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Experimental Energy Recovery from a Backpack Using Various Harvester Concepts

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ABSTRACT

Energy harvesting from human body kinetics is a crucial issue. The primary challenge lies in designing and optimizing the energy converter. This paper presents an analysis of energy harvesting using three variants of electromagnetic harvesters designed for backpack integration. The first harvester comprises a single levitating magnet within a coil. The second concept involves a specially designed oscillating magnet consisting of two divided magnets with a separator. The third harvester variant utilizes two levitating magnets within the coil. The results indicate that, for harmonic excitation, the harvested power is the highest for the classical harvester with a single oscillating magnet. However, when integrated into a backpack, the concept of two levitating magnets proves to be more effective in lower speed ranges.

Keywords: energy harvesting, magnetic levitation, vibration, electromagnetic induction.

INTRODUCTION

The term energy harvesting (EH) or energy recovery is nowadays defined as a process of converting energy from various sources on a small scale. Potential sources include motion, vibration, heat, and radiation, with the choice of the conversion technique dependent on the specific application. Dedicated energy recovery devices can be found in wireless vibration sensors [1], microgenerators [2], implants [3, 4], or internet of things (IoT) [5]. Energy recovery from mechanical vibrations has become a crucial technology in our quest for sustainable and efficient energy solutions. This process entails capturing and converting ambient vibrations into usable electrical energy, presenting a promising way for powering various electronic devices and systems. The primary advantages of energy harvesting from mechanical vibrations stem from its abundance in diverse environments, offering a reliable and renewable source of energy. This method of harvesting contributes to reducing our dependence on nonrenewable energy sources, consequently lowering carbon emissions. Generally, there are three types of vibration harvester transducers: electromagnetic, piezoelectric, and electrostatic. However, electromagnetic vibration energy harvesters (EVEHs) have a relatively simple construction and can operate at low frequencies. Many electromagnetic harvesters rely on suspension systems, utilizing either a coil or a magnet supported by a spring or magnetic levitation. These systems function as a spring-mass-damper system [6, 7], and consequently they have garnered significant attention [8–11]. One of the most interesting EVEHs is the magnetic levitation harvester which exhibits a nonlinear stiffness profile due to the repulsive force between magnetic poles. This nonlinearity can improve the bandwidth and power output. Due to their simple structure and reliable operation, such mechanisms can easily be implemented in various devices and everyday items. It has been noted that the human body can be a rich source of energy. It is estimated that the recovered power can be up to 70 W [12]. Portable electronic devices like mobile phones typically use about 1 W of energy daily [13]. This suggests that the kinetic energy from the human body could promisingly be used as a power source for portable electronics. Researchers have successfully demonstrated the feasibility of energy harvesting from various human activities. For example, Paulides et al. [14] proposed energy harvesting from dance through special tiles mounted in the floor. The results demonstrated that the obtained approximated power ranged from 20–30 W. Rocha et al. [15] described the use of a piezoelectric polymer harvester embedded in a shoe that generated energy of 50 mW, while in [16] achieved up to 700 mW. Xie et al. [17] demonstrated energy harvesting from swinging it human arms, obtaining power up of to 45 mW.

One intriguing solution for energy harvesting from human motion is a backpack designed to harness mechanical energy generated during the user's walking motion. Granstrom et al. [18] introduced the energy harvesting concept that utilizes a backpack incorporating a piezoelectric polymer in a strap. This design cleverly exploits the contrasting forces between the wearer and the backpack to generate electric energy, resulting in a recovered energy of approximately 50 mW. Mostafavi et al. [19] presented the design and modelling of an energy-harvesting backpack that utilizes a mass-spring-damping oscillating system and a mechanical motion rectifier unit. The prototype designed for normal walking speed exhibited an average power of 4.37 W. Huang [20] discussed the power generation performance and efficiency of two types of harvesters installed in backpacks during human walking, suggesting the potential to generate electrical power of 6 W without increasing metabolic costs. Liu et al. [21] conducted an analysis and comparison of three different backpacks, considering the dynamic interaction between the human body and the backpack. Hou et al. [22] proposed a biomechanical model for an energy harvesting backpack, emphasizing the crucial role of the human factor in the energy harvesting system. Wang [23] took a different approach, investigating the impact of wearing a backpack with an energy recovery system on kinematics, kinetics, and lower limb muscle activity in comparison to conventional backpacks. In the paper by Wu et al. [24], an energy harvester based on electromagnetic induction with high power and efficiency was presented. The design relied on a tiny compound mechanism comprising a symmetrical lever-sector gear, resulting in an average power output of about 1 W. Enhancing the efficiency of harvesters typically requires adjusting system parameters, and one intriguing solution involves modifying the coupling properties. To improve energy harvesting performance, electromechanical coupling can be enhanced by modifying the conversion mechanism which consists of a coil and magnet [25].

This paper focuses on the modification of an oscillating magnet, assuming its invariant mass. It has been shown that, this modification affects the level of harvested energy, increasing at low running speeds. The rest of this paper is organized as follows: the second section, "Materials and Methods", introduces the structural design of the three proposed energy harvesters. Subsequently, Section 3, "Results and Discussion", provides the results and discussion on the recovered energy for the three harvester concepts, tested on an shaker and mounted in a backpack. Finally, Section 4 presents conclusions drawn from the research described in this paper.

