Department of Mechatronics

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ANTILOCK BRAKING SYSTEM FUZZY CONTROL

MITTEBLOKEERUVATE PIDURITE SÜSTEEMI HÄGUSALOOGIKA REGULAATORI MODELLEERIMINE

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AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently.
These materials have not been submitted for any academic degree.
All the works of other authors used in this thesis have been referenced.

The thesis was completed under Mr. Leo Teder's supervision

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The thesis complies with the requirements for graduation theses.
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4.	1. Analysis and comparison of the result 2. Conclusion and Summary 3. Make all necessary references 4. Final submission (May 20th 2016)	May

Engineering and economic problems to be solved:
Design of a controller for an ABS model by Inteco. The result of the project will be used as a teaching tool in the Alpha Control Laboratory at the computer systems department and as a reference for future research work.

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FOREWORD

This thesis is part of the ongoing academic research works at alpha control laboratory at Tallinn University of Technology. The research aims to analyze the antilock braking system model by designing a Fuzzy controller with better efficiency and superiority compared with the classical controllers, such as PID and bang bang controllers.

At the beginning of this project, a number of existing approaches was reviewed in order to give the author a sufficient knowledge on the dynamics of the controlled system and to establish a solid understanding of the fuzzy controller. Based on this, a fuzzy controller was designed and implemented on the ABS simulation model.

In respect of the success achieved, I would like to sincerely appreciate everyone who had contributed to the success of this work. All thanks to Prof. Trieu Vu, Mr. Leo Teder and Prof. Kristina Vassiljeva for all their contributions towards the success of this thesis. Also, I would like appreciate Prof. Mart Tamre, head of Department of Mechatronics, for his enviable leadership character and mentorship throughout my program.

Finally, I humbly appreciate the entire governing body of the Tallinn University of Technology for offering me the opportunity to study at the University.

EESSÕNA

Käesolev doktoritöö osaks oleva uurimistöö eesmärk on analüüsida mitteblokeeruva pidurisüsteemi süsteemi mudelit ning luua uus ja parem kontroller, mis oleks efektiivsem võrreldes klassikaliste kontrolleritega, nagu PID ja muud kontrollerid.

Käesoleva doktoritöö töid teostati TTÜ laboris veebruarist maini 2016. Töö alguses vaadati mitmeid olemasolevaid lahendusi, mis olid teiste autorite poolt kasutusele võetud. Autori poolt sai analüüsitud kontrolleri lahendusi süsteemi dünaamika alusteadmiste põhjal ja kehtestatud kindlad nõudmised millistele tingimustele kavandatud fuzzy kontroller peaks vastama.

Selles projektis saavutatud eduga seoses ma tahaksin sügavalt tänada kõiki, kes oli aidanud mind selle töö eduka lõppemiseni. Eriline tänu Prof. Vu Trieule ja hr. Leo Tederile, kes juhtisid mind selles aruandes esitatud tulemuste saavutamiseks. Minu eriline tänu läheb ka Prof. Kristina Vassiljevale, kes andis mulle võimaluse töötada nende laboris ja kes oli alati saadaval ja andis vajadusel vajalikku abi.

Lõpuks ma tahaksin öelda suur aitäh prof. Mart Tamrele, Mehhatroonika osakonnale ja TTÜ’le võimaluse eest õppida teie ülikoolis ja töötada huvitava projekti kallal.

ABSTRACT

Modern automobile vehicles are continuously challenged with the need of constantly changing their speeds and directions during transit while keeping the vehicle steerable and stable irrespective of the conditions prompting such actions. The steerability and stability of the vehicle is of critical importance to the designer since safety of the occupants are not compromisable. A common solution to these inherent problem is the integration of a braking control system called ’Antilock braking system’.

Antilock braking systems are designed to optimize the effectiveness of braking systems by maintaining the maneuverability and stability of the vehicle [9]. To achieve its purpose, the ABS ensures that the slip of the vehicle wheels are kept at a level with the best coefficient of friction despite the varying road conditions. However the effectiveness and behavior of the ABS to various road conditions are determined by the robustness of controller in use.

The design of an anti-lock braking systems (ABS) controllers often pose some certain difficulties to the designer. Such include adaptiveness to varying road condition, required braking torque for specific condition and transportation delay which limit the control frequency.

In these project, we have proposed a fuzzy control approach for a laboratory anti-lock braking model. The fuzzy logic control scheme was designed to maintain a slip ratio of 0.2 while bring the vehicle to a stop in the best possible distance. To evaluate the performance of the fuzzy controller, a simulation with a simple PID controller was also presented as a basis for our analysis. The simulation has been done a single surface assumed to be dry with some amount of friction.

Based on the analysis of the two control schemes, fuzzy logic controller showed superiority over the PID controller as it yielded a better slip ratio tracking and a shorter braking distance was reached.

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1 INTRODUCTION

1.1 Motivation

In order to maintain the controllability and stability of a vehicle when brakes are applied it is important to control the process of brake application such that on application of brake the effect of applied force on the brake pads will be balanced with the real time parameters such as road condition, vehicle speed status, mass and center of gravity of the vehicle. All these can however be realized in a system called Antilock Braking System (ABS). The basic aim of an ABS system is to generate the largest and sufficient amount of braking force under a range of various road conditions while maintaining the vehicle maneuverability as well as preventing unwanted wheel slippage [2]. Current approaches to ABS control can be classified in two categories, wheel acceleration and tire slip control. The first category deals with the slip control indirectly by controlling the deceleration/acceleration of the wheel through the brake pressure control from the actuator while the second is the direct slip control approach [3].

The antilock braking system (ABS) is developed to prevent the wheels of an automobile from locking up while braking and to maintain controllability and stability of the vehicle. When brakes are applied the braking force is normally greater than the road surface friction and this often leads to slip of vehicle wheels or increase in braking distance respectively. The ABS system is designed to minimize these inherent problems during braking process. The slippage of car wheels is even more pronounced when brakes are abruptly applied on a moving vehicle, resulting in a loss of vehicle stability and controllability such that the steering input no longer have significant effect on the vehicle; a situation that could lead to severe damage to the vehicle and a threat to the driver's life.

For optimal utilization of the functionalities and capabilities of an ABS system it is necessary to design a robust controller which is capable of simulating the braking force (input variable) and the road condition so as to ensure a reasonable braking distance/slip distance (output variables). However, two major challenges: nonlinearity of the model and the uncertainties such as road conditions often emerge when ABS controllers are being designed. Overtime these factors have hampered the design of a robust mathematical model since they cannot be easily accounted for. At the moment there are no readily available sensors capable of measuring the road conditions and recording the data for use in the controller and the available sensor signals are relatively noisy and characterized with uncertainties [17].

Although to accurately determine the vehicle speed, a number of velocity estimators have been proposed [2]. However these are still clouded with some errors hence a need to propose an advanced and robust controller capable of managing the uncertainties of the road in order to ensure a minimal wheel slip and braking distances respectively. In any ABS controller design consideration should be given to both the brake and the wheel dynamics respectively. This is because the interaction between the road and the vehicle wheels can be evaluated using the wheel slip ratio. The wheel slip ratio is governed by eq. (1.1).

$$S=\frac{V-\omega R}{V}, \tag{1.1}$$

Where S = wheel slip ratio

V = velocity of car

$\boldsymbol{\omega}$ = angular velocity of wheel and

R = wheel radius

Under an optimal braking condition, S = 0 but under a severe braking condition, S = 1. The later depicts a condition called wheel blockage in which the maneuverability of the vehicle and stability are totally lost and this in turn results to longer braking distance. The ABS system could be said to perform optimally if wheel slippage of a vehicle is operating at points very close to the peak of the force - slip ratio curve shown in Figure 1.1. Although the optimal wheel slip ratio [22] for most road surfaces is between 0.1 and 0.3, although most ABS control designs aim at maintaining the wheel slip ratio at a compromise value 0.2.

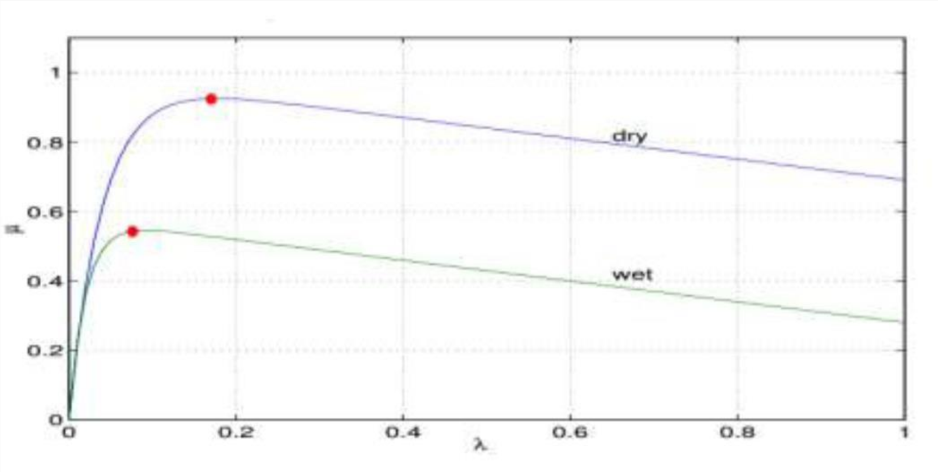


Figure 1.1 Friction coefficient vs slip according to [21, p. 31]

Due to the non-linearity, time variance and complexity of the ABS system, fuzzy control proves to be the most viable option when compared to the more classical approaches such as the sliding mode, gain-scheduled, neural network and generic algorithm.

1.2 System description

The proposed approach in this project was implemented on a quarter laboratory ABS system model (Figure 1.2) provided by INTECO company. The equipment consists of physical systems and the DAQ controller which transfers real time signals from model and is interfaced to computer trough PCI or USB connection. The ABS system consists of two powerful flat DC motors and two encoder systems that measure the rotational angle of two wheels (representing car wheel and road surface respectively) and the angle of deviation of the balance lever. The encoders' resolution is 4096 pulses per revolution. During the testing or simulation process, the power interface amplifies the control signals which are transmitted from the PC to the DC motor. In the reverse direction, the power interface converts the encoders' signals to the digital 16-bit form to be read by the PC. Making connection between model and PC is out of topic of this work. The mathematical model for the dynamics and required parameters of the ABS system are provided by INTECO Company. The system equations as well as model description are in Chapter 3.

At the start of the experiment the lower wheel which animates the car-road motion is set in motion and accelerated to a predefined velocity. The upper wheel which animates the car wheel also accelerates with respect to the lower wheel. When the peak velocity is reached, the DC supply to the servo motors are cut off and the wheel begins to decelerate either freely or aided by brake application.

As shown in Figure 1.2, there are two inputs to the ABS model. The first input (drive) provides the inertia in form of a PWM which will accelerate the wheel to the required velocity. When this velocity value is reached, the drive supply is cut off and the braking process starts immediately. The time spent to bring the wheels to a stop depends mainly on the braking force applied. However care must be taken not to apply too much braking that will result to wheel locking and this one of the aim of this project; to design a controller capable of bringing the wheels to a stop in a minima time without locking the wheels at minima braking distance and slip. The model provides us with six outputs which can be used for analysis and as inputs for the controller design.

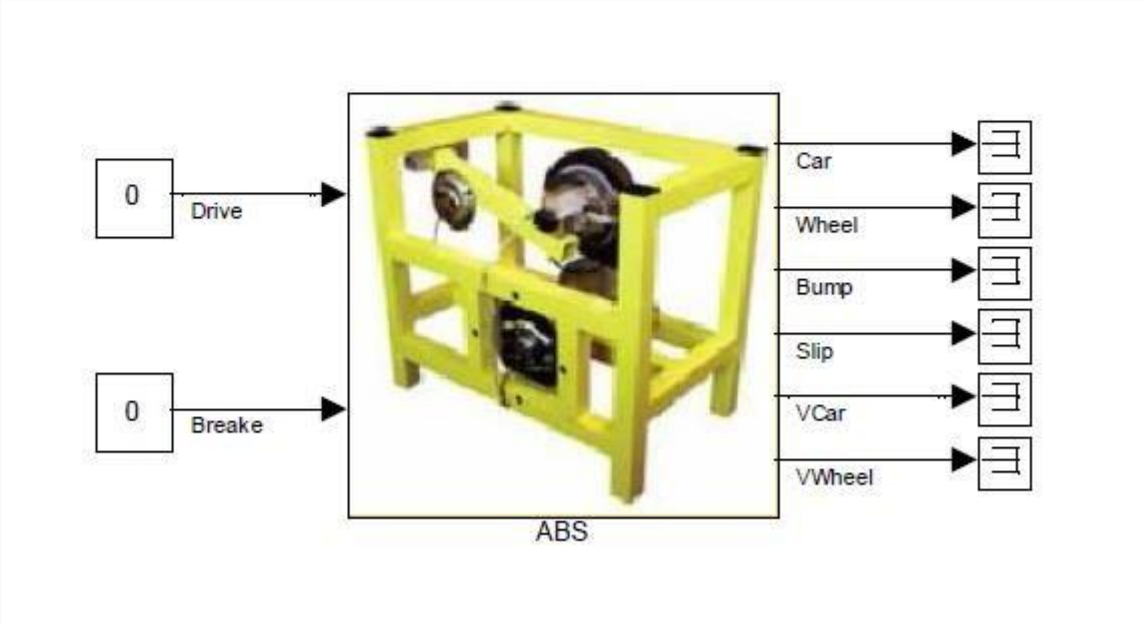


Figure 1.2: Antilock braking system [28]

2 LITERATURE REVIEW

The advent of the fuzzy control theory came into limelight in the earlier 1960s [23], and since then the development fuzzy control has continue to gain attention and application in the control theory world and it has since found applicability in various systems. The fast development of fuzzy approach is traceable to its simple design and application method. It allows even the less knowledgeable in control theory to write their own control algorithms with less complications. Fuzzy control employs the use of linguistic rule to design the controller actions rather than the more generic mathematical model based approach that is normally employed in the classical controllers like the PID- and relay-based controllers.

In recent years, a number of fuzzy logic based approaches have been proposed. For example in [17] a neuro-fuzzy adaptive control design approach is proposed for nonlinear dynamic systems taking into consideration the unknown dynamics, modeling errors, and various possible disturbances. This was used to design a wheel slip regulating controller. Here the implemented control algorithm consists of a conventional controller and a neuro-fuzzy network-based feedback controller. The conventional controller which produces an output that serves as an error signal to the neuro-fuzzy controller guarantees the dynamic stability of the system while the neuro-fuzzy uses the error signal to update its parameters through an incremental learning algorithm. In this way, a sliding motion based on neuro-fuzzy controller parameters is established, forcing the learning error towards zero. This approach has been verified under simulation and experimented and the results support the analytical claims even under the existence of uncertainty.

The Fuzzy inverse model is responsible for mapping $y\_e(kT)$ (representing the deviation from the desired behavior), to changes in the process inputs $p = p[p\ 1 \ldots p\ r]\^t$ that are needed to force $y\_e(kT)$ to zero. Likewise, the knowledge base modifier functions to modify the fuzzy controller's knowledge base in order to effect the necessary changes in the process inputs.

In [8], a digital controller design which combines fuzzy logic element and decision logic is proposed. Here, the controller recognizes the current road condition and generates a command braking pressure signals based on existing and past readings of slip ratio and brake pressure. The controller detects wheel blockage immediately and avoids excessive slipping. Although this shows some level of improvements over previous designs but since the controller will need to always sample any new sets of data points in order to compute new poles and zeroes for the new control, especially in the case of change in road surface, then there is additional delay to the system response. Fuzzy logic-based controllers however provides a solution to this challenge due to the fact that it has a parallel structure which helps it to respond quick to any new situation.

