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Investigation of a Magnetic Levitation Architecture with a Ferrite Core for Energy Harvesting

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Abstract: This work presents the development of a magnetic levitation system with a ferrite core, designed for electromagnetic energy harvesting from mechanical vibrations. The system consists of a fixed enamel-coated copper coil and five neodymium-iron-boron permanent magnets housed within a PVC spool. To enhance magnetic flux concentration, a manganese-zinc ferrite (Mn-Zn) ring was employed within the spool. Experimental tests were conducted at frequencies up to 20 Hz, demonstrating the device's potential for harvesting energy from small vibrations, such as those generated by human biomechanical movements, achieving operating voltages up to 3 V. Additionally, the architecture is scalable for larger systems and allows for the integration of multiple transducers without magnetic field interference, independent of the frequency or excitation phase of each transducer.

Keywords: energy harvesting; vibration; kinetic energy; electromagnetic; magnetic levitation

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1. Introduction

Energy harvesting involves collecting energy from available sources in the environment, such as vibrations, heat, and electromagnetic waves, and converting these energies into electrical energy for powering systems and possibly storing it for later use [1–3]. In the context of kinetic energy harvesting, the foundation lies in converting mechanical vibrations from the environment into electrical energy through a transducer mechanism. This mechanism converts energy from the pressure or relative displacement within the system, with both velocity and position being coupled to the transducer [4]. Regarding pressure, the transducer is coupled to the deformation within the mechanical system using active materials, typically employing piezoelectric ceramics and piezoelectrets [5,6]. Various transduction mechanisms exist for electrical energy generators based on vibrations, such as piezoelectric (PE), electromagnetic (EM), and electrostatic (ES) transducers. Additionally, there are magnetostrictive and flexoelectric mechanisms, as well as hybrid systems formed by combining different mechanisms [7,8].

Electrostatic and piezoelectric transducers are well-suited for integration with micro-electro-mechanical systems (MEMS), making them ideal for energy generation in micro and nanoscale applications. On the other hand, electromagnetic and magnetostrictive transducers are more appropriate for larger-scale systems [9–11]. Human motion, particularly gait, is another compelling energy source, where electromagnetic transducers stand out due to their ease of implementation and ability to generate high levels of current. Additionally, as noted in [12], piezoelectric and electromagnetic transducers are among the most efficient for energy harvesting, based on their energy density—i.e., the amount of energy that can be stored in a system. Given that electromagnetic systems offer both straightforward implementation and energy densities comparable to piezoelectric transducers (around 30 mJ/cm^3), this paper presents an electromechanical device designed for harvesting energy from human motion, based on magnetic levitation principle.

An electromagnetic transducer is based on Faraday's law of electromagnetic induction and the architecture presented here uses magnetic levitation for harnessing biomechanical vibrations, such as those generated during human walking. In order for the EM transducer to be effective a Ferrite coil was added to the structure to enhance magnetic flux concentration and provide the necessary amount of energy for powering devices; that is, operating voltages between 2 and 3 V.

Additionally, the proposed architecture allows for the integration and close proximity of transducers without the magnetic fields interfering with the operation of neighbouring transducers. This design facilitates integration of multiple transducers, thus improving harvesting. Therefore, an electric circuit was implemented to compose the transducers, enabling the association of multiple units independently of the association process, frequency, or excitation phase of each individual coil.

Nevertheless, for a proper presentation of this electromechanical device the paper is presented as follows: Section 2 provides relevant background and Section 3 presents the literature review and analysis. Section 4 describes the developed magnetic levitation system and its experimental setup, whereas Section 5 presents the corresponding results and discussion. Finally, Section 6 presents the conclusions.

2. Background

2.1. Principles

The conversion of kinetic energy from environmental vibrations into the electrical form in electromagnetic energy harvesting devices is based on the Faraday law, typically through the relative motion of a permanent magnet and a conductive coil. Equation (1) shows the Faraday law, where V is the produced electromotive force, N is the coil number of turns and φ is the magnetic flux over a single coil [13,14].

$$V = -N\frac{d\varphi}{dt} \tag{1}$$

Figure 1 presents a scheme of a simple linear EM harvester composed of a permanent magnet attached to a spring of elastic constant k, moving relatively to a coil of length L with a magnetic field of intensity B connected to a circuit of impedance Z.

