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Investigation on Potential in Regenerative Passive Suspension System for Automotive Technology

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Abstract

Modern vehicles dissipate vibration energy from road irregularities as heat through conventional suspension systems, resulting in energy loss. Recent research works in engineering explores energy harvesting with various method including the application of piezoelectric to generate electricity. The research in this paper addresses the engineering challenge by exploring the potential of a piezoelectric-based regenerative suspension system capability to harvest wasted energy. A quarter-car model was implemented using MATLAB Simulink and Simscape to simulate the electromechanical response under different road profiles and vehicle speeds. Key simulations used harmonic excitations and speed-dependent road inputs to evaluate both energies harvesting potential and application. The system achieved a maximum output of 30 V, 120 μA, and 2.1 mW on rough roads, with peak power of 0.75 W recorded at a low speed of 40 km/h. These results indicate the potential of exploring the integration of piezoelectric regenerative suspension systems to support advanced subsystem in modern vehicle.

1. Introduction

In conventional vehicle suspensions, vibrational energy from road irregularities is passively dissipated as heat, resulting in significant energy loss. Active suspension systems improve ride quality but consume too much power for energy-conscious EVs and HEVs. Regenerative suspension systems offer a promising alternative by converting mechanical vibrations into reusable electrical energy [1], [2]. Traditional suspension systems use passive dampers that dissipate kinetic energy as heat during the absorption of vibrations and shocks from road irregularities. In contrast, regenerative suspensions harness this otherwise wasted energy, converting it into electrical energy that can be reused to power vehicle systems, improve fuel economy, or enhance vehicle performance. This energy recovery capability makes regenerative suspensions a promising technology for reducing energy losses and contributing to self-sustained suspension control. The growing interest in regenerative suspensions is due to their dual benefit which are enhancing ride comfort and vehicle dynamics while contributing to energy efficiency.

Regenerative suspension systems are categorized by their mechanisms for converting vibrational energy into usable electrical energy, which is stored for powering vehicle systems. These systems include rotary motors, linear motors, and hydraulic-electric composite types, each with unique designs and functions. Linear mechanisms include linear motors and piezoelectric transducers. Linear motors utilize electromagnetic induction to generate electricity through the interaction between magnetic fields and coils. In this system, permanent magnets and coils are housed within the shock absorber cylinder. As the suspension oscillates due to road irregularities, the relative motion induces an electromotive force (EMF) in the coils, resulting in electricity generation. In another method, the rotary motor electromagnetic regenerative suspension operates by converting the linear motion of the suspension into rotational motion. This conversion is achieved using mechanisms like ball screws, rack-and-pinion systems, or rocker arms. In this mechanism, a ball-screw motion transforms suspension movement into rotary motion that drives an electric generator, producing energy. This design is compact and reliable but may suffer from mechanical wear, especially under high-frequency road vibrations. Linear systems offer higher power density and lower mechanical friction, making them ideal for modern vehicles, although their relatively large size can limit implementation in compact designs [2]. Table 1 below summarized the comparison between the 3 types of regenerative suspension design.

Table 1 *Comparison for different idea in regenerative suspension design*

Suspension type	Description	Advantage	Disadvantageous
Conventional suspension	Comprise of springs and dampers to absorb shocks and provide ride comfort	Simple design, low cost and effective for basic ride comfort and handling	Energy loss as heat, limited adaptability to varying road conditions.
Regenerative suspension (rotary)	Converts linear motion into rotational motion using mechanism such as ball screw	Compact design, reliable energy conversion and improve energy efficiency	Mechanical wear under high-frequency vibrations, complexity in design
Regenerative suspension (linear)	Directly generates electricity through the motion of coils and magnets	High power density, low mechanical friction, quick response time	Larger size may limit use in compact vehicles, higher initial costs
Hydraulic-electric composite	Integrates hydraulic systems with electrical generation for energy recovery	High damping forces and adaptable to heavy vehicles	Complexity in integration, potential for hydraulic fluid leakage, maintenance challenges

The effectiveness of these energy harvesting mechanisms varies based on design parameters and operational conditions. For example, field tests on an electromagnetic regenerative shock absorber utilizing a ball screw mechanism demonstrated an average power output of 13.3 W at 40 mph while significantly improving ride comfort by reducing chassis acceleration compared to conventional shock absorbers [3]. In contrast, simulation studies of piezoelectric harvesters have projected power outputs ranging from 16W under good surface conditions to 242W under poor surface conditions at higher speeds [4]. Additionally, a dual-mass piezoelectric harvester has shown potential energy harvests of up to 738W from road roughness vibrations, while hydraulic electromagnetic regenerative systems have been reported to harvest 525W at lower speeds on rough roads [5].

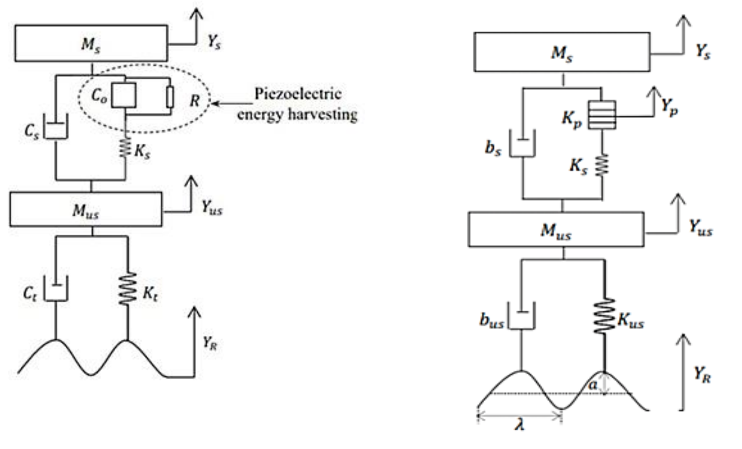
Among various methods, piezoelectric systems are gaining attention due to their compactness, scalability, solid-state design, and direct energy conversion capability. However, most piezoelectric systems face challenges such as low current output, limited efficiency, and integration difficulties that can compromise suspension dynamics and passenger comforT. Additionally, few studies evaluate both energy harvesting and ride quality using realistic models and unified simulation environments. Many rely on overly complex or idealized full-vehicle models, limiting practical application. This study addresses these gaps by developing a quarter-car piezoelectric regenerative suspension model in MATLAB/Simulink Simscape. The main contributions of this paper are to simulate a simplified and comprehensive electromechanical model of regenerative suspension system and analyse the energy output across different road profiles and speeds to set a baseline value for further experimental research work in regenerative suspension.

