Comparative Analysis of Different Controllers in Antilock Braking System

Embedded Systems for Automotive Applications
Project Report

Submitted by

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Abstract

This project presents the study of comprehensive design, simulation and performance analysis of different controllers used in an Antilock Braking System for an automobile using MATLAB Simulink. The objective of this project is to design and compare three different control strategies—Bang-Bang, Fuzzy Logic, and Proportional-Integral (PI)—for an Anti-lock Braking System (ABS) using MATLAB/Simulink. ABS is a critical component in modern vehicles, designed to prevent wheel lock-up during braking and to maintain traction with the road surface.

In this work, a standard quarter car ABS model is developed and simulated under identical braking conditions. The Bang-Bang controller is implemented using a simple on/off control logic, the PI controller employs feedback-based tuning using error values, and the Fuzzy controller uses a rule-based decision-making approach inspired by human reasoning. Key parameters such as wheel slip ratio, wheel angular velocity, vehicle speed, and wheel acceleration are analyzed to assess each controller's performance.

This project demonstrates how intelligent control systems can significantly improve the effectiveness and safety of automotive braking systems.

Contents

Chapter 1

Introduction

The Anti-lock Braking System (ABS) is a fundamental innovation in the field of automotive safety, playing a critical role in preventing wheel lock-up during emergency braking scenarios. By doing so, ABS maintains traction between the tires and the road surface, allowing the driver to retain steering control and significantly reducing the chances of accidents, especially on slippery or uneven surfaces. With the growing emphasis on intelligent vehicle systems and road safety standards, advanced control strategies in ABS have become a focus of both academic and industrial research.

Traditionally, Bang-Bang controllers (also known as on-off controllers) were used in early ABS designs due to their simplicity and fast response. These controllers operate by rapidly switching the brake pressure on and off based on threshold values of wheel slip, effectively reducing wheel lock-up. However, this method often leads to high-frequency oscillations, mechanical wear, and less comfort for passengers, making it less suitable for modern applications.

To overcome the limitations of on-off control, Proportional-Integral (PI) controllers were introduced. These controllers continuously regulate brake pressure based on the error between the actual and desired slip ratio. The PI control method improves system stability and performance by minimizing steady-state error and overshoot. However, PI controllers depend heavily on precise tuning and struggle to adapt to dynamic and nonlinear road conditions, such as sudden changes in road surface or weather.

In recent years, Fuzzy Logic Controllers (FLCs) have emerged as a promising solution to these limitations. Fuzzy controllers do not require an accurate mathematical model of the system, and they can incorporate human-like reasoning through a rule-based approach. By using linguistic variables such as "slight slip," "high slip," or "rapid deceleration," fuzzy controllers can handle system uncertainties and nonlinearities more effectively. This makes them particularly advantageous in complex systems like ABS, where real-time adaptability and smooth control are crucial.

Chapter 2

Literature Review

1. **ABS System Design Based on Improved Fuzzy PID Control** (Bo Lu,Yu Wang,Jing-jing Wu ,Jin-ping Li):

   The Anti-lock Braking System (ABS) enhances vehicle safety by preventing wheel lock during braking, especially under adverse road conditions. This study proposes an improved control design for ABS using a fuzzy PID controller, which integrates the advantages of both fuzzy logic and classical PID strategies. The aim is to enhance vehicle stability and shorten braking distances across varying road surfaces. MATLAB/Simulink is used to simulate the vehicle dynamics and control strategy, evaluating the performance under different conditions including dry, wet, and icy roads. Comparative analysis is conducted between traditional PID, fuzzy control, and the proposed fuzzy PID controller. Simulation results demonstrate that the fuzzy PID controller significantly improves braking performance and vehicle control, providing an effective solution for modern ABS implementation.