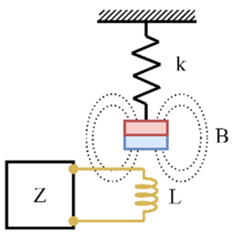


Figure 1. General linear electromagnetic energy harvester scheme.

Energy harvesting from electromagnetic devices is also classified based on the vibration source characteristics to which they best respond as resonant (Figure 1), non-resonant, and hybrid.

Resonant devices are suitable mostly for energy sources vibrating at a particular frequency, matching by design their resonance frequency with the source, while non-resonant harvesters usually require rotational motion, e.g., a permanent magnet rotor, operating in the same way as large-scale magnetic generators. Hybrid devices are designed to operate with irregular motion or a broader range of vibration [13].

The example of resonant EM energy harvester architecture shown in Figure 1 can be modeled as a linear spring-mass-damper system, as seen in Figure 2. The dynamic behavior, *z(t)*, under an external harmonic excitation, *y(t)*, can be described by Equation (2), where m is the inertial mass, k is the spring stiffness and c_T is the damp coefficient of the system composed by the parasitic mechanical loss (c_m) and the extracted electrical energy by the transducer (c_e) [15].

$$m\ddot{z}(t) + c_T\dot{z}(t) + kz(t) = -m\ddot{y}(t) \tag{2}$$

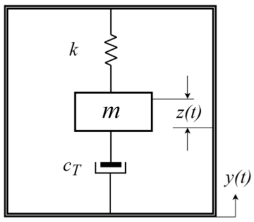


Figure 2. Linear electromagnetic energy harvester model.

The transfer function is given by Equation (3), where $\omega_n = \sqrt{\frac{k}{m}}$ is the natural frequency of the system and $\frac{c_T}{m} = 2\zeta_T\omega_n$.

$$\frac{Z(s)}{Y(s)} = \frac{-s^2}{s^2 + 2\zeta_T\omega_n s + \omega_n^2} \tag{3}$$

The solution of Equation (2) for the permanent regime of the system is given by Equation (4):

$$z(t) = \frac{-\omega^2}{\sqrt{\left(\frac{k}{m} - \omega^2\right)^2 + \left(\frac{c_T\omega}{m}\right)^2}} Ysen(\omega t - \delta), \tag{4}$$

where δ is the phase angle given by Equation (5).

$$\delta = tg^{-1}\left(\frac{c_T\omega}{k - \omega^2 m}\right) \tag{5}$$

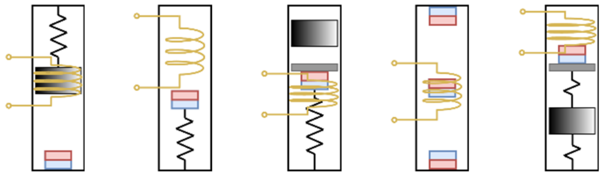
As the instantaneous electrical power (P_i) is given by $P_i = c_e\dot{z}(t)^2$, the electrical power generated by the harvester (P), given by Equation (6), is obtained from Equation (4) as a function of c_e.

$$P = \frac{m\zeta_e Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta_T\left(\frac{\omega}{\omega_n}\right)\right]^2} \tag{6}$$

Linear resonant systems may assume different configurations; therefore, more details are presented regarding these structures.

2.2. Resonant Linear Architectures

There are a few different types of resonant linear structures for electromagnetic energy harvesting, and they are mainly represented in Figure 3 [14].



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 3. Linear EM energy harvesting architectures: (**a**) spring-mass with moving coil; (**b**) spring-mass with moving magnet; (**c**) free impact mass frequency-up converter; (**d**) magnetic levitation; and (**e**) double spring-mass with moving magnet.

The model represented in Figure 3a was made by Amirtharajah et al. [16], with a mechanical spring attached to a mass fixed to a moving coil in addition to a permanent magnet fixed at the bottom of the harvester container. The design shown in Figure 3b was presented by Von Büren and Tröster [17], who used three magnets separated by a spacer translating inside a cylindrical container with multiple coils placed around it.

