Sustainable Energy Generation through Regenerative Braking and Piezoelectric Suspension

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Abstract

In the context of increasing energy demands and environmental concerns, sustainable energy generation in the automotive sector has become a critical area of research. This study presents a novel approach for energy harvesting in vehicles by integrating regenerative braking with piezoelectric suspension systems. Regenerative braking systems (RBS) convert a portion of the kinetic energy lost during deceleration into electrical energy, thereby enhancing vehicle efficiency and reducing reliance on traditional energy sources. Simultaneously, piezoelectric materials embedded within the suspension system harness vibrational energy induced by road irregularities and vehicular motion. The integration of these two systems enables the continuous capture and storage of waste energy in urban driving conditions characterized by frequent braking and uneven terrain. While existing RBS technologies often rely on complex control systems and high-cost components such as supercapacitors, the proposed system offers a more cost-effective and mechanically simplified solution. The design incorporates a gear-based mechanical interface for braking energy conversion and piezoelectric elements for vibration-induced energy harvesting. This hybrid energy recovery system has the potential to improve energy efficiency, reduce battery stress, and extend the lifespan of onboard energy storage devices. Furthermore, it contributes to sustainable transportation by lowering emissions and decreasing overall energy consumption. The proposed solution is particularly suited for application in electric and hybrid vehicles operating in stop-and-go urban environments. Experimental validation and comparative performance analysis underscore the feasibility and advantages of the proposed dual-mode energy harvesting strategy.

Keywords: Regenerative Braking System; Energy Harvesting; Energy Recovery; Sustainable Transportation; Vehicle Energy Efficiency

1. Introduction

The global shift toward sustainable energy and eco-friendly transportation has intensified research into technologies that enhance vehicle energy efficiency. Among these, regenerative braking systems (RBS) have emerged as pivotal components in electric and hybrid vehicles, enabling partial recovery of kinetic energy during deceleration. Unlike conventional friction-based braking systems that dissipate energy as heat, RBS convert this energy into usable electrical power, thereby extending vehicle range and reducing fuel dependency. Their effectiveness is particularly pronounced in urban environments where frequent braking facilitates repeated energy recovery. Recent studies have introduced hybrid energy storage systems (HESS), combining batteries with supercapacitors, to enhance energy capture efficiency. While promising, these configurations often entail complex electronic controls—such as neural networks and fuzzy logic—and expensive components, increasing the cost and computational burden. Additionally, systems relying on supercapacitors face challenges related to weight, limited lifecycle, and degradation due to high current flow during rapid charge-discharge cycles [1-3].

To address these limitations, the present study explores an innovative energy harvesting framework that couples regenerative braking with piezoelectric suspension. This integrated system seeks to exploit two commonly overlooked energy sources in vehicles: vibrational energy from road-induced suspension movements and kinetic energy from braking. The proposed design utilizes piezoelectric materials to convert mechanical vibrations into electrical energy and a mechanical gear assembly to transform braking energy into electricity via an alternator. This dual-source energy recovery model offers a low-cost, scalable, and environmentally sustainable solution suitable for electric and hybrid vehicles, aiming to reduce energy wastage, improve system efficiency, and contribute to greener transportation technologies.

