A SLIDING MODE ANTI-LOCK BRAKING CONTROLLER FOR A VEHICLE WITH ELECTRIC MOTOR BRAKING

A Thesis

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by

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Abstract

Anti-Lock Brake Systems are used by most modern vehicles during aggressive braking maneuvers to prevent excessive slippage between the tires of the vehicle and the road. These systems allow the operator to maintain control of the vehicle as well as decreasing the stopping distance.

In this thesis, the sliding mode controller will be investigated as a potential solution to this control problem.

This thesis aims to create such a system for a sub-scale electric vehicle, for which the only method of braking is to use the electric motor on each wheel to provide braking torque.

No table of figures entries found.

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[1 Introduction 6](#_Toc23602374)

[1.1 Background 6](#_Toc23602375)

[1.2 Problem Description 6](#_Toc23602376)

[1.2.1 6](#_Toc23602377)

[1.2.2 Simulated Procedure 6](#_Toc23602378)

[2 Literature Review 7](#_Toc23602379)

[2.1 Vehicle Modeling 7](#_Toc23602380)

[2.2 Anti-Lock Braking Systems 7](#_Toc23602381)

[2.3 Sliding Mode Controllers 7](#_Toc23602382)

[2.4 State Estimation with Kalman Filters 7](#_Toc23602383)

[3 Vehicle Longitudinal Model 8](#_Toc23602384)

[3.1 Longitudinal Bicycle Model 8](#_Toc23602385)

[3.2 Tire Model 8](#_Toc23602386)

[3.3 Vehicle Parameters 8](#_Toc23602387)

[3.4 Simulation Setup 8](#_Toc23602388)

[4 State Estimation with a Modified Kalman Filter 9](#_Toc23602389)

[4.1 Modification of traditional Kalman Filter, non-conventional inputs 9](#_Toc23602390)

[4.2 Longitudinal and Tire State Spaces 9](#_Toc23602391)

[5 ABS Sliding Mode Controller 10](#_Toc23602392)

[5.1 Anti-Lock Braking Systems 10](#_Toc23602393)

[5.2 Sliding Mode Control 10](#_Toc23602394)

[5.3 Controller Switching 10](#_Toc23602395)

[5.4 Comparison of Results 10](#_Toc23602396)

[6 Model Brakedown 11](#_Toc23602397)

[6.1 Vehicle Parameters 11](#_Toc23602398)

[6.2 Function Files 11](#_Toc23602399)

[6.3 Simulink 11](#_Toc23602400)

[7 Theory 12](#_Toc23602401)

[7.1 Plant Model 12](#_Toc23602402)

[7.1.1 Overall Vehicle Dynamics 12](#_Toc23602403)

[7.1.2 Wheel Dynamics 12](#_Toc23602404)

[7.1.3 Slip Dynamics 13](#_Toc23602405)

[7.2 State Estimation with Modified Kalman Filters 13](#_Toc23602406)

[7.2.1 Simulating Real Measurements, Noise Generation 14](#_Toc23602407)

[7.2.2 State Estimation 14](#_Toc23602408)

[7.3 The Sliding Mode ABS Controller 15](#_Toc23602409)

[7.3.1 Why Sliding Mode Control? 15](#_Toc23602410)

[7.3.2 The Controller 15](#_Toc23602411)

# Introduction

## Background

Safety…

ABS…

State Estimation…?

The vehicle…??

## Problem Description

The ultimate goal of this thesis is to develop and test the validity of a sliding mode controller for an anti-lock braking system. To do this, a vehicle longitudinal model will be developed which mimics a vehicle. An Anti-Lock braking system and a state estimator will be developed to robustly control the vehicle using measurements from onboard sensors. The system will be tested in simulation (and physically???) and compared with a non-ABS braking procedure.

### 

### Simulated Procedure

To simulate an aggressive braking maneuver, the vehicle will first accelerate to 20 m/s, then at a simulation time of 5 seconds, the vehicle will begin braking (either by ABS or standard max braking).

# Literature Review

## Vehicle Modeling

One of the components necessary to create a controller is an accurate model of the vehicle. In this case a mathematical model which matches the dynamics of the vehicle must be obtained.