Despite significant advancements in suspension technologies, critical issues continue to hinder their widespread adoption and efficiency, particularly concerning the integration of energy recovery systems into modern vehicle suspensions. While traditional passive systems have been widely studied, they primarily dissipate vibrational energy as heat and thus fail to utilize the full potential for energy recovery. Active suspension systems offer real-time adaptability and dynamic response capabilities, but their complexity and energy demands make them less favorable in terms of energy efficiency. Piezoelectric regenerative suspension systems represent a promising alternative by converting vibration-induced mechanical stress directly into electrical energy. These systems capitalize on the piezoelectric effect and are structurally simpler than electromagnetic or hydraulic systems. However, they are often challenged by low energy conversion efficiency and the complexity of integrating piezo elements into the mechanical structure.

Another issue lies in the experimental validation and modeling accuracy. While many researchers rely on theoretical or finite element models, the integration into full vehicle systems remains underdeveloped. The mismatch between simulation environments and real-world conditions has further hindered the commercial application of piezo-regenerative technologies. Although MATLAB/Simulink offers a versatile simulation platform, few studies have exploited its full potential to simulate multi-domain interactions in piezoelectric regenerative suspension systems. In addition, the piezoelectric material's response is highly sensitive to the amplitude and frequency of vibrations, necessitating precise tuning of the stack configuration and placement. Moreover, the lack of standardization in experimental setups and road profiles complicates result comparisons across different studies. Therefore, there is a pressing need for consistent methodologies that can evaluate both energy harvesting and ride performance comprehensively. In a nutshell, while piezoelectric regenerative suspension systems have demonstrated substantial promise in improving vehicular energy efficiency, several technical and methodological challenges need to be addressed. These include improving energy output, enhancing simulation accuracy, and ensuring system integration without compromising ride comfort. This study aims to contribute to this field by developing a piezo-regenerative suspension model using MATLAB/Simulink and Simscape to explore its dual potential in energy harvesting and ride quality optimization.

1.1 Theoretical Framework to Model Regenerative Suspension

Fig. 1 depicts the Piezo-stack Regenerative Suspension system's structure. In a quarter-car model, the system operates by responding to vertical disturbances from the road surface, which cause the unsprung mass, representing the wheel and axle assembly to move. This motion is transmitted through the tire, modelled with its own stiffness and damping characteristics, to the suspension system. The suspension, consisting of a spring and damper, manages the relative motion between the unsprung mass and the sprung mass, which represents the vehicle body. As the suspension reacts to road-induced vibrations, relative displacement occurs between the two masses. A piezoelectric stack is integrated into the suspension system, positioned such that it experiences mechanical strain during this relative motion. As the suspension compresses and extends, the piezoelectric material deforms, converting the mechanical vibrations into electrical energy through the direct piezoelectric effect. The electrical behavior of the piezoelectric stack is represented by a capacitor and resistor. The capacitor models the intrinsic capacitance of the piezoelectric material, while the resistor represents the load or energy storage circuit. As the piezoelectric element generates charge, voltage builds across the capacitor and a small current flow through the resistor, allowing energy to be harvested from the suspension's vibration without affecting its primary function of ride comfort.



(a) **(b)**

Fig. 1 *Mass spring damper quarter model for vehicle (a) The concept; (b) The model with piezoelectric*

The 2-Degree of Freedom Quarter Car Model where *Ms* and *Mus* are the sprung mass and unsprung mass, *Ys* and *Yus* are the displacement of the sprung mass and unsprung mass, *YR* is the road displacement, K*s* is the suspension stiffness, *Kt* is the tire stiffness, *bs* is the damper coefficient of the system; and *Kp* is the piezoelectric constant. Based on Newton second Law, the equation of the model is can be expressed as:

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

$$M_{us}\ddot{Y_{us}}K_s(Y_s - Y_{us}) + b_s(\dot{Y_s} - \dot{Y_{us}}) + K_pY_p - K_{us}(Y_{us} - Y_R) - b_{us}(\dot{Y_{us}} - \dot{Y_R}) \quad (2)$$

1.2 Piezoelectric Deformation and Electronic circuit of Piezoelectric Harvesting System

The piezoelectric element is deformed by the relative motion between *Ms* and *Mus*, modeled as:

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

This deformation produces voltage through the direct piezoelectric effect, though electrical dynamics would be modeled separately using constitutive piezoelectric equations or an equivalent circuit. The open-circuit electrical voltage generated by a piezo stack is related to the applied mechanical stress or force:

$$V = d_{33}.\frac{F.L}{\varepsilon_r \varepsilon_o.A} \quad (4)$$

where V is the voltage generated, d_{33} is piezoelectric charge constant (m/V), F is the applied force, ε_o is the permittivity if free space ($8.854 \times 10^{-12}\ F/m$), ε_r relative permittivity of the material and A is the electrod area (m). The piezoelectric current is produced when the force applied to the stack changes with time. It is expressed as:

$$I = d_{33}.\frac{dF}{dt} \quad (5)$$

where I is the current (A) and $\frac{dF}{dt}$ is the rate of change of force with respect to time. Lastly, the instantaneous electrical power output is calculated using the voltage and current $P = VI$. The harvested energy which collected from the piezoelectric material will be accumulated and stored accordingly. Without proper energy storage mechanism, the resultant harvested power will be wasted. To complete the electrical circuit, a piezoelectric energy harvester requires a rectifier circuit to convert the AC wave from the harvester to the DC voltage which is suitable for energy storage [6]-[8]. The common rectifier circuit can used is the full-wave rectifier with diode bridge.

2. Methodology

This study employs a simulation-based methodology to design, implement, and evaluate a piezoelectric-based Regenerative Suspension System using a simplified quarter-car model. The methodology comprises four key stages: system modeling, simulation environment setup, performance evaluation under varying conditions, and ride comfort analysis. The first step involves system modelling. The suspension system is modeled as a two degree- of-freedom (2-DOF) quarter-car model comprising a sprung mass (vehicle body) and an unsprung mass (wheel assembly) as shown in Fig. 1. These masses are connected via a spring-damper pair representing the suspension, while the unsprung mass is connected to the road surface through the tire modeled with its own stiffness and damping. A piezoelectric stack is embedded in parallel with the suspension spring to harvest vibrational energy. Mechanical deformation of the piezo element due to relative motion between the sprung and unsprung masses induces voltage and current via the direct piezoelectric effect. The generated AC signal was subsequently passed through a full-wave rectifier and smoothing capacitor for energy storage modeling. The simulation was implemented using MATLAB Simulink with the Simscape library. The simulation parameters were set as in Table 2 below.

