CHAPTER 1

INTRODUCTION

1.1 Overview of ABS

The technology and understanding in antilock braking system is continuously evolving. The development of antilock braking system (ABS) is currently an important problem in the automotive industry and ABS is recognized as important features to the road safety. Antilock braking systems (ABS) has been developed to reduce tendency of wheel lock up and to improve vehicle control during sudden braking especially on slippery road surface. The aim of such control is to increase wheel tractive force in the desired direction while maintaining adequate vehicle stability and steerability and also reducing the vehicle stopping distance. The performance of ABS however relies upon proper identification of road surface. The type of road surface can be inferred from the vehicle's brake pressure, wheel slip measurement and deceleration rate comparison.

The input forces which control the vehicle motion come from the road-tire interaction and have 2 components – one in longitudinal direction and one in the lateral direction (Kachroo, 1993). The tractive force in the lateral direction depends on the cornering stiffness and can be controlled by the steering. The tractive force in the longitudinal direction on the other hand, is a nonlinear function of the wheel slip and can be controlled by making the wheel slip follow some time varying function.

Thus, one of the objectives of an ABS system for longitudinal direction tractive force control is to regulate the wheel slip so that the road adhesion or friction coefficient is maximized. This in turn leads to the minimization of the vehicle stopping distance (Kachroo, 1993).

1.1.1 Structure and operation

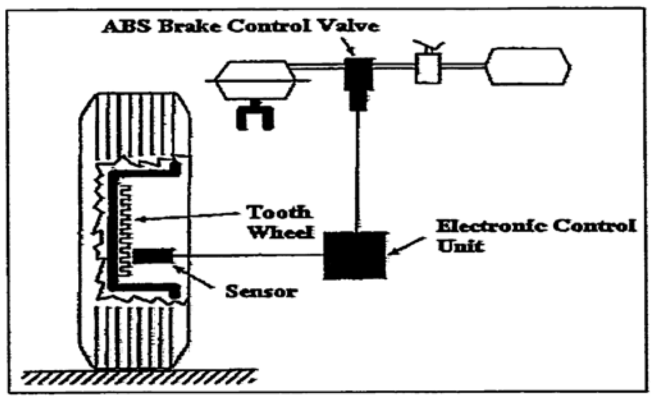

Figure 1.1: Configuration of an ABS

Typically ABS consist of three major parts: 1) electronic sensors which measure the wheel velocities, the brake pressure and the vehicle acceleration, 2) an Electrical Control Unit (ECU) which is a microprocessor based system, and 3) electrically controllable valves or pumps to control the pressure in brake cylinders (Jiang, 2000). ABS work in a closed loop control system by modulating the brake torque that is applied to the tires in response to measured deceleration of the wheel. This will prevent the controlled wheels from the lockup effect. Wheel lockup often happens when braking on a slippery road surface or during a severe braking. During wheel lockup, the vehicle loses its steering ability and the longitudinal friction force, which stops the vehicle, is also reduced.

In normal driving condition, the vehicle velocity is almost equal as the wheel velocity. However, when a wheel becomes locked and slips, the vehicle velocity and the wheel velocity are not equally same. The difference between the wheel velocity and the vehicle velocity is defined as

$$\lambda = \frac{v - \omega r}{v} \tag{1.1}$$

where

λ	: wheel slip
v	: longitudinal vehicle velocity
ω	: wheel angular velocity
r	: the rolling radius

In severe braking, it is common to have $\omega = 0$ while $v \neq 0$, thus $\lambda = 1$, which is called wheel lockup.

ABS is designed to manipulate the wheel slip at certain level so that a maximum friction force is achieved and the steering stability (also known as lateral stability) is maintained (Jiang, 2000). In a severe braking situation, ECU assists the vehicle operator to prevent wheel lockup by regulating the wheel slip. It monitors the wheel velocity and the vehicle velocity. When a wheel lockup is detected or deemed eminent, ECU releases the brake pressure to allow the wheel velocity to increase and the wheel slip to decrease. Once the wheel velocity spins up, ECU re-applies the brake pressure to confine the wheel slip to a predetermined value or interval.

