MODELLING AND CONTROL OF AN ELECTRO-MECHANICAL DRUM PARKING BRAKE SYSTEM FOR VEHICLE ROLLAWAY PREVENTION

AHMAD HUMAIZI BIN ROZAINI

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Faculty of Engineering
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Dedicated to:

My beloved parents:
Hj Rozaini Bin Hj Jasmin
Hjh Rosnah Bin Hj Abd Hamid

My beloved parent in law:
Hj Amir Husain Bin Daud
Faridah Binti Syed Abdul Rahman

My lovely wife:
Fatahna Binti Amir Husain

My beloved son and daughter:
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Nur Atikah Binti Ahmad Humaizi

My sisters
Nurulaini Binti Rozaini, Nurulaidah Binti Rozaini,
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ABSTRACT

The main function of parking brake system is to hold the vehicle stationary on flat or sloped roads. A fully mechanical parking brake (MPB) system seems to have a few drawbacks and rollaway is one of them. A vehicle rolls unintentionally in parking mode when the torque produced by the brake is less than the torque required to hold the vehicle. Rollaway occurs on a MPB-equipped vehicle if the gradient of the road is more than 11.3 degrees and the friction coefficient is less than 0.3. Furthermore, the driver and four passengers on-board also experiences a rollaway if the handbrake force applied is less than 220N when the vehicle in an upward direction and less than 200N when the vehicle in a downward direction. The aim of this research is to evaluate the performance of an electro-mechanical parking brake (EMPB) system. A mathematical modelling of the parking brake assembly based on the drum brake design was firstly developed. Then, an electronic control unit (ECU) model with different controller schemes such as proportional controller (P), and Proportional-Derivative (PD) controller was considered and simulated using MATLAB/SIMULINK to enhance its response performances. The parking brake model and ECU model have been validated using experimental works and it shows a good correlation. From the experimental results, the PD controller of the EMPB performs satisfactorily with engagement time of 1.05s, the steady state error, E_{ss} of 1.66% and percentage overshoot, *POS* of 5.8%. In conclusion, the performance of the EMPB is within one second engagement time and the error percentage is less than 10%. The results were as good as other electric parking brake (EPB) mechanisms that has been accepted by many researchers. Furthermore, validated mechanical parking brake (MPB) and electro-mechanical parking brake (EMPB) models have been established and rollaway issue has been completely solved.

ABSTRAK

Fungsi utama sistem brek parkir adalah untuk memegunkan kenderaan di atas jalan yang rata atau bercerun. Sistem brek parkir mekanikal (MPB) dilihat mempunyai beberapa kekurangan dan salah satunya adalah isu gelungsur. Kenderaan akan bergelungsur secara tidak sengaja dalam mod parkir apabila daya kilas yang dihasilkan oleh brek kurang daripada daya kilas yang diperlukan untuk memegunkan kenderaan. Isu gelungsur akan berlaku kepada kenderaan yang dilengkapi dengan brek parkir mekanikal jika sudut cerun adalah melebihi daripada 11.3 darjah dan pekali geseran kurang dari 0.3. Tambahan pula, pemandu bersama empat penumpang di dalamnya juga akan mengalami isu gelungsur jika daya tarikan tangan yang digunakan adalah kurang daripada 220N apabila kenderaan mengarah ke atas dan kurang daripada 200N apabila kenderaan mengarah ke bawah. Tujuan kajian ini adalah untuk menilai prestasi sistem brek parkir elektro-mekanikal (EMPB). Pertama sekali, pemodelan matematik brek parkir berdasarkan reka bentuk gelendong brek dibangunkan. Kemudian, model unit kawalan elektronik (ECU) dengan skema pengawal yang berlainan seperti pengawal berkadar (P), dan pengawal Perkadaran-Terbitan (PD) dipertimbangkan dan disimulasi menggunakan MATLAB / SIMULINK untuk menilai prestasi tindakbalasnya. Model brek parkir dan model ECU telah ditentusahkan dengan data eksperimen dan ia menunjukkan pertalian yang baik. Dari hasil eksperimen, pengawal PD bagi EMPB telah berfungsi dengan memuaskan dengan masa penglibatan sekitar 1.05s, ralat keadaan mantap, E_{ss} sebanyak 1.66% dan peratusan terlebih sasar, *POS* sebanyak 5.8%. Kesimpulannya, prestasi EMPB adalah sekitar satu saat untuk menarik brek parkir dan peratus ralat adalah kurang daripada 10%. Hasil kajian ini adalah setanding dengan mekanisma brek parkir electrik (EPB) yang lain yang telah diterima oleh ramai penyelidik. Tambahan lagi, model MPB dan model EMPB telah ditentusahkan dan isu gelungsur telah diselesaikan sepenuhnya.