2. **Modeling and Simulation of ABS through Different Types of Controllers Using Simulink** (Mohammed Wafi):

   The Anti-lock Braking System (ABS) is a crucial development in automotive technology aimed at improving vehicle and traffic safety. This thesis investigates the modeling and simulation of ABS using various control strategies within the MATLAB/Simulink environment. The study evaluates the system's response using bang-bang, PID, and PD controllers at a constant vehicle speed of 100 km/h under different road conditions. The research highlights the importance of ABS in preventing wheel lock-up and maintaining steering control during braking. Simulation results demonstrate the effectiveness of these control strategies in enhancing vehicle performance and safety, with detailed analysis of vehicle behavior with and without ABS implementation.

3. **Comparative Study of the intelligent Techniques (Fuzzy logic and Neural Network) of the ABS system** (Ait Abbas Hamou,): Ait Abbas et al. (2022) conducted a comparative study on intelligent control techniques applied to an Anti-lock Braking

System (ABS), focusing on Fuzzy Logic Control (FLC) and Neural Network (NN) approaches. The study aimed to evaluate their performance against traditional controllers such as Bang-Bang (BB) and Proportional-Integral (PI) controllers within a nonlinear quarter-vehicle ABS model.

The Neural Network controller demonstrated the best overall performance, with the shortest stopping distance (407.35 m) and time (18.27 s), showcasing its superior ability to handle nonlinearities and parametric uncertainties.

The Fuzzy Logic controller also performed robustly, achieving a stopping distance of 416.249 m and time of 18.45 s, benefiting from its capacity to model human-like reasoning and manage uncertain environments.

Among the traditional controllers, the PI controller outperformed the BB controller, yielding shorter stopping distance (422.5 m vs. 459.3 m) and better tracking of the desired slip ratio.

Controllers based on intelligent techniques (FLC and NN) were found to be more resilient to model uncertainties and delivered more accurate slip control, essential for maintaining vehicle stability during braking.

These results affirm that integrating intelligent control methods significantly enhances ABS performance and reliability compared to classical control strategies.

Chapter 3

System Design

The ABS is designed to prevent wheel lock during emergency braking, thus maintaining vehicle control and minimizing stopping distance. The system consists of sensors to monitor wheel speed, an electronic control unit (ECU) to process data and make control decisions, and actuators (usually modulating hydraulic pressure) to apply braking force accordingly.

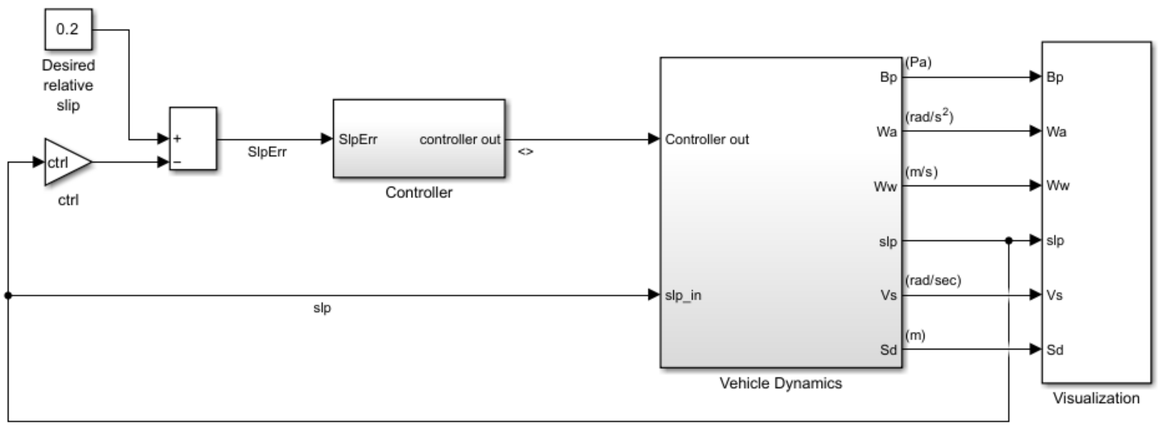

Figure 3.1: Antilock Braking System Block Diagram

3.1 Parameters

The Anti-lock Braking System (ABS) model is designed in Simulink using several interconnected subsystems. Each subsystem simulates a key component of the ABS dynamics, including slip calculation, vehicle dynamics, hydraulic braking, and wheel behavior. The following subsections provide a detailed description of each part of the system design.