1.1.2 Tire-Road Interaction

Understanding of the tire-road interaction in both the longitudinal and the lateral directions is vital. When a braking torque is applied to a tire, due to its elasticity, the leading half of the tire tread stretches, before it enters the contact patch as shown in Figure 1.2. Thus the longitudinal tire travel is greater when it is subjected to a braking torque compared to free rolling.

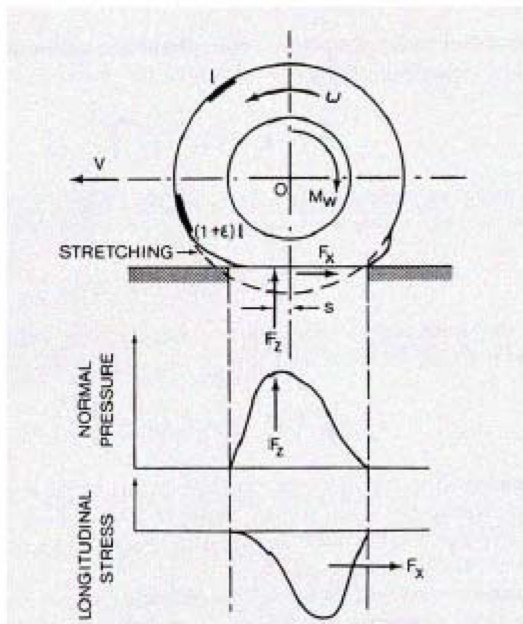

Figure 1.2: Behavior of tire under the action of brake torque

Due to stretching of the tire, a tractive force is developed by the tire proportional to the applied brake torque. This tractive force increases linearly with the applied torque within the elastic limit of the tire, corresponding to section OA of the curve as shown in Figure 1.3. Once the tire starts to slide on the ground, the tractive force becomes a nonlinear function of the slip, entering section AB of the curve. Further increase in the torque then causes an unstable condition wherein the tractive force drops off from the peak value (which occurs at a slip value of approximately 0.2 for most surfaces) to a much lower value when the tire locks up (i.e., at slip of 1.0). The unstable region is shown by section BC of the curve.

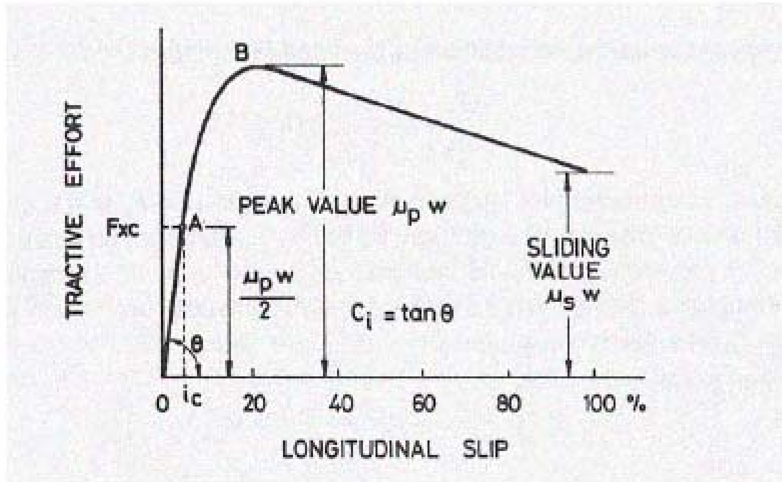

Figure 1.3: Variation of tractive effort with longitudinal slip

1.1.3 μ-λ curve

The relation between slip, vehicle velocity, and the coefficient of friction (μ) is complicated, nonlinear and changes with different road conditions, different vehicle speeds, and tire types. Figure 1.4 (Mirzaei, 2005) shows typical lateral and longitudinal coefficients of friction as a function of wheel slip. The lateral friction provides lateral stability, the ability to steer and control the direction of the vehicle. The lateral coefficient of friction is greatest at zero slip, decreases as wheel slip increases and settle at zero when the slip equals to 1. The longitudinal coefficient of friction (μ) on the other hand is zero at zero slip and as wheel slip increases; it increases to a point (peak value), then μ start to decrease as slip increases.

