ELECTRO-MECHANICAL FRICTION CLUTCH CONTROL USING PROPORTIONAL DERIVATIVE PLUS CONDITIONAL INTEGRAL CONTROLLER

MOHD SALMAN BIN CHE KOB

UNIVERSITI TEKNOLOGI MALAYSIA

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MOHD SALMAN BIN CHE KOB

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ABSTRACT

Electro-Mechanical Friction Clutch (EMFC) is a clutch-by-wire system developed in Universiti Teknologi Malaysia (UTM) that uses a power screw mechanism for the engagement process. The mechanism provides self-lock capability that eliminates the requirement of continuous hydraulic pressure that leads to inefficiency during operation. Together with Electro-Mechanical Dual Acting Pulley Continuously Variable Transmission, an internal combustion engine (ICE) based powertrain efficiency improves significantly. However, its performance during vehicle start-stop, which is particularly critical during driving, has not been studied so far. Thus, the aim of this research was to simulate and experimentally validate the best controller for EMFC so that the start-stop condition can be executed smoothly and quickly for driving comfort. It was started by developing a mathematical model of the EMFC's actuator. Next, axial movement of the actuator was studied in the model for closed loop system using Proportional Integral Derivative (PID) based control algorithm. Relay feedback and Ziegler-Nichols's methods were utilized to tune the PID controller parameters. Based on the tuned parameters, various PID controller schemes such as Proportional (P), Proportional Integral (PI), PID and Proportional Derivative (PD) controllers were evaluated and the one with the best performance in terms of response time (T_r), percentage overshoot (*PO*), and steady state error (E_{SS}) was determined. From the evaluation, PD controller showed the best overall performance in terms of T_r (1.3 s), *PO* (0.7%) and E_{SS} (0.04 mm), hence it was selected as the reference. To further reduce the E_{SS}, which is crucial for precise clutch engagement, conditional integral parameter was activated in the controller, hence, it became Proportional Derivative Plus Conditional Integral (PDPCI). As a result, the E_{SS} was reduced to 1 μm while maintaining the T_r and *PO*. Subsequently, PD and PDPCI controller schemes were adopted for experimental work, to verify that they were safe to be implemented. Comparing the experimental results of the two controllers, PDPCI controller improved the EMFC performance against PD controller in terms of *PO* and E_{SS} by 32.8% (1.8% against 2.7%) and 77.3% (0.05 mm against 0.22 mm), respectively. The PDPCI was selected as the EMFC controller for the vehicle testing. In the testing, axial movement of the EMFC's actuator was controlled by the PDPCI controller to regulate the clutch engagement process. During the process, two clutch engagement strategies based on single-step-up (SSU) and double-step-up (DSU) inputs for the PDPCI controller were used. It was found that PDPCI using SSU input strategy makes the ICE stalled. PDPCI with DSU input strategy, on the contrary, shows a good EMFC engagement performance in terms of smooth engagement process with less than ±8 mm/s^3 jerking, no ICE stalling and minimum engagement time of less than 4 seconds for the vehicle start-stop under low, medium and full throttle pedal opening. In conclusion, the best EMFC controller has been successfully simulated and validated experimentally. It was shown that these outcomes provide an important contribution towards achieving EMFC desired engagement performance during vehicle launching condition.

ABSTRAK

Cekam Geseran Electro-Mechanical (EMFC) ialah sistem cekam-dengan-wayar yang dibangunkan di Universiti Teknologi Malaysia (UTM) yang menggunakan mekanisme skru kuasa untuk proses cekaman. Mekanisme ini menyediakan keupayaan kunci-kendiri yang menghapuskan keperluan tekanan hidraulik berterusan yang membawa kepada ketidakcekapan semasa operasi. Bersama-sama dengan Transmisi Nisbah Berterusan dengan Penggerak Elektro-Mekanikal, kecekapan penjana kuasa berasaskan enjin pembakaran dalaman (ICE) meningkat dengan ketara. Walau bagaimanapun, prestasinya semasa mula-henti kenderaan, yang mana amat penting semasa pemanduan, masih belum dikaji setakat ini. Oleh itu, tujuan penyelidikan ini adalah untuk mensimulasi dan mengesahkan secara eksperimen pengawal terbaik untuk EMFC supaya keadaan mula-henti dapat dilaksanakan dengan lancar dan cepat untuk keselesaan pemanduan. Ia dimulakan dengan membangunkan satu model matematik penggerak EMFC. Kemudian, pergerakan paksi penggerak dikaji dalam model sistem gelung tertutup menggunakan algoritma kawalan berasaskan pengawal Terbitan Kamiran Berkadar (PID). Dalam kajian ini, kaedah geganti suap balik dan Ziegler-Nichols telah digunakan untuk penalaan parameter pengawal PID. Berdasarkan parameter yang telah ditala, pelbagai skim pengawal berasaskan PID seperti pengawal berkadar (P), kamiran berkadar (PI), PID dan terbitan berkadar (PD), telah dinilai supaya pengawal yang mempunyai prestasi terbaik dari segi masa sambutan (T_r), peratusan terlajak (*PO*) dan ralat keadaan mantap (E_{SS}) boleh ditentukan. Daripada penilaian ini, pengawal PD menunjukkan prestasi keseluruhan yang terbaik dari segi T_r (1.3 s), *PO* (0.7%) dan E_{SS} (0.04 mm), justeru ia telah dipilih sebagai rujukan. Untuk mengurangkan lagi E_{SS}, yang mana sangat penting untuk cekaman yang tepat, parameter kamiran bersyarat telah diaktifkan dalam pengawal tersebut, maka ia menjadi Terbitan Berkadar Tambah Kamiran Bersyarat (PDPCI). Hasilnya, E_{SS} telah dikurangkan kepada 1 μm dengan mengekalkan T_r dan *PO*. Seterusnya, skim pengawal PD dan PDPCI diguna pakai dalam kerja eksperimen bagi menunjukkan bahawa keduanya selamat untuk dilaksanakan. Dari perbandingan keputusan eksperimen kedua-dua pengawal tersebut, pengawal PDPCI menunjukan peningkatan prestasi EMFC berbanding pengawal PD dari segi *PO* dan E_{SS} masing-masing sebanyak 32.8% (1.8% berbanding 2.7%) dan 77.3% (0.05 mm berbanding 0.22 mm). PDPCI telah dipilih sebagai pengawal EMFC untuk ujian kenderaan. Dalam ujian tersebut, PDPCI mengawal paksi pergerakan penggerak EMFC untuk melakukan proses mengawal selia masukan cekam. Semasa proses ini, dua strategi cekam berdasarkan masukan satu-langkah-menaik (SSU) dan dua-langkah-menaik (DSU) bagi penggerak PDPCI telah digunakan. Hasil dapatan menunjukkan PDPCI menggunakan strategi masukan SSU menyebabkan ICE terhenti. PDPCI dengan strategi masukan DSU, sebaliknya, menunjukkan prestasi cekaman EMFC yang baik, dari segi kelancaran proses masukan cekaman kurang daripada ±8 mm/s^3, ICE tidak terhenti, dan masa cekaman kurang daripada 4 saat untuk mula-henti kenderaan bagi bukaan pedal pendikit yang rendah, sederhana dan penuh. Kesimpulannya, pengawal EMFC terbaik telah berjaya disimulasikan dan disahkan secara eksperimen. Ia menunjukkan bahawa hasil ini memberikan sumbangan penting ke arah pencapaian prestasi penglibatan EMFC yang diingini semasa pelancaran kenderaan.

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LIST OF ABBREVIATIONS

AMT	-	Automated Manual Transmission
AT	-	Automatic Transmission
CVT	-	Continuously Variable Transmission
DC	-	Direct Current
DCT	-	Dual Clutch Transmission
DRG	-	Drivetrain Research Group
DSU	-	Double-Step-Up
EMDAP	-	Electro-Mechanical Dual Acting Pulley
EMFC	-	Electro-Mechanical Friction Clutch
EMP	-	Electromagnetic Powder Clutches
FEA	-	Finite Element Analysis
FVC	-	Frequency to Voltage Converter
ICE	-	Internal Combustion Engine
MT	-	Manual Transmission
PDPCI	-	Proportional Derivative Plus Conditional Integral
PID	-	Proportional Integral Derivative
PO	-	Percentage Overshoot
SDU	-	Speed Driver Unit
SSU	-	Single-Step-Up
TC	-	Torque Converters
UTM	-	Universiti Teknologi Malaysia
WC	-	Wet Clutches