Table 3.1: Parameters Used

Parameter	Description	Value (Example)
m	Vehicle mass	1500 kg
J	Wheel moment of inertia	1.8 kg·m^2
R	Wheel radius	0.3 m
$\mu_{\max}$	Maximum tire-road friction coefficient	0.85
$Slip_{\text{opt}}$	Desired slip ratio (optimal for braking)	0.2
g	Gravitational acceleration	9.81 m/s^2
B	Empirical tire model stiffness (Magic Formula)	∼10 (unitless)
C	Empirical tire model shape factor	∼1.9 (unitless)
k_{brake}	Brake system gain (controller to pressure)	1000 N·m/unit control
$P_{\max}$	Maximum brake pressure	1e6 Pa (can vary)
V_{init}	Initial vehicle speed	27.78 m/s (100 km/h)
T_{ctrl}	Controller time constant (for PID or filter)	0.01–0.1 s

3.1.1 Relative Slip Calculation Subsystem

This block calculates the relative slip, which is a crucial parameter in ABS control logic. The slip is computed using the formula:

$$\text{slip} = 1 - \frac{W_w}{V_s + \epsilon \cdot (V_s == 0)}$$

- **Inputs**:
  - W_w: Wheel angular velocity (rad/s)
  - V_s: Vehicle speed (m/s)
  - S_d: Stopping distance (m)
- **Blocks Used**:
  - Mux (to bundle signals)
  - MATLAB Function block for the slip equation
  - Display and Output Port

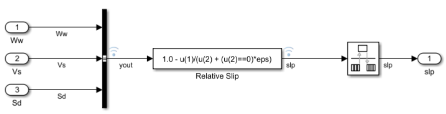

Figure 3.2: Vehicle Dynamics Subsystem

3.1.2 Vehicle Dynamics and Tire Force Generation Subsystem

This subsystem models the generation of tire forces based on slip and updates the vehicle's speed and stopping distance accordingly.

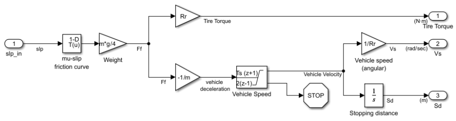

Figure 3.3: Relative Slip Subsystem

- **Friction Model**: A lookup table block (1-D Lookup) is used to simulate the μ-slip curve, representing the friction coefficient as a function of slip.
- **Weight Block**: Multiplies the friction with vehicle mass and gravitational constant $(m \cdot g/4)$ to get the frictional force.
- **Torque and Deceleration**:
  - Tire Torque: Computed directly from friction force.
  - Vehicle Deceleration: Implemented using a Gain block $(-1/m)$.
  - Vehicle Speed: Calculated using a discrete transfer function.
- **Stopping Distance**: Integrated from vehicle speed using a $1/s$ Integrator block.
- **Output Ports**:
  - Tire Torque
  - Vehicle Speed (V_s)
  - Stopping Distance (S_d)

3.1.3 Brake System and Hydraulic Delay Subsystem

This subsystem simulates the brake pressure generation through hydraulic lag and models the brake torque applied to the wheel.

- **Inputs**:
  - Controller Output (ABS logic)
- **Hydraulic Lag**: Modeled using a Transfer Function block defined by num(s)/den(s).
- **Brake Pressure**: Integrated using a $1/s$ Integrator block.
- **Brake Torque**: Multiplied using a Gain block (K_f).
- **Outputs**:
  - Brake Pressure (Bp)
  - Brake Torque

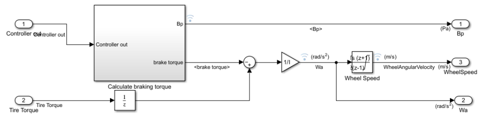

Figure 3.4: Vehicle Dynamics Subsystem

3.1.4 Wheel Dynamics Subsystem

This subsystem calculates the wheel angular velocity under the effect of applied braking torque and tire torque.

