SYSTEM IDENTIFICATION AND SPEED CONTROL OF ELECTRO-MECHANICAL DUAL ACTING PULLEY CONTINUOUSLY VARIABLE TRANSMISSION

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Specially dedicated to:

My beloved parents:
Mat Dzahir Ali
Zaimah Mohamad

My brother and sisters:
Siti Nor Azlima, Mohd Azuwan, Nor Azmiera,
Nor Anisa and Nor Atiqah

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ABSTRACT

Researchers at Universiti Teknologi Malaysia (UTM) has designed, developed and patented an Electro-Mechanical Dual Acting Pulley Continuously Variable Transmission (EMDAP CVT). The newly developed EMDAP CVT is a complex nonlinear system. Since the system is difficult to be modeled, designing the suitable controller for the EMDAP CVT is a challenging task. However, it is possible to obtain model system and transfer function by employing System Identification (SI) technique. By having mathematical representation of the EMDAP CVT in form of transfer function, controller's analysis and future works relating to the EMDAP CVT will be much easier. The main part of this research is to develop a model which is able to imitate the current EMDAP CVT system behaviours. Therefore, SI was performed to develop the model system and transfer function. Genetic Algorithm (GA) is used as an estimator with Nonlinear ARX (NARX) as a model structure. The mathematical modelling of the EMDAP CVT system is successfully presented and verified in form of 3rd order nonlinear transfer function. The focus of this research work is more on the implementation of speed control for the EMDAP CVT system based on model obtained from the SI. The EMDAP CVT speed controllers are designed for adjusting speed through providing appropriate CVT ratio to the system. The control objective is to achieve a desired output speed, which is used to specify and maintain the desired CVT ratio for the EMDAP CVT system. Proportional-Integral-Derivative (PID) controller is used as the basis and then fined tuned using conventional Ziegler-Nichols and Particle Swarm Optimization (PSO) method. Three controllers which are Proportional-plus-PSO (P-PSO), Proportional-Derivative-plus-PSO (PD-PSO) and Proportional-Integral-Derivative-plus-PSO (PID-PSO) were developed to test the reliability of the obtained model system and transfer function. The performance of the designed controllers was demonstrated and validated through simulations and experiments. The error performance of the developed controllers is evaluated in terms of Integral of Absolute Error (IAE), Integral Square of Errors (ISE), Integral of Time multiplied by Absolute Errors (ITAE), and Mean Square Error (MSE). Based on the results, the PIDPSO speed controller gives a sufficient performance, such as settling time, overshooting and error performance. The validation approach resulted in lower than 5% percentage error thus verified the 95% confidence limit of the model system. Further controller's analysis using Fuzzy Logic (FL) and Neural Network (NN) controllers were performed on the obtained model system and transfer function. The performance of the tested controllers were evaluated in terms of Steady State Error (SSE) and MSE values. All of the tested controllers produced good performance with steady state response within 5 seconds and SSE percentage lower than 5%. The end results show that, NARMA-L2 neural speed controller gives the best performance with SSE percentage of 0.91% and smallest MSE value of 3.28.

