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ELECTRIC POWER GENERATION FROM A TRICYCLE SUSPENSION SYSTEM USING A PIEZOELECTRIC ENERGY HARVESTER

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Abstract. This study presents the experimental study of a tricycle's suspension system fitted with piezoelectric energy harvester. The aim is to harness the vibration energy from the suspension movement and convert it into usable electrical energy using piezoelectric transducers. The piezoelectric transducers made of lead zirconate titanate (PZT) are arranged serially between steel plates which was attached to the suspension system of the tricycle to effectively capture vibrations. The research was carried out on different road terrains; urban road with IRI (international roughness index) between 2 – 5, gravel road with IRI between 5-10, and unpaved road with IRI between 10 – 20. Experiments demonstrate that the piezoelectric suspension system successfully converts vibration energy into electricity, with power generation dependent on factors like vibration intensity and automobile speed. The stored energy in the battery increased with time. The lowest energy for the road types were obtained after the first five minutes with the urban, gravel and unpaved roads having generated power of 0.0000169, 0.00114852, and 0.010818, respectively. The highest power generated was from the unpaved road with a maximum is 698.8 mW while that of the urban road is 0.3 mW at the end of a 30-minute drive test. The findings reveal the potential of vibration energy harvesting in automobile suspensions using piezoelectric transducers. This represents a sustainable approach for onboard power generation, enhancing energy efficiency. Further research on optimization and practical implementation could advance the feasibility of piezoelectric energy harvesting for electric vehicles.

Keywords: Energy harvester, vibration, automobile, suspension system, piezoelectric transducer

1. Introduction

Vehicles in motion are subjected to different disturbances that results in vibration of their mechanical components due to road irregularities, braking forces, acceleration forces, and centrifugal forces. Vibration from vehicle suspension systems and other mechanical processes represents an abundant yet untapped energy resource which can be converted into useful energy through energy harvesting and can be utilized in charging batteries or supply D.C. current for applications such as monitoring sensors or wireless communication devices [1]. Energy harvesting from vibration has gained a lot of interest due to the increase of portable electronic devices [2]. In recent times, harvesting energy from vibration is one among the foremost promising technologies [3].

One of the ways of harvesting vibration energy is through the use of piezoelectric transducers. These are devices that can convert mechanical energy (such as pressure or vibrations) into electrical energy. In a typical piezoelectric transducer, a crystal that generates electric voltage when stressed mechanically or deformed is placed in between two electrodes. When pressure is applied on an electrode, it pushes against the crystal and an output voltage is produced. An illustration of the transducer showing the applied force, electrodes, piezoelectric crystal and output voltage is shown in Fig. 1.

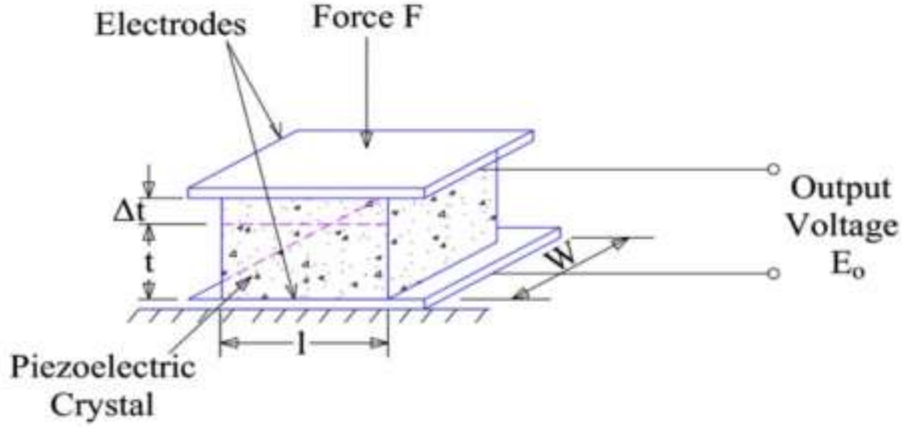

Fig. 1: Illustration of a piezoelectric transducer showing physical and electronic components [4].

Retrofitting automobile suspension with piezoelectric energy harvesters not only enhances vehicle fuel efficiency by converting mechanical vibrations into electrical energy but also contributes to a cleaner environment by reducing reliance on fossil fuels, consequently mitigating pollution and promoting sustainable energy practices [5].