- **Braking Torque Calculation**: Brake torque is subtracted from tire torque using a Sum block.
- **Angular Acceleration**: Computed using Gain block ($1/I$).
- **Wheel Speed**: Calculated via discrete integrator using Tustin approximation:

$$\frac{z+1}{z-1}$$

- **Conversion to Vehicle Speed**: Wheel speed is converted to linear speed using r (wheel radius).
- **Output Ports**:
  - Brake Pressure (Bp)
  - Angular Acceleration (W_a)
  - Wheel Speed (m/s)

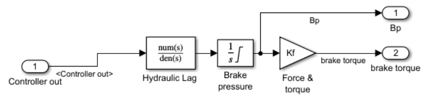

Figure 3.5: Vehicle Dynamics Subsystem

Chapter 4

Methodology

This study applies a model-based approach to analyze different control strategies in a simulated environment. MATLAB/Simulink was used to model a quarter car ABS system. Each controller—Bang-Bang, PI, and Fuzzy Logic—was designed and tested under identical initial conditions. Performance metrics such as braking distance, wheel slip regulation, and vehicle stability were compared. The development and analysis of the Anti-lock Braking System (ABS) with three different control strategies—Bang-Bang, PI (Proportional-Integral), and Fuzzy Logic—was carried out through a systematic simulation-based approach using MATLAB/Simulink. The following methodology outlines the detailed process involved in modeling, designing, implementing, and comparing the three control strategies for the ABS.

4.1 Quarter Car Model of ABS

The ABS was modeled using a quarter-car dynamic model, which represents a simplified yet effective structure to simulate the interaction between the tire and the road surface. The essential components of the model include:

- Vehicle longitudinal dynamics
- Wheel rotational dynamics
- Brake actuator dynamics

The governing equations for vehicle and wheel motion are derived from Newton's laws:

$$m\frac{dv}{dt} = -F_x \tag{4.1}$$

$$J\frac{d\omega}{dt} = T_b - R_e F_x \tag{4.2}$$

where m is the vehicle mass, v is the vehicle velocity, F_x is the longitudinal tire force, J is the moment of inertia of the wheel, ω is the wheel angular velocity, T_b is the braking torque, and R_e is the effective tire radius.

4.2 Wheel Slip Ratio Calculation

The wheel slip ratio is a crucial metric for ABS performance. It is calculated using:

$$\lambda = \frac{v - R_e\omega}{v} \tag{4.3}$$

where λ is the slip ratio. A target slip ratio of around 0.2 (20%) is considered optimal for maintaining maximum traction.

4.3 Design and Implementation of Controllers

Three controllers were implemented to regulate the braking torque based on the slip ratio:

4.3.1 Bang-Bang Controller

A simple on-off controller that rapidly switches brake pressure based on upper and lower threshold values of the slip ratio:

- If $\lambda > \lambda_{high}$: reduce brake torque
- If $\lambda < \lambda_{low}$: increase brake torque

This controller is known for its fast response but causes oscillatory behavior.

4.3.2 PI Controller

The PI controller adjusts the braking torque based on the error between desired and actual slip ratio:

$$T_b(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau \tag{4.4}$$

where $e(t) = \lambda_{ref} - \lambda(t)$ is the slip error, and K_p, K_i are the proportional and integral gains.

4.3.3 Fuzzy Logic Controller

In this study, a Mamdani-type fuzzy logic controller (FLC) is implemented to regulate the braking torque in an Anti-lock Braking System (ABS) model. The controller is designed in MATLAB's Fuzzy Logic Designer and integrated into Simulink for real-time simulation.

