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Comparative Analysis on the Performance of a PDMS-Based Electromagnetic Vibrational Energy Harvester (EM-VEH): Functionality Test on Rotating Machinery

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ABSTRACT

This study aims to analyze the performance of an energy harvester prototype consisting of a Polydimethylsiloxane (PDMS) membrane and electromagnetic components. The working principle of the energy harvester is to convert vibration energy into low-power electricity. The prototype was tested under various conditions, including a dynamic rotor engine, a motorcycle engine, and a Boeing 737-600 aircraft turbine. Vibration measurements under different conditions were obtained using a CF360A FFT analyzer as the excitation source on the energy harvester prototype. At the same time, the output voltage was recorded with a Hantek 20 MHz 2-channel digital oscilloscope connected to a PC. The results showed that with a dynamic rotor engine, the energy harvester prototype produced the highest output voltage of 0.989 Volts at 40 Hz (14,800 RPM). While with an excitation frequency of 200 Hz, it produced a much lower voltage (0.25 V) on the Boeing 737-600 aircraft turbine. This shows that the prototype is effective at low excitation frequencies for rotating machines.

Keywords: *Energy harvester, Polydimethylsiloxane, electromagnetic components, excitation frequency*

1. INTRODUCTION

The growing need for portable energy, driven by the increasing use of electronic devices, requires scientists to develop alternative electromagnetic vibration harvesters (em-veh) to meet household power needs. Em-veh is a system that transforms ambient mechanical energy that is initially wasted into electrical energy based on Faraday's law of induction**.**

The advantage of portable electronics lies in the readily available energy requirements, such as those generated by vibrations in industrial machinery, making them an effective alternative. This method can reduce reliance on conventional batteries, which have a greater environmental impact.

The em-veh has been shown to have several advantages over its predecessor, the piezoelectric approach. This method produces stronger, more durable power and is highly scalable even at lower vibration frequencies. Typically, installing batteries in certain devices is complicated because it requires setting up a wireless sensor network. This is not the case with the em-veh. where it is more efficient if the coils, magnets, and power circuits are arranged in a certain way to obtain optimal results, in addition to relatively low maintenance costs [1].

Vibrations generated in the oil, bridge, and construction industries can be converted into electrical energy using low-power, self-sustaining, long-distance electromagnetic induction [2].

Several key components, when optimized, can improve the system's efficiency. These include coil geometry, magnetic strength, and resonant frequency matching to the ambient vibration spectrum of around 10–200 Hz for industrial applications [3]. Recent advances in materials science and power electronics have further improved energy conversion rates, with some EM-VEHs achieving power densities of 1–100 mW/cm^3—sufficient to power wireless sensors, IoT devices, or wearable technology without batteries.

The key mechanical limitations of this system are its low power output, primarily caused by the membrane's rigid material properties, and the excessive size of the current generator designs, hindering their practical application in confined or off-grid environments [4] [5] [6].

In the last decade, Micro-Electro-Mechanical Systems (MEMS) have revolutionized mechanical engineering by enabling the shift from large, traditional machinery to microscale devices. MEMS technology offers advantages in energy efficiency, material optimization, and compact system integration, aligning with sustainable and cost-effective industrial solutions [7] [8].

In our prior study, we investigated the mechanical performance of a MEMS structure and evaluated a PDMS-based planar electromagnetic membrane for use as a mechanical vibration energy capturer.

In the current study, the research focuses on integrating PDMS membranes with electromagnetic coils and permanent magnets to form a micropower generator system (EM-VEH). Structural mechanics theory indicates that membranes equipped with planar arms can deform better, resulting in maximum energy generation. To test this, the study sought to optimize the geometry of the PDMS membrane by evaluating its constituent components. Furthermore, experiments were conducted to assess whether the maximum strain distribution did not exceed the vibration load while still ensuring stable mechanical durability. This approach aims to significantly improve power output and reliability for low-frequency environmental vibrations, addressing key limitations in existing EM-VEH systems. In this paper, we present a performance analysis of the fabricated EM-VEH through functional testing on rotating machines.