A vehicle suspension is a system of springs, shock absorbers, and other components that connect a vehicle's body to its wheels. The suspension system serves several important functions, including improving ride comfort, handling, and stability, and protecting the vehicle's occupants and cargo from road shocks and vibrations [6]. The suspension system works by absorbing and dissipating the energy generated by the wheels as they encounter bumps, potholes, and other road irregularities. The springs, which can be made of steel, air, or other materials, compress and expand to absorb the energy and provide a cushioning effect. The shock absorbers, also called dampers, help to control the motion of the springs and prevent the vehicle from bouncing excessively. Excessive bouncing not only compromises the comfort and safety of vehicle occupants but also places undue stress on the mechanical components. The shock absorbers, also referred to as dampers, play a crucial role in regulating the motion of the springs. By effectively controlling the rebound, they mitigate the risk of the vehicle bouncing excessively, safeguarding both the comfort of passengers and the longevity of mechanical parts. A piezoelectric device that is in contact with a vibrating body experiences a piezoelectric effect and produces piezoelectricity. Piezoelectricity refers to the generation of electrical energy as a result of mechanical deformation in specific crystalline materials. In the direct piezoelectric effect, the application of mechanical stress alters the spatial distribution between positive and negative charges within the crystal lattice, inducing polarization and thereby generating an electric field. Conversely, in the inverse piezoelectric effect, an externally applied electric field interacts with internal charges, producing an elastic strain that changes the crystal's physical dimensions.

Numerous studies have demonstrated the potential of piezoelectricity for energy harvesting. For instance, Hossain et al. [7] developed a system that converts mechanical energy from human footsteps into electrical power. In their design, piezoelectric sensors were embedded in footwear to capture vibrational energy generated during movement. This energy could be stored in supercapacitors for future use. The proposed application targeted public spaces with high foot traffic to optimize electricity generation through human motion. For automobile applications, Wei and Taghavifar [8] presented a novel approach by introducing a distinctive method to quantify and analyze energy harvesting potential from vehicle suspensions using a half-car model under both harmonic and random road excitations. Zhao *et al.* [9] employed a combination of experimental and analytical methods to produce and test a prototype suspension system equipped with piezoelectric energy harvesters. The experimental phase involved subjecting the vehicle to various operating conditions, including different speeds and road surfaces, to capture the mechanical vibrations generated by the suspension system. The results demonstrated the ability of the harvesters to capture mechanical vibrations and convert them into electrical energy in a substantial and consistent quantity, indicating the potential for utilizing this technology to power various electrical systems within the vehicle.

Ghormare [10] conducted a study that focused on the development of a laboratory scale energy harvesting device tailored specifically for vehicle suspension systems by employing a systematic methodology that involved both analytical and experimental approaches. The study encompassed the design and fabrication of the energy harvesting device, which was customized to suit the characteristics of vehicle suspension systems. The researcher utilized advanced analytical modelling and simulation techniques to evaluate the device's performance under different operating conditions. These simulations provided valuable insights into the behaviour and efficiency of the device in capturing and converting the vibrational energy. Specialized equipment and measurement tools were utilized to measure and quantify the energy harvested from the vehicle suspension system. This allowed for a detailed analysis of the device's efficiency, power generation capabilities, and response to varying operational conditions.

Lee *et al.* [11] investigated the feasibility of integrating piezoelectric technology into the existing shock absorber system and assess the potential for generating electrical energy from the mechanical vibrations induced by vehicle movement. The authors proposed a design concept that involved integrating piezoelectric transducers into the shock absorber system. The materials used in the design included piezoelectric ceramics, which exhibit the desired properties for effective energy conversion.

Al-Yafeai *et al.* [12] evaluated the harvested energy from a car suspension system using the piezoelectric method. Influence of factors such as the amplitude and frequency of the mechanical excitation on energy generation were studied. A mathematical model of the car suspension system, incorporating vehicle weight, suspension stiffness, and damping coefficients was developed. Simulations were then performed to evaluate the generated electrical energy under different operating conditions, allowing for a comprehensive analysis of the energy harvesting potential.

While many of these studies have focused on four-wheeled automobiles, it is clear that energy harvesting in tricycles is rare. Thus, the aim of the research retrofit a tricycle suspension with a Piezoelectric harvester and evaluate its performance on various types of road surfaces. The research centres on the generation and storage of electricity derived from the vibration energy harvested from a tricycle suspension system.