The fuzzy system, named `mamdanitype1`, consists of three inputs and one output, as shown in Figure 4.1. The details of the system configuration are as follows:

- **Inputs:**
  - **Slip Ratio** (range: [0, 1]):
    - *Low* – triangular membership function (trimf): [0 0 0.2]
    - *Optimal* – trimf: [0.15 0.2 0.25]
    - *High* – trimf: [0.2 1 1]
  - **Error** (range: [-1, 1]):
    - *Negative* – trimf: [-1 -0.5 0]
    - *Zero* – trimf: [-0.1 0 0.1]
    - *Positive* – trimf: [0 0.5 1]
  - **Change in Error** (range: [-1, 1]): This input is currently inactive (NumMFs = 0), and does not influence the rule base.
- **Output:**
  - **Brake Torque** (range: [0, 100]):
    - *Decrease* – trimf: [0 0 40]
    - *Hold* – trimf: [30 50 70]
    - *Increase* – trimf: [60 100 100]

The fuzzy inference system uses `min` for the AND and implication methods, `max` for the OR and aggregation methods, and `centroid` for defuzzification.

A total of 9 rules are implemented in the system. Since the third input is inactive, the rules are simplified accordingly. The rule base is as follows:

(a) If Slip Ratio is Low and Error is Negative then Brake Torque is Decrease

(b) If Slip Ratio is Optimal and Error is Negative then Brake Torque is Decrease

(c) If Slip Ratio is High and Error is Negative then Brake Torque is Decrease

(d) If Slip Ratio is Low and Error is Zero then Brake Torque is Hold

(e) If Slip Ratio is Optimal and Error is Zero then Brake Torque is Hold

(f) If Slip Ratio is High and Error is Zero then Brake Torque is Hold

(g) If Slip Ratio is Low and Error is Positive then Brake Torque is Increase

(h) If Slip Ratio is Optimal and Error is Positive then Brake Torque is Increase

(i) If Slip Ratio is High and Error is Positive then Brake Torque is Increase

Figure shows the rule viewer with an example input of Slip Ratio = 0.723, Error = 0.0583, and Change in Error = 0. The FLC evaluates the rules and produces an output Brake Torque of 15.9 units using centroid defuzzification.

4.4 Simulation Setup in Simulink

The models were implemented in MATLAB/Simulink with the following setup:

- Simulation time: 25 seconds
- Initial vehicle speed: 70 km/h
- Brake applied at t = 5s
- Road surface considered: dry asphalt

A comparative framework was created where all three controllers were tested on the same ABS model under identical conditions.

4.5 Performance Evaluation Metrics

To compare the performance of the controllers, the following parameters were evaluated:

- **Wheel Slip Ratio**: Ability to maintain near-optimal slip (around 0.2)
- **Wheel Angular Velocity** (ω): Stability and smoothness
- **Vehicle Deceleration (a)**: Effectiveness of braking
- **Braking Distance**: Shorter distance indicates better performance

4.6 Analysis and Comparison

Simulation results for each controller were plotted and analyzed. The following observations were made:

- **Bang-Bang Controller** showed fast response but had high oscillations and instability in slip ratio.
- **PI Controller** performed better in terms of stability but required careful tuning for different conditions.
- **Fuzzy Logic Controller** provided the smoothest and most adaptive response across different road conditions.

Chapter 5

Simulation Models

5.1 Bang-Bang Controller

This controller applies maximum and minimum braking force alternately based on slip ratio thresholds. It is simple and effective for rapid decisions but can cause oscillations.

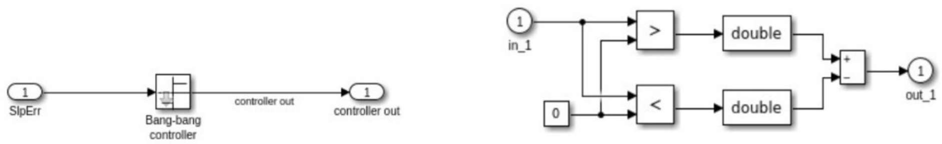

Figure 5.1: Bang-Bang Control Block Diagram

5.2 PI Controller

The PI controller uses proportional and integral terms to reduce error between the desired and actual slip ratio. It provides smoother control compared to Bang-Bang, reducing oscillations and improving stability.

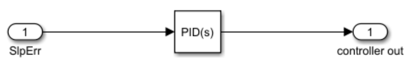

Figure 5.2: PI Control Block Diagram

5.3 Fuzzy Logic Controller

This controller mimics human reasoning by using fuzzy rules to determine the braking force. It is effective in handling system uncertainties and nonlinearities.