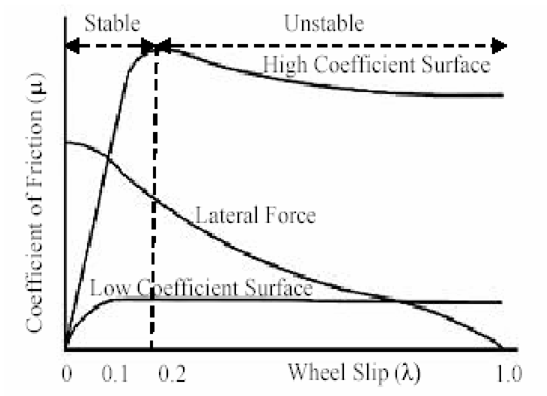

Figure 1.4: Coefficient of friction vs wheel slip

Open loop braking for the increasing part of the μ-λ curve is stable but is unstable for the decreasing part of the curve (Jiang, 2000). The brake torque, T_b caused the wheel velocity to decrease, thus it increase the wheel slip. The tire force from the road surface caused the wheel velocity to increase, thus it decrease the wheel slip. A high μ leads to a large tire force and a low μ leads to a small tire force. In the increasing part of the μ-λ curve, an increase of the wheel slip leads to a larger μ and larger tire force, which reverse the wheel slip to a small value. However, in the decreasing part of the μ-λ curve, an increase of the wheel slip leads to a smaller μ and smaller tire force which cause the wheel slip to increase continuously. Therefore, the peak point of the μ-λ curve is critical.

The position of the peak or maximum coefficient of friction varies for different road conditions, different vehicle speeds, and tire types as indicates in Figure 1.5. Thus, the optimum wheel slip value for maximum friction is also different. The optimal wheel slip ratio of the majority road surfaces is between 0.1 and 0.3 (Wang, *et al.,* 2003). Most of the control strategies define the performance goal in maintaining a wheel slip close to 0.2 throughout the braking trajectory (Baker, 1986). This represents a compromise between lateral stability, which is best at zero slip, and maximum deceleration, which usually appears when slip is between 0.1 and 0.3. Forcing the wheel slip ratio to track optimal slip ratios, which causes the maximal tire/road friction force, can minimize the vehicle stopping distance.

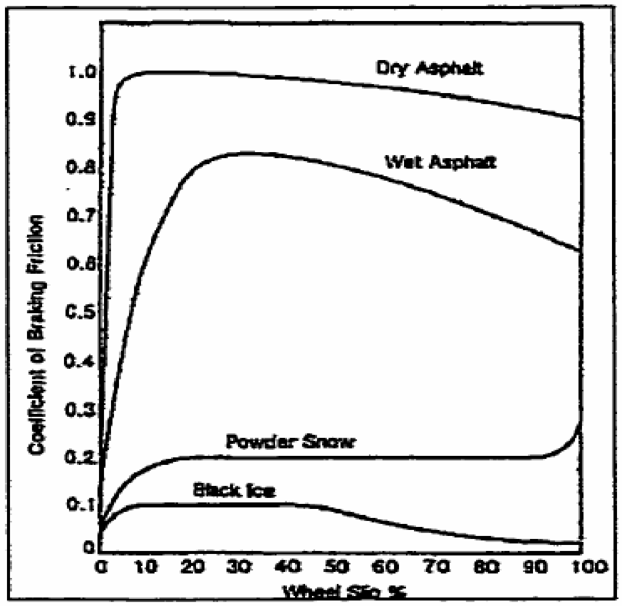

Figure 1.5: The μ-λ curve varies on different road surface

1.2 ABS control

Although in most cases, it is ideal for the ABS to work at the peak point of the μ-λ curve, this point however is open loop unstable as illustrated in Figure 1.4. Even when a fixed wheel slip value (from 0.1 to 0.3) is selected, cases still exist that this slip value is located in the unstable part of the μ-λ curve. Thus, the ABS has to be controlled in closed-loop arrangement to achieve good performance (Jiang, 2000).

