



Faculty of Mechanical Engineering

**MODELLING, SIMULATION AND CONTROL OF
A SERIES HYBRID ELECTRIC VEHICLE**

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**MODELLING, SIMULATION AND CONTROL OF A SERIES HYBRID
ELECTRIC VEHICLE**

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**A thesis submitted
in fulfillment of the requirements for the degree of Master of Science in
Mechanical Engineering**

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2015

DECLARATION

I declare that this thesis entitled “Modelling, Simulation and Control of a Series Hybrid Electric Vehicle” is the result of my own research except as cited in the references. This thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name :

Date :

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 Master of Science in Mechanical Engineering.

Signature :

Supervisor Name :

Date :

DEDICATION

To my beloved father, mother, wife, brother, sister, lecturers, son and friends

ABSTRACT

Series hybrid electric vehicles (SHEVs) are efficiently used in many cities to reduce harmful exhaust emissions, as well as, fuel consumption. The vehicles are propelled with an electric motor that can achieve high efficiency at low speed with an internal combustion engine being operated at optimum fuel consumption for battery charging. Human interaction is being increasingly used to assist the development propulsion systems for road vehicles. The modelling of the hybrid electric powertrain for mobility is indeed challenging. The model should not only adequately simulate the vehicle longitudinal dynamics, it should also account for the load control of the propulsion system. The aims of this study are to design a control strategy for an electric motor of a SHEV longitudinal model and to assess its mobility performance. A mathematical model, for a vehicle with an internal combustion engine, was set-up to simulate its longitudinal dynamics using a high-level programming language software; i.e. Matlab Simulink. The multibody system approach was employed to model the vehicle dynamics with six degree of freedoms. Cases to investigate the inertia performance, such as sudden acceleration and braking, were conducted. The model was verified using a commercial vehicle simulation software; i.e. Car Simulation for Education (CarSimEd). The finding suggests that the model works as desired and was verified by CarSimEd. The SHEV propulsion system utilises a PMSM model to provide a driving effort to propel the vehicle. The SHEV operates at high efficiency when the model had applied a control strategy for the PMSM model to track a desired torque. The gain scheduling controller was selected for the motor due to its effectiveness provide a drive torque in various driving conditions. The performance for the control strategy was tested using the sine, square, sawtooth and step inputs. The results indicate that the controller for motor control is sufficiently efficient to track various types of the desired inputs. The SHEV was set up by integrating the vehicle longitudinal model and the electric motor model. Longitudinal tests were performed; i.e. sudden acceleration and braking, tracking road gradient and unbounded motion. The findings suggest that the SHEV model is suitable for use in the preliminary assessment for other types of HEVs or EVs. Simulations using the CarSimEd show similar results.

ABSTRAK

Kenderaan hibrid sesiri berkesan digunakan di kebanyakan kawasan bandar untuk mengurangkan pelepasan gas ekzos yang berbahaya dan juga penggunaan bahan api. Kenderaan ini dipacu oleh motor elektrik yang boleh mencapai kecekapan tinggi pada kelajuan rendah dengan menggunakan enjin pembakaran dalam yang beroperasi pada penggunaan bahan api optimum untuk pengecasan bateri. Interaksi manusia di dalam simulasi banyak diaplikasikan untuk membantu membangunkan sistem pacuan untuk kenderaan. Pemodelan bagi sesebuah kenderaan hibrid dari segi dinamik begitu mencabar. Model tersebut bukan sahaja perlu membuat simulasi pergerakan lurus, ia juga mesti mengambil kira kawalan beban bagi sistem pacuan kenderaan. Tujuan kajian ini adalah untuk merekabentuk strategi kawalan untuk sebuah motor elektrik bagi satu model kenderaan hibrid sesiri dan untuk menilai prestasi pecutannya. Model matematik bagi kenderaan dengan enjin pembakaran dalam telah dibangunkan dengan menggunakan perisian pengaturcaraan berkeupayaan tinggi iaitu Matlab Simulink. Pendekatan sistem berbilang jasad telah digunakan untuk mewakili model dinamik kenderaan yang terdiri daripada enam darjah kebebasan. Ujian pecutan dan brek mengejut telah dilakukan untuk menilai prestasi model kenderaan ini. Model ini telah disahkan dengan menggunakan perisian simulasi kenderaan iaitu Simulasi Kenderaan Pendidikan (CarSimEd). Hasil daripada kajian menunjukkan bahawa model kenderaan ini dapat berfungsi mengikut seperti yang dikehendaki dan telah disahkan oleh CarSimEd. Sistem pacuan SHEV yang menggunakan motor searah magnet tetap (PMSM) memberikan daya pacuan untuk menggerakkan kenderaan. SHEV beroperasi pada kecekapan tinggi apabila model ini diberikan satu strategi kawalan untuk model motor elektrik PMSM bagi mencapai nilai daya kilas yang dikehendaki. Sistem kawalan Gain Scheduling telah dipilih untuk motor elektrik PMSM kerana keberkesanannya mencapai daya kilas dalam pelbagai keadaan. Isyarat kemasukan seperti gelombang sinus, persegi, gigi gergaji dan tangga telah digunakan untuk menguji keberkesanan sistem pengawalan. Keputusan menunjukkan bahawa Gain Scheduling berkesan untuk mengawal motor elektrik bagi mencapai pelbagai kemasukan parameter yang dikehendaki. Kenderaan hibrid sesiri telah dibangunkan dengan menggabungkan model dinamik kenderaan dan model motor elektrik. Ujian seperti pecutan dan brek mengejut, capaian kecerunan jalan dan tekan lepas pedal pecutan telah dilaksanakan untuk menguji keberkesanan prestasi kenderaan dalam pergerakan lurus. Hasil kajian ini menunjukkan model SHEV sesuai digunakan untuk menilai prestasi awal bagi jenis kenderaan hibrid yang lain. Keputusan simulasi dan perisian CarSimEd telah menunjukkan keputusan yang sama.