A more recent approach [18] is Adaptive Neuro-fuzzy self-learning PID controller. The method proposed here utilizes an adaptive neuro-fuzzy system (ANFIS) to estimate self-tuning PID parameters in an ABS system. This was realizable due to the ability of ANFIS to adjust parameters of a system by varying the inputs and outputs of the system at every point in time.

More advanced approach was proposed in [5] where fuzzy logic control (FLC) is integrated into a discontinuous sliding mode control (SMC) to form a robust system called fuzzy adaptive sliding mode control (FASMC). Here an adaptive tuning logic is developed to adjust the fuzzy parameters based on the road surface transition. By comparing the obtained result to that of a pure sliding mode controller approach, the FASMC achieved a better result as it completely eliminates chattering and better slip control performance.

So far all the aforementioned works have been implemented on a quarter vehicle braking system but recently a work [24] was been done on full vehicle model (suspension, steering system, braking system, tire, engine and body). Here an ABS Model of three-channel ABS using the logic threshold controller and the fuzzy logic controller are developed in Matlab/Simulink. The control was achieved through Adams/Control module which comprise of a full vehicle model in Car to the model of the ABS in Simulink. In order to create a platform for comparison, the two controllers were supplied with same inputs (tire slip ratio and wheel angular acceleration) and same output (pressure variation) in the wheel cylinder. Based on the simulation result it was obvious that the fuzzy logic controller can manage the slip ration at an optimal value with smaller fluctuations coupled with improved braking efficiency and prolonged hydraulic system’s service life.

The results in [26] showed that the fuzzy logic can limit the slip ratio about an optimal value even when brake is abruptly applied and also the wheel deceleration was relatively steady when compared to the logic threshold controller. In addition the fuzzy logic based controller can make the braking distance relatively shorter when compared to the logic threshold based controller, and there is also an increase in the service life of the cylinder as the pressure fluctuations in the hydraulic systems are brought to minimal range.

Based on the aforementioned Fuzzy logic based approaches in controlling ABS, the reality is that in modern problems, fuzzy controllers seems to be winning the race and the major reasons could be summarized in the fact that its approach is heuristic and its performance capabilities and design possibilities are implementable over a wide range of plants. Also due to its robustness even with the absence of any analytical model, Fuzzy controller has proved to be more reliable for controlling systems such as ABS. However, fuzzy controller kind of exhibits a relatively low sensitivity to large signal noise levels in the case of high road roughness.

Hence this work will be focusing on designing a system that is noise-sensitive and able to react when the noise level exceeds a set threshold. Based on the aforementioned Fuzzy logic based approaches in controlling ABS, the reality is that in modern problems, fuzzy controllers seems to be winning the race and the major reasons could be summarized in the fact that its approach is heuristic and its performance capabilities and design possibilities are implementable over a wide range of plants.

In [12], a fuzzy model reference learning control (FMRLC) technique is proposed. This is a hybrid of Sliding mode control (SMC) and fuzzy logic control (FLC). Here, the controller utilizes a learning mechanism to observe the system output and adjust the rules in a direct fuzzy controller making the overall system to work as a "reference model". The performance of this technique was simulated using varying road surface conditions (wet, asphalt, icy). The learning model in the FMRLC was designed to monitor the output of the fuzzy controller and tune it if necessary for correct adaptation with possible adverse road conditions when encountered. The mechanism involves modifying the knowledge base of a direct fuzzy controller by observing data from the controlled process, reference model and the fuzzy controller. The learning process consists of two parts; a fuzzy inverse model and a knowledge base modifier.

3 ANTILOCK BRAKING SYSTEM

An antilock braking system is a safety procedure integrated into the braking system of an automobile which helps the wheels in maintain an efficient and sufficient tractive force on the road when brakes are applied. By maintaining sufficient tractive contact with the road surface prevents wheels from locking up and ensures that vehicle maneuverability and stability are maintained while applying brakes.

ABS is designed to ensure that braking pressure is not instantly applied to rotating wheels as this could result to locking and skidding of wheels. The system is such that it passes in discrete the applied braking pressure on the wheels. In addition to the fundamental function of the ABS as mentioned it eventually ensures reduced braking distance irrespective of the road surface.

3.1 Objectives of Antilock braking systems

The antilock braking system as previously mentioned is designed to prevent the wheels of an automobile from locking up while braking and to maintain controllability and stability of the vehicle. The aftermath of the action include braking distance reduction, stability and maneuverability control.

When brakes are applied to a moving vehicle, it is expected that the vehicle comes to rest in the earliest possible time and shortest distance. This distance otherwise known as braking distance is a function of three (3) main parameters:

1. Vehicle mass

2. Initial velocity

3. Applied braking force or pressure

The first two parameters are always constant therefore only the braking force can be manipulated to achieve the expected braking distance. From the perspectives of dynamics, we can achieve efficient braking when there is enough tractive contact between the wheels and the road surface. Hence it is necessary to keep the vehicles wheels very close to this condition so as to achieve the maximum coefficient of friction and thus shortest braking distance. However while ensuring an automobile comes to halt in the shortest distance, the issue of safety during braking must be put into consideration. This safety issues are normally accounted for via two (2) main factors: vehicle stability and maneuverability.

Stability is normally called into question when there is a road transformation such that the vehicle moves from one type of road surface to another e.g. wet to dry surface. In this case the applied brake cannot be the same since there is a variation in the coefficient of friction. Hence it necessary that the correct about of braking force is exerted for a particular surface so as to achieve the same stability. Also the slip ratio and coefficient of friction relationship is maintained.

Maneuverability is the ability to steer a moving vehicle such in order to avoid obstacles and when brakes are abruptly applied. Efficient steerability of a moving vehicle is achievable if the friction coefficient can be maintained at a peak with minimal slip ratio. The capability to maintain slip ratio in the premise of the predefined value keeps the vehicle steerable for the driver.

3.2 Principles of operation of an Antilock Braking system

A typical antilock braking system consists of four (4) basic components:

1. Speed sensor

2. Valve assembly

3. A pump motor

4. A controller or electronic control unit (ECU)

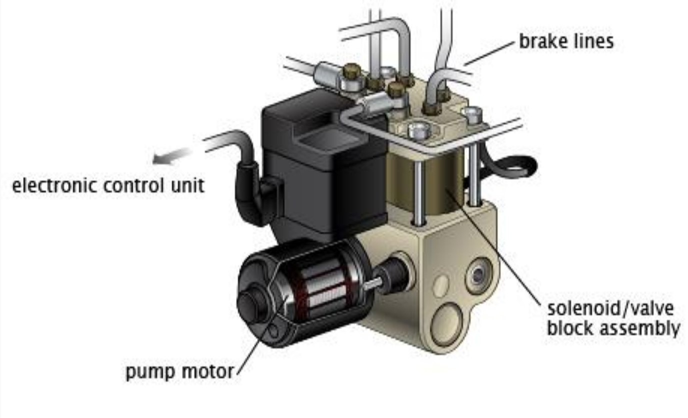


Figure 3.1: Pump motor and valve assembly [27]

Figure 3.1 is a typical ABS system used in automobile systems. The ECU which is the heart of the system controls the system behavior. It detects the relative speed of the wheels and make the necessary corrective action whenever there are significant differences in the speed of the rotating wheel. This action is repeated until a speed balance between the wheels is established. The control logic implemented by the ECU is done by manipulating the valve's opening area in order to control the hydraulic pressure. For wheels moving at relatively high speed for instance, the ECU increases the valve opening in order to ensure more hydraulic pressure is released for the purpose of higher braking.

An overview of the anti-lock braking system description presented above is shown in Figure 3.2

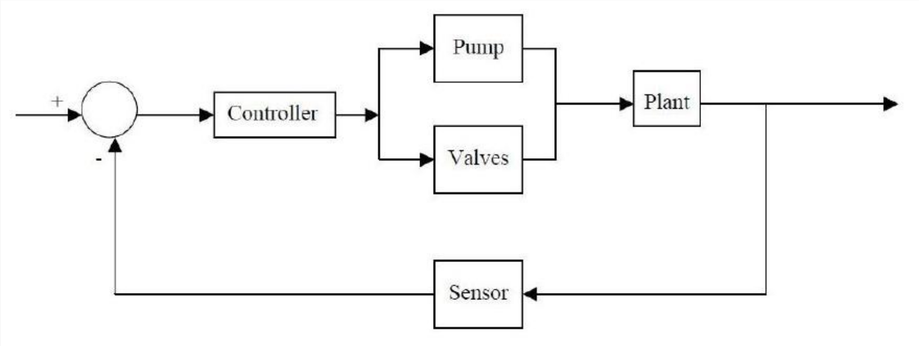


Figure 3.2: ABS control schematic

4 THEORETICAL ANALYSIS OF ABS

4.1 Mathematical model

Figure 4.1 is a schematic of the laboratory ABS model for our analysis. The system consists two wheels, upper and lower wheels that are in constant contact. The lower wheel represents the car road and animates the relative road motion while the upper wheel represents the vehicle wheel. The surface of the lower wheel is smooth but can be coated with materials of varying roughness in other to experiment the road surface effect on vehicle braking process.

The ABS system model is built with three encoders. Two of which measures the rotational angles of the upper and lower wheels while the third encoder measures the change in angular position of the balance wheel. The accuracy of the encoders is ${}^{2\Pi}\!/_{4096} = 0.0015rad$. The respective wheel angular velocities are rather observed using a sample time of 0.5s and not measured.

The upper wheel is embedded in a disc brake system that is controlled by a hydraulic coupling connected to a level. After the DC motors are powered and accelerated to the specified level, the power to the DC motors is turned off and the braking process starts immediately.

For our analysis, the car velocity is evaluated as the product of the angular velocity of bigger wheel and the radius of the same wheel while the velocity of the lower wheel is the product of the angular velocity of the lower wheel and its radius. The state variables and the necessary parameters required for our analysis are all stated in the table.

Table 4.1 Parameters of the model

Name	Description	Units
x_1	angular velocity of the upper wheel	rad/s
x_2	angular velocity of the lower wheel	rad/s
M_1	braking torque	Nm
r_1	radius of the upper wheel	m
r_2	radius of the lower wheel	m
J_1	moment of inertia of upper wheel	kgm^2
J_2	moment of inertia of the lower wheel	kgm^2
d_1	viscous friction coefficient of the upper wheel	kgm^2/s
d_2	viscous friction coefficient of the lower wheel	kgm^2/s
F_n	total force generated by the upper wheel and pressing on the lower wheel	N
$\mu(\lambda)$	friction coefficient between wheels	
λ	slip - the relative difference of the wheel velocities	
F_n	normal force - the upper wheel acting on the lower wheel	N
M_{10}	static friction of the upper wheel	Nm
M_{20}	static friction of the lower wheel	Nm
M_g	gravitational and shock absorber torques acting on the balance lever	Nm
L	distance between the contact point of the wheels and the rotational axis of the balance lever	m
φ	angle between the normal in the contact point and the line L	^{o}
u	control of the brake	

From the Table 4.1, it is assumed that the frictional force is proportional to the normal pressing force $F_{n.}$ Where μ (λ) is the proportionality constant.

By representing slip (the relative difference of the wheels velocities) as λ we have the following expression:

$$\lambda = \begin{cases} \frac{r_2x_2 - r_1x_1}{r_2x_2}, r_2x_2 \geq r_1x_1, x_1 \geq 0, x_2 \geq 0, \\ \frac{r_1x_1 - r_2x_2}{r_1x_1}, r_2x_2 < \ r_1x_1, x_1 \geq 0, x_2 \geq 0, \\ \frac{r_2x_2 - r_1x_1}{r_2x_2}, r_2x_2 < r_1x_1, x_1 \geq 0, x_2 \geq 0 \\ \frac{r_1x_1 - r_2x_2}{r_1x_1}, r_2x_2 \geq \ r_1x_1, x_1 < 0, x_2 \geq 0 \\ 1, x_1 < 0, x_2 \geq 0, \\ 1, x_1 \geq 0, x_2 < 0 \end{cases} \tag{4.1}$$

4.2 Equations of motion

To derive the equations of motion we need to identify the parameters of the system. There are three torques acting on the upper wheel: the braking torque, the friction torque in the upper wheel bearing and the friction torque between the wheels. Also for the lower wheel we have two torques: the friction torque in the lower wheel bearing and the friction torque between the wheels. In addition to the torques, we also have two major forces acting on the lower wheel and these include the gravitational force and the pressing force from the shock absorber.

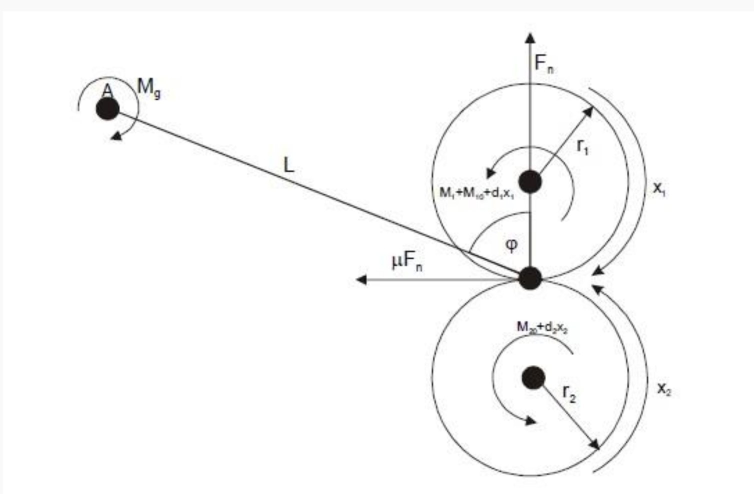


Figure 2.1: Free body diagram for ABS model

From the free body diagram (4.1) and using newton's law of inertia, we can write the equation of motion for the upper wheel as

$$J_1\dot{x}_1 = F_n r_1(\lambda) - d_1 x_1 - s_1 M_{10} - s_1 M_1 \tag{4.2}$$

And for the lower wheel we have

$$J_1\dot{x}_2 = -F_n r_2 s\mu(\lambda) - d_2 x_2 - s_2 M_{20} \tag{4.3}$$

To derive an expression for the normal force F_n we sum up the torques corresponding to the point A as follows

$$\sum M = 0 \tag{4.4}$$

$$F_n L(sin\varphi - s\mu(\lambda)cos\varphi) = M_g + s_1 M_1 + s_1 M_{10} + d_1 x_1 \tag{4.5}$$

Where $s, s_1 \, and \; s_2$ are auxiliary variables.

$$F_n = \frac{M_g + s_1 M_1 + s_1 M_{10} + d_1 x_1}{L(sin\varphi - s\mu(\lambda))cos\varphi} \tag{4.6}$$

Substituting (4.6) into (4.2) and (4.3) we have the following expression

$$J_1\dot{x}_1 = \frac{M_g + s_1 M_1 + s_1 M_{10} + d_1 x_1}{L\big(sin\varphi - s\mu(\lambda)\big)cos\varphi} r_1 s\mu(\lambda) - d_1 x_1 - s_1 M_{10} - s_1 M_1 \tag{4.7}$$

$$J_2\dot{x}_2 = \frac{M_g + s_1 M_1 + s_1 M_{10} + d_1 x_1}{L\big(sin\varphi - s\mu(\lambda)\big)cos\varphi} r_2 s\mu(\lambda) - d_2 x_2 - s_2 M_{20} \tag{4.8}$$

Due to the complexity of the equation, it was important to simplify the equation as follows

We assign a variable

$$S(\lambda) = \frac{s(\mu)}{L(sin\varphi - s\mu(\lambda)cos\varphi} \tag{4.9}$$

and by allocating parameters $c_{11}, c_{12}, c_{13}, c_{14}, c_{15}, c_{16}$ and $c_{21}, c_{22}, c_{23}, c_{24}, c_{25}$ for eq. (4.7) and eq. (4.8) respectively.