2. METHODS

In basic theory, an electric generator is a machine that converts kinetic energy into electrical energy. The working principle of an electric generator is based on Faraday's law of electromagnetic induction. Electric generators can produce two types of electric current: direct current (DC) and alternating current (AC).

An electric generator that produces direct current is called a DC generator, while a generator that produces alternating current is called an AC generator. The number of slip rings in an electric generator determines the type of electric current it produces. An AC generator has two slip rings, whereas a DC generator uses a split-ring commutator (not just one slip ring) to produce direct current. This condition is explained in Equation 1.

$$\varepsilon = B.A.\omega.N.\sin\theta \quad (1)$$

Faraday's law of induction describes the electromagnetic generation of energy from vibrations arising from the interaction of magnetic fields. The mechanical force of the external vibrations causes relative motion between the magnet and the coil, creating a magnetic flux that continuously adjusts its shape through the coil. According to Faraday's law, this flux variation induces an electromotive force (EMF) across the coil. The induced voltage was measured using formula 2.

$$\varepsilon = -\frac{d\phi_B}{dt} \quad (2)$$

The formula shows that Faraday's law of induction governs the induced voltage (ε) and magnetic flux (Φ_B). The amplitude depends on the relative velocity of the magnet's displacement and the coil [9]. It allows mechanical vibrations to be converted into usable electrical energy with time-varying magnetic flux linkage.

Functional testing and performance evaluation of a vibration energy harvesting prototype fabricated from PDMS membranes with optimized design and geometries, and selected electromagnetic parts, were conducted to construct a vibration energy harvesting generator unit. The prototype's performance was evaluated under controlled vibration conditions to simulate real-world operational environments.

The prototype is engineered through a multi-step fabrication process. The primary housing is constructed from acrylic via 3D printing to ensure structural integrity and design flexibility. A key functional component, a geometrically patterned PDMS membrane, is produced via precision laser cutting. This membrane is then assembled within the acrylic housing. Finally, the actuation system is implemented by integrating selected permanent magnets with a precisely wound copper coil, forming the device's core electromechanical transducer [13].

A schematic of the device under test (DUT) and its parts is shown in Figure 1. The prototype assembly comprises an upper and lower housing cover, two spacers to precisely control the air gap between the magnets and coils, and a central coil holder that rigidly secures the upper and lower coils. Two permanent magnets are bonded to the upper and lower PDMS membranes, enabling vibration-induced displacement relative to the coils to harvest energy.

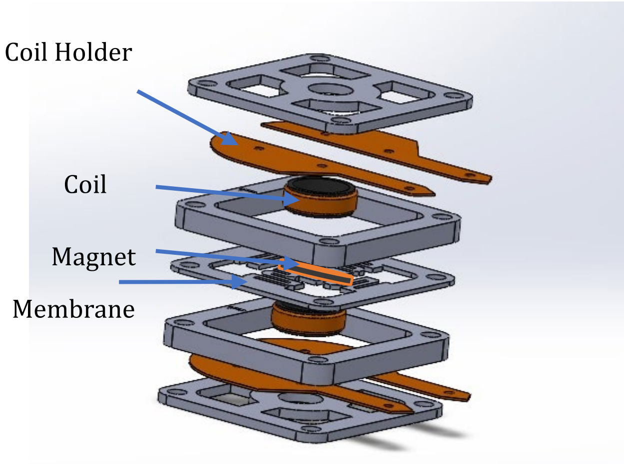

Figure 1. Schematic and parts from prototype EM- VEH.

To evaluate the energy-harvesting capability of the device under test (DUT), further testing was performed by mounting the EM-VEH container on the machine. During machine operation, the generated vibrations are collected (harvested) and converted into electricity. The power generated is measured at different vibration frequencies and amplitudes to test the device's performance. Conversion efficiency is then calculated as the ratio of generated electricity to the mechanical energy input from the vibrations. The tests include:

1. A CF360A FFT analyzer to characterize mechanical vibration frequency spectra.
2. A Hantek 20MHz 2-channel digital oscilloscope interfaced with a PC-based data acquisition system to record the generated electrical output.
3. The measurement procedure is carried out over time, ensuring accurate data are obtained.

Functional prototypes of a balancing machine, a motorcycle engine, and an aircraft turbine were tested.