MATERIALS AND METHODS

Design of harvesters

In this paper, three variations of a magnetically coupled electromagnetic energy harvester are proposed and investigated (Figure 1). Each harvester consists of a colourless acrylic glass (PMMA) cylinder tube, an oscillating levitating magnet (or magnets), fixed ring magnets mounted to the tube's end, and a coil. The levitating magnets are placed inside the cylinder and are suspended by the repulsive force of two magnets on both sides. The coil is wrapped around the outer surface of the cylindrical tube. The levitating magnets consist of four identical neodymium magnets (N38) with a diameter of 20 mm and a height of 7.5 mm. In the first harvester variant, the four identical magnets were properly magnetically connected, forming one stack of magnets (Fig. 1a and Fig. 2b). In this way, the classical one-degree of freedom (1DOF) magnetic levitation harvester was obtained. The second variant involved using a levitating magnet composed of four magnets separated by a special lightweight plastic separator with a height of 7.5 mm and a diameter of 20 mm. The separator was positioned in the middle of the magnet stack, resulting in two magnets on either side (Fig. 1b and Fig. 2b). Subsequently, we obtained a modified harvester with one degree of freedom (1DOFS). The third variant involved two oscillating magnets, each composed of two identical magnets, resulting in a two degree-of-freedom (2DOF) magnetic levitation harvester (Fig. 1c and Fig. 2b).

Note that, in this case, to maintain the repelling effect of magnets, the orientations of the top fixed magnet and the top oscillating magnet were changed. In each harvester, the total mass of the oscillating magnets was identical. Only the spacing between the magnets in the oscillating magnet stack was changed, resulting in a variation in the magnetic field and electromechanical coupling. The parameters of the proposed harvester can be found in Table 1.

When the harvester experiences a certain acceleration, the levitating magnet moves relative to the coil, causing a change in the magnetic flux through the coil. According to Faraday's law, this movement generates an induced voltage in the coil. Adjusting the distance between the top and bottom fixed magnets alters the characteristics of the magnetic suspension. This enables easy tuning of the system to resonant frequencies. The numerical analysis of the harvesters presented in Figure 1 has been discussed in [26–28], demonstrating that modifying in the design of the oscillating magnet results in changes in both the electromechanical coupling as well as recovered energy.

Experimental methodology

Experimental tests were conducted in two variations. In the first stage, the harvester was

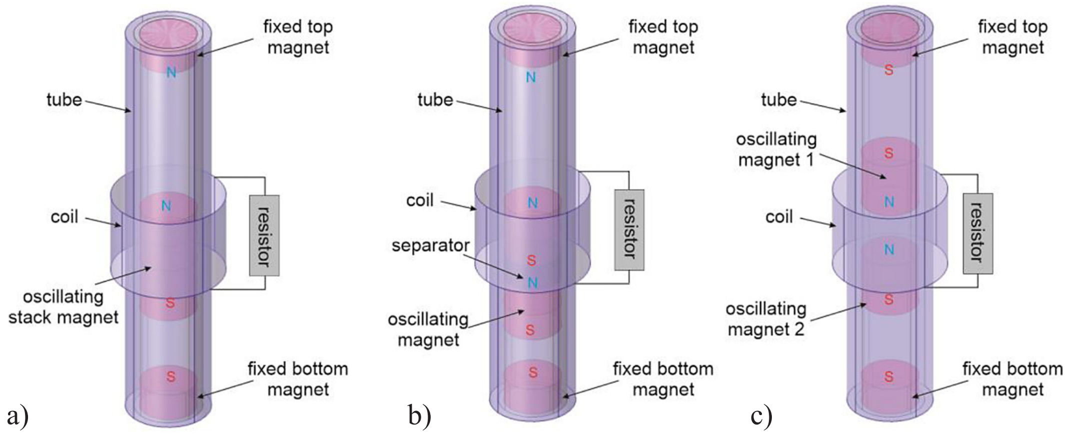

Figure 1. Three designs of electromagnetic harvesters: (a) 1DOF, (b) 1DOF with separator (1DOFS), and (c) 2DOF

Table 1. Parameters of the proposed harvesters

Component	Parameter	Quantity
Coil windings	Wire diameter	0.14 mm
	Number of turns	12740
	Coil resistance	1148 Ω
	Load resistance	1-4000 Ω
	Inductance	1.46 H
Levitating magnet	Grade	NdFeB, N38
	Magnet diameter	20 mm
	Magnet height	7.5 mm
Fixed magnet	Grade	NdFeB, N38
	Magnet diameter	20 mm
	Magnet height	7.5 mm
Separator	Grade	PMMA
	Separator diameter	20 mm
	Separator height	7.5 mm

mounted on a shaker and subjected to harmonic forcing. In the second stage, the harvesters were installed in a hiking backpack worn by a running person. The first experimental setup (see Fig. 2a) consisted of a harvester (1) mounted on a TIRA Vib shaker (2), connected to an amplifier (3) and controlled by LMS Scadias III (4). The harvester included two fixed magnets (8), various oscillating (levitating) stack of magnets (9), and a coil (10). A computer (6) with the Test.Lab14A software was used to control the shaker. Additionally, induced voltage was monitored by a harvester module (5) and a computer with software prepared in C+ (7). Both software applications were integrated, enabling simultaneous recording of signals. The harvester module (5) comprises a system conditioning and MicroDAQ control and measurement module with an OMAP L137 multicore application processor. This module allows for modifications in load resistance and enables the measurement of induced voltage. Additionally, a small prototype acceleration sensor (11) was mounted on the oscillating magnet. A photo of the harvester mounted on the shaker stand is shown in Figure 2