We have a simplified equations of

$$\dot{x}_1 = S(\lambda)(c_{11}x_1 + c_{12}) + c_{13}x_1 + c_{14} + (c_{15}S(\lambda) + c_{16})s_1M_1 \tag{4.10}$$

$$\dot{x}_2 = S(\lambda)(c_{21}x_1 + c_{22}) + c_{23}x_2 + c_{24} + c_{25}S(\lambda)M_1 \tag{4.11}$$

The driving system of the brake is defined by equation 4.12

$$\dot{M}_1 = c_{31}(b(u) - M_1) \tag{4.12}$$

Where b is parameter of third, braking equation, u is input to the brake, and M1 is output braking moment.

$$b(u) = \begin{cases} b_1u + b_2, u \geq u_0 \\ 0, u < u_0 \end{cases}$$

Where c_{11} to c_{25} are model parameters, S is function defined in eq. (2.10), b is parameter of third, braking equation, u is input to the brake, and M1 is output braking moment. The next important approximation is friction coefficient which depends on slip itself and can be approximated by

eq. (2.11).

Where the parameters

$$c_{11} = \frac{r_1d_1}{J_1}, c_{12} = \frac{(s_1M_{10} + M_g)r_1}{J_1}, c_{13} = -\frac{d_1}{J_1}, c_{14} = -\frac{s_1M_{10}}{J_1}, c_{15} = \frac{r_1}{J_1}, c_{15} = \frac{r_1}{J_1}, c_{16} = -\frac{1}{J_1},$$
$$c_{21} = \frac{r_2d_1}{J_2}, c_{22} = -\frac{\left(s_1M_{10} + M_g\right)r_2}{J_1}, \quad c_{23} = -\frac{d_2}{J_2}, c_{24} = -\frac{s_2M_{20}}{J_2}, c_{25} = \frac{r_2}{J_2}$$

Also, the coefficient of friction μ (λ) between the car wheel and the road surface is nonlinear, an approximate expression for our ABS model coefficient of friction will be

$$\mu(\lambda) = \frac{w_4\lambda^p}{a+\lambda^p} + w_3\lambda^3 + w_2\lambda^2 + w_1\lambda, \tag{4.13}$$

Where w_1 to w_4 are weights of approximated friction depending on slip and power coefficient. We get all the unknown coefficients (Table 4.2) from producer of this model and thus no further identification is required.

Table 4.2 System model coefficients

$c_{11} = 0, 002$	$c_{22} = 75{,}87$
$c_{12} = 2{,}59e + 002$	$c_{25} = 3{,}87$
$c_{13} = c_{21} = 2{,}59e + 002$	$c_{31} = 20{,}37$
$c_{14} = 0{,}40$	$w_1 = 0{,}042$
$c_{15} = 13{,}22$	$w_2 = 0$
$c_{16} = 132{,}84$	$w_3 = 0{,}04$
$c_{21} = 132{,}84$	$w_4 = 0{,}41$
$c_{23} = 0{,}009$	$a = 0{,}00026$
$c_{24} = 3{,}63$	$p = 2{,}099$

The Matlab model was designed using eq. (4.10) and eq. (4.11). The model with all the coefficients in Table 4.2 are used for experimenting and for testing the controller. The simulation model (Figure 4.2) is designed by Matlab S-function of level 2.

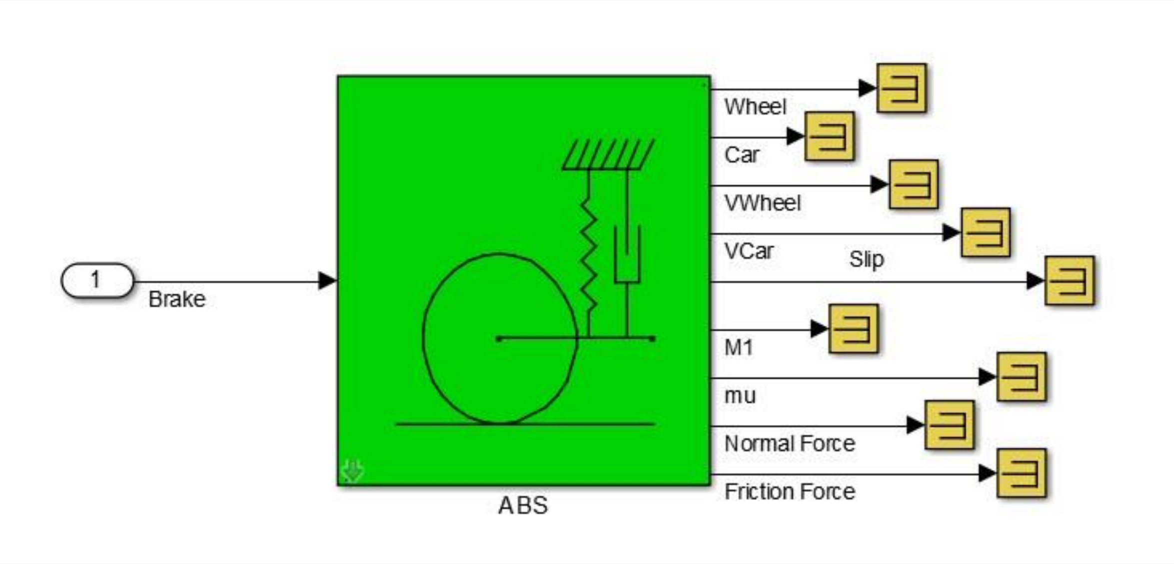


Figure 4.2: Simulation model

4.3 Friction coefficient

Considering eq. (4.10) to eq. (4.12), the first two equations describe the wheel dynamics while the third equation describe the transformation of brake input into braking moment. The braking moment is multiplied by S-function. This function together with eq. (4.13) are approximation of dependence of friction coefficient on wheel Slip. This is the main drawback of our design. The difference between real plant in Figure 2.2 and model in Figure 4.2 are the missing output for

Friction forces and Normal forces acting on both wheels. Since we don't have dynamometers in our plant we cannot express and measure our own dependence between slip and friction coefficient. This dependence is crucial in designing efficient controller. For a better understanding, a short description of the relation is required using eq. (4.14).

$$F_F = F_N \mu(\lambda) \tag{4.14}$$

From the above relation, eq. (4.14), it can be said that the frictional force which is needed for bringing a vehicle to a stop depends on both the normal force and the coefficient of friction. The normal force which is dependent on the mass of the vehicle is always constant hence we can only manipulate the coefficient of friction in order to have an optimal braking. To have a maximal for our coefficient of friction we need to plot the relationship between the coefficient of friction and the slip.

A Typical shape of this curve is shown in Figure 1.1. Two different functions are depicted, one for wet and for dry friction. We see that the maximal friction force is much lower in case of wet surface than as in the case of dry surface. For this reason car brakes are less effective while raining. By using the $\mu - \lambda$ relationship in eq. (4.13), we obtain the curve in Figure 4.3.

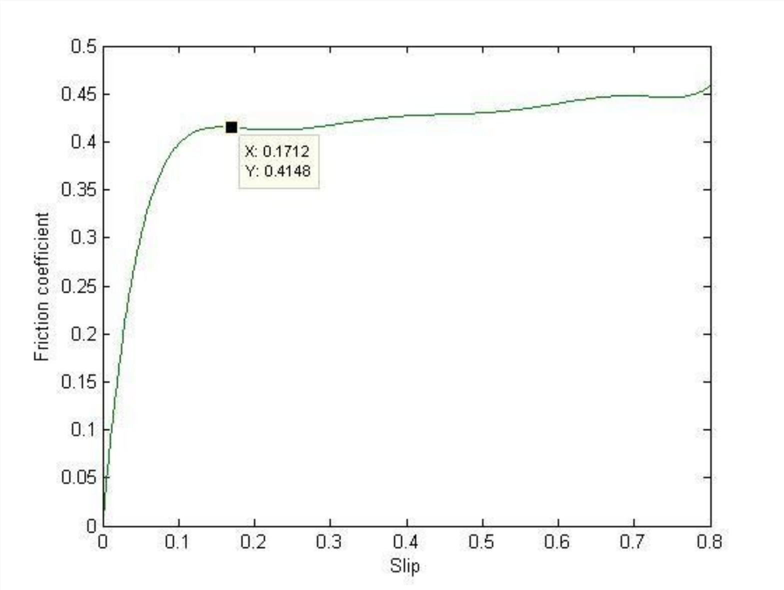


Figure 4.3 Friction coefficient against slip

By comparing our plot (Figure 4.3) with the reference plot (Figure 1.1), we have chosen our optimal slip value as 0.1712 because it gives us a maximal friction for braking. Beyond this point we could obtain higher friction coefficient but that will be to the detriment of the slip as we will have a higher slip value which contradicts the aim of this project.

4.4 Model parameters verification

The parameter verification process involves acquiring a set of training data via experiment and physical measurement of the model parts. However in our own case the system parameters have been predetermined by the model provider. Although we intended to verify this parameters but that became impossible as we could not disassemble the model for physical weighing. We therefore choose to rely on the parameters given in Table 4.1 and the mathematical models in eq. (4.10), eq. (4.11) and eq. (4.12) respectively for our system design.

4.5 Controller task definition

We have previously established in Figure 4.4 that the optimum slip ratio for our model will be approximately 0.2 hence we will be designing a fuzzy controller (Chapter 6) expected to keep the slip ratio in the premise of this value. It is however expected that the optimum slip ratio will yield a considerable braking distance in a very short period of time. To verify the performance of our controller, we have compared the results with that of a simple PID controller (Chapter 5).

4.6 Summary

Here we has given the mathematical analysis of the ABS system. The mathematical expressions offers to us the theoretical analysis for the system model parameters. Eq. (4.1) gave the mathematical expressions for the slip ratio and the domain for each expression. Eq. (4.6) is the normal force exacted by the upper wheel on the lower wheel while eq. (4.7-4.9) were necessary for deriving the rate of change of the velocities in eq. (4.10) and eq. (4.11).

Also, in Figure 4.3, we have shown the relationship between the coefficient of friction and the slip ratio. It was necessary as we needed to establish the slip ratio value (≈0.2) for maximum coefficient of friction for braking. Finally, we defined the task for our controller which is to maintain a slip ratio level of 0.2 at a considerable braking distance.

5 PID CONTROL

We need to establish a basis for the analysis of our proposed fuzzy controller. For this purpose we have chosen the PID controller. The proportional-integral-derivative controller is one of the popularly used control approach in the industry. Unlike the modern control schemes which present the Engineer a wide range of design flexibility, the PID limits the designer with the tuning of three constants called proportional (K_p), integral (K_i) and derivative (K_d) parameters. However despite of the limited areas of application, the PID controller have been immensely used in the industries. The mathematical representation of the 3 parameters is given by:

$$u = K_p e + K_i \int edt + K_d \frac{de}{dt} \qquad (5.1)$$

These PID parameters can either be manually or automatically tuned. It is however important to know that each of the PID parameter gives a distinctive effect on the controlled variable. The effects of tuning each parameter are shown in Table 5.1.

Table 5. 1 PID controller parameters and their effects

Response	Rise time	Overshoot	Settling time	Steady State error
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small Change	Decrease	Decrease	Small Change

In order to design a PID controller that is suitable for our model we used the manual tuning or simply 'trial-and-error' approach since the purpose of our work is not focused on PID controller but rather just to establish a background for our fuzzy controller. The approach requires that we set the values K_p, K_i and K_d parameters one after the other while observing the respective responses. Before the tuning process began we set the reference value for our slip, in this case we have chosen slip = 0.2 since we believed the highest coefficient of friction is achieved at the point (Figure 4.4).

The ABS model architecture with PID controller is given in Figure 5.1

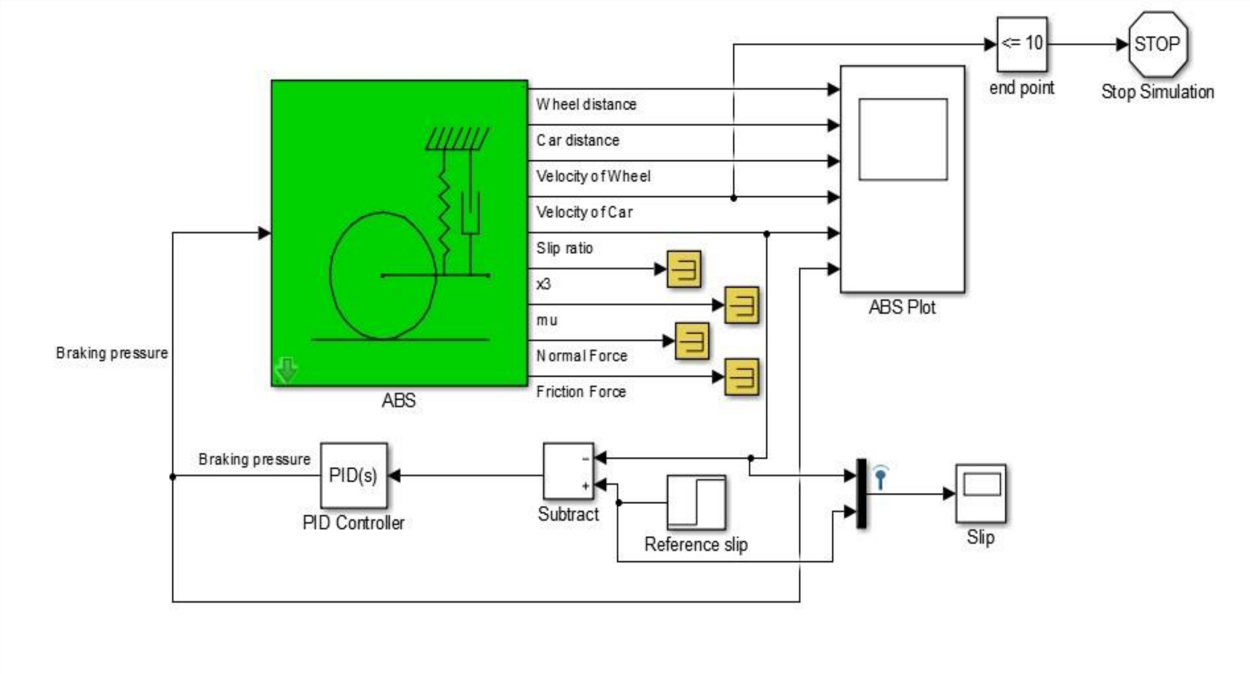
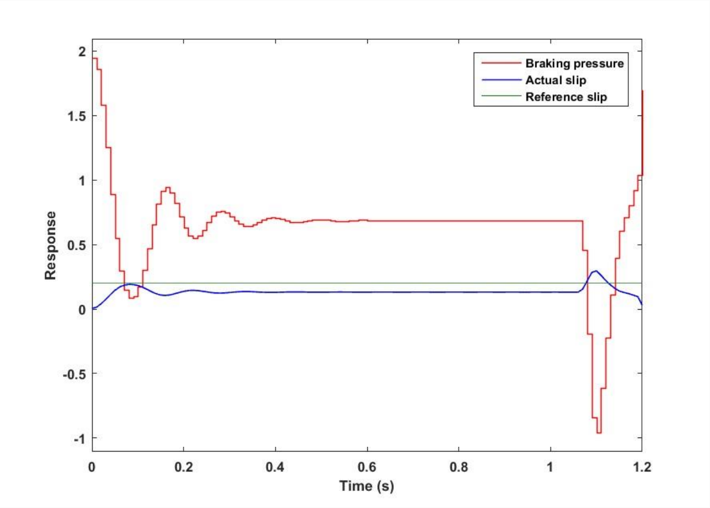


Figure 5.1: ABS simulation model with PID controller

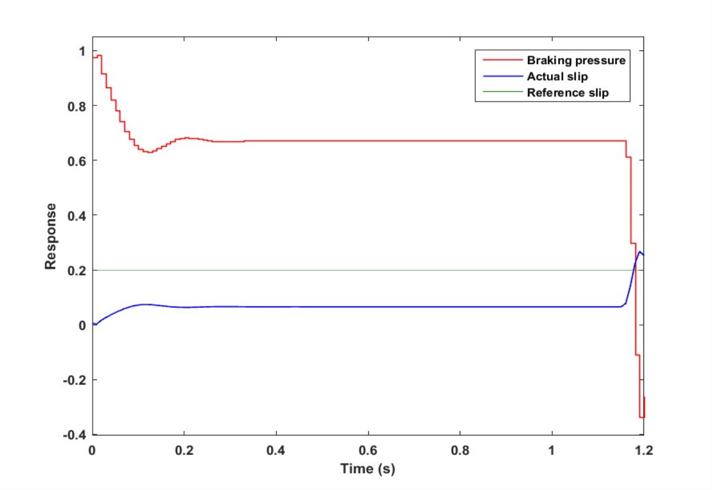
5.1 Tuning and Simulation of PID Controller

After setting a reference value of 0.2 for our slip then we started tuning our PID parameters and observing the effect on the slip. The procedure of the tuning process is such that we keep other parameters ($K_i = 0$ and $K_d = 0$) constant while we tune the K_p parameter.