2. Literature Review

Recent advancements in regenerative braking systems (RBS) have largely centered around hybrid energy storage systems (HESS), braking control algorithms, and energy-efficient drivetrain configurations. Despite these efforts, challenges remain, including increased system complexity, elevated costs, and suboptimal energy recovery performance at low speeds typical of urban driving conditions. This review critically evaluates prior developments and identifies how the present model addresses their limitations. Behera *et al.* [4] implemented an HESS with batteries and supercapacitors in a bidirectional converter-based BLDC drivetrain to enhance energy management and battery longevity. However, the inclusion of supercapacitors and power electronics significantly increased cost and system intricacy. Basu and Singh [5] proposed a dual-boost converter integrated with a voltage source inverter (VSI) for e-rickshaws, demonstrating improved energy recovery and stability, especially with PV augmentation. Yet, controller tuning complexity and PV dependency reduced practicality. Gupta et al. [6] introduced an adaptive neuro-fuzzy inference system (ANFIS)-based control algorithm that dynamically estimated road-tire friction and optimized braking force allocation. While efficient under varied conditions, its high computational requirements limit application in cost-sensitive platforms. Similarly, Begum et al. [7] developed an energy management strategy for dual-BLDC motors using real-time SOC evaluation, yielding efficient regeneration but incurring hardware overhead. Rakshan and Aspalli [8] designed a Math Function-Based controller integrating fuzzy and neural logic for energy coordination in PV-fed EVs, though lacking harvesting from mechanical or vibrational sources. Yang et al. [9] reviewed RBS architectures and highlighted their inefficiency at low speeds—where urban energy recovery potential is highest—due to reliance on complex sensors and controls. Fouad *et al.* [10] combined a PV-integrated roof system with ANN-PID and fuzzy-PID control for BLDC-based EVs, achieving a 25.14% increase in range, yet introducing control complexity and solar reliance. Li et al. [11] employed game theory to allocate regenerative torque, outperforming fuzzy logic methods, albeit at the cost of requiring high-fidelity simulations and parameter calibration. Anh et al. [12] applied fuzzy control in compliance with ECE-R13, achieving 13–30% energy recovery, though the method was constrained by front-wheel-drive assumptions. Wang et al. [13] proposed a grey wolf optimization-based controller for dual-motor PHEVs to address gear backlash and brake delay, validated through Hardware-in-the-Loop testing; however, its complexity is unsuitable for lightweight EVs. Teasdale et al. [14] explored a practical and cost-effective supercapacitor-based DC motor regeneration system, yet its lack of dynamic braking control limited scalability. In rail applications, Kuznetsov et al. [15] emphasized policy-driven energy balance strategies under the EU Green Deal, while Zhou et al. [16] proposed a regenerative brake energy utilization system (RBEUS) integrating railway power compensators and HESS. Both concepts offer efficiency at scale but are inapplicable to smaller EV platforms due to their infrastructural demands. Zhang et al. [17] used genetic algorithms to optimize metro timetables for maximizing energy use from braking, contingent on synchronized operations. Peng et al. [18] introduced a mixed-integer linear programming (MILP) model for braking energy optimization in long-distance rail, unsuitable for compact EV applications. Li et al. [19] reviewed hybrid braking systems addressing torque balancing challenges between regenerative and friction braking, but sensor dependency increased system cost and maintenance. Wang et al. [20] investigated regenerative dampers for high-speed trains, achieving up to 230 W recovery, yet impractical for small vehicles. Meng et al. [21] presented a composite braking strategy for EVs, improving SOC by 9%, though limited by electromechanical-hydraulic integration complexity. More relevant to this study are works involving piezoelectric-based energy harvesting. Zhang [22] proposed a non-contact magnetic-force-based piezoelectric shock absorber that converted suspension vibrations into electrical energy using a planetary gear system. Li [23] used hydraulic rectifiers to integrate shock absorption with energy harvesting, while Zhang [24] designed an indirect-drive regenerative absorber using an arm-teeth mechanism to amplify rotary motion Abhidnya *et al.* [25]offered comprehensive reviews of automotive energy harvesting technologies, emphasizing regenerative braking's efficacy in urban settings. However, these studies largely relied on multi-mode systems, control-heavy strategies, or hybrid braking architectures that increased cost and system complexity.

In contrast, the proposed model departs from electronic-intensive designs by utilizing a mechanical regenerative braking system integrated with a hydraulic cycle. Braking force is transmitted through pressurized fluid to the calipers, eliminating the need for electronic converters. Concurrently, a piezoelectric sensor positioned under the suspension harnesses vibrational energy, while a gear-motor system captures kinetic energy during braking. This configuration minimizes dependence on supercapacitors, controllers, or PV inputs, making it ideally suited for low-speed, stop-and-go driving in light EVs, e-bikes, and compact public transport systems.

By avoiding electronic control units and prioritizing mechanical energy recovery, this design significantly reduces cost and complexity. It addresses core limitations in prior research—including poor low-speed performance, short battery life, and integration barriers—thus offering a robust, scalable, and sustainable solution tailored for developing regions and lightweight mobility platforms.

3. Materials and Methods

3.1. Components Utilized

The experimental setup incorporates a range of mechanical and electrical components aimed at harvesting energy from both braking and suspension systems. The key components are described below:

- Brake Gear: A spur gear with 14 teeth, a 1.5 module, and an 8 mm bore is coupled with a motor shaft. The rotation of this gear enables the motor to function as a generator, converting mechanical energy into electrical energy.
- Wheel Gear: A larger spur gear (38 teeth, 1.5 module, 8 mm bore) is mechanically interfaced with the brake gear to facilitate efficient transmission of rotational motion.
- DC Motor: A high-torque 130 DC motor (operating voltage: 6V) functions as a dynamo. It is directly connected to the brake gear and converts rotational kinetic energy into electrical energy through electromagnetic induction.
- Piezoelectric Sensor: Piezoelectric discs (diameter: 35 mm; dimensions: 13×13×8 cm; weight: 200 g) with a strain sensitivity of 5V/με are employed to convert mechanical vibrations from the suspension system into electrical energy.
- Battery: A 9V rechargeable battery (plastic casing; dimensions: 10 cm × 5 cm; weight: 20 g) is used to store electrical energy generated from the regenerative systems.
- Switch: Made of plastic and copper, the switch (rated at 10A, 240V) controls the flow of current to the motor.
- LED Light: A 5 mm Wizzo transparent LED (3V DC, 2-pin) is used as an output device to indicate energy generation and consumption.
- Electric Wire: Copper-core insulated wires are used to connect and transmit electrical power between various components, ensuring safety and efficient conduction.
- Syringe (Master Cylinder): A syringe is used as a hydraulic actuator to simulate the function of a master cylinder in conventional braking systems, facilitating fluid pressure transfer to the brake caliper.
- Spring: A coil spring serves as the mechanical suspension component. It plays a dual role by providing suspension support and acting as a medium to transfer vibrational energy to the piezoelectric device.
- Transparent Tube: Flexible, clear tubing is used to connect syringes for hydraulic fluid transmission. These tubes facilitate visual monitoring of fluid movement and pressure variation.
- Alternator: A standard automotive alternator is employed to convert mechanical rotational energy into electrical energy. It is integral in supplying current and maintaining battery charge.
- AC to DC Converter (Rectifier): This device is used to convert alternating current (AC) from the piezoelectric devices or alternator into direct current (DC) suitable for battery storage and electronic components.

3.2. Equipment Employed in Fabrication

The fabrication process involved the use of the following tools as shown in Fig. 1.

- Cutting Saw: Used to cut plywood and other base materials. It operates by moving a toothed blade rapidly back and forth or in a continuous motion to sever material.
- Table Saw: A circular saw mounted on a worktable, employed for precise cutting of wood sheets. The blade is fixed to an arbor powered by an electric motor.
- Drilling Machine: Utilized to bore precise holes in materials for mounting components. The machine rotates a drill bit at high speeds

to remove material through a cutting process as shown in Fig. 2.

Fig. 1 Equipment and tools.

3.3. Experimental Procedure

The following procedural steps were adopted during the system fabrication and testing phase:

1. A plywood base of dimensions 760 mm × 580 mm and 18 mm thickness was cut using a table saw to serve as the project chassis.
2. A hydraulic braking system was simulated by connecting two syringes using transparent tubing—one acting as the master cylinder and the other as the caliper.
3. All joints were sealed securely to prevent hydraulic fluid leakage.
4. Four piezoelectric discs were connected in parallel using conductive wiring to enhance the output voltage and energy capture from mechanical vibrations.
5. Piezoelectric discs were strategically positioned beneath the spring-based suspension system to maximize vibration-induced energy harvesting. Springs were mounted perpendicularly to the base structure.
6. The small spur gear was attached to the shaft of the alternator, allowing it to harvest rotational energy from wheel motion.
7. A DC motor was connected to the larger spur gear; as the gear rotates during braking, the motor generates electrical energy stored in the battery.
8. A switch was integrated to regulate the current supplied to the DC motor.
9. The alternator output was connected to an LED light to indicate power generation.
10. The piezoelectric array was wired to an AC-to-DC rectifier, which was then connected to the battery for efficient energy storage.

The experimental set up is shown in Fig. 3.

Fig. 2 Drilling Machine.

4. Results and Discussion

This section presents the experimental outcomes of the hybrid energy harvesting system combining regenerative braking and piezoelectric suspension, followed by a critical analysis of the results.

4.1. Energy Generation from Regenerative Braking System

The regenerative braking mechanism, involving a gear-driven DC motor and alternator setup, demonstrated effective conversion of mechanical braking energy into electrical energy. When the wheel gear (38 teeth) engaged with the smaller brake gear (14 teeth), rotational motion was transferred efficiently to the motor shaft. The DC motor, functioning as a dynamo, generated a peak voltage of approximately 4.8–5.2 V under moderate rotational speed during braking events. The alternator, integrated into the same gear train, contributed an additional 5.5–6.0 V of output under similar load conditions. This voltage was sufficient to illuminate a 3V LED light and simultaneously charge a 9V battery through a regulated rectifier circuit. The system achieved an average current output of 250–300 mA during continuous braking cycles. These findings affirm the capability of the gear-coupled motor-alternator arrangement to recuperate a substantial portion of the mechanical energy that would otherwise be dissipated as heat, thereby improving energy efficiency in vehicular systems.