Table 2 *Parameter of study*

Parameter	Values
Sprung mass, *Ms*	260 kg
Unsprung mass, *Mus*	40 kg
Suspension spring stiffness, *Ks*	26000 N/m
Tire stiffness, *Kt*	130000 N/m
Suspension damping coefficient, *Cs*	520 Ns/m
Tire damping coefficient, *Ct*	265 Ns/m

Fig. 2 presents the overall Simulink architecture of the regenerative suspension system, which integrates both the vehicle's mechanical response to road disturbances and the energy harvesting functionality of a piezoelectric stack. The simulation begins with a random number generator, configured to produce a signal representing road velocity input in centimeters per second (cm/s). This input is used to mimic the behavior of road irregularities, such as smooth or rough surfaces. The generated signal is applied to an Ideal Translational Velocity Source, which serves as the interface between the simulated road surface and the mechanical model of the suspension system. This excitation mimics the vertical disturbances experienced by a real vehicle traveling over varying terrain.

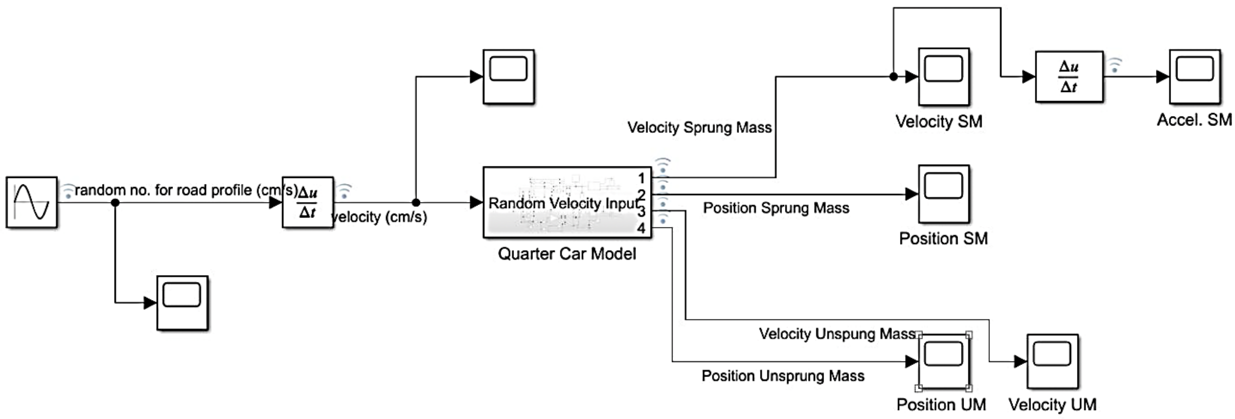


Fig. 2 *General Simulink model for vehicle suspension system*

The core of the model is the quarter car system, which simulates the dynamic interaction between the sprung mass (the vehicle body) and the unsprung mass (the wheel assembly). This subsystem receives the velocity input and produces output of the resulting motions for the two masses in terms of velocity and displacement. These outputs provide critical data for evaluating the performance of the energy harvesting mechanism. The model also includes a pathway to compute the acceleration output of the sprung mass by differentiating its velocity signal. Fig. 3 illustrates the detailed Simulink and Simscape implementation of the quarter car suspension system coupled with the piezoelectric-based energy harvesting circuit. The mechanical portion of the model is constructed using Simscape Translational Mechanical blocks and represents a two-degree-of-freedom system consisting of the sprung mass and the unsprung mass. These masses are connected through a suspension spring and damper, with the unsprung mass additionally connected to the road via the tire spring and tire damper. The road excitation is applied using a Random Velocity Source block that transmits the vertical motion of the road to the base of the tire.

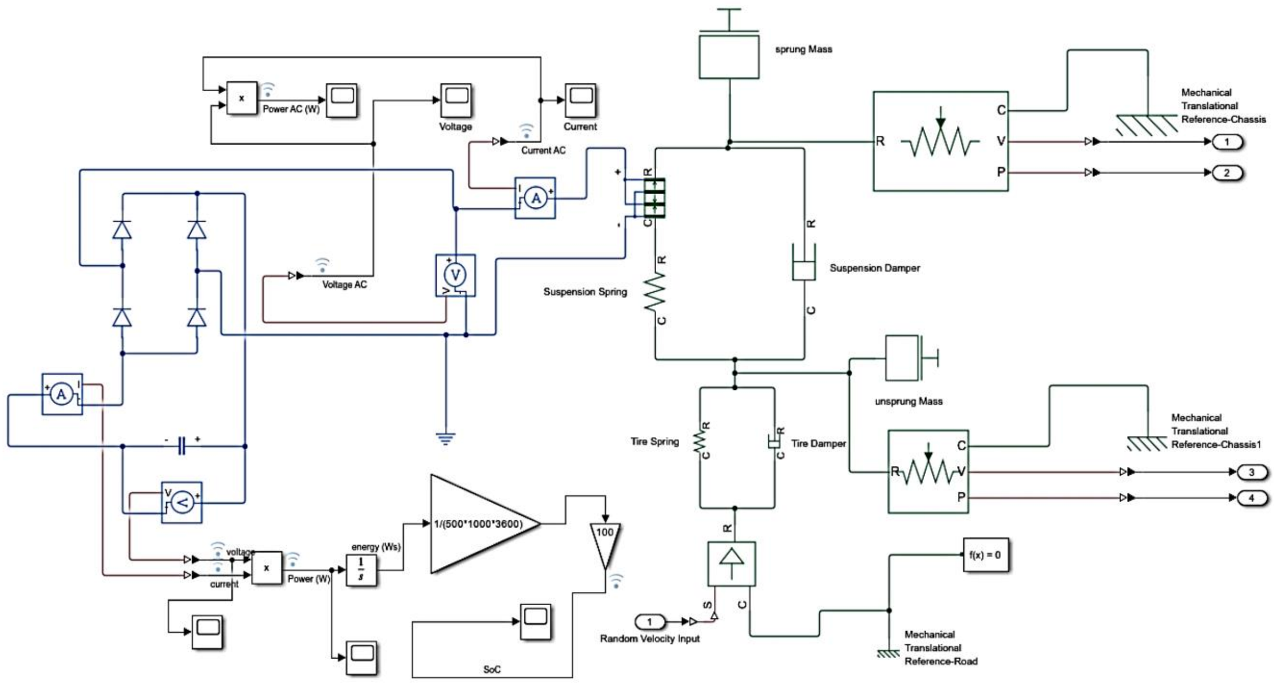


Fig. 3 *Detailed MATLAB model for the regenerative suspension system*

Subsequently, the piezoelectric energy harvesting subsystem is implemented in series with the suspension spring, where it captures the relative displacement between the sprung and unsprung masses. As the suspension undergoes compression and extension due to road vibrations, the piezoelectric material is deformed, producing an alternating voltage through the direct piezoelectric effect. This AC voltage is routed into a full-wave bridge rectifier made up of four diodes. The rectifier converts the alternating signal into a direct current (DC) voltage suitable for storage or use. The rectified signal is then passed through a smoothing capacitor to reduce voltage ripple, and through a resistive load that emulates a power-consuming or storage element. To measure the effectiveness of energy harvesting, the model includes voltage and current sensors that monitor the electrical output of the piezoelectric stack. The instantaneous power generated by the system is calculated by multiplying the voltage and current signals.