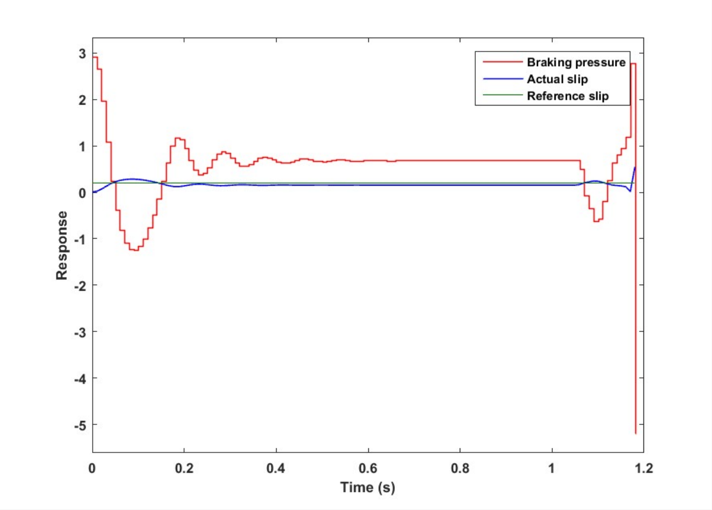
Considering the results shown in Figure we can infer that our system reacts faster as the value of K_p increases even as the slip response approaches the reference signal. After making the trial-and error with 3 different values of the proportional gain K_p, we choose $K_p = 15$ since this gave us a response in the premise of the reference slip.



(a) Proportional parameter Kp = 10



(b) Proportional parameter Kp = 5



(b) Proportional parameter Kp = 15

Figure 5.2: System response with varying Kp

We then went further to tune the K_i and K_d parameters so as to minimize the steady state error and the boost the reaction time. For the K_i, our intention is to choose a value such that our system response will not be too slow (low K_i value) and we must avoid unwanted oscillation (too high K_i). Likewise for the K_d value we intend to have a moderate system response i.e. not too low and not too high. Based on these objectives and while tuning the K_i and K_d parameters we discovered that there was a need to adjust the K_p parameters and as such we arrived at the following combination:

$K_p = 5$, $K_i = 45$, and $K_d = 1$

Based on the above PID parameters we obtained the system slip response in Figure 5.3

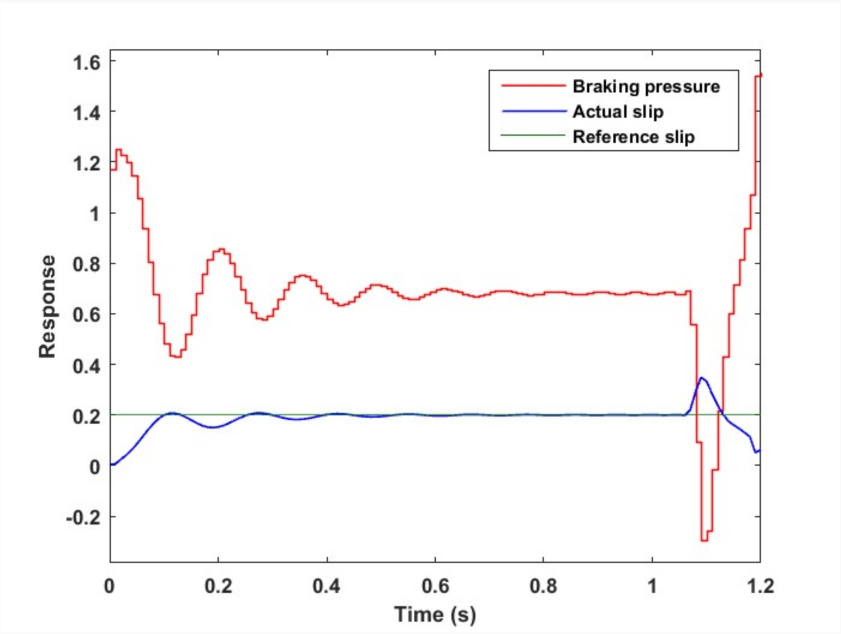
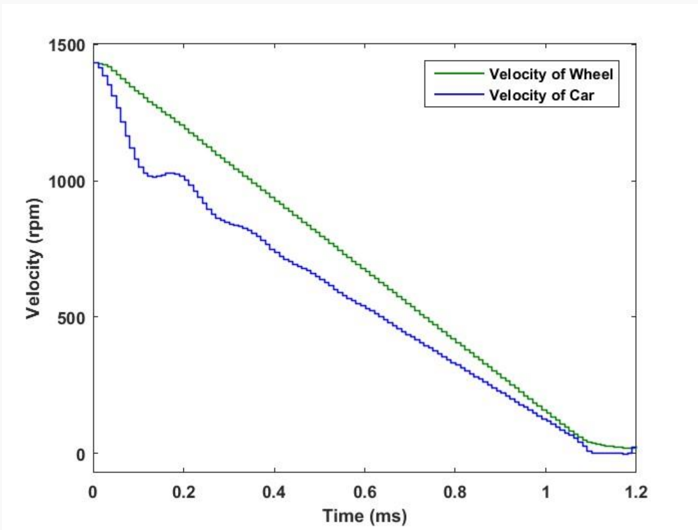


Figure 5.3 PID slip control

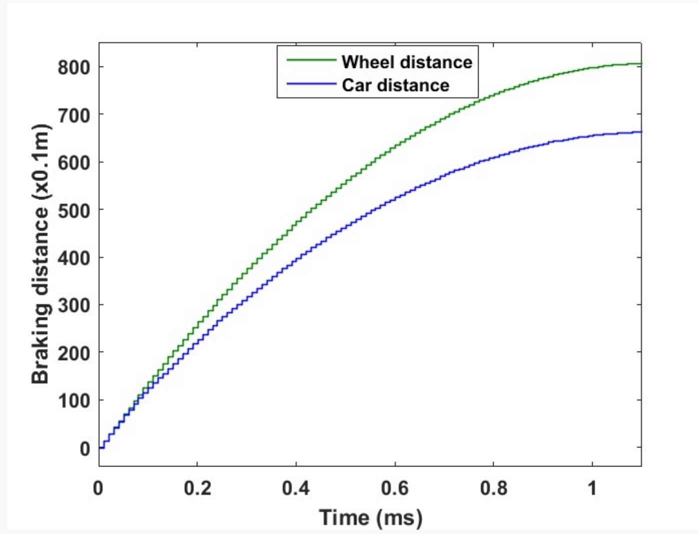
The overall PID controller performance is shown in Figure 5.4. As previously mentioned, the aim of this chapter is to set a basis for the evaluation of our proposed controller. We will be comparing the results obtained in Figure 5.4 with our own proposed fuzzy controller in the next chapter.

5.2 Summary

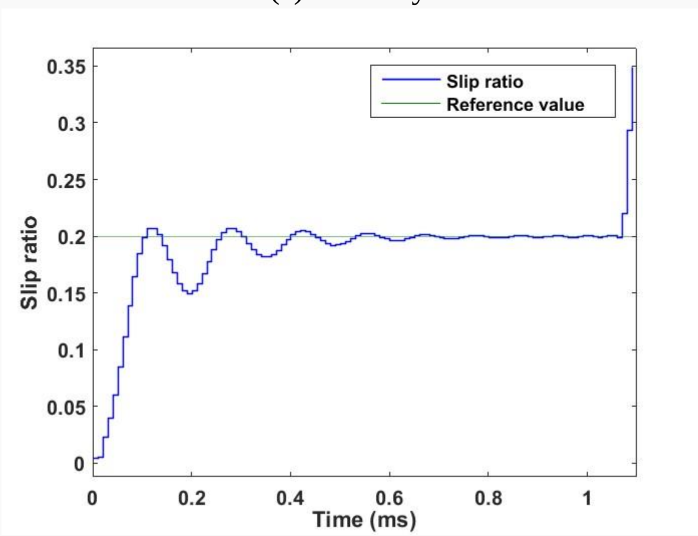
We have designed and implemented a PID controller on our ABS model. The PID was manually tuned as we only needed a simple PID controller for analysis purpose. The final PID parameter values were $K_p = 5$, $K_i = 45$, and $K_d = 1$. The results in Figure 5.4 showed that the slip response control is characterized with some initial oscillation and took some couple of seconds to settle. Also the wheel velocity control response had some initial oscillations and the tracking rate was not too good. In addition the controller response' amplitude was initially high but gradually diminishes as the slip oscillation diminishes.



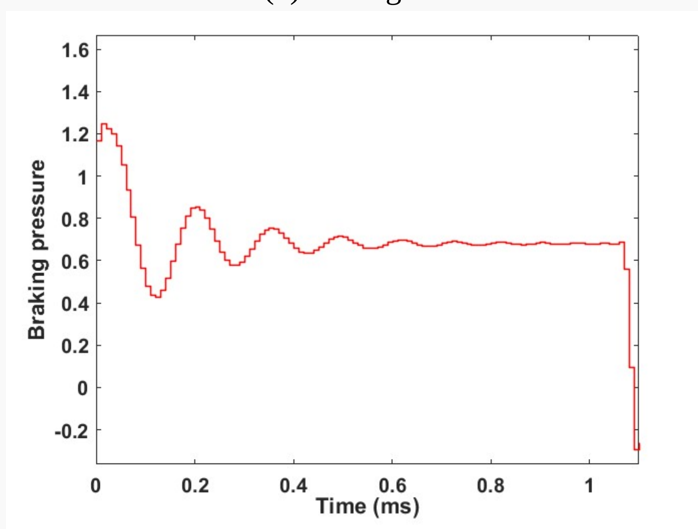
(a) Velocity



(b) Baking distance



(c) Slip ratio



(d) Braking pressure

Figure 5.4: ABS responses for PID controller

6 FUZZY CONTROL

In Chapter 4, we have established the relationship between coefficient of friction and the slip ratio. The aim in this Chapter is to therefore design a controller that is capable of minimizing and keeping the slip ratio in the premise of our specified value and in the process bringing the vehicle to a safe stopping distance. We have applied a similar concepts to that in [4].

6.1 Fuzzy Controller design

Fuzzy control is one of the modern intelligent control methods that uses linguistic variable approach rather than the classical approaches that use mathematical model for their design. A fuzzy controller consists of four major parts [20] as shown in Figure 6.1. For instance the classical PID and relay controllers use mathematical model as the bases for their design but in the case of fuzzy control, a linguistic base rules are employed as the basis for the design. Although the rules requires the knowledge of experts who understand the principle of operation of the system to be controlled. Hence a necessary criteria for the design of a fuzzy controller is the fundamental understanding of the dynamics of the system. Fuzzy logic based controllers consists basically of four main parts: fuzzification, inference mechanism, rule base and defuzzification. The connections and the mode of operation of the four processes are depicted in Figure 6.1.

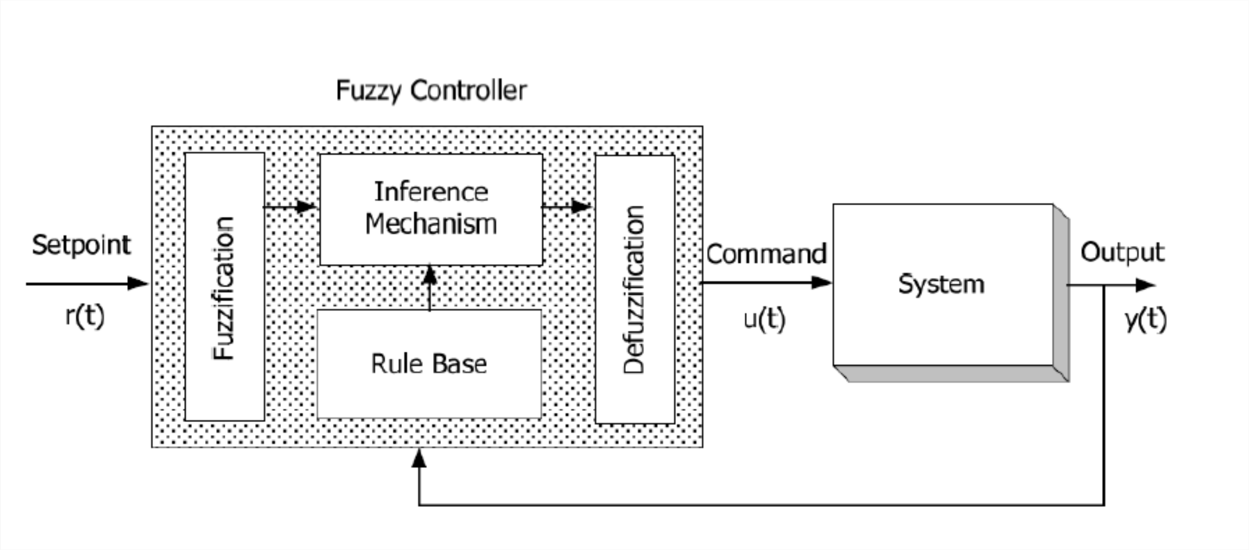


Figure 6.1 Fuzzy controller [20]

1. A rule-base (a set of If-Then rules), which is collection of the expert's linguistic description of how to achieve the control process having understood the plant behavior.
2. The inference mechanism (or fuzzy inference module) interprets the expert's decision making and thereafter apply such knowledge on how best to control the plant. It basically evaluates which rules should be applied to each and every situation as they present themselves.
3. The fuzzification interface helps to convert the controller crisp input into a fuzzy format that the inference system can easily understand and compare with the rules in the "Rule-base".
4. The defuzzification interface functions in opposite to the fuzzification. It converts the interpretation of the inference system into a crisp output that will serve as input to the system.

The crisp inputs and outputs form a system called "fuzzy system". A Fuzzy system is a static nonlinear mapping between its inputs and outputs (i.e. it is not a dynamic system).

The fuzzy logic controller consists of two logic inputs from the vehicle deceleration and the braking distance respectively and an output which is the braking force or pressure. The controllers analyzes the following sets of 25 rules each as shown in Table 6.1.

6.2 Rule-Base Design

The major and important step in fuzzy controller design is the rule base design. After establishing our control task the next task is to decide and select the best controller inputs combinations that will yield the expected results. This results can however be achieved with a proper rule design that will effectively manage and combine the inputs in the premise of the selected membership functions. A good combination of rules signifies a good controller output. It is therefore important that I discuss the steps and the processes involved in my design.