To verify and compare the effectiveness of various harvesters during real human motion, the harvester was placed vertically in a backpack, as shown in Fig. 3b. Figure 3a shows the photo of an exemplary prototype harvester (2DOF)

The installation of the harvester in the backpack provides an opportunity for energy generation. During walking or running a cyclic movement occurs, offering an ideal source of mechanical power input for an energy-harvesting backpack. The three variants of harvesters (Fig. 1) were mounted in a hiking backpack and tested during human running. The harvester was attached vertically to the backpack with straps that prevented the backpack from moving relative to the harvester. For this case, the measuring system only consisted of the harvester module. To enhance stability, the backpack was loaded with a weight of 1kg, while the weight of the energy recovery system was 0.45 kg. Tests were carried out on an electric treadmill, where a healthy male completed a 30-second run. A break was taken before each attempted run to minimize the effect of fatigue. The experimenter travelled with the backpack on the treadmill at constant speeds of 5 km/h, 7 km/h, 9 km/h, 11 km/h, and 13 km/h respectively. Additionally, the tests were conducted at various load resistances and treadmill gradients.

RESULTS AND DISSCUSION

Energy harvesting under harmonic excitation

A frequency sweep enables rapid observation of a response across the applied frequency range, encompassing the resonance frequency. In a sine sweep test, a vibration shaker moves or sweeps through a range of frequencies. The shaker's motion is sinusoidal, but the frequency of the vibration increases with a resolution of 0.01 Hz throughout the test with a constant amplitude acceleration of 0.8 g and a load resistance of 1 kΩ.

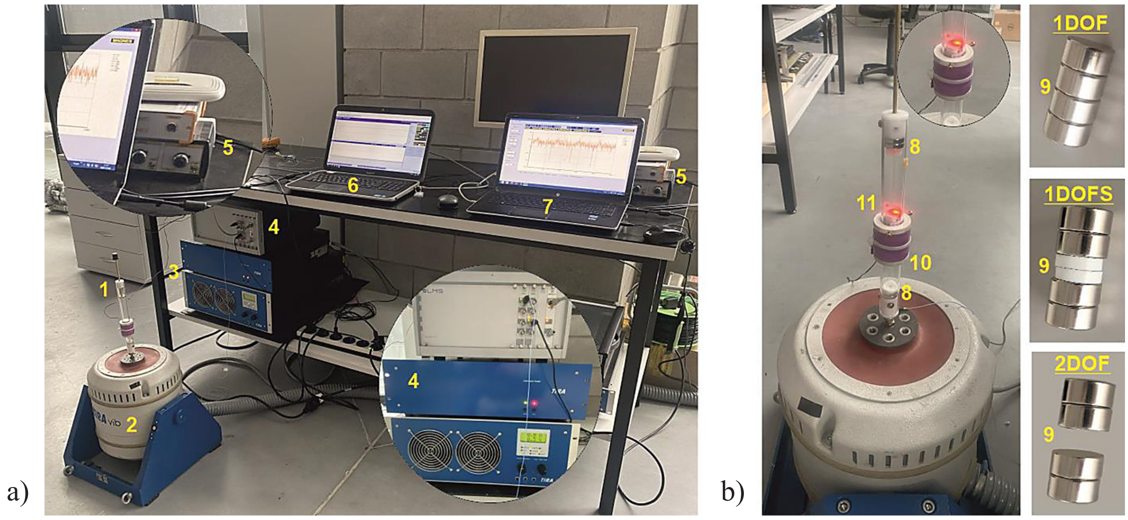

Figure 2. The experimental setup: (a) and electromagnetic harvester mounted in the electro-magnetic shaker with various oscillating magnets (b)

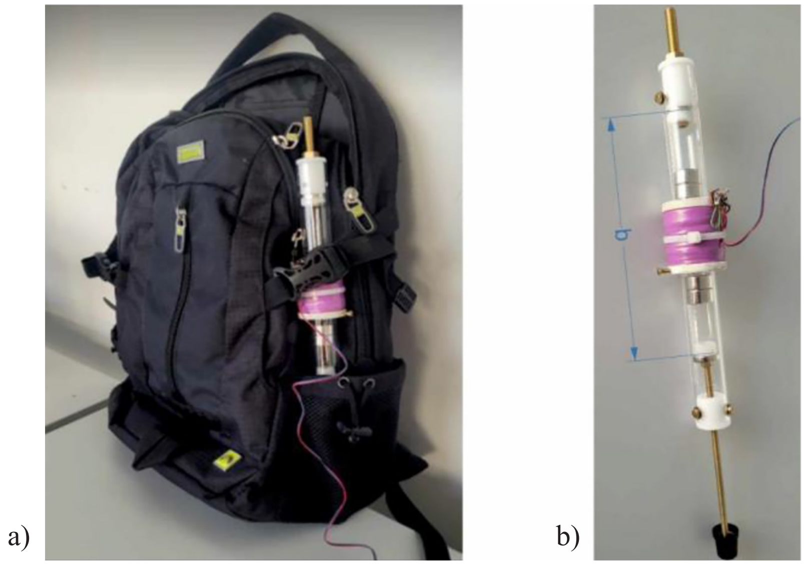

Figure 3. (a) Energy harvesting backpack and (b) 2 DOF electromagnetic harvester

Figure 4 shows the induced current during a frequency sweep test in the range of 4−11 Hz for different fixed magnet distances (parameter b in Fig. 2a). The blue line represents the results for b = 160 mm, the orange line for b = 150 mm, and the yellow line for b = 140 mm. An analysis of the graphs makes it possible can identify a resonance frequency. It is evident that manipulating the spacing between the magnets has a discernible impact on the resonance position. For the 1DOF harvester with a magnet distance of 160 mm, it is observed that the resonance occurs at a frequency of approximately 5 Hz (Fig. 4a). In contrast, for the 1DOFS harvester, the resonance is situated near 7 Hz (Fig. 4b). For the 2DOF system, the resonance is very weak but discernible above a