2. Materials and Method

The materials and methods that were used in the execution of this study are presented in this section.

2.1. Materials

The mechanical and electrical components that make up the piezoelectric harvester include (i) 22 piezoelectric sensors (35 mm Sebsor Disc, ~60 V), (ii) steel plates, (iii) bolts, nuts and washers, (iv) stainless steel springs, (v) 1N4007 diode, (vi) capacitor, (vii) a 12 V rechargeable battery, and (viii) connecting wires.

A piezoelectric sensor is a device that uses the piezoelectric effect to measure changes in pressure, acceleration, temperature, strain, or force by converting them to an electrical charge.

Steel is a widely used metal for projects requiring high compressive strength. It is an alloy composed primarily of iron and carbon, with other elements added to enhance its properties. Steel's ability to withstand high compressive forces is due to its excellent strength and rigidity. The crystalline structure of steel provides strong internal bonds, enabling it to resist deformation under pressure.

In this project four pieces of nut were used with their bolts and the washer helped to prevent the nut from entering the hole, The bolt and nuts will be use to hold the top and base of the platform, which is placed in the 20 mm hole drilled into the wood, the nut is 10mm in diameter and is 75mm long, with a 20 mm head cap.

A spring is a mechanical component capable of storing energy through elastic deformation. Typically fabricated from spring steel, springs come in various forms, including torsion springs, which operate by twisting around an axis. When subjected to angular displacement, a torsion spring generates a restoring torque that is directly proportional to the angle of twist.

A rectifier diode is a type of semiconductor device designed to convert alternating current (AC) into direct current (DC), often implemented in rectifier bridge circuits. Schottky barrier diodes are frequently preferred in digital electronics due to their lower forward voltage drop and faster switching speeds, offering an alternative to conventional rectifier diodes.

A capacitor is a passive two-terminal electronic component that stores energy in the form of an electric field. Its defining characteristic, capacitance, represents its ability to store electric charge. While some level of capacitance is inherently present between any nearby conductors, capacitors are specifically engineered to introduce and control capacitance within an electrical circuit.

A battery functions as a portable energy source, composed of one or more electrochemical cells connected externally to provide electrical power to devices such as mobile phones, flashlights, and electric vehicles. The terminals of the battery are soldered to the piezoelectric sensor in order to allow reading of the voltage being generated. The size of wire used is 1.25 mm and 1.5 mm, the wire is used to connect the disc.

The exploded CAD view of the structural components PZT energy harvester in SolidWorks software is shown in Fig. 2 while the final assembly view is presented in Fig. 3. Plate 1 shows the completely assembled device while Fig. 4 presents the working drawing.

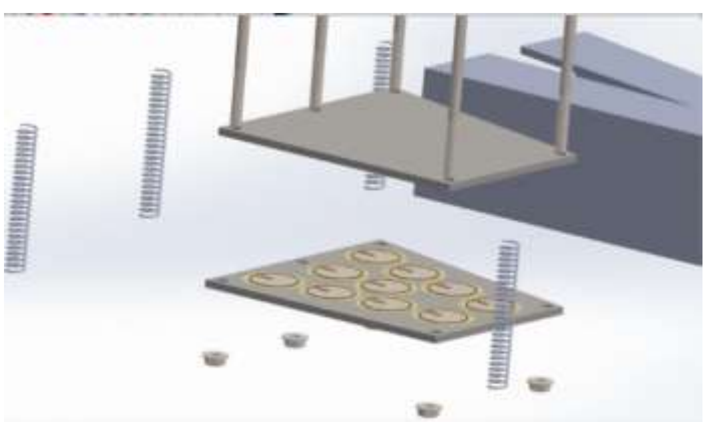

Fig. 2: Computer Aided Diagram (CAD) of the structural component of the piezoelectric harvesting system.

