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PERFORMANCE ANALYSIS OF ELECTROMAGNETIC VIBRATION ENERGY HARVESTING DUE TO DIFFERENT VIBRATION SOURCES

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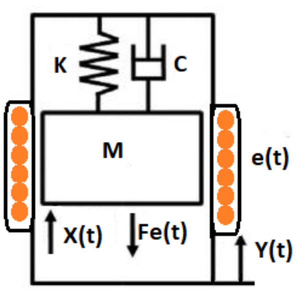
Graphical abstract



Abstract

As industry requires more real-time monitoring and interconnected systems, the need for wireless sensors will increase. Vibration Energy Harvesting (VEH) has played an important role as an alternative energy source to provide power to wireless sensors. In this paper we report the analysis of an electromagnetic energy harvester driven by vibrating plate. An experimental method where energy sources originating from vibrating mechanical machines were used. Mechanical machines such as milling machines, dynamic rotors, and four-stroke engines were implemented to prove the performance of the device. where the output signal from the vibration source is measured using a CF-3600 FFT analyzer, while the output signal from the electromagnet is measured using an oscilloscope (Hantek 6022BE). This paper has discussed several sources of vibration originating from industrial equipment with a vibration source frequency of around 10 to 100 Hz. The findings show that the voltage produced by an electromagnetic energy harvester is 130 mV, 120 mV, and 30 mV on a milling machine, dynamic rotor, and four-stroke engine. Additionally, the results contribute to the optimization of vibration energy harvesting parameters, facilitating the maximization of energy extraction in diverse applications.

Keywords: Vibration energy harvesting, electromagnetic, vibration source, frequency, voltage

Abstrak

Memandangkan industri memerlukan lebih banyak pemantauan masa nyata dan sistem yang saling berkaitan, keperluan untuk penderia wayarles akan meningkat. Penuaian Tenaga Getaran (VEH) telah memainkan peranan penting sebagai sumber tenaga alternatif untuk membekalkan kuasa kepada penderia wayarles. Dalam makalah ini kami melaporkan analisis penuai tenaga elektromagnet yang didorong oleh plat bergetar. Penyelidikan ini dijalankan menggunakan kaedah eksperimen di mana sumber tenaga yang berasal daripada mesin mekanikal bergetar, seperti mesin pengisar, pemutar dinamik, dan enjin empat lejang dilaksanakan untuk membuktikan prestasi peranti. di mana isyarat keluaran daripada sumber getaran diukur menggunakan penganalisis CF-3600 FFT, manakala isyarat keluaran daripada elektromagnet diukur menggunakan osiloskop (Hantek 6022BE). Kertas kerja ini telah membincangkan beberapa sumber getaran yang berasal daripada peralatan industri dengan frekuensi sumber getaran sekitar 10 hingga 100 Hz. Dapatan kajian menunjukkan bahawa voltan yang dihasilkan oleh penuai tenaga elektromagnet ialah 130 mV, 120 mV, dan 30 mV pada mesin pengisar, pemutar dinamik, dan enjin empat lejang. Selain itu, hasilnya menyumbang kepada pengoptimuman parameter penuaian tenaga getaran, memudahkan pemaksimuman pengekstrakan tenaga dalam pelbagai aplikasi

Kata kunci: Penuaian tenaga getaran, elektromagnetik, sumber getaran, frekuensi, voltan

1.0 INTRODUCTION

In 2010, many countries were aware of the importance of using renewable energy sources as the replacement for conventional energy like oil, coal, and gases that mostly have a negative impact on the earth. Nowadays, one of the most developed energies is vibration-harvesting energy. Vibration harvesting energy has attracted scientists as an alternative way to replace conventional internal energy sources, which are generally in the form of primary batteries [1].

The vibration energy source can originate from fatigue of machines, structures, buildings, bridges, pipelines, and also other electrical and mechanical equipment [2], which is then transformed into electrical energy through piezoelectric, electrostatic, and electromagnetic methods [3], [4]. Therefore, electromagnetic energy harvester has great potential to achieve self-powered implantable systems and power for low-power electronic monitoring systems [5], [6]. The great feature of electromagnetic harvesting is the ability to capture the kinetic energy in the low-frequency range [7]. Electromagnetic energy harvesting using rectangular permanent magnetic order as spring resistance mass and ferrofluid as lubricant material produces a maximum output power of 71,26μW, and a device with ferrofluid lubricant could produce 40,8Ω [8]. Energy harvester could produce output voltage/current and power of 8,35 V/17,39 mA and 15,13 mW (proper resistance of 200 Ω) at the acceleration of 5 $m{\cdot}s^{-2}$ [9]. The influence of spring stiffness, load weight, and movement speed will affect the energy-consuming vibration performance [10].