Resonant linear energy harvesters like these have their best performance at their resonance frequency. For these kinds of harvesters, the efficiency outside their resonance frequency drastically decreases. This implies that they usually operate at a particular high and narrow frequency band, limiting their capability to function with different vibration sources [18]. Since ambient vibration energy is usually found over a low-frequency spectrum, which presents challenges regarding the dimension optimization of the harvester, instead of seeking to design frequency-matching structures with low resonant frequencies, another idea is to use a frequency up-conversion mechanism as shown in Figure 3c.

This type of mechanism converts low-frequency vibrations into a higher bandwidth vibration to maximize the harvester's conversion efficiency [18]. First studied by Umeda et al. [19,20] based on a low-frequency mechanical impact PE-based energy harvester, it was further explored by Halim et al. [21] and implemented using a set of fixed spring-magnet-coil systems on both ends of the harvester's container.

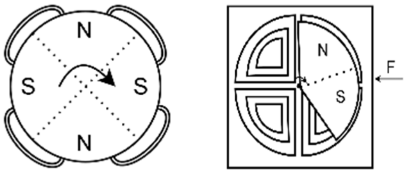
For magnetic levitation, as represented in Figure 3d, the basic architecture consists of a hollow cylindrical container with three permanent magnets and a coil. Two of the magnets are fixed while the third is held in suspension by the interaction of the opposite magnetic fields of the arrangement. They were classified by Carneiro et al. [22] into four categories based on the number of permanent magnets in levitation and the number of coils: (1) single coil, single levitating magnet; (2) single coil, multiple levitating magnets; (3) multiple coils, single levitating magnet; and (4) multiple coils, multiple levitating magnets.

In total, the authors identified twenty-nine different models developed to describe the most relevant physical phenomena occurring in twenty-one proposed designs [22]. Regarding the design optimization of magnetic levitation architectures, besides the highly non-linear behavior, the challenges are to address the broadband, unknown, and time-varying behavior of the vibration source. This implies a degree of architectural adaptability, as well as the need to consider dimensional constraints for practical usability.

The double spring-mass architecture shown in Figure 3e is based on the resonance coupling of the springs to enhance the harvester's output. Wu et al. [23] successfully demonstrated this type of architecture using a triboelectric transduction mechanism, it being selected by Siang et al. [14] as a valid magnet-coil equivalent.

2.3. Non-Resonant Architectures and Hybrid Architectures

Non-resonant energy harvesters, known as rotational generators, are based on the same principle utilized in fluid-powered turbines and heat engines [13]. They consist of a permanent magnet rotor and coils, and their operation mechanism relies on a steady source of rotational mechanical movement. Examples of non-resonant energy harvesters are represented in Figure 4.



(**a**) (**b**)

Figure 4. Non-resonant EM energy harvesters: (**a**) rotational, steady torque conversion (**b**) hybrid, converts linear to rotational movement.

In the pursuit of optimizing the performance of resonant energy harvesters under unknown and time-varying mechanical power source excitations, Carneiro et al. [24] investigated the concept of self-adaptiveness in electromagnetic energy harvesting systems. They employed a magnetic levitation architecture that autonomously adjusted its configuration in response to variations in the excitation patterns of the external source. This adaptiveness was achieved through a control strategy that dynamically modulates the distance between fixed, non-levitating magnets, leveraging prior identification of the optimal harvester length corresponding to various excitation conditions and load resistances. This approach allowed the system to maintain optimal performance by continuously aligning the harvester's dynamic properties with the changing characteristics of the input excitation.

3. Proposed EM Structure

3.1. Proposed Resonant Linear Architecture

Based on EM levitation architectures, depicted in Figure 3d in this work, a linear structure is proposed. The EM device consisted of a fixed coil, four mobile magnets, and a stationary magnet housed within a PVC spool as represented in the schematic in Figure 5. In this design, in order to enhance the concentration of magnetic flux within the spool, an externally inserted manganese-zinc (Mn-Zn) ferrite core was employed.

