MODELLING AND CLAMPING FORCE CONTROL OF ELECTRONIC WEDGE BRAKE

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DECLARATION

I declared that this project entitled "Modelling and Clamping Force Control of Electronic Wedge Brake" is the result of my own work except as cited in the references.

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APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :
Supervisor's Name :
Date :

DEDICATION

This report is dedicated to my beloved parents, family members and friends who have been with me and also who loves me in every situation I am facing throughout my bachelor's program.

ABSTRACT

This thesis presents an investigation the performance of fixed caliper based electronic wedge brake (FIXEWB) in vehicle braking system. Two techniques were used as an assessment method, which are simulation via Matlab Simulink software and experimental study through hardware-in-the-loop-simulation (HILS). In the simulation study, the vehicle braking system was simulated by using a validated quarter vehicle traction model with a validated FIXEWB model as the brake actuator. Proportional-integral-derivative was utilized as the brake torque control, whereas proportional-integral and proportional controllers were used as the position and speed control of the actuator respectively. To study the effectiveness of the FIXEWB, the response of the vehicle using FIXEWB is compared with the responses of the vehicle using conventional hydraulic brake. A dynamic test namely sudden braking at constants speed was then used as the testing method. The simulation results show that the usage of FIXEWB with an appropriate control strategy produces similar behavior as hydraulic brake in terms of the produced desired braking torque but with faster the time response. To study the performance of FIXEWB when implement on a real vehicle, an experimental rig using HILS was designed and the results are analyzed using the same dynamic tests. The performances evaluated are vehicle body speed, wheel speed, tire longitudinal slip, and the stopping distance experience by the vehicle. An antilock braking system control strategy namely adaptive fuzzy fractional gain PID (AFFPID) with active learning rate (ALR) controller was than developed. In presented scheme the result verifies improved performance of the proposed control structure during braking maneuvers compared to the passive braking system. It is also noted that the additional active learning rate to the controller is able to further improve the performance of the adaptive fuzzy for the system. The effectiveness of the proposed control algorithm on a real vehicle was also observed through hardware-in-the-loop simulation. Finally, potential benefits in the use of this control and the FIXEWB are investigated. The result of the study demonstrates the potential benefits of the AFFPID with ALR controller as the ABS control system and the capability of the FIXEWB as the brake actuator.

ABSTRAK

Tesis ini menunjukkan penyelidikan mengenai prestasi brek elektronik berasaskan kaliper tetap (FIXEWB) dalam sistem brek kenderaan. Dua teknik digunakan sebagai kaedah penilaian, yaitu simulasi melalui perisian Matlab Simulink dan kajian eksperimental melalui hardware-in-the-loop-simulation (HILS). Dalam kajian simulasi, sistem pengereman kenderaan disimulasikan dengan menggunakan model daya tarikan kenderaan seperempat yang disahkan dengan model FIXEWB yang disahkan sebagai penggerak brek. Untuk mengkaji keberkesanan FIXEWB, tindak balas kenderaan yang menggunakan FIXEWB dibandingkan dengan tindak balas kenderaan menggunakan brek hidraulik konvensional. Ujian dinamik iaitu pengereman secara tiba-tiba pada kelajuan pemalar kemudian digunakan sebagai kaedah ujian. Hasil simulasi menunjukkan bahawa penggunaan FIXEWB dengan strategi kawalan yang sesuai menghasilkan tingkah laku yang serupa dengan brek hidraulik dari segi daya kilas brek yang diinginkan tetapi dengan tindak balas masa yang lebih cepat. Untuk mengkaji prestasi FIXEWB ketika diimplementasikan pada kendaraan nyata, rig eksperimen menggunakan HILS dirancang dan hasilnya dianalisis menggunakan ujian dinamis yang sama. Persembahan yang dinilai adalah kelajuan badan kenderaan, kelajuan roda, slip longitudinal tayar, dan pengalaman jarak berhenti oleh kenderaan. Strategi kawalan sistem brek antilock iaitu PID gain adaptif kabur (AFFPID) dengan pengawal kadar pembelajaran aktif (ALR) adalah lebih baik daripada yang dikembangkan. Dalam skema yang disajikan hasilnya memverifikasi peningkatan prestasi struktur kontrol yang dicadangkan selama manuver pengereman dibandingkan dengan sistem pengereman pasif. Juga diperhatikan bahawa kadar pembelajaran aktif tambahan kepada pengawal dapat meningkatkan lagi prestasi kabur adaptif untuk sistem. Keberkesanan algoritma kawalan yang dicadangkan pada kenderaan sebenar juga diperhatikan melalui simulasi perkakasan-dalam-gelung. Akhirnya, kemungkinan faedah dalam penggunaan kawalan ini dan FIXEWB disiasat. Hasil kajian menunjukkan potensi keuntungan AFFPID dengan pengawal ALR sebagai sistem kawalan ABS dan kemampuan FIXEWB sebagai penggerak brek.