6.2.2 Controller inputs and outputs

Another major task in the controller design is the selection of the inputs. We have employed the MISO structure type in our input-output structure. According to [20] the number of controller inputs must not be too much as this will impair the controller response rate. Therefore for each of our controllers we have used two inputs and one output respectively. As previous mentioned we have combined two controllers in our design in order to have an optimal result. The inputs to the controller are stated as follows

Input 1: Slip error between actual slip and the reference slip e_θ

Input 2: Rate of change of optimum slip error $\dot{e}_\theta$

6.2.2 Linguistic variables and values

As earlier mentioned in section 4.1, we have used the natural language known as linguistic variables to describe our system behavior. The fuzzy controller has the capability of interpreting this linguistic variables based on the assigned membership functions of each variables. The linguistic variable that we have used are:

e_θ- slip error

$\dot{e}_\theta$ - Change in error

Each of the linguistic variable is assigned a linguistic value which will eventually carry a numerical value each. All the linguistic variables were assigned five linguistic values each. In the rule design, each value from a variable is compared to all values from the other variable. Each variable is assigned with all the following linguistic values.

- negative large in size
- negative small in size
- zero
- positive small in size
- positive large in size

The linguistic values are however abbreviated in our rule design to

- negative large in size - NL
- negative small in size - NS

- zero - Z
- positive small in size - PS
- positive large in size - PL

However in our rule Table 6.1, for simplicity and easy understanding, we have assigned numerical values which signifies the relative sizes of our inputs and output linguistic values [20]. For instance as an example we can say that:

- For slip ratio, positive large in size indicates that the slip ratio is positively far from the reference or desired value.

The numerical values used for our linguistic values are:

- “negatively large in size” is -2
- “negatively small in size” is -1
- “zero” is 0
- “positively small in size” is 1
- “positively large in size” is 2

6.2.2 Rule base

We need to establish rules that will govern the relationship between our inputs and output variables respectively. Here we are expected to imitate the expert knowledge on the dynamics of the system to develop the “Rule-base” of our controller. The general format used for MISO system is:

“If *premise* Then *consequence*”

The premise consists of the inputs linguistic variables which are either connected with the "OR" or "AND" operator while the consequence consists of the applicable output linguistic variable which is the expected reaction of the controller. For example in our case, the statement:

"IF *Slip Error Is Negatively Large* AND *change in error is positively small* THEN *braking pressure is positive large"*

Simply means a situation when the wheels are moving faster than the car and the rate of increase is very high. Hence, we need to apply a large force which will quickly reduce the wheel speed to a value in the premise car speed.

6.2.2 Linguistic rules

In our work we have used two (2) inputs namely slip ratio error and rate of change of slip ratio. The output from the system is the braking pressure which is dependent on variability of the two inputs. There five linguistic values considered for each variable as previously stated: negative largely (NL), negatively small (NS), zero (Z), positively small (PS) and positively large (PL). By combining the linguistic values together according to [20] and based on the expert's knowledge [4] we have designed twenty five (25) sets of rules for our system. The rules established for the fuzzy control of our ABS model are:

1. When Slip Error is NL and change in error is PL then braking pressure is ZE.

2. When Slip Error is NL and change in error is PS then braking pressure is PS.

3. When Slip Error is NL and change in error is ZE then braking pressure is PL.

4. When Slip Error is NL and change in error is NS then braking pressure is PL.

5. When Slip Error is NL and change in error is NL then braking pressure is PL.

6. When Slip Error is NS and change in error is PL then braking pressure is NS.

7. When Slip Error is NS and change in error is PS then braking pressure is PS.

8. When Slip Error is NS and change in error is ZE then braking pressure is PS.
9. When Slip Error is NS and change in error is NS then braking pressure is PL.
10. When Slip Error is NS and change in error is NL then braking pressure is PL.
11. When Slip Error is ZE and change in error is PL then braking pressure is NL.
12. When Slip Error is ZE and change in error is PS then braking pressure is NS.
13. When Slip Error is ZE and in change in error is ZE then braking pressure is ZE.
14. When Slip Error is ZE and change in error is NS then braking pressure is ZE.
15. When Slip Error is ZE and change in error is NL then braking pressure is PS.
16. When Slip Error is PS and change in error is PL then braking pressure is NL.
17. When Slip Error is PS and change in error is PS then braking pressure is NL.
18. When Slip Error is PS and change in error is ZE then braking pressure is NS.
19. When Slip Error is PS and change in error is NS then braking pressure is NS.
20. When Slip Error is PS and change in error is NL then braking pressure is NS.
21. When Slip Error is PL and change in error is PS then braking pressure is NL.
22. When Slip Error is PL and change in error is ZE then braking pressure is ZE.
23. When Slip Error is PL and change in error is NS then braking pressure is NS.
24. When Slip Error is PL and change in error is NL then braking pressure is NS.
25. When Slip Error is PL and change in error is PL then braking pressure is NL.

6.2.2 Rule Table

According to [20], a convenient way to list all the rules governing the rule base is to list them in a table such that at a glance anyone can understand the controller behavior. We have put the rules in simpler form as shown in Table 6.1.

Table 6.1 Rule table

Design for the optimal slip						
Braking Pressure		Change in error				
Slip error		2	1	0	-1	-2
	-2	0	1	2	2	2
	-1	-1	1	1	2	2
	0	-2	-1	0	0	-1
	2	-2	-2	-1	-1	-1
	1	-2	0	-1	-1	-1

6.2.2 Rule viewer

The rule viewer (Figure 6.2) gives a picture of the road map of the entire fuzzy inference process. It is the rule viewer which helps in viewing the entire process from beginning to the end. The rule viewer also gives a picture of how the shape of each membership function influences the overall result. The first two columns of plots show the membership functions representing antecedent, or the if-part of each rule while the third column represent the consequence or the then-part of each rule. The current value for each variable is display at the top of each column respectively. At the lower left field is where specific values can be entered for each of the input variable. When the lines of each input is slide in either direction, the implication on the output variable can be viewed at the top of the output variable column. The rule viewer displays one calculation at a time when the slider position is altered.

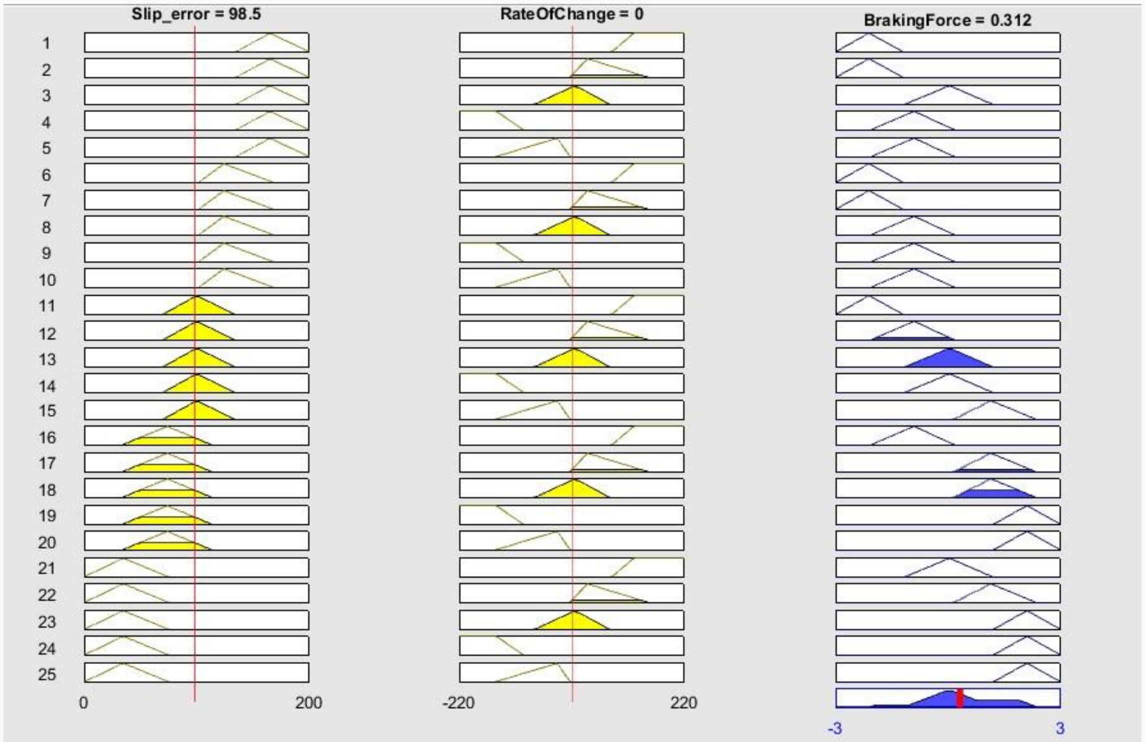


Figure 6.2: Rule viewer

6.2.2 Surface viewer

The surface viewer displays a nonlinear three-dimensional curve which shows the mapping from slip error and change in error to the braking pressure. It can be observed that the surface represents in a compact way all the information in the fuzzy controller. The surface viewer basically shows the activeness of the membership functions based on color variation. For instance in Figure 6.3 the shading from blue, to cyan, to yellow, on the surface viewer indicates progression in time of rules that were (are) ON and the fully shaded yellow colors are the rules that are currently ON. The aim of tuning the fuzzy membership functions is to shape the nonlinearity that is implemented by the fuzzy controller.

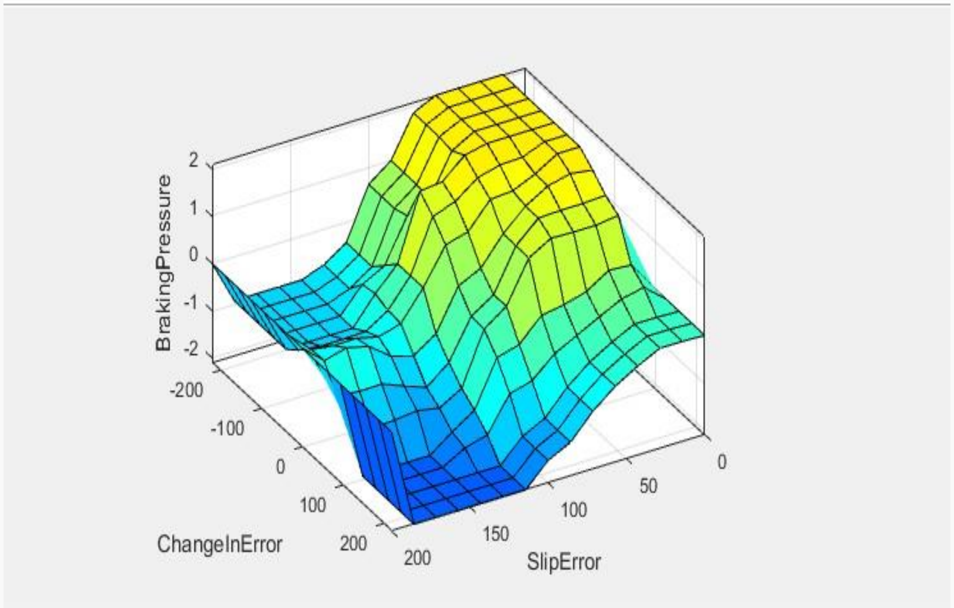


Figure 6.3: Surface viewer

6.2.3 Inference Mechanism Design

The inference system is responsible for the decision making. As previously mentioned it compares the fuzzification result with the rule base and assigns the best rule to the current situation. This concept of comparison by the inference system is called matching. The inference process generally involves two steps [20]:

- The premises of all the rules are compared to the controller are compared to the controller input in order to determine which rules apply to the current situation. This “matching” process takes into consideration the certainty of each rule. After the inference system has matched the inputs to the rules, a decision will be made whether to use the *minimum* certainty of the two rules or to use the *product* of both certainty level. Here we have used the minimum certainty level for our decision.
- The conclusion i.e. the control action to be implemented are determined by the rule that was selected.

6.2.3 Membership Functions

The membership functions are used to describe the degree of certainty of each rule. For instance given a universe of discourse U_i and a linguistic value $\tilde{A_i^j} \epsilon \tilde{A^i}$ for the linguistic variable $\tilde{u_i}$, The function $\mu(u_i)$ associated with $\tilde{A_i^j}$ that maps U_i to [0, 1] is called a "membership function". Once again the expert knowledge was used to select the best membership functions. The membership functions have various forms such as the triangular, trapezoidal, Gaussian etc. However for simplicity we have used the combination of the triangular and trapezoidal membership functions.

The number of membership functions used was determined by the number of the linguistic values we used.

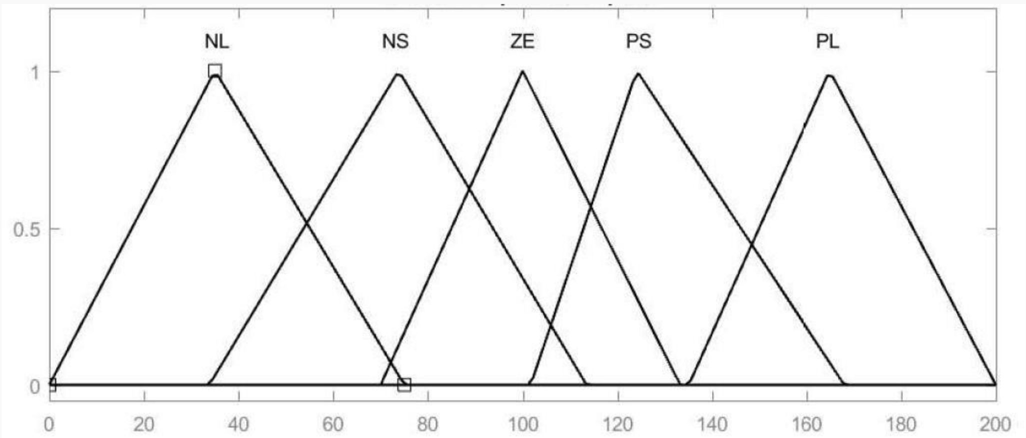
Based on our understanding of the system dynamics we created the membership functions (Figure 6.4) suitable for our design. The bounds used for the membership functions are stated as follows:

Input membership functions

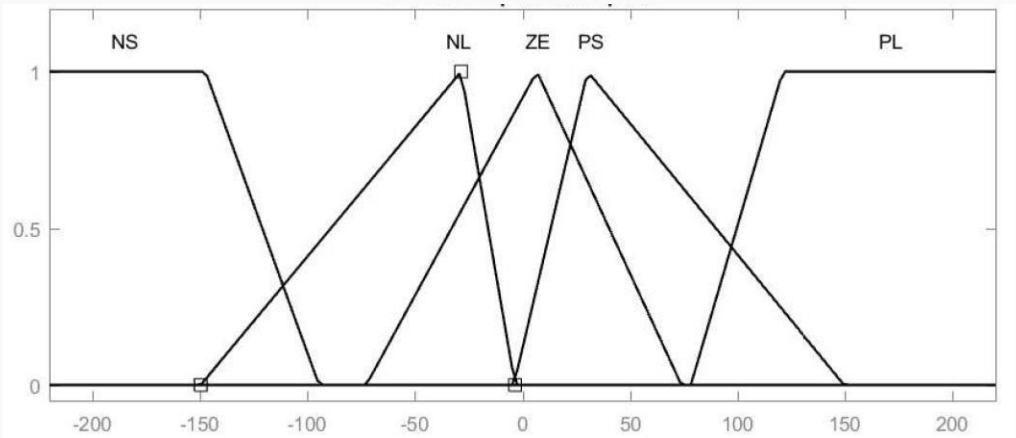
- Slip ratio error [0 200]
- Change in error [-220 220]

Output membership function

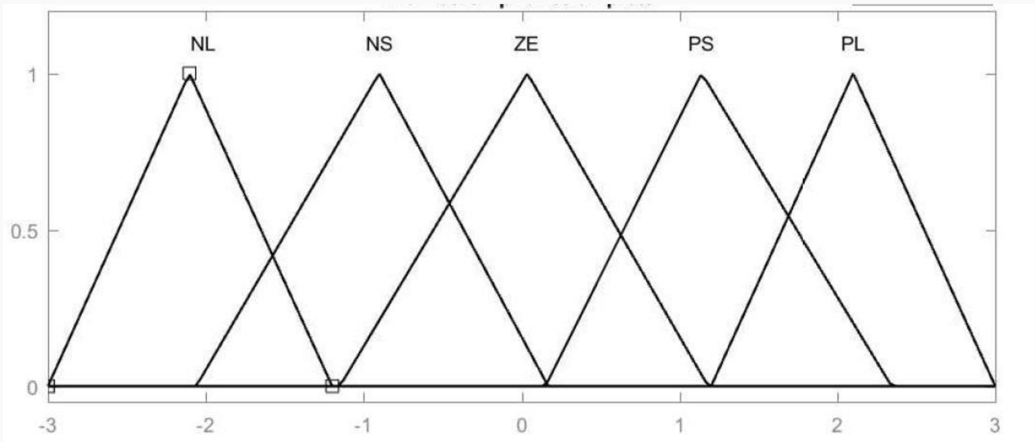
- Controller output [-3 3]



(a) Membership function for slip ratio error



(b) Membership function for change in error



(c) Membership function for braking pressure

Figure 6.4: Membership Functions for controller

6.3 Simulation Model

Figure 6.5 is the Simulink simulation model for our ABS analysis. The model is designed to control both the slip ratio and braking distance respectively. The simulation Simulink structure consists of the system and the controller. The system is a SIMO system with the braking force as the only input while there are nine outputs while the controller is a MISO system with car braking distance and the car velocity as the inputs and the braking force as the only output. The system is designed based on the mathematical model shown in section 4.2.