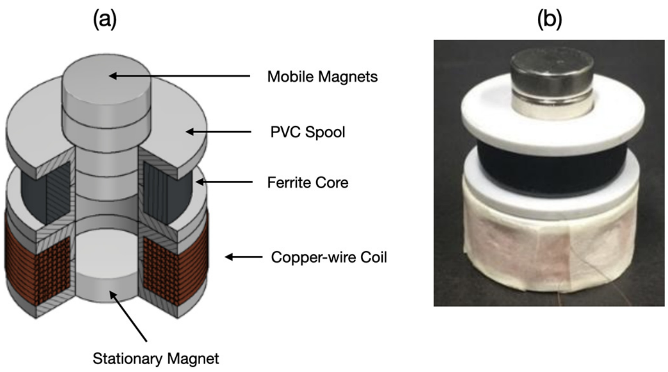


Figure 5. (**a**) Schematic of the developed energy harvester: coil with an air core, ferrite, four levitating magnets, and one fixed magnet; (**b**) final assembly.

The incorporation of a ferrite core into the system enhances the concentration of magnetic flux within the material, which imparts several key dynamic properties to the architecture. For instance, it minimizes the external magnetic field outside the harvester's enclosure, allowing multiple harvester units to be placed in close proximity without the magnets from one unit affecting the performance of adjacent units.

Another feature is that by interacting with the magnetic field of the magnets and the magnetic attraction force between the magnets and the ferrite ring, it helps stabilize the magnet arrangement. Besides, the ferrite core also serves as a restorative element, eliminating the need for a mechanical spring while allowing controlled, well-defined relative motion between the permanent magnets and the coil.

3.2. EM Transducer Characteristics

The intended application of the EM transducer, i.e., human motion energy harvesting, was intentionally designed to present a compact layout. The most relevant construction characteristics are presented as follows:

- PVC spool: an outer diameter of 27 mm, an internal diameter of 12 mm, and a height of 12.4 mm;
- Coil: 1500 turns of enamel-coated copper wire with a diameter of 35 AWG (0.1426 mm) and a height of 8.40 mm (representing 33.87% of the container);
- Cylindrical permanent magnets of neodymium-iron-boron ($Nd_2Fe_{14}B$), with a mass of 3.35 g, a diameter of 12 mm, and a height of 4 mm;
- Ferrite ring: an internal diameter of 14 mm, an external diameter of 23 mm, and a height of 8.4 mm

The final dimensions of the transducer were the following:

- Height of 32.8 mm;
- Internal radius of 6 mm;
- Effective stroke of 8 mm;
- Volume of 15.10 cm^3.

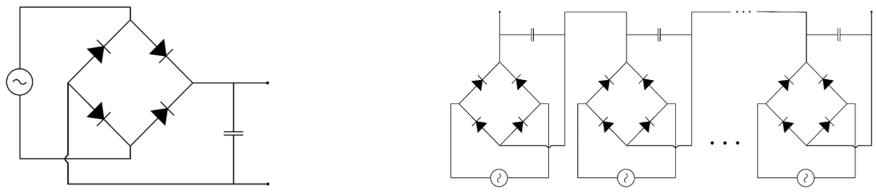
The dimensions and characteristics of the designed energy harvester were compared with other levitation-based models from the literature, as shown in Table 1. However, it is important to note that these models were developed for different purposes, making direct comparisons less meaningful.

Table 1. Dimensions and characteristics of the developed energy harvester and other levitation-based energy harvesters available in the literature.