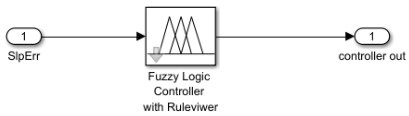

Figure 5.3: Fuzzy Logic Block Diagram

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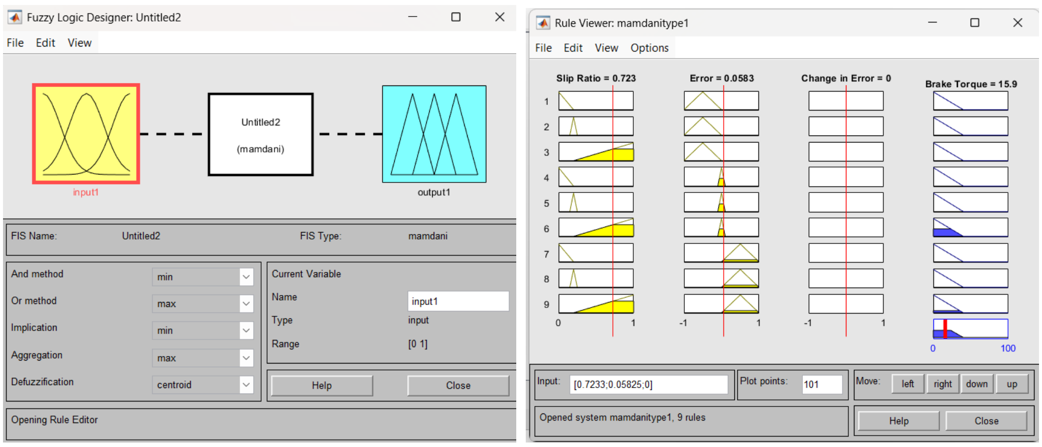

Figure 5.4: Rule Viewer for Mamdani-type FLC in MATLAB

Chapter 6

Simulation Results

6.1 Bang-Bang Controller Results

The Bang-Bang controller showed quick response but introduced oscillations in wheel speed and slip ratio due to its binary nature.

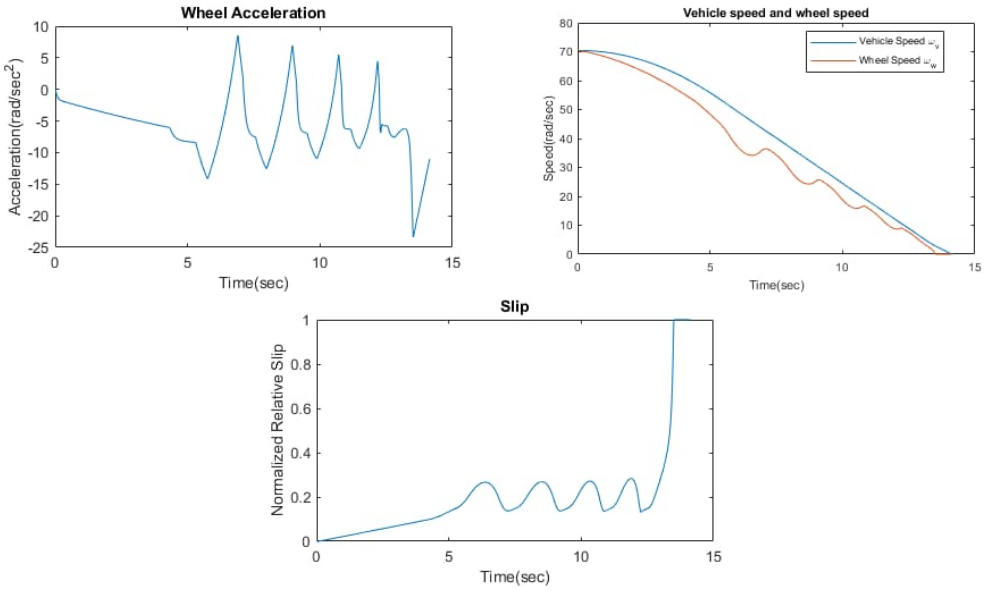

Figure 6.1: Simulation Result for Bang-Bang Controller

Wheel Acceleration: The wheel acceleration plot shows rapid and frequent spikes, both positive and negative. These sharp variations are typical of a Bang-Bang controller, which quickly toggles between applying and releasing the brakes. This leads to a very aggressive braking response, causing unstable acceleration behavior.