Additionally, an integrator is used to compute the total harvested energy over time in joules (or watt-seconds). This energy is scaled and displayed as a percentage representing the State of Charge (SoC) of an equivalent energy storage device, such as a battery or supercapacitor. The SoC indicator provides a visual understanding of how much energy the system has captured from the suspension vibration over the simulation period. In terms of simulated road condition, the parameters in Table 3 are to be included in the Simulink simulation. To investigate the performance of the Quarter Car Model with built in piezoelectric stack, MATLAB/Simulink model was built to carry out the time domains simulation. The car excitation input was tested by different road roughness profiles. To simulate varying levels of road roughness, three road profiles were defined and labeled as Road Profile A, B, and C. These profiles were modeled using sine wave signals with amplitudes of 0.3 cm, 0.6 cm, and 0.9 cm respectively, applied as vertical velocity inputs with the same frequency of 9.17 rad/second or 1.46 Hz.

Furthermore, road Profile A, with an amplitude of 0.3 cm, represents a smooth road surface, typically found on well- maintained highways or urban streets with minimal surface irregularities. Road Profile B, with an amplitude of 0.6 cm, characterizes a moderately rough surface, similar to secondary roads or suburban routes where slight wear or patching may be present. Lastly, Road Profile C, with the highest amplitude of 0.9 cm, simulates a rough road surface, representative of rural, unpaved, or poorly maintained roads that exhibit larger undulations and vibrations. These varying road conditions enable the evaluation of the suspension system response and energy harvesting capabilityunder realistic driving environment. The key simulation parameters such as mass, stiffness, and damping coefficients were set based on realistic values, and the model was evaluated under different road profiles. The system performance was assesed in terms of electrical output. This structured methodology enables the evaluation of the system in generating usable electrical energy from road-induced vibrations.

Table 3 *Road class and amplitude*

Road class	Amplitude of sine wave (V)
A (smooth)	0.003
B (moderate)	0.006
C (rough)	0.009

3. Results and Discussion

3.1 The Effect of Road Profile

In this research, the piezoelectric stack with a surface area and length of 49 mm^2 and 40 mm respectively was considered in harvesting the dissipated power from the suspension systems. The steady-state responses for evaluating the harvested voltage, current and power were simulated by exciting the car using sinusoidal acceleration excitation input with three different road profiles. Of A (smooth), B (moderate) and C (rough). Starting with the voltage response, based on the Fig. 4, the DC voltage plot clearly reveals a progressive increase over time for all three road conditions, with the steepness and final magnitude varying in accordance with the severity of the road profile. For the smooth road profile, the voltage rises gradually, reaching a maximum of just under 10 volts at the end of the simulation window. This relatively low voltage is expected, as a smooth surface induces minimal vertical displacement in the vehicle suspension system, resulting in low levels of mechanical strain applied to the piezoelectric stack.

In contrast, the moderate road profile with a 6 mm amplitude yields a considerably higher voltage, climbing steadily to around 19 volts. This increase indicates a stronger and more frequent mechanical interaction between the vehicle suspension and the piezoelectric stack, causing more substantial deformation and hence, greater charge accumulation over time. The rough road profile, characterized by a 9 mm amplitude, exhibits the highest performance, with the voltage escalating to nearly 30 volts. What is particularly notable in this case is the step-like increase in the voltage waveform, which reflects the repeated and forceful interactions between the vehicle suspension system and the road surface. These discrete jumps in voltage are tied to the rhythmic deformation of the piezo stack under high-frequency, high-amplitude excitation, thus demonstrating the effectiveness of rougher terrains in energizing piezoelectric harvesting mechanisms.

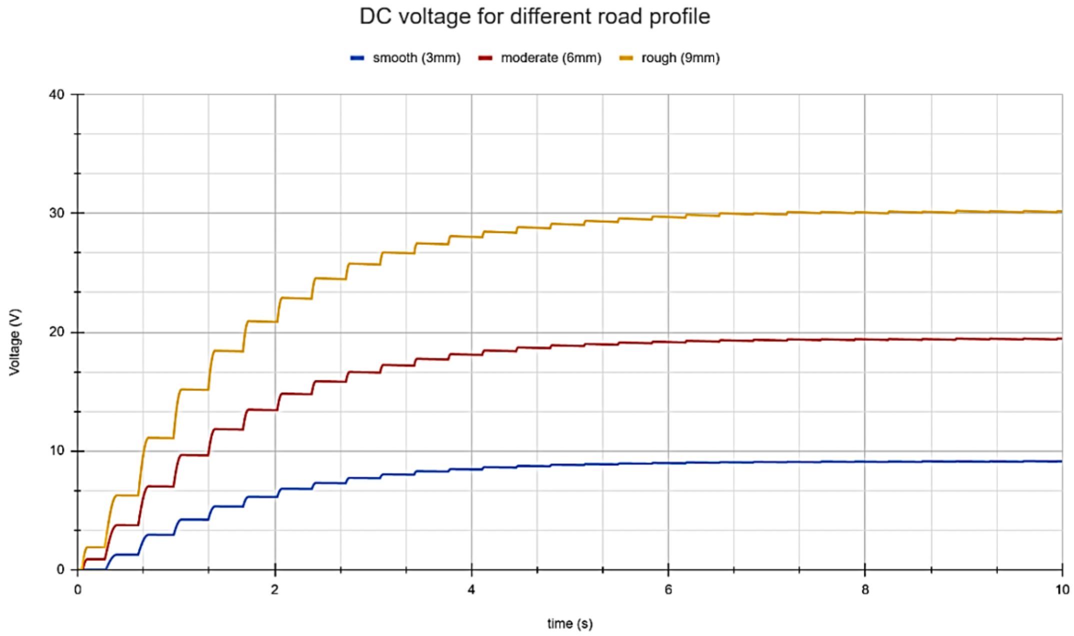


Fig. 4 *Result for DC voltage generated from the simulation*

Moving on to the current response, based on the Fig. 5, the DC current plot shows sharp periodic spikes for all three road profiles, albeit with different magnitudes and durations. For the smooth road condition, the current remains relatively low, with peak values around 20 to 30 microamperes, and the overall waveform tapers off quickly. This subdued response is a consequence of the low rate of force change imposed by minor bumps, leading to only slight dynamic deformation of the piezo stack. The moderate road profile, however, produces more pronounced current spikes, reaching up to 70 microamperes. These spikes are more sustained and frequent, indicating a higher and more consistent rate of mechanical strain experienced by the piezoelectric material.