2.1. Dynamic Rotor machine

Dynamic rotor machines are used in the learning process to determine whether rotor rotation is balanced [10], [11]. The balancing machine plays an important role in aligning the vibrations so that the rotor rotates in balance. These machines typically consist of:

- Measurement sensors (e.g., vibration pickups, phase detectors)
- Rotor support mechanisms (bearings or pedestals)
- Data acquisition and analysis systems.

Various types exist depending on application requirements, including:

- Hard-bearing balancing machines (for low-speed applications)
- Soft-bearing balancing machines (for high-speed precision)
- Portable field balancing systems
- Specialized designs for specific components like turbine rotors or automotive parts

Experimental methodology for vibration energy harvesting prototype testing from a dynamic rotor machine proceeded by mounting the vibration energy harvesting (DUT) at the dynamic rotor position.

An FFT analyzer sensor was positioned at the operational interface point to evaluate system performance across six rotational speeds: 1300 rpm (standard operating speed), 1350 rpm, 1400 rpm, 1450 rpm, 1480 rpm, and 1530 rpm.

Measurements captured two key output parameters: electrical output voltage (measured via oscilloscope) and mechanical vibration frequency (acquired through FFT spectrum analysis). The schematic function test settings on the balancing machine are shown in Figure 2.

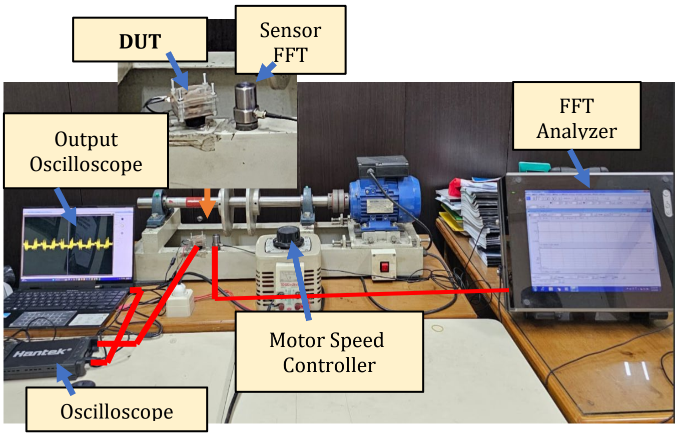

Figure 2. Schematic function test settings on the dynamic rotor machine.

Figure 2 is saved for further analysis, while the data generated by the FFT analyzer in the form of machine vibration data is then processed using the MATLAB application to obtain the frequency and amplitude values of the machine as a source of vibration.

2.2. Motorcycle Engine

Vibration in a motorcycle is caused by moving components such as pistons and the crankshaft. These parts undergo reciprocating motion, inducing vibrations across the entire engine at specific frequencies. The engine's type and size determine normal vibration frequency. Smaller engines, such as those typically used in motorcycles, will produce higher vibrations.

Vibration in an engine is caused by moving components such as pistons and the crankshaft. These parts undergo reciprocating motion, inducing vibrations across the entire engine at specific frequencies. The engine's type and size determine normal vibration frequency. Smaller engines, such as those typically used in motorcycles, will produce higher vibrations.

In general, a 4-stroke motorcycle engine produces vibrations in the range of 20 to 200 Hz [11]. Engine components, material type, and operating method influence vibration frequency. Engine performance testing typically involves testing the chassis to determine the power output.

The functional test begins with installing the DUT on the motorcycle's engine mount. The engine is then started and conditioned at low (700 rpm), medium (1000 rpm), and high (1100 rpm) rpm. This testing is illustrated in the following figure.

Vibrations in a 4-stroke motorcycle engine will produce a frequency range of 20 to 200 Hz [11], [12]. Engine components, material type, and operating method influence vibration frequency. Engine performance testing typically involves testing the chassis to determine the power output.