Characteristics	Developed Energy Harvester	Other Models in the Literature [22]
Container material	PVC	PTFE and others
Container height	24.8 mm	20 to 254 mm
Total height	32.8 mm	20 to 254 mm
Internal radius of the container	6.0 mm	2.2 to 28.6 mm
Total magnet stroke	12.8 mm	13 to 184 mm
Effective magnet stroke	8 mm	13 to 184 mm
Total volume	15.1 cm^3	0.5 to 235 cm^3
Rectangular coil height	8.4 mm	4 to 1000 mm
Coil height to container height ratio	33.87%	10 to 50%
Distance between coil inner radius and magnet stack radius	2.00 mm	0.5 to 9 mm
Number of coil turns	1500 turns	240 to 15,000
Copper coil wire diameter	35 AWG (142.6 µm)	40 to 635 µm
Inertial mass	13.7 g	1.2 g to 1.54 kg
Used permanent magnet	Neodymium	Neodymium
Magnet grade	N35	Up to N45
Total number of magnets	5	Up to 10
Number of levitating magnets	4	Up to 6
Other materials	Mn-Zn Ferrite	---

3.3. Bridge Rectifier Circuit

To facilitate energy storage and the use of oscillating electrical signals, rectification is necessary. In this setup, a simple bridge rectifier circuit was employed, as shown in Figure 6a, using low-threshold voltage 1N60 germanium diodes (Vth = 0.3 V) to minimize voltage drop. A 22 µF capacitor was connected at the output to store the harvested energy.



(**a**) (**b**)

Figure 6. (**a**) Schematic of the full-wave rectifier circuit; (**b**) in-series association of full-wave rectifier circuits.

To enable the integration of multiple devices, regardless of the number of transducers, their phase, or the excitation frequency of each energy harvester, a multi-bridge rectification circuit was proposed and implemented individually for each transducer, as shown in Figure 6b. This approach allows the rectified output from any number of generators to be combined, independent of the characteristics of each excitation source. The rectification circuits were connected in series, as this configuration produced superior performance.

4. Mechanical Vibrational Stimulation

To conduct a frequency domain analysis of the EM transducer, a mechanical stimulation device was constructed. It consists of an aluminium cylindrical piston (200 mm in length and 10 mm in diameter) connected to a DC motor with a wound armature via an acrylic crank-slider mechanism. This setup is capable of generating a piston displacement of 30 mm, as shown in Figure 7.

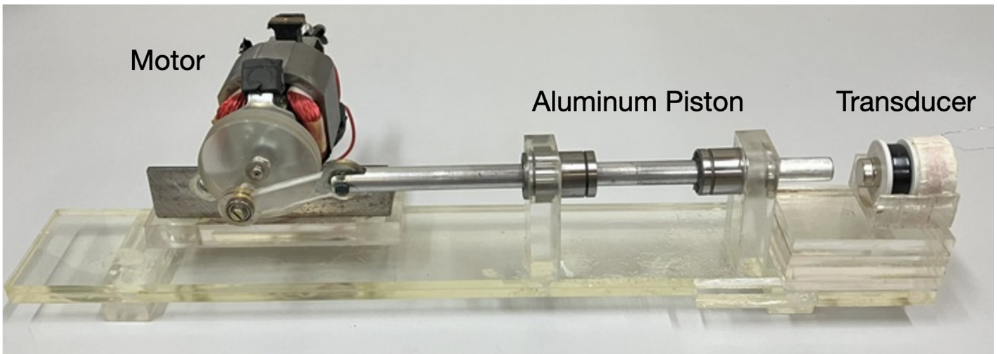


Figure 7. System built for the mechanical stimulation of the transducers.

5. Results and Discussion

By using the mechanical stimulation system to drive the aluminium piston at various frequencies, the EM transducer was analyzed in terms of the rectified signal output and the performance of transducer associations.

5.1. Output Voltage and Power of the Designed Energy Harvester

Figure 8 shows the waveform of a typical signal generated by the constructed energy harvester when harmonically excited at a constant frequency of 10 Hz. Figure 8 also shows a selected segment of the signal generated by the energy harvester to allow a better visualization of the main transients in response to the excitation. As was expected, the patterns of these segments repeat with the same frequency of the excitation. It is possible to observe backward whiplash when the wave falls toward the minimum value. This backward whiplash has a duration of 2 ms and features an inverted valley with an amplitude of approximately 2.09 V, measured relative to the negative peak.