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LIST OF SYMBOLS

m	-	Vehicle mass
$\dot{v}$	-	Longitudinal acceleration
v	-	Longitudinal velocity
F_x	-	Longitudinal force
J	-	Wheel moment inertia
$\dot{\omega}$	-	Wheel angular acceleration
ω	-	Wheel angular velocity
τ_a	-	Throttle torque
τ_b	-	Brake torque
R_w	-	Wheel radius
μ	-	Coefficient of friction
g	-	Gravitational acceleration
λ	-	Longitudinal slip
λ_{des}	-	Longitudinal slip desired
λ_{act}	-	Longitudinal slip actual
P_b	-	Brake pressure
K_c	-	Pressure gain
u_b	-	Brake setting
τ_{bs}	-	Brake lag
μ_p	-	Pad coefficient of friction
F_m	-	Motor force
F_c	-	Clamping force
α_w	-	Wedge angle
R_{eff}	-	Wheel effective radius

F_n	-	Normal force
V	-	Voltage
I	-	Current
R	-	Resistor
L	-	Inductance
E	-	Electromagnetic force
J_m	-	Rotor inertia
B	-	Damper constant
T_e	-	Reaction torque
$PI^{\lambda}D^{\mu}$	-	Fractional order
k_p	-	Proportional gain
k_i	-	Integral gain
k_d	-	Derivative gain
e	-	Control error
u	-	Controller output
α	-	Nonlinear integer for proportional gain
β	-	Nonlinear integer for integral gain
γ	-	Nonlinear integer for derivative gain
Δv	-	Relative velocity between body and wheel
μ_{ij}	-	Output Membership Function
x_j^i	-	Input to Fuzzy Network
b_i	-	Fuzzy rule
c_j^i	-	Centre of Gaussian Antecedent Membership Function
σ_j^i	-	Spread of Gaussian Antecedent Membership Function
$f(x\|\theta)$	-	Fuzzy Logic System Output
e_m	-	Error
λ_1	-	Learning Rate for Updating Parameterb_i
λ_2	-	Learning Rate for Updating Parameterc_j^i
λ_3	-	Learning Rate for Updatingσ_j^i
y^m	-	Desired Output

LIST OF ABBREVIATIONS

IBS	-	Intelligent Braking System
EMB	-	Electromechanical Brake
EHB	-	Electrohydraulic Brake
EPB	-	Electro-pneumatic Brake
EWB	-	Electronic Wedge Brake
ABS	-	Antilock Braking System
ESP	-	Electronic Stability Program
EPB	-	Electronic Parking Brake
EBD	-	Electronic Brake Distribution
FIXEWB	-	Fixed Calliper Based Electronic Wedge Brake
PID	-	Proportional integral derivative
DOF	-	Degree of Freedom
DAS	-	Data Acquisition system
DC	-	Direct Current
NI	-	National Instrument
BLDC	-	Brush less Direct Current
ECU	-	Electric Control Unit
AI	-	Artificial Intelligent
FLC	-	Fuzzy Logic Control
IMC	-	Integrated Measurement Control
MCU	-	Microcontroller unit
KVL	-	Kichoff Voltage Law
P	-	Proportional
RMS	-	Root Mean Square

FOPID	-	Fractional Order Proportional Integral Derivative
FPID	-	Fractional Gain Proportional Integral Derivative
CHR	-	Chien-Hrones-Reswick
Z-N	-	Ziegler-Nichols
FFPID	-	Fuzzy Fractional Gain Proportional Integral Derivative
AFFPID	-	Adaptive Fuzzy Fractional Gain PID
ALR	-	Active Learning Rate
AFC	-	Adaptive Fuzzy Control

CHAPTER 1

INTRODUCTION

1.1 Overview

The traffic jam present has led to the necessity for driver assistance systems, not only to monitor the present traffic situation, but exactly to help the driver during driving and in emergency situations. This autonomous intervention in vehicle dynamics will be increasingly help keep the vehicle under control, even in difficult operating conditions. One of the foundations of the driver assistance is an intelligent braking system (IBS) that has a faster in responses, reliable and energy efficient.