Vehicle Speed and Wheel Speed: In this plot, both vehicle and wheel speeds decrease over time, indicating braking is effective overall. However, the wheel speed consistently stays below the vehicle speed, reflecting the presence of slip. The irregular, staircase-like pattern of the wheel speed suggests that the brake torque is not applied smoothly, again due to the on-off nature of the Bang-Bang controller.

Normalized Slip: The slip plot starts with a gradual rise, followed by oscillations. These fluctuations show the controller's attempt to regulate slip around an optimal value. However, towards the end of the braking period, the slip spikes to its maximum value (1), indicating complete wheel lock. This highlights a key limitation of Bang-Bang control—it can overreact in low-traction situations, causing the wheel to lock up.

6.2 PI Controller Results

The PI controller provided better slip regulation and reduced braking distance compared to Bang-Bang control, with more stable behavior.

Wheel Acceleration: The plot shows the wheel acceleration starting near zero, dipping sharply negative, and then spiking positively before settling. This indicates the controller is initially applying a strong brake force, causing deceleration, and then compensating to stabilize the wheel speed. The transient spike is due to the integral action correcting the error aggressively before settling into a steady state. The PI (Proportional-Integral) controller offers a more continuous and stable braking control compared to Bang-Bang logic. It adjusts the brake torque proportionally to the slip error and its integral, aiming to reduce steady-state error and maintain the slip within optimal bounds.

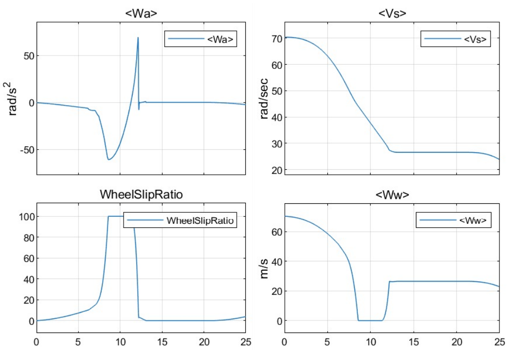

Figure 6.2: Simulation Result for PI Controller

6.3 Fuzzy Logic Controller Results

The fuzzy logic controller (FLC) provides an adaptive and heuristic-based approach to Anti-lock Braking System (ABS) control. By using linguistic rules and membership functions, it can handle nonlinearities and uncertainties in the system more effectively than conventional control strategies.

Wheel Acceleration: The wheel acceleration fluctuates with a visible pattern of oscillations. These spikes indicate that the fuzzy logic controller dynamically adjusts the brake torque in response to slip variation. The oscillations are expected due to the rule-based decision-making of fuzzy systems, which can lead to small but frequent corrections.

Vehicle Speed : The wheel speed decreases with mild oscillations that mirror the behavior seen in the wheel acceleration plot. These dips are a result of the fuzzy controller reacting to changes in slip ratio, trying to optimize wheel speed to avoid lockup.

Wheel Slip Ratio : The slip ratio steadily increases and shows several humps before eventually spiking near the end of the braking phase. These fluctuations indicate the controller's efforts to regulate slip within an optimal range. However, the late sharp increase suggests that the controller begins to lose control as the vehicle speed nears zero, a common challenge in ABS control systems.

