ADAPTIVE-FUZZY PID CONTROLLER FOR ANTILOCK BRAKING SYSTEM UTILIZING ELECTRONIC CONE WEDGE BRAKE

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A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy

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DECLARATION

I declare that this thesis entitled "Adaptive-Fuzzy PID Controller for Antilock Braking System Utilizing Electronic Cone Wedge Brake " is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

Signature :…………………………………………….

Supervisor Name : Dr. Ahmad Kamal bin Mat Yamin

Date : 17/09/2024

DEDICATION

To my beloved parents, my wife, my children, and all my supportive friends.

ABSTRACT

The prevalence of accidents resulting from vehicle braking failures has led to advancements in active safety technology, resulting in the development of brake-by-wire (BBW) systems, which completely revamp conventional braking mechanisms. Due to the need for high braking torque and quick response within a 12 V power source, BBW systems now increasingly integrate electronic wedge brake (EWB) technology. This study aims to develop and optimize a new EWB mechanism to reduce power consumption, validate its mathematical model, and evaluate its performance in a hardware-in-the-loop-simulation (HILS) environment. Additionally, the study seeks to assess the effectiveness of the proposed anti-lock braking system (ABS) controller in maintaining desired tire slip during braking, using the optimized EWB as the brake actuator. To achieve these, two evaluation methods were employed namely the MATLAB Simulink program and HILS methodology. In the simulation investigation, both the validated quarter vehicle traction model and the CW-EWB actuation model were utilized to simulate the vehicle's braking system. Afterwards, the braking system's performance was assessed using dynamic tests that simulated sudden braking conditions at 40 km/h and 60 km/h and verified through HILS experiments conducted on a test rig. Brake performance, such as vehicle body speed, wheel speed, longitudinal slip and stopping distance, are the parameters evaluated. Moreover, the validated CW-EWB system was further integrated with the ABS. The developed ABS control mechanism was incorporated into the CW-EWB model utilizing conventional PID and self-tuning PID control strategies, namely Fuzzy Logic PID (FPID) and Self-Tuning Fuzzy PID (SFPID). These control techniques were compared and evaluated in dynamic simulation tests. The findings reveal that SFPID is the most efficient ABS control technique compared to PID and FPID, as it is 10 % and 1 % faster in stopping time, 8 % and 1 % shorter in stopping distance, 9 % and 1 % faster in settling time, and 40 % and 5 % more efficient in achieving the target slip, respectively. For future work, ABS evaluation must be measured to confirm the prediction from the ABS control technique. Experiments on actual vehicles are also required to replace the HILS test method in order to analyze the brake system's performance more precisely.

