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Fast Fourier Transform-Based Performance Analysis of a Hybrid Piezoelectric-Electromagnetic Energy Harvester

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Abstract

Energy harvesters that combine multiple conversion mechanisms, such as piezoelectric and electromagnetic, offer an improved solution for powering small, portable devices. These hybrid systems exploit the complementary strengths of each method, where piezoelectric materials excel at generating high voltages in response to mechanical stress. At the same time, EM harvesters are more effective at low frequencies, addressing the limitations of piezoelectric devices. However, despite overcoming these individual shortcomings, hybrid harvesters still face the challenge of generating sufficient power output under low-frequency, random excitations commonly found in real-world environments. This study addresses this limitation by integrating Fast Fourier Transform (FFT) analysis to identify dominant frequencies and optimise system performance. Additionally, signal rectification methods, including the use of a voltage doubler circuit, were explored to enhance the energy conversion efficiency. Experimental results show that under random excitation frequencies ranging from 1 Hz to 4 Hz, the hybrid harvester consistently generated stable peak voltages, with the voltage doubler achieving a significant improvement, producing 3.8 V compared to the 1.5 V generated by the full bridge circuit. This work demonstrates that hybrid energy harvesting systems can provide efficient power generation under unpredictable, low-frequency conditions when coupled with optimized signal processing techniques. The findings contribute to the advancement of energy harvesting technologies, offering a sustainable and maintenance-free power source for low-power electronics in dynamic and mobile environments.

1. Introduction

Modern electronic systems are increasingly deployed in applications that demand long-term operation with minimal human intervention. From implanted biomedical devices and smart textiles to wireless sensor networks embedded in structures or environmental settings, these systems are expected to function autonomously, often in locations where maintenance is difficult or impractical. Their integration into the Internet of Things (IoT) ecosystem has pushed the limits of conventional power solutions, particularly chemical batteries, which are hindered by finite lifespans, environmental toxicity, and physical bulk [1]–[3]. Although batteries have long provided a convenient energy source, their limitations are increasingly constraining system reliability, miniaturization, and sustainability. To address these limitations, research in recent years has shifted toward energy-autonomous systems that can scavenge energy directly from their surroundings [4].

This transition is not merely driven by technological convenience but is becoming a necessity in fields such as wearable health monitoring, innovative infrastructure, and distributed sensing, where system accessibility and longevity are essential [5]. Among the available ambient sources, which are light, heat, electromagnetic waves, and vibrations, mechanical vibrations stand out as particularly compelling due to their wide availability and persistence in diverse environments [6]. These vibrations, from human motion, engine operation, and structural oscillations, offer a viable basis for powering low-energy electronics under various operating conditions [7]. Harnessing mechanical vibration for energy generation introduces a range of engineering possibilities and challenges. Rather than focusing immediately on specific mechanisms, it is vital to understand the fundamental requirements of vibration energy harvesting. Devices must be compact, sensitive to varying excitation conditions, and capable of efficient conversion over a wide range of frequencies. However, real-world vibrations are rarely periodic or consistent. These vibrations are irregular, multi-directional, and often unpredictable in both amplitude and orientation, particularly in dynamic contexts such as wearable devices [8], [9].

Within this context, hybrid energy harvesters have emerged as a promising solution. Unlike single-mode harvesters, which are constrained by narrow operational bandwidth or unidirectional sensitivity, hybrid systems integrate multiple conversion mechanisms into a unified structure [10]. This design enables the system to respond to a wider variety of inputs and harness multiple aspects of mechanical energy simultaneously. For instance, a combination of piezoelectric and electromagnetic mechanisms can leverage both voltage and current benefits across different frequencies [11], while piezoelectric and triboelectric hybrids combine internal material deformation with surface charge transfer to boost power density [12]. Some advanced designs include all three methods (piezoelectric, electromagnetic, and triboelectric) to maximise adaptability and energy capture under varying mechanical stimuli [13]. These multimodal systems are attractive in applications where movement is irregular and directionally complex [14], [15]. Shaukat et al. [16] and Xu et al. [17] have extensively reviewed the configuration and performance of hybrid harvesters in contexts ranging from smart wearables to structural monitoring. Their work highlights the benefits of combining multiple modes of energy harvesting to improve total output and responsiveness.