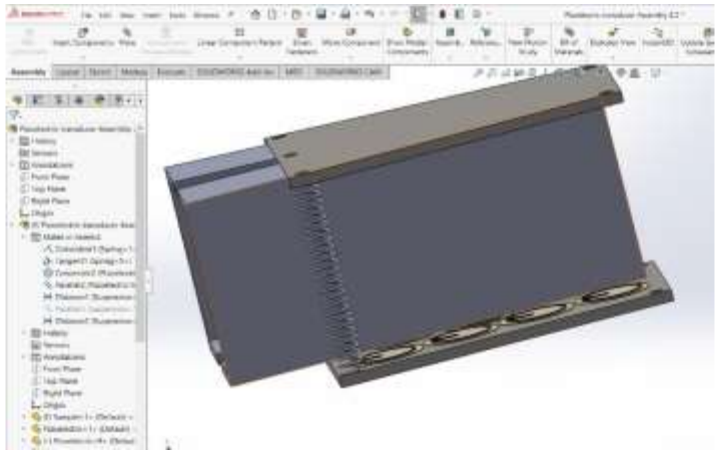

Fig. 3: Final assembly of the energy harvester in SolidWorks software.

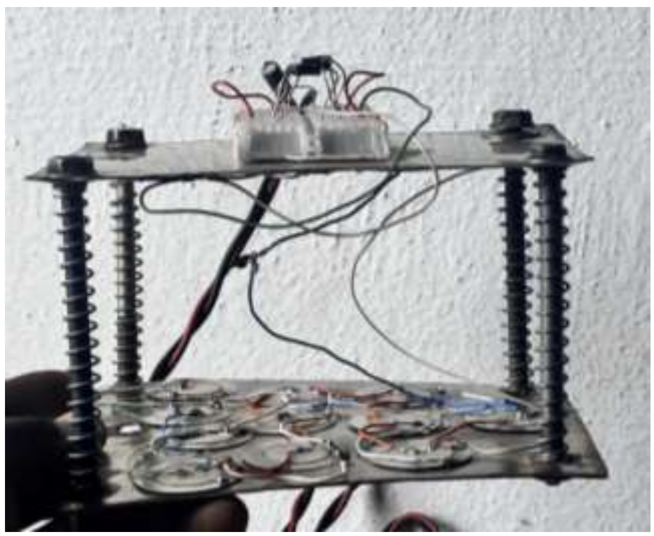

Plate 1: The real assembly of the energy harvester

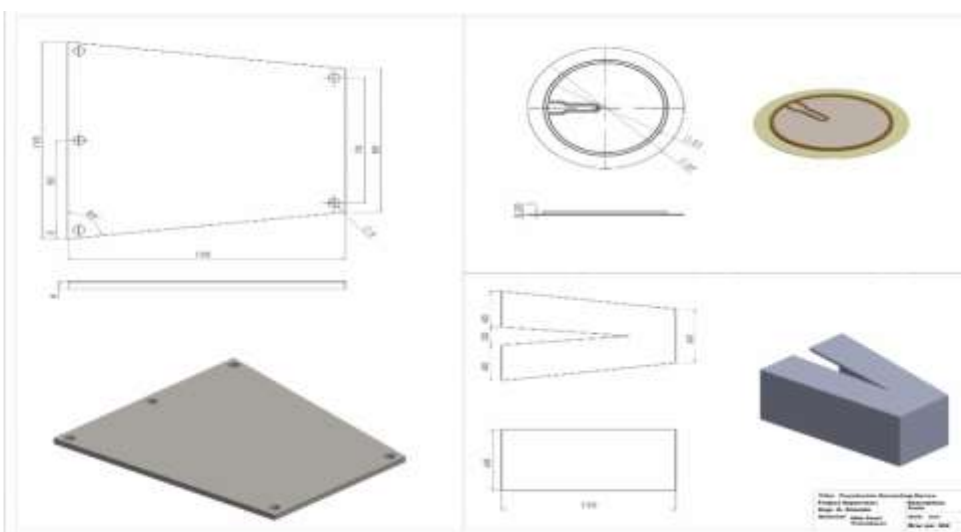

Fig. 4: Working drawing of the energy harvester showing the dimensions of the steel plates and the piezoelectric transducer.

2.2. Methods

The methodology integrates a configuration of 20 piezoelectric transducers composed of lead zirconate titanate (PZT), a 12 V capacity battery, sheet metals, and helical springs. The retrofitted suspension of the tricycle used for the study is shown in Plate 2. The experiments were conducted on diverse road surfaces characterized by varying International Roughness Index (IRI) values, encompassing an urban road with IRI ranging from 2 to 5, a gravel road with IRI between 5 and 10, and an unpaved road with IRI ranging from 10 to 20.

