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Micropower design of energy harvesting based on piezoelectric transducer array circuit

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ABSTRACT

This article reveals the conceptualization and implementation of energy harvesting system that utilize piezoelectric arrays within environments marked by elevated ambient noise levels. The selected methodology involves conducting an empirical study where the system is introduced into a room with pronounced ambient noise. A series configuration is adopted for assembling the piezoelectric sensors. For this particular experiment, 36 piezoelectric sensor units were arranged, each equipped with a voltage doubler circuit, aiming to harness a specific micropower energy threshold. The experimental results validate the successful development of an energy harvesting mechanism employing a piezoelectric array within a noisy setting. Notably, the device functions optimally at a frequency of 250 Hz. Additionally, a series of controlled experimental tests were executed at a sound level of 95.8 dBA to assess the efficacy of the piezoelectric array. Measurements taken at the voltage doubler output reveal that the device achieves its peak output signal at 3.32 Vpp and 50.42 Hz. The maximum attainable direct current (DC) voltage stands at 1 Volt, complemented by a current of 0.45 mA.

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1. INTRODUCTION

Energy harvesting, commonly referred to as energy scavenging or power harvesting, is an innovative approach to generate usable energy by utilizing the existing sources present in the surrounding environment [1]. The process involves harnessing various forms of naturally occurring energy, such as sunshine [2], [3], radio frequency (RF) signals [4], [5], mechanical vibrations [6], [7], thermal gradients [8], [9] and usually converting them into electrical energy for a wide range of applications [10]. The concept outlined above has received considerable attention in recent years because of its ability to provide sustainable and self-sustaining power solutions for a wide range of devices and systems.

The energy harvesting technique is a technological methodology that enables the generation of electrical power by obtaining small amounts of energy from one or more nearby energy sources [11]. In order to mitigate the concern around the dependence on traditional energy sources derived from fossil fuels, the implementation of energy harvesting techniques may offer a viable and ecologically sustainable substitute in the shape of renewable energy [12]. Energy harvesting operates on the fundamental principle of converting extremely minute quantities of unused energy into usable electrical energy that can then be stored and utilized to power electronic devices [13]. This technique exhibits potential in situations where conventional power sources, such as electrical outlets or batteries, are impracticable, cumbersome, or unsustainable over an extended period of time. Energy harvesting systems are anticipated to offer significant benefits not just in remote areas but also in numerous industrial sectors, wearable electronics, and internet of things (IoT) devices [14].

Energy harvesting systems typically consist of three main components: energy transducers or sensors, power management circuits, and energy storage devices [15]. Energy transducers, such as solar panels, piezoelectric materials, thermoelectric generators, and electromagnetic coils, are employed to collect and convert ambient energy into electrical energy. Power management circuits play a crucial role in the control and enhancement of harvested energy to effectively cater to the unique demands of the intended devices. Moreover, energy storage components such as supercapacitors or batteries are employed to store any excess energy for subsequent utilization in scenarios when the acquired energy is insufficient or inaccessible [16].

Energy harvesting technology offers various advantages, such as reducing environmental impact, prolonging device lifespans, and lessening dependence on traditional power sources that might not be renewable or have restrictions [17]. Applying this technology shows potential in advancing self-sustaining systems, enhancing energy efficiency, and introducing new features in devices previously limited by power constraints [18]. Previous research [19] successfully developed a substation monitoring system. The installation expenses can be notably decreased by employing WSN and this device utilizes an energy harvesting mechanism.

The potential applications of energy harvesting technology are extensive, encompassing several areas such as supplying power to remote sensors and wireless sensor networks, enhancing the capabilities of wearable devices, and integrating energy harvesting into intelligent infrastructure. Sound energy, (concentration of this article) is a widely experienced and widespread form of energy. The allocation of acoustic energy is observed within a frequency spectrum that extends from 20 Hz to 20 kHz, namely in the form of audio frequencies. Certain geographical areas exhibit a conspicuous prevalence of auditory phenomena or things that emit sound, notably in sectors where industrial apparatus with high sound intensity is regularly utilized. Various energy harvesting techniques can be utilized to capture the abundant sound energy that exists in the natural world [20].