TABLE OF CONTENTS

3 RESEARCH METHODOLOGY 69

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

DAS	-	Data Acquisition System
FPD	-	Fuzzy-Proportional Derivative
EMPB	-	Electro-Mechanical Parking Brake
EPB	-	Electric Parking Brake
IEPB	-	Integrated Electric Parking Brake
MPB	-	Manual Parking Brake
PC	-	Personal Computer
P	-	Proportional
PD	-	Proportional-Derivative
PDCI	-	Proportional-Derivative with Conditional-Integral
PID	-	Proportional-Integral-Derivative
UTM	-	Universiti Teknologi Malaysia
ZN	-	Ziegler-Nichols
FMVSS	-	Federal Motor Vehicle Safety Standard
NHTSA	-	National Highway Traffic Safety Administration
DC	-	Direct Current

LIST OF SYMBOLS

SYMBOLS	DESCRIPTION	UNIT
A_p	Area of the pad	[m^2]
A_d	Area of the disc	[m^2]
A_{cal}	Area of the calliper	[m^2]
A_{cal}	Area of the cable	[m^2]
A_c	Cross sectional area	[m^2]
A_{piston}	Surface area of piston	[m^2]
A	Surface area	[m^2]
a	Amplitude of the waveform oscillation	
B_m	Viscous friction coefficient	[Nm.sec]
C_p	Drum specific heat capacity	[J/kg·K]
c_p	Specific heat capacity of the pad	[JKg^{-1} °C^{-1}]
c_d	Specific heat capacity of the disc	[JKg^{-1} °C^{-1}]
c_{cal}	Specific heat capacity of the calliper	[JKg^{-1} °C^{-1}]
c_{cab}	Specific heat capacity of the cable	[JKg^{-1} °C^{-1}]

d	Relay amplitude	
E_{ss}	Steady state error	
E_c	Modulus of elasticity	[Nm^{-2}]
e_b	Back emf	[mV]
F_{d1}	Brake force 1 at drum/pad surface	[N]
F_{d2}	Brake force 2 at drum/pad surface	[N]
F_c	Cable force/Real time clamping force	[N]
F_{a1}	Force at cable 1	[N]
F_{a2}	Force at cable 2	[N]
F_{a3}	Force at cable 3	[N]
F_l	Force at pad	[N]
F	Force exerted	[N]
F_s	Force at strut	[N]
$F_{clamping}$	Clamping force	[N]
F_r	Normal force at rear wheel	[N]
F_f	Normal force at front wheel	[N]
F_{N1}	Normal force 1 at drum/pad surface	[N]
F_{N2}	Normal force 2 at drum/pad surface	[N]
F_{hb}	Handbrake force	[N]
F_{cs}	Maximum clamping force	[N]
$F_{clamping_{MAX}}$	Maximum clamping force	[N]