LIST OF SYMBOLS

θ_3	-	Angle of Displacement of clutch fork (internal)
θ_4	-	Angle of Displacement of diaphragm spring A
θ_5	-	Angle of Displacement of diaphragm spring B
θ	-	Angular displacement
θ_2	-	Angle of Displacement of clutch fork (external)
a	-	Amplitude of the waveform of oscillation
b_e	-	Viscous friction coefficient
B_m	-	Viscous friction coefficient
b_v	-	The corresponding friction coefficient and
d	-	Relay amplitude
d_m	-	Mean diameter of power screw
D_x	-	Axial force
E_b	-	Back emf
E_{ss}	-	Steady state error
F_a	-	Normal force applied to the friction clutch
f_N	-	Friction force
i_a	-	Motor Current
I_e	-	Engine inertia
I_v	-	The equivalent vehicle moment of inertia
J_m	-	Motor Inertia
K_b	-	Back emf constant
K_c	-	Critical gain
K_d	-	Derivative gain
K_i	-	Integral gain
K_p	-	Proportional gain
K_T	-	Torque Constant
l	-	Pitch of power screw
L_a	-	Motor Inductance
N	-	Normal force

N_p	-	The number of friction plate surface
P	-	Force required to lowering the load
P_R	-	Force required to raising the load
R	-	Equivalent disk ratio
R_a	-	Motor Resistance
r_i	-	Inner radius of friction plate
r_o	-	Outer radius of friction plate
S_1	-	Displacement of inner power screw
S_2	-	Angular Displacement of clutch fork arm (external)
S_3	-	Angular Displacement of clutch fork arm (internal)
S_4	-	Angular Displacement of diaphragm spring A
S_5	-	Angular Displacement of diaphragm spring B
T_c	-	Critical period of waveform oscillation
T_{cl}	-	The torque transmitted by the clutch
T_d	-	Derivative time
T_e	-	Engagement time
T_i	-	Integral time
T_{in}	-	The engine torque
T_l	-	The equivalent load torque
T_L	-	Load Torque
T_{lift}	-	Torque for lifting load
T_{lower}	-	Torque for lowering load
T_m	-	Motor Torque
T_r	-	Rise time
V_a	-	Motor Voltage
x_1	-	Clutch spring displacement
X_1	-	Number of revolutions of outer power screw
X_a	-	Actual inner power screw position for clutch engagement
X_d	-	Desired inner power screw position for clutch engagement
μ_m	-	Friction of power screw surface contact
μ_d	-	The friction coefficient of the clutch surface material
ω_e	-	engine speed
λ	-	Lead angle

CHAPTER 1

INTRODUCTION

1.1 Introduction

Automotive engineering technology related to the enhancement of fuel efficiency has recently gained great attention form researchers from all over the world. In dealing with such issue, some new transmission technologies have thus been developed, and one of them is continuously variable transmission (CVT). Currently, the majority of CVT vehicles use wet clutches (WC), electromagnetic powder clutches (EPC) and torque converters (TC). TC is well-known for its excellent ride during the vehicle start-up and changing gears ratio, but deviates from the overall drivetrain production pattern due to its high cost, low performance, and complicated design. (Guoling Kong et al. 2009). EPC can be controlled electronically because it is connected by excitation coil that generates a magnetic flux for engagement process, but it has a problem of heat dissipation (Kim and Choi, 2011). Moreover, the hydraulic actuation devices for WC have a high percentage of energy loss in the transmission systems due to continuous power to maintain the desired WC engagement process, although they are commonly used in transmissions. All of these clutches used commonly consume continuous power to hold the clutch engagement process continuously and suffer from energy losses in terms of heat dissipation. According to Kim and Choi (2011), automated manual transmission (AMT) and dual clutch transmission (DCT) meet the requirement of better fuel efficiency with up to 15% compared to planetary gearset automatic transmission (AT) that use TC. In addition, by employing dry friction clutches in AMT or DCT applications, fuel efficiency is expected to be further enhanced by up to 1.5% (Kim, 2011).

Taking advantage of the dry clutch engagement process with electro-mechanical actuator and by totally eliminating the application of hydraulic-based actuation system, transmission researchers and engineers from Drivetrain Research

Group (DRG), Universiti Teknologi Malaysia (UTM) have been working very hard to design and develop such technology, and as a result, a novel Electro-Mechanical Dual Acting Pulley (EMDAP) continuously variable transmission (CVT) was introduced (Che Kob *et al*. 2015; Mazali, 2017; Tawi *et al*. 2014). Elsewhere, researchers from Technische Universiteit Eindhoven (TU/e) have also developed their own prototype of electro-mechanical CVT (EM CVT) named Electro-Mechanical Pulley Actuation CVT (EMPACT CVT) based on Jatco CK2 transmission. Descriptions of EMPACT CVT can be found in Vroemen (2001), Meerakker *et al*. (2004), Klaassen *et al*. (2004), Klaassen *et al*. (2008), and Klaassen *et al*. (2007). There is also a design of EM CVT that applies one-motor-one-belt approach has been developed by Aichi Machine Industry, named Electro-Mechanical Controlled (EMC) CVT, and such design is reviewed previously by Xinhua *et al*. (2008). Based on these transmission developments, an internal combustion engine (ICE) based powertrain with CVT can be a viable solution to achieve low fuel consumption requirement because of its wide and continuous ratio coverage which allows the engine to run within the most efficient operating range for various load conditions. (Liu and Paden, 1997, Delhaise *et al*. 2020; Cholis, Ariyono, and Priyandoko 2015; Supriyo 2014; Supriyo *et al*. 2013; Tawi *et al*.2014).

For the vehicle powered by ICE and equipped with metal pushing V-belt CVT, the CVT ratio can be constantly varied without interruption of a clutch disengagement and engagement. However, during the vehicle launching condition, the driveline oscillations can easily be produced, which significantly affects driving comfort (You *et al*. 2019; Wang *et al*. 2020). Besides, proper clutch engagement is also required to prevent ICE from stalling, since it cannot run slower than its idle speed, usually measured at around 900 RPM. In order to prevent the ICE from stalling and to ensure a smooth clutch engagement, an electro-mechanical friction clutch (EMFC) is designed and developed for integration with the EMDAP CVT. Moreover, a good control strategy is required to provide a smooth EMFC engagement process with minimum engagement time without sudden stopping of the ICE turning during the vehicle launching condition. Thus, this research is carried out to achieve a smooth clutch engagement process with minimum engagement time that can increase the overall vehicle powertrain efficiency especially for the real potential of EMDAP CVT powertrain application in ICE.

The major components of EMFC include a newly designed mechanical actuator, a standard dry friction clutch and torque multiplier gears for a direct current (DC) motor, as shown in Figure 1.1. A dry friction clutch is used to engage and disengage power from an ICE via the EMDAP CVT gearbox. A release bearing is attached to the mechanical actuator with a clutch linkage. The mechanical actuator is powered by the DC motor. A series of gear reducers and a power screw mechanism are mounted directly to the output shaft of the DC motor.

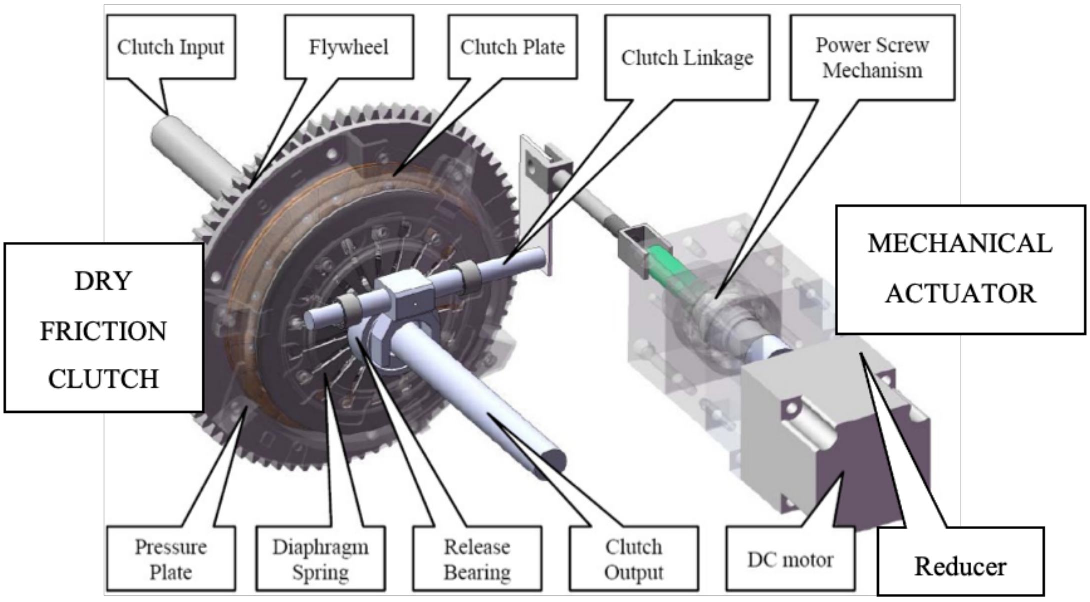

Figure 1.1 EMFC system's main parts

Figure 1.2 shows the stepless transmission which is called the EMDAP CVT system. EMFC's mechanical actuator is designed using the drive principle of power screw mechanism actuated by DC motor, in conjunction with electronic control technology to eliminate the conventional hydraulic actuation systems which is consumed continuous power during system operation.

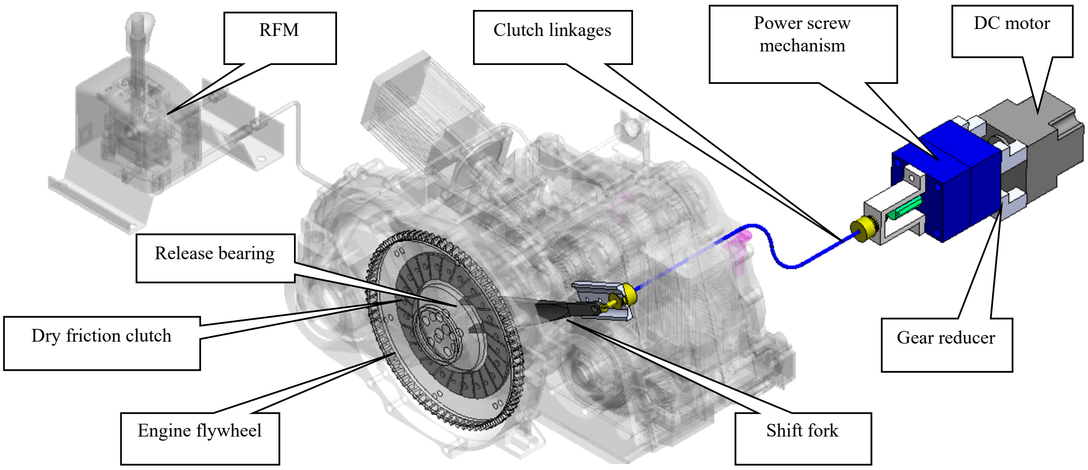

Figure 1.2 EMFC integrated with EMDAP CVT.

The engagement and disengagement processes of EMFC are operated by DC motor. The output shaft of the DC motor is connected to the reduction gears in order to multiply the DC motor output torque which enables the DC motor to supply adequate power. This power is transferred to an inner power screw rotation and converted into axial force by the linear movement of outer power screw. This linear motion is then transmitted to either engage or disengage the dry clutch to actuate the shift fork. The shift fork is connected to the inner power screw via the clutch linkages. Figure 1.3 shows that when the inner control screw moves outward from the EMFC actuator, the clutch is disengaged, and when the actuator moves inward, the clutch is engaged. There is a release bearing between the diaphragm spring and the shift fork. This release bearing is used to press the rotating diaphragm spring during the disengagement process and vice versa.

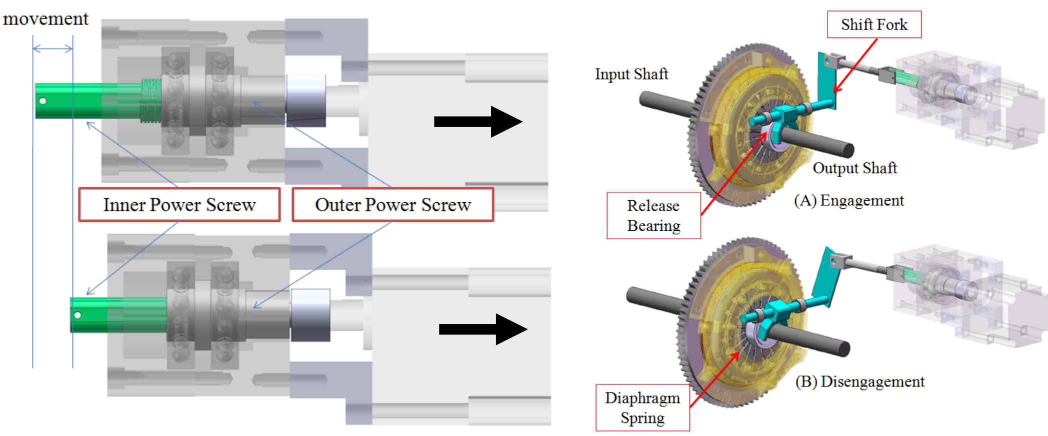

Figure 1.3 EMFC engagement and disengagement conditions

Electronic control can be used in EMFC operations, allowing a closed-loop control strategy to be applied to enhance the EMFC engagement process during vehicle launching condition. Hence, an optimum performance of EMFC in EMDAP CVT powertrain applications can be achieved. This current research emphasizes on the closed loop controller strategy of electro-mechanical actuator to control EMFC engagement process during vehicle launching condition. This research focused on designing and developing EMFC engagement controller strategy in time domain analysis based on proportional-derivative-conditional (PID) based controller variants consisting of P, PI, PD, PID and proportional-derivative-plus-conditional-integrator (PDPCI) controller. This research covers the simulation and real-time experimental work. In the simulation work, the EMFC actuation position control is used to test various PID controller variants in terms of percentage overshoot (*PO*), rise time (T_s), and steady state error (E_{ss}) of the actuator movement position. The experimental work on actual vehicle equipped with EMDAP CVT powertrain evaluated the clutch speed engagement time and vehicle jerk to demonstrate the practicability of the control strategy proposed during the vehicle launching process.

1.2 Problem Statement

Conventional continuously variable transmission (CVT) uses hydraulic pressure generated by the internal combustion engine (ICE) to clamp its metal pushing V-belt and to vary the ratio accordingly. Because of that, the usual moving-off element used in a CVT is either wet clutch or torque converter. Wet clutch normally consists of multi-plate construction regulated by hydraulic pressure to execute proper engagement and disengagement of the internal combustion engine (ICE) to the CVT. Torque converter, on the other hand, uses hydraulic pressure between its impeller and turbine to facilitate the aforementioned engagement and disengagement properly. In both cases, the hydraulic pressure is produced by consuming a portion of ICE power and this reduces the overall efficiency of the vehicle powertrain. As a result, the improved efficiency gained from the CVT’s continuous ratio range is cancelled out; hindering the real potentials of the CVT. Dry friction clutch, while eliminates the hydraulic pressure for the engagement and the disengagement, is difficult to be implemented with the conventional CVT due to the hydraulic actuation system of the CVT. An alternative actuation system is required to replace the hydraulic actuation system before the dry friction clutch can be practically integrated with the CVT. Hence, the introduction of electro-mechanical dual acting pulley CVT (EMDAP CVT) recently by UTM researchers opens up the possibility for the implementation of dry friction clutch in the CVT. This is because EMDAP CVT applies power screw actuation system instead of the hydraulic actuation system to vary the ratio and to clamp the belt. However, proper research works have to be conducted to investigate the effectiveness of implementing the clutch in the EMDAP CVT and eventually to compare its practicality against the existing CVTs with wet clutch and torque converter. Therefore, electro-mechanical friction clutch (EMFC) with its controller is proposed in order to achieve clutch engagement control objectives. EMFC consists of dry friction clutch integrated with an actuation system. The actuation system comprises power screw mechanism and DC motor to control the engagement and disengagement of the clutch. With EMFC, the application of hydraulic pressure is eliminated entirely, which means no power from the ICE is consumed for the operation of the CVT and its moving-off element. As such, the efficiency of the vehicle powertrain can be maximised.

1.3 Research Objectives

The main goal of the research is to design and implement an appropriate control strategy that would be able to control the clutch engagement smoothly with minimum engagement time of EMFC without engine stall during vehicle launching process for EMDAP CVT powertrain vehicle prototype. To achieve this, the following sub-objectives had been considered:

i. To design and develop the electronic hardware for EMFC integrated with EMDAP CVT powertrain on actual vehicle test.

ii. To design, develop and implement several real-time PC based of EMFC engagement control algorithms which include PD and PDPCI controllers.

iii. To evaluate and compare vehicle launching condition in terms of vehicle jerk below $\pm 10 m/s^3$, engagement time less than 5 seconds and no engine stall occurs according to current vehicle transmission performances.

1.4 Research Scope

This study involves simulation and experimental works on EMFC control system. All experimental studies were performed in UTM Automotive Laboratory. The scope of the research is as follows:

i. Simulation and experimental works are carried out using MATLAB Simulink software only.

ii. Tuning of PID based controller parameters is based on relay feedback and Ziegler-Nichols methods.

iii. The best PID based controller from the simulation work is validated and adopted as reference for conducting experimental work.

iv. Design and development of EMFC controller is based on prototype of EMDAP CVT powertrain for an application with 1.6L Proton Persona petrol engine.

v. Experimental work is carried out by applying the actual vehicle loads from idle speed up to 3000 RPM engine speed during vehicle launching process on the flat ground.

vi. Performance evaluation indexes of clutch engagement process are based on vehicle jerk (below ± 10 m/s^3, clutch engagement time (below 5 seconds) and no engine stall occurs during vehicle launching process.