The evolution of materials and structures in the field of piezoelectric energy harvesting is done by [21]. It emphasizes the development of novel designs and materials to boost the effectiveness and efficiency of piezoelectric energy harvesting systems. Piezoelectric possesses the capacity to serve as a transducer, facilitating the conversion of sound energy into electrical energy. Piezoelectricity is a phenomenon that is distinguished by the production of an electric charge on the surface of a material when it is exposed to an externally applied force [22]. The extraction of piezoelectric energy is contingent upon the amplitude of the vibrating source and its resonance frequency. To attain the utmost potential output voltage, it is important for the piezoelectric material to undergo a vibration of increased magnitude, thereby nearing its resonant frequency. Piezoelectricity is frequently employed as a means of energy harvesting in many ways. One approach to harnessing energy from rainfall involves the application of energy harvesting methodologies. Piezoelectric materials demonstrate a pronounced response when exposed to the impact of precipitation, leading to the production of electrical energy. Previous studies have investigated the utilization of piezoelectric implementations as prospective energy harvesters in situations characterized by elevated levels of noise [23]. Moreover, there have been research efforts focused on exploring the potential of piezoelectric systems in the realm of vibration sensing and dynamic movement detection. Additionally, a separate study investigated the application of piezoelectricity for the purpose of extracting energy from the acoustic emissions produced by vehicles as they traverse roadways [24].

Diverse structural configurations, including arrays and composites, and the use of various piezoelectric materials are investigated in an effort to optimize the conversion of mechanical vibrations into energy. The authors explain how these advancements have increased the overall functionality and applicability of piezoelectric energy harvesting technologies, thereby advancing the field in terms of research and application. Another experiment [25], [26] focuses on the development and evaluation of energy harvesting systems based on piezoelectric tube stacks in the context of railway environments. The study highlights the unique challenges and opportunities presented by vibrations from railroad operations. The authors describe the design considerations, including the arrangement and configuration of piezoelectric tubes, that are necessary for the efficient extraction of energy from mechanical vibrations caused by train motion. Through experimental evaluation, this paper quantifies the energy yield and efficiency of the proposed system, providing valuable insights into the practicability and effectiveness of piezoelectric tube stack energy harvesters for capturing energy from railway infrastructure. Sarker *et al.* [27] provides an exhaustive analysis of piezoelectric energy harvesting systems and the application of optimization techniques to improve their performance. The article focuses on design, materials, and applications. The importance of optimization techniques is emphasized, along with the significance of enhancing energy conversion output and efficiency. This article examines how structural and parameter optimization improves the overall functionality of piezoelectric energy harvesting systems for a variety of applications.

A notable contribution to the field lies in the experimental design and implementation of a piezoelectric array configuration tailored for enhanced energy harvesting from ambient noise, particularly from a winder machine's generated noise. This configuration leverages the piezoelectric array's capability to yield higher voltage levels, strategically positioned to optimize energy production. Integration with a voltage doubler circuit amplifies the generated signal, converting it into direct current (DC) voltage. Such innovations not only support the efficiency of energy harvesting systems but also position them as viable alternatives for powering low-energy electronic devices, marking a significant stride towards sustainable and eco-friendly energy solutions.

2. METHOD

The flowchart illustrating the energy harvesting system in a noisy room is presented in Figure 1. The primary objective of this study is to investigate the utilization of piezoelectric array transducers that are organized in a sequential manner for the purpose of energy harvesting inside environments characterized by high levels of noise. The origin of the auditory disturbance is derived from the operation of winding machines, which are abundant within the confines of an industrial space. The piezoelectric arrays are organized in a series configuration consisting of 36 individual components, with each group including four arrays. These arrays are connected to an oscillator constructed from flexible nylon material. The oscillator under consideration has a configuration like that of a cantilever beam, characterized by a lengthy and slender rod-like structure. In this arrangement, one extremity of the beam is securely fixed, while the opposite end is capable of unrestricted movement. The oscillator has been specifically engineered to produce sound frequencies that are generated by the winder machine. The oscillator is set into motion by the sound and vibration produced by the winder, along with the accompanying piezoelectric array that is connected to it.