F_j	Reaction force at pivot B	[N]
F_j	Reaction force at pivot B	[N]
g	gravity	[m/s^2]
h_p	heat transfer coefficient of the pad	[Wm^{-2} °C^{-1}]
h_d	heat transfer coefficient of the disc	[Wm^{-2} °C^{-1}]
h_{cal}	heat transfer coefficient of the calliper	[Wm^{-2} °C^{-1}]
h_{cab}	heat transfer coefficient of the cable	[Wm^{-2} °C^{-1}]
H	Coefficient of heat transfer	[W/(m^{2}K)]
i_a	Motor current	[A]
J_{gear_belt}	Moment of inertia of gear and belt	[Nm.sec^2]
$J_{spindle}$	Moment of inertia of spindle	[Nm.sec^2]
J_m	Motor Inertia	[Nm.sec^2]
K_{cab1}	Stiffness of cable 1	[N/m]
K_{cab2}	Stiffness of cable 2	[N/m]
K_p	Proportional gain	
K_{dd}	Stiffness of disc	[N/m]
K_d	Derivative gain	
K_b	Back emf constant	[mV/(rad/sec)]
K_c	Critical gain	
$k_{\beta_{PAD}}$	Stiffness constant for pad	[N/m]
$k_{\beta_{nut}}$	Stiffness constant for nut	[N/m]

K_R	Rollaway safety factor	
K_i	Integral gain	
K_{pad}	Pad stiffness for disk brake	[N/m]
K_{brake1}	Equivalent stiffness of brake 1	[N/m]
$K_{brake\,2}$	Stiffness of cable 3	[N/m]
$K_{wheel\,1}$	Equivalent stiffness of the wheel station of brake 1	[N/m]
K_{cal}	Stiffness of calliper	[N/m]
K_T	Torque constant	[Nm/A]
l_{0p}	Initial thermal contractions of the pad	[m]
l_{0d}	Initial thermal contractions of the half disc	[m]
l_{0cal}	Initial thermal contractions of the calliper	[m]
l_{0cab}	Initial thermal contractions of the apply cable1	[m]
l_c	Brake component length	[m]
l_d	Brake component length	[m]
l_e	Brake component length	[m]
l_f	Brake component length	[m]
l_h	Brake component length	[m]
l_j	Brake component length	[m]
l_m	Brake component length	[m]
l_{cab1}	Thermal contractions of the apply cable 1	[m]

l_{cab}	Thermal contractions of the apply cable 1	[m]
l_p	Thermal contractions of the pad	[m]
l_d	Thermal contractions of the half disc	[m]
l_{cal}	Thermal contractions of the calliper	[m]
l_c	Initial thickness of component	[m]
L_a	Motor inductance	[H]
M_{PAD}	Mass for the pad	[kg]
M_{nut}	Mass for the nut	[kg]
m	Weight of vehicle	[kg]
m_d	Weight of passenger	[kg]
N	Normal load	[N]
ρ	Density of the drum	[kg/m^3]
POS	Percentage overshoot	
$p_{wheelpress\ ure}$	Wheel pressure	[N/m^2]
R_a	Motor resistance	[Ω]
R_c	Calliper ratio	
r_{wheel}	Radius of wheel	[m]
r_d	Radius of drum	[m]
r	Mean rubbing radius of pad	[m]
T_{0p}	Initial temperature of the pad	[°C]
T_{0d}	Initial temperature of the disc	[°C]

T_{0cal}	Initial temperature of the calliper	[°C]
T_L	Load torque	[Nm]
T_r	Load torque of other system part	[Nm]
T_{0cab}	Initial temperature of the cable	[°C]
T_c	Critical period of waveform oscillation	[s]
$T_{openNORM}$	Normalized friction torque during opening when maximum clamping force applied	[Nm]
$T_{closeNORM}$	Normalized friction torque during closing when maximum clamping force applied	[Nm]
T_{amb}	Ambient temperature	[°C]
T_c	Maximal friction torque i.e. static frictional torque (Nm)	[Nm]
$T_{open\ c}$	Maximal friction torque during closing when maximum clamping force applied	[Nm]
$T_{close\ c}$	Maximal friction torque during closing when maximum clamping force applied	[Nm]
$T_{Nut\_friction}$	Friction torque of the nut	[Nm]
T_m	Motor torque	[Nm]
T_i	Integral time constant	
T_d	Derivative term constant	
T_p	Temperature of pad	[°C]
T_d	Temperature of disc	[°C]
T_{cab}	Temperature of calliper	[°C]
T_o	Initial Temperature	[^oC]