Plate 2: The tricycle suspension system fitted with the energy harvester

2.2.1. Displacement of the suspension system

Engineers use mathematical models to study the behaviour of the suspension system and design it to achieve desired ride comfort, handling, and stability characteristics. Fig. 5 shows the mathematical model for a car suspension system. This model can also be referred to as the quarter car model [8].

The obtain the effects of road irregularities on the vehicle, it is important to obtain the mathematical model of the equivalent mechanical diagram for the system shown in Figure 5, where M_s, M_{us}, K_s, K_t, b_s, b_{us}, x, Y_{us}, and Y_R are the mass of vehicle body (sprung mass), mass of tire (unsprung mass), suspension stiffness, tyre stiffness, suspension damping, tyre damping, displacement due to road irregularities, displacement of vehicle body and displacement of tyre, respectively.

Based on Newton's second law, Equation (1) and (2) presents the balance of the forces acting on the sprung and upsprung masses, respectively, assuming that there is no tyre damping.

$$M_s\ddot{Y}_s = -K_s(Y_s - Y_{us}) - b_s(\dot{Y}_s - \dot{Y}_{us}) \quad (1)$$

$$M_{us}\ddot{Y}_{us} = K_s(Y_s - Y_{us}) + b_s(\dot{Y}_s - \dot{Y}_{us}) - K_t(Y_{us} - Y_R) \quad (2)$$

The suspension displacement (u) is the relative displacement between the sprung and unsprung mass and can be written as Equation (3).

$$u = Y_s - Y_{us} \quad (3)$$

Voltage and current generated by the piezoelectric energy harvesting system
The output voltage generated by a piezoelectric transducer can be expressed as a function of the mechanical displacement, u, which in turn is governed by the applied mechanical force, F. The strain (ε) induced in the piezoelectric material due to mechanical deformation by the action of the suspension system can be determined by Equation (4).

$$\varepsilon = d_m \cdot u \tag{4}$$

where d_m is the piezoelectric strain coefficient (a property of the material).

The electric field generated (E) can be computed by Equation (5).

$$E = d_e \cdot F \tag{5}$$

where d_e is the piezoelectric charge coefficient of the material.

Equation (6) computes the amount of electric charge (q) while Equation (7) can be used to derive the capacitance (C) of the transducer.

$$q = d_e \cdot \varepsilon \tag{6}$$

$$C = \frac{\varepsilon_0 \cdot A}{d} \tag{7}$$

where A and d are the effective area of the transducer and the thickness of the piezoelectric material respectively.

Equation (8) gives the total voltage output of the transducer.

$$V = \frac{q}{C} \tag{8}$$

Equation (6) can be expanded by substituting for ε to give Equation (9).

$$q = d_e \cdot (d_m \cdot u) \tag{9}$$

Also, Equation (8) transforms into Equation (10) by substituting for the expressions of Equation (6) and (7).

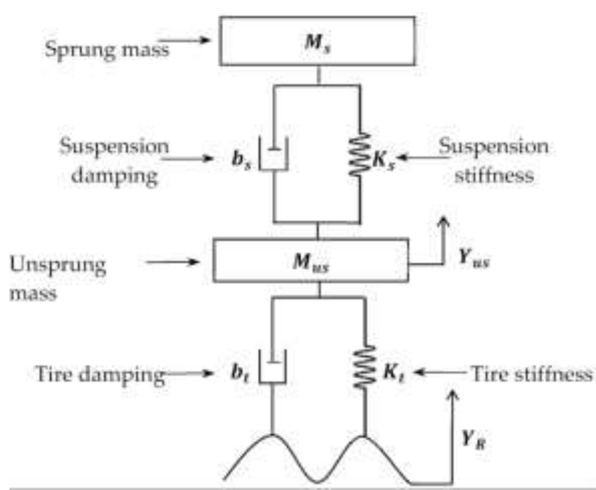

Fig. 5: Mathematical model for a car suspension system [13].

$$V = \frac{d_e \cdot d_m \cdot u}{\varepsilon_0 \cdot A/d} \quad (10)$$

This can be further simplified as Equation (11).

$$V = \frac{d_e \cdot d_m \cdot u \cdot d}{\varepsilon_0 \cdot A} \quad (11)$$

The electric current can be calculated based on the capacitance and voltage according to Equation (12).

$$I = C \cdot \frac{dV}{dt} \quad (12)$$

where dV and dt are the changes in voltages and time respectively.