Piezoelectricity, functioning as a transducer, has the ability to produce an alternating current (AC) voltage due to the oscillation of the cantilever beam. The alternating current (AC) voltage is subsequently transformed into DC voltage by the utilization of a voltage doubler circuit. In addition to its capacity for converting AC voltage to DC voltage, the voltage doubler circuit possesses the capability to amplify the input AC voltage level. The voltage doubler circuit has the ability to generate a DC output voltage of 2 times the peak voltage (2 Vpp) from the input voltage supplied by the piezoelectric array. The voltage output of the voltage doubler circuit is measured by utilizing a microcontroller that is based on the ESP microcontroller unit. The utilization of a microcontroller is employed in order to capture and document the voltage level of the output, thereby mitigating the impact of capacitor discharge during measurements conducted with a multimeter. The voltage doubler circuit's output voltage data is recorded in the comma separated value (CSV) format on the MicroSD card. The system receives input in the form of noise and vibration generated by the winder machine. The cantilever beam oscillator may exhibit vibrations in reaction to noise and vibrations originating from the winder machine. The AC voltage is generated by the piezoelectric array that is affixed to the beam and undergoes vibration and response. Upon entering the voltage doubler, signal undergoes a process of multiplication and rectification, resulting in the generation of a direct current (DC) voltage. Simultaneously, the voltage logger, which utilizes the ESP32 microcontroller, fulfills its function of documenting the output voltage magnitude of the voltage doubler circuit. Subsequently, the voltage level data should be stored in comma-separated values (CSV) format on a microSD card.

The piezoelectric array circuit is configured in a series arrangement consisting of up to 36 individual components, with the objective of achieving the highest possible peak voltage. A total of six oscillators are mounted as a cantilever beam, with each oscillator accommodating four piezoelectric elements connected in series. The schematic diagram in Figure 2 illustrates the arrangement of a piezoelectric array that is coupled in a series configuration. The system will consist of two output lines, each capable of producing both positive and negative voltages. These output lines will be afterwards connected to either a voltage doubler circuit or a voltage multiplier circuit.

The electrical output produced by the piezoelectric configuration is subsequently linked to a voltage doubler circuit. The voltage doubler circuit utilized in the system is depicted in Figure 3. The voltage doubler circuit employs a pair of 1N4001 diode, while two 47µF capacitors are utilized to mitigate ripple and generate a smoother. The DC voltage output of the diode-capacitor circuit is equivalent to the peak-to-peak value of the input signal derived from the piezoelectric array. Put simply, this circuit has the ability to amplify the peak value of the input signal by a factor of two due to the effective collaboration between the diode and capacitor. The resulting output current of the voltage multiplier circuit is determined by the presence of a load resistor.

The measurement of output voltage can be conducted by employing an oscilloscope and a digital multimeter. However, in specific instances, the utilization of a digital multimeter for voltage measurement has the potential to significantly deplete the voltage stored in the capacitor. In order to mitigate voltage depletion during the voltage measuring procedure and enhance the quality of data records, a microcontroller based on the ESP32 platform is employed. Figure 4 depicts a set of voltage loggers employing the ESP32 microcontroller, which is seamlessly integrated with the MicroSD module to serve as a data storage medium for capturing and storing voltage level measurements. Figure 5 illustrates the configuration of a piezoelectric array consisting of six piezoelectric elements interconnected in a series arrangement. This array is strategically positioned near the center of the beam, and it is accompanied by two output cables, one for positive and one for negative electrical signals.