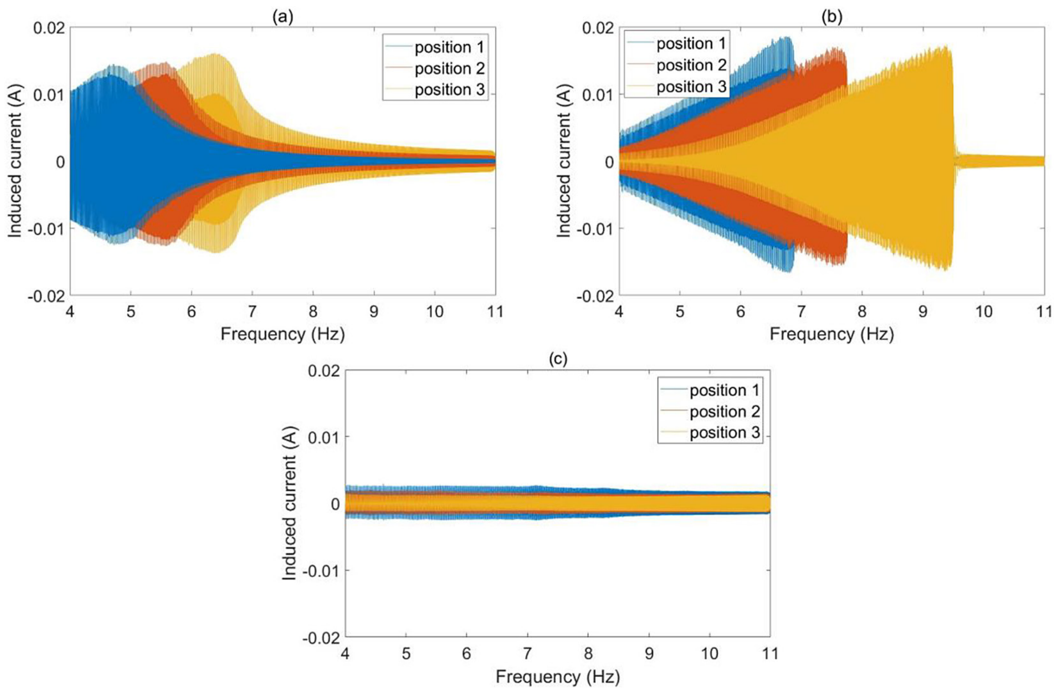

Figure 4. Frequency sweep responses obtained from three harvesters: 1DOF (a), 1DOFS (b), and 2DOF (c) for three different magnetic suspensions. The amplitude of the shaker's excitation was 0.8g. The blue line represents the separation between the fixed end magnets b = 160 mm, the orange line for b = 150 mm, and the yellow for b = 140 mm

frequency of 7 Hz (Fig. 4c). Reducing the distance between the permanent magnets induces a shift in the resonance towards higher frequencies.

For instance, with a magnet spacing of 140 mm (represented by the yellow line) in the 1DOF harvester, we shifted the resonance peak from 5 Hz to 6.5 Hz, and in the 1DOFS system from 7 Hz to 9.5 Hz. In contrast, within the 2DOF system, the resonance was shifted to a considerable distance. Interestingly, the induced current from the 1DOF harvester slightly increases as the distance between the fixed magnets is decreased, whereas for the 1DOFS harvester it decreases. However, in the 2DOF system, there is a noticeable slight decrease in the induced current as the frequencies increase.

Figures 5a–c shows the resonance curves of frequency versus recovered power. Considering all harvester concepts, it is clear that for all settings of the b parameter, the highest instantaneous power recovered of approximately 0.4 W was obtained for the 1DOFS system, while the lowest of about 0.04 W for the 2DOF system.

Furthermore, for the 1DOFS harvester, fluctuations in the power close to the resonance peak are observed. This is likely due to the rotation of the magnet within the tube. The fluctuations intensify for smaller magnet spacing (higher magnetic forces). It is worth noting that the differences in recovered power between the 1DOF and 1DOFS harvesters diminishes as the distance between magnets is decreased. This could imply that with a different magnet spacing, these proportions may be reversed. The power obtained for the 2DOF system under sinusoidal excitation is significantly lower compared to the other analyzed concepts. This can likely be attributed to the system's nonlinearity, increased stiffness, and modified in electromechanical coupling.