The energy harvesting technique offers an easy working mechanism, an inexpensive fabrication process, scalability, and adaptability [11]. Tensile stress boosts the Electromagnetic Vibrational Energy Harvester (EVEH) resonance frequency, while compressive stress first reduces the resonance frequency and then improves the resonance frequency due to buckling [12]. Harvester in a bridge result in a peak load voltage of 0.27 V and peak power of 0.13 mW at a resistive load of 555 Ω and peak bridge acceleration of 0.024 g. On the second bridge with a peak acceleration of 0.017 g, the harvester could produce a load voltage of 0.32 V and a power of 0.18 mW [13]. It can be seen that an energy harvester with a magnet could result in a normal induction voltage, which is real at 0.7 Hz. In contrast, the energy harvester without a magnet still needs an excitation frequency of 1,0 Hz to reach a similar level [14]. Using energy involves harvesting electrodynamic vibration energy generated by the tension in wires and beams. These structures vibrate in response to turbulence, creating external forces that result in the isolation of the cylinder [15]. An analysis of the electro-mechanical characteristics of the actuator reveals that the 20 μm silicon membrane can undergo deformation of up to 4.5 μm, a deformation that diminishes notably with increasing input current. The maximum deflection height was observed at an input power of 800 mWatt [16]. Small embedded power harvesters must rely on energy harvesting systems capable of capturing milliwatts of energy from sources such as light, vibration, heat, or other extremely low-power energy outlets. The collection of energy obtained from vibrations due to ignition of the vehicle's brakes will result in a voltage that is only significant at low vehicle speeds [17].

These micro-powered energy harvesters are crucial in extending battery life across consumer, industrial, and medical applications. This is particularly essential since replacing the battery may prove challenging, expensive, or even impossible in certain scenarios. With meticulous design, energy harvesting devices can potentially replace batteries altogether. Therefore, this research paper aims to explore the utilization of Vibration Energy Harvesters (VEHs), designed to convert energy from external vibration sources into electrical power, thus enabling the operation of small equipment. The specific sources of vibration examined in this study include milling machines, rotor dynamics testing machines, and single-cylinder Four-stroke engines.

2.0 METHODOLOGY

The primary objective of this research is to analyze the mechanical and electrical characteristics of the Vibration Energy Harvester (VEH) illustrated in Figure 1. The overall dimensions of the device are 70 mm × 70 mm × 50 mm, made by joining two silicon wafers. The springs, processed through wire cutting, are made from copper, measuring 70 mm x 70 mm x 0.4 mm. This configuration results in a compact linear generator comprising a seismic mass mounted on a mechanical spring plate (Figure 2). the structure is designed to induce up-and-down movement of a magnet in response to vibrations. Copper coils surrounding the magnet are responsible for converting external vibrations into electrical energy. As depicted in Figure 2, the VEH comprises three main components: the spring plate, coil turn, and magnet. The spring plate, made of copper, possesses a modulus of elasticity of 117 GPa, a density of 8.92 g/cm³, and a tensile strength of 200 – 360 MPa.

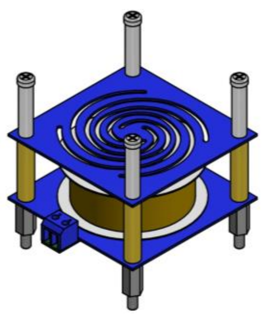


Figure 1 Vibration Energy Harvester

The seismic mass is assembled from three main constituents. A flat cylindrical magnet crafted from neodymium-ferrite (NdFeB, grade N55), with a density of 7.6 g/cm³ and a flexural strength of 285 MPa. Then, the coil consists of 700 turns of wire with a diameter of 0.2 mm. The connector linking the core to the mechanical spring is composed of copper material.