ABSTRAK

Penyelidik di Universiti Teknologi Malaysia (UTM) telah mereka bentuk, membangun dan mempatenkan sebuah penggerak-dua-takal-elektro-mekanikal penghantar kuasa pembolehubah berterusan (EMDAP CVT). Oleh kerana sistem ini sukar dimodelkan, mereka bentuk pengawal yang sesuai untuk EMDAP CVT adalah tugas yang mencabar. Walaubagaimanapun, adalah mungkin untuk mendapatkan sistem model dan fungsi pindah dengan menggunakan teknik Pengenalan Sistem (SI). Dengan mempunyai perwakilan matematik untuk EMDAP CVT dalam bentuk fungsi pindah, analisis pengawal dan kerja-kerja masa depan yang berkaitan dengan EMDAP CVT akan menjadi lebih mudah. Bahagian utama penyelidikan ini adalah untuk membangunkan model yang dapat meniru tingkah laku sistem EMDAP CVT. Oleh itu, SI telah dilakukan untuk membangunkan sistem model dan fungsi pindah. Algoritma Genetik (GA) digunakan sebagai penganggar dengan Nonlinear ARX (NARX) sebagai struktur model. Permodelan matematik untuk sistem EMDAP CVT berjaya dibentangkan dalam bentuk fungsi pindah tak linear ketiga. Tumpuan kerja penyelidikan ini lebih kepada pelaksanaan kawalan laju untuk sistem EMDAP CVT dengan berdasarkan model yang diperolehi daripada SI. Pengawal kelajuan EMDAP CVT direka untuk menyesuaikan kelajuan dengan memberikan nisbah CVT yang sesuai kepada sistem. Objektif kawalan adalah untuk mencapai kelajuan output yang dikehendaki, yang digunakan untuk menentukan dan mengekalkan nisbah CVT yang dikehendaki sistem EMDAP CVT. Pengawal Proportional-Intergal-Derivative (PID) telah digunakan sebagai pengawal asas dan kemudian ditala menggunakan kaedah konvensional Ziegler-Nichols dan kaedah Particle Swarm Optimization (PSO). Tiga pengawal seperti Proportional-plus-PSO (P-PSO), Proportional-Derivative-plus-PSO (PD-PSO) dan juga Proportional-Integral-Derivative-plus-PSO (PID-PSO) dibangunkan untuk menguji sistem model EMDAP CVT dan fungsi pindah yang diperolehi. Prestasi pengawal yang direka telah ditunjukkan dan disahkan melalui simulasi dan eksperimen. Prestasi kesilapan pengawal yang dibangunkan dinilai dari segi Integral of Absolute Error (IAE), Integral Square of Errors (ISE), Integral of Time multiplied by Absolute Errors (ITAE), dan juga Mean Square Error (MSE). Berdasarkan keputusan, pengawal kelajuan PID-PSO memberikan prestasi yang mencukupi, seperti masa penetapan, keterlaluan dan kesilapan prestasi. Pendekatan pengesahan menunjukkan ralat peratusan dibawah 5% mengesahkan had keyakinan 95% sistem model. Analisis pengawal lanjutan menggunakan pengawal Fuzzy Logic (FL) dan Neural Network (NN) dilakukan pada sistem model dan fungsi pindah yang diperolehi. Prestasi pengawal yang diuji telah dinilai dari segi Steady State Error (SSE) dan nilai MSE. Kesemua pengawal yang diuji menghasilkan prestasi yang bagus dengan respon keadaan mantap sekitar 5 saat dan peratusan SSE dibawah 5%. Keputusan akhir menunjukkan pengawal kelajuan NARMA-L2 neural memberikan prestasi terbaik dengan peratusan SSE 0.91% dan nilai MSE terkecil 3.28.

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LIST OF ABBREVIATIONS

AANN	-	Adaptive Artificial Neural Network
A/F	-	Active Force
AMT	-	Automated Manual Transmission
ARMA	-	Auto-regressive with Moving Average
ARX		Auto-regressive with eXogenous
AT	-	Automatic Transmission
BLDC	-	Brushless DC
CVT	-	Continuously Variable Transmission
DAF	-	Van Doorne's Automobiel Fabriek
DAS	-	Data Acquisition System
DC	-	Direct Current
DCT	-	Dual Clutch Transmission
DRG	-	Drive-train Research Group
ECU	-	Electronic Control Unit
ECVT	-	Electronically Controlled CVT
EMAPS	-	Electro-Mechanical Actuated Pulley Sheaves
EMDAP	-	Electro-Mechanical Dual Acting Pulley
EMPAct	-	Electro-Mechanical Pulley Actuation
FAM	-	Fuzzy Associate Memory
FIS	-	Fuzzy Inference System
FL	-	Fuzzy Logic
FLC	-	Fuzzy Logic Controller
FPID	-	Fuzzy PID
FPID-5MF	-	Fuzzy Proportional Integral Derivative with 5 Membership Functions
FPID-7MF	-	Fuzzy Proportional Integral Derivative with 7 Membership