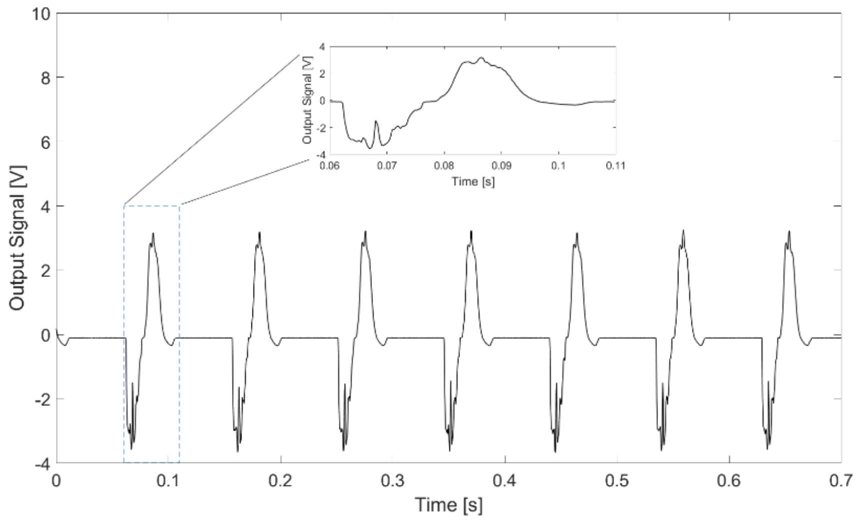


Figure 8. Signal generated by the energy harvester when excited with a harmonic signal of 10 Hz frequency, with a selected segment of the signal.

Table 2 presents, for an excitation signal with a frequency (*f*) varying from 5 to 20 Hz, the peak-to-peak voltage of the transducer's output signal (V_{pp}), the root mean square voltage of the output signal (V_{rms}), and the root mean square power of the output signal (P_{rms}) of the developed energy harvester. All measurements were conducted with a load of 10 MΩ.

Table 2. Measured peak-to-peak voltage (V_{pp}), root mean square voltage (V_{rms}), and root mean square power (P_{rms}) of the output signal for various operating frequencies.

f [Hz]	V_{pp} [V]	V_{rms} [V]	P_{rms} [μW]
5	3.5	0.595	0.035
10	7.0	1.227	0.151
15	10.4	1.926	0.371
20	12.0	2.491	0.621

The peak-to-peak voltage (V_{pp}) generated by a transducer varied from 3.5 V to 12 V, being capable of producing average voltages (V_{rms}) between 0.95 V and 2.49 V. Given the large load of 10 MΩ used at the system's output, relatively low average power values were obtained. However, smaller loads would allow the system to deliver higher power levels.

5.2. Voltage Across the Output Capacitor of the Rectifier Circuit

For an excitation signal with a frequency (*f*) varying from 5 to 20 Hz applied to a transducer connected to the rectification circuit depicted in Figure 6a, the measured voltages across the output capacitor of the circuit (V_{cap}) can be seen in Figure 9.

DC voltage levels between 1.05 V and 3.92 V were obtained across the capacitor, achieving the desired values using only a single transducer, with the possibility of combining multiple transducers for better results. Due to its reactance, which decreases as the signal frequency increases, the capacitor filters high-frequency components from a certain point onwards. As the frequency increases, more energy is concentrated in these components, causing the capacitor to filter more energy from the signal. In this case, the obtained signal tends to reach a maximum level and then decreases with increasing frequency.

The series connection of full-wave rectification circuits, as depicted in Figure 6b, allows for the combination of voltages from different transducers. This expands the potential for utilizing kinetic energy present in the environment, regardless of the frequency and phase of operation. This approach proved effective when two similar transducers were connected in series. The output voltage across the two capacitors (V_{cap}) was measured for various input signal frequencies and phases. The capacitors had a value of 22 μF, and the results are summarized in Table 3. Notice that, the output voltage is 8.5 V at 4 Hz, which is more than double the output voltage obtained with a single transducer at 5 Hz.