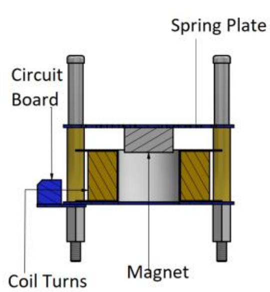


Figure 2 The structure of Vibration Energy Harvester components

2.1 Mathematical Model Electromagnetic Energy Havesting

Since most of the transducer mass is concentrated in the seismic mass and the stiffness of the metal spring is much lower than that of other components, a one-degree of Freedom (DoF) equivalent system can be considered to describe its dynamic behavior when harmonics are present. Excitation is applied to the generator base, in this case, the outer ring [18]. In Figure 3, the corresponding free-body diagram for such a system is shown, where the vertical displacement of the magnet with respect to time is represented by x(t). From Figure 4, we get the Equation (1).

$$m\ddot{z}(t) + c\dot{z}(t) + kz(t) + NBli\dot{z}(t) = -m\ddot{y}(t) \quad (1)$$

Where m is the permanent mass of the magnet, c is the damping of the spring plate material, and k is the spring plate constant. Meanwhile, from Figure 5, we obtained the equation (2). N is the number of coils, B is the amount of magnetic flux, and l is the length of the coil wire

$$NBli\dot{z}(t) - L\frac{di(t)}{dt} - R_{coil}i(t) - R_{Load}i(t) = 0 \quad (2)$$

$$F_e = d_e\dot{z}(t) \quad (3)$$

$$P(t) = F_e\dot{z}(t) \quad (4)$$

where i(t), Rc, RL, L, N, B, l represents the current flowing in the circuit, coil resistance, load resistance, coil inductance, number of coils turns, magnetic flux density, and circumference. coil length. Fe(t) is the electromagnetic force, expressed as NBli(t), and Voc is the induced electromotive force, expressed as NBlz(t), seen in Figure 5.

The product of electrical damping and relative speed is expressed as electromagnetic force, and if speed is used again, it can be expressed as uniform power.

If vibration occurs, it will produce a power of:

$$P = \frac{mY_0^2\,\zeta r^3\omega}{[(1-r^2)^2+(2\zeta r)^2]} \quad (5)$$

where, r = ω/ω_n, where ω is the excitation frequency, ω_n is the system resonance frequency, ζr is the mechanical damping ratio, and Y_0 represents the maximum amplitude of the absolute displacement.

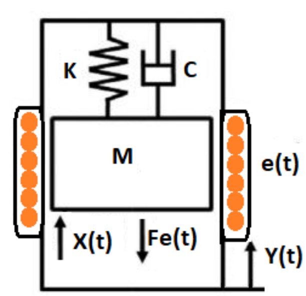


Figure 3 Vibration Energy Harvester

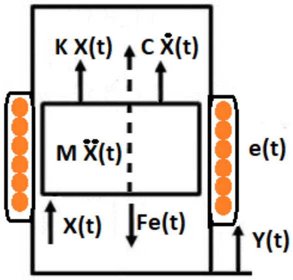


Figure 4 Free body diagram of a mechanical system

The generated power is intricately influenced by various factors, namely the frequency, weight of the permanent magnet, and the maximum induced vibration. In the context of electromagnetic harvesting energy, the mechanical system is intricately linked to the electrical system. By amalgamating the elements expressed in Equation (2), the resultant outcome is aptly represented by Equation (6).

$$P = \frac{mY_0^2\ \omega^3 S^2}{8\zeta_T^2(R_L+R_C)} \tag{6}$$

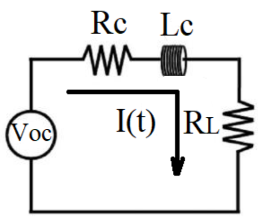


Figure 5 Electrical System

where ζ_T is a value that includes the mechanical damping ratio (ζ) and electrical damping ratio (ζe). By using equation (6), the position of the moving magnet, which is an element is ignored. A function of the magnetic flux density produced in the coil, the current flowing in the coil functions to dampen electromagnetism that occurs between the magnets. Errors can occur because the spring constant is expressed with an approximate force.

2.2 Experiment

In this study, vibration comes from milling machines [19], rotor dynamics [20], and Four-stroke engines [21]. The choice of vibration source is because these three machines are often found in the machining industry, where milling machines are one of the machine tools that have an important role in the manufacturing and machining industry. Apart from that, in the machinery industry there is a one cylinder four stroke engine portable air compressor which of course will experience rotor dynamics [22]-[25]. The physical behavior of rotating machines is strongly influenced by vibration, which is exacerbated by the rotation and structure of the machine itself. Standardizing the rotational speed of the vibration source at 60 is a crucial aspect of the experimental design. A schematic representation of the measurement circuit integrated into the system is illustrated in Figure 6.

In Figure 6 Vibrations generated by the sources were measured using the FFT analyzer CF-3600, manufactured by Ono Sokki in Japan. The Ono Sokki settings encompass a frequency range of 0 – 5 kHz, employing a Hanning window with a dataset of 4096 points. The FFT analyzer is directly connected to an accelerometer, which is strategically positioned on the vibration source. Subsequently, in the same orientation, the vibration energy harvesting apparatus is affixed to the vibration source. Measurements were carried out using a digital PC oscilloscope from HANTEK 6022BE which is an oscilloscope device connected to a computer. The vibration energy harvesting prototype is characterized by a variable magnetic force modulated by the proximity of a mobile permanent magnet located within the coil. This magnetic force adjustment is contingent upon the external excitation frequency originating from the vibration source.

