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Hybrid Braking System: Electromagnetic and Disc Braking

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Abstract

The hybrid braking system combines electromagnetic braking and traditional disc braking to enhance vehicle safety, improve braking response, and reduce mechanical wear. This system integrates sensor fusion technologies, including ultrasonic and infrared sensors, to enable adaptive braking based on real-time road conditions. A PID-based control algorithm optimizes braking force distribution, ensuring smooth and controlled deceleration. Additionally, the incorporation of regenerative braking allows for energy recovery, increasing vehicle efficiency and sustainability. The proposed system is designed to be cost-effective and scalable, making it suitable for a wide range of vehicles, from two-wheelers to four-wheelers. This project outlines the design, working principle, hardware implementation, and performance analysis of the hybrid braking system, demonstrating its potential to revolutionize modern braking technology. To provide better stopping performance, enhanced safety, and improved energy efficiency, the proposed hybrid braking system combines electromagnetic braking with traditional disc braking. Conventional disc brakes are prone to wear, heat generation, and maintenance issues, but they provide dependable friction-based stopping capability. The system significantly reduces mechanical wear and improves response time by utilizing electromagnetic brakes, which operate without physical contact. To ensure smooth and stable vehicle control, the hybrid approach enables both braking mechanisms to work in tandem, with electromagnetic braking handling the initial deceleration and disc braking providing the final stopping force. The system continuously monitors obstacles, vehicle speed, and road conditions by integrating ultrasonic and infrared sensors through sensor fusion technology, thereby increasing adaptability. A PID-based control algorithm processes these inputs and intelligently distributes the braking force between the two systems to maximize performance and prevent wheel lock or skidding.

Keywords: Hybrid braking, electromagnetic braking, disc braking, regenerative braking, adaptive braking, sensor fusion, PID control

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INTRODUCTION

The demand for vehicle safety, performance, and energy sustainability has increased; consequently, braking systems have undergone a remarkable evolution. Traditional braking systems, such as hydraulic disc and drum brakes, are effective at stopping a vehicle; however, they are less effective in terms of energy efficiency, heat dissipation, and mechanical reliability under extremely high loads. In these systems, kinetic energy is converted entirely into heat, resulting in energy loss and increased maintenance because of wear and tear. Modern transportation systems have increasingly adopted intelligent braking technologies that not only enhance safety but also improve energy efficiency. Hybrid braking systems, which incorporate electromagnetic braking (EMB), conventional disc braking, regenerative braking, and other technologies, have emerged as a promising solution [1–5].

Because of excessive mechanical wear and inefficient heat dissipation, traditional braking systems often become less efficient and require high maintenance costs. Modern braking systems have introduced a new area of development in terms of adaptive performance and real-time control. Regenerative braking is one of the most significant developments in this field, offering the opportunity to recover a portion of the energy lost during braking, thereby increasing vehicle efficiency. The integration of sensors and intelligent control mechanisms into braking systems has significantly advanced sustainable vehicle safety by improving the precision and responsiveness of braking actions [6–10].

A complete hybrid braking system combines these advanced techniques to address these challenges. Electromagnetic braking (EMB) provides non-contact deceleration, resulting in reduced wear and rapid response times. However, conventional disc brakes are still required to provide an immediate and reliable mechanical stopping force when necessary. Regenerative braking occurs when the kinetic energy generated during deceleration is converted into electrical energy. Sensor fusion further enhances the system by combining data from infrared (IR) and ultrasonic sensors to assess environmental conditions and detect obstacles. PID control algorithms are at the heart of the integrated system, enabling smooth adjustments to braking force in response to various driving scenarios, thereby improving performance and safety (Figure 1).

The proposed system offers a robust solution for urban and electric vehicles, for which energy efficiency and adaptive safety mechanisms are paramount. This integration not only reduces dependence on mechanical systems but also improves overall braking performance and energy efficiency.

LITERATURE REVIEW

Xing et al. (2024), in their study titled "Regenerative Braking Control Strategy of Vehicle with In-Wheel Motor Drive System Confronting Converter Fault," published in IEEE/ASME Transactions on Mechatronics, investigated regenerative braking control strategies for vehicles equipped with in-wheel motor drive systems, focusing on maintaining braking performance under converter fault conditions [1].