Energy harvesting from a backpack

The three harvester concepts were used to explore energy recovery from a backpack. In this scenario, the excitation is not purely sinusoidal but includes harmonic and random components. This is due to the motion of the person wearing the backpack and the movement of the backpack relative to the person's back. Firstly, the power output from the three harvesters was tested at various running velocities (Figs. 6a–c). Based on results for harmonic excitation, the distance between the fixed magnets was set at 160 mm. The velocity range was estimated to be between 5–13

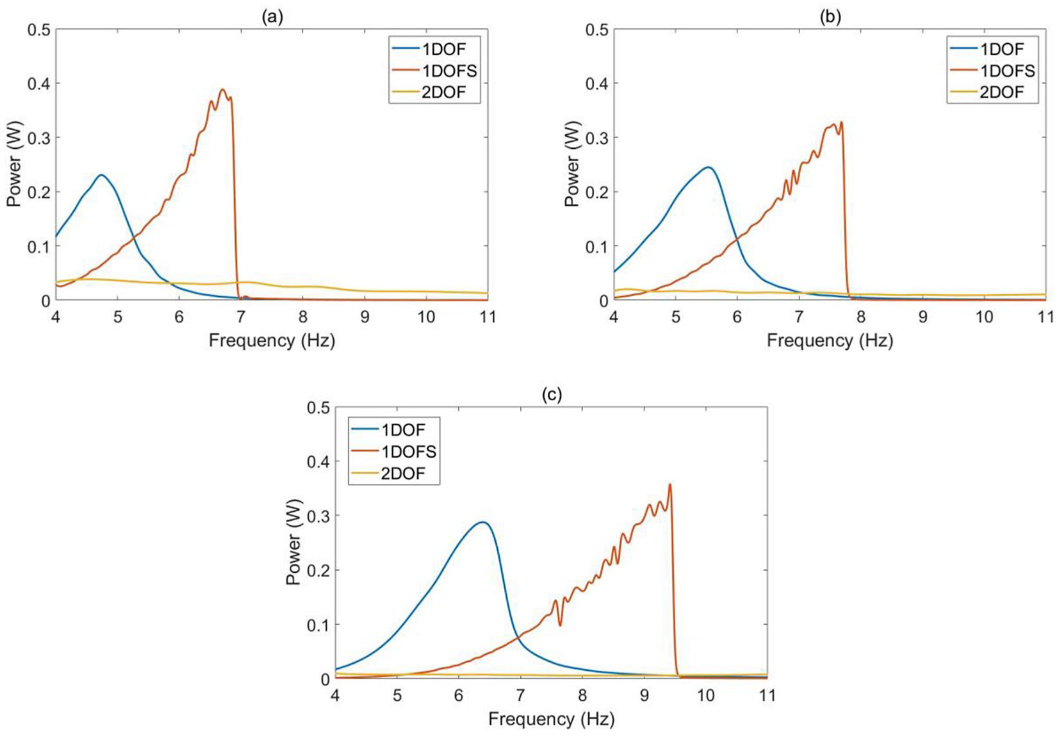

Figure 5. Recovered instantaneous power versus excitation frequency obtained from three harvester configurations: (a) b = 160 mm, (b) b = 150 mm and (c) b = 140 mm. The amplitude of the shaker's excitation was 0.8 g

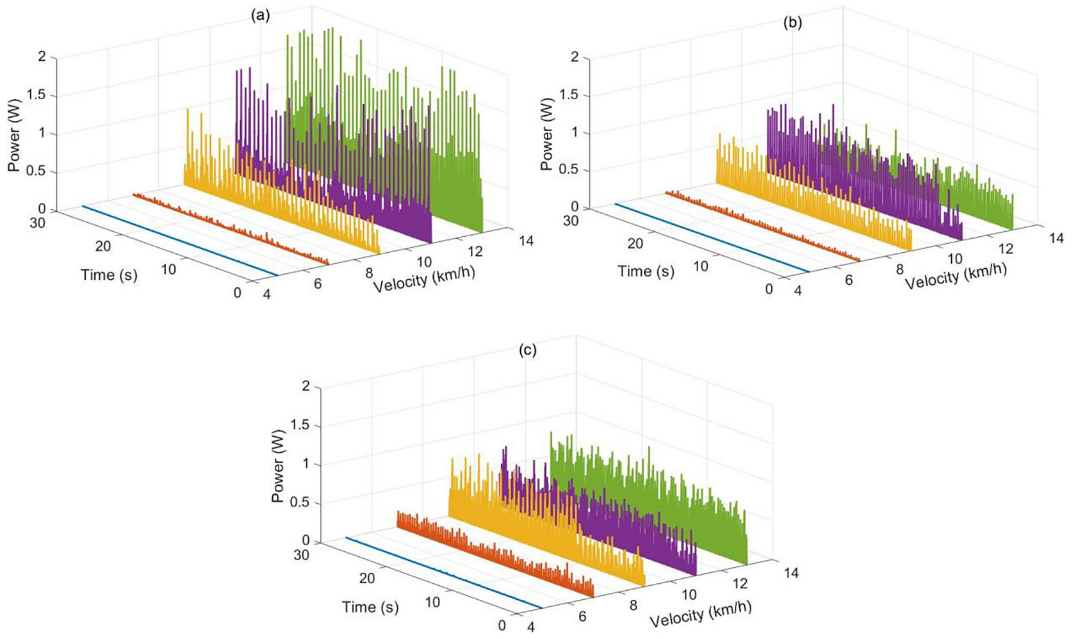

Figure 6. Instantaneous power obtained from three harvesters: (a) 1DOF, (b) 1DOFS and (c) 2DOF. The tests were conducted with a load resistance of 1 kΩ and in a horizontal treadmill setting

km/h, with each test lasting 30 seconds. The blue line represents the results for a velocity of 5 km/h, the red line for 7 km/h, the yellow line for 9 km/h, the purple line for 11 km/h, and the green line for 13 km/h. Figure 6a shows the power output obtained for the 1DOF harvester. As expected, the maximum instantaneous power, close to 2 W, was obtained for a moving speed of 13 km/h, while the lowest power was obtained for a speed of 5 km/h. However, for the 1DOFS harvester, the power is the highest at 11 km/h, with the maximal values reaching 1 W (Fig. 6b). For the 2DOF harvester, the situation varies slightly. The recovered power for three velocities (9 km/h, 11 km/h, and 13 km/h) is similar and amounts to about 0.8 W.