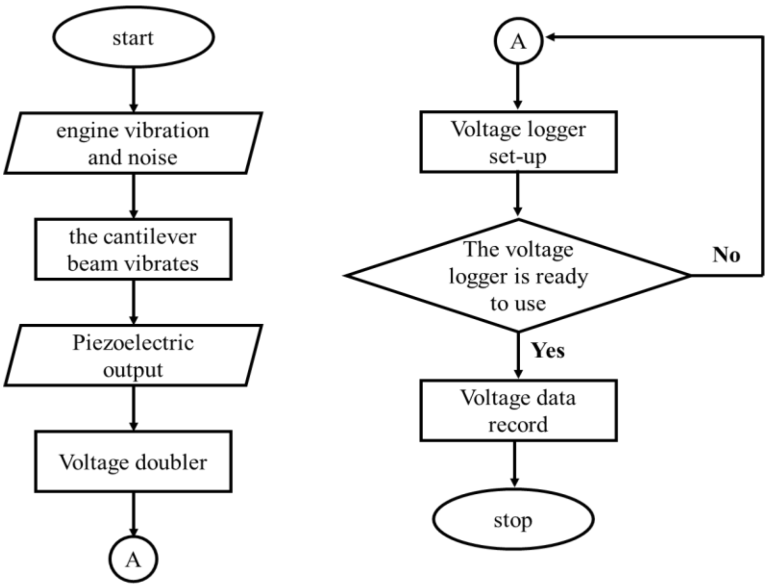

Figure 1. Flowchart system

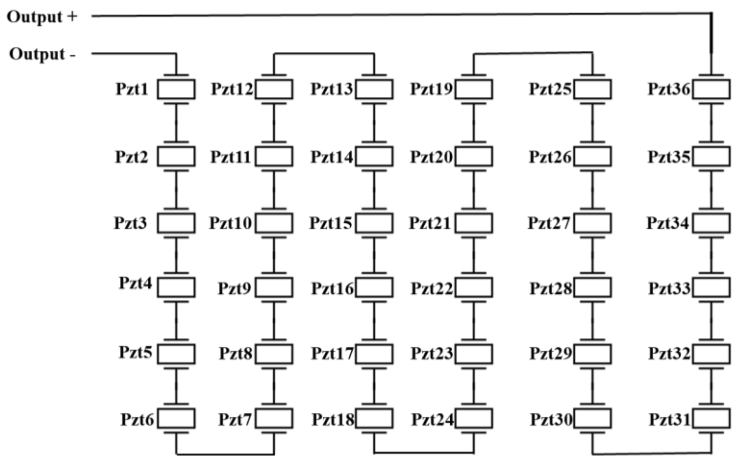

Figure 2. Array of piezoelectric

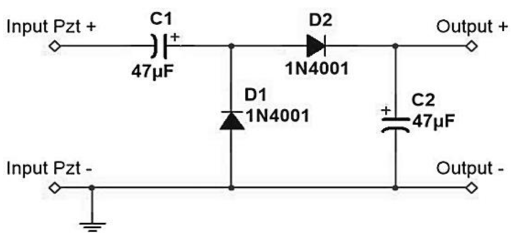

Figure 3. Voltage doubler circuit

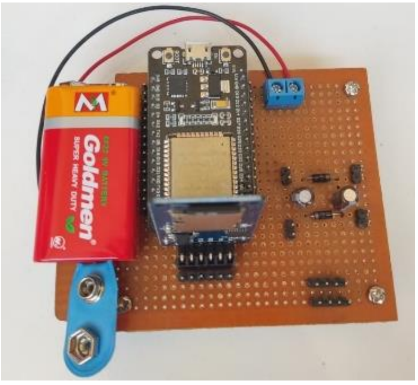

Figure 4. Voltage logger circuit based on ESP32

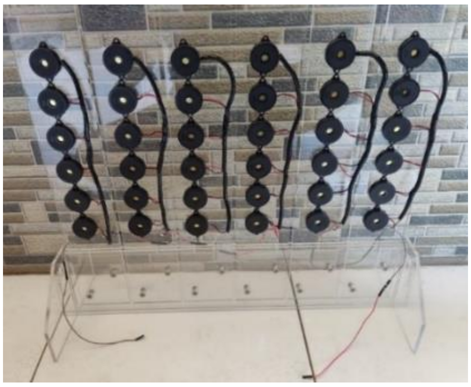

Figure 5. Array piezoelectric

3. RESULTS AND DISCUSSION

3.1. Measurement of noise levels in a room with sound pressure level at manufacturing plant

The audible noise level (SPL) produced by winders in manufacturing plants is quantified using a sound level meter. The measurement outcomes are depicted in Figure 6. According to the obtained measurement findings, it is determined that the loudness level at the specified area is 95.8 dBA. When considering short distances, it is important to note that a loudness level of 95.8 dBA might be perceived as quite loud, causing a disturbance and potential harm to one's hearing if exposed for an extended duration. Hence, it is imperative to prioritize the aspect of safety and security when it comes to testing equipment.

Audio signals can be perceived and analyzed not just in the temporal domain, but also in the frequency domain. The sound signal that has been captured is depicted in the time domain, wherein it can be visually represented as a graph showcasing the relationship between time and amplitude. The conversion of sound signals from the time domain to the frequency domain can be achieved through the utilization of the fast fourier transform (FFT) spectrum analyzer application. The application of FFT spectrum analyzer is executed on an Android-based device in order to observe the frequency domain noise caused by wind turbine machines.