Principle of operation

PZT-5 sensors were employed due to their superior piezoelectric characteristics, and they are both mounted at opposite ends of the energy harvesting device. The objective is to harvest vibrational energy by capturing energy from undesired vehicular oscillations. A basic energy harvester comprises a seismic mass connected via an elastic component to the vibrating body. In addition to the stiffness needed to induce harvester vibrations, a damping element is also essential. This damping component ensures effective power transfer from the harvester and facilitates the conversion of mechanical power into electrical energy.

Consequently, the sensors were connected in series because the parallel configuration did not produce a significant increase in voltage output. The series connection was adopted to yield voltage output with enhanced current density.

When the tricycle moves, the vibration intensity of the suspension system activates the harvester, and contact between the suspension and the PZT device generates electrical power. As a single piezo sensor outputs very low voltage, 22 piezoelectric sensors were combined in series. Given the unregulated nature of piezoelectric output, a variable-to-linear voltage converter rectifier was used. Specifically, an AC ripple neutralizer circuit was implemented to eliminate output ripples. The AC ripple neutralizer is composed of a rectifier and a ripple filter. The ripple filter removes AC fluctuations and additional variations, after which the signal passes through a regulator to stabilize it, remaining consistent if load and input voltage are steady.

Furthermore, the voltage regulator's output is connected to a unidirectional current controller that restricts current flow to a single direction. In this system, diodes were utilized as unidirectional current controllers, enabling current flow in one direction while blocking it in the reverse. Finally, a battery was integrated into the system to store the generated energy for future applications.

The block diagram which is shown in Fig. 6 is used for illustrating the processes involved in producing electricity from a vibration energy harvester and captures the essential components of a system designed to harness ambient vibrations and convert them into electrical power. At its core, the vibration energy harvester captures mechanical vibrations through transducers, typically piezoelectric materials, converting them into electrical energy. This generated electrical signal is then conditioned through a series of components, including rectifiers, and energy storage elements such as capacitors or batteries. The final output is a usable electrical power source, illustrating a concise and systematic representation of the energy harvesting process from vibrations.

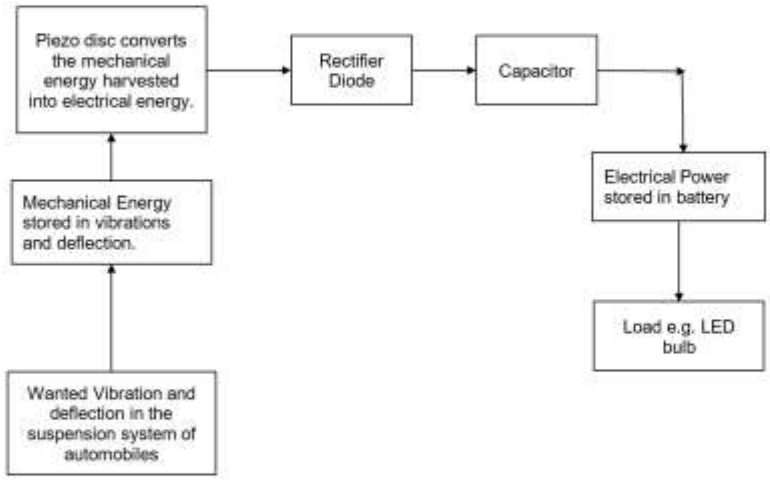

Fig. 6: Block diagram of producing electricity from vibration energy harvester

3. Results and Discussion

Moving considerably at low speeds, below 50 km/h, the energy harvesting system was tested on three types of road surfaces which were classified based on their IRI (international roughness index). The voltage and current readings were taken by the aid of a multimeter that was connected to the storage battery. The IRI is used to measure the road roughness intensity and is calculated as the accumulated vertical suspension movement divided by the distance travelled by the distance travelled by a simulated vehicle model of a measuring profile [14]. Different roads have different ranges of IRI; urban roads which are generally smooth have IRI between 2-5, for gravel roads the value is in the range of 5 to 10, while unpaved roads which represent the roughest road types have values between 10 and 20. For the urban road, the paved road from the main gate of FUNAAB (Federal University of Agriculture, Abeokuta) through the entire campus was used for the test. For the gravel road, the stretch from behind the ceremonial building of FUNAAB to the Olusegun Obasanjo's College of Engineering building was used. Finally, the road along FUNAAB's NEEDS hostel was used to test for the unpaved/rough road. The duration of drive test for all the road types is 30 minutes.