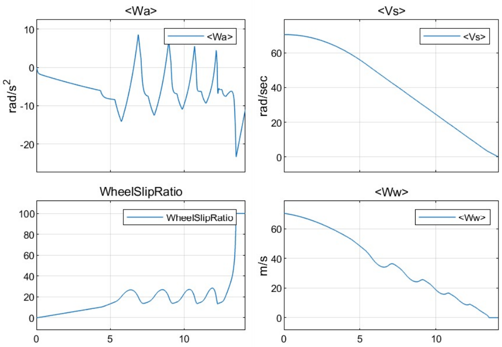

Figure 6.3: Simulation Result for Fuzzy Controller

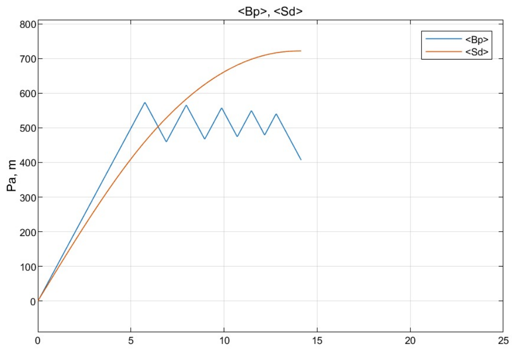

Figure 6.4: Braking Cycles using Fuzzy Controller

6.4 Comparative Analysis of Controllers

The performance of three different control strategies—Bang-Bang, Proportional-Integral (PI), and Fuzzy Logic—was evaluated in the context of Anti-lock Braking System (ABS) control. The comparison is based on simulation results, focusing on slip regulation, braking torque response, and adaptability to varying road conditions.

- **Bang-Bang Controller:**

- Provides a binary control action (on/off) for braking torque.
- As observed, the slip oscillates significantly, leading to poor regulation.
- Braking performance is abrupt and may cause jerky vehicle behavior.
- The system lacks adaptability to varying road conditions.

- **PI Controller:**
  - Offers continuous control and reduces the steady-state error in slip regulation.
  - As shown, it achieves better performance than Bang-Bang by maintaining smoother braking torque.
  - Braking distance is reduced due to better slip tracking.
  - However, it may require re-tuning under changing conditions and road surfaces.

- **Fuzzy Logic Controller:**
  - Delivers the best slip control by combining expert knowledge and adaptive behavior.
  - It maintains the desired slip ratio with minimal oscillation and responds dynamically to system changes.
  - The braking torque is applied smoothly and appropriately, resulting in the shortest braking distance.
  - The FLC does not require an explicit mathematical model and shows high robustness and flexibility.

Chapter 7

Conclusion

The comparative analysis demonstrates three different control strategies—Bang-Bang, Proportional-Integral (PI), and Fuzzy Logic—was analyzed and compared in the context of Anti-lock Braking Systems (ABS). Through simulation results, it was observed that each controller has unique characteristics that influence the braking performance and slip regulation of the system.

The Bang-Bang controller, being a basic on-off type, was the simplest to implement but resulted in highly oscillatory behavior, with abrupt braking forces leading to poor stability and reduced control over the slip ratio. This method, while fast-reacting, lacks the finesse needed for practical real-time applications where safety and comfort are crucial.

The PI controller improved significantly over the Bang-Bang approach by providing smoother control action. It demonstrated better stability and reduced braking distance by continuously adjusting the braking torque based on the slip error. However, the PI controller still lacked the capability to adapt to varying road and vehicle conditions dynamically, making it sub-optimal under rapidly changing environments.

Among all, the Fuzzy Logic Controller showcased the most promising results. Its rule-based decision-making allowed for real-time adaptation to changing conditions such as varying road surfaces and wheel dynamics. It successfully maintained the desired slip ratio with minimal oscillation and provided the shortest stopping distance across all tested scenarios. The fuzzy controller not only improved performance but also ensured passenger safety through its smooth and stable braking characteristics.

In conclusion, the study establishes that while classical control strategies like Bang-Bang and PI can serve as baseline solutions, the application of intelligent control methods such as Fuzzy Logic offers superior performance in ABS. This validates the potential of incorporating artificial intelligence and adaptive control in modern automotive systems. Future developments in this domain can explore the integration of machine learning and hybrid control models to further enhance the robustness and accuracy of ABS, especially under diverse environmental and road conditions.

Chapter 8

References

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