Yet, these designs still commonly fall short in practice due to one persistent limitation, which is directional dependence. The vast majority of systems are optimised for excitation along a fixed axis, which significantly reduces their effectiveness in environments characterised by random or chaotic motion [9], [18]. Additionally, hybridisation often introduces new challenges related to component alignment, energy conditioning, and mechanical integration, which can reduce efficiency or increase system complexity [19], [20]. To make hybrid harvesting viable for deployment in unpredictable environments, future systems must be designed with multi-directional sensitivity and mechanical resilience as primary objectives. A suitable solution must also be lightweight, compact, and integrable with standard electronics without excessive power conditioning or voltage balancing. These requirements frame the core objective of this research.

This work advances the field by introducing a novel hybrid energy harvester that integrates piezoelectric and electromagnetic conversion through a non-contact magnetic plucking technique, addressing limitations of conventional single-mode harvesters [21]. Unlike the conventional direct contact exciters, this approach utilises magnetic repulsion from a rotating magnet to induce beam vibrations. The system exploits frequency up conversion, allowing the beam to resonate at or near its natural frequency even when subjected to irregular or slow external motion [22], [23]. This method reduces mechanical wear and broadens the harvester's responsiveness to random excitation. The alternating current (AC) generated by the system is subsequently processed by a voltage doubler, which increases the output voltage and stabilises it for low power applications such as wireless nodes or wearable sensors [8].

In conclusion, this research addresses key limitations in existing hybrid energy harvesters, including poor performance under random motion, sensitivity to directional input, and inefficient power conversion. The proposed solution offers a compact, efficient, and practical method for powering portable electronic devices without relying on traditional battery systems.

2. Research Methodology

The research methodology was structured to assess the performance of the proposed hybrid energy harvester through system design and experimental validation. The design stage integrated piezoelectric bimorph beams, electromagnetic coils, and a magnetically actuated plucking mechanism, while the experimental stage employed randomized excitation frequencies between 1 Hz and 5 Hz to replicate dynamic conditions such as walking and running. An Arduino-controlled setup with motorized and manual inputs enabled precise frequency adjustments and reliable characterization of the harvester's electrical outputs. The microcontroller was programmed in the Arduino IDE, and data acquisition and analysis were performed using LabVIEW, MATLAB, and Microsoft Excel.

2.1 System Design

This research builds upon the earlier research, where the energy harvester progressed from a mechanically plucked piezoelectric system [24] to a magnetically actuated configuration, effectively reducing mechanical wear while enhancing overall performance [25], the design was later refined through the adoption of a beam deflection strategy to accommodate low-frequency excitations better [23]. The current work still retains lead zirconate titanate (PZT-5H) piezoelectric bimorph beams, maintaining the original dimension of 40mm x 10mm x 0.5mm. Additionally, a copper coil with a 0.2 mm diameter was wound to 1000 turns, with a length of 0.1mm. As shown in Fig. 1, the hybrid energy harvester prototype integrates an 80 mm diameter eccentric mass and a 65 mm long shaft to convert linear motion into rotational motion.

An eccentric rotating mass initiates motion, and as it rotates, the magnet at its ends approaches those on the piezoelectric beam, causing a repulsive magnetic force that deflects the beam. This interaction simultaneously induces mechanical stress in the PZT-5H beam and alters the magnetic field around the coil, enabling energy conversion through both piezoelectric and electromagnetic mechanisms. The proof mass consists of neodymium iron boron (NdFeB) magnets, each 12 mm in diameter and 3 mm in height. A 10 mm long rectangular NdFeB magnet is also incorporated to facilitate magnetic plucking of the piezoelectric beam.