Interestingly, when comparing all three types of harvesters, it can be observed that at lower speeds (i.e., 5 km/h and 7 km/h), the 2DOF harvester performs the best, exhibiting the highest instantaneous energy recovery. These results are of practical significance, suggesting that the 2 DOF harvester appears more effective for typical human motion (like walking or jogging). Obviously, we observe significant fluctuations in instantaneous power values for all harvesters. Therefore, a more effective comparison seems to be the energy calculated as the root mean square (RMS) of the summation of instantaneous values, which is presented in the next section. Figs. 7a–c show the output current of all harvesters for a human velocity of 7 km/h. As shown in Figure 7a, when the moving speed was 7 km/h, the maximum current for the 1DOF harvester reached 7 mA. It can also be observed from Figure 7b that the maximum current is similar to that of the 1 DOFS harvester. However, the highest instantaneous current (at a speed of 7 km/h) was obtained from the 2DOF harvester (Fig. 7c), reaching a value of 0.012 A. The current signals from all harvesters are distinct, featuring multiple peaks. The signal from the classical harvester (1DOF, Fig. 7a) shows both high and low peaks spread out fairly reproducibly. For the case of the oscillating magnet with the separator (1DOFS, Fig. 7b), two low peaks side by side close to high peaks are noticeable, while the signal from the 2DOF harvester practically does not contain low peaks (2DOF, Fig. 7c). Comparisons of the output currents from the 1DOF harvester at moving speeds of 5 km/h and 13 km/h are given in Figs. 8a and b, respectively. At the moving speed of 5 km/h, the maximal current reached approximately 2 mA. Naturally, the current increased significantly with higher moving speeds. When the moving speed nearly tripled, the output current reached a value of about 30 mA.

Similar trends were observed for the other two harvester concepts: as the moving speed increased, the current output also increased (Fig. 9 for the 1DOFS harvester, Figure 10 for the 2DOF harvester). It should be noted that the current output is nonsymmetric for the 1DOF harvester,

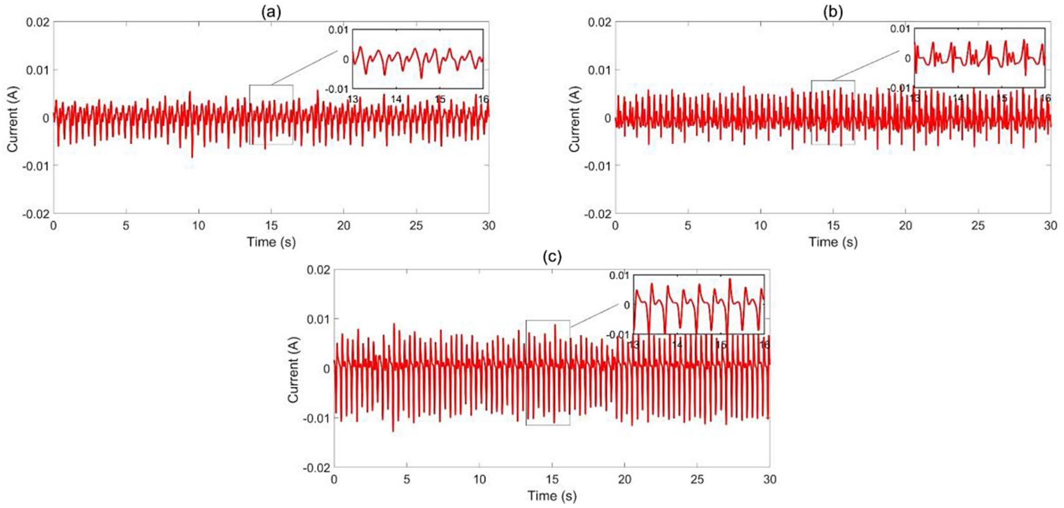

Figure 7. Instantaneous power obtained from three harvesters: (a) 1DOF, (b) 1DOFS and (c) 2DOF. The tests were conducted with a load resistance of 1 kΩ and in a horizontal treadmill setting

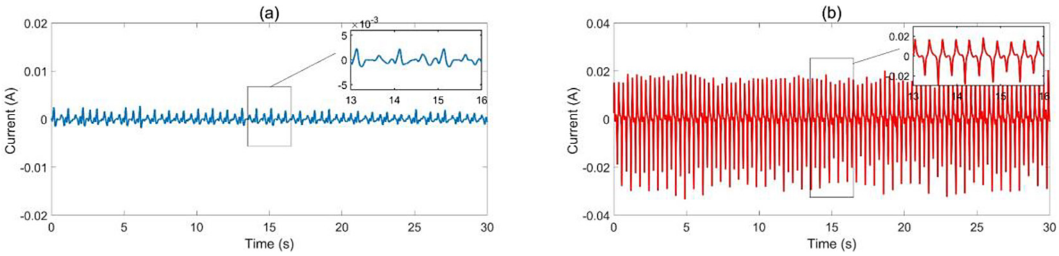

Figure 8. Current output from the 1DOF harvester for moving speeds: (a) 5 km/h and (b) 13 km/h