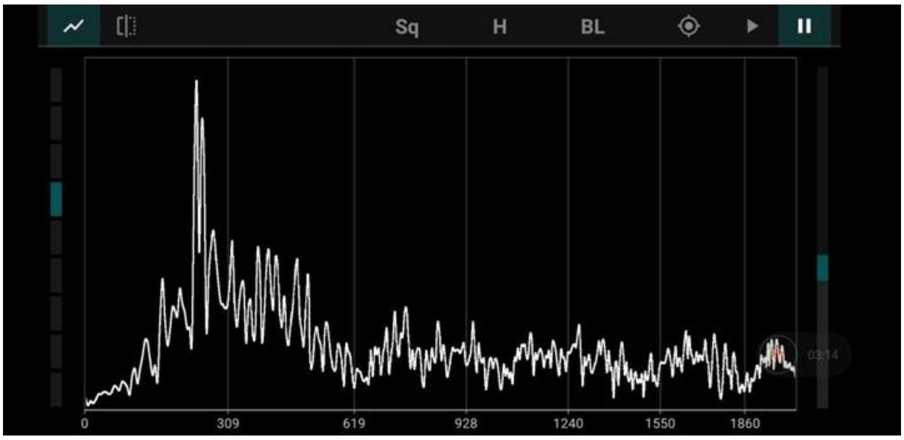

Figure 6. FFT Perform at the sound emitted by the winder machine present in the room

3.2. Piezoelectric array testing on each beam

Prior to subjecting the piezoelectric device to a loud environment, it is imperative to assess the beam structure. The experimental configuration features a cantilever beam that incorporates four interconnected piezoelectric components arranged in series. An impulse is initiated by snapping a finger at the beam's free end. This action produces a piezoelectric signal that is subsequently analyzed using an oscilloscope, revealing sinusoidal waveforms as illustrated in Figures 7(a)-7(f). While the estimations of the finger snap strength remain consistent across trials, there exists variability in the amplitude levels of the piezoelectric signals generated by individual beams. The beam designed for oscillation displays significant deformations, reaching maximum amplitude when disturbed, and subsequently undergoes gradual restoration to its initial configuration due to its inherent elastic properties. As the oscillations diminish, the signal amplitude also decreases, ceasing entirely once the beam halts its movement. These observations are concisely summarized in Table 1. The oscilloscope readings for finger movements indicate voltage peaks ranging from 0.88 Vpp to 2.88 Vpp or root mean square (RMS) values between 0.220-0.950 Vrms. Additionally, the frequency values associated with finger flicks span between 12.83-21.28 Hz.