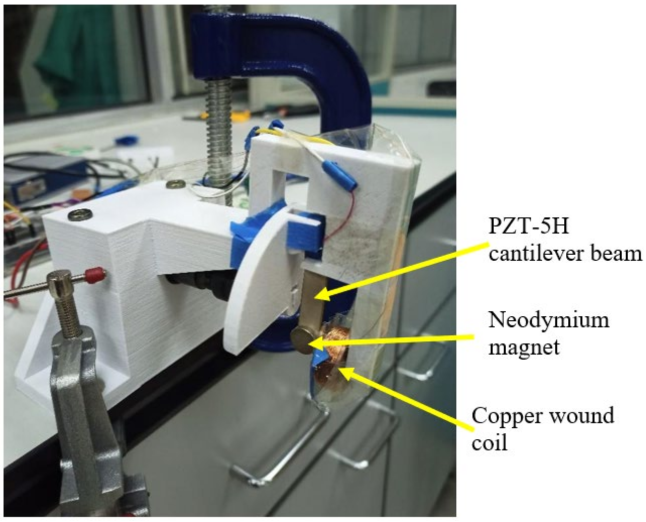

Fig. 1 *Fabricated hybrid energy harvester prototype*

2.2 Random Excitation Experimental Setup

To stimulate real-world conditions such as human walking or running, the hybrid energy harvester was tested under randomised excitation frequencies ranging from 1 Hz to 5 Hz [26]. These excitations were introduced using both manual hand rotation and motorised input. The experimental setup consisted of the fabricated hybrid harvester, an Arduino Uno microcontroller, a motor driver (L298N), a DC motor, and a tachometer for frequency measurement. The Arduino Uno was programmed using the Arduino IDE to control the motor's speed through pulse width modulation (PWM), allowing precise adjustments of the eccentric mass's rotation speed.

The DC motor (755 model) was connected to the eccentric mass and mounted securely on a test bench along with the harvester prototype to avoid vibrations that could affect frequency stability. The *analogWrite()* function in the Arduino IDE generates PWM signals with values ranging from 0 to 255, corresponding to duty cycles of 0% to 100%, respectively. A tachometer was used to measure the motor's speed in RPM, and a conversion formula programmed in the Arduino IDE allowed real-time frequency adjustments. Fig. 2 illustrates the setup and equipment connections.

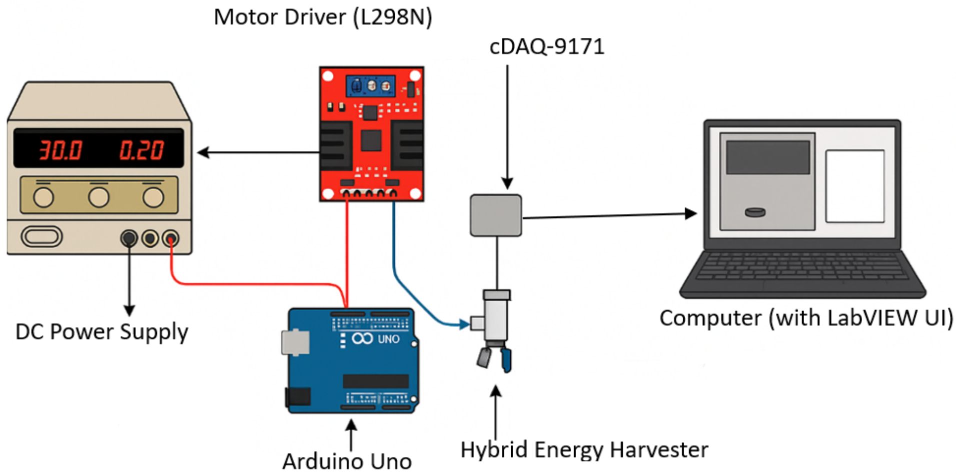

Fig. 2 *The experimental setup illustration for the experiment*

3. Result and Analysis

The results and analysis section presents the performance of the hybrid energy harvester under randomized excitation conditions representative of hand motion. Measurements of output voltage were obtained from both the piezoelectric and electromagnetic components. These findings are compared with earlier harvester configurations to demonstrate the improvements achieved by integrating eccentric mass and a magnetic plucking mechanism, emphasizing efficiency under low-frequency and irregular inputs.