		Functions
GA	-	Genetic Algorithm
HEV	-	Hybrid Electirc Vehicle
HMCVT	-	Hydro-Mechanical CVT
I/0	-	Input/Output
IAE	-	Integral of Absolute Error
ICE	-	Internal Combustion Engine
IEEE	-	Institute of Electrical and Electronics Engineers
ISE	-	Integral of Square Error
IS-PID	-	Integral Separation PID
ITAE	-	Integral Time of Absolute Error
MPC	-	Model Predictive Control
MSE	-	Mean Square Error
MT	-	Manual Transmission
NARMA	-	Nonlinear Autoregressive-moving Average
NARX	-	Nonlinear ARX
NB	-	Negative Big
NN	-	Neural Network
NS	-	Negative Small
OOL	-	Optimal Operating Line
PB	-	Positive Big
PC	-	Personal Computer
P	-	Proportional
PPSO	-	Proportional-Particle-Swarm-Optimization
PD	-	Proportional-Derivative
PDPCI	-	Proportional-Derivative-plus-Conditional -Integrator
PDPSO	-	Proportional-Derivative-Particle-Swarm-Optimization
PID	-	Proportional-Integral-Derivative
PIDPSO	-	Proportional-Integral-Derivative-Particle-Swarm-Optimization
P-line	-	Pressure Line
PMF	-	Poison Moment Function
PRBS	-	Pseudo-Random Binary Signal
PRMS	-	Pseudo-Random Multi-level Signal

PS	-	Positive Small
PSO	-	Particle Swarm Optimization
PWM	-	Pulse-Width-Modulation
RCV	-	Ratio Control Valve
RCSV	-	Ratio Control Solenoid Valve
SI	-	System Identification
SISO	-	Single Input Single Output
SPU	-	Speed Controller Unit
TCVT	-	Toroidal CVT
TSK	-	Takagi-Sukeno-Kang
TVO	-	Throttle Valve Opening
UTM	-	Universiti Teknologi Malaysia
VDT	-	Van Doorne's Transmissie B.V.
ZN	-	Ziegler-Nichols

LIST OF SYMBOLS

R_P	-	primary pulley running radius
R_S	-	secondary pulley running radius
$RCVT$	-	CVT ratio
$RCVT_{output}$	-	output CVT ratio
$RCVT_{desired}$	-	desired CVT ratio
V_m	-	BLDC motor speed adjustment voltage
X_P	-	primary pulley position
X_{PO}	-	initial primary pulley position
X_S	-	secondary pulley position
X_{SO}	-	initial secondary pulley position
r_g	-	geometrical ratio
r_s	-	speed ratio
ω_e	-	angular speed of the engine
ω_P	-	angular speed of the primary (input) shaft
ω_S	-	angular speed of the secondary (input) shaft
e	-	system error
e_P	-	primary error
e_S	-	secondary error
$e(s)$	-	error response
de	-	derivative error
K_c	-	critical gain
K_d	-	derivative gain
K_i	-	integral gain
K_p	-	proportional gain
$r(s)$	-	input response
r_{out}	-	output CVT ratio
r_{des}	-	desired CVT ratio

r_{new}	-	new CVT ratio
T_c	-	critical period of oscillation
T_d	-	derivative time
T_P	-	primary torque
T_S	-	secondary torque
T_i	-	integral time
$u(s)$	-	control response
v	-	relative slip
F_P	-	primary clamping force
F_S	-	secondary clamping force
$y(s)$	-	output response

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CHAPTER 1

INTRODUCTION

1.1 Introduction

A continuously variable transmission (CVT) is used to exchange energy between the flywheel and the wheels. Most of the belt type CVT used in cars are hydraulically actuated. This kind of CVT has efficiency of approximately 85% (Kluger and Long, 1999) which is lesser than manual transmission which has 96% efficiency. The drawback of it is mostly related to high pump and high oil pressure of the hydraulic system. There is also drawback which is caused by the belt loss (Micklem et al., 1996; Ide, 2000; Matthes, 2005). The continuous power consumption of the hydraulic actuator, especially when driving using a constant transmission ratio, causes a power loss which contributes to a big part of the overall CVT loss.