PENGAWAL PID ADAPTIF-KABUR UNTUK SISTEM BREK ANTIKUNCI MENGGUNAKAN BREK BAJI KON ELEKTRONIK

ABSTRAK

Kelaziman kemalangan akibat kegagalan brek kenderaan telah mendorong kepada kemajuan dalam teknologi keselamatan aktif, iaitu pembangunan teknologi brek melalui wayar (BBW), yang merombak sepenuhnya mekanisme brek konvensional. Disebabkan keperluan untuk tork brek yang tinggi dan tindak balas pantas dalam sumber kuasa 12 V, sistem BBW kini semakin menyepadukan teknologi brek baji elektronik (EWB). Kajian ini bertujuan untuk membangunkan dan mengoptimumkan mekanisme EWB baharu bagi mengurangkan penggunaan kuasa, mengesahkan model matematiknya dan menilai prestasinya dalam persekitaran simulasi perkakasan-dalam-gelung (HILS). Selain itu, kajian ini bertujuan untuk menilai keberkesanan pengawal sistem brek anti-kunci (ABS) yang dicadangkan dalam mengekalkan gelinciran tayar yang dikehendaki semasa brek, menggunakan EWB yang dioptimumkan sebagai penggerak brek. Untuk mencapai matlamat-matlamat ini, dua kaedah penilaian digunakan iaitu program MATLAB Simulink dan metodologi HILS. Dalam kajian simulasi, kedua-dua model cengkaman kenderaan suku dan model penggerak CW-EWB yang disahkan telah digunakan untuk mensimulasikan sistem brek kenderaan. Selepas itu, prestasi sistem brek dinilai menggunakan ujian dinamik yang mensimulasikan keadaan brek mengejut pada 40 km/j dan 60 km/j dan disahkan melalui eksperimen HILS yang dijalankan pada pelantar ujian. Prestasi brek, seperti kelajuan badan kenderaan, kelajuan roda, gelinciran membujur dan jarak berhenti, adalah parameter yang dinilai. Selain itu, sistem CW-EWB yang disahkan telah disepadukan lagi dengan ABS. Mekanisme kawalan ABS yang dibangunkan telah digabungkan ke dalam model CW-EWB menggunakan strategi kawalan PID konvensional dan penalaan sendiri, iaitu Fuzzy Logic PID (FPID) dan Self-Tuning Fuzzy PID (SFPID). Teknik kawalan ini dibandingkan dan dinilai dalam ujian simulasi dinamik. Penemuan menunjukkan bahawa SFPID adalah teknik kawalan ABS yang paling cekap berbanding dengan PID dan FPID, kerana ia adalah 10 % dan 1 % lebih cepat dalam masa berhenti, 8 % dan 1 % lebih pendek dalam jarak berhenti, 9 % dan 1 % lebih cepat dalam masa menetap, dan 40 % dan 5 % lebih cekap dalam mencapai slip sasaran, masing-masing. Untuk kerja akan datang, penilaian ABS mesti diukur untuk mengesahkan ramalan daripada teknik kawalan ABS. Eksperimen pada kenderaan sebenar juga diperlukan untuk menggantikan kaedah ujian HILS bagi menganalisis prestasi sistem brek dengan lebih tepat.

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LIST OF ABBREVIATIONS

ABS	-	Anti-lock braking system
AC	-	Alternating current
ACC	-	Adaptive cruise control
AFC	-	Active force control
AGE-FLC	-	Adjustable gain enhanced fuzzy logic controller
AI	-	Artificial intelligence
ANFIS	-	Adaptive neuro-fuzzy system
ASS	-	Active suspension system
BA	-	Brake assist
BBW	-	Brake by wire
BLDC	-	Brushless direct current
BLF	-	Barrier Lyapunov function
CAD	-	Computer-aided design
CHB	-	Conventional hydraulic brake
CW-EWB	-	Cone wedge based electronic wedge brake
DAQ	-	Data acquisition
DC	-	Direct current
DOF	-	Degree of freedom
EBA	-	Emergency brake assist
EBD	-	Electronic brake distribution
ECU	-	Electronic control unit
EHB	-	Electronic hydraulic brake
EMB	-	Electronic mechanical brake
EMF	-	Electromotive force
EPB	-	Electronic pneumatic brake
EPM	-	Electro-pneumatic modules
ESC	-	Electronic stability control
ESP	-	Electronic stability programme
EWB	-	Electronic wedge brake

FBD	-	Free body diagram
FBM	-	Foot brake module
FFPID	-	Fuzzy fractional PID controller
FIXEWB	-	Fixed calliper-based electronic wedge brake
FLC	-	Fuzzy logic controller
FLPID	-	Fuzzy logic PID controller
FOESC	-	Fractional order extreme search control
FPID	-	Fuzzy logic PID
HCU	-	Hydraulic control unit
HILS	-	Hardware-in-the-loop-simulation
IO	-	Input-output
IOESC	-	Integer-order extreme search control
IP	-	Internet protocol
IR 4.0	-	Fourth industrial revolution
LAN	-	Local area network
LSMC	-	Lyapunov based sliding mode controller
MIMO	-	Multi input multi output
MIROS	-	Malaysian Institute of Road Safety Research
MMSO	-	Multi-model switching observer
MODA	-	Multi-objective dragonfy algorithm
MRAE	-	Mean relative absolute error
MRSP	-	Malaysian road safety plan
MSSA	-	Multi-objective salp swarm algorithm
NAP	-	National automotive policy
NB	-	Negative big
NI	-	National instruments
NN	-	Neural network
NPC	-	Nonlinear predictive control
NS	-	Negative small
NSGA-II	-	Non-dominated sorting genetic algorithm II
NxGV	-	Next generation vehicle
ODE	-	Ordinary differential equations