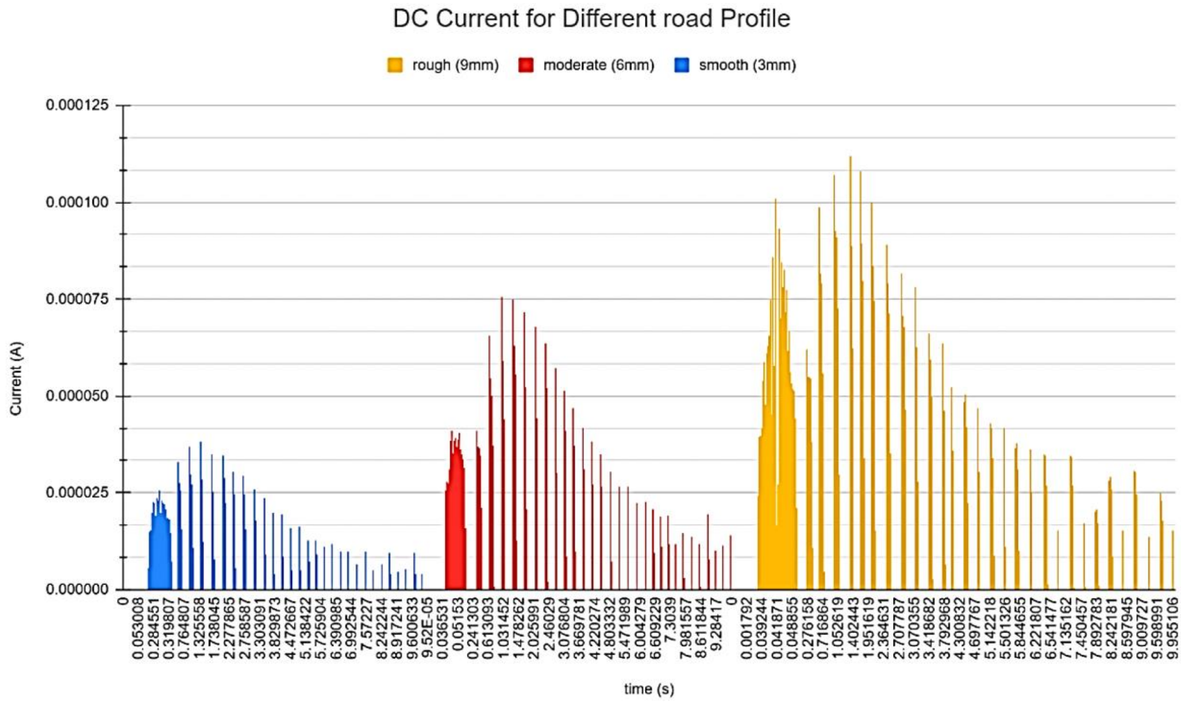


Fig. 5 *Result for DC current generated from the simulation*

When examining the power output over time, which represents the product of voltage and current, it can be observed that direct correlation with the trend observed in the voltage and current graphs as in Fig. 6. The power graph highlights the exponential increase in energy harvesting capability with worsening road profile conditions. For the smooth road profile, the harvested power remains low throughout the simulation period, peaking at around 0.3 milliwatts. This result reinforces the earlier observation that minimal mechanical excitation limits the potential for meaningful energy extraction. Under the moderate profile, the power output improves substantially, peaking around 1 milliwatt. This fourfold increase compared to the smooth road demonstrates that even moderate terrain conditions provide sufficient mechanical disturbance to enable viable energy recovery. However, it is the rough road profile that exhibits the most significant energy harvesting performance, with power outputs reaching up to 2.1 milliwatts. The waveform in this case is not only higher in amplitude but also more consistent and prolonged, suggesting sustained energy conversion over time. This outcome confirms the hypothesis that piezoelectric energy harvesting systems are particularly effective in scenarios where the vehicle encounters frequent and large suspension displacements [9]-[11].

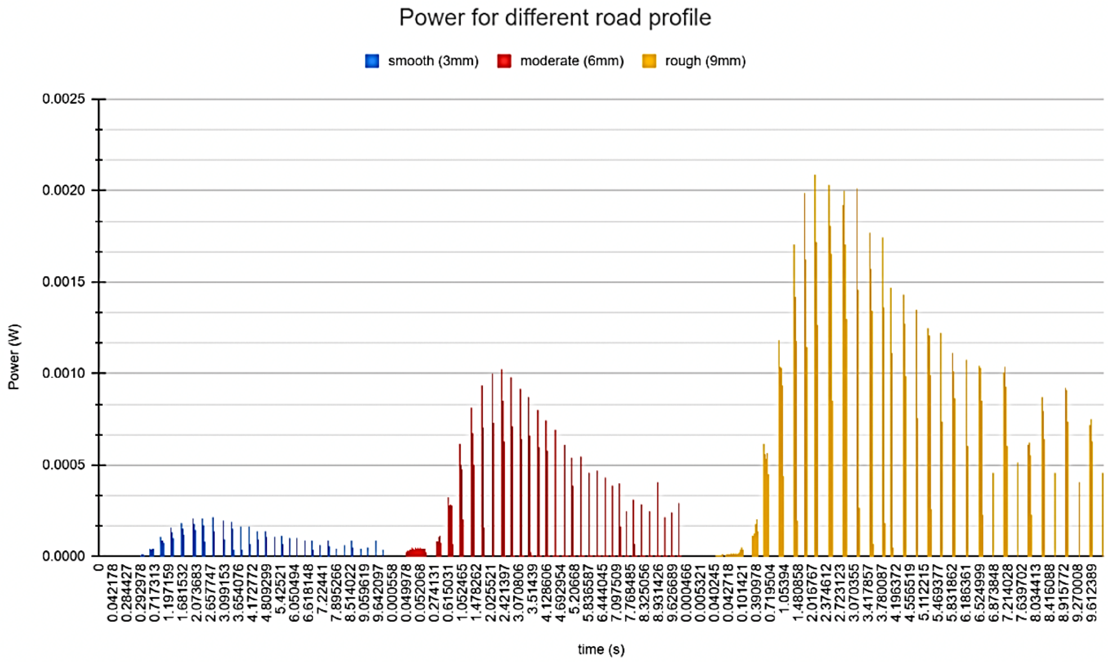


Fig. 6 Result for DC voltage generated from the simulation

The simulation results from the quarter-car model with a piezoelectric regenerative suspension system highlight its potential in energy harvesting. When tested with different road profiles at a fixed frequency (9.17 rad/s), energy output increased with road roughness from 0.3 mW on smooth roads to 2.1 mW on rough roads. This shows that greater mechanical excitation enhances harvesting performance. Under road Profile C excitation (9.17 rad/s), the system generated 30V and 2.1 mW, showing a 10.47% lower voltage and 96.27% lower power compared to [11], [12] optimized design. This discrepancy stems from differences in piezoelectric stack configuration. Table 4 shows the summary results of different road profiles.

