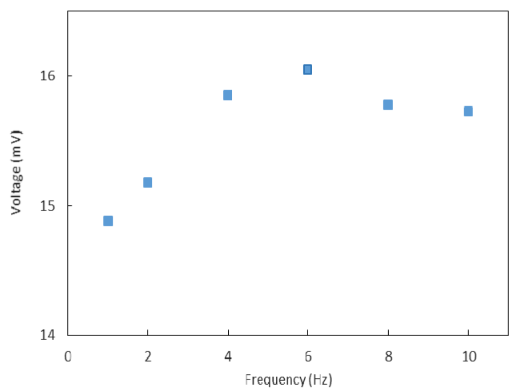


Figure 10. Analytical output voltage at different applied frequencies

Table 3. Comparison of calculation analysis results in different modes

Frequency (Hz)	Quality factor	Voltage (mV_{rms})	Power (μW_{rms})	Max. voltage (mV)	Max. power (μW)
4	71.42	15.85	1.31	44.38	10.48
6	110.86	16.05	1.34	44.94	10.72
8	147.06	15.78	1.29	44.18	10.32
10	185.19	15.73	1.28	44.04	10.24

To study the performance of the device at other possible frequencies of environmental movements and in the desired applications, analysis of voltage was performed in the frequency range of 1 to 10 Hz. The results are shown in figure 10.

The maximum effective voltage values are obtained at 4 and 6 Hz frequencies. In figure 11, the analytical and experimental values of voltage at these two frequencies are compared.

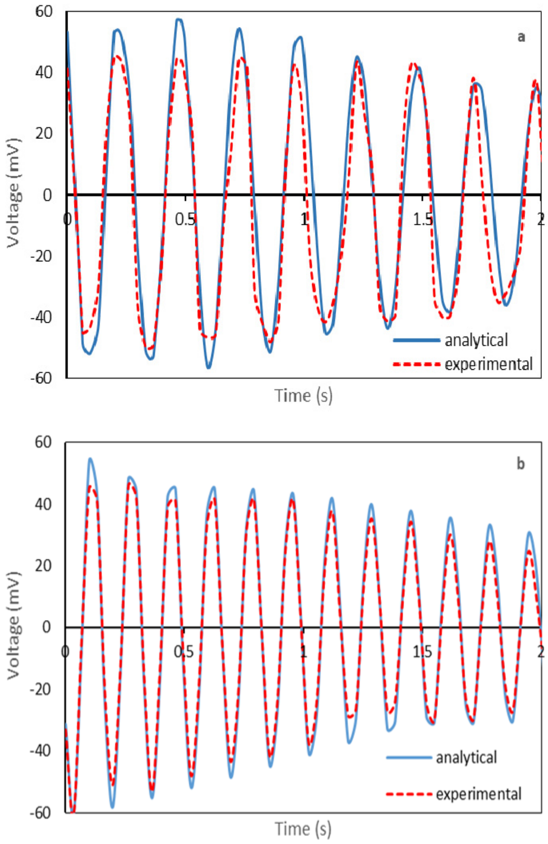


Figure 11. Comparison of the analytical and experimental output voltage at a frequency of a. 4 Hz b. 6 Hz

Analytical results in different modes are given in table 3. The differences observed in the experimental and analytical results can be due to the neglect of friction and environmental effects such as temperature and pressure. In calculating the mechanical damping coefficient, only the effect of air viscosity is considered. Due to the mechanical structure and type of movement, mechanical losses in the harvester are inevitable. It can also be due to assembly methods. For example, the magnet is attached to the screen with glue without alignment methods.

Another fundamental quantity for the study of energy harvesters is efficiency. However, in these systems, compared to the maximum output power, it has received less attention [29]. Efficiency is the ratio of output power (electrical) to input power (mechanical).

$$E = \frac{P_{out}}{P_{in}} \tag{9}$$

The electrical and mechanical power is calculated from the equations (10) and (11), respectively.

$$P_{out} = \frac{V^2}{R_L + R_c} \tag{10}$$

$$P_{in} = \frac{1}{2}\left(b_m + \frac{B^2 l^2}{R_L + R_c}\right)\omega_n^2 Z^2 \tag{11}$$

The efficiency at 4 and 6 Hz were calculated to be 45.86 and 46.69%, respectively. The results are shown that the analytical model used for the energy harvester is suitable.

Table 4 shows the comparison of this work with previous reports. As shown in table 4, [18] harvests the electricity energy from high frequency, and [23] was obtained power of 46 μW from the generator with a 2300 turns coil. The proposed MS-EMG has the power of 10.48 μW with a 600 turns coil at low-frequency vibration.

Table 4. Comparison of this work with previous reports

Reference	Input Freq. (Hz)	Voltage (mV)	Power (μW)	Efficiency (%)
[14]	70-150	0.57	0.25×10^{-3}	-
[15]	5-10	18	8.1×10^{-3}	-
[18]	100-400	16.8	1.5	-
[23]	45-65	428	46	30
[24]	20-100	18	0.8×10^{-3}	-
Present Study	1-10	44.41	10.48	46.69

5. CONCLUSION

In this study, an electromagnetic energy harvester device was fabricated and its performance was studied at low frequencies high amplitude excitation forces, with the frequency in the range of 1 to 10 Hz. The devices were incorporated with PU foam to prepare reciprocal movement. The elastic foam increased the displacement of the magnet under impact loading. An analytical model was developed to analyze the performance of the harvester. The analytical results agree with the experimental results. Both theoretical and experimental results show that the harvester has two resonant modes, 4 and 6 Hz. The harvester can produce a maximum power of 10.48 μW at 6 Hz and 9.28 μW at 4 Hz. Due to the characteristics of the harvester such as simple construction method, low cost, and appropriate level of output voltage, it can be a good option for working at low frequencies.

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ПРОИЗВОДЊА И ИСПИТИВАЊЕ ЕЛЕКТОРМАГНЕТНИХ ГЕНЕРАТОРА МИЛИМЕТАРСКЕ СКАЛЕ ЗА УДАРНЕ КРЕТЊЕ ВИСОКИХ АМПЛИТУДА

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Вибрације околине су важан извор енергије и често се јављају на веома ниским фреквенцијама, али са великом амплитудом. Могућност коришћења ве–ликих амплитуда покрета је важна за повећање излазне снаге комбајна за енергију.

У овом раду, електромагнетни комбајн енергије је дизајниран и произведен да производи електричну енергију од ударних покрета ниске фреквенције високе амплитуде користећи еластични поли–уретански цилиндар. Овај електромагнетни генератор милиметарске скале (МС-ЕМГ) укључује покретни магнет причвршћен за слободну клизну масу, фиксни калем и полиуретанску комору за држање.

Полиуретан као веома стабилан еластични полимер обезбеђује континуирано кретање магнета велике амплитуде и игра ефикасну улогу у способности удара. Због тога је истовремено истражен ефекат ударне побуде и полиуретанске пене. Перформансе уређаја су експериментално проучаване за вибрације околине у опсегу од 1 до 10 Hz. Ударни покрети су примењени на симулатору који је направљен за овај рад. Произведени МС-ЕМГ запремине 1,07 цм3 и масе 8,74 г показује способност да произведе напон од 44,41 мВ и снагу од 10,48 μВ преко отпорног оптерећења од 100 Ω, користећи ударно кретање фреквенције од 6 Hz. Коначно, за симулацију перформанси уређаја коришћен је аналитички модел који је показао добру сагласност са експерименталним резултатима.