However, in 2010, Universiti Teknologi Malaysia Drive-train Research Group (UTM-DRG) developed the Electro-Mechanical Dual Acting Pulley Continuously Variable Transmission (EMDAP CVT). The EMDAP CVT system which adopts power-screw mechanism, to overcome hydraulic power loss when maintaining constant transmission ratio, and two movable pulley sheaves on each of its pulley shaft, to eliminate belt misalignment. Axial movements of both primary (input) and secondary (output) movable pulley sheaves are electro-mechanically controlled by direct current (DC) motors that turn the power screw mechanism and shift the movable V-pulley sheaves axially. The axial movements of pulley sheaves change the effective pulley-belt contact radii and then consequently change the transmission ratio. In order to provide sufficient clamping force on the V-belt to avoid slipping or overstress, the secondary DC electric motor adjust the length of the disk spring on secondary pulley accordingly. Therefore, the indirect control objective of the research is to specify the ratio of primary to secondary pulley speed by means of primary axial movements. Importantly, the primary control objective will be to achieve a desired output speed, which is considered a known function of throttle angle and vehicle speed. This desired output speed will be used to specify the desired CVT ratio ($RCVT_{desired}$), and then used it to specify the control input.

Previous work involving the EMDAP CVT mostly emphasizes on the developing the system itself. The first work was carried out by Ariyono (2009) focussed more on controlling the DC motor rotation accordingly to achieve the desired CVT ratio based on intelligent control system using adaptive artificial neural network (AANN). Ariyono's method provides an appropriate CVT ratio based on a vehicle maximum power strategy. He also used the EMDAP CVT as a means of matching the power transfer function between the engine and the transmission system. Additionally, the Proportional-Derivative (PD) ratio controller was applied to provides a suitable CVT ratio to the system such that the engine speed can be kept within its effective range. Ariyono stated that, the end results show the controller developed using standard vehicle performance equations and simplified powertrain model was able to varying the EMDAP CVT ratio from underdrive to overdrive in less than 15sec.

The work was then continued by Supriyo (2010) which emphasizes on the inner loop controller part of the work previously done by Ariyono, in order to improve the EMDAP CVT ratio controller. Supriyo's work focussed more on controlling the movement of the pulley sheaves to provide a suitable CVT ratio to the EMDAP CVT system based on several control algorithms such as PID based controllers consisting of PD and Proportional-Derivative-plus-Conditional-Integrator (PDPCI) and Fuzzy-PID (FPID) controllers. Supriyo's study shows that, the steady state error cannot be eliminated permanently by PD controller. On the other hand, PD-PCI and Fuzzy-PID controllers was able to reduce it significantly. Supriyo's experimental results confirm that when Fuzzy-PID control algorithms applied in EMDAP CVT ratio controller, it provides better performance compared to PD or

PDPCI control algorithms. Both of Ariyono and Supriyo research work around CVT ratio to improve the EMDAP CVT performance. Even though, it able to provide a good CVT ratio into the EMDAP CVT system, the EMDAP CVT output speed performance is still far from exceptional. By directly control the output speed of the EMDAP CVT while providing a good CVT ratio into the EMDAP CVT system, the performance of the EMDAP CVT system can be improve further. It is also hard to develop a controller using the existing system. However, by having mathematical representation of the EMDAP CVT system, controller's development and implementation will become much easier.