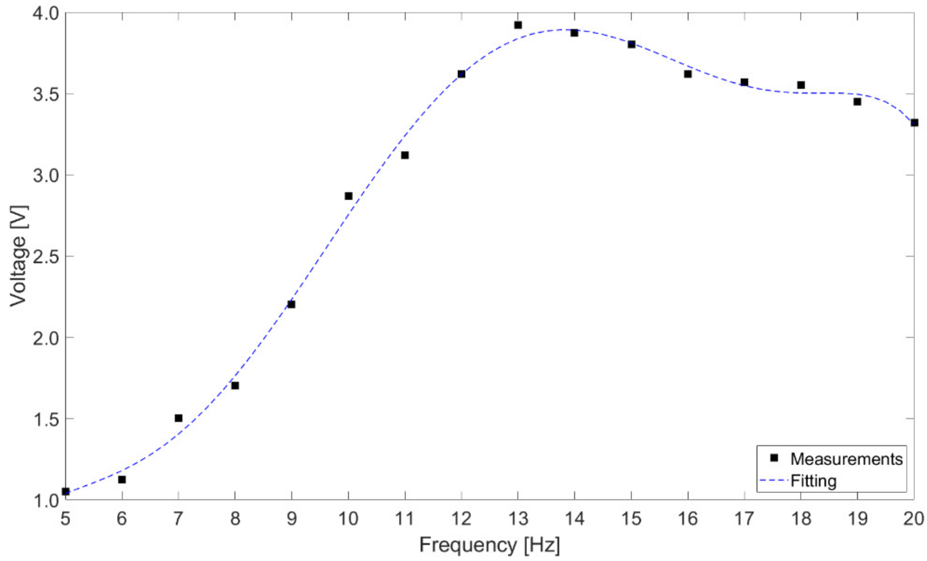


Figure 9. Voltage measurements at the output capacitor of the rectifier circuit connected to the energy harvester for input signals with frequencies from 5 to 20 Hz.

Table 3. Voltage measurements at the output of the series connection of two rectification circuits, each connected to an energy harvester excited by signals of the same frequency and a phase difference of 90°.

f [Hz]	V_{cap} [V]
1	6.42
2	6.9
3	7.6
4	8.5

6. Conclusions

After studying several devices that use linear architectures to harvest energy, it was observed that most of them rely on coil-spring models. Some exceptions relate to a permanent magnet moving relative to a coil. Based on this last model and levitation architecture, a transducer with a fixed coil and mobile magnets that are supported by fixed magnets was presented here. The advantage of the proposed device is that, by using a ferrite core, it was not only possible to eliminate the need for a spring, thus enhancing the system's mechanical lifespan by avoiding fatigue and wear, but it also reduced external influences which promote the usage of multiple transducers simultaneously independent of their frequencies and phases, which normally can cause mutual cancellation.

It has been shown here that the proposed transducer can be constructed at relatively low cost, with durability, compactness for human motion energy harvesting, and sufficient power density to power other systems. Furthermore, it was demonstrated that such transducers are frequency-dependent, with power generation increasing as the frequency increases. Finally, it has also been shown that connecting two transducers results in a generated voltage almost 8× larger at frequencies around 4 and 5 Hz. Ongoing studies are now focussing on the determination of the internal resistance of the system, in order to ascertain the maximum power that can be transferred.

Author Contributions: Conceptualisation: I.N.S., R.A.C.A. and R.A.P.A.; methodology: I.N.S., R.A.C.A., R.A.P.A., M.d.M.A.C.M., F.S.I.d.S., J.A.A., J.P.C. and R.d.A.F., validation: I.N.S., R.A.C.A., R.A.P.A., J.A.A., J.P.C. and R.d.A.F.; investigation and simulation: I.N.S., R.A.C.A., R.A.P.A., M.d.M.A.C.M., F.S.I.d.S., J.P.C. and R.d.A.F.; writing—original draft preparation: I.N.S., R.A.C.A., R.A.P.A., J.P.C. and R.d.A.F.; writing—review and editing: J.A.A., I.N.S., R.A.C.A., R.A.P.A., J.P.C. and R.d.A.F., project administration: I.N.S., R.A.C.A., R.A.P.A., J.P.C. and R.d.A.F., funding acquisition: I.N.S., R.A.C.A., R.A.P.A. and J.A.A. All authors have read and agreed to the published version of the manuscript.

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