3.1 Result for voltage readings

The voltage readings obtained for the three road types at test times of 5, 10, 15 and 20 minutes are presented in Table 1. The readings were taken with the aid of a voltmeter that was attached directly to the storage battery. The results reveals that the highest voltage was obtained from the rough road and is significantly higher than the others. At the end of the test period, the percentage difference between the voltage read from the battery for the rough road and the gravel and urban roads are 111% and 194%, respectively. The low voltage recorded for urban road is due to its smoothness and lower levels of displacement occurring in the suspension system. In many cases, the voltage is absolutely zero as seen in Fig. 7 which shows the graph of instantaneous velocities recorded over the test period. The amplitudes of the velocities for the three road surfaces show stark differences. The amplitude of that of the rough road is more than the sum of the amplitudes of the other two road surfaces. The trend in this result is comparable to that of Wei *et al*. [8] where the instantaneous power generated between the front and rear wheels were compared using the half-car model. It is also in good agreement with the result of open circuit voltage of an energy harvesting system recorded by Zhao *et al*. [15] for laden and unladen vehicles.

A rough road has very uneven surface and causes higher displacement in the suspension system of an automobile. The higher displacement will translate to more deformation and more strain on the piezoelectric transduces, producing higher potential difference between their electrodes. Thus, it is recommended that vehicles that ply unpaved road can be retrofitted with energy harvest systems for charging and powering small electronic gadgets like light emitting diodes, power banks and mobile phones. Car should however be taken to check the amount of force being exerted on the transducers so as not to damage them or shorten their life span.

Table 1: Voltage readings for the three road types

Time (Mins)	Urban Road Voltage (mV)	Gravel Road Voltage (mV)	Rough Road Voltage (mV)
5	9.7	112.6	180
10	10.8	167.5	340
15	11.4	218.6	1000
20	21.2	321.8	1300
30	30.7	543.2	1900

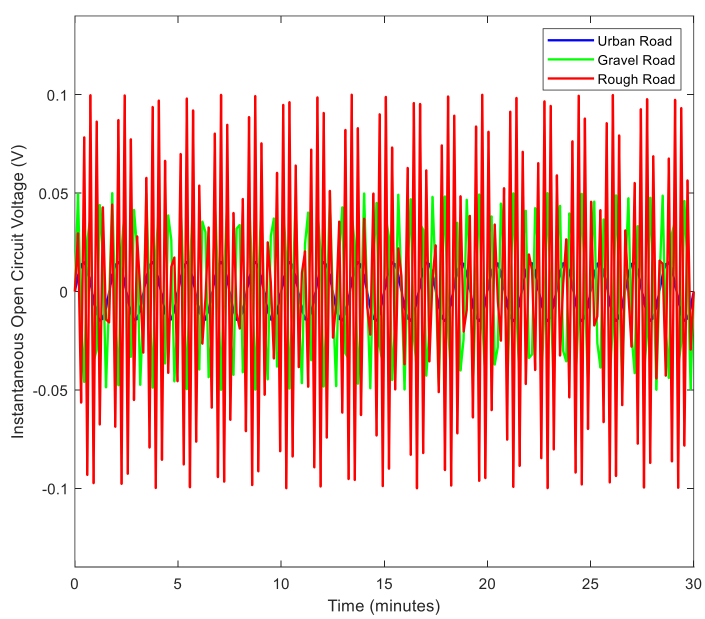

Fig. 7: Graph of instantaneous velocities recorded against time

3.2 Electric current readings

The electric current readings are shown in Table 2 for the various road surfaces considered in this study. The trend observed is similar to that of the voltage. The current reading from the battery increased with time as more distance is covered. It shows that the battery develops more electric current with time. On the urban road, the current increases gradually from 1.74 mA at 5 minutes to 10.17 mA at 30 minutes. This slow growth reflects the smoother nature of urban roads, which produce fewer vibrations and therefore less mechanical strain on the piezoelectric materials. The increase in current is relatively linear. For the gravel road, the current starts at 10.2 mA and reaches 101.7 mA by the 30th minute. Compared to the urban road, the gravel surface induces more mechanical disturbance, resulting in more significant vibration energy. The current output grows more rapidly and follows a nonlinear trend. Finally, the rough road data shows the highest current values, beginning at 60.1 mA and rising sharply to 367.8 mA. The surface condition of rough roads causes intense and frequent vibration, which generates a much larger strain on the piezoelectric transducers. The urban road had the least amount of current while rough road had the highest. The percentage difference between the current for rough road and gravel at the end of the test period is 113% while the former and urban road is 189%. This result again affirms that observation that the energy harvesting system performs better on rough roads.