The current research involves the identification of the EMDAP CVT system speed change dynamics for improving the ratio change model. The main part of this research, work intensively on developing a system model and transfer function which able to exactly imitate the current EMDAP CVT system behaviours. System Identification (SI) is the field of mathematical modelling of systems using an experimental data. During an identification experiment, signals that excite all relevant system dynamics, are applied to the system inputs, while the system outputs are recorded. By means of a computational method, a mathematical description of the relation between the inputs and outputs is determined. This input-output description is called a mathematical model. However, there exist nonlinearities in the current EMDAP CVT system such as geometrical composition, friction, backlash and dead zone. To overcome this, a nonlinear autoregressive with exogenous input (NARX) is used as a model structure since it does not require detailed knowledge on the complex physical phenomena of the EMDAP CVT system. In following Chapter 4, the EMDAP CVT system dynamics were identified using this procedure.

This research also works on designing and developing a robust EMDAP CVT speed controller on several control algorithms such as PID speed controllers consisting of Proportional-plus-Particle-Swarm-Optimization (P-PSO), Proportional-Derivative-plus-Particle-Swarm-Optimization (PD-PSO), Proportional-Integral-Derivative-plus-Particle-Swarm-Optimization (PID-PSO), Fuzzy Logic (FL) and also Neural Network (NN) speed controller based on model obtained from system identification. The genuity of the proposed speed controllers is validated through simulation and experimental results.

1.2 Problem Statement

The newly developed EMDAP CVT is a complex and non-linear system. Therefore, the challenge of this research is to obtain a model which able to describe the exact behaviour of the EMDAP CVT system. However, it is possible to obtain the system model and transfer function by employing system identification techniques. Secondly, to develop a robust speed controller with a good performance for the EMDAP CVT system. Results from simulation with real system verification and validation will justify the findings.

1.3 Research Objectives

The general research objective is to study the speed change behaviours of the EMDAP CVT system by designing, developing and implementing a speed controller into the system. Several specific objectives are determined as follows:

(i) to study System Identification (SI) techniques and optimization methods suitable for dynamic modelling of the EMDAP CVT system.
(ii) to verify and validate the obtained system model and transfer function using simulated system and real plant data.
(iii) to develop and implement robust speed controllers that able to provide the required transmission speed for the current EMDAP CVT system.

1.4 Scopes and Limitations

The scopes and limitations of this research are:

(i) The modelling and experimental works are based on the present EMDAP CVT system.

(ii) Input-output data from experimental is assumed representing the actual EMDAP CVT in vehicle operation.

(iii) System response delay could occur due to the belt slip, mechanism friction and sensors delay with minimum effect.

(iv) The nonlinearities are limited to geometrical composition, backlash, friction and dead zone might exist within the system.

(v) EMDAP CVT ratio shifting only occurs every 0.2 CVT ratio change.

(vi) Simulation and implementation of the algorithm are conducted using MATLAB/Simulink environment.

1.5 Research Methodology

The methodology of this research, as presented in Figure 1.1 and Figure 1.2, can be described as follows:

(i) The first phase involves the literature reviews on the EMDAP CVT system, SI, and speed ratio controllers. The literature review provides a deep understanding on EMDAP CVT system and its functions, which is necessary before performing any other activities. The SI method was applied to get the mathematical representation of the EMDAP CVT system. The particular SI procedure used in this research is shown in Figure 1.1.

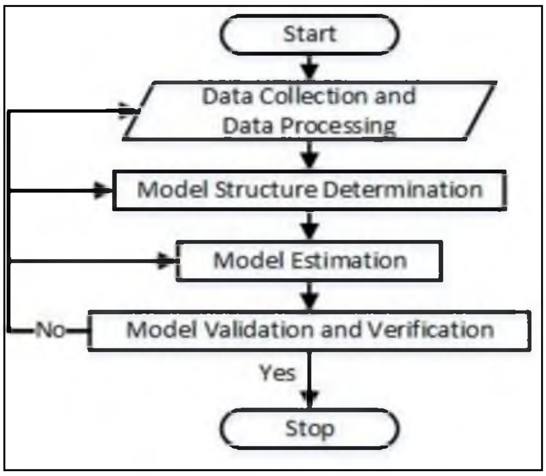

Figure 1.1 The System Identification (SI) procedure.