3.1 Random Frequency Excitation

Manual rotation of the attached eccentric mass was performed over a 10-second duration, generating random mechanical excitations within a low-frequency range of approximately 1 Hz to 4 Hz. These excitations were irregular in nature due to the manual input, effectively simulating unpredictable environmental vibrations. During this testing phase, the fabricated energy harvester, which incorporates a piezoelectric (PZT) cantilever beam, was exposed to these random vibrations. It was observed that under such conditions, the magnetic attraction force acting between the moving magnet and the PZT beam tip was strong enough to cause the beam to deflect by more than 2 mm, which exceeded its designed maximum deflection limit. Excessive bending posed a significant risk of inducing mechanical stress or even structural failure in the PZT beam over prolonged use. To mitigate this risk and ensure long-term reliability of the harvester, the configuration was modified to utilise only magnetic repulsion instead of attraction. This adjustment provided sufficient dynamic actuation while preventing the beam from overstressing. Interestingly, even with magnetic repulsion alone, the PZT beam consistently achieved near-maximum deflection across the 1–4 Hz frequency range, generating stable and repeatable peak voltage outputs. These results are illustrated in Fig. 3. The red line indicates the voltage generated by the hybrid energy harvester, showing the highest output. The blue line represents the piezoelectric energy harvester, while the orange line corresponds to the electromagnetic energy harvester, which exhibits the lowest voltage.

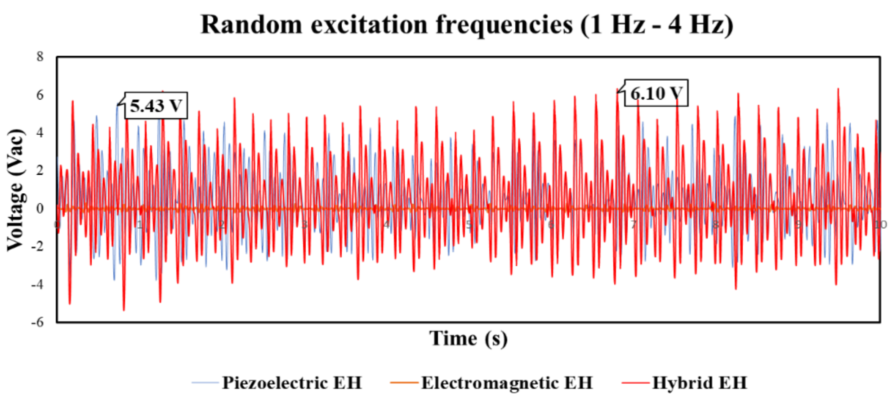

Fig. 3 *AC voltage signals are output when under random input frequencies*

In a subsequent test aimed at simulating more consistent and controlled dynamic loading, a DC motor was employed to rotate the eccentric mass at varying speeds. The rotational frequency of the motor was gradually increased from 5 Hz up to 20 Hz in incremental steps. This controlled frequency sweep enabled a comprehensive analysis of the energy harvester's performance across a broad range of excitation conditions. As the frequency increased, the output of the piezoelectric energy harvester was measured as alternating current (AC) voltage and was recorded in real-time. As shown in Fig. 4, the voltage output exhibited a pronounced peak when the excitation frequency approached approximately 14 Hz, which corresponds to the resonant frequency of the PZT cantilever beam (14 Hz). The system achieved maximum energy transfer at resonance, resulting in the highest voltage output. However, when the frequency exceeded the resonant point, the voltage began to decline steadily, reflecting the typical behaviour of a damped resonant system. These findings were consistent with results obtained from earlier frequency sweep experiments conducted on the same PZT beam, as previously documented in the reference [22], thereby reinforcing the repeatability and reliability of the system's dynamic response characteristics.