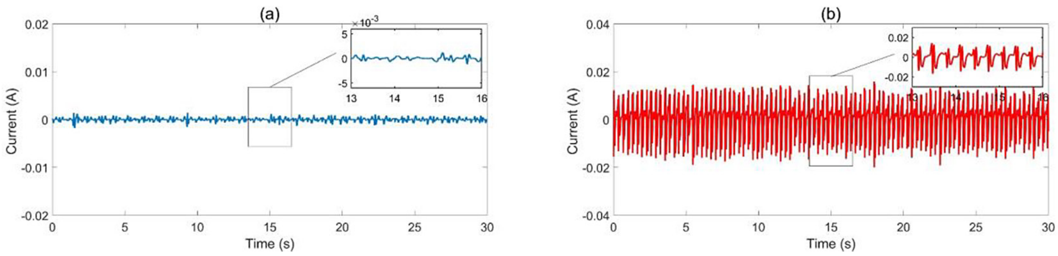

Figure 9. Current output from the 1DOFS harvester for moving speeds: (a) 5 km/h and (b) 13 km/h

while for the other two cases, the output current curves are close to symmetrical.

Parameter influence and RMS power

In this section, a comparison of the RMS power (Fig. 11a) and current (Fig. 11b) among the three harvesters is made for various moving speeds. The tests were conducted with a load resistance of 1 kΩ and in a horizontal treadmill setting. RMS values typically provide an indication of the actual capacity of unit. As anticipated, the effectiveness of all harvesters increases with higher moving speeds. The RMS power (and current) from the 1DOF harvester is represented by the blue line, from the 1DOFS harvester by the red line, and from the 2DOF harvester by the yellow line. The 1DOF harvester achieved a maximum RMS output power of 150 mW at 13 km/h. Interestingly, up to 9 km/h, the 2DOF harvester exhibits the highest energy recovery, while the 1 DOF and 1DOFS harvesters demonstrate in this range a similar level of recovered energy. At high velocities, the recovered energy from the 1DOFS and 2DOF harvesters may experience a slight drop. The next parameter under consideration

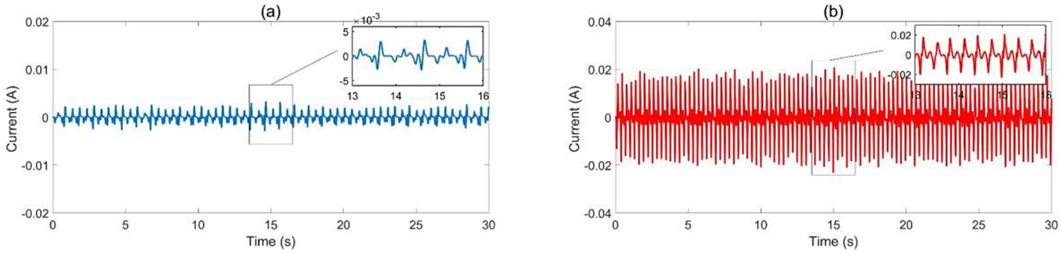

Figure 10. Current output from the 2DOF harvester for moving speeds: a) 5 km/h and b) 13 km/h

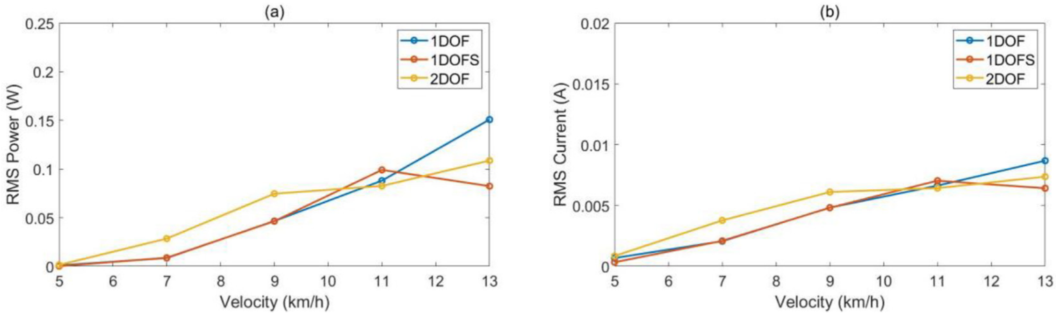

Figure 11. RMS: (a) power and (b) current from various energy harvester concepts at different moving speeds, for a load resistance of 1 kΩ and horizontal gradient of the treadmill

is load resistance. Traditionally, high load resistance corresponds to low electrical current consumption, whereas low load resistance results in high electrical current consumption. Typically, the most effective energy recovery occurs when the load resistance closely aligns with the coil resistance [29]. However, in a study by [30], the authors improved this relationship by incorporating the mechanical damping of the oscillating magnet. Figure 12 shows the influence of load resistance on harvested power at a moving speed of 9 km/h. Recovered power (Fig. 12a) and output current (Fig. 12b) for all harvesters depend on the load resistance. The highest recovered energy occurs near a load resistance of 1 kΩ. The 2DOF harvester achieves a power of approximately 100 mW, the 1DOFS harvester reaches 70 mW, and the 1DOF harvester shows 60 mW. Across the entire range of resistance, the 2DOF harvester exhibits the highest recovered energy.