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LIST OF SYMBOLS

F_x	-	Forces acting in the direction of a movement on x-axis
F_{tr}	-	Resistance forces that acting in the direction of a movement on the z-axis
M	-	Lumped mass
V	-	Linear velocity
ω_f	-	Front angular velocity
ω_r	-	Rear angular velocity
R_f	-	Front rolling radius
R_r	-	Rear rolling radius
I_f	-	Front wheel moment inertia
I_r	-	Rear wheel moment inertia
μ_f	-	Coefficient of friction front wheel tyre
μ_r	-	Coefficient of friction rear wheel tyre
θ	-	Incline road degree
F_z	-	Normal force
F_{xtotal}	-	Total force in X- direction acting on the vehicle body
F_d	-	Drag force
F_a	-	Aerodynamic force
F_r	-	Resistance force
C_r	-	Rolling resistance coefficient
A	-	Frontal area of vehicle

- C_d - Aerodynamic drag coefficient
- ρ - Density of air
- B - Distance from front axle to center of gravity
- C - Distance from rear axle to center of gravity
- L - Wheelbase
- Cg - Center of gravity
- H - Height of vehicle to ground
- μ - Coefficient of force transfer
- R - Rolling radius
- λ_f - Front wheel longitudinal slip
- λ_r - Rear wheel longitudinal slip
- j - Right or left
- T_{bf} - Front wheel braking torque
- T_{br} - Rear wheel braking torque
- T_{af} - Front wheel throttling torque
- T_{ar} - Rear wheel throttling torque
- τ_{rf} - Front wheel reaction torque
- τ_{rr} - Rear wheel reaction torque
- C_{ff} - Front wheel viscous friction coefficient
- C_{fr} - Rear wheel viscous friction coefficient
- τ_{es} - Throttle lags
- μ_e - Energy transfer coefficient
- T_{MAX} - Maximum torque
- μ_i - Throttle setting
- η_g - Current gear ratio

- η_f - Final gear ratio
- \dot{m}_a - Mass rate of air in intake manifold
- \dot{m}_{ai} - Mass rate of air entering intake manifold
- \dot{m}_{ao} - Mass rate of air leaving intake manifold
- MAX - Maximum flow rate
- TC - Throttling characteristic
- PRI - Normalized pressure function
- α - Throttle angle
- P_m - Intake manifold pressure
- P_{atm} - Atmospheric pressure
- V_m - Intake manifold volume
- ω_e - Engine angular velocity
- η_{vol} - Volumetric efficiency
- \dot{m}_{fi} - Fuel rate entering combustion chamber
- \dot{m}_{fc} - Command fuel rate
- T_f - Effective fueling time constant
- β - Desired air/fuel ratio
- I_e - Effective inertia of the engine
- T_i - Indicated engine torque
- T_f - Engine friction torque
- T_a - Accessories torque
- Δt_{it} - Intake to torque production delay
- Δt_{st} - Spark to torque production delay
- C_T - Maximum torque production capacity of the engine
- A/F - Actual air/fuel ratio

- M_a - Molar mass
- R - Entropy
- T_m - Manifold Temperature
- MTB - Minimum spark advanced from top dead center
- P_b - Brake pressure
- K_c - Simple pressure gain
- u_b - Brake setting
- T_{bs} - Brake time lags

LIST OF ABBREVIATIONS

AFI	-	Air/fuel ratio influence
SI	-	Spark influence
TDC	-	Top dead center
HEV	-	Hybrid electric vehicle
PMSM	-	Permanent Magnet Synchronous Motor
DOF	-	Degree of freedom
CarSimEd	-	Car Simulation for Education
SHEV	-	Series hybrid electric vehicle
IM	-	Induction motor