The ABS system measures the vehicle variables such as the wheel velocity, the vehicle acceleration, the brake pressure and etc. The control algorithm then calculates the actual wheel slip, compares it with the desired value and determines the amount of brake torque to be applied based on the wheel slip error. The desired wheel slip is set accordingly for a different ABS systems. Some system set it as a fixed number while in some other system, it is determine by another high level control block which updates the desired wheel slip value continuously. As a result, various control algorithms has been proposed and utilized for the ABS control which maintains the wheel slip to a desired level.

Various researchers have focused on application of sliding mode control in ABS. The sliding mode control has good robustness and faster response speed, and it is insensitive to parameter change and disturbance. The main idea of sliding mode control is to restrict the system motion in a plane called the sliding surface, where a predefined function of error is zero (Jiang, 2000). However, there are two main problems associated with the sliding mode control which are the chatter during switching line sliding process and how to realize fast tracking in control process (Unsal and Kachroo, 1999).

Drakunov *et al.* (1995) developed an ABS control algorithm to find the optimal slip using friction force observer via the sliding modes. A simplified four wheel vehicle brake model without the lateral motion and model of the brake hydraulic system is considered in the designed. Two versions of the control algorithm with different levels of complexity related to the hydraulic system were developed. Unsal and Kacroo (1999) on the other hand, employ an overall system which consists of a quarter vehicle model, a nonlinear observer and slip ratio model. The nonlinear observer is used to estimate the vehicle velocity from the output and a sliding mode controller is used to maintain the slip at a given value. Buckholtz (2002), also present a sliding mode controller for tracking the reference wheel slip. However, the control is developed based on four-wheel vehicle and taking into account the vehicle lateral dynamics. In addition, the information on the wheel speed, vehicle acceleration, yaw rate and tire is assumed available. Chikhi *et al.* (2005) proposed an adaptive sliding mode control for optimal ABS system. The strategy of control is based on the generation of the wheel slip control reference. A sliding mode observer is used to estimate the friction coefficient. Schinkel and Hunt (2002) employ the sliding mode like approach for the ABS controller. The nonlinear dynamics of the vehicle wheel system is assessed by using two uncertain linear systems.

Since the ABS system is nonlinear and dynamic in nature, hence it is candidates for the intelligent control such as Fuzzy Logic Control (FLC), Artificial Neural Network (ANN), Genetic Algorithm (GA) and etc. Wang et al. (2003) has designed the ABS Control using Output feedback Direct Adaptive Neural Fuzzy Control. Half vehicle brake model and hydraulic brake system model is incorporated in the study. The main control strategy is to force the wheel slip ratio to track an inconstant optimal slip ratio, whose value varies with the environment and assumed to be known during the vehicle-stopping period. An observer is adopted to estimate the system states from the measurable system output. Lee and Zak (2001) considered a vehicle-free body diagram for straight line braking maneuver. The ABS controller is designed using genetic neural fuzzy control. This consists of a neural optimizer to find the optimal wheel slip and a fuzzy component to compute the brake torque needed to track the optimal slip. Genetic algorithm is used to tune the fuzzy logic component. Mauer (1995) designed a fuzzy logic ABS controller which is able to identify the road surface condition. The braking command is based on the current and past reading of the wheel slip and the brake pressure.

Armeni and Mosca (2003) has developed the wheel slip controller based on minimum energy control law with constraint. The study is based on the dynamic model of a quarter vehicle. The relationship between the friction and slip, $\mu(\lambda)$ is represented by the Pacejka's magic formula ($\mu(\lambda) = D\sin\left(C\arctan(B\lambda - E(B\lambda - \arctan)))\right)$). The control algorithm to implement the ABS controller is using gain scheduled based on longitudinal vehicle velocity. Liu and Sun (1995) on the other hand proposed a gain scheduling for optimal target slip tracking. The controller regulates the target slip to the respective optimal values at different vehicle speed. A quarter vehicle model taking into consideration the drag force and Pacejka's tire model is used. Johansen *et al.* (2003) also used the gain scheduling approach in designing the ABS controller. Although a quarter car model is use in modeling, the validation is carried out experimentally. The vehicle speed is view as a slow time-varying parameter and the model is linearized about the nominal wheel slip. The gain matrices for the different operating condition are designed using LQR approach.