Surprisingly, the recovered power from the 2 DOF harvester exhibited a similar level across all resistance ranges compared to the other two harvesters, where power slightly decreased with increasing resistance. The induced current and power from the 1DOF and 1DOFS harvesters are nearly identical for the resistance values greater than 1 kΩ.

Another parameter under analysis is electric treadmill incline. As the slope increased, a person's running experience becomes more fatiguing and impacts movement accuracy. Data in

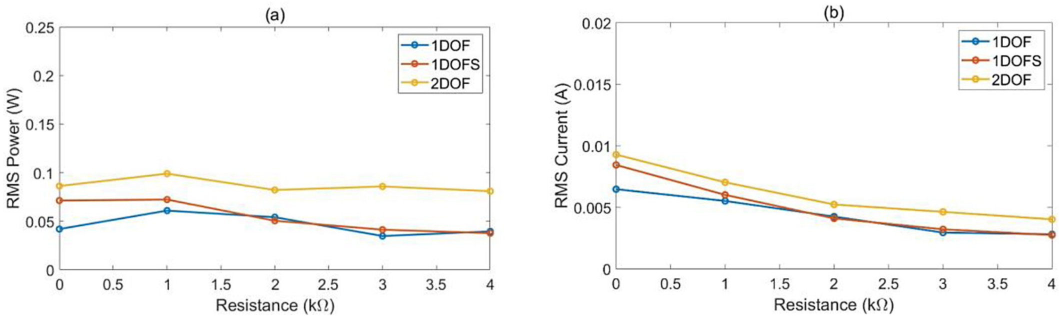

Figure 12. RMS: (a) power and (b) current from various energy harvesters concepts at different load resistances, for a moving speed of 9 km/h and horizontal gradient of the treadmill

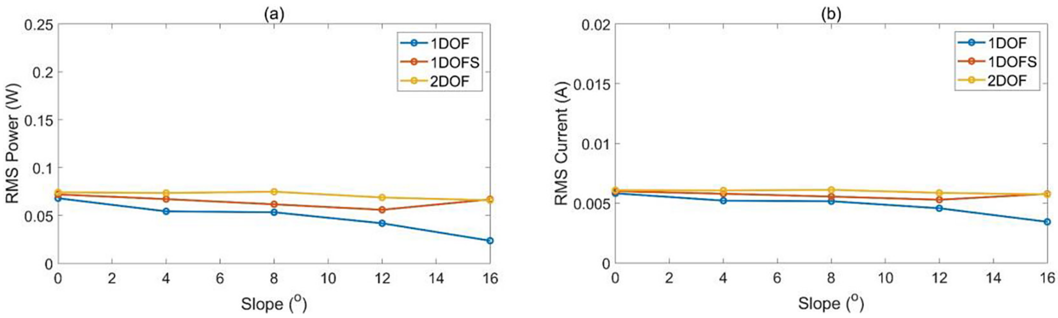

Figure 13. RMS: (a) power and (b) current from various energy harvesters at different treadmill slopes, for a moving speed of 9 km/h and a load resistance of 1 kΩ

Figure 13 indicates that as the treadmill slope increases, the effectiveness of energy recovery diminishes. This effect is particularly pronounced for the system with a single classical oscillating magnet (blue line in Fig. 13a).

For a vertical treadmill position, the harvested energy was approximately 60 mW, whereas for a slope of 16° the recovered energy decreased to about 25 mW. For the other two harvesters, this decrease was much smaller. A similar trend was observed in the current analysis (Fig. 13b). As evident from the analysis, the harvester with two levitating magnets seems most promising considering the treadmill slope.

CONCLUSIONS

In this paper, three variants of electromagnetic energy harvesters were proposed to convert human body kinetic energy into electric energy. The first concept relied on the oscillations of a classical levitating magnet within a coil. The second concept involved the use of a modified oscillating magnet, inside of which a separator was inserted. In contrast, the third concept utilized two levitating oscillating magnets. The modification of the magnets involved adjusting the magnet stack to ensure the same volume of magnets was used in each variant. The results showed, that the recovered power depended on the frequency, moving speed, resistance, treadmill slope, and the construction of the oscillating magnet. By properly designing the oscillating magnet, it was possible to increase energy harvesting, especially at low moving speeds.

In the first stage of the research, the harvesters were tested under harmonic forcing conditions to identify the resonance position. These tests revealed that the device with the oscillating magnet containing the separator recovered the highest instantaneous power, while the system with two levitating magnets exhibited the lowest power. The maximum recovered power amounted to 400 mW.

In the second stage of testing, the harvester was placed upright in a backpack. The backpack was tested with the assistance of an electric treadmill at speeds ranging from 5 to 13 km/h. The objective was to analyze both the instantaneous values and the root mean square of the recovered power. As anticipated, each harvester concept generated more power with an increase in running speed. The maximal RMS power of about 150 mW was obtained from the 1DOF harvester. However, the harvester with two levitating magnets performed better at the lower tested moving speeds (5–9 km/h). Moreover, it was less sensitive to changes in load resistance and treadmill slope. Therefore, this concept seems promising and will undergo a more comprehensive investigation in future studies.

Acknowledgements

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