Toward this IBS, several braking systems have been invented such as an electronic wedge brake (EWB) (Abd. Rahmanet al., 2013), electro-hydraulic brake (EHB) (Milanes et al., 2010; Farshizadehet al., 2015), electro-pneumatic brake (EPB) (Bauer and Fleischhacker, 2015) and electromechanical brake (EMB) (Kim et al., 2014; Haggag and Abidou, 2013). Among them, according to Ho et al. (2006) EWB is the perfect platform and the effective way to be used as the IBS because of the ability that can provide a higher braking torque and quicker response by using the standard 12V power supply system.

The EWB is a self-reinforcing electromechanical brake system that uses the so-called ‘wedge principle’ and to clamps brake pads with a friction lining to a brake disc. The exploration of the EWB generally is initiated by the advancement in the safety standards requirement which emphasizes on the active safety system in a vehicle particularly in braking system (Hartmann et al., 2002).This system is a relatively young technology of the automobile whose primary goal is to avoid accidents and at the same time facilitating better vehicle controllability and stability, especially in emergency situations.

In certain cases, as a result of environmental or vehicle conditions, or the driver’s actions, the car may end up in an unsafe state, with the driver’s ability to control the vehicle curtailed. Thus active systems correct such situations by automatically applying differential braking and cutting engine torque (and in the near future, correction of wheel turn) (Hartmann et al., 2002).The active safety system requires a fast response actuator to interact efficiently with the critical situations.

However, it has been impossible to meet these requirements with conventional braking systems. Even though it has been continuously upgraded by adding hydraulic pumps or magnetic valves. Due to the characteristics that are highly non-linear two-step controls, the possibility of achieving high control quality regarding the braking pressure is also rather limited. Furthermore the hydraulic brake system that requires significant amount of energy to function, leakage in the hydraulic line and vaporization of hydraulic fluid at high temperature are also major problems that degraded the functionality of the system (Aparow et al., 2014).

1.2 Background of Study

Today in the automotive industries, there is a strong trend towards ‘power-by-wire’ technologies with the aimed at replacing hydraulic or pneumatic systems by using the EMB. However the EMB designs which uses a motor through a gearbox, required actuation power that corresponds to the required clamping force to halting a wheel (Schwarz et al., 1998; Day, 2014).

As for mid-size vehicle, a 42kN (for a front wheel) and a 20kN (for a rear wheel) clamping forces are required, meaning that, at least 42V power supply is needed to stopping a vehicle (Kim et al., 2009). Indirectly, it is seen in contravention to the existing power supply capacity on existing vehicles that just have a 12V power supply only. Concurrent with the extensive investigation of the EMB, researchers started to search for other techniques to take advantage of EMB to achieve higher clamping forces with standard 12V power supply.

Therefore, the EMB based wedge mechanism later known as EWB is appeared to be one of the most interesting modes to be investigated. The exploration of the mechatronic wedge brake was firstly started by German Aerospace Centre (eStop®-GMBH) with proposing a simple and efficient mechatronic wedge brake namely eBrake® (Hartmann et al., 2002). The wedge mechanism designated EWB can produce compressive and higher clamping force and this have generated new interest in this approach (Abd. Rahmadet al., 2013).

The actuator of earlier EWB is a double motor system. Under the synergy of the double motor system, the wedge block is moved along tangential direction through ball screw, and the extrusion between wedge block and rollers makes positive axial pressure, in hence the brake works. Then later a new prototype generation with only one motor is designed (Fox et al., 2007). The structure of EWB is complex and it is hard to fix such double motors in the wheel.

Meanwhile, it is extremely necessary to take into account the high-cost and reliability of double motors. Emamet al. (2012) also designed an electronic wedge brake and the performance of its prototype is simulated and compared between different structures and control parameters. The results showed that the lower wedge mass, the bigger calliper stiffness and reasonable control are better for braking force and operation response. Mando Corporation designed a new electronic wedge brakes that have the feature of cross-wedge with optimized volume and use no roller due to its weakness.

Besides the main braking function, the electro wedge brake implements various additional functions, such as a function for maintaining a set clearance of a pad, a Fail-Safe function, and an EPB function, by using a solenoid mechanism interlocked with a main braking motor (Jongsung, 2011). In year 2013, there are two innovation of electronic wedge brake have been reported. The results show that it can generate the same braking force only at nearly one third multiple hydraulic pressure of conventional disc brake.

From the above discussion, even though extensive research on the EWB have been made, it is clear to say that a details study of the EWB in vehicle braking usage is still not complete. The capability of the EWB in breaking a vehicle, even though in active braking system is still limited up to simulation only. So, a new design of EWB that capable to provide a reasonable torque for a high speed dynamic vehicle is essential to be developed and understand. Therefore, a systematic and thorough further study of EWB based fixed calliper needs to be conducted.