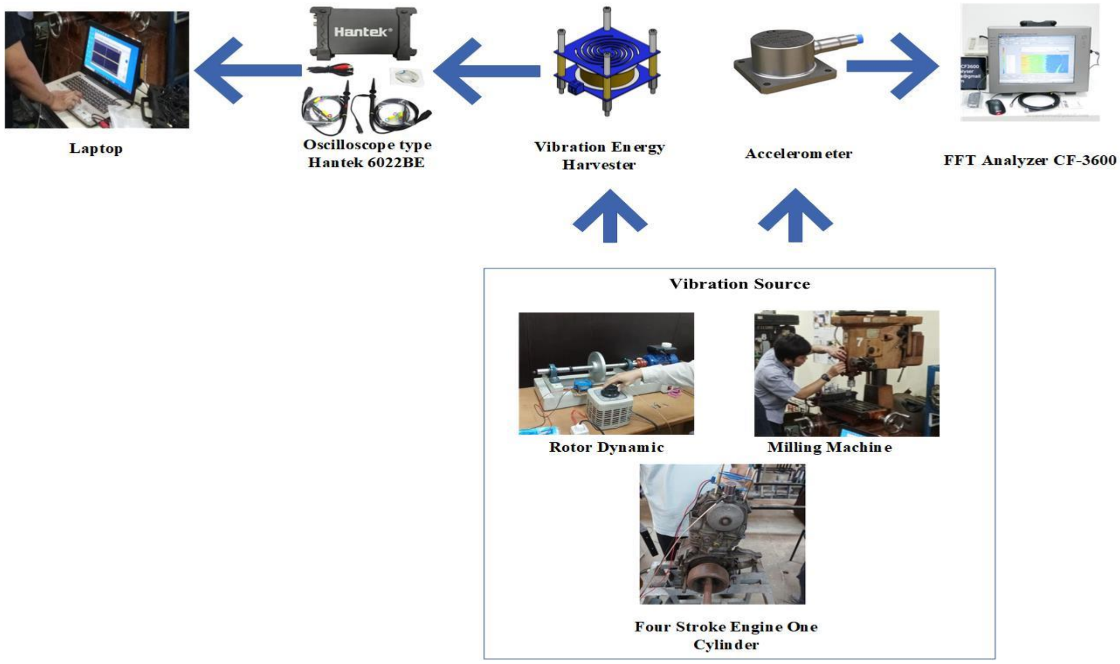


Figure 6 Vibration measurement of three vibration sources in the time domain

3.0 RESULTS AND DISCUSSION

3.1 Mechanical Energy

This study explores the extraction of mechanical vibration energy from various vibration sources, specifically a Four-stroke engine, dynamic rotor, and a milling machine. All machines are operating at a consistent rotational speed of 1200 rpm or 60 Hz. To induce mechanical vibrations in the milling machine, a depth of 2 mm is achieved through an ingestion process into iron material. A 10-gram eccentric mass is introduced in the dynamic rotor case.

Figure 7 shows the raw signals (m/s^2 (rms)) acquired from various vibration sources, specifically a Four-stroke engine, dynamic rotor, and a milling machine in the time domain. On a Four-stroke engine, it is shown that the resulting signal produces an impulse signal. The signal originated from the collision between the rocker arm component and the airflow valve. Interestingly, no impulse signal was detected in the dynamic rotor vibration source and the milling machine. Subsequently, a fast Fourier transformation was employed to analyze the frequency characteristics at the vibration source, as depicted in Figure 8. Within the mechanical system of the vibration source, the Four-stroke engine exhibited a dominant frequency in the first shape mode at 60 Hz. In contrast, the milling machine's first shape mode occurred at 75 Hz, while the dynamic rotor's first shape mode was observed at 45 Hz. This observation implied that the dynamic rotor had the lowest vibration frequency, followed by the milling machine, and the highest frequency was recorded in the four-stroke engine.