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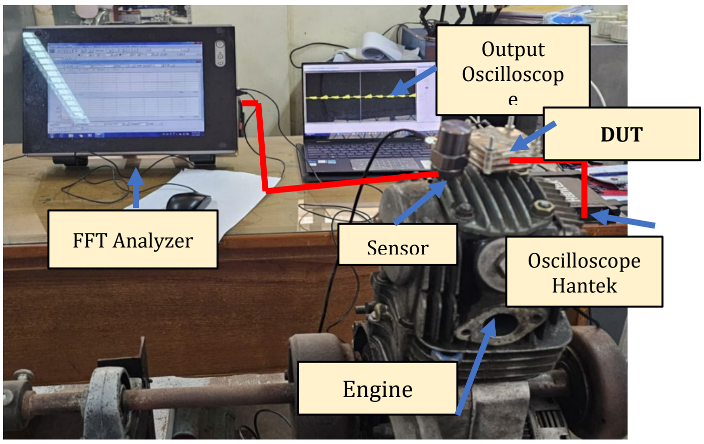


Figure 3. The schematic function test settings for the motorcycle engine.

The resulting voltage can be monitored in real time via the device. This data can also be stored for later analysis. The FFT (fast Fourier transform) analysis aims to collect data on machine vibrations that MATLAB can use to identify the frequency and amplitude of the vibration source.

2.3. Airplane Turbine 737-600

The aircraft turbine is the most important component of the propulsion system, converting thermodynamic energy into kinetic energy. The resulting kinetic energy is then converted into mechanical work through the rotation of the axle, which drives the compressor and fan assemblies. The Boeing 737-600 uses the CFM56-7 turbofan engine, which, with its swept compressor and advanced airframe, is the most modern, efficient, and reliable turbofan ever compared to the previous CFM56-3 engine that powered the 737-300/-400/-500 variants [13].

The aircraft turbine used in the measurements was a repaired and recertified unit, tested under no-load, 10 kVA, 20 kVA, and 50 kVA load conditions. The schematic function test settings for the 737-600 Airplane Turbine are shown in Figure 4.

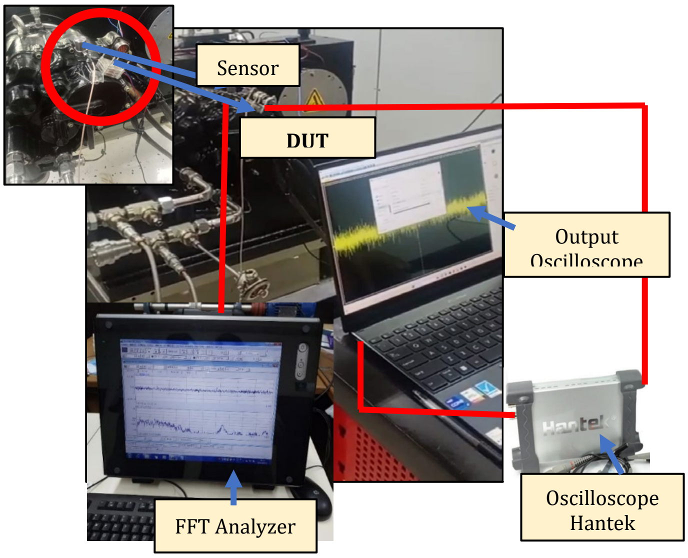


Figure 4. The schematic function test settings for airplane turbine 737-600.

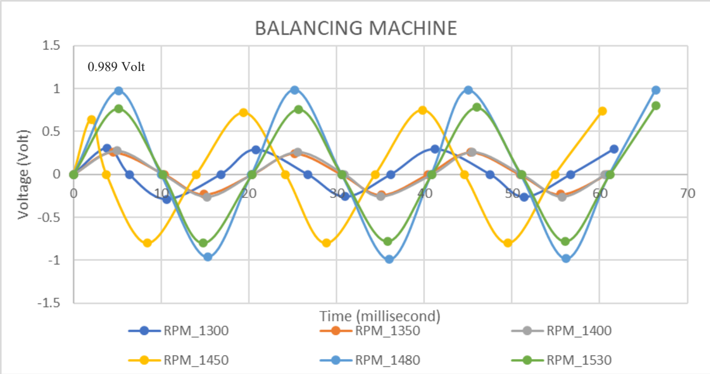
3. RESULTS AND DISCUSSION

This test evaluates the device's performance under operational vibration conditions. Vibrations from three machines are analyzed via FFT in the frequency domain, while the induced voltage from electromagnetic conversion is measured in volts using an oscilloscope.

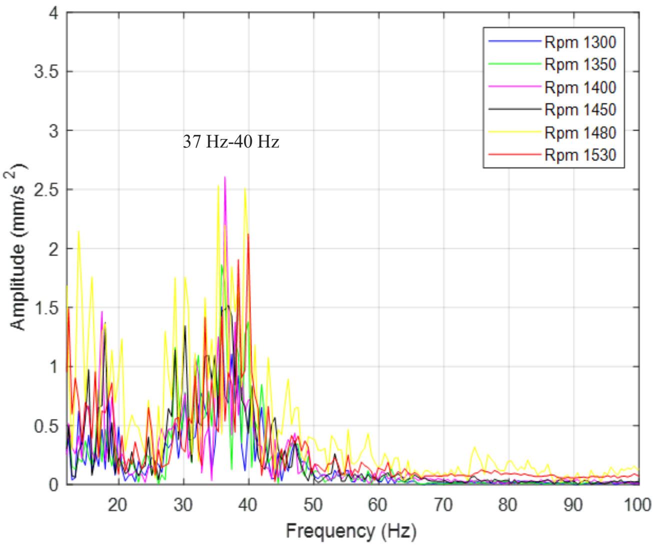
3.1. Result

3.1.1 Device performance on the balancing machine

The functionality test was conducted by attaching the device container to the engine mounting section at rotational speeds of 1300 rpm (base engine speed), 1350 rpm, 1400 rpm, 1450 rpm, 1480 rpm, and 1530 rpm. The measured voltage values during this functionality test are shown in Figure 5.



(a) Dynamic Rotor Machine Voltage Measurement Results



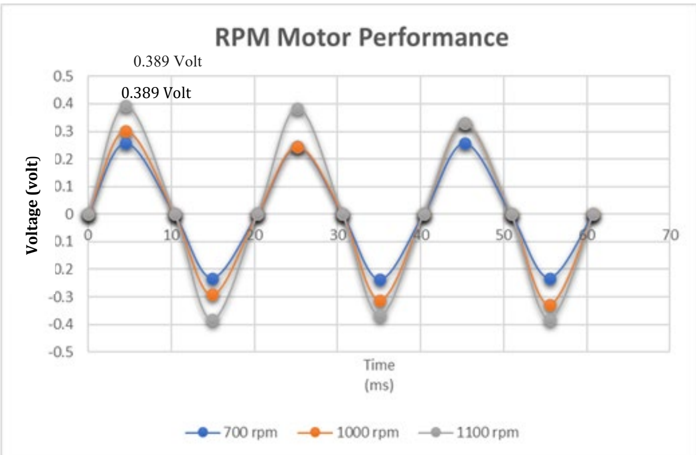
(b) Dynamic Rotor Machine frequency measurement results

Figure 5. Vibration Measurement of Dynamic Rotor Machine Frequency.

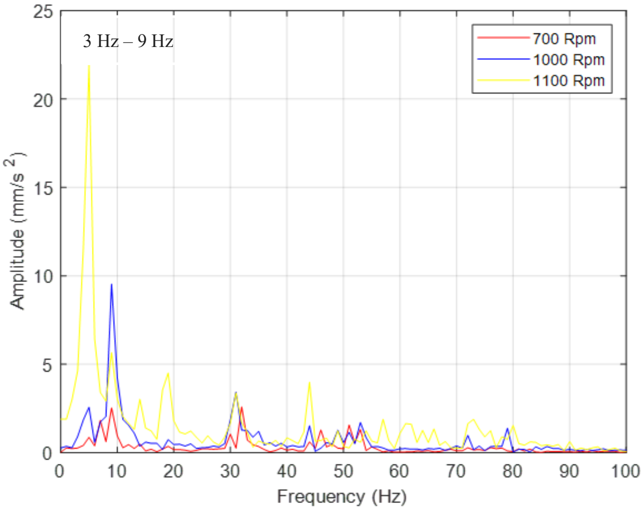
Figure 5 shows the voltage measurement results obtained using an oscilloscope at an engine speed of 1480 rpm, with the highest recorded voltage reaching 0.989 volts. The prototype also demonstrated optimal vibration performance within the frequency range of 30–40 Hz.