Table 4 *Summary of results for different road profiles*

Road profile	Max voltage (V)	Max current (μA)	Max power (mW)
A	9	30	0.3
B	19	70	1
C	30	120	2.1

3.2 The Effect of Different Speeds Profile

To analyse the effect of vehicle speed on the performance of the piezoelectric regenerative suspension system, a series of simulations were conducted using MATLAB/Simulink. In this case, the road profile was fixed at 0.006 m amplitude (Road Profile B, representing moderate road conditions), while the vehicle speed was varied to simulate different levels of dynamic excitation. Based on Table 5, the selected vehicle speeds were 40 km/h, 60 km/h, and 100 km/h, corresponding to low, medium, and high-speed driving conditions. These speeds were translated into excitation frequencies of 13.96 rad/s, 20.94 rad/s, and 34.91 rad/s respectively, using the relationship between speed and wavelength.

Table 5 *Speed variation for simulation*

Speed (km/h)	Speed (m/s)	Wavelength (m)	Frequency (rad/s)
40 (slow)	11.11	5	13.96
60 (medium)	16.67	5	20.94
100 (fast)	27.78	5	34.91

A fixed spatial wavelength of 5 meters was assumed, representing the average length between successive road bumps or undulations. This assumption is commonly used in vehicle dynamics studies to simulate road excitations that induce realistic suspension deflections over common rough terrains [8], [13]. The choice of wavelength 5 m is based on a representative value that reflect moderately-spaced road irregularities commonly encountered in rural or semi-urban environments. It provides a suitable basis for frequency derivation while avoiding unrealistically sharp or smooth input signals.

The graph shown in Fig. 7 illustrates the DC voltage output of a piezoelectric regenerative suspension system under three different vehicle speeds which are 40 km/h (low speed), 60 km/h (medium speed), and 100 km/h (high speed). It captures how vibration frequency, resulting from vehicle velocity over a consistent road profile, influences the electrical energy harvesting performance, particularly in terms of maximum voltage output. At 40 km/h, the vehicle traverse's road irregularities more slowly, allowing the piezoelectric stack embedded in the suspension to fully experience and respond to each excitation cycle. This means the mechanical strain imposed on the piezo material is more complete, enabling greater charge generation and thus a higher voltage output. Furthermore, the relatively low excitation frequency of 13.96 rad/s may be closer to the resonance frequency of the piezo-suspension system, where the transfer of vibrational energy to electrical energy is maximized. The slow but steady interaction with road disturbances allows energy to be harvested more efficiently, with minimal losses from damping or system lag.

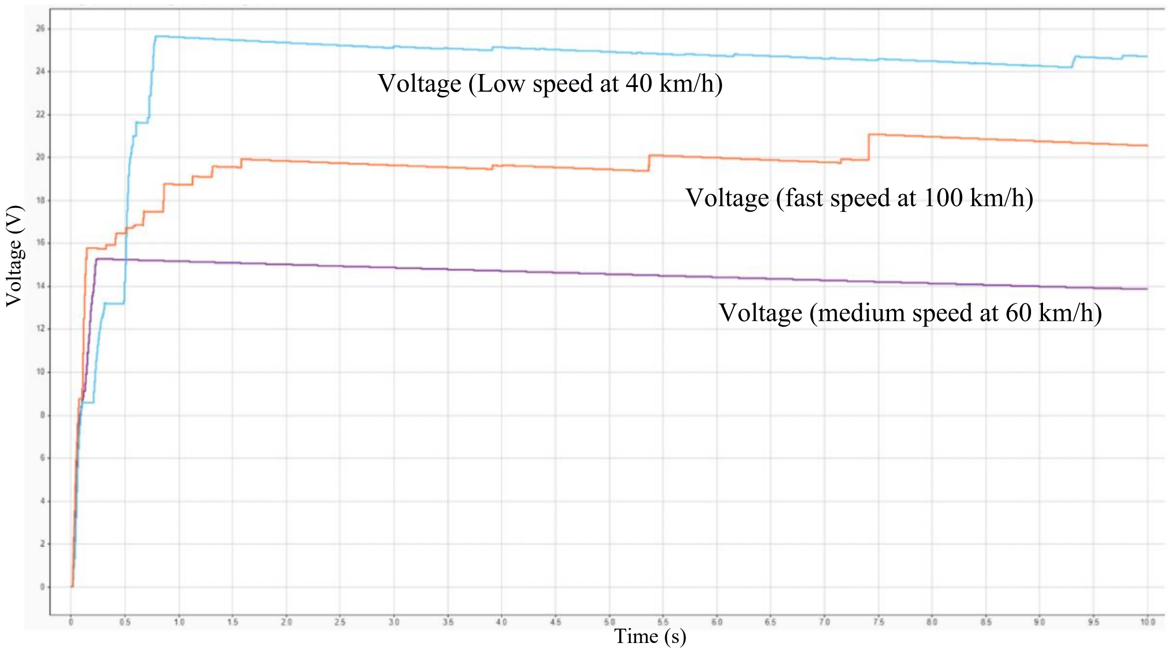


Fig. 7 *Result for DC voltage generated from the simulation*

When the speed increases to 60 km/h (medium), however, the voltage output drops to 15.0 V. This counterintuitive result can be attributed to dynamic mismatch. At this intermediate speed and frequency, the system may be operating away from resonance and thus is less efficient in harvesting energy. The suspension reacts less effectively to road input because the excitation frequency does not align well with the mechanical response characteristics of the piezo stack. Additionally, the suspension system may absorb and dissipate a larger portion of the input energy before it reaches the piezo element, leading to lower mechanical strain and reduced electrical output [14]. As the speed increases further to 100 km/h, the voltage output rises again to 20.7 V.

Although the time of contact between the wheel and each road irregularity is shorter, the number of vibration cycles per second increases significantly. This higher frequency of mechanical excitation translates into more opportunities for the piezo stack to generate charge, even if the deformation in each cycle is smaller. Moreover, at high speed, the acceleration of the suspension components increases, and since force is directly proportional to acceleration, this can result in stronger compressive forces acting on the piezo stack. Consequently, a balance is achieved where the loss in individual cycle deformation is offset by increased excitation frequency and force, resulting in a moderate but consistent voltage output.