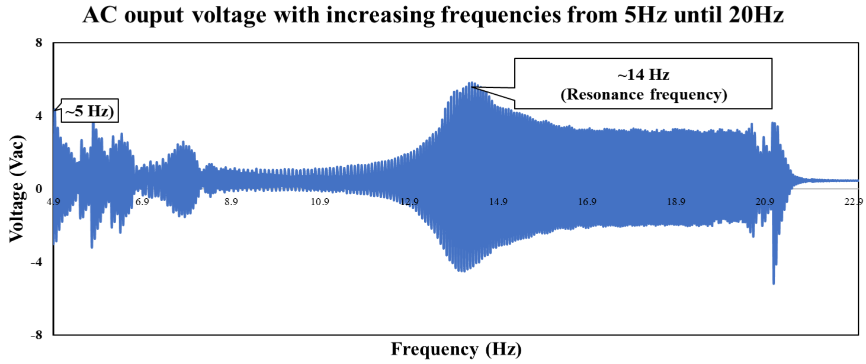

Fig. 4 *AC output voltage generated by the piezoelectric with increasing frequencies under a repulsive force*

3.2 Fast Fourier Transform (FFT) Analysis

A Fast Fourier Transform (FFT) analysis was performed on the alternating current (AC) voltage output generated by the piezoelectric energy harvester to identify the dominant frequency components and validate the effectiveness of the magnetic plucking excitation mechanism. This analysis offered valuable insight into the system's ability to convert mechanical input into electrical signals through the piezoelectric effect. At a motor rotation speed of 5 Hz, the FFT results showed that the dominant frequency in the voltage spectrum closely matched the natural resonant frequency of the PZT cantilever beam. This strong correlation confirmed that the beam was consistently and efficiently deflected near its resonance point, where energy harvesting performance is maximised. A well-defined spectral peak indicated that the magnetic plucking mechanism, driven by the rotating eccentric mass and its interaction with the beam's magnetic tip, effectively induced periodic excitation. Fig. 5 presents the FFT result, clearly illustrating a peak in the spectral magnitude at approximately 16 Hz, reinforcing the conclusion that resonance-based excitation was successfully achieved during operation.

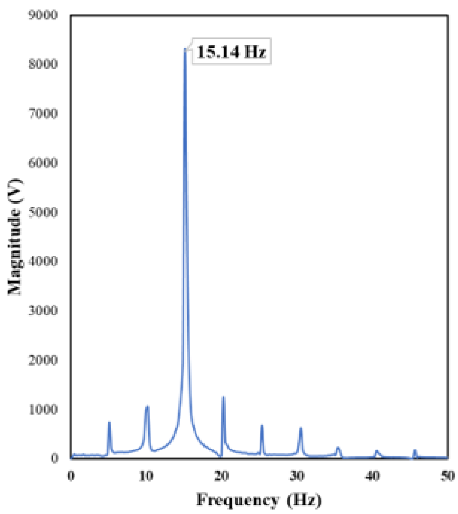

Fig. 5 *Eccentric mass rotates at 5Hz*

Manual rotation trials were conducted to further validate the frequency response characteristics of the energy harvester under low-frequency, non-uniform excitation. During these tests, the eccentric mass was manually rotated within a variable frequency range of 0 to 5 Hz to simulate irregular, real-world vibration conditions. Despite the randomness of the input, the system consistently produced dominant frequency components near the beam's resonant range. Specifically, the peak frequencies recorded across three separate trials were 13.67 Hz, 16.11 Hz, and 16.11 Hz, respectively. These values yielded an average dominant frequency of approximately 15.3 Hz, aligning with the resonant frequency identified in previous controlled motor-driven experiments. This strong agreement across different excitation methods reinforces the stability and repeatability of the magnetic plucking mechanism in effectively exciting the PZT beam at or near resonance. Fig. 6 illustrates these findings, highlighting the consistency of spectral peaks across all manual trials.