Zhang et al. (2022), in their study titled "Research on the Influence Factors of Brake Regenerative Energy of Pure Electric Vehicles Based on the CLTC," published in Energy Reports, examined the factors affecting regenerative braking energy recovery in pure electric vehicles using the China Light-Duty Vehicle Test Cycle (CLTC) as the basis for analysis [2].

Figure 1. Actual model of hybrid braking system.

Zhou et al. (2025), in their study titled “Anti-Lock Braking System Performance Optimization Based on Fitted-Curve Road-Surface Recognition and Sliding-Mode Variable-Structure Control,” published in the World Electric Vehicle Journal, focused on optimizing the performance of the Anti-Lock Braking System (ABS) using road-surface recognition techniques combined with sliding-mode variable-structure control [3].

Tian, Li, and Ye (2020), in their study titled “Study on Braking Characteristics of a Novel Eddy Current-Hydraulic Hybrid Retarder for Heavy-Duty Vehicles,” published in IEEE Transactions on Energy Conversion, explored the braking characteristics of a novel eddy current-hydraulic hybrid retarder system for heavy-duty vehicles that combines eddy current and hydraulic braking mechanisms [4].

Guo et al. (2021), in their study titled “Research on Regenerative Braking Strategies for Hybrid Electric Vehicle by Co-Simulation Model,” published in the International Journal of Vehicle Performance, investigated and evaluated regenerative braking strategies for hybrid electric vehicles using co-simulation models [5].

Zhang, Zhao, and Li (2020), in their conference paper titled “Electric Vehicle Regenerative Braking System Simulation Based on Kalman Filter,” presented at the 2020 Chinese Automation Congress (CAC), presented a simulation of an electric vehicle regenerative braking system incorporating a Kalman filter for state estimation and noise reduction in the control process [7].

Meng et al. (2020), in their study titled “A Survey of Brake-by-Wire Systems for Intelligent Connected Electric Vehicles,” published in IEEE Access, provided a comprehensive survey of brake-by-wire systems, discussing their applications and importance in intelligent connected electric vehicles [9].

METHODOLOGY

A hybrid braking system was developed through hardware-software integration, focusing on the design and development of a cost-effective, scalable system capable of performing intelligent braking under different real-world conditions. The following is a detailed, step-by-step account of the processes undertaken to coordinate braking force between different braking mechanisms, minimizing jerk and maintaining vehicle stability under varying driving conditions.

System Design

The system architecture comprises three key braking mechanisms: electromagnetic braking (EMB), disc braking, and regenerative braking. The initial engagement of EMB provides rapid, contactless braking, ensuring a quick response and reduced mechanical wear. As the braking demand increases, disc brakes are applied to deliver greater stopping force and ensure reliable operation under all conditions. Simultaneously, regenerative braking is used to recover kinetic energy and convert it into electrical energy, improving overall system efficiency and sustainability.

The standard braking procedure, as used in the current vehicle, provides smooth deceleration, followed by disc braking for improved stopping performance in emergency and high-speed situations. The regenerative braking module efficiently captures and stores kinetic energy during deceleration (Figure 2).

Sensor Fusion

Infrared (IR) and ultrasonic sensors detect the distance to nearby obstacles and monitor vehicle speed. These sensors form the sensory backbone of the adaptive braking logic and continuously feed data to the controller

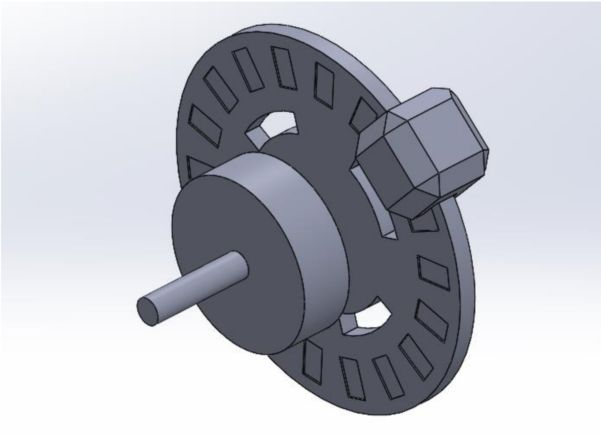

Figure 2. Design of prototype.