In our design architecture (Figure 6.5) we have combined two controllers in which one determines the road condition so as to establish an optimum slip ratio that will serve as an input for the next controller. The second controller combines the slip ratio and its rate of change to generate the required input to the system.

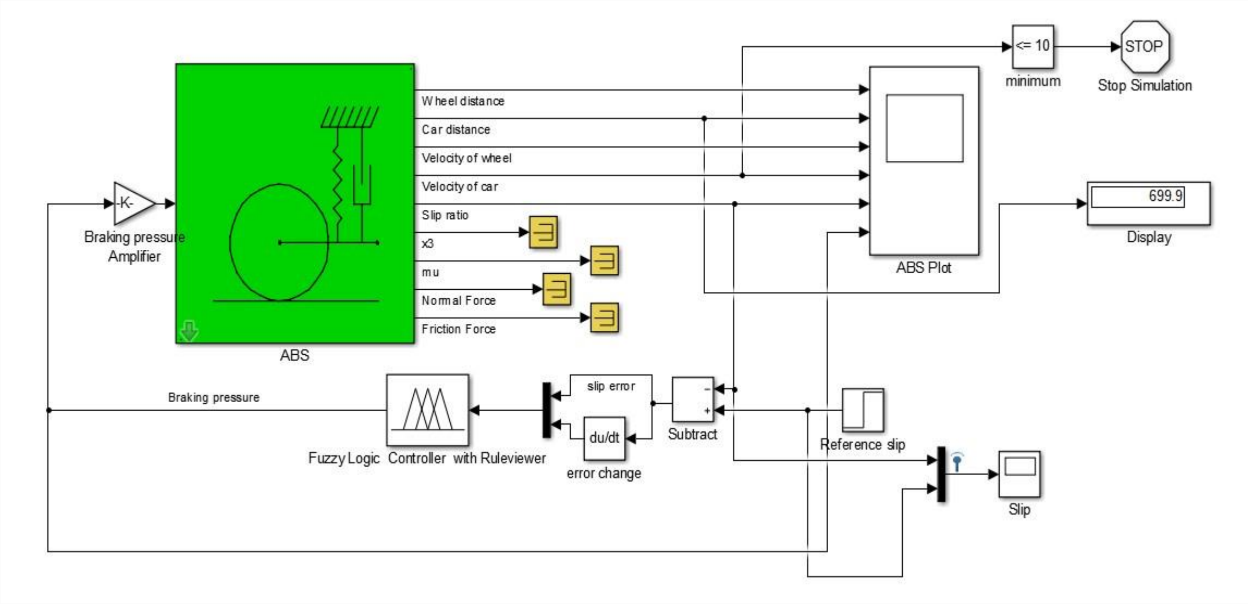


Figure 6.5: ABS Simulation Model with Fuzzy Controller

6.4 Summary

In this Chapter, we have given the theoretical description of the fuzzy controller. Figure 6.1 showed the structure of a fuzzy controller which included fuzzification, rule base, inference system and the defuzzification. Fuzzification stage converts the crisp input to fuzzy linguistic value, inference system compares the linguistic values with the rule base in order to decide which rule should be activated for the current situation, rule base consists of the rules dictating the behavior of the controller and finally, the defuzzification converts the linguistic value back to crisp output. We have used 25 expert-based rules in designing our controller.

The smallest and most important unit of the fuzzy controller is the membership function (6.4). Here we have used a combination of the triangular and trapezoidal membership function as this combination seems to offer the best result in our design. The adjustment of each membership function had a quick and observable influence on the controller output. Also the selected universe of discourse for each membership function affects the system responses.

Finally, the fuzzy simulation model is shown in Figure 6.5. The controller inputs are the slip ratio error and the rate of change of slip error. The reference signal was maintained at 0.2 as we have previously mentioned in Chapter 4.

7 IMPLEMENTATION AND IMPROVEMENT OF CONTROLLER

The proposed fuzzy control scheme in Chapter 5 is been implemented here. As earlier mentioned, the purpose of our study is to provide a good slip control and to have a minimal braking distance. The controller performance therefore implemented here and will be evaluated based on:

1. Minimum slip variation from the set point

2. Proper velocity control

3. Shorter braking distance

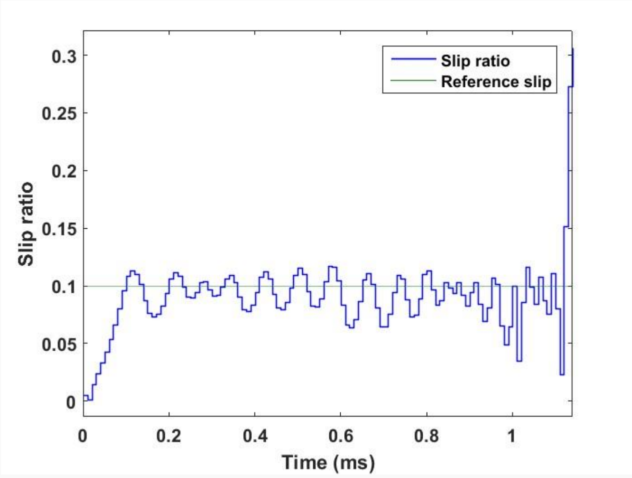
We conducted our simulation using Matlab SIMULINK. The speed of the model prior braking process was set to 1500rpm. At the initial stage of simulation, we tested our model using three slip ratio values in order to evaluate its performance in tracking the slip ratio. Also for proper evaluation of our controller, we will be comparing its performance with that of PID controller.

7.1 Model evaluation

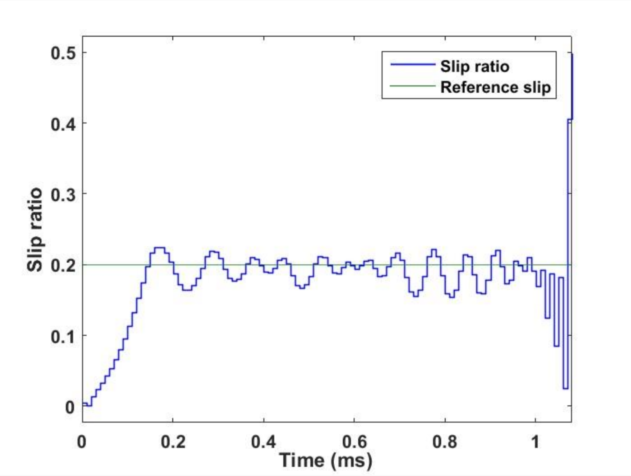
After designing our controller, it was necessary to evaluate its performance by varying the slip ratio for different reference values.

7.1.1 Slip ratio analysis

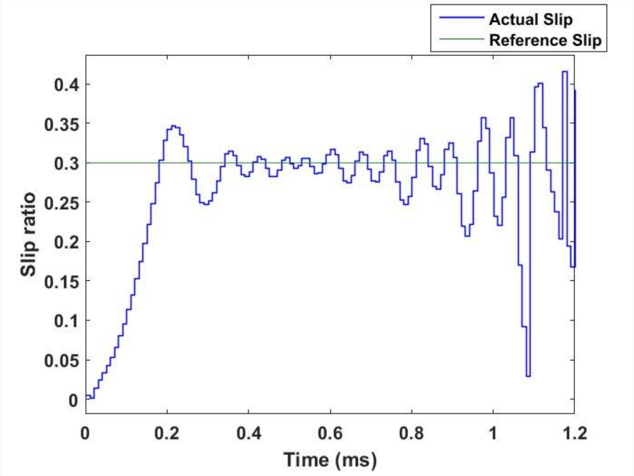
Figures 7.1a, 7.1b and 7.1c show our system output slip ratio as we vary the set point from 0.1 to 0.3. The results indicates the fact that our controller is sensitive to slip errors as the system dynamics vary with changing surfaces or any form of perturbation, for example road surface friction coefficient. By comparing the outputs for the three slip ratio values, it can be deduced that our slip offered a better result when the slip ratio is maintained at 0.2 since we were able to bring the vehicle to a stop in a shorter time. Also, the tracking ability of our controller is swift with little initial delay. Hence we can conveniently say that our fuzzy controller can perform reasonably given various circumstances.



(a) Slip ratio = 0.1



(b) Slip ratio = 0.2



(c) Slip ratio = 0.3

Figure 7.1: Slip ratio tracking

7.1.2 Fuzzy slip control

Based on the goal of our work which was to keep the slip ratio in the premise of 0.2, a value which offers optimal coefficient of friction, it was important that our controller continue to react to any form of deviation from this reference value. Also as previously mentioned when defining the rules guarding our controller behavior, it is expected that when there is a possibility of high slip ratio, the controller should react in such a way as to bring the slip ratio back to the reference level and vice versa. In practical sense, it simply means that the braking pressure should be reduced for high slip and increased for low slip. Considering these facts we can say that our controller is at per with our expectation. Figure 7.2 explains our controller behavior relative to slip ratio.

The controller response was constant for the first 0.1ms, a behavior which is due to a slip ratio below reference value. Prior to reaching the reference value, the controller reacts by decreasing the braking pressure so as to keep the slip ratio in the premise of the reference value of 0.2. Before the slip ratio attains its peak the controller's response had started approaching its minimum value of zero. This behavior was integrated into the controller via the fuzzy rules so as to always return the slip ratio to the reference value in order to provide an effective coefficient of friction needed for braking. As the slip ratio continues to oscillate within the premise of the reference value, the controller shows activeness by constantly reacting to the slip errors. Also from the perspective of the rate of change of the slip ratio we can vividly say that the controller's reaction is in order as it reacts swiftly to every notable changes in the slip ratio. Furthermore, it can observed that for relatively low error change (between 0.1-0.6s), the controller reacts moderately as well while for higher error change rate (between 0.9-1.0s), the controller's reaction was relatively faster.

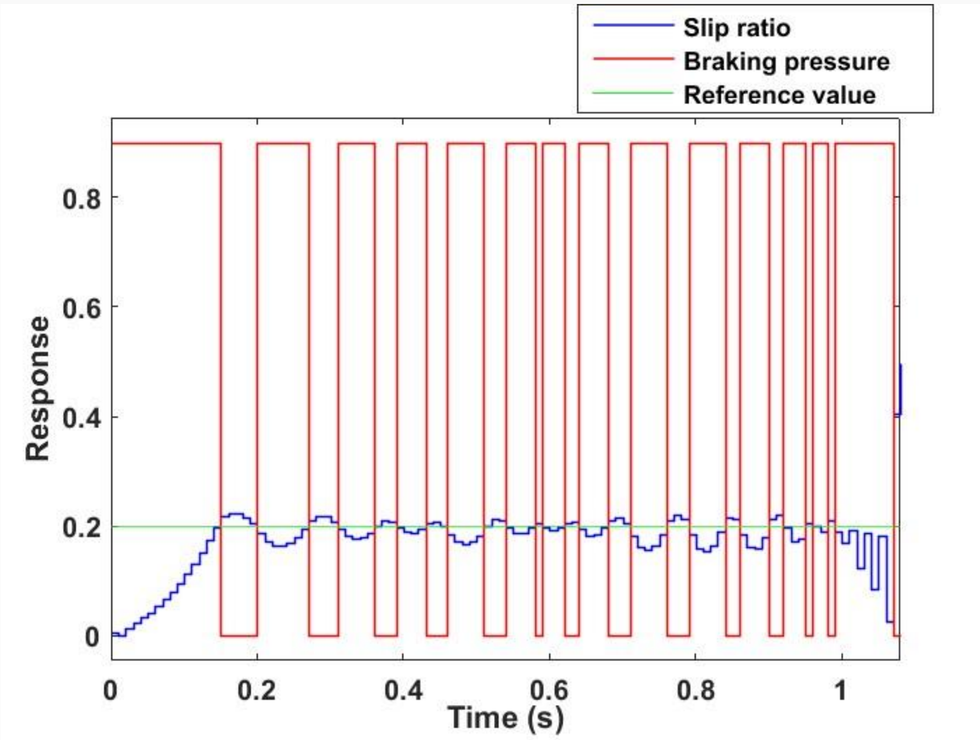


Figure 7.2 Slip control

Finally, the slip ratio goes to infinity even as the controller response attains its minimal at a point where the car's velocity is relatively very low. Although the simulation continues beyond this point but it was logical that we end the simulation at this point because the velocity of the vehicle is very low (<10rpm) and at low velocity the ABS action is very minimal and non-effective because there is virtually no need to use ABS at minimal velocity since the vehicle is stable and controllable.

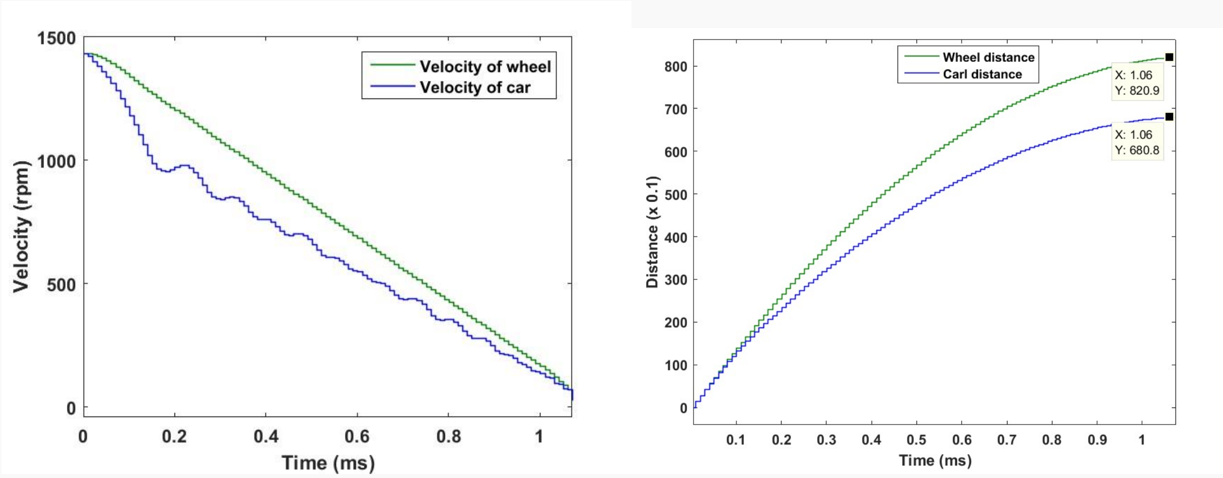
7.1.3 Fuzzy velocity and braking distance control

We expect that as the braking pressure changes there should be a corresponding change in the deceleration process for both the car and the wheels. To evaluate our model based on this, we included in our model design (Figure 6.5) a braking pressure amplifier so as to be able to check the car and wheel deceleration even as we vary the amplification. The simulation was implemented with values of K= 1, 3 and 4 respectively.