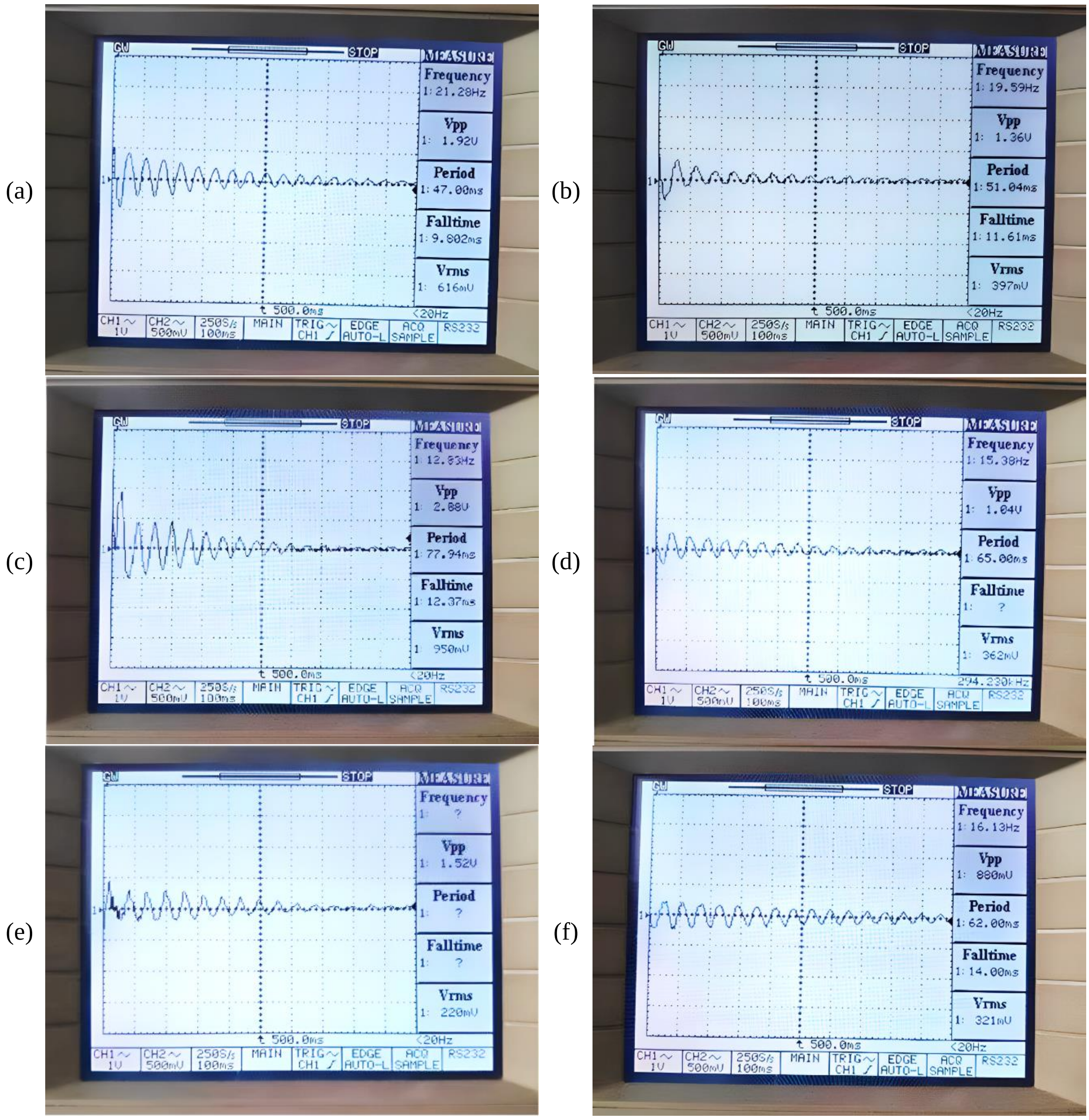

Figure 7. Variations in the amplitude of the signal produced when the piezoelectric receives a finger flick at (a) 21.28 Hz, (b) 19.59 Hz, (c) 12.83 Hz, (d) 15.38 Hz, (e) 20.50 Hz, and (f) 16.13 Hz

Table 1. The piezoelectric signal that outputs by flicking motion with the finger