1.5 Research Contributions

This study provides the following main research contributions:

(i) PID based control algorithm developed specifically for EMFC engagement control. The PID controller parameters are tuned using relay feedback and Ziegler-Nichols methods in simulation environment. The best performance controller is then implemented on the real vehicle experimental rig to validate its performance for safety purpose.

(ii) Design, development and implementation of electronic hardware for the EMDAP CVT powertrain prototype with integration of MATLAB Simulink control algorithm programs for EMFC engagement control strategy.

(iii) Complete mechanical system of EMFC which is integrated with EMDAP CVT in a test car for various research activities.

1.6 Research Methodology

Figure 1.4 shows the flow chart of the research methodology. It can be described as follows:

1. Literature review was conducted to determine typical methods, parameters and PID based controllers used for modelling and experimental works related to automotive clutches. The information from the review is crucial for the development of the EMFC's mathematical model, its controller and also for the planning and execution of the experimental works.

2. The mathematical model of EMFC actuator was designed and developed for simulation purpose. The EMFC model consisted of DC motor, gear reducer and power screw mechanism. Basic equations of the circuit equivalent of DC motor and data sheet parameters were used for DC motor modelling. Its torque-

speed performance was validated with torque speed curve stated on the datasheet of the DC motor. Gear reducer was used as the torque multiplier and modelled as a gain block. The basic equations of power screw are used to model the mechanical power screw actuator. It served as a rotational movement converter into linear movement.

3. After performing a simulation with the open loop of EMFC model, a PID based controller model was proposed. The proposed control model was applied with the desired input position strategy control of clutch plate in order to manage the clamping force related to the clutch pressure plate during the engagement phase. Initial parameters of PID based controller had to be determined to prove whether the position control strategy can be used to control the EMFC engagement process or not. Both EMFC and PID-based controller models were combined to perform EMFC engagement controller simulation, resulting in a closed loop system. Modelling and simulation work were performed using MATLAB Simulink software. The simulation data were used as the preliminary results to evaluate the EMFC's actuator output performance and mechanical safety purpose, prior to the experimental work.

4. EMFC vehicle test was designed and developed accordingly for experimental works. The development process involved integration of software and hardware based on the prototype of EMDAP CVT powertrain arrangement.

5. The test rig was set-up accordingly by performing the sensors calibration for accurate measurement of data, so that the simulated controllers for EMFC can be validated experimentally.

6. The initial parameters of PID controller were determined based on the relay feedback of Astrom Hagglund method and the parameters were calculated using Ziegler-Nichols formula. PD, and PDPCI control algorithms were selected to perform the EMFC engagement controllers based on the simulation results following to mechanical safety limit before all these PID parameters are used to test the EMFC engagement control algorithms for PC based control application.

7. For each control algorithm, the EMFC actuator output performance was evaluated based on the PO, T_s, and E_{ss}. Modification of PID based controller is conducted to obtain the best result. The selected control algorithm based on the actuator performance evaluation was applied with different desired actuator inputs strategy to perform dry friction clutch engagement process. The actual load from vehicle was applied during the experiment. The engine speed was set up to 3000 RPM for vehicle launching condition. EMFC engagement strategy performance was assessed based on clutch engagement time between engine and output of clutch rotational speeds. Moreover, the smoothness of EMFC engagement phase during the vehicle launching process was evaluated based on the vehicle jerk on the driver compartment.

8. EMFC engagement control strategy performance was then analysed based on the clutch engagement control objectives (no jerking, minimum engagement time and no engine stalling) during vehicle launching process in order to make a proper assessment of the proposed control strategy.