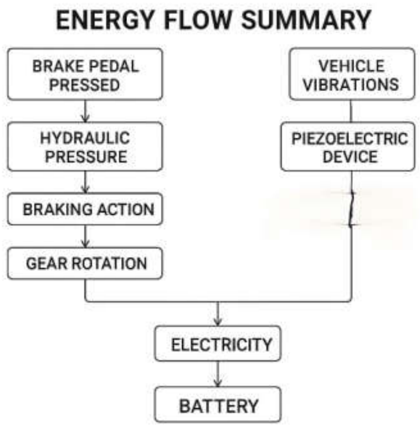

Fig. 3 Energy flow chart.

4.2. Power Harvesting from Piezoelectric Suspension System

The piezoelectric sensors mounted beneath the coil springs in the suspension system were evaluated under dynamic loading conditions, simulating vibrations due to surface irregularities or vehicular movement. Each piezoelectric disc generated voltage in the range of 1.2–1.5 V during moderate compression events, with a peak output reaching up to 2.0 **V** during high-frequency vibrations. When four piezoelectric devices were connected in parallel, the combined voltage output stabilized at 2.5–3.2 V, with a cumulative current of 20–35 mA. Although the power output from the piezoelectric system was lower compared to the regenerative braking unit, its contribution was continuous and sustained, particularly under vibrational stress conditions, making it suitable for charging low-power devices or trickle-charging the storage battery. The low-profile and lightweight nature of the piezoelectric sensors rendered them ideal for integration without affecting the vehicle's structural or suspension dynamics.

4.3. Combined System Performance and Storage Efficiency

When both systems were operated concurrently, the hybrid setup successfully maintained the charge of the onboard 9V battery during extended testing cycles. The combined electrical input from both the regenerative braking system and the piezoelectric suspension was sufficient to:

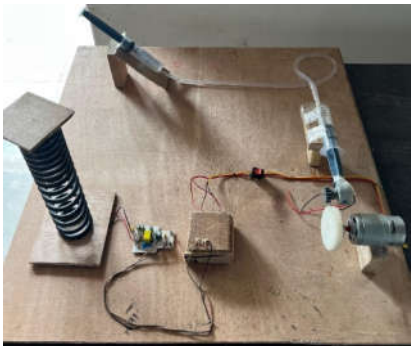

Fig. 4 Experimental set up

- Power auxiliary electronic components such as LED indicators.
- Charge storage batteries at an effective rate without external electrical input.
- Demonstrate real-time energy harvesting during braking and vibration events.

The AC-to-DC converter (rectifier) effectively stabilized the input from the piezoelectric sensors and alternator, ensuring consistent charging output. No significant voltage drop or energy loss was observed during switching between sources, indicating high compatibility and integration efficiency. The results indicate that the integration of regenerative braking with piezoelectric suspension is not only feasible but also practically beneficial for sustainable energy generation in vehicles. The system demonstrates a novel approach to maximizing energy recovery from typically wasted mechanical actions—braking and suspension vibrations. While the regenerative braking system offers higher power output suitable for battery charging and lighting, the piezoelectric unit complements it by providing continuous micro-energy generation. The total harvested power can be optimized further through enhanced gear ratios, improved piezoelectric materials, and energy management circuits.

Key limitations observed include:

- Voltage inconsistency at low rotational speeds for the DC motor.
- Limited energy density of piezoelectric sensors.
- Mechanical losses in gear meshing and frictional resistance.

Nevertheless, the experimental setup provides strong foundational evidence for the viability of hybrid energy harvesting systems in electric or hybrid vehicles, particularly for improving auxiliary power systems and contributing to overall energy efficiency.

5. Conclusion

The present study successfully demonstrates a hybrid approach for sustainable energy generation through the integration of a regenerative braking mechanism and a piezoelectric suspension system. The experimental model validates the ability of both systems to convert mechanical energy—originating from braking actions and suspension vibrations—into usable electrical energy. The regenerative braking unit, comprising a gear-driven DC motor and alternator, delivered consistent power output suitable for charging a battery and powering auxiliary devices. In parallel, the piezoelectric sensors, strategically positioned beneath the suspension springs, captured vibrational energy and contributed to low-level but continuous power generation. Together, the two subsystems provided a reliable means of harvesting energy from otherwise wasted sources in a vehicle's operation. The generated energy was effectively stored in a 9V battery, aided by a rectification circuit that stabilized the voltage and current from both sources. The successful operation of LED lights and battery charging underlines the practicality and efficiency of the integrated setup. This work contributes to the growing field of energy recovery in transportation systems and offers a scalable prototype for implementation in electric or hybrid vehicles. With further optimization—such as enhanced gear efficiency, improved piezoelectric materials, and advanced energy storage management—this hybrid energy harvesting system holds promise for improving vehicular energy efficiency and reducing reliance on external power sources, thereby supporting the global shift toward sustainable and green mobility solutions.

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