A ROBUST CONTROLLER DESIGN FOR CLOSED-LOOP ELECTRO-HYDRAULIC ACTUATOR MODEL WITH REAL-TIME SIMULATION

TAN TIAN POH

BACHELOR OF ELECTRICAL ENGINEERING WITH HONOURS
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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TAN TIAN POH

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DECLARATION

I declare that this thesis entitled "A ROBUST CONTROLLER DESIGN FOR CLOSED-LOOP ELECTRO-HYDRAULIC ACTUATOR MODEL WITH REAL-TIME SIMULATION " is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : TAN TIAN POH

Date : 25 June 2021

APPROVAL

I hereby declare that I have checked this report entitled "A ROBUST CONTROLLER DESIGN FOR CLOSED-LOOP ELECTRO-HYDRAULIC ACTUATOR MODEL WITH REAL-TIME SIMULATION" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Electrical Engineering with Honours

Signature :

Supervisor Name : Assoc. Prof. Dr. Rozaimi Ghazali

Date : 25/6/2021

DEDICATIONS

To my supervisor,

Assoc. Prof. