MODEL-IN-THE-LOOP SIMULATION OF ELECTRONICALLY CONTROLLED WEDGE TORQUE COUPLER FOR PARALLEL HYBRID ELECTRIC VEHICLE

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ABSTRACT

In conventional Parallel Hybrid Electric Vehicle (PHEV), a mechanical coupling device used to couple the power between two different power sources is normally implemented using the planetary gear unit or gearbox unit. Several drawbacks from the implementation of the conventional mechanical coupling into PHEV have been highlighted by some researchers. The first drawback is that, when passing through a narrow speed region, the engine operating point of the PHEV cannot be fixed and thus reduces the engine efficiency. Another drawback is that, complex structure and control scheme are needed for the PHEV to operate properly. In this study, a new mechanical coupling device using the rotational wedge mechanism to combine the power between the ICE and electric motor has been developed and named as Electronic Wedge Torque Coupler (EWTC). Based on the design developed, a mathematical and simulation model has been derived and modelled using kinematic analysis and Matlab Simulink respectively. The model is then verified using experimental technique. The EWTC model is then be tested using the model in the loop simulation technique which the EWTC model is applied into the parallel hybrid electric vehicle test rig and be tested together with the simulation model of the EWTC. Based on the experimental results, the proposed EWTC mechanism is able to distribute the torque from the gasoline engine and electric motor by controlling the rotational wedge mechanism. The three modes of operations in parallel hybrid electric vehicle which are electric mode, ICE mode and hybrid mode were also achieved. Compared to the ICE mode, the hybrid mode has increased the PHEV speed performance by 7%.

ABSTRAK

Dalam kenderaan konvensional hibrid elektrik selari (PHEV), peranti gandingan mekanikal yang digunakan untuk menggabungkan kuasa antara dua sumber kuasa yang berbeza biasanya dilakukan dengan menggunakan unit gear planet atau unit kotak gear. Seperti yang ditemui oleh penyelidik, beberapa kelemahan daripada pelaksanaan gandingan mekanikal tersebut kepada PHEV telah ditemui. Kelemahan pertama adalah, semasa PHEV melalui rantau kelajuan yang sempit, titik operasi enjin tidak boleh tetap dan dengan itu mengurangkan kecekapan enjin. Satu lagi kelemahan adalah bahawa, struktur dan skim kawalan yang kompleks diperlukan untuk membuat PHEV itu berfungsi dengan baik. Di dalam kajian ini, sebuah peranti gandingan mekanikal baru dengan menggunakan mekanisme baji putaran untuk menggabungkan kuasa di antara enjin dan motor elektrik telah dibangunkan dan dinamakan sebagai *Electronic Wedge Torque Coupler* (EWTC). Berdasarkan reka bentuk yang telah dibangunkan, model matematik dan simulasi telah diperolehi dan dimodelkan menggunakan kaedah analisis kinematik dan dibina di dalam perisian *Matlab Simulink*. Model ini kemudian telah disahkan menggunakan teknik eksperimen. Model EWTC ini juga telah diuji melalui kaedah simulasi model dalam gegelung di mana model EWTC tersebut digunakan ke dalam rig kenderaan elektrik hibrid selari dan diuji bersama dengan model simulasi EWTC. Berdasarkan keputusan eksperimen, mekanisme EWTC yang dicadangkan telah dapat mengedarkan tork daripada enjin petrol dan motor elektrik dengan baik melalui kawalan mekanisme baji putaran. Tiga mod operasi kenderaan hibrid elektrik selari iaitu mod elektrik, mod ICE dan mod hibrid juga telah dicapai. Berbanding dengan mod ICE, mod hibrid telah meningkatkan prestasi kelajuan PHEV sebanyak 7%.

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APPROVAL

I certify that an Examination Committee has met on **16TH FEBRUARY 2017** to conduct the final examination of **MOHAMAD IZZAT BIN SATAR** on his degree thesis entitled **'MODEL IN THE LOOP SIMULATION OF ELECTRONICALLY CONTROLLED WEDGE TORQUE COUPLER FOR PARALLEL HYBRID ELECTRIC VEHICLE'.** The committee recommends that the student be awarded the degree of Master of Science (Mechanical Engineering).