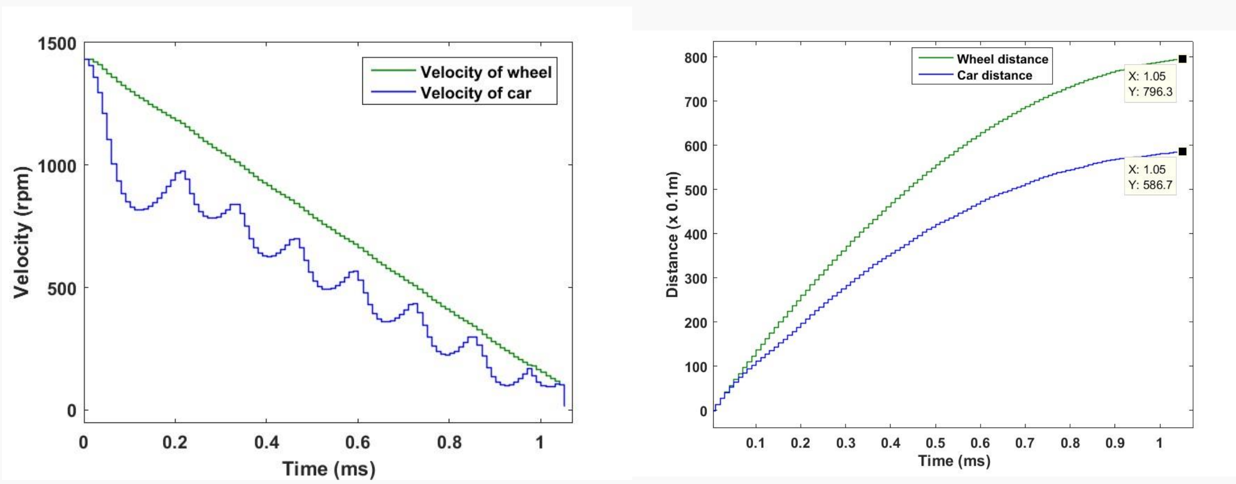
From the simulation for the various values of K, we obtained the results shown in Figure 7.3 which are the effects of the fuzzy controller output (or braking pressure) amplification of the velocity and braking distance of our system.

At first (Figure 7.3a) when K = 1, the system decelerated to zero in 1.06s and the braking distance covered was approximately 82m and 68m for the wheel and car respectively. As we continue to amplify the value of the controller output by changing the value of K, we observed a reduction in the braking distances of the wheel and car. However, as the braking distances are being further minimized (Figures 7.3b and 7.3c), we observed that deceleration of the car deviates further from the wheel's velocity. This is an expected behavior from our system since too high a braking force will increase the slip and as such will inject some irregularities to the vehicle deceleration process. When we tried to give further larger values to K, we obtained some irrational system behaviors. This obviously explains the fact that the ABS works within certain limits of controller output.

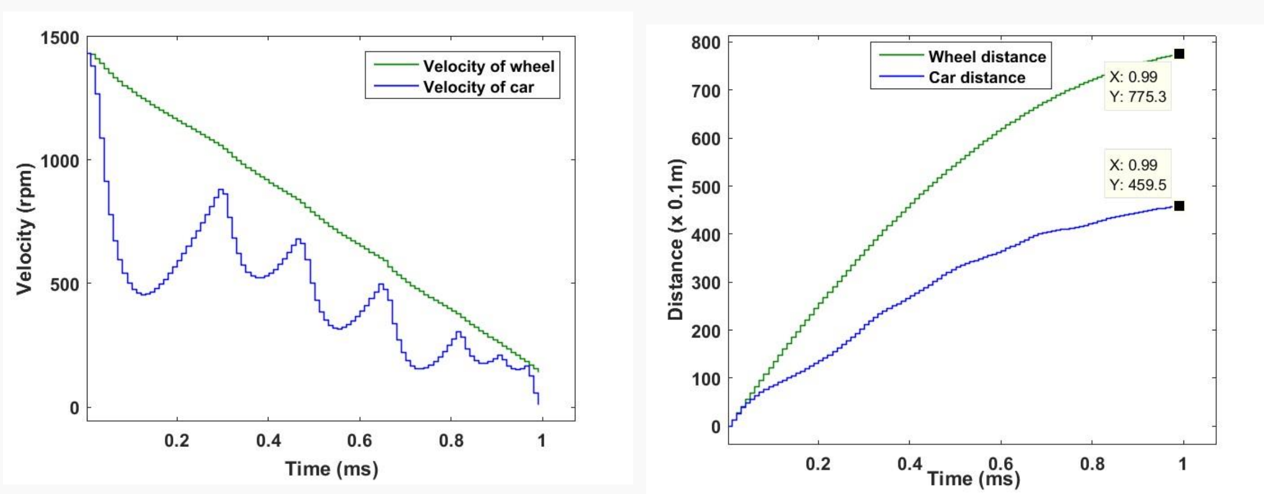
Hence, for the remaining evaluation of this project we will only be using K=1 (Figure 7.3a).



(a) Amplification K = 1



(b) Amplification K = 3

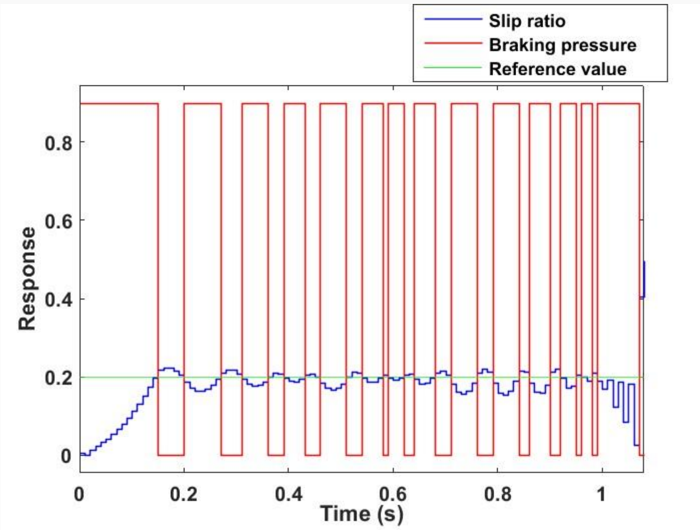


(c) Amplification K = 4

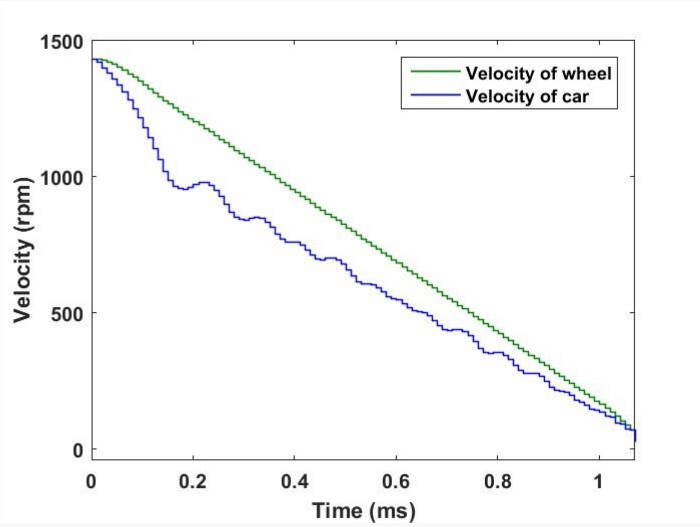
Figure 7.3: Velocity and braking distance

7.1.4 Overall Fuzzy control output

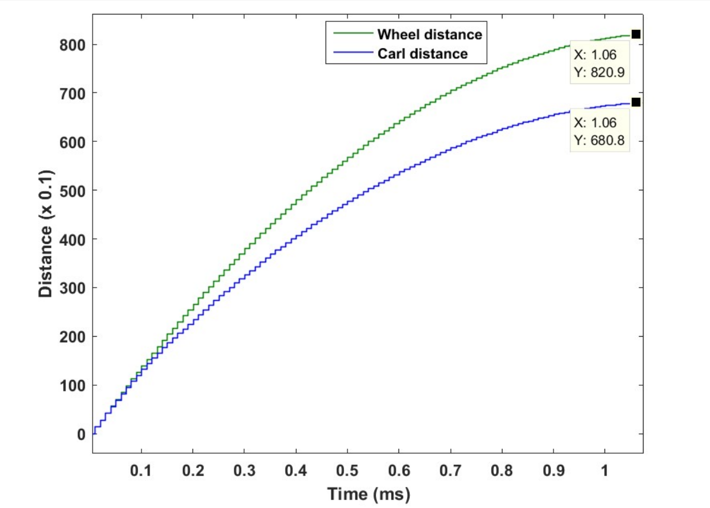
The overall fuzzy control responses for our simulation is given in Figure 7.4. Comparing these responses with that of PID in Figure 5.4, we realized that our fuzzy controller still requires some improvement as the performance of the PID looks better. And since previous research works had proven that the Fuzzy logic control approach is more effective than that of PID, we then tried to adjust our system as shown in the next section.



(a) Slip ratio and Controller output



(a) Velocity control



(b) Braking distance

Figure 7.4: Overall Fuzzy control responses

7.2 Improvement of Controller

The slip response shown in Figure 7.1 (fuzzy slip control) is characterized with numerous oscillation when compared to that of Figure 5.3 (PID slip control). The implication of this is that our system is continuously unstable and the controller is overworked. Also, for Figure 7.4b which shows the velocity control with fuzzy, we observed that the relative velocity between the car and the wheel is not good enough when compared with that given by PID in Figure 5.4. And finally the braking distance using PID proved better than that of our fuzzy controller. Hence we needed to improve the performance of our controller.

From the study of Fuzzy control it has been discovered that the following parameters influence the performance of the controller:

1. Membership function

2. Universes of discourse

3. Fuzzy rule

In our case we needed not to make any adjustment to the fuzzy rules since they were expert-based. However our improvement was focused on the other two parameters. The modification made on the parameters were similar to when PID parameters are being tuned. Every change made on each of the MFs had significant influence on the controller and system outputs respectively. For instance, changes made on the slip ratio error's MFs is observable on the overshoot and oscillations of the slip ratio and controller output responses.

7.2.1 Membership function

The membership functions form the critical part of the fuzzy control logic. The shape and the position of the membership functions (MFs) can influence the controller behavior. Based on this fact we were able to improve the performance of our controller by adjusting the shape of the membership functions as shown in Figure 7.5. Comparing these with the MFs in Figure 6.4, we have modified the MFs by including trapezoidal membership functions to the slip ratio error and braking pressure MFs. These makes them open-ended which in turn influenced our controller behavior. Also there is a shift in position of some of the MFs for the controller output (or braking pressure) as seen in Figure 7.5c.

7.2.2 Universes of discourse

Universes of discourse are the intervals or domains for the membership function. They can either be open-ended or close-ended. When close-ended, they are called effective universes of discourse. The implication of this is that beyond such points, the controller will not give an output.

In our improved MF functions, we have made all the universes of discourse open-ended i.e. not saturated as shown in Figure 7.5. These was however determined after making several trials with different number of values.

As displayed on the MFs, the new universes of discourse for each of our variables are:

Input membership functions

- Slip ratio error [-2 1.01]

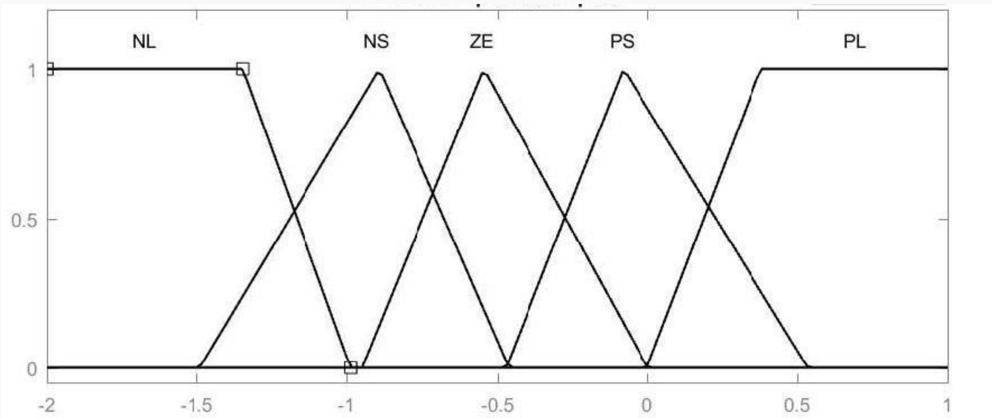
- Change in error [-300 300]

Output membership function

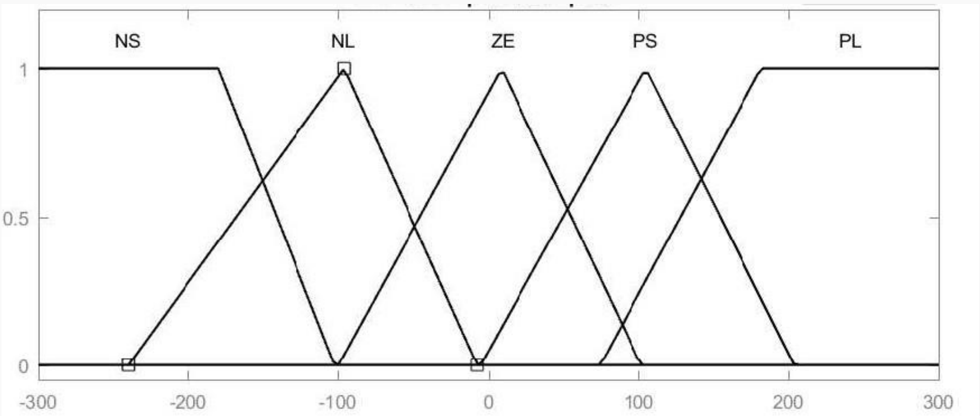
- Controller output [0 2.403]

Based on the modified membership functions and the universes of discourse, we have new responses for our control system as shown in Figure 7.6. In contrast to the previous result, we obtained a slip response (Figure 7a) with little or no oscillation. Also the settling time was very minimal and there were no overshoot in the signal. The implication is that our controller provided a very good slip control and that gives a better stability and maneuverability to our system. Also the amplitude of the controller response (Figure 7b) was very much lower than that of the previous result, indicating a more efficient controller.

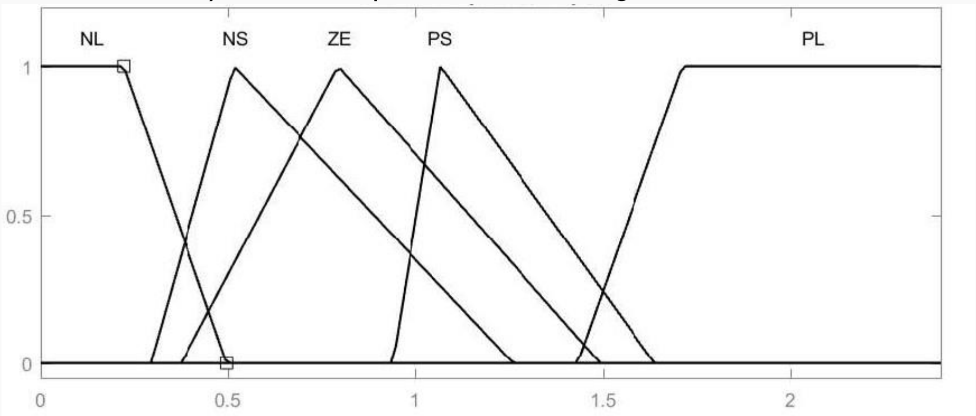
Also, the velocity control (Figure 7c) was much better as well. The relative velocity between the car and the wheel was with less oscillation and with better gradient. Finally the braking distance (Figure 7d) control was better since the distances obtained were shorter than the previous result.