1.2.1 Summary of Existing Control Methods and Antilock Braking Models

Various control strategies have been proposed to control the antilock braking system for either quarter vehicle model, half vehicle model or a complete vehicle model. These control strategies may be loosely group into nonlinear control and intelligent control. Intelligent control techniques although have shown satisfactory result for the antilock braking control, may have potential problem on stability. Usually, the discussion on stability is ignored in the design (Sam, 2004).

The ABS dynamic which exhibit strong nonlinear characteristic requires robust control. This makes the sliding mode control a suitable control approach due to its robustness and faster response speed, and it is insensitive to parameter change and disturbance. Literature review on the application of sliding mode control for the antilock braking control also shows satisfactory result.

A dynamic model of the vehicle is then needed to provide the necessary guidelines for the controller design. The model should describe the essential dynamics of the system during braking maneuver.

1.3 Research Objectives

The objectives of this project are:

i) To establish the mathematical model of the ABS in a state space representation.

ii) To design and develop the control algorithm based on Sliding Mode Control for the vehicle wheel system and Bang-bang Control as a comparison

iii) To evaluate and compare the ABS performances using both control strategies.

1.4 Scope of Project

The scope of work for this project includes:

i) Modeling of a vehicle wheel system (Quarter vehicle model) in a straight line braking process with zero steering wheel input.

ii) Modeling of hydraulic brake dynamics.

iii) Sliding Mode Controller and its application to the plant in controlling the output slip, thus providing shorter stopping distance.

iv) Bang-bang Controller which is use as a comparison in analyzing the performance of the controller in part (iii)

v) Simulation study conducted in MATLAB-Simulink on the slip, vehicle speed, wheel speed and stopping distance profile.

1.5 Research Methodology

The research work is undertaken in the following stages:

1) Development of the mathematical model of the antilock braking system in state space. The steps taken in this stage are:

    i) Literature review on the vehicle wheel system mathematical model.
    ii) Literature review on the hydraulic brake system dynamics
    iii) Develop the state space representation of the ABS system

2) Application of the Sliding Mode Controller to the ABS system. The steps taken in this stage are:

    i) Literature review on the existing control technique of the ABS system
    ii) Literature review on the existing robust control technique based on Sliding Mode Control algorithm
    iii) Implement the SMC technique to the ABS system. The procedures performed in this stage are:
        i. Definition of a sliding surface
        ii. Determination of the system dynamics during Sliding Mode
        iii. Establishment of the final control law

3) Simulation of the proposed controller in MATLAB Simulink.

4) Comparison of the performance of Sliding Mode Control and Bang-bang Control.

5) Analysis of the simulation results.

1.6 Structure and Layout of Thesis

This thesis is organized into six chapters. Chapter 1 gives the background and overview of ABS control. It also defines the objectives, scope of work and the approach that is followed to meet the objectives. Chapter 2 deals with the formulation of the mathematical modeling of the antilock braking systems. This chapter describes the dynamics of the vehicle-wheel system for a quarter vehicle model as well as the hydraulic brake system dynamics. Based on the dynamic models, the state space representation of the quarter vehicle model will be derived.

In Chapter 3, the sliding mode control theory for nonlinear system is presented. The design requirement of the sliding mode control will be discussed. Chapter 4 presents the control strategy for the antilock braking system based on the sliding mode control approach. A systematic approach and basic assumptions taken while establishing the control law are outlined in this chapter. For the sliding mode controller, Lyapunov stability method is applied to keep the nonlinear system under control.

Chapter 5 discusses the performance evaluation of the proposed sliding mode controller by means of computer simulation in MATLAB-SIMULINK. The Bang–bang control is used as a mean of comparison. The performances of both types of controller in terms of velocity, slip and distance profile as well as percent reduction in stopping distance is evaluated and compared. Conclusion on the effectiveness of the approach are made and discussed based on the results obtained in this chapter.

The thesis ends with Chapter 6, where the summary of the results and future research based on this study will be presented.