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LIST OF SYMBOLS

$\omega_1, \omega_2, \omega_3$	- Angular velocity
T_1, T_2	- Propelling torque
T_3	- Load torque
k_1, k_2	- Structural parameters
T_{out}	- Output torque
n_{out}	- Output speed
R_w	- Wedge radius
θ_w	- Wedge angle
S	- Length of the arc
α	- Wedge ramp
S_w	- Wedge displacement
W	- Spring force
F	- Tangential force
R	- Clutch effective radius
μ	- Coefficient of friction
T_c	- Clutch torque
r_1, r_2	- Outer and inner radius of clutch
n	- Total surface contact
X	- X-axis
Z	- Z-axis
V	- Forward velocity
ω_f	- Front rotation rate
ω_r	- Rear rotation rate
R_f	- Front wheel radius
R_r	- Rear wheel radius
$\mu_{f,r}$	- Coefficient of friction of wheels and contact surface
$J_{f,r}$	- Moment inertia of wheels
F_x	- Longitudinal force
F_z	- Normal force
l, r	- Left, right
m	- Vehicle mass
g	- Gravitational force
c	- Distance of rear wheel to center of gravity
b	- Distance of front wheel to center of gravity
θ	- Road gradient
H	- Height from ground to vehicle center of gravity
L	- Vehicle total wheelbase
F_d	- Drag force

F_a	-	Aerodynamic force
F_r	-	Resistance force
ρ	-	Density of air
A	-	Vehicle frontal area
C_d	-	Drag coefficient
C_r	-	Rolling resistance
$\lambda_{f,r}$	-	Longitudinal slip front and rear
τ_e	-	Engine torque transfer to each wheel
τ_b	-	Brake torque
τ_r	-	Reaction torque
C_f	-	Coefficient of viscous friction
R	-	Engine speed
T_{max}	-	Maximum engine torque
n_g	-	Gear ratio
n_f	-	Final gear ratio
$\vec{V}_{abcs}$	-	Stator phase voltage at abc reference frame
$\bar{R}_s$	-	Stator phase resistance
$\vec{\iota}_{abcs}$	-	Stator current
$\bar{\lambda}_{abcs}$	-	Flux linkages
T_e	-	Electromagnetic torque
$\bar{L}_s$	-	Inductance
$\bar{\lambda}_f$	-	Amplitude of flux linkage
J	-	Rotor inertia
F	-	Coulomb friction
T_l	-	Load torque
P	-	Number of poles
ω_r	-	Mechanical rotor speed

LIST OF ABBREVIATION

HEV	-	Hybrid Electric Vehicle
PHEV	-	Parallel Hybrid Electric Vehicle
EM	-	Electric Motor
ICE	-	Internal Combustion Engine
EWTC	-	Electronic Wedge Torque Coupler
MILS	-	Model in the Loop Simulation
HILS	-	Hardware in the Loop Simulation
SILS	-	Software in the Loop Simulation
DC	-	Direct Current
AC	-	Alternate Current
DOF	-	Degree of Freedom
PMSM	-	Permanent Magnet Synchronous Machine
CVT	-	Continuous Variable Transmission
EWB	-	Electronic Wedge Brake
PID	-	Proportional Integrator Derivatives
CAD	-	Computer Aided Drawing
LVDT	-	Linear Variable Displacement Transducer
PC	-	Personal Computer
NI	-	National Instrument

CHAPTER 1

INTRODUCTION

1.1 Overview

The development of Hybrid Electric Vehicle (HEV) has been proven to be one of the effective alternative approaches to reduce greenhouse gas effects as well as to tackle the fossil fuel shortage problems (Chan, 2002; Hannan et. al., 2014). One of the key to the effectiveness of the HEV as the green technology is the proper implementation of powertrain layout as well as an efficient power management for the vehicle (Wirasingha and Emadi, 2011). Compared to series and series-parallel HEV, parallel HEV (PHEV) requires a smaller Internal Combustion Engine (ICE) and single Electric Motor (EM). Therefore, a lot of research on improving the energy management and control system of HEV were done using PHEV.

In PHEV, the ICE and EM of the powertrain deliver their power through a mechanical coupling which can either be speed or torque coupling. The conventional mechanical coupling device is usually developed by using a planetary gear train (PGT) unit. However, due to the mechanical drawback, the PGT is considered as inefficient to be used as the main mechanism in the mechanical coupling device.

Therefore, this study will focus on developing a new mechanical coupling device to improve the existing drawback.

The goal of this study is to develop a new prototype of an electro-mechanical coupling called Electronic Wedge Torque Coupler (EWTC) focusing on the torque coupling in the parallel HEV application. In developing the mechanical coupling, the main mechanisms used are the rotational wedge and multi-plate clutch mechanism. Additionally, a parallel hybrid vehicle consisting of ICE powertrain, electric motor powertrain and vehicle dynamic is to be studied and developed by means of simulations and hardware development. Next, the EWTC mechanism is characterized and the performance of the proposed EWTC is evaluated by using the simulation and hardware-in-the-loop simulation (HILS) results.

1.2 Problem Statement

Parallel hybrid vehicle or mechanically coupled hybrid drivetrain is the most viable type of HEV in terms of the structure and cost. However, the weakness of this kind of HEV is that the engine delivers its mechanical power directly to the driven wheels without undergoing energy form change. Therefore, the engine cannot always operate in a narrow speed region because of its mechanical coupling to the driven wheels which is a major disadvantage. Hence, the average engine efficiency is lower compared to series hybrid drivetrain. Besides, the conventional mechanical coupling of the PHEV requires complex structure and control due to the planetary gear implementation.

In order to increase the engine efficiency and also reduce the complexity of the mechanical coupling, an Electronic Wedge Torque Coupler (EWTC) is to be designed to control the torque from the engine or electric motor. The function of the EWTC is to decouple the engine speed from the vehicle speed, and a shaft-fixed gear unit is used to decouple the engine torque from the driven wheels. In this way, the engine can potentially operate in a narrow speed and torque region, and at the same time, the engine can deliver its mechanical power directly to the driven wheels.

1.3 Background of the study

The development of gasoline engine automobiles is one of the supreme achievements in modern technology of automotive engineering. However, the extremely developed automotive industry as well as increasing number of automobiles in use around the world have triggered serious problems to the environment and also to the fuel consumption. The worsening air quality, global warming issues, and depleting petroleum resources are some of the serious threats to the environment. Due to these issues, proper emissions and fuel efficiency standards have been introduced by the government to encourage the developer to produce a safer, cleaner and more efficient vehicles.

To achieve this, a new concept in powertrain system has been introduced and used by the automotive industries. The new powertrain is used for conventional passenger vehicle and is known as Hybrid Electric Vehicle (HEV). It is well recognized that HEV is the most viable approach to produce low harmful gas emission and low fuel consumption. Two power supplies are commonly used to power an HEV, which are electric motor and gasoline engine. The purpose of using the combination of two different power sources is to reduce the load capacity of the gasoline engine. Based on the drivetrain design, HEV can be categorized into three types namely series, parallel and series-parallel HEV drivetrain.

The typical series HEV drivetrain comprises a single IC engine-generator drivetrain and a battery-motor drivetrain (Ehsani et. al., 2014). The two drivetrains are connected in series through the battery and the generator. Power from either or both drivetrains can be controlled to fulfill the driving condition. The classical configuration of a series HEV drivetrain is developed by coupling the IC engine drivetrain to the bidirectional electric motor power source in order to create the charging-discharging ability of a battery. Commonly, the working principle of the series HEV is similar to the electric vehicle in which the electric motor is only used to propel the vehicle. However, the energy efficiency of the series HEV is much higher compared to pure electric vehicle due to the contribution of the gasoline engine that support the energy supply from the electric motor.

The structural layout of the parallel HEV is normally arranged with a mechanical coupling mechanism. A typical parallel hybrid drivetrain consists of a single IC engine mechanical power source and a battery/electric motor power source to propel the vehicle. Both of the powers are connected at the mechanical coupler that directly drives the wheels through the drive shaft. The parallel hybrid electric drivetrain can be considered as a conventional drivetrain with an additional batteries/motor which is used to improve the fuel economy of the IC engine. The only feature of this structure that differ is that two mechanical powers from the engine and electric motor are merged together by a mechanical torque coupler.

It is believed that between the three types of HEV available in the market, the Parallel Hybrid Electric Vehicle (PHEV) is the most simple, low-cost and require less space (Kumar and Subramanian, 2012;Ehsani et al., 2010). Several studies that have been done in the field of PHEV were focusing on the mechanical coupling device in the powertrain. For many years, the common mechanical coupling used to distribute the power between the ICE and electric motor were the mechanical and electro-mechanical transmission system utilizing the planetary gear unit together with the clutch mechanism (Salman et. al, 2000). Due to the limitation of the planetary gear in terms of control and design, the application of the mechanical transmission as the mechanical coupler in PHEV becomes less effective (Amarnath & Seth, 2014). Therefore, a new type of mechanical coupling mechanism based on the torque coupling is required to improve the torque distribution of PHEV.