T_{∞}	Ambient Temperature	$[{}^{o}C]$
T_s	Settling time	[s]
T_c	Time for one cycle	[s]
T_{out}	Output torque	[Nm]
T_{fric_motor}	Electrical motor friction torque	[Nm]
u_1	Displacement at point 1	[m]
u_2	Displacement at point 2	[m]
u_3	Displacement at point 3	[m]
u_4	Displacement at point 4	[m]
u_5	Displacement at point 5	[m]
u_6	Displacement at point 6	[m]
u_7	Displacement at point 7	[m]
V_p	Volume of the pad	[m^3]
V_d	Volume of the disc	[m^3]
V_{cal}	Volume of the calliper	[m^3]
V_{cab}	Volume of the cable	[m^3]
V_a	Motor voltage	[V]
V	Volume of the drum	[m^3]
ω_m	Angular velocity of motor	[rad/s]
$\omega_{spindle}$	Angular velocity of spindle	[rad/s]
X	Linear displacement	[m]

x_c	Cable displacement	[m]
$x_{spindle}$	Spindle position	[m]
x_{piston}	Braking piston position	[m]
$\dot{x}$	Angular velocity	[rad/s]
x_o	Pad/disk kiss point position	[m]
α_p	Thermal expansion coefficient of pad	[ºC^{-1}]
α_d	Thermal expansion coefficient of disc	[ºC^{-1}]
α_{cal}	Thermal expansion coefficient of calliper	[ºC^{-1}]
α_{cab}	Thermal expansion coefficient of cable	[ºC^{-1}]
ρ_p	Density of the pad	[Kgm^{-3}]
ρ_d	Density of the disc	[Kgm^{-3}]
ρ_{cal}	Density of the calliper	[Kgm^{-3}]
ρ_{cab}	Density of the cable	[Kgm^{-3}]
θ	Road slope	[degree]
θ_d	Angular displacement	[rad]
$\vartheta_{spindle}$	Angular displacement	[rad]
μ_d	Coefficient of friction of drum and brake shoe	
μ_r	Coefficient of friction of road and tyre	
μ	Coefficient of friction	
$\delta_{l,d}$	Drum displacement due to radial load	[m]
$\delta_{T,d}$	Drum displacement due to thermal reaction	[m]

δ_c	Linear deformation	[m]
$\delta_{l,l}$	Lining displacement due to radial load	[m]
$\delta_{T,l}$	Lining displacement due to thermal load	[m]
τ	Gear ratio	

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Brake system is one of the most important subsystems for safety roles in a vehicle. The primary functions of the brake system are reducing vehicle speed, maintaining the speed and lastly, stopping the vehicle. The secondary function is to park the vehicle on flat or gradient roads in the absence of the vehicle driver (Limpert, 1999; Bill and Breuer, 2008; Lunia *et al.*, 2015). Most of the vehicles are designed with mechanical parking brake system. There are several disadvantages found in this system.

The first disadvantage of the mechanical parking brake system is that the driver has to pull the hand lever with sufficient force to ensure the vehicle stationary at the most critical condition i.e. when parking on the gradient road (Ji and Zhong, 2016). Thus, this would cause a problem to the elderly, woman and disable person.

Another disadvantage of the mechanical parking brake is that there is no safety measure activated when the driver forgets to engage and disengage the handbrake. It was reported that almost 18% of the manual transmission vehicle and 75% of the automatic transmission vehicle were parked without engaging the hand brake (Becker, 2013). These two disadvantages could lead to catastrophic consequences due to the unintentional movement of the vehicle known as vehicle rollaway.

In order to solve the aforementioned issue, an Electric Parking Brake (EPB) system was introduced. EPB system is a push button intelligent mechanism that is able to park the vehicle on the gradient road without causing any hassle, hence more convenient for the driver and most importantly, it provides a better safety aspect (Wu *et al.*, 2015). The EPB is also appreciated by the drivers because it has more integrated functions that enhance the performances of the vehicle. For example, the hill start function helps reducing stress and burden to the driver in the situation of gradient road. Besides, it is more environmental friendly interior design, easy to handle and has less efforts through the push button (Wang *et al.*, 2015; Wu *et al.*, 2015). Some examples of car manufacturers that have used EPB system are Audi, BMW, Jaguar, Porsche, Chevrolets, and Volkswagens (Balnus, 2003; Becker, 2013).