The combined current analysis across low, medium, and high vehicle speeds in Fig. 8 clearly reveals how the piezo-regenerative suspension system behaves under varying dynamic excitations. Each speed level introduces distinct suspension. At low speed (40 km/h), corresponding to a frequency of 13.96 rad/s, the piezoelectric system demonstrates an initially strong and active current generation phase. The current output begins with a series of high-frequency, high-amplitude spikes within the first 1.5 seconds, with the peak current reaching up to approximately 0.034 A. This indicates that at slower speeds, the suspension has time to compress and rebound more fully, allowing the piezoelectric stack to undergo significant deformation. Such full-range mechanical strain leads to effective charge generation and discharge. However, once the initial road-induced excitation fades, likely after the suspension settles, the current drops sharply and becomes highly intermittent. Only sparse pulses appear throughout the remainder of the simulation, suggesting that without continuous road disturbances or higher input energy, the piezoelectric output weakens quickly. This behavior is consistent with the capacitive nature of piezo stacks, where charge builds up and is released only when sufficiently disturbed by mechanical input [15].

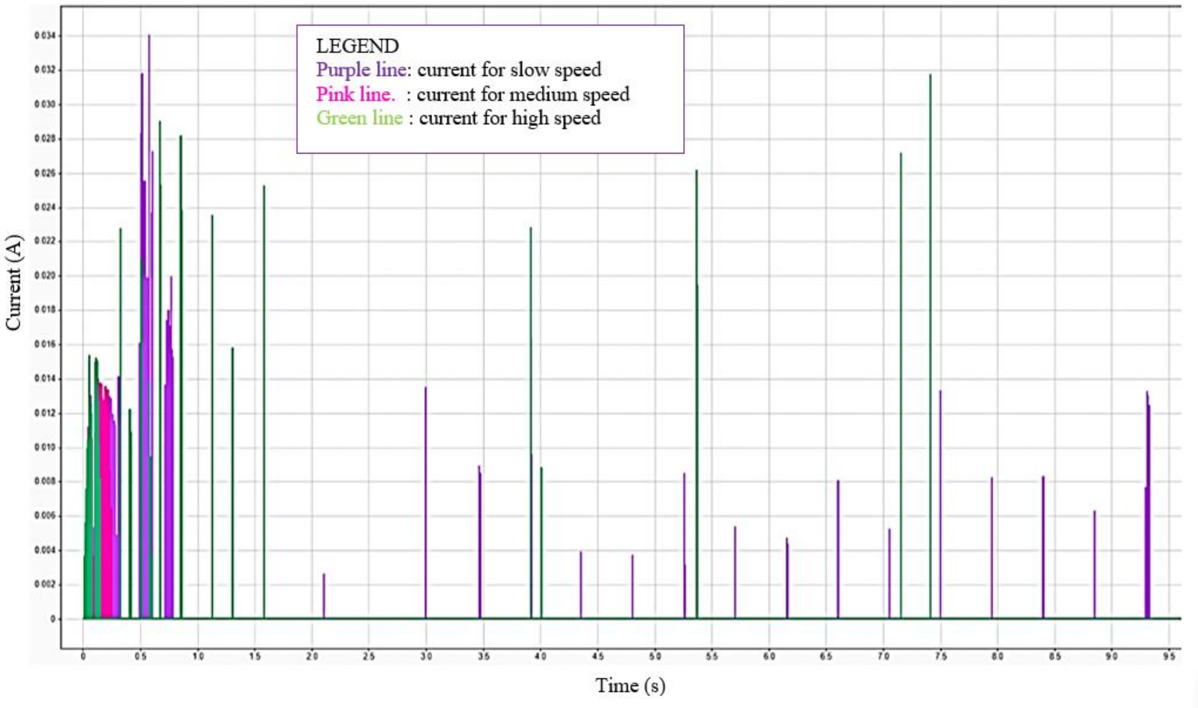


Fig. 8 *Result for current generated from the simulation*

In contrast, at medium speed (60 km/h), which corresponds to 20.94 rad/s, the current waveform displays a noticeably weaker and shorter-lived response. The current spikes are limited to the first 0.3 seconds, reaching a peak value of about 0.015 A, after which the graph flattens out for the rest of the 10-second period. This suggests that at this intermediate speed, the suspension compresses and relaxes too quickly for the piezo stack to respond with sufficient charge displacement. The deformation occurs at a rate or amplitude that may be suboptimal, neither slow enough for full strain nor fast enough for sharp force changes. Consequently, current generation is minimal and unsustainable, with no significant activity beyond the transient phase. The stack essentially fails to accumulate meaningful electrical output after the initial impact, indicating that energy harvesting at medium speed is inefficient without resonance or continuous deformation.

At the high speed (100 km/h) condition, where the excitation frequency reaches 34.91 rad/s, a more intense and scattered current profile is observed. During the initial phase (0-1.5 s), the current output reaches peaks close to 0.033 A, similar to the low-speed case. However, what distinguishes the high-speed result is the continuation of current generation in the form of intermittent but high-amplitude spikes that occur throughout the simulation period, especially near 4 s, 5.5 s, and between 7 to 8 s. These bursts indicate that at high speed, the wheel interacts with the road in such a way that sharp, irregular mechanical inputs trigger sudden deformation of the piezo stack. The large rate of change of force values under fast motion produces more intense piezoelectric responses, resulting in stronger electrical pulses. Yet, because these events are not continuous or uniform, the current output becomes burst-like and unpredictable. While this offers potential for harvesting higher peak energy, it also introduces challenges in designing storage systems that can capture and regulate these surges efficiently.

The Fig. 9 illustrates the electrical power output generated by the piezoelectric regenerative suspension system at three different vehicle speeds. Since power is the product of voltage times current, the pattern of this graph inherently follows the current behavior discussed earlier, modulated by the voltage at each respective speed. Starting with the slow speed case (40 km/h), it is observed that the power output is most active and sustained throughout the simulation. In the first second, power spikes occur densely, with some values reaching above 0.7 W, which is the highest instantaneous power recorded among all three cases. These peaks occur due to the simultaneous presence of moderate-to-high voltage and a series of distinct current bursts, allowing the power product to be maximized. After 1.5 seconds, the power output becomes intermittent but remains present across the 10 seconds, indicating that the slow suspension movement continues to cause meaningful piezo deformation, albeit less frequently. This highlights that low-speed motion allows consistent mechanical-to-electrical conversion, especially where suspension travel is more pronounced due to longer dwell times on road bumps.