Chunyun Fu, in his thesis on direct yaw moment control (citation), derives a model for the dynamics of the vehicle including yaw rate and steering angle. For this project …

## Anti-Lock Braking Systems

## Sliding Mode Controllers

## State Estimation with Kalman Filters

# Vehicle Longitudinal Model

## Longitudinal Bicycle Model

## Tire Model

## Vehicle Parameters

## Simulation Setup

# State Estimation with a Modified Kalman Filter

## Modification of traditional Kalman Filter, non-conventional inputs

## Longitudinal and Tire State Spaces

# ABS Sliding Mode Controller

## Anti-Lock Braking Systems

## Sliding Mode Control

## Controller Switching

## Comparison of Results

# Model Brakedown

## Vehicle Parameters

## Function Files

## Simulink

# Theory

This section describes the theory used to create the simulation.

## Plant Model

This section describes the vehicle dynamics model with inputs of torque at each wheel and measurement outputs of wheel angular velocity and vehicle longitudinal acceleration. Other outputs used for validation include vehicle speed, wheel slip rate, and motor output torque.

The dynamic model contains three major components: the longitudinal and pitch dynamics of the vehicle as a whole, the dynamics of the wheels, and the slip dynamics between the wheels and the road surface.

### Overall Vehicle Dynamics

To start I made some simplifying assumptions. First, that the vehicle will not turn, allowing the steering angle to always be 0. Second, I chose to neglect sideslip on the wheels as the vehicle is not turning. These assumptions together allow us to neglect any dynamics in the yaw direction. With these assumptions, the overall longitudinal dynamics of the vehicle become quite simple. For this we look at the forces acting on the body of the vehicle from the road surface.

|  |  |  |
| --- | --- | --- |
|  |  | (C.2) |

Where is the longitudinal acceleration of the vehicle, is the total mass of the vehicle, and is the force on each tire from the ground in the longitudinal direction.

The pitch dynamics are slightly more complicated, but they should not be neglected as the normal force, and thus maximum braking force, is much different between the front and rear wheels during a braking procedure. To model the pitch motion, I used the pitch model from…

### Wheel Dynamics

To model the wheel dynamics, I used a state space representation of the motor/wheel system. Since there were no yaw dynamics the dynamics of a wheel were only determined by whether the wheel was in the front or rear. The input to this each state space was a vector containing the longitudinal force from the ground, , and the voltage command from a controller external to the plant model, . The state vector contained the angular velocity of the wheel, , and the motor current, . The output of the state space is the angular velocity, . The state update function looks as so:

|  |  |  |
| --- | --- | --- |
|  |  | (C.2) |

Where is the damping factor representing rolling resistance on the wheel, is the motor constant for the electric motor on each wheel, is the resistance inherent to the motor, is the rotation inertia of the motor and wheel, is the wheel radius, is the inductance inherent to the motor, and is the voltage input to the motor.

### Slip Dynamics

The slip dynamics were modeled using Pajelka’s Magic Formula (). The first building block of this modeling method is the quantity, slip rate. For a vehicle undergoing deceleration, It is defined as such:

|  |  |  |
| --- | --- | --- |
|  |  | (C.2) |

Where is the slip rate of the I’th wheel, is the angular velocity of the I’th wheel, R is the tire radius, and is the longitudinal velocity of the wheel. The second piece is the magic formula itself, which relates friction coefficient, μ, to the slip rate, λ, for a given road surface. The variation of the magic formula that I used takes the following form:

|  |  |  |
| --- | --- | --- |
|  |  | (C.2) |

Where B, C, D, and E are coefficients based on the road surface as defined by the following table:

Table \_\_. Pacejka tyre model constants.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Dry | Wet | Snow | Icy |
| B (stiffness) | 10 | 12 | 5 | 4 |
| C (shape) | 1.9 | 2.3 | 2.0 | 2.0 |
| D (peak) | 1.0 | 0.82 | 0.3 | 0.1 |
| E (curvature) | 0.97 | 1.0 | 1.0 | 1.0 |

Do I want an example plot of µ vs. ? For the road condition I’m using?