EPB system can be divided into two actuator types, namely cable puller (Electro-Mechanical Parking Brake, EMPB) and calliper integrated (Integrated Electric Parking Brake, IEPB) (Cheon *et al.*, 2009; Wang *et al.*, 2015). IEPB type consists of a disc brake DC motor, a gear reducer and a force sensor. It has a locked mechanism that commonly uses screw-shaft-nut mechanism. When the parking brake is initialized, the DC motor starts to rotate the gear set as well as the screw shaft. Hence, it pushes the brake pad toward the disc to provide the brake clamping force. The EMPB type, on the other hand, consists of a mechanical actuator that is connected to the brake cable. When the system is initialized, the mechanical actuator, which consists of a DC motor, gear reducer, force sensor and brake cable, pulls the cable brake that is attached to the rear drum brake unit to make the vehicle stays stationary. Brake cable pulls the brake level that is connected to strut in the drum brake. Then the strut pushes the brake shoe toward the lining to generate the braking torque.

The EMPB systems must comply with the brake regulations set by the National Highway Traffic Safety Administration (NHTSA). For a light vehicle or a passenger car with a gross weight of 3500kg and below, the parking brake test will be conducted at a surface gradient of 20% or 11.3-degree slope and should be able to hold the vehicle for 5 minutes in upward and backward directions. Besides, the maximum applied force at the hand brake lever should be 400N and 500N on the foot paddle (U.S, 2005).

1.2 Problem Statement

Rollaway occurs when the torque generated by the vehicle on the tyres in parking mode on a gradient road is higher than the torque produced by the parking brake. From the literature, there are very limited studies of the vehicle rollaway based on the drum type parking brake, both in the fully mechanical and electro-mechanical parking brake. Ishak *et al.*, (2016) studied brake torque performances based on a mechanical-drum type parking brake and vehicle rollaway with the inclusion of the thermal effect. Therefore, there is a necessity to develop a mathematical model of drum type parking brake without the thermal effect then, studying the vehicle rollaway. Due the disadvantages of the mechanical-drum type parking brake, it is important to provide a solution to avoid a vehicle from slipping down the hill while parking. This can be achieved by using an Electro-Mechanical Parking Brake (EMPB) system. An ON-OFF controller type for EMPB is the simplest method (Wang *et al.*, 2015) but according to (Lee *et al.*, 2011) it has the disadvantage of having brake torque over specification as compared to the actual brake torque requirement. The simple ON-OFF controller may not perform well in a wide range of operation due to various weight of the car and road inclination (Lee *et al.*, 2008). Therefore, a robust and efficient controller has been considered to be designed to address the problem. The EMPB system design must comply with the brake regulations such as Federal Motor Vehicle Safety Standard (FMVSS) 135 by the National Highway Traffic Safety Administration (NHTSA) where the passenger car with a gross weight of 3500kg and below must be able to park on the gradient road about 20% or 11.3-degree slope (U.S, 2005). Furthermore, the car must also be able to stay stationary for 5 minutes in the upward and downward directions. In addition, the maximum allowable applied force of the handbrake lever should be 400N and 500N at the foot paddle (U.S, 2005).

1.3 Objectives

The objectives of this research are presented as follows;

i. To model and control the design of an Electro-Mechanical Parking Brake (EMPB) system in order to prevent vehicle rollaway by simulation studies
ii. To evaluate and validate the design of the EMPB system with selected controller schemes through an experimental study