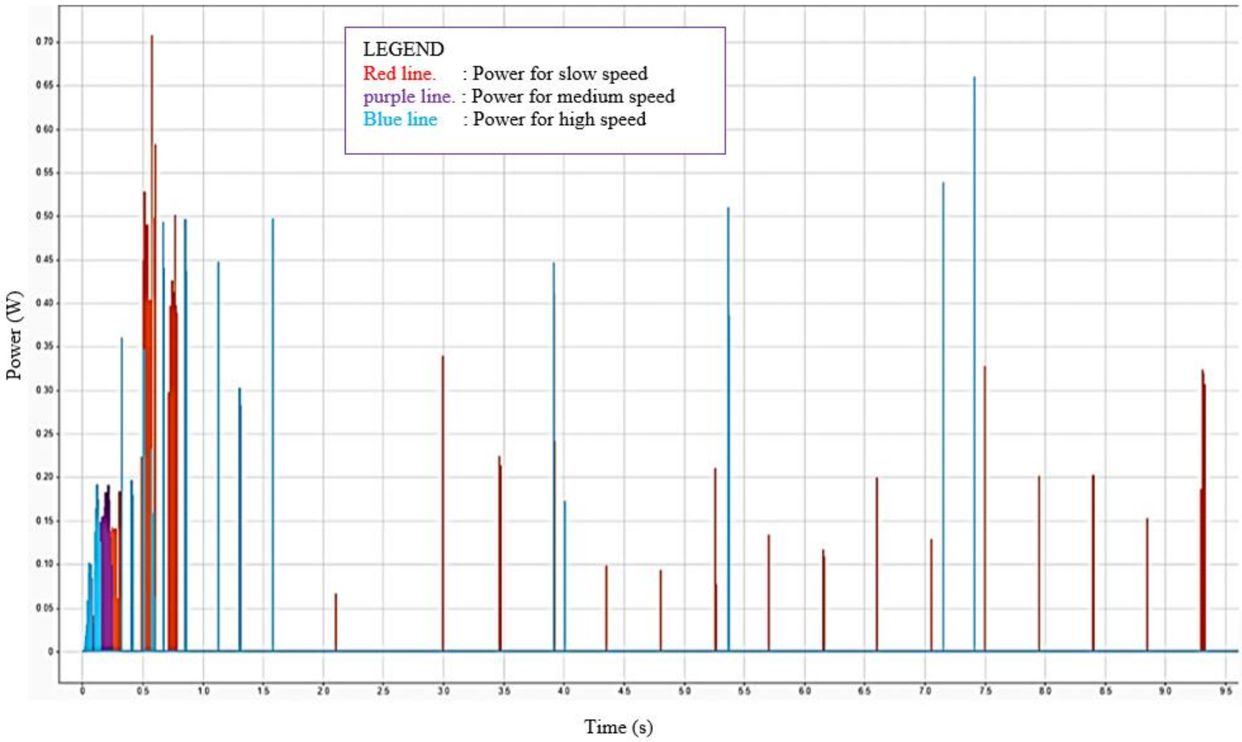


Fig. 9 *Result for power generated from the simulation*

In the medium speed case (60 km/h), the waveform is confined to a very narrow window between 0 to 0.3 seconds, with small peak values below 0.2 W. The early spikes correspond to a brief period of piezo stack excitation immediately after the simulation begins, matching the transient current response previously observed. However, beyond this point, the power signal completely vanishes, indicating that the current falls to nearly zero while voltage alone is insufficient to maintain any meaningful power output. This outcome reinforces the earlier conclusion that the suspension system at medium speed dampens road excitation effectively, preventing sufficient strain on the piezo stack and thus leading to poor energy generation.

In contrast, the high-speed case (100 km/h) presents a different profile. Here, the light blue spikes extend intermittently throughout the simulation, with some peaks reaching just above 0.65 W, close to the highest values observed at slow speed. However, these power spikes are sporadic and isolated, appearing at scattered time intervals like 1 s, 4 s, 5.5 s, and 7.5 s. This distribution reflects a condition where the suspension is subjected to rapid, high-frequency shocks, which create short but intense bursts of both current and voltage. These high-magnitude, short-duration spikes indicate that while the piezoelectric stack is being strongly activated, it is only under specific and brief force events rather than continuous excitation. This means the overall energy (area under the curve) might be lower than expected unless properly harvested using energy storage or smoothing circuits.

Under constant rough road conditions but varying speeds, the system generated its highest power at 40 km/h (0.75 W), dropped to 0.20 W at 60 km/h, and rose again to 0.65 W at 100 km/h. This non-linear trend suggests that energy harvesting is influenced by suspension dynamics and resonance behaviour, not speed alone. At variable speeds (40-100 km/h), the measured power range of 0.20–0.75W significantly exceeds typical literature values. For instance, reported only 3–6mW under similar road conditions using d31/d33 mode harvesters [3]. This 2–3 order-of-magnitude difference may originate from scaling assumptions: our quarter-car model might overestimate force transmission compared to full-vehicle simulations. Additionally, the 13μF capacitance value and ideal electrical load assumptions in our model potentially ignore impedance matching losses documented by previous literature [15]-[17]. Table 6 presents the summary of results for different speed of vehicle.

Table 6 *Summary of results for different speed of vehicle*

Speed (km/h)	Frequency (rad/s)	Max voltage (V)	Max current (A)	Max power (W)
40 (low)	13.96	25.8	0.034	0.75
60 (medium)	20.94	15	0.015	0.2
100 (fast)	34.91	20.7	0.033	0.65

4. Conclusions

This study explored the feasibility and performance of a piezoelectric-based regenerative suspension system designed to harvest energy from road-induced vibrations. Tt has successfully simulated the implementation of a piezoelectric regenerative suspension system that is capable of harvesting energy from various road conditions and has high potential to become secondary power source for sensors and other small subsystems. The simulation results demonstrated that road profile significantly affects energy output and confirms that rougher roads enhance the mechanical excitation transmitted to the piezoelectric harvester, resulting in greater energy generation. The variations of vehicle speeds suggested a nonlinear relationship between speed and energy harvesting, likely influenced by the interplay between vibration frequency and system resonance. It was observed that an optimal energy harvesting does not always correspond to the highest speed, indicating that frequency alignment is more critical than speed alone. The energy generated from a single bump or even minor vibrations from the system is sufficient to power a complete sensing and communication system, such as wireless, battery-less sensors for Tire Pressure Monitoring Systems (TPMS), Suspension health monitors, Smart window/door/latch sensors. The findings also demonstrated that road profile and vibration frequency are influential factors in energy output, more so than speed alone. The promising results obtained will help for further experimental investigation to develop optimized piezoelectric-based Regenerative Suspension System for automotive application

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Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *M.F. Aladdin, S. Ahmad* ***data Simulation:*** *M.H Tahir;* ***analysis and interpretation of results:*** *M.F. Aladdin, M.H Tahir, S. Ahmad;* ***draft manuscript preparation:*** *M.F. Aladdin, M.H Tahir. All authors reviewed the results and approved the final version of the manuscript.*

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