PERFORMANCE EVALUATION OF AN ELECTRIC VEHICLE USING IN-WHEEL MOTOR IN THE LONGITUDINAL DIRECTION

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DECLARATION

I declare that this thesis entitled “Performance Evaluation of An Electric Vehicle Using In-Wheel Motor In The Longitudinal Direction” 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.

Signature :

Name : Muhammad Shukri Azizi bin Razak

Date : 28 December 2023

APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is sufficient in terms of scope and quality for the award of the degree of Master of Science in Mechanical Engineering.

Signature :

Supervisor Name : Ir. Ts. Dr. Fauzi bin Ahmad

Date : 28 December 2023

DEDICATION

To Prophet Muhammad (S.A.W), my beloved father and mother, family and teachers.

ABSTRACT

This study explores the latest electric vehicle driving system concept, the in-wheel motor (IWM) on the rear drive to minimize the weight carried by the current dynamic electric vehicle. The current electric vehicle driving system is a single motor integrated with a gearbox and differential mechanism. The integration of these three mechanical systems causes the dynamic performance of the electric vehicle to not be fully exploited. Therefore, the objective of this study is to evaluate the capability of electric vehicles based on in-wheel motors. To achieve this goal, the first step is to develop a mathematical model of the in-wheel motor using MATLAB/Simulink software. This mathematical model uses the actual parameters of the in-wheel motor, controlled by a PID controller, and verified through a series of experiments. Furthermore, to improve the confidence in the capability of the in-wheel motor, it has been applied to a mathematically developed vehicle model. The IWM based vehicle sub-model simulation has been validated in a hardware-in-the-loop simulation (HILS) using a sub-vehicle model integrated with an actual IWM. The IWM test on the sub-vehicle shows good results and increases confidence that it can be used in actual vehicles. Besides, the rear-wheel-based electric vehicle model has been designed using SolidWorks software. This design is done in detail based on the actual hardware dimensions to ensure the feasibility and functionality of the prototype to be fabricated. Subsequently, the in-wheel motor-based electric vehicle has been fabricated in the Autotronic laboratory based on the designed dimensions. At the same time, a 5-DOF longitudinal simulation model of a vehicle integrated with an in-wheel motor has been developed using actual parameters from the fabricated electric vehicle. This simulation model has been verified through a series of experiments conducted on two different road surfaces, flat and uphill with a gradient of 8.45°. Each experimental test was performed at different speeds of 10, 20, and 30 km/h. The results show that the minimum relative absolute error (MRAE) value is less than 5 %, increasing confidence that the developed simulation model is adequate. Therefore, researchers and the industry can utilize the findings of this study for observation and application of in-wheel motor systems on actual vehicles.

PENILAIAN PRESTASI KENDERAAN ELEKTRIK MENGGUNAKAN RODA BERMOTOR DALAM ARAH MEMBUJUR

ABSTRAK

Kajian ini meneroka sistem pemanduan kenderaan elektrik terkini yang berkonsepkan motor dalam roda pada pacuan belakang bagi meminimumkan berat yang ditampung oleh dinamik kenderaan elektrik pada masa ini. Sistem pemanduan kenderaan elektrik pada masa ini adalah berkonsepkan motor tunggal yang bersepadu dengan kotak gear serta mekanisme pembezaan. Penyepaduan ketiga-tiga sistem mekanikal ini menyebabkan prestasi dinamik kenderaan elektrik tidak dapat dieksploitasikan sepenuhnya. Oleh itu, objektif kajian ini adalah untuk menilai keupayaan kenderaan elektrik berasaskan motor dalam roda. Bagi mencapai matlamat ini, langkah pertama yang diambil adalah membangunkan model matematik motor dalam roda menggunakan perisian MATLAB/ Simulink. Model matematik ini menggunakan parameter motor dalam roda yang sebenar, dikawal menggunakan pengawal PID dan disahkan melalui beberapa siri eksperimen. Selain daripada itu, bagi meningkatkan keyakinan keupayaan motor dalam roda, ia telah diaplikasikan pada model suku kenderaan yang dibangunkan secara matematik. Model simulasi suku kenderaan berasaskan motor dalam roda telah divalidasi secara perkakasan dalam simulasi gegelung menggunakan model suku kenderaan bersepadu dengan motor dalam roda yang sebenar. Pengujian motor dalam roda pada kenderaan suku menunjukkan keputusan yang baik dan meningkatkan kepercayaan bahawa ia mampu untuk digunakan pada kenderaan sebenar. Lanjutan daripada itu, model kenderaan elektrik berasaskan motor dalam roda pada pacuan belakang telah direka bentuk menggunakan perisian SolidWorks. Reka bentuk ini dilakukan secara terperinci berdasarkan ukuran sebenar perkakasan bagi memastikan kebolehlaksanaan dan kefungsian prototaip yang akan difabrikasi. Seterusnya, kenderaan elektrik berasaskan motor dalam roda telah difabrikasi di dalam makmal autotronik berdasarkan ukuran yang telah ditetapkan. Dalam masa yang sama, model simulasi kenderaan membujur 5-DOF bersepadu dengan motor dalam roda telah dibangunkan menggunakan parameter sebenar daripada kenderaan elektrik yang telah difabrikasi. Model simulasi ini telah disahkan melalui beberapa siri eksperimen yang dijalankan pada dua permukaan jalan yang berbeza iaitu jalan rata dan jalan berbukit yang mempunyai kecerunan 8.45°. Setiap pengujian eksperimen dilakukan pada kelajuan yang berbeza-beza iaitu 10, 20 dan 30 km/j. Keputusan menunjukkan nilai minimum ralat mutlak relatif kurang daripada 5 % meningkatkan keyakinan bahawa model simulasi yang dibangunkan adalah mencukupi. Oleh itu, para penyelidik dan industri boleh memanfaatkan penemuan kajian ini untuk pemerhatian dan aplikasi sistem motor dalam roda pada kenderaan sebenar.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF SYMBOLS