1.3 Problem Statement

From the explanations in the background of study, it can be observed that the research on EWB has significant impact to the advancement in automotive technology. Even that so, through the studies of the system are still lacking and have some limitations that require to be solved. The lacking of the studies in EWB is listed as follows:

a. Within the existing EWB designs, the wedge mechanism is stuck at the abutment, due to the wedge‘s shape isn't properly optimized.
b. The validation results of the EWB model between simulation and experiment produce high percentage of disparities.
c. Problem in implementing the EWB within the real vehicle system thanks to several questions of safety.

1.4 Objective and Scope of Study

The main objectives of this study are to investigate the effectiveness of electronic wedge brake for a vehicle braking system as well as to improving the active braking in vehicle dynamics performance, particularly as it pertains to passenger vehicles; to evaluate, both analytically and experimentally, the electronic wedge brake control strategy that utilizing PID controller; to study the potential benefits in the use of adaptive fuzzy fractional gain PID with active learning rate controller in antilock braking control system and to assess the control policies that can provide improved antilock braking performance through quarter car braking and full car braking.

The scopes of this study are defined as the followings:

1. Design and development of an electronic wedge brake based fixed calliper.
2. A second order transfer function is used to model the proposed electronic wedge brake system.
3. The vehicle parameters for quarter car model are selected to represent the parameters of a class of passenger vehicle of Malaysian National car.
4. Only antilock braking system analysis is performed in this study, and another active braking system such as EBD and automatic braking system is ignored.
5. The performance of the controller is investigated on the capability to provide stability during braking as well as the ability to reduce the stopping distance during deceleration and the effect of weight transfer during braking is neglected.

The experimental investigation on the performance of normal braking and antilock braking system based electronic wedge brake just reach at the hardware in the loop simulation only.

1.5 Methodology

The research methodology implemented in this study is described as the following steps of works:

1. Design and development of EWB

   The study begins on designing and development of electronic wedge brake (EWB) system. The design of EWB is based on fixed calliper and was equipped with a DC motor as the actuator. Experimental works for investigating the behaviour of the EWB for different displacement of DC motor's rotor to the clamping force at the brake pad were conducted. The mathematical model then, was constructed based on the experimental data. As the accuracy of the EWB model plays an important role in designing a braking control, extensive validation tests were carried out with an EWB test rig.

2. Modelling of EWB model.

   This study was continued with the modelling and development of an accurate vehicle dynamic model to describe analytically the dynamic behaviour of a vehicle in longitudinal direction. The model that include hydraulic brake subsystem are then validated experimentally using an instrumented experimental vehicle. Several dynamic braking tests were conducted, which are sudden braking test at low speed and medium speed. The behaviours of the vehicle models were then verified with the behaviour of the instrumented experimental vehicle under the same input brake and vehicle speed.

3. Clamping force of EWB

   Study on the effectiveness of the EWB along with the control strategies for vehicle braking system was also been investigated. The main activity in this stage is to assess the capability of the EWB in braking of a vehicle. Several tests were examined for quarter car braking such as sudden braking tests at low speed, medium speed and high speed of a vehicle. After that, the study was continued on investigating the benefits of the same EWB on a full vehicle mode. Then, performance of the EWB braking system was evaluated by comparing the character of vehicle using EWB and vehicle using hydraulic brake.

4. Experimental study and validation of EWB model using EWB test rig

   As the capability of EWB in usage as the braking system has been established, this study proceeds with the experiment on the model that was designed by simulation of antilock braking system (ABS). Performance evaluation of the control strategies were characterized by the ability of the control strategies to halt a vehicle in shortest period of time and the shortest stopping distance as well as their consistency in providing the optimum target slip. The optimum controller then was also been implemented on the full vehicle model to examine the efficiency of the controller in full vehicle braking system.

5. Performance of EWB analysis using HILS

   The final stage in this study was the experimental investigation of effectiveness of the EWB through hardware in the loop simulation. All the simulation studies in normal braking and ABS were then evaluated experimentally and compared with the simulation results. It should be noted that all numerical computations, computer simulations and HILS were conducted using the MATLAB SIMULINK programming software version R2009B developed by the Math Works Inc.

1.6 Thesis Organization

This thesis is organized in seven chapters. A brief and comprehensive overview of the main points of the research process is shown in Figure 1.1. The thesis contains an introductory chapter which gives a brief introduction on EWB and its capabilities as new coming of automotive braking system. This chapter presents about previous research findings leading to the objectives of this study. Each chapter in this thesis