Table 2: Voltage and current readings

Time (Mins)	Urban Road Current (mA)	Gravel Road Current (mA)	Rough Road Current (mA)
5	1.74	10.2	60.1
10	2.40	33.7	80.3
15	4.71	52.8	124.5
20	7.12	81.6	251.6
30	10.17	101.7	367.8

3.3 Power harvested

The graph of total power harvested with time is presented in Fig. 8. The results reveal that the power increased with road IRI and time. This is in close agreement with the result reported by Wei *et al*. [8] where the power harvested for highway with gravels and smooth highways were compared. It can also be seen from the graph that there is gradual power harvesting for the first 10 minutes for all cases, after which the rate increased remarkably for rough and gravel road surfaces. The smooth road generated very low power. This is expected since urban roads typically offer smoother surfaces, generating fewer vibrations to activate the piezoelectric transducers effectively. The Rough terrain, however, with its frequent and intense suspension movements, delivers the highest energy, making it the most effective for power generation in this setup.

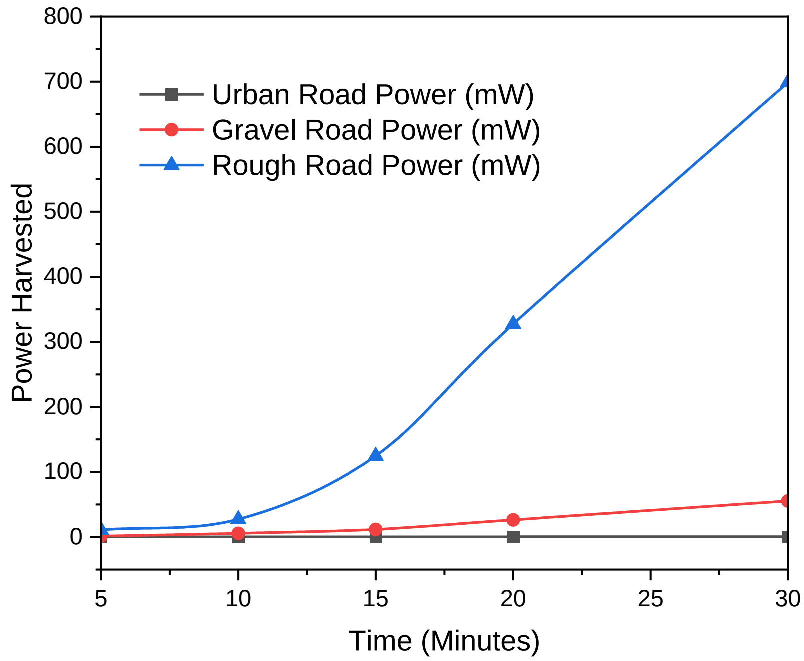

Fig. 8: Power harvested for the three road surfaces

From the results, it is confirmed that the voltage and power generated by the energy harvesting device is dependent on the total time of travel and road IRI.

4. Conclusion

This work has presented an experimental study of the potential of harvesting energy by retrofitting the suspension of a tricycle with a piezoelectric energy harvesting system. Twenty piezoelectric transduces connected in series, four helical springs and steel plates were assembled to produce the piezoelectric energy harvester. The tricycle was tested on three road surfaces including, an urban road, gravel road and rough or unpaved road. The stored voltage and electric current were read from the battery using a multimeter. The study revealed the following:

- The instantaneous open circuit voltage for rough road is higher than those obtained from other road surfaces.
- The voltage and current measured from the storage battery were many times higher for the rough road while that of urban road is small and very low.
- The power developed increases with time and is gradual for the first 10 minutes but increases rapidly and almost linearly after.
- The piezoelectric system is recommended for tricycles that are often used on rough surfaces for powering small electronic gadgets.

The findings of this study emphasize the potential of a tricycle's suspension system as a viable source of electricity generation. It showcases how the kinetic energy generated from suspension movements can be effectively converted into electrical energy through the use of piezoelectric materials.

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