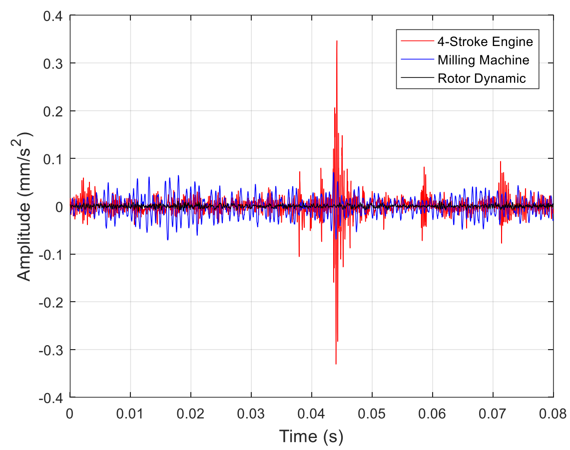


Figure 7 Vibration measurement of three vibration sources in the time domain

3.2 Energy Harvesting

This paper proposes the design and harvesting of electromagnetic energy using the stiffness of metal springs. Energy harvesters are contained to produce energy from low frequency vibration sources of less than 100Hz and ensure effectiveness over a broad frequency bandwidth [26]. During the conversion between mechanical and electrical energy in a machine, or vice versa, there is usually vibration (or rotational speed disturbance). This vibration can be converted into electrical energy using harvesting energy vibrations, the source of vibration from the milling machine is caused by strong shocks, which occur during cutting of material. whereas in dynamic rotors the source of vibration comes from Unbalance, Misalignment, Bearing Failure, Rub and Looseness. In four-stroke engines, the source of vibration comes from torsional vibrations and translation of the engine block is known to be mainly influenced by the gas combustion force and the inertial force of the reciprocating mass.

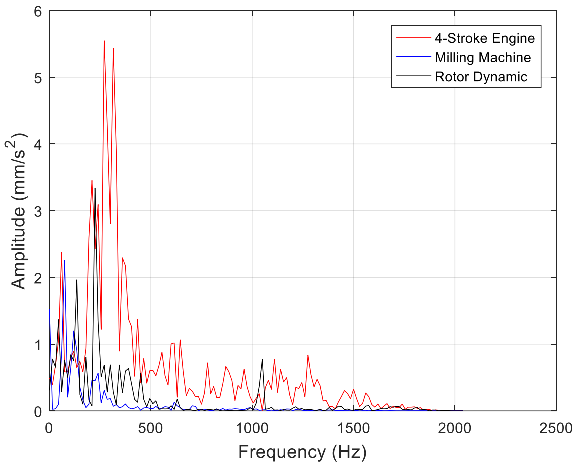


Figure 8 Results of Vibration source FFT

Therefore, in this paper, a real application of vibration-based energy harvesters due to these three vibration sources will be carried out. The output voltage is measured by the oscilloscope type Hantek 6022BE. An oscilloscope is used as a tool to read the signal form generated from the energy harvester and send the signal form to a personal computer, so that it can see the signal form in the time domain, as shown in Figure 9. The resulted signals are observed using oscilloscope. Notably, in the vibration source arising from the Four-stroke engine, it is evident that the resulting voltage surpasses that observed in the vibration sources originating from the milling machine and dynamic rotor machine. Specifically, the dynamic rotor yields a comparatively lower voltage output when compared to the other vibration sources. Subsequently, an essential step is taken following the observations in Figure 9 – a Fast Fourier Transform (FFT). This procedure aims to unveil the frequency domain in electromagnetics resulting from the impact of the vibration source, as illustrated in Figure 10.

In Figure 10, it is evident that the vibration source of the Four-stroke engine yields a voltage of 700 mV at a frequency of 400 Hz. In contrast, the vibration sources from the milling machine and dynamic rotor produce a voltage of 130 mV at a frequency of 550 Hz. This discrepancy underscores that the vibration source stemming from the Four-stroke engine generates a notably higher voltage compared to the voltage originating from the other two vibration sources. The heightened voltage in the Four-stroke engine is attributed to the impulse signal arising from the collision between the rocker arm and the exhaust valve, along with the incoming airflow characteristic of the Four-stroke engine. Subsequently, the analysis will progress to a Hilbert transform for further insights.