(ii) The second phase of the research is the experimental test-rig set up. The experimental test-rig was set up to conduct all experiments including prior experimental test for data collection and also to test the performance of the developed EMDAP CVT speed controller at later stage of the research. To manage all task including the data collection, calibration test as well as the speed controller implementation, a control program was develop using MATLAB/Simulink application.

(iii) The third phase of the research is system identification experiment. To perform the system identification, a set of time response sample data is needed. A prior experiment was conducted to gather the required data (input and output) from the current EMDAP CVT system for system identification purposes. The system was injected with various input signal such as step, sinusoidal, and also Pseudo-Random Multi-level Signal (PRMS) where these signal represents speed shift patterns. During the data processing, the unwanted noise and delay were removed to obtained the usable data for SI. The data obtained from the experiment the divided into two parts; one for the use of estimation process and the other part for validation purposes. The system parameters needed to construct the model structure of the system were first defined using the estimation data. To construct the model structure, an algorithm was developed using MATLAB/Simulink environment. The model of the system was obtained using this procedure. The model was then validated with the validation data. If the model is acceptable, a simulation process can be conducted and the control algorithm can be implemented; if not, the model needs to be identified again.

(iv) The fourth phase of the research is evaluation of the proposed controllers for the EMDAP CVT system. Proportional-Integral-Derivative (PID) controller is used as the base controller. After performing calibration, initial PID parameters were estimated. Some of the existing experimental PID tuning techniques from literatures were reviewed. The selected tuning method to acquire initial PID parameters was based on Ziegler-Nichols formula utilizing relay feedback experiment of the EMDAP CVT system to determine the critical gain (K_c) and critical period (T_c). The initial PID parameter were then, fined tuned using an algorithm based on Particle Swamp Optimization (PSO) method. Several literatures on PSO were reviewed to assists the construction of the tuning algorithm. The controller is tuned and acceptable results were achieved.

(v) The fifth phase of the research is the validation results. In this phase, the developed controllers from the simulation were tested onto the experimental test-rig. Tests were conducted to observed the performance of the developed controllers. The output results were validated by comparing the results from the actual experimental tests with the results from the simulation. The research control diagram is shown in Figure 1.2 and the research flow chart is shown in Figure 1.3 respectively.

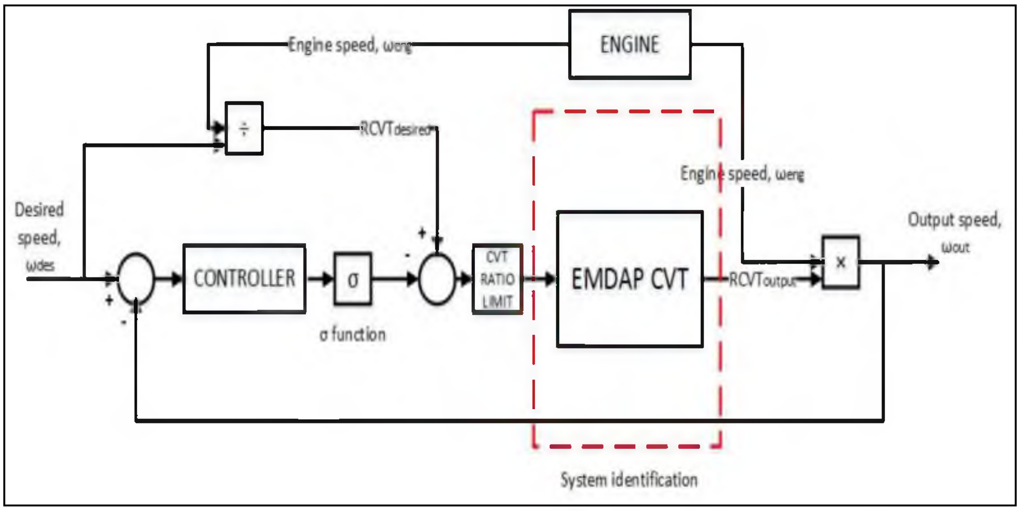

Figure 1.2 Research control diagram.