3.1.2 Device performance on a motorcycle engine

Function tests on motorcycle engines were conducted by attaching the fabricated device to the engine at three speeds: low (700 rpm), medium (1000 rpm), and high (1100 rpm). The measurement results are shown in Figure 6.



(a) Motor Engine voltage measurement results



(b) Motor Engine frequency measurement results

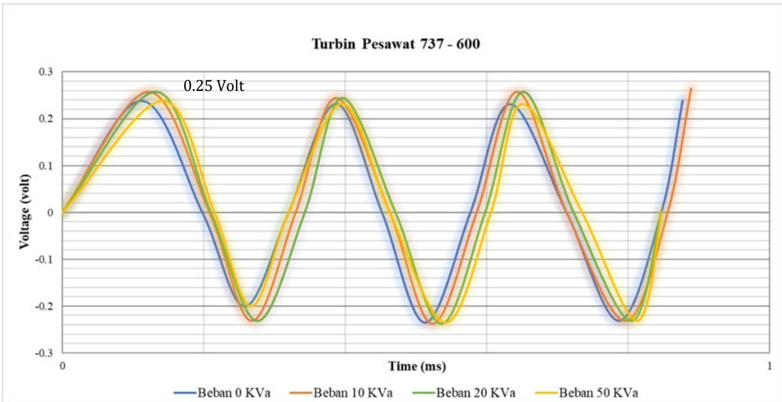
Figure 6. Vibration Measurement of Motor Engine Result.

In Figure 6, the voltage measurement results obtained with an oscilloscope at an engine speed of 1100 rpm show that the highest converted vibration is only 0.389 volts. The vibration frequency generated by the motorcycle engine is relatively low, ranging from 5 Hz to 9 Hz, with the highest rotation value occurring at 1100 rpm.

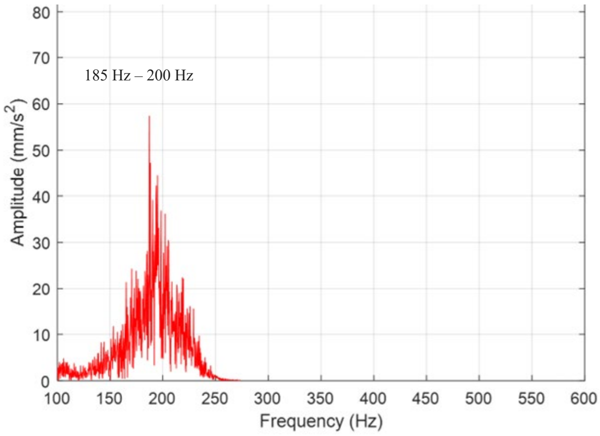
3.1.3 Device performance on airplane turbine 737-600

The subsequent function test was performed on a repaired turbine engine from a Boeing 737-600 aircraft that had previously exhibited rotational instability. The prototype electromagnetic vessel was mounted on the turbine section, and measurements were taken under varying load conditions. The test aimed to verify whether the turbine could maintain stable frequency output despite applied loads.

The measurement results are shown in Figure 7. Airplane Turbine 737-600 voltage measurement results:



(a) Airplane Turbine 737-600 voltage measurement.



(b) Airplane Turbine 737-600 frequency measurement results

Figure 7. Vibration measurement of motor engine result.

Figure 7 shows that the FFT (fast Fourier transform) analysis revealed that the turbine engine's operational frequency remains constant at ≈200 Hz, demonstrating stable performance under varying load conditions, even though the generated voltage was small at 0.250 Volts. This consistency confirms the repaired aircraft turbine is now airworthy and operational. For comparison, Figure 8 shows the steady rotational speed monitored on PT Garuda Maintenance Aero's test bench, showing the generator output synchronized with engine rotation.