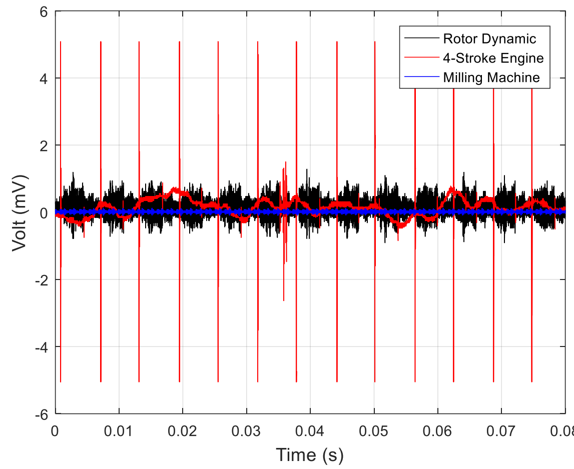


Figure 9 Measurement Results in the Time Domain on the Vibration Energy Harvester

The Hilbert method was employed to analyze the correlation between frequency and time, voltage and frequency, and the utilization of Equation (6) for power over time. This method served as a tool for decision-making in normal conditions or for showcasing damage detection in alternators [27]. The Hilbert method revealed that the frequency relationship (Hz) on the milling machine exhibited a higher frequency value compared to the two other vibration sources. As illustrated in Figure 11, the vibrations resulting from the linear movement process of the milling cutter generated a stable frequency in electromagnetic energy harvesting.

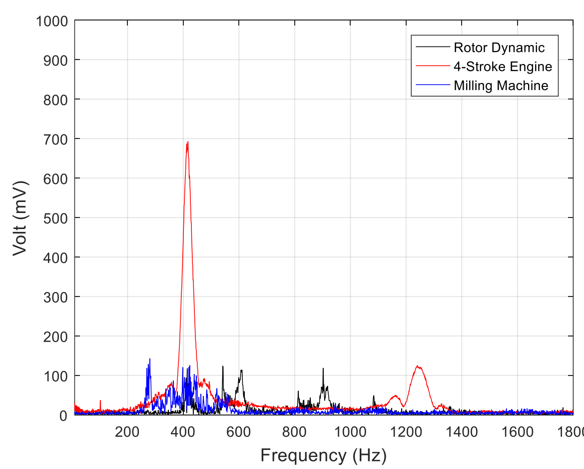


Figure 10 FFT analysis at Vibration Energy Harvester

By introducing an unbalanced mass onto the dynamic rotor, the excitation force was heightened, leading to vibrations. These vibrations, in turn, caused the magnet to move up and down, inducing corresponding movements into the coil, as depicted in Figure 12. Figure 12 illustrates that the resultant frequency remains stable but is lower in comparison to Figure 11.

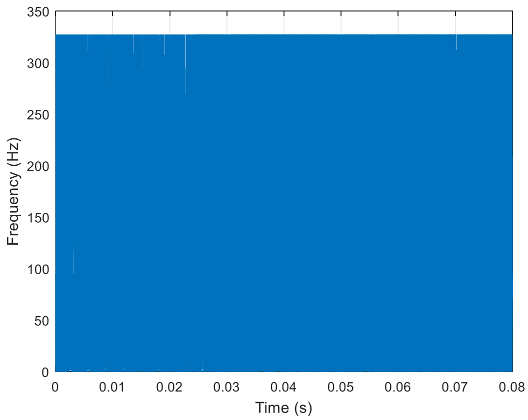


Figure 11 Milling machine

This discrepancy arises from the relatively modest eccentric mass introduced, contributing to a stable dynamic rotor rotation and consequently yielding a lower electromagnetic frequency. Increasing the eccentric mass would escalate the excitation force, potentially leading to a higher resultant frequency. In Figure 13, the relationship between frequency and time in electromagnetic energy harvesting from the vibration source in a Four-stroke engine is presented. The unstable frequencies observed in Four-stroke engines were generated during electromagnetic energy harvesting, primarily due to the placement point above the rocker's arm. In the locker arm, backlash occurs between the locker arm and the exhaust and suction air duct valves. However, the resulting frequency was akin to that in Figure 6b, hovering around 80 Hz.