Beam	Vpp (V)	Vrms (V)	Frequency (Hz)
A	1.92	0.616	21.28
B	1.36	0.397	19.59
C	2.88	0.950	12.83
D	1.04	0.362	15.38
E	1.52	0.220	20.50
F	0.88	0.321	16.13

3.3. Piezoelectric array testing in a noisy room

Piezoelectric arrays are strategically positioned on the winder machine to provide support to clamps and beams. When the winter machine is operated concurrently, it will generate a considerable level of noise and vibration. Simultaneously, the beam that is affixed exhibits vibratory motion, together with the piezoelectric material that is connected to it. The output signal of the piezoelectric array in Figure 8 exhibits a sinusoidal waveform, characterized by a near-perfect sinusoidal shape. The observed pattern suggests that the amplitude of the positive cycle exhibits periodic fluctuations, alternating between increases and decreases. Similarly, within a negative cycle, the amplitude level exhibits periodic fluctuations, increasing and decreasing with time. The amplitude value that reached the greatest recorded level was measured at 3.32 Vpp, accompanied by a frequency of 50.42 Hz. The signal is generated through the summation or amalgamation of signals originating from 36 piezoelectric elements. The signal produced by the piezoelectric array is linked to the voltage doubler circuit at the input. The present circuit entails the amplification of the signal originating from the piezoelectric device, resulting in a doubling of its amplitude, followed by the conversion of the amplified signal into a DC voltage through rectification. The load resistor R_L with a resistance value of 2.2 kΩ is connected to the output of the voltage doubler circuit.

The voltage level of the output signal captured by the voltage recorder for the voltage doubler circuit is depicted in Figure 9. The output voltage level of the voltage doubler circuit in the time domain for a duration of 25 seconds. The experimental findings demonstrate the output voltage of the voltage doubler circuit, which is produced by the input signal derived from the piezoelectric array. The resultant voltage is characterized by direct current (DC) and exhibits fluctuating voltage levels, lacking constancy over the temporal domain. The inability of the piezoelectric array to consistently generate a sinusoidal signal is the reason behind this. One possible explanation for this occurrence is the inherent instability of the captured noise source, despite its high noise intensity. The noise generated by each machine winder exhibits asynchronous beats, which vary based on the ongoing activity. The instability of the piezoelectric array output is a consequence of this phenomenon.

Furthermore, the output of the voltage doubler circuit is also influenced by the capacitance value of the inserted capacitor. The presence of ripple in the output signal suggests that the utilization of a capacitor with a value of 47 μF is insufficient. Consequently, a residual alternating current (AC) voltage persists, which remains unmitigated or eradicated in its entirety. According to the voltage logger, the maximum recorded voltage level is 1000 mV DC, while the average voltage level is 610 mV DC.

In order to examine the operational frequency response of the constructed device, an experiment was conducted wherein the device was subjected to external noise originating from various sources. The origin of the auditory disturbance can be attributed to the presence of motorcycles in unenclosed areas. The sound pressure level of the noise emitted by a motorcycle engine is significantly elevated during engine ignition and acceleration. The sound level was quantified at 87.9 dBA using a sound level meter. The generated sound intensity is significantly elevated, approaching the sound intensity level of the wind turbine apparatus utilized in the preceding trial, which measured 95.8 decibels A-weighted (dBA).

The output voltage level of the voltage doubler circuit in the time domain for a duration of 25 seconds can be viewed in Figure 10. The experimental findings indicate the output voltage of the voltage doubler circuit, which is produced by the input signal derived from the piezoelectric array and the sound source originating from the motorbike engine. According to the voltage logger, the maximum achievable voltage level is 110 mV DC, while the average voltage is 80 mV DC. The resultant voltage is characterized and exhibits a fluctuating, non-constant voltage magnitude. One of the primary factors contributing to this phenomenon is the inherent instability of the noise source generated by a motorcycle engine.