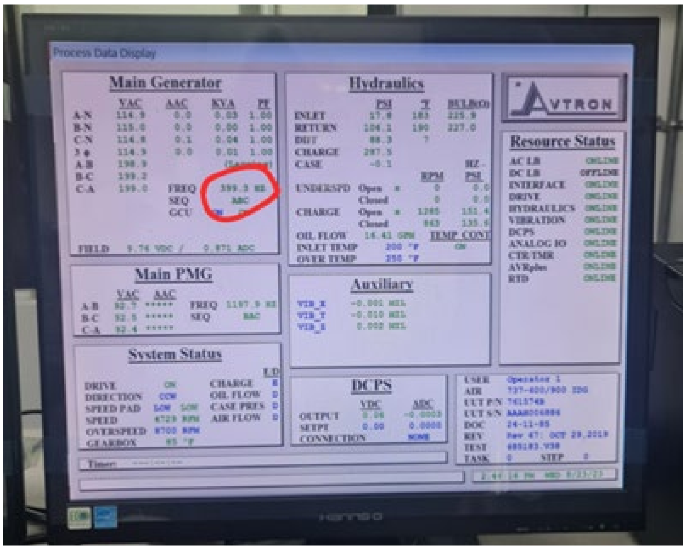


Figure 8. 737-600 aircraft turbine test data process display.

In Figure 8, the frequency received by the generator to generate electrical power is 399 Hz-400 Hz, indicating that the rotational speed is precisely doubled relative to the turbine output frequency (≈200 Hz). This 2:1 ratio confirms the presence of a gearbox transmission system rather than direct coupling between the turbine and generator. The voltage output data can be cross-analyzed with vibration spectra to determine whether the repair process successfully addressed the original instability issues, while also providing insights to optimize the electromagnetic vessel's positioning for maximum energy conversion. A comparison of the experimental results from the functional tests carried out is shown in Table 1.

Table 1 Comparison functional test table

Functional Test	Optimal operational frequency (Hz)	Output (Volt)
Balancing Machine	40	0.989
Motorcycle Engine	3-9 (unstable)	0.389
Airplane Turbine 737-600	200	0.25

According to the experimental data table, the tested prototype (1–500 Hz range) successfully transmitted vibrations and converted energy continuously, even under unstable machine conditions and at high frequencies. The tests demonstrated that the balancing machine effectively transferred the vibration energy harvesting prototype's performance at an optimal frequency of 40 Hz. This data will illuminate the vibration-energy-generating device.

4. DISCUSSION

After testing the engine balance, we found that the generated voltage from the EM-VEH (1480 RPM) was quite strong, indicating an electromagnetic clutch. Meanwhile, the vibrations that appeared were between 30 and 40 Hz, meaning the resonance frequency was stable. In such conditions, mechanical wear and energy release do not occur quickly. Statistical analysis applied to the voltage-RPM relationship can indicate efficiency limits. Furthermore, data on time-frequency vibrations indicate that structural damping is needed for the engine to maintain optimal performance over the long term.

The application of the energy hoisting prototype under industrial conditions, where motorcycle engine testing is carried out with a variation of rotational speeds from low to high. This is done to activate the EM-VEH's adaptability to the excitation-frequency conditions encountered. Low-frequency vibrations (5–9 Hz) are in the subharmonic range and can cause resonance, so the damping system must be properly modified to ensure stable energy harvesting.

For high-speed applications, such as aircraft turbines, frequency stability is crucial to achieving high energy-harvesting efficiency. Furthermore, the close agreement between prototype data and GMF reference measurements validates the EM-VEH's precision, demonstrating its potential for aerospace and automotive applications. Figure 9 shows the power output under various excitation conditions, including rotor dynamics, variable (motorcycle), and extreme (turbine). This holistic analysis confirms the system's robustness while identifying specific areas (e.g., dumping at subharmonic frequencies) for further refinement. Experimental results demonstrated that an electromagnetic transduction method, coupled with a planar PDMS membrane for vibration transmission, achieved an operational frequency of up to 40 Hz. This performance surpasses the prior work of Feng et al. (2023), whose zigzag-geometry MEMS harvester was limited to ultra-low resonant frequencies of 3 and 23 Hz. The superior frequency output is attributed to the inherent efficiency of the electromagnetic method in harnessing mechanical vibrations.