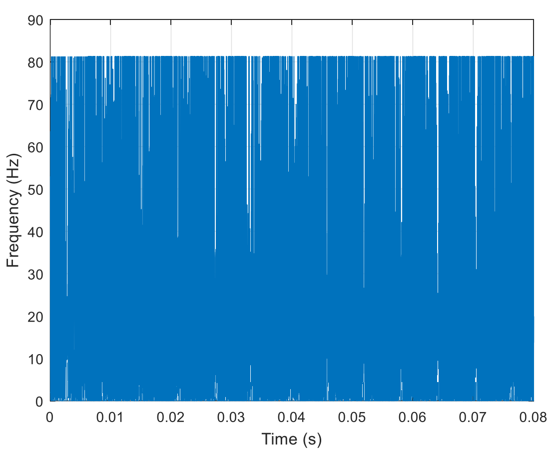


Figure 12 Rotor dynamics

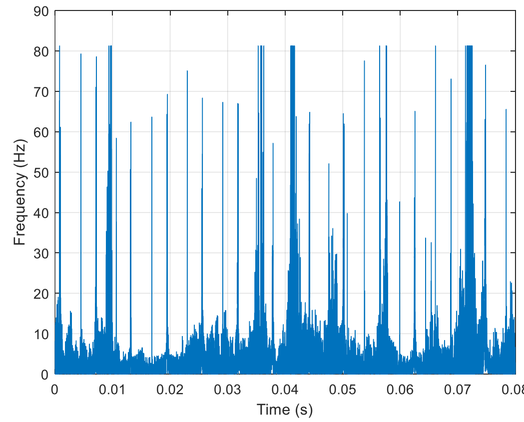


Figure 13 Four-stroke engines

The correlation between the resultant frequency for the operating frequency of the device at f<100Hz and the corresponding voltage is depicted in Figure 14, 15 and 16. Notably, on the milling machine, the impact of a 3 mm Pa ingestion is evident at a frequency of approximately 100 Hz, yielding a voltage of around 130 mV, as illustrated in Figure 14. This differs from the voltage generated by the eccentric mass of the dynamic rotor, which exhibits a lower frequency of around 15 Hz, resulting in a voltage of 120 mV, as demonstrated in Figure 15.

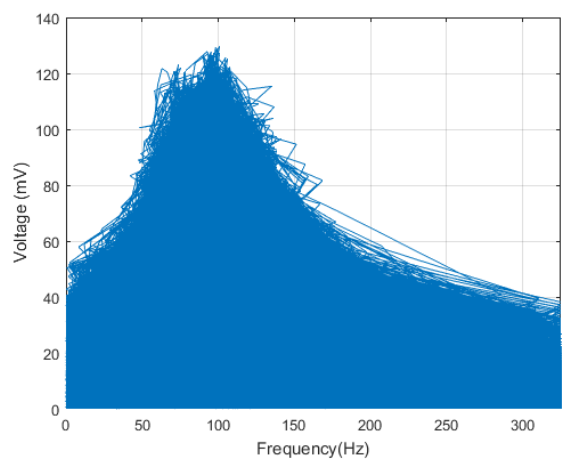


Figure 14 Milling machine

The intriguing aspect of this research lies in the voltage produced by the Four-stroke engine, indicating that the voltage increases with frequency, as depicted in Figure 16. Specifically, Figure 16 illustrates that the resulting voltage is approximately 30 mV at a frequency of 20 Hz. The phenomenon observed in the relationship between voltage and frequency in a 4-stroke reciprocating motor highlights a nonlinear characteristic. Consequently, this nonlinear behavior suggests that the system design is not well-suited for utilization as a vibration source of the developed energy harvester device [28].

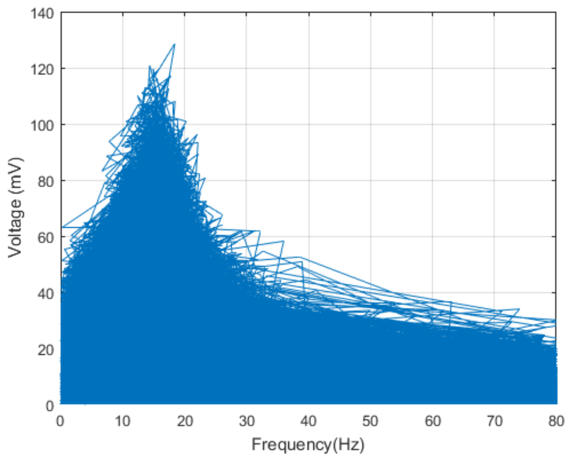


Figure 15 Rotodynamic

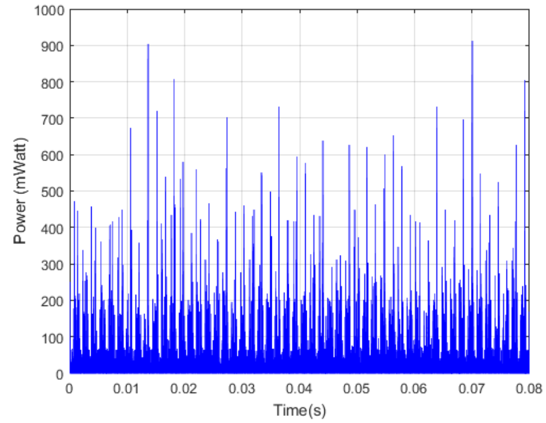


Figure 18 Milling machine

Equation (6) represents the correlation governing the power produced, elucidated in Figure 18, 19, 20. This figure elucidates the intricate relationship between power and time, commonly referred to as instantaneous power. Instantaneous power, a periodic function of time, is distinctly portrayed. Notably, the ratio of the pulse duration to period corresponds precisely to the ratio of average power to peak power. In Figure 18, it is evident that the obtained power hovers around 900 mW, exhibiting fluctuations over time. The power production demonstrates a periodicity closely aligned with time.