a	-	Distance of CG From The Front Axle
b	-	Distance of CG From The Rear Axle
e	-	Error
d	-	Distance Travel of the Vehicle
F_d	-	Drag Force of the Vehicle
F_x	-	Longitudinal Tyre Force
F_z	-	Normal Force
h_{CG}	-	Distance From The CG From The Plane Axis
h	-	Distance of CG Above the Ground
i_a	-	Current on Phase A for Permanent Magnet Synchronous Motor
i_b	-	Current on Phase B for Permanent Magnet Synchronous Motor
i_c	-	Current on Phase C for Permanent Magnet Synchronous Motor
i_d	-	Stator Current on D-Axis for Permanent Magnet Synchronous Motor
I_{IWM}	-	IWM Current for In-Wheel Motor
i_q	-	Stator Current on Q-Axis for Permanent Magnet Synchronous Motor
J	-	Polar Moment of Inertia
K_b	-	Cylinder Pressure Gain
K_c	-	Pressure Gain
K_i	-	Integral Gain
K_p	-	Proportional Gain
L_{aa}	-	Inductance on Phase A-A for Permanent Magnet Synchronous Motor
L_{ab}	-	Inductance on Phase A-B for Permanent Magnet Synchronous Motor

L_{ac}	-	Inductance on Phase A-C for Permanent Magnet Synchronous Motor
L_{bb}	-	Inductance on Phase B-B for Permanent Magnet Synchronous Motor
L_{bc}	-	Inductance on Phase B-C for Permanent Magnet Synchronous Motor
L_{cc}	-	Inductance on Phase C-C for Permanent Magnet Synchronous Motor
L_d	-	Inductance on D-Axis for Permanent Magnet Synchronous Motor
L_q	-	Inductance on Q-Axis for Permanent Magnet Synchronous Motor
L_w	-	Width of The Experimental Vehicle
m	-	Mass of Quarter Car
m_b	-	Body Mass of Quarter Car
m_w	-	Wheel Mass of Quarter Car
P	-	Number of Pole for In-Wheel Motor
P_b	-	Brake Pressure Applied
R_a	-	Resistance on Phase A for Permanent Magnet Synchronous Motor
R_b	-	Resistance on Phase B for Permanent Magnet Synchronous Motor
R_c	-	Resistance on Phase C for Permanent Magnet Synchronous Motor
R_f	-	Front Radius of Experimental Vehicle
R_r	-	Rear Radius of Experimental Vehicle
R_s	-	Stator Resistance for In-Wheel Motor
R_w	-	Radius of The Wheel
t	-	Time
T_{cmd}	-	Command Torque
T_e	-	Electromagnetic Torque
T_{IWM}	-	IWM Torque for In-Wheel Motor
u_b	-	Brake Setting
v_x	-	Vehicle Velocity

