

MICROCONTROLLER BASED RATIO CONTROL FOR ELECTRO-
MECHANICAL DUAL ACTING PULLEY CONTINUOUSLY VARIABLE
TRANSMISSIONS

ARIES BUDIANTO

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Dedicated to:

My beloved parents:

Slamet Mudjihardjo

Nur Chofifah

My beloved parents in law:

Alm. Sidiek Rochmanto

Sumiati

My beloved wife:

Septi Dwi Jayanti

My brother:

Hendra Kurniawan

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ABSTRACT

Electro-Mechanical Dual Acting Pulley Continuously Variable Transmission (EMDAP CVT) is a transmission operated by electro-mechanical actuated system. It has a potential to reduce energy consumption where power is only needed during changing of CVT ratio and no additional power is needed to maintain the CVT ratio due to self-lock mechanism design feature of the EMDAP CVT. In this research, simulation of an EMDAP CVT model was first performed in order to evaluate controller system performance using MATLAB/Simulink software package. Then, confirmation of the simulation results is made by experimental data that is being measured from EMDAP CVT test rig. In order to obtain adequate performance, basic Proportional Integral Derivative (PID), Proportional Derivative (PD) and Proportional Derivative with Conditional Integral (PDCI) controller schemes were proposed to control EMDAP CVT ratio. Relay feedback and Ziegler-Nichols methods were utilized to tune the PID based controller parameters. From simulation analysis, the basic PID based controller shows a huge overshoot up to 280% and it takes very long settling time up to 65 seconds. However, this controller generates very small steady state error which is around 0.2%. The PD controller shows better performance where there is no overshoot occurred and faster settling time, i.e. 8 seconds, but steady state error is a bit higher, i.e. 3.2%, than the basic PID based controller. The best performance is predicted by PDCI controller where it shows maximum overshoot at 0.2%, 8 seconds in settling time and steady state error at 0.1%. In the experimental work, only PD and PDCI controller schemes are adopted because of their good control performance in the simulation. It is found that performance of the PD and PDCI controllers in the experiments are quite close to those predicted in the simulation. For the PD controller, experimental results show no overshoot, it takes only 4 seconds in settling time and produces steady state error of 10%. As for the PDCI controller, it shows 1% in maximum overshoot, 8 seconds in settling time and steady state error at 1%. This indicates that the PDCI controller is superior than the PD controller in terms of steady state error and this is confirmed by simulation and experimental results.

ABSTRAK

Takal Dwi Tindakan Elektro-Mekanikal Transmisi Sentiasa Berubah (EMDAP CVT) adalah transmisi yang dikendali oleh sistem penggerak elektro-mekanikal. Ia mempunyai potensi untuk mengurangkan penggunaan tenaga di mana, kuasa hanya diperlukan semasa penukaran nisbah CVT dan tiada kuasa tambahan diperlukan untuk mengekalkan nisbah CVT disebabkan oleh ciri rekabentuk mekanisma terkunci sendiri bagi EMDAP CVT. Dalam kajian ini, kerja-kerja simulasi bagi model EMDAP CVT dilakukan terlebih dahulu bagi menilai prestasi sistem kawalan menggunakan pakej perisian MATLAB/Simulink. Seterusnya, pengesahan keputusan simulasi dibuat melalui keputusan eksperimen yang diperoleh daripada pelantar ujian EMDAP CVT. Dalam usaha untuk mendapatkan prestasi yang mencukupi, skim pengawal asas PID, PD dan PDCI dicadangkan untuk mengawal nisbah EMDAP CVT. Kaedah *relay feedback* dan *Ziegler-Nichols* digunakan untuk melaras parameter pengawal PID. Daripada analisis simulasi, pengawal asas PID menunjukkan lajukan besar berlaku sehingga 280% dan ia mengambil masa penganapan yang sangat panjang sehingga 65 saat. Bagaimanapun, pengawal jenis ini hanya menjana ralat keadaan mantap yang sangat kecil iaitu 0.2%. Pengawal PD pula menunjukkan prestasi yang lebih baik dengan tiada lajukan terhasil dan masa penganapan yang lebih cepat iaitu 8 saat, namun, ralat keadaan mantap adalah sedikit besar iaitu 3.2% daripada pengawal asas PID. Prestasi terbaik diramal oleh pengawal PDCI di mana ia menunjukkan lajukan maksimum pada 0.2%, 8 saat masa penganapan dan ralat keadaan mantap pada 0.1%. Di dalam kerja-kerja eksperimen, hanya skim pengawalan PD dan PDCI yang digunapakai kerana ia memberikan prestasi kawalan yang baik di dalam simulasi. Didapati bahawa prestasi pengawal PD dan PDCI di dalam eksperimen hampir menyamai apa yang diramal di dalam simulasi. Bagi pengawal PD, keputusan eksperimen menunjukkan tiada lajukan berlaku, ia hanya mengambil 4 saat masa penganapan dan menghasilkan ralat keadaan mantap sebanyak 10%. Bagi pengawal PDCI, keputusan eksperimen menunjukkan 1% dalam lajukan maksimum, 8 saat masa pemendapan dan ralat keadaan mantap pada 0.1%. Ini menunjukkan bahawa pengawal PDCI adalah lebih baik daripada pengawal PD berdasarkan ralat keadaan mantap dan ini disahkan oleh keputusan simulasi dan eksperimen.

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LIST OF ABBREVIATIONS

AANN	-	Adaptive Artificial Neural Network
ADC	-	Analog to Digital Converter
BLDC	-	Brushless DC
CVT	-	Continuously Variable Transmission
DAC	-	Digital to Analog Converter
DAS	-	Data Acquisition System
DC	-	Direct Current
DRG	-	Drivetrain Research Group
EMDAP	-	Electro-Mechanical Dual Acting Pulley
I/O	-	Input/Output
PC	-	Personal Computer
PD	-	Proportional-Derivative
PDCI	-	Proportional-Derivative with Conditional-Integral
PID	-	Proportional-Integral-Derivative
PMPS	-	Primary Minimum Position Sensor
PPS	-	Pulley Position Sensor
RFTM	-	Relay Feedback Tuning Method
SCU	-	Speed Controller Unit
SMPS	-	Secondary Minimum Position Sensor
UTM	-	Universiti Teknologi Malaysia
VSC	-	Voltage for Speed Controller
ZN	-	Ziegler-Nichols

LIST OF SYMBOLS

α	-	half the increase in the wrapped angle on the primary pulley
$\tilde{\omega}_p$	-	angular speed of the primary shaft
$\tilde{\omega}_s$	-	angular speed of the secondary shaft
B	-	viscous friction coefficient
c	-	pulley center distance
d_p	-	pitch diameter of screw thread
F	-	tangential force of helical gear inner thread
F_z	-	force for clamping or release MPVB
I_m	-	motor current
J_m	-	motor inertia
K_e	-	back EMF constant
K_T	-	torque constant
L	-	pitch length
L_m	-	motor inductance
P	-	thrust bearing force
r_{cvt}	-	CVT ratio.
r_{gm}	-	motor gear ratio
R_m	-	motor resistance
R_p	-	primary running radius
R_{p0}	-	minimum primary running radius
R_s	-	secondary running radius
R_{s0}	-	minimum secondary running radius
T_{gr}	-	gear reducer torque
t_{hg}	-	helical gear teeth number
T_{hg}	-	helical gear torque
T_L	-	load torque

T_m	-	motor torque
t_p	-	pinion teeth number
T_p	-	pinion gear torque
T_{psc}	-	torque of power screw for clamping MPVB
T_{psr}	-	torque of power screw for release MPVB
V_b	-	back EMF voltage
V_m	-	motor voltage
X_p	-	primary pulley position
X_s	-	secondary pulley position
	-	pulley angle
μ	-	friction coefficient
m	-	motor angular speed

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CHAPTER 1

INTRODUCTION

1.1. Introduction

In automotive industry, green technology has been widely developed for saving fuel consumption and minimizing gas emission to reduce environment pollution. One of them is development in automotive transmission. There are various technologies in automotive transmission, such as; manual transmission, semi automatic transmission, automatic transmission and continuous variable transmission (CVT). Among the automotive transmission types, CVT has a great advantage in saving fuel consumption because its wide variable ratio coverage characteristic can maintain the engine speed independently under various load condition. Maintaining engine speed means maintaining engine power. Thus, it minimizes the fuel consumption (Wang and Chu, 2009).

Common CVT which widely used in the market is electro-hydraulically actuated type. It needs continuous power to supply force to maintain the desired ratio and preventing gross belt slip. Thus, it can reduce CVT efficiency (Akerhurst et al., 1999). An alternative solution to enable economic fuel consumption is to use electro-mechanical CVT type with single acting pulley system because it only operates during changing the transmission ratio (van de Meerakker et al., 2004). The single acting pulley mechanism used in this system causes misalignment of metal belt. This belt misalignment may reduce the belt life. Another solution is to use Electro-Mechanical Dual Acting Pulley (EMDAP) CVT designed by Drivetrain Research Group of Universiti Teknologi of Malaysia, (DRG UTM). EMDAP CVT utilizes two

DC motors as actuator, power screw mechanism and two moveable sheaves in both primary and secondary pulley (Supriyo, 2011). Two moveable sheaves move identically to keep the belt align in the center, thus, eliminate belt misalignment. Also, this system only operates during the changing of ratio transmission, thus, save fuel consumption. By controlling two DC motors precisely and accurately, desired CVT ratio can be achieved accordingly

In order to create high efficiency of CVT for automotive application, a precise and accurate control method is also important. A common Proportional, Integral and Derivative (PID) control method has been widely used in industry because of its precision, accuracy, simplicity and robustness (Shen, 2002). PID based parameters can be set independently and its scheme can be arranged according to the need. Thus, parameters of P, I and D are tuned and combined to obtain the optimal performance.

1.2. Problem Statement

The latest research of Electro-Mechanical Dual Acting Pulley CVT was developed by Supriyo (2011). Two DC motors as actuators for primary and secondary pulley have been utilized. Both DC motors are controlled using various control methods, such as Proportional and Derivative (PD), Proportional Derivative with Conditional Integral (PDCI), and Fuzzy-PID which are implemented on PC utilized by MATLAB/SIMULINK software and data acquisition system card to control EMDAP CVT ratio.

As a continuation of EMDAP CVT development, standalone controller device, such as microcontroller, is needed in order to implement EMDAP CVT ratio control in the car. In a car, there may be hundreds of microcontrollers inside it. For example: one to monitor and control automatic fuel injection, one to monitor ABS break system, one to monitor and control cabin temperature and so on. For these intelligent automatic control applications, it is very inefficient to PC due to its big

size and high cost. Therefore, a microcontroller is very important for many automatic control applications. In this research, a microcontroller is proposed as a standalone controller device. By using a microcontroller, EMDAP CVT ratio control can be implemented and integrated in the car.

1.3. Objectives

The main objective of this research is to design and develop a microcontroller based EMDAP CVT ratio controller as standalone controller device. The specific objectives are stated as follows:

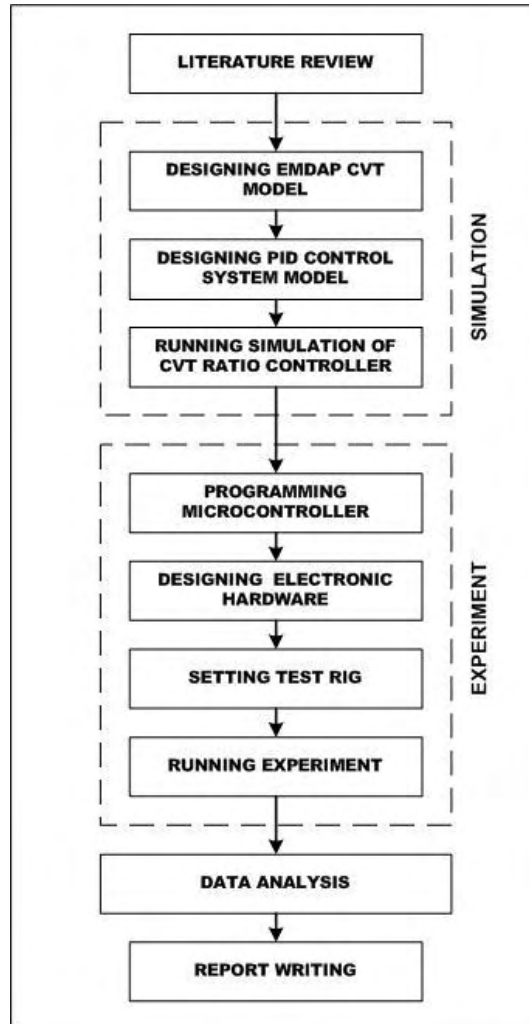
- i. To design simulation model of EMDAP CVT ratio control using PID based control method for obtaining PID based combination and parameters tuning based on relay feedback and Ziegler-Nichols methods.
- ii. To design electronic hardware for EMDAP CVT experiment rig to test the effectiveness of EMDAP CVT ratio control.

1.4. Research Scope

The scopes of the research are stated as follows:

- i. Simulation of EMDAP CVT is build based on mathematical models of mechanical system, brushless DC motor and PID.
- ii. Simulation is carried out using MATLAB/SIMULINK software.
- iii. Experimental work is carried out using existing EMDAP CVT test rig, developed by DRG UTM, as shown in Figure 1.1.
- iv. Experimental work is carried out without applying external load on output shaft.
- v. Microcontroller module used in this research is Aimagin Rapid STM32 board, which can be operated standalone or online with PC using MATLAB/SIMULINK software.





basic equations of power screw are used. It acts as a converter of rotational movement into linear movement.

- iii. PID based controller model is designed based on PID based controller equations. For PID based parameter tuning, Ziegler Nichols and relay feedback methods are used. Parallel PID based controller scheme is designed in order to independently modify PID based parameter tuning.
- iv. To perform CVT ratio controller simulation, both EMDAP CVT and PID based controller models are combined resulting closed loop system. This closed loop system is simulated using MATLAB and SIMULINK software. The performances of the CVT ratio control system are recorded and analyzed. Modification of PID based controller is carried out to obtain the best result.
- v. Once the best simulation result has been obtained, a PID based control algorithm and its parameter values are adopted as pattern reference for programming microcontroller.
- vi. Electronic hardware consists of potentiometer as position sensor, rotary encoder as speed sensor, brushless DC motor and its speed driver as actuator and Aimagin Rapid STM32 microcontroller module as controller device.
- vii. The existing EMDAP CVT test rig enables to vary the CVT ratio from 0.6 up to 3.0. It consists of mechanical and electrical parts. The mechanical parts consist of electric motor which is used to drive the primary pulley shaft, gear reducer which has ratio 30:1, pinion gear which has 14 gear teeth, helical gear which has 60 gear teeth, power screw which has rotation to linear converter ratio 2 mm/rotation and axial range 0 up to 10 mm, dual moveable pulleys on every shaft and a metal pushing V belt. Once all the components are assembled, calibration of power screw movement, related to speed and position sensors values reading, is carried out in order to achieve accurate parameter values.
- viii. The experiment work is carried out using existing EMDAP CVT test rig, EMDAP CVT ratio controller system based on microcontroller, sensors and signal conditioners. Just for monitoring and recording data,

the system have to be set in online mode, thus, PC utilized by MATLAB and SIMULINK software is used during the experiment.

- i. Various step inputs are applied to test the EMDAP CVT ratio changing of six steps ratio, namely: 3.0 to 2.5, 2.5 to 2.0, 2.0 to 1.5, 1.5 to 1.0, 1.0 to 0.8 and 0.8 to 0.6.
- x. Experimental results, in term of settling time, error steady state and maximum overshoot, are recorded, analyzed and discussed.

1.6. Research Contribution

The main research contribution is to bring an implementation opportunity of EMDAP CVT ratio control in the car. Whereas regarding EMDAP CVT simulation, it enables to tune PID based control scheme to obtain a good EMDAP CVT ratio control performance before implementing on EMDAP CVT test rig. So, experimental work can be carried out safely.

1.7. Organization of Thesis

This thesis consists of 6 chapters. In chapter 1, the background, problem statement, research objectives, research scope, methodology and research contribution are outlined. Chapter 2 describes literature reviews. Previews works of controlling CVT ratio, latest work of EMDAP CVT ratio, basic principle of EMDAP CVT, PID based control method, including relay feedback and Ziegler-Nichols formula, and Aimagin Rapid STM32 microcontroller module are outlined.

Chapter 3 presents simulation of EMDAP CVT ratio control. Building EMDAP CVT model is started with creating brushless DC motor model, then, simulating brushless DC motor torque and speed performance compared to brushless DC motor datasheet. Next step is to build mechanical model of EMDAP CVT, which

consists of power screw, pinion gear, helical gear and gear reducer. While PID based control model is build based on its equation, then, it is combined with EMDAP CVT mechanical model to perform EMDAP CVT ratio control simulation.

Chapter 4 describes hardware and software of experimental works. It consists of EMDAP CVT test rig set up, pulley linear movement calibration and setting up parameters of microcontroller module using MATLAB/SIMULINK software integrated with a PC.

In chapter 5, PID based control algorithm is implemented on experimental works of EMDAP CVT ratio control. The real responses of the system are analyzed. Chapter 6 presents conclusion of the works and recommendation for future research.

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