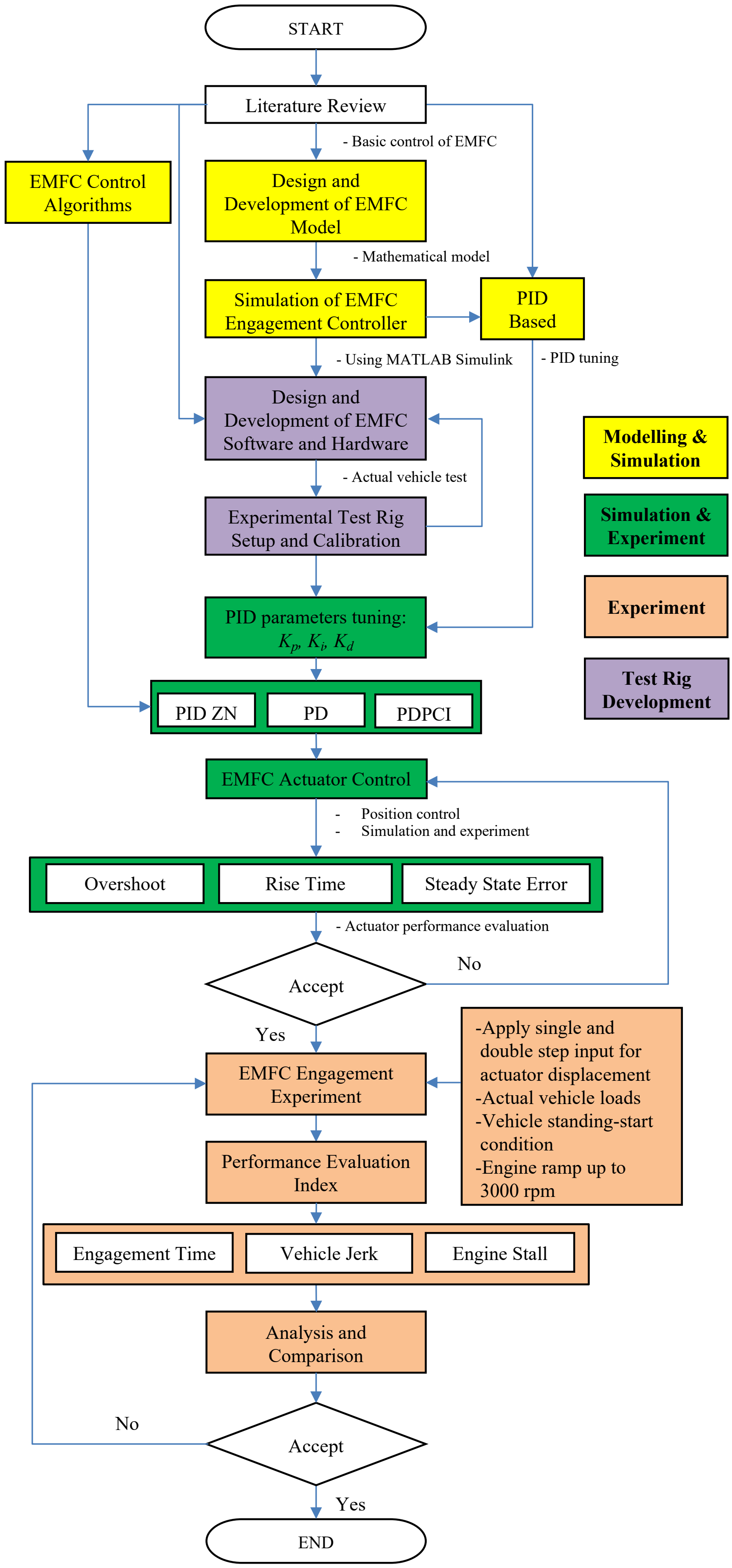

Figure 1.4 Flow chart of research methodology

1.7 Thesis outline

The thesis contains six chapters. Chapter 1 introduces and highlights the importance of the study. Chapter 2 presents the literature review. Several types of transmission and clutches are briefly reviewed. Then, the review focuses on existing works related to clutch control, specifically involving PID based controls, and DC motors for position control applications as well as software application. Gaps are identified and justifications of the research objective and research methodology are presented.

Chapter 3 presents modelling and simulation of EMFC and its control. Development of the model started by creating a DC motor model, and then, simulating the model to obtain motor torque and speed performance for validation with the datasheet. The next step is to build mechanical model of EMFC system, which consisted of power screw mechanism and gear reducer. Subsequently, PID control model was built based on its equation, and finally, it was combined with EMFC mechanical model to perform EMFC actuator control simulation.

Chapter 4 presents the EMFC system description. This chapter presents the basic concept of clutch engagement and covers more detail on EMFC test rig especially in terms of hardware and software design as well as the procedure of performing clutch control. This chapter describes the main mechanical and electronic parts of EMFC, also the interfacing unit which makes possible for the EMFC to communicate with computer via Data Acquisition System.

Chapter 5, meanwhile, explains the implementation of PID control algorithm in the experimental works of EMFC engagement control. The real responses of the system are analyzed and discussed. Finally, Chapter 6 presents the conclusions and recommendations for future research.

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