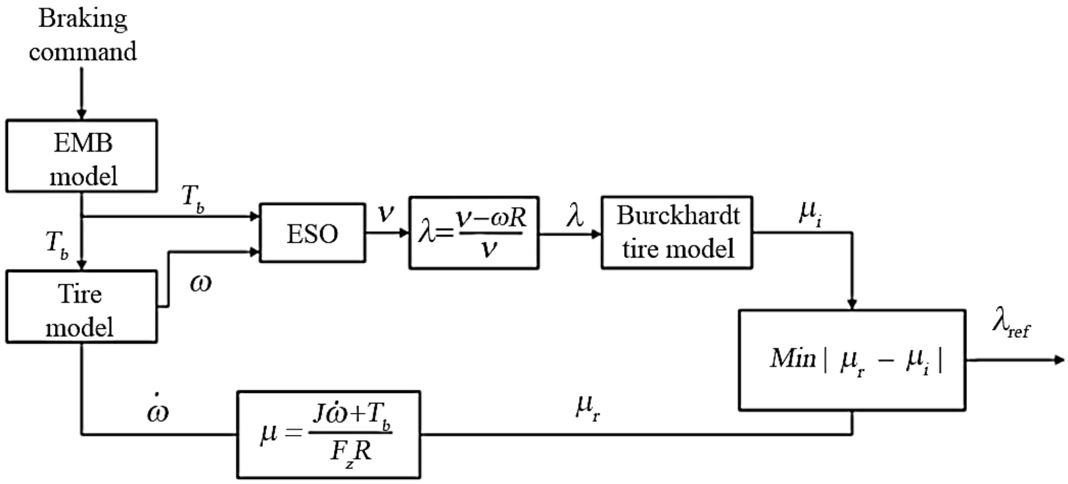

Figure 3. Proportional–integral–derivative.

Control System

A proportional–integral–derivative (PID) control algorithm analyzes the sensor inputs to determine the optimal distribution of braking force between the EMB and the disc brakes. To ensure smooth transitions without sudden jolts, the PID parameters were tuned based on simulations and real-world testing (Figure 3). The hybrid braking force was controlled using a PID algorithm. The system receives input from various sensors (distance, speed, and angular tilt from the gyroscope) to compute the braking force distribution that minimizes the stopping distance while maintaining a smooth braking experience.

The controller ensures:

- Smooth transitions between braking modes.
- No jerks, skidding, or imbalance caused by vehicle tilt.
- The ability to adapt in real time to road slopes and vehicle lean.

The control logic is consistent with the ABS tuning approach described by Zhou et al. (2025) and the regenerative braking strategies proposed by Guo et al. (2021) [3, 5].

Energy Recovery Setup

During deceleration, regenerative braking converts mechanical energy into electrical energy, which is routed through a buck converter and stored directly in a battery pack or capacitor. The recovered energy was monitored and recorded for further analysis.

WORKING PRINCIPLE

The hybrid braking system operates by actively managing and distributing the braking force among three subsystems: electromagnetic braking (EMB), conventional disc braking, and regenerative braking. The system makes intelligent decisions based on vehicle speed, distance to obstacles, and braking urgency to determine which braking mode should be given priority. The operation is explained step-by-step in Figure 4.

Sensor-Based Triggering

Through this mechanism, the system receives continuous real-time input from IR and ultrasonic sensors mounted on the vehicle to measure the distance to nearby obstacles and the vehicle's current speed. The collected data are processed in real time using a Raspberry Pi, which serves as the central control unit.

PID Controlled Braking Logic

The PID controller uses information from the sensor inputs to calculate the required braking force. Based on the required deceleration, the controller determines the percentage of braking to be provided by the EMB, disc brake, and regenerative braking modules. This approach ensures a smooth transition between the braking systems.

Activation of Electromagnetic Braking

Even under moderate braking conditions, the electromagnet is activated using a PWM signal generated by the Raspberry Pi. The electromagnetic coil, mounted near the rotating wheel or brake disc, generates a magnetic field that induces eddy currents, which oppose the rotation of the wheel, slowing the vehicle without physical contact.