(vi) The final phase of the research is further controller's analysis which involve further speed control evaluation of the EMDAP CVT system to test the reliability and robustness of the EMDAP CVT system model obtained and best controller for EMDAP CVT application.

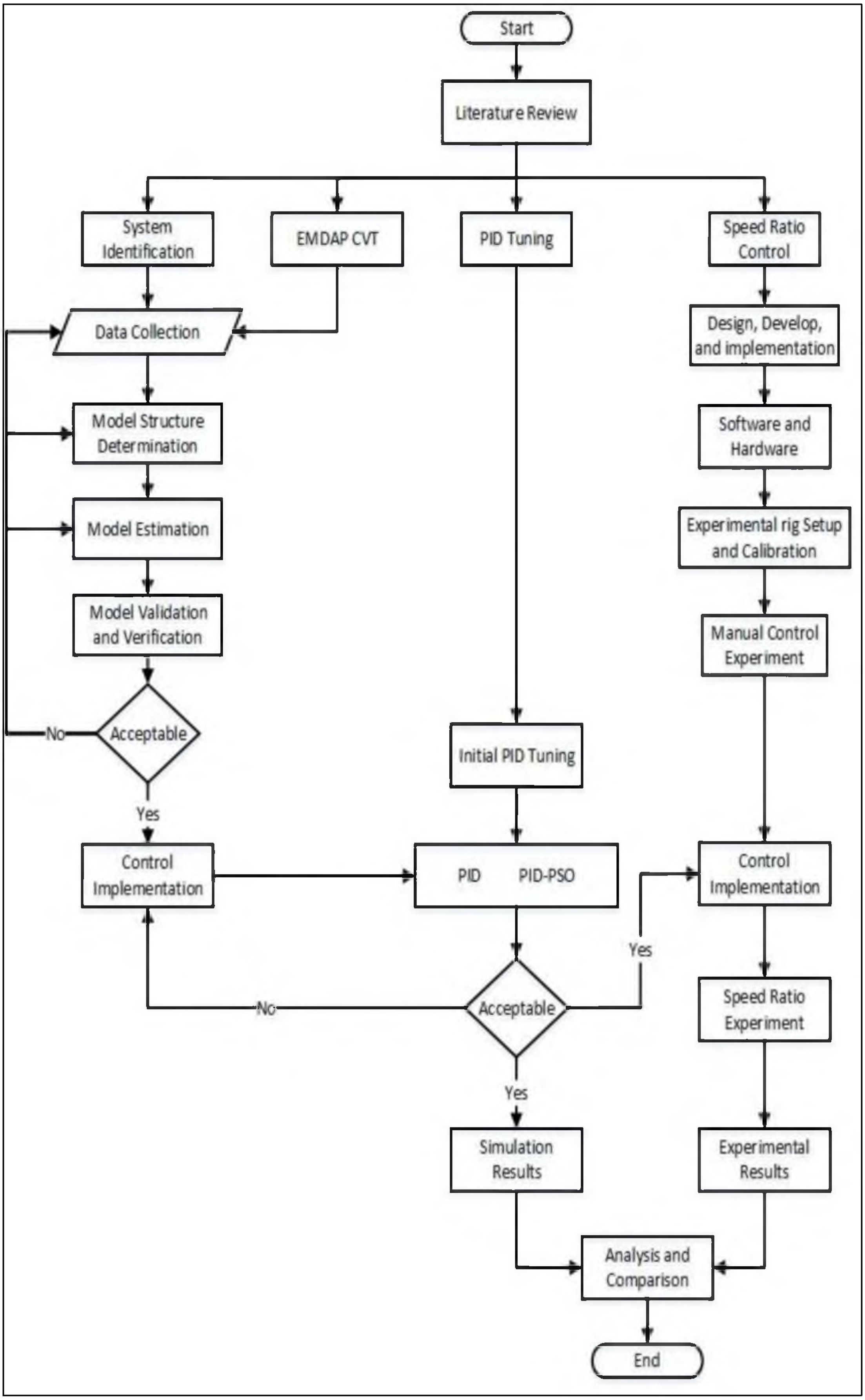

Figure 1.3 Research flow chart.