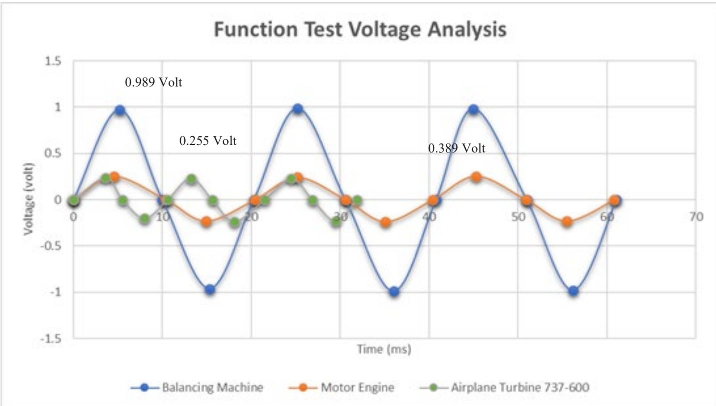


Figure 9. Function test voltage analysis.

In the functional testing of this prototype, the geometry of the arm on the membrane plays a fundamental role in determining how mechanical vibrations from the source are transmitted and converted into electromagnetic induction. The dimensions of the energy harvester prototype with a PDMS membrane are strongly influenced by the arm's shape, length, and cross-section, thereby affecting the system's dynamic response and the coil's motion in the magnetic field. A long, specifically shaped arm cross-section will stabilize the energy harvester's mechanical system, allowing it to adjust its high-frequency characteristics with low amplitude. At the same time, high amplitude will optimize the magnetic flux and the resulting induced voltage. Conversely, a short-arm cross-section can result in a mechanical impedance mismatch, preventing the effective capture and transmission of low-frequency vibrations and thereby reducing electrical output. Thus, optimizing the arm cross-section not only improves vibration-transmission performance but is also key to maximizing voltage and power output in energy-harvesting devices, especially in operational environments with complex and diverse vibration profiles.

5. CONCLUSION

Based on several tests that have been carried out, several findings in this study are summarized as follows:

1. Tests under different excitation-force conditions show that the resulting mechanical vibrations can be converted into electrical energy. conditions on a dynamic rotor with excitation force variations of 1300 rpm to 1530 rpm. At 1480 rpm, the optimal

frequency due to the excitation force is 40 Hz, resulting in a generated voltage of 990 mV. The final functional test involved a Boeing 737-600 aircraft turbine to assess its energy-harvesting potential. The measurements revealed that the turbine's operating frequency ranged from 190 Hz to 200 Hz, while the output voltage remained relatively low at approximately 250 mV. This discrepancy in voltage output—compared to the rotor engine tests—can be attributed to the high-frequency, low-displacement vibration characteristics of aircraft turbines, which pose challenges for efficient electromagnetic energy harvesting.

2. The dynamic rotor engine test demonstrates that mid-range frequencies (40 Hz) with sufficient displacement yield higher voltage outputs (~990 mV), making them ideal for vibration-based energy harvesting.
3. In contrast, the aircraft turbine's high-frequency vibrations (190–200 Hz) produce significantly lower voltage (~250 mV), suggesting the need for specialized transducer designs (e.g., capacitor or optimized coil configurations) to improve energy conversion efficiency in aerospace applications.
4. Vibration optimization testing is required, in which the prototype should be tested on a single machine with varying vibration frequencies. This aims to determine the prototype's optimal operating frequency.
5. This study has certain limitations. The tests were conducted on engines under specific operating conditions that may not represent their full operating range or load variations. Furthermore, the conventional electromagnetic prototype used is inherently less responsive to high-frequency, low-amplitude vibrations.
6. Future research should therefore focus on two main paths. First, comprehensive vibration optimization testing on a controlled shaker table is needed to systematically map the prototype's response to isolated changes in frequency and amplitude. Second, exploring alternative transducer architectures is crucial. For environments with high-frequency excitation forces, the use of piezoelectric, capacitive (electret), or hybrid designs is optimal for increasing energy conversion efficiency. Therefore, the energy harvesting prototype, made of a Polydimethylsiloxane (PDMS) membrane and electromagnetic components, needs improvement to be an important step towards practical implementation.

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