v_b	-	Vehicle Body
v_w	-	Wheel Speed
$\dot{v}$	-	Vehicle Acceleration
V	-	Voltage
V_b	-	Battery Voltage
V_a	-	Voltage on Phase A for Permanent Magnet Synchronous Motor
V_b	-	Voltage on Phase B for Permanent Magnet Synchronous Motor
V_c	-	Voltage on Phase C for Permanent Magnet Synchronous Motor
V_d	-	Stator Voltage on D-Axis for Permanent Magnet Synchronous Motor
V_q	-	Stator Voltage on Q-Axis for Permanent Magnet Synchronous Motor
W	-	Weight of The Experimental Vehicle
W_f	-	Vehicle Weight on The Front
θ	-	Road Inclination Angle
λ^*	-	Desired Longitudinal Tyre Slip
μ	-	Road Coefficient of Friction
τ_a	-	Traction Torque
τ_b	-	Braking Torque
τ_{bs}	-	Brake Lag
ψ_a	-	Flux on Phase A for Permanent Magnet Synchronous Motor
ψ_b	-	Flux on Phase B for Permanent Magnet Synchronous Motor
ψ_c	-	Flux on Phase C for Permanent Magnet Synchronous Motor
ψ_d	-	Stator Flux on D-Axis for Permanent Magnet Synchronous Motor
ψ_f	-	Stator Flux for Permanent Magnet Synchronous Motor
ψ_{ma}	-	Motor Flux on Phase A for Permanent Magnet Synchronous Motor
ψ_{mb}	-	Motor Flux on Phase B for Permanent Magnet Synchronous Motor

ψ_{mc}	-	Motor Flux on Phase C for Permanent Magnet Synchronous Motor
ψ_q	-	Stator Flux on Q-Axis for Permanent Magnet Synchronous Motor
ω_{act}	-	Actual Wheel Angular Speed
ω_r	-	Reference Angular Speed
ω	-	Wheel Angular Velocity
g	-	Gravitational Acceleration
%	-	Percentage
C°	-	Degree Celcius

LIST OF ABBREVIATIONS

AC	-	Alternating Current
ADC	-	Analog To Digital Converter
API	-	Air Pollution Index
AWD	-	All Wheel Drive
BEV	-	Battery Electric Vehicle
CG	-	Center Of Gravity
CMCO	-	Conditional Movement Control Order
CO	-	Carbon Monoxide
CVT	-	Continuous Variable Transmission
DAC	-	Dogital To Analog Converter
DC	-	Direct Current
DMD	-	Dual Motor Drive
DOE	-	Department of Environment
DOF	-	Degree of Freedom
DYC	-	Direct Yaw Control
EV1	-	Electric Vehicle 1
EWD	-	Electric Wheel Drive
FBD	-	Free Body Diagram
FLC	-	Fuzzy Logic Controller
FWD	-	Front Wheel Drive
GM	-	General Motor
HDD	-	Hard Disc Drive
HEV	-	Hybrid Electric Vehicle

HILS	-	Hardware-In-The-Loop Simulation
I/O	-	Input/Output
ICE	-	Internal Combustion Engine
IWM	-	In-Wheel Motor
IWM-EV	-	In-Wheel Motor Electric Vehicle
JPJ	-	Jabatan Pengangkutan Jalan
km/h	-	Kilometer Per Hour
MAA	-	Malaysian Automotive Association
MCO	-	Movement Control Order
MET Malaysia	-	Meteorologi Malaysia
MPC	-	Model Predective Controller
MRAE	-	Mean Relative Absolute Error
MIMO	-	Multiple Input and Multiple Output
N/A	-	Naturally/ Aspirated
NEP	-	National Energy Policy
NiMH	-	Nickel Metal Hydride
NNC	-	Neural Network Controller
NO_2	-	Nitrogen Oxide
ODE	-	Ordinary Differential Equation
OPEC	-	Organization of The Petroleum Exporting Countries
PI	-	Proportional-Integral
PID	-	Proportional-Integral-Derivative
PMSM	-	Permanent Magnet Synchronous Motor
PPEM	-	Physical Parametric Estimation Modelling
QC-EV	-	Quarter Car Electric Vehicle
RMS	-	Root Mean Square

RWD	-	Rear Wheel Drive
Rx	-	Signal Receiver
SIM	-	System Identification Method
SMC	-	Sliding Model Controller
SMD	-	Single Motor Drive
SO_2	-	Sulfur Oxide
SSD	-	Solid State Drive
SSM	-	State Space Model
SUT	-	System Under Tests
SVPWM	-	Space Vector Pulse Width Modulation
Tx	-	Signal Transmitter
UNFCCC	-	United Nation Framework Convention On Climate Change
USB	-	Universal Serial Bus
USPTO	-	United State Patent Trademark Office
UTeM	-	Universiti Teknikal Malaysia Melaka
VLM	-	Vehicle Longitudinal Model
ZEV	-	Zero Emission Vehicle