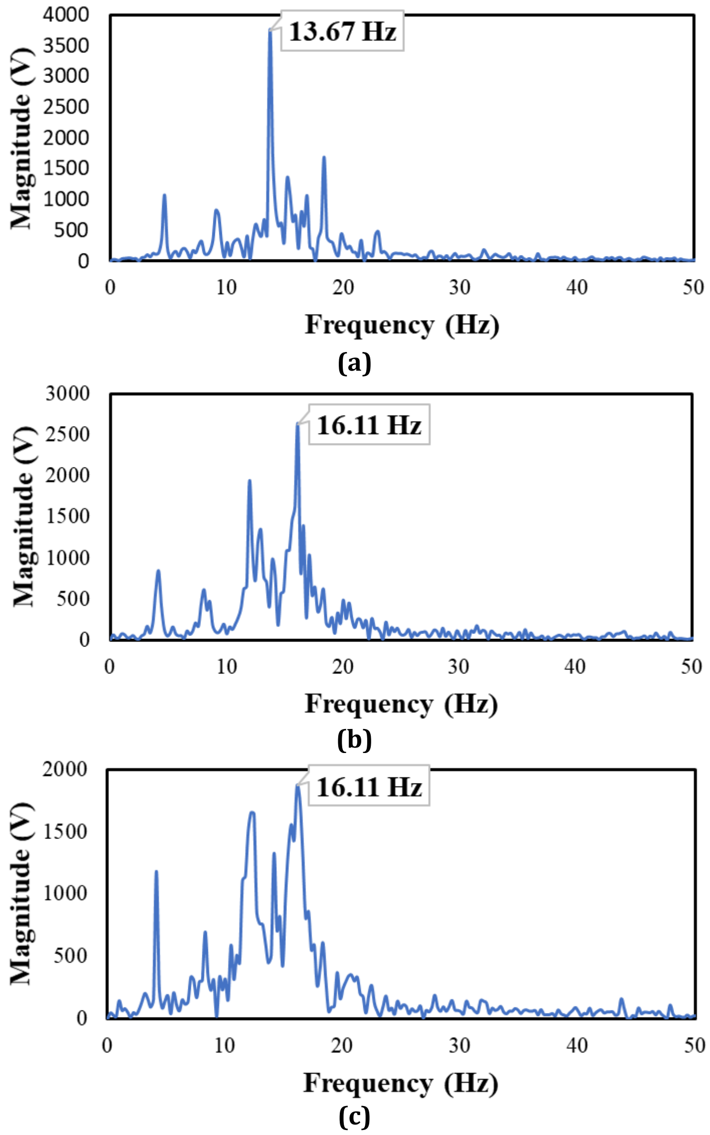

Fig. 6 *Dominant frequencies of the piezoelectric beam during manual rotation of the eccentric mass (a) First trial; (b) Second trial; (c) Third trial*

3.3 Voltage Rectification Using Voltage Doubler

To improve the DC output of the energy harvester, a voltage doubler circuit was implemented, as shown in Fig. 7. This simple yet effective circuit configuration utilised only two diodes and two capacitors, making it more efficient compared to a traditional full-bridge rectifier [22]. The reduced number of components minimised voltage drops across diodes and enabled better energy storage capabilities within the capacitors. As a result, the voltage doubler offered lower conduction losses and improved conversion efficiency, which is especially beneficial for low-power energy harvesting applications. Performance evaluations under constant and random excitation conditions further demonstrated the circuit's effectiveness.