LIST OF PUBLICATIONS

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Mohd Sabirin Rahmat., Fauzi Ahmad, Ahmad Kamal Mat Yamin, Noreffendy Tamaldin and Vimal Rau Aparow, 2013. Modeling And Torque Tracking Control of Permanent Magnet Synchronous Motor (PMSM) for Hybrid Electric Vehicle, *International Journal of Automotive and Mechanical Engineering*, Vol. 7, pp. 955 – 967. (SCOPUS Indexed)

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Light Weight Engine Mounting for UTeM Formula Varsity Race Car. *World Virtual Conference on Advanced Research in Mechanical and Material Engineering* March 18-22, Kuala Lumpur, Malaysia.

Article

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CHAPTER 1

INTRODUCTION

1.0 Introduction

In a hybrid electric vehicle (HEV), two or more power sources work together to deliver power that greatly surpasses any single source working alone. Through the design, it is possible to improve their dynamics characteristics such as acceleration, emission, fuel efficiency and total cost of ownership. Of these characteristics, the one to see the greatest improvement will depend on the design of the system and the control strategy utilised.

In a conventional vehicle, the powertrain generally consists of an internal combustion engine (ICE) and a multi-gear mechanical transmission. Normally, the engines used are either spark ignition (SI) gasoline or compression ignition (CI) diesel. As an automotive power plant, the ICE alone had proven itself to be suitable for many decades. However, in recent times, with declining fuel supplies and increasing environmental awareness of the general public, it is apparent that the vehicle demands alternatives power plants.

Fuel cell has recently shown up on the future powertrain roadmap to be alternates power trains. Fuel cells are as much as 20 years away from widespread commercial viability since high costs, poor cold start performance and hydrogen storage issues all remain unsolved (Helmolt & Ulberle, 2007). Batteries are much closer to becoming a viable replacement on their own; with recharge time, longevity and cost being the main

issues (Bosschea et al., 2006). Since no new technology is readily available to completely usurp the engine, the best course of action is to find suitable ways of making better use of them. Hybridising ICE with batteries could potentially be a reasonable method for this purpose.

In this research, a hybrid electric vehicle based on the series drive train layout was investigated and virtually developed. Six degrees of freedom (6-DOF) vehicle longitudinal model was designed to evaluate the performance of a vehicle in longitudinal or forward direction. The vehicle model consists of a tyre, transmission, brake, engine, electric powertrain and vehicle dynamic. The study includes the human interaction to provide real time driver input which are the throttle and brake during simulation operations. In order to control the electric motor, Gain Scheduling control method was utilised in this study. This controller is able to deliver enhanced performance and response of the electric motor to drive the vehicle.

1.1 Problem Statement

The intention of this research was to design a control strategy for an electric motor, of a SHEV longitudinal model and to assess the mobility performance of the vehicle using real time driver input. A control strategy for the electric motor was developed to achieve an optimum operation at low and high speed. The vehicle longitudinal model was set up for SHEV simulation development to assess the mobility performance.

The development of the control strategy was challenging as to achieve the optimum performance of the electric motor. The selection of proper control strategies for the electric motor was according to the capability and adaptability of the controller to achieve optimum performance. In this study, the Gain Scheduling was designed to control the

motor, while the effectiveness of this controller was assessed in torque tracking control; thus, the results were compared with the PID controller.

It is challenging integrated mechanical and electrical components i.e vehicle longitudinal model and the electric motor model. The two components connected along a single path (series) in the powertrain system. The ICE and alternator were connected to recharge the battery, while the electric motor and transmission were incorporated to drive the vehicle.

1.2 Research Background

Significant studies on HEV were established in the late 1970s, in the USA, as a reaction to the oil crisis (Trummel & Burke, 1983). Since then, there were numerous advances in technology in the areas of power electronic devices, control strategies and battery technology. At the same time, the cost associated with deploying such technology had continuously decreased.

However, to develop vehicles in cost effective ways, the assessment through simulation methods using simulation tools (i.e. Matlab Simulink software) should be performed in the preliminary stage. Butler et al. (1997) identified a new simulation tool, Versatile-Elph, for the development of the HEV. The tool facilitated in-depth studies of any type of hybrid or total configurations through visual programming. The V-Elph was compatible with the Matlab Simulink software to simulate the vehicles. Simulation studies were performed to illustrate the applicability of V-Elph to the HEV design.

In a similar research, Senger et al. (1998) made improvements on the simulation tool to simulate HEV using ADVISOR. The study was specific to series hybrid electric vehicles and the induction motor was utilised to propel the vehicle. The basic equation of the solid-body motion (Newton's second law) was applied to assess the performance of the