The main benefit of the parallel hybrid drivetrain compared to the series HEV drivetrain is that both the engine and the electric motor in the PHEV directly supply torques to the driven wheels without energy conversion, thus the energy loss may be less. Besides, the parallel hybrid drivetrain is compact due to the traction motor is smaller and there is no need for an additional generator. However, Ehsani et. al., (2004), Menyang et. al., (2012) and Pritchard et. al., (2011) reported that the usage of a conventional torque coupler made the engine operating points cannot be fixed in optimum speed and torque region. It is due to the mechanical interaction between the engine and the electric motor. In order to surpass this problem, an electronic torque coupling called Electronic Wedge Torque Coupler (EWTC) mechanism is to be developed to replace the existing mechanical gear based mechanical coupling.

In this study, the electronically wedged mechanism model will be developed, characterized and tested. The electronic wedge mechanism works similarly to the principle that applied in electronic wedge brakes (Aparow et. al., 2014; Hudha et. al., 2014). The conceptual design of the proposed electronically controlled wedge mechanism for torque coupler will be discussed in detail on Chapter 3. The model is controlled using a brush DC motor where the motor drives the input through slider screw mechanism. The proposed design of the EWTC will then be characterized, simulated and controlled to observe the performance of the design.

1.4 Objectives and scopes of the study

The objectives of this proposed research work are as follows:

i. To design and develop an electronically controlled wedge mechanism for torque coupler of parallel hybrid electric vehicle.
ii. To develop the optimum control structure for position tracking control for the electronically controlled wedge mechanism.
iii. To evaluate the performance of an electronically controlled wedge mechanism for torque coupler in parallel hybrid vehicle, using hardware in the loop simulation (HILs) technique.

The scopes of this study are defined as follows:

i. Development of electronically controlled wedge prototype for torque coupler.
ii. Development of Permanent Magnet Synchronous Motor (PMSM) model using Matlab Simulink software .
iii. Characterization and validation of the electronically controlled wedge mechanism model.

iv. Development of the electronic wedge torque coupler simulation model using Matlab Simulink software.
v. Development of the five degree of freedom (DOF) vehicle longitudinal model using Matlab Simulink software.
vi. Development of the software in the loop and hardware in the loop simulation control for position tracking control of the electronically controlled wedge mechanism.
vii. Performation evaluation of torque coupler with parallel hybrid electric vehicle model and parallel hybrid electric vehicle test rig.

1.5 Significance of the Study

i. Design and fabrication of an electronic wedge torque coupler for parallel hybrid electric vehicle.
    - An electronic wedge torque coupler will be designed and fabricated in this study. The electronic wedge torque coupler will be used to effectively distribute the torque from the engine as well as from the DC motor to drive the drive shaft.

ii. Effective algorithm for torque distribution in parallel hybrid electric vehicle powertrain using electronic wedge torque coupler.
    - This research is expected to provide an efficient mechanism for controlling the torque distribution between the engine and DC motor in parallel HEV in which the torque can either be used separately or merged according to the desired condition.

1.6 Methodology

A flow chart describing the analysis methodology is shown in Figure 1.1. The procedure of the methodology is divided into seven different stages.

i. Literature review and patent search on related fields

   Literature study on established researches on parallel hybrid electric vehicle will be conducted focusing on the mechanical coupling of the drivetrain. Recent development related to the electronically controlled wedge mechanism will also be reviewed in this section.

ii. Design and development of the electronically controlled wedge mechanism

   In this section, the design and development of the electronically controlled wedge mechanism for torque coupler is developed to replace the gearbox/planetary gear system on the conventional mechanical coupler.

iii. Characterization of the electronically controlled wedge mechanism behavior

   In this section, the behavior of the developed electronic wedge torque coupler will be analyzed and the mathematical equation representing the actual system will be derived.

iv. Experimental setup and HIL setup

   Sensors and data acquisition card are prepared on the experimental test rig for torque coupler mechanism testing procedure in this section.

v. Position tracking control of the electronically controlled wedge mechanism

   Position tracking control of torque coupler mechanism using software-in-the-loop (SIL) and hardware-in-the-loop (HIL) simulation development.

vi. Development of vehicle longitudinal model