The power generated from the vibration source of the dynamic rotor, as illustrated in Figure 19, displays a power density of approximately 600 mW, diverging from the observed power dynamics. Meanwhile, the power derived from the vibration source of the 4-stroke reciprocating motor exhibits a more relaxed periodicity when juxtaposed 20with the vibration sources originating from the milling machine and dynamic rotor, as depicted in Figure 20. This impact imposes additional constraints on the attainable electrical power and is explored in the subsequent section. This exploration is undertaken with the aim of enhancing the power output.

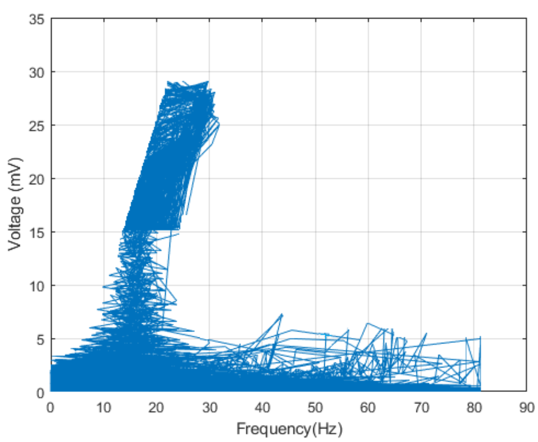


Figure 17 Four-stroke engine

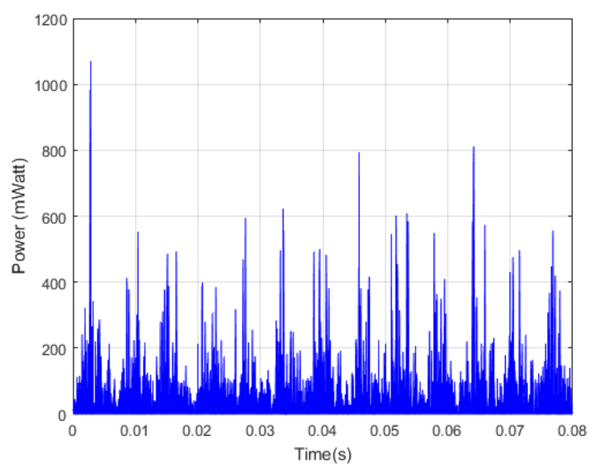


Figure 19 Rotodynamic

Contrasting with the power generated from the vibration source of the dynamic rotor, which reveals a power density of approximately 600 mW in Figure 19, the power obtained from the vibration source of the 4-stroke reciprocating motor exhibits a more relaxed periodicity. This distinct periodic behavior is apparent when compared to the vibration source of the milling machine and dynamic rotor, as depicted in Figure 20.

4.0 CONCLUSION

This paper details the outcomes of experiments focused on harnessing energy from vibrations through electromagnetic means across various sources, including milling machines, dynamic rotors, and single-cylinder Four-stroke engines. The analysis reveals that linear energy harvesters exhibit superior output power in comparison to nonlinear counterparts [29]. The findings underscore the critical influence of application-specific considerations on the design of vibration energy harvesters. Through these experiments, we gain valuable insights into selecting the most suitable type and transduction mechanism for a given application. Furthermore, the results contribute to the optimization of vibration energy harvesting parameters, facilitating.

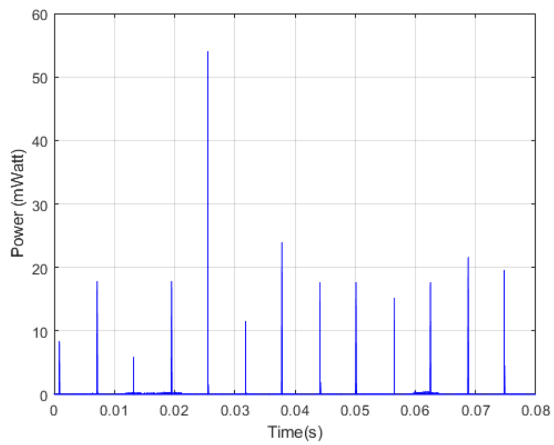


Figure 20 Four-stroke engine

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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