1.6 Research Contributions

This research aims to provide further improvement to the EMDAP CVT system. In 2009, Ariyono designed the EMDAP CVT prototype based on the dual acting pulley electromechanical system. Ariyono developed a drivetrain model of a vehicle equipped with EMDAP CVT system. Most of his work was focused on control strategy to control EMDAP CVT ratio using adaptive neural network (ANN). The research was then further continued by Supriyo (2010). In his research, Supriyo designed, developed and implemented electronic hardware for EMDAP CVT experimental test-rig and MATLAB/Simulink control algorithm program for EMDAP CVT ratio controller. His work focussed more on designing and developing EMDAP CVT ratio controllers in time domain analysis based on several algorithms. Two most important objectives of Suptiyo work are to eliminate both steady state power loss and belt misalignment (Supriyo, 2010). By implementing power screw mechanism to maintain its constant transmission ratio, the first problem was solved without consuming any power. Then the second problem was overcome by adopting two movable pulley sheaves on each pulley shaft to keep the belt continuously aligned.

The newly developed EMDAP CVT is a complex and non-linear system as mentioned in Section 1.2. One of the contributions of this research is to develop a simple and reliable transfer function of the EMDAP CVT system which is able to precisely imitate the actual system process. With the acquired transfer function model, future works related to the system will be much easier. This can be achieved by performing a System Identification (SI) on the EMDAP CVT system. The SI process of the EMDAP CVT will be further discussed in Chapter 4.

Both of the previous researchers, Ariyono (2009) and Supriyo (2010), contribute to the ratio controller of EMDAP CVT system. However, they barely mention about the speed control. The second contribution of this research is designing, developing and implementing the speed controller for the EMDAP CVT system. Besides controlling the EMDAP CVT system speed, the developed controller should also able to provide an appropriate transmission ratio for the current system. The detailed explanation about the EMDAP CVT speed control is discussed in Chapter 5. In addition, for the third contribution of the research, a control algorithm program for EMDAP CVT speed controller using MATLAB/Simulink platform was also developed.

1.7 Structure of Thesis

This thesis contains seven chapters. Chapter 1 introduces and highlights the importance of the study. Chapter 2 presents the literature review. Several types of transmissions are briefly reviewed. Then, the review focuses on existing works related to CVT controls. The gaps are identified, and justifications of the research objectives and research methodology are presented.

Chapter 3 presents the EMDAP CVT system descriptions. This chapter presents the basic concept of CVT and elaborates more on EMDAP CVT especially in terms of hardware and software design, as well as procedure of performing speed control. This chapter describes the main mechanical and electronic parts of EMDAP CVT, and also the interfacing unit which makes possible for the EMDAP CVT to communicate with the computer via Data Acquisition (DAQ) system. The experimental test rig is set up and the CVT ratio is validated based on geometrical CVT ratio. The development of the manual control for EMDAP CVT system Simulink program was also presented in this chapter.

Chapter 4 presents the system identification process performed on the EMDAP CVT system. The input and output data were obtained from the prior experimental test conducted in Chapter 3. Nonlinear ARX (NARX) model was introduced as the model structure, and was constructed using genetic algorithm (GA). The obtained system model was also validated using several validation test methods such as Mean Square Error (MSE) and correlation tests.

Chapter 5 presents the control system part of the research. Using the obtained EMDAP CVT system model, control simulation testing was performed. At the start

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