(a) Membership Function for Slip ratio error

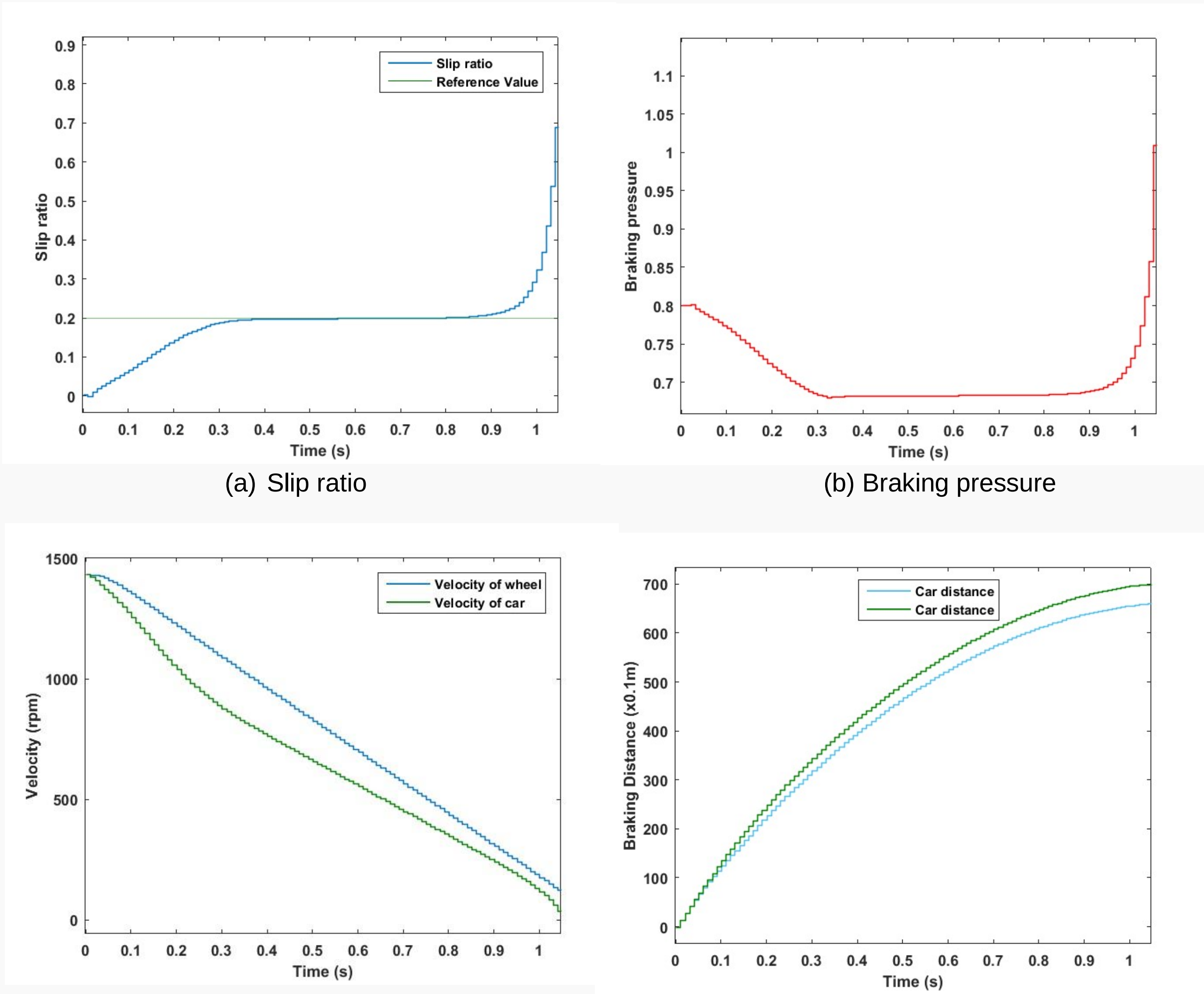


b) Membership function for change in error



(c) Membership Function for Braking Pressure

Figure 7.5 Improved Membership Functions



(a) Slip ratio (b) Braking pressure

(c) Velocity (d) Braking distance

Figure 7.6: Overall Responses for Improved Fuzzy control

7.3 Summary

We have implemented the fuzzy controller that was previously designed in Chapter 6. The results (Figure 7.4) shows lower performances when compared to that obtained from the PID controller in Figure 5.3. It was observed that the fuzzy controller results were characterized by various oscillations with longer settling time in the case of the slip ratio control and poor tracking in the case of the velocity control. Hence we needed to improve our controller. This was done by adjusting the membership functions and the universe of discourse.

The improved controller in section 7.2 showed a better performance over the PID controller. As shown in Figure 7.6, the slip response was with no observable oscillation and the settling time was very minimal. Also the amplitude of the controller response was minimized and better than that of the PID controller, an indications of better lifespan for the controller and lower cost as well. In addition we obtained a better braking distance as the model came to a stop in a shorter time.

Finally, we were able to establish, just as in previous literatures that fuzzy controllers offer better performance than PID controllers especially in a non-linear control scheme.

8 RESULTS AND CONCLUSION

In this chapter, we have compared our proposed fuzzy controller results in Chapter 7 with the PID controller in chapter 5.

8.1 Results

Our evaluation will be based on:

1. Slip control

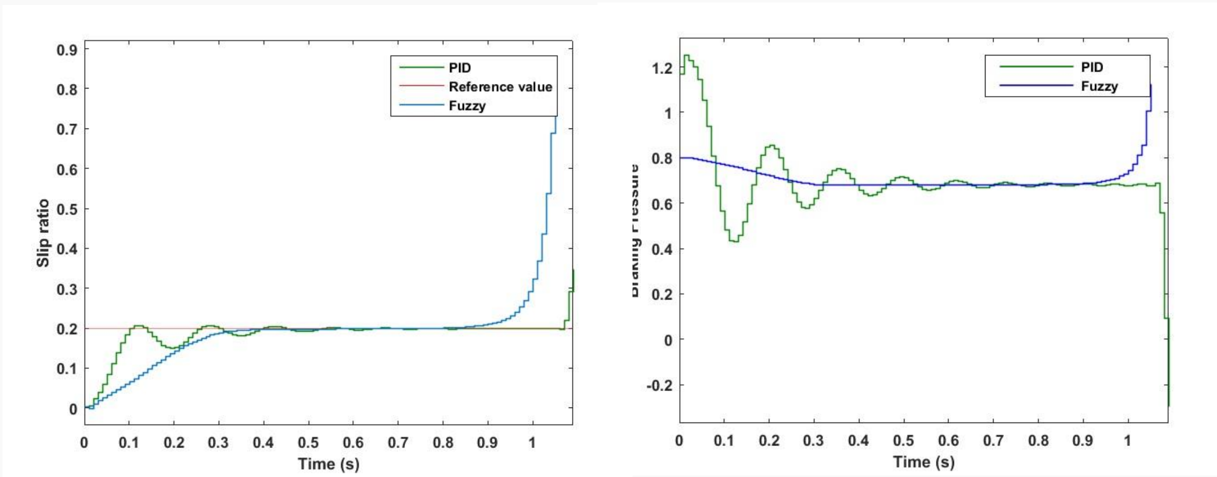
2. Braking distance

3. Velocity control

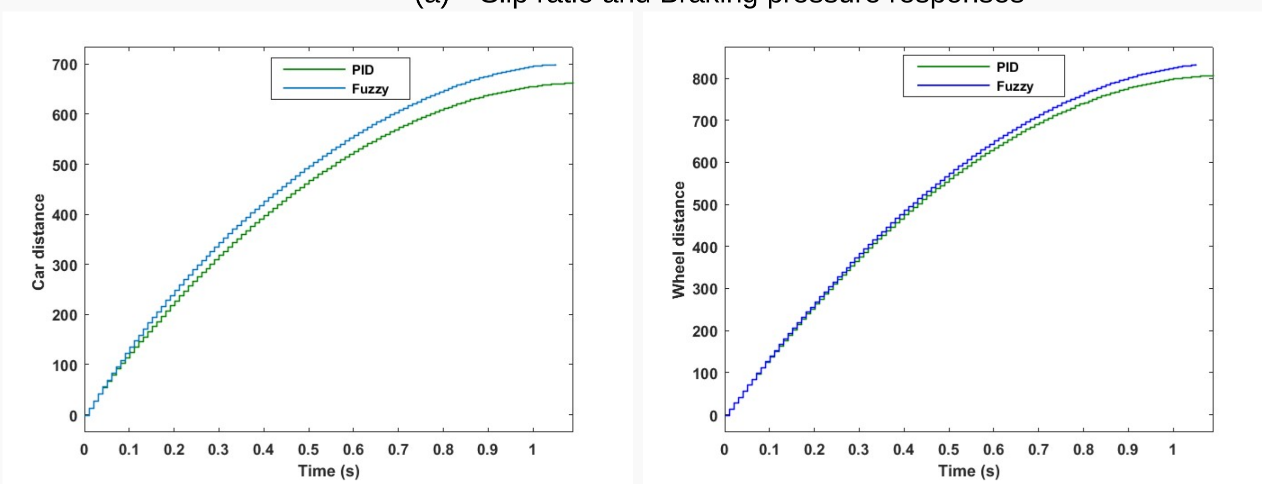
4. Controller output or braking pressure

The simulation results for our proposed fuzzy control scheme and the PID control scheme are shown in Figure 8.1. The slip ratio response from the system and the braking pressure responses from the controllers are shown in Figure 8.1a. Also Figure 8.1b gives the braking distance responses from the two control schemes. The wheel and car velocity controls are presented in Figure 8.1c.

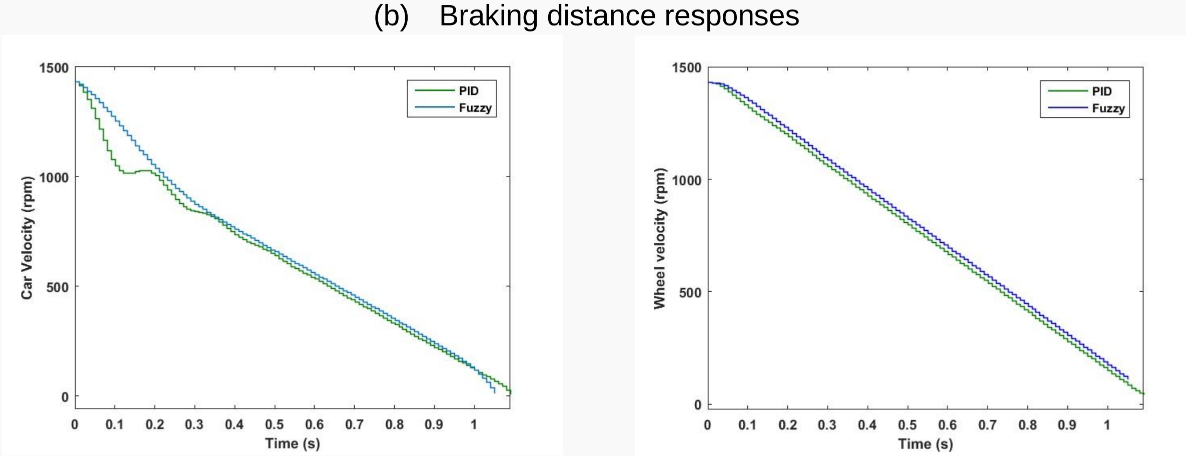
The overall performance of the two controllers can be said to be in line with our expectations although with better performances from the fuzzy control approach. The slip control by the fuzzy controller scheme exhibit a good convergent rate with little or no overshoot while for the PID, quite a number of overshoots were observed and the convergent rate was relatively slow. The braking pressure in the case of the fuzzy control scheme was maintained at a level with relatively low amplitude with no chattering while in the case of the PID control scheme the braking pressure exhibited a higher amplitude with some amount of chattering. Also the wheel velocity control by Fuzzy was with minimal fluctuation compared with that of PID. Finally, we observed that the braking distance in the case of fuzzy control was better since a longer distance was covered in a shorter time duration compared to that of the PID.



(a) Slip ratio and Braking pressure responses



(b) Braking distance responses



(c) Velocity control responses

Figure 8.1: Fuzzy control vs PID control of ABS

8.2 Conclusion

We have presented two ABS controllers, a proposed Fuzzy controller and the commonly used PID controller for comparison. A detail study of their performance after implementation on the ABS simulation model showed that our proposed Fuzzy controller exhibited better and superior performances than the PID control. The Fuzzy control approach provided slip control with quicker convergent rate and no observable overshoots. Also the deceleration control was with minimal fluctuation and a better braking distance was achieved.

9 KOKKUVÕTE JA EDASPIDINE TEGEVUS

Käesolevas töös ehitati hägusa loogika kontrolleri mudel ABS mudeli põhjal. Alguses peatükkides 1. ja 2. Tutvustatakse taustinformatsiooni olemasolevaid töid. Antakse üksikasjalik ülevaade erinevatest lähenemistest juhtimisteoorias.

Peatükis kolm on ülevaade pidurisüsteemidest, nende tööülesannetest ja pidurisüsteemi mõjust sõiduki juhtimissüsteemile. Kolmandas peatükis on antud süsteemi matemaatiline mudel üksikasjalike selgitustega. Siin esitatud teadmised on vajalikud selleks, et mõista dünaamika meie mudeli ülesehitust.

Peatükkides viis ja kuus oleme pakkunud PID ja hägusloogika juhtimissüsteemi analüüsid. Need on tulemused, kus on kasutatud neid kahte kontrolli meetodit ja võrreldud seejärel järgnevas peatükis nii, et saaks hinnata väljatöötatud hägusloogika kontrolleri töö tulemuslikkust.

Siiski tuleks tulevikus hägusloogika kontrolleri tööd uurida mõnes teises ABS laboris et täielikult veenduda tema töökindluses. Edasine tegevus on vajalik ka kontrolleri muutmiseks adaptiivsemaks selliselt, et ta arvestaks keskkonnamuutusi, teeolusid, mis sageli erinevad sõltuvalt asukohast ja ilmastiku tingimustest.

9 SUMMARY AND FUTURE WORK

In this thesis, a fuzzy logic controller was implemented on an ABS model. At the beginning, Chapter 1 and Chapter 2, a background information and state of art on the existing work was established. A detailed review of various approaches especially those related to modern control approach such as fuzzy logic.

In Chapter 3 we gave a general overview on antilock braking systems taking into account its functions, objectives and benefits to vehicle system control. Also, in Chapter 4, we gave a detailed explanation about the mathematical model of our control system. The knowledge presented here was necessary for the purpose of understanding the dynamics of our model.

In the next chapters, we have provided the PID and fuzzy logic control scheme so as to enable us provide separate analysis for each scheme. These results established for the two control approaches were then compared in Chapter 6 so as to evaluate the performance of our proposed fuzzy controller.

However, future work should be targeted at evaluating the fuzzy controller on a laboratory ABS in other to fully ascertain its robustness. Also, further work can be done on the controller design by making it more adaptive such that it can respond to environmental changes in the likes of road surface friction which often vary with location and weather conditions.

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