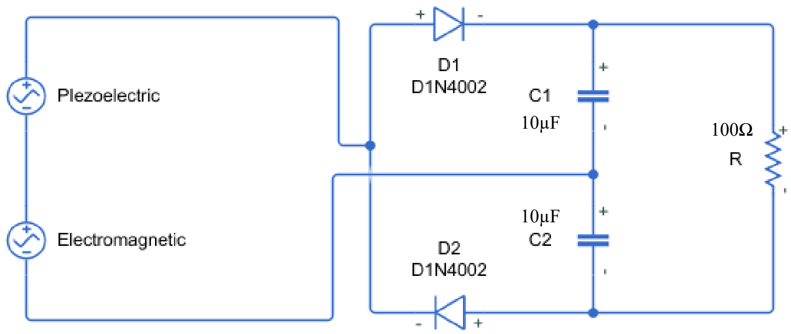

Fig. 7 *Voltage doubler circuit*

Specifically, as illustrated in Fig. 8 and Fig. 9, the voltage doubler consistently produced higher output voltages when the system was excited at a steady frequency of 5 Hz, as well as under variable frequency conditions ranging from 0 to 4 Hz. These results highlight the circuit's ability to enhance energy capture and improve the overall electrical output of the system across different vibration scenarios. For frequencies exceeding 5 Hz, the output voltage consistently corresponds to the resonance frequency (~14 Hz), as the magnetic plucking mechanism with the eccentric mass continuously excites the beam at resonance.

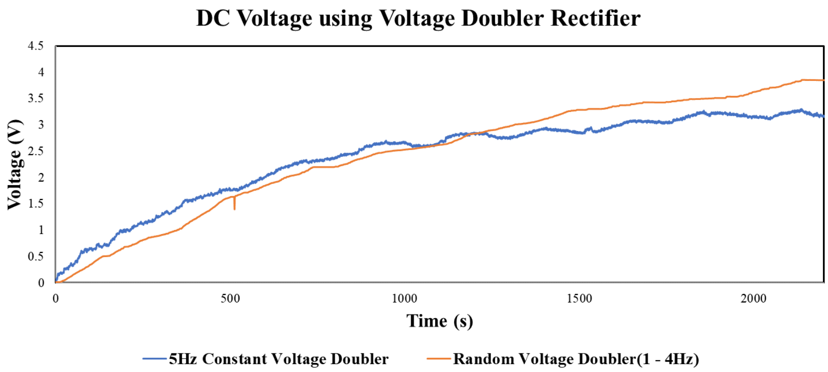

Fig. 8 *DC voltage output with a constant 5Hz and random (0 – 4Hz) eccentric mass*

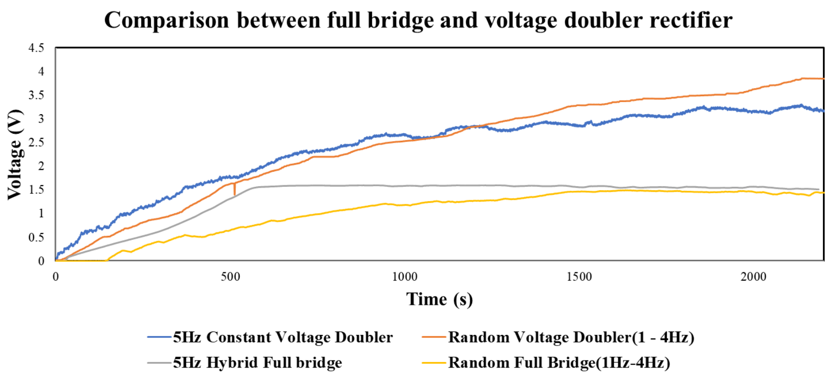

Fig. 9 *Comparison of the DC voltage output between the full bridge circuit and the voltage doubler circuit*

The significant voltage gain demonstrates the voltage doubler's efficiency in minimising losses typically associated with conventional rectification methods. However, there are certain limitations to consider. Under higher load conditions, the output voltage may drop due to the limited current-handling capability of the capacitors and diodes used in the circuit. As the current demand increases, the diodes experience higher forward voltage drops, while the capacitors are unable to maintain stable charge storage. These factors combine to reduce the circuit's ability to regulate voltage, leading to a noticeable decline in output under heavy loading. Additionally, the voltage doubler does not provide inherent voltage regulation, which could be a drawback in applications that require a stable and consistent DC output. Therefore, while the voltage doubler offers clear advantages in boosting output voltage, its performance may vary depending on load demands and should be complemented with appropriate regulation if used in sensitive electronic systems. Table 2 shows the summarised data from the graph in Fig. 9.