PB	-	Positive big
PC	-	Personal computer
PCI	-	Peripheral component interconnect
PI	-	Proportional–integral
PID	-	Proportional–integral–derivative
PMDC	-	Permanent magnet direct-current
PMSM	-	Permanent magnet synchronous motors
PPEM	-	Physical parametric estimation method
PS	-	Positive small
PWM	-	Pulse width modulation
RSMC	-	Reaching-law-based sliding mode controller
SAS	-	Steering angle sensor
SFPID	-	Self-tuning fuzzy PID
SILS	-	Software in the loop simulation
SIM	-	System identification method
SMC	-	Sliding mode control
SUT	-	System under test
TCP	-	Transmission control protocol
TCS	-	Traction control system
WSP	-	Wheel speed sensor
YRS	-	Yaw rate sensor
Z	-	Zero

LIST OF SYMBOLS

α	-	Wedge angle
β	-	Driver screw angle/ Motor axial angle
η	-	Lead Screw efficiency
μ	-	Coefficient of friction/ Brake pad coefficient/ Gaussian membership function
τ_a	-	Traction torque
τ_b	-	Braking torque
τ_d	-	Drive torque
τ_{load}	-	Load torque
σ_j^i	-	Spread of Gaussian antecedent membership function
$\dot{\omega}$	-	Angular acceleration
ω_m	-	Motor speed
ω_w	-	Wheel angular velocity
b_i	-	Singleton control action
C^*	-	Brake factor
c_j^i	-	Center of Gaussian antecedent membership function
D_a	-	Axial viscous friction constant
D_m	-	Motor viscous friction constant
$\dot{e}$	-	Error rate
e	-	Error
$e(t)$	-	Error signal
F_b	-	Stopping force
F_c	-	Clamping force
F_m	-	Motor force/ wedge actuation forces
F_n	-	Normal force
F_r	-	Wedge friction force/ reaction forces
F_x	-	Longitudinal tire force
F_z	-	Normal force

g	-	Gravity mass
I_m	-	Motor current
i	-	Rule
J_{all}	-	Total inertia
J_m	-	Motor moment inertia
J_ω	-	Wheel inertia
j	-	Input
K_a	-	Axial stiffness
K_{cal}	-	Calliper stiffness
K_e	-	Electromotive force constant
K_t	-	Torque constant
k_d	-	Derivative gain
k_i	-	Integral gain
k_p	-	Proportional gain
L_a	-	Lead screw pitch
L_m	-	Motor inductance
M_w	-	Wedge weight
m	-	Body mass
m_{load}	-	Load mass
m_{wheel}	-	Wheel mass
N_a	-	Gear reduction
R_{eff}	-	Pad's effective radius
R_m	-	Motor resistance
R_w	-	Wheel radius
r	-	Effective radius
r_{load}	-	Load radius
r_{wheel}	-	Wheel radius
S	-	Longitudinal tire slip
S_d	-	Stopping distance
s_{act}	-	Actual tire longitudinal slip
s_{des}	-	Desired tire longitudinal slip

T_l	-	Load torque/motor load
T_{screw}	-	Motor torque screw
u	-	Output variable
$u(t)$	-	Controller signal
V_m	-	Motor voltage
V_v	-	Vehicle speed
V_w	-	Wedge speed/wedge velocity
$\dot{v_x}$	-	Vehicle acceleration
v_w	-	Wheel speed
v_x	-	Vehicle velocity
X_w	-	Wedge position
x	-	Input variable
x_j^i	-	Input to the membership function