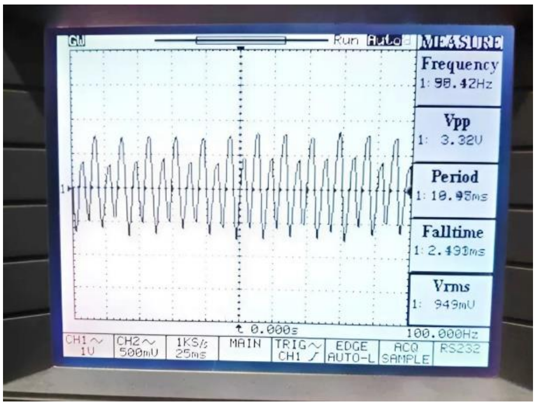

Figure 8. The output signal of a piezoelectric array is affected by noise originating from a winder machine

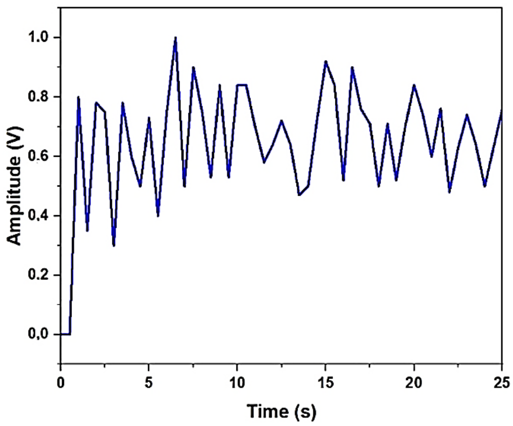

Figure 9. Graphical representation of the recorded voltage data

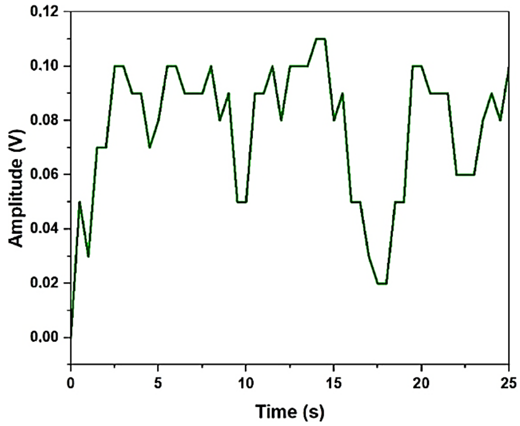

Figure 10. Captured voltage data using a logger device on a motorcycle engine

4. CONCLUSION

Through experimental analysis which has been demonstrated, the development of an energy harvesting device utilizing a piezoelectric array in a disruptive setting has been accomplished, effectively functioning at a frequency of 250 Hz. Furthermore, experimental testing carried out in a controlled environment, specifically a machine room with a noise level of 95.8 decibels A-weighted (dBA), reveals that the piezoelectric array exhibits its maximum output signal of 3.32 V peak-to-peak (Vpp) when subjected to a frequency of 50.42 Hz. Moreover, the assessment of a voltage doubler configuration, employing the input signal derived from the piezoelectric array, yields a maximum DC voltage of 1 V, accompanied by a current of 0.45 mA. Nevertheless, it has been noted that the resultant DC voltage displays a considerable level of fluctuation, which can be attributed to the utilization of a very little capacitor with a capacitance value of 47μF.

This study highlights several challenges that persist. Specifically, it is observed that the voltage multiplier is adequate for implementing a voltage doubler. This is attributed to the fact that a reduction in the number of diodes employed results in a decrease in voltage loss caused by diode drops. However, it is important to thoroughly investigate alternative approaches to voltage amplification and current amplification in order to improve the resultant output. The cantilever beam's design is modified either in terms of material composition or dimensions in order to mitigate the generation of wave harmonics resulting from piezoelectric effects. The quantity of piezoelectric devices employed is augmented, accompanied by an enlargement in the diameter of the piezoelectric material, with the objective of generating a greater output. In order to mitigate the ripple present in DC voltage, it is necessary to increase the capacitance of the capacitor employed inside the voltage doubler circuit.

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