Table 1 *DC voltage generated by the full bridge and the voltage doubler circuit*

Eccentric mass rotation frequency	Full bridge circuit (V)	Voltage doubler circuit (V)
Constant (5Hz)	1.5	3.2
Random (0 – 4Hz)	1.4	3.8

3.4 Simulation Versus Experimental Results

Based on the earlier paper, voltage outputs from simulations [23] were generally higher than those from experimental trials due to the ideal conversion efficiency in simulations. Table 3 compares simulation and experimental data:

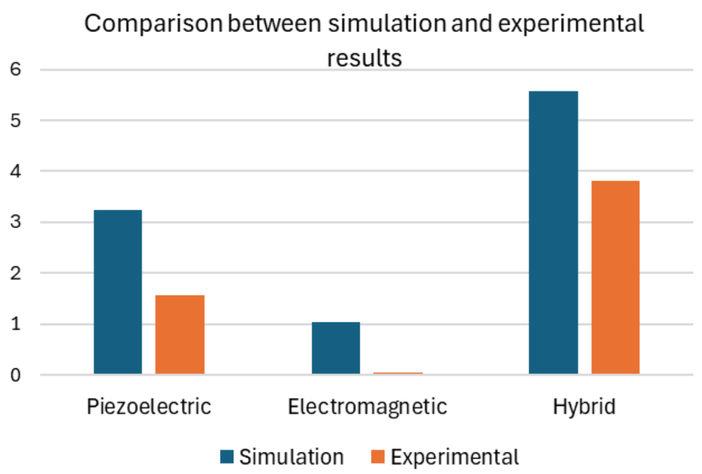

Fig. 10 *Comparison between simulation and experimental results*

Table 2 *Comparison between simulation and experimental results*

Energy harvester	Simulation (V)	Experimental (V)
Piezoelectric	3.23	1.56
Electromagnetic	1.04	0.04
Hybrid	5.57	3.8

Based on Table 3, the simulation produced an output voltage of 5.57 V, whereas the experimental setup yielded only 3.8 V. The primary reason for this discrepancy lies in the efficiency of the AC-to-DC conversion process. In simulations, ideal conditions are assumed, components are modelled without losses, and the converter can convert AC signals to DC with 100% efficiency. In contrast, real-world components introduce various inefficiencies. In the experimental setup, the rectifier exhibited an efficiency of approximately 68%, which aligns well with values reported by other researchers, typically around 65% or lower [27]. These losses can be attributed to several factors, including the forward voltage drop across diodes, internal resistance in passive components, and energy dissipation during switching and charging cycles. Additionally, parasitic effects such as leakage currents and imperfect filtering further reduce the net output voltage. Nevertheless, despite these practical limitations, the hybrid energy harvesting configuration consistently outperformed standalone approaches, demonstrating its effectiveness in maximising energy extraction under both simulated and real-world conditions.

4. Conclusion

In conclusion, integrating piezoelectric and electromagnetic energy harvesting mechanisms within a hybrid system presents a promising solution for overcoming the limitations associated with each method. By incorporating FFT analysis and an advanced rectification technique, this study demonstrates significant improvements in power generation under low-frequency random excitations, making the system more robust and reliable for practical applications. The voltage doubler circuit further enhances energy conversion efficiency, providing higher output voltages in both steady and random excitation scenarios. These advancements highlight the potential of hybrid energy harvesters to serve as a sustainable power source for portable devices, thereby reducing dependence on conventional batteries and ensuring long-term, environmentally friendly operation in various dynamic environments.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *N.H.H. Mohamad Hanif;* ***data collection:*** *M.S. Mohamad Tahir;* ***analysis and interpretation of results:*** *M.S. Mohamad Tahir, N.H.H. Mohamad Hanif, A.N. Wahid;* ***draft manuscript preparation:*** *M.S. Mohamad Tahir, N.H.H. Mohamad Hanif. All authors reviewed the results and approved the final version of the manuscript.*

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