The final component of this model is the relationship between the force from the ground on each tire, , and the friction coefficient, . For this, a normal force, , on each wheel is calculated based on the pitch model used above. Then the friction force is calculated as such:

|  |  |  |
| --- | --- | --- |
|  |  | (C.2) |

## State Estimation with Modified Kalman Filters

This section describes the state estimation model with inputs of longitudinal acceleration, wheel angular velocity, and the controlled input, motor voltage. Since the input signals come from a simulated plant rather than real measurements from a vehicle, I added noise to these measurements and sampled them discreetly rather than continuously. The state estimator outputs an estimation for vehicle longitudinal speed and wheel angular velocity for use in the ABS controller.

### Simulating Real Measurements, Noise Generation

To simulate real measurements, noise must be added to the plant model outputs. To make these signals representative of actual measurements, I modulated the power and frequency of additive noise on each of the signals until the noise level matched that of some real-world data taken from experiments.

Figure \_\_. Comparison of noise in simulated data with added noise vs. experimental data.

To further simulate real world data, the signals must be sampled discreetly rather than continuously. The maximum sampling rate is determined by the rate at which the signals can be transferred to Simulink. This has been shown to be approximately 10ms based on the maximum computation time of a model step, so the continuous data is sampled at this rate.

### State Estimation

The first step in the state estimation process is to estimate the longitudinal force on each wheel. For this I used the same slip dynamics formulas from the previous section, with the simplification that the normal force was the same on each wheel (no pitch dynamics). Since the Kalman filters will use real world measurements as well as this simplified plant model, this simplification will not significantly change the results of the estimation.

The second step was to split the estimation into two separate Kalman filters. The first was to estimate the longitudinal dynamics, or vehicle speed, and the second was to estimate the angular velocity of each wheel. For the longitudinal estimator the measurement input was the measured longitudinal acceleration , and the controlled input was the sum of the forces on a front and a rear tire . The state space equation for this estimator is as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (C.2) |

The output of this filter is an estimation for vehicle acceleration, , which is then integrated to produce an estimated vehicle velocity, .

The second filter was to estimate wheel angular velocities. Since the yaw motion of the vehicle is neglected in this model, there will be no difference between the right and left wheel for a given axle. Because of this, the state vector for this filter contains the angular velocity of a wheel and the current applied to a motor on each axle. The measurement input for this filter is the measured angular velocity at each wheel. The controlled input for this filter consists of the force on that wheel from the ground as well as the voltage input for each motor. The state space equation for this estimator is as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (C.2) |

The output of this filter is an estimation for the angular velocity at each wheel as well as the current at each motor (though these currents are not used).

Other LQR parameters common to the two filters…

## The Sliding Mode ABS Controller

This section describes the sliding mode ABS controller used to control the vehicle during deceleration. The inputs are the vehicle velocity, and the angular velocity of each wheel. The output is a Voltage to be applied at each motor. There are two goals during an ABS event. The first is to decelerate the vehicle as quickly as possible. The second is to maintain a slip rate for which the vehicle is controllable. Based on the Pajelka tire curve, the optimum slip rate for deceleration is 0.1. This value is below the \_\_\_ slip rate for which control is lost (as defined by \_\_\_) so both goals are satisfied if this slip rate can be maintained.

### Why Sliding Mode Control?

### The Controller

The first step in the process was to generate slip rates for each tire based on the estimates of the current state from the Kalman filter. The same slip rate formula that was used in the plant model was used for this. The next step was to filter this signal to create a less erratic controller response. This was done with a low-pass filter with a time constant of 0.05s.

Figure \_\_. Comparison of unfiltered vs filtered estimated slip rates.

From this point, an error could be calculated between the estimated slip rate and the desired slip rate of -0.1. This error is then fed into a pd controller with a proportional gain of 10 and a derivative gain of 1. Since the magnitude of the error is always less than 0.1 a gain of 12 is applied to generate a control signal that will have significant effects. Finally, this signal is applied to a saturator so that it never exceeds the physical limits of the system (+24V to -24V).

## Controller Switching Logic

One problem that comes up when trying to control the vehicle with a sliding mode controller is that the slip rate calculation becomes increasingly unstable around the point of zero velocity. To solve this issue, A maximum braking torque controller was used for speeds less than 3 m/s.

Figure \_\_. Instability of SMC at low speeds

This controller simply applies maximum braking torque at each motor to bring the vehicle to a complete stop.