1.4 Research Scope

The scopes of this research covers the following:

i. Vehicle rollaway is investigated using a mathematical model of conventional mechanical parking brake system that is experimentally validated at various vehicle conditions such as vehicle weight, friction coefficient between drum and lining and road gradient.
ii. The mathematical model of the proposed EMPB system consists of an electric DC Motor, a motor driver, an electrical control unit, a gear reducer, a power screw mechanism and brake cables that connected to rear drum type parking brake. The model is integrated with some selected controller schemes such as Proportional-Integral-Derivative (PID) based controller. The brake torque calculated from the model is compared with the brake torque obtained in the experiment for model validations. The model robustness is verified through vehicle rollaway study.
iii. The parameters of both parking brake model and parking brake test rig are selected based on a Malaysian National car, namely Saga BLM.
iv. The PID based controller is developed to study the performance of the EMPB system in terms of steady state error, E_{ss}, percentage overshoot, POS and response time of the engagement and disengagement of parking brake. The drum type parking brake system is assumed as rigid body and the brake torque generated is assumed to be a linear model.

v. An experimental test rig with conventional mechanical parking brake and electro-mechanical parking brake is used to verify the calculated brake torque obtained in the mathematical model.

1.5 Research Contribution

The main research contributions are as follows:

i. A validated mathematical model of a conventional mechanical parking brake system. The model consists of hand brake lever, brake cable, drum brake lever, strut, brake shoe and drum lining. The model can predict brake torque in the upward and downward directions.

ii. A validated mathematical model of an EMPB system. The model consists of DC motor, motor driver, electric control unit, gear reducer, a power screw mechanism to replace the hand brake lever and the brake cable that connected to drum type parking brake. Brake torque can be obtained from this model.

iii. A working prototype of an EMPB system with selected controller schemes. PID based control unit will be developed due to its simple implementation structure, satisfactory performance, straight forward parameter tuning and robust performance in various operating condition (Kaya *et al.*, 2003) . To enhance the performance of the PID controller, the P controller, the PD controller have been tested. All the proposed controllers are has been tested to evaluate their performance in term of robustness and effectiveness to solve the rollaway problem.

iv. Vehicle rollaway studies for a passenger car fitted with either a conventional mechanical parking brake or an EMPB system. From the studies, it is clear that the vehicle has a tendency to rollaway with the conventional mechanical parking brake system at particular vehicle conditions. However, the rollaway problem has been totally solved with the application of the EMPB system.

1.6 Organization of the Thesis

This thesis consists of five chapters. Chapter 1 explains the background and the importance of the research. Chapter 2 provides the review of mechanical parking brake (MPB), electro-mechanical parking brake (EMPB) and rollaway issue that is usually associated with the parking brake systems. This chapter also includes review on the control algorithm, especially PID based controller that is available for the parking brake.

Chapter 3 covers the research methodology involving the modelling and simulation of the EMPB system. The modelling of EMPB system starts with the establishment of the mathematical model of the parking brake with the relation of the rollaway. Then, the process continues with the development of mechanical model that consists of DC motor, power screw, cable displacement in relation to brake torque and gear reducer. The PID based controller was developed and combined with the EMPB mechanical model to perform complete system simulation. The experimental works of the EMPB system are also described in this chapter. It consists of integration of the hardware and software into the parking brake test rig. Initially the experiment was conducted on the real passenger car and validated with the parking test rig. Once the parking test rig was validated, modifications of the manual parking to electro-mechanical were carried out. Then the process of integrating the mechanical system with MATLAB/SIMULINK software and National Instrument data logger was also carried out. PID based controller which were P and PD controller were developed. The initial PID parameter are determine based on the Ziegler-Nichols formula and Astrom-Hagglund relay feedback method. The performances of the proposed controller were evaluated based on the steady state error, percentage overshoot, settling time and rise time of its transient response.

Chapter 4 presents the results and discussions of the simulation and experimental work of the MPB system and EMPB system. The results include performance analysis of the MPB system On-vehicle test and On Bench test in relation to rollaway event. Analytical and experimental studies were conducted on the EMPB system to analyse the rollaway event. These studies provide a solution to avoid the rollaway problem completely. Besides, a new operation method were introduced to ease the process of engaging and disengage the parking brake for the driver. The

EMPB system test rig was developed for the experimental study to validate the simulation results of the EPMB system.

Lastly, Chapter 5 provides the research conclusions with the recommended areas to be studied in the future.

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