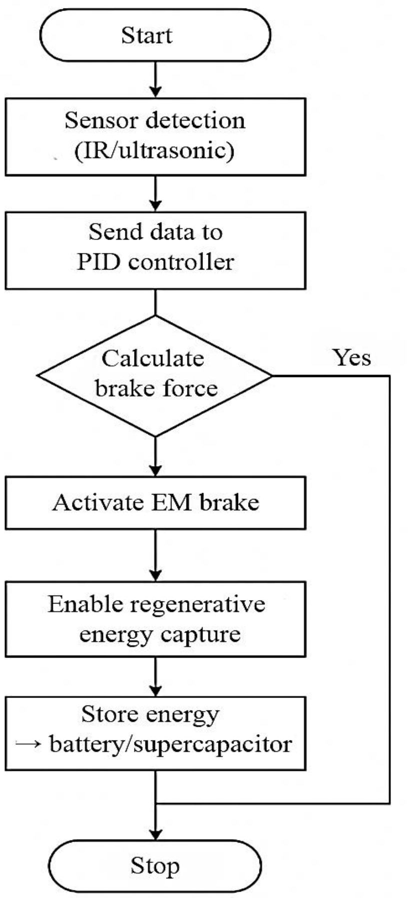

Figure 4. Working of the hybrid braking system.

Disc Braking Activation

In cases of high-speed or emergency braking, the system activates a relay that engages the hydraulic or mechanical disc brakes. The disc braking subsystem provides strong friction-based deceleration and serves as a reliable backup to the electromagnetic braking system.

Regenerative Braking Method

During deceleration, the regenerative braking module captures the kinetic energy of the rotating wheels and converts it into electrical energy, which is routed through a DC–DC converter and stored in a battery or capacitor bank for later use by the vehicle's auxiliary systems or traction motors in electric vehicles.

RESULTS AND DISCUSSION

In braking systems, a theoretical model provides an understanding of the performance characteristics that can be expected prior to full-scale implementation. This section combines fundamental physics and control system principles to explain the expected performance of the hybrid braking system.

Performance Metrics from Theory

The hybrid braking system was evaluated through theoretical computation, component testing, and prototype simulation. The theoretical evaluation covered basic parameters, such as braking time, stopping distance, and energy recovery, under different speed conditions. These results were compared with those of conventional braking methods to evaluate the improvements.

Theoretical Performance Metrics

Derived from the theoretical model and prototype testing, as discussed in Zhang et al. (2022) and Guo et al. (2021) [2, 5], Table 1 illustrates a comparison of the conventional disc brake, electromagnetic brake, regenerative brake, and hybrid braking system.

Performance Principles and System Foundation

Adapted from the principles presented in Zhang et al. (2022) [2], Guo et al. (2021) [5], Zhou et al. (2025) [3], Meng et al. (2020), and standard vehicle dynamics textbooks, such as Gillespie, Fundamentals of Vehicle Dynamics (SAE International, 1992), this section presents the theoretical models that underlie the design of the hybrid braking system.

PID Control Theory

The PID controller enhances braking stability by regulating the braking output based on sensor inputs. This approach helps prevent overshoot and enables rapid settling with a smooth transition.

Gyroscope Principle

MEMS (micro-electro-mechanical systems) gyroscopes measure rotational speed and tilt to maintain proper braking while negotiating curves or descending slopes. This information is fed back to the controller, thereby improving system stability and responsiveness.

Table 1. Comparison of the braking system.

Parameter	Conventional disc brake	Electromagnetic brake	Regenerative brake	Hybrid braking system
Average stopping distance (m)	6.5	5.8	6.2	4.7
Response time (ms)	120	80	100	60
Wear and tear	High	Low	Very low	Minimal
Energy recovered (%)	0	0	10–12%	12–15%
Heat generation	High	Low	Very low	Significantly low

Table 2. Comparative summary table.

Key performance indicator	Traditional disc brake	Hybrid braking system
Braking response time (ms)	120	60
Stopping distance (m)	6.5	4.7
Component wear rate	High	Minimal
Energy recovery capability	None	12–15%
Control adaptability	Manual	PID + sensor fusion

System Insights

These theoretical insights and simulation results demonstrate that the hybrid braking system has the potential to provide improved safety and efficiency compared with conventional braking systems. Its modular architecture makes it adaptable for future integration with smart vehicle networks (Table 2).

CONCLUSION

This hybrid braking system, which combines electromagnetic, disc, and regenerative braking, provides a solution to modern safety and energy requirements. It ensures smooth and responsive braking through PID control, along with partial energy recovery. The low cost of hardware makes the system suitable for commercial two-wheelers, small cars, and academic prototyping.

Its cost-effective hardware design and scalability make it a practical solution for two-wheelers, small cars, and academic research applications, supporting future advancements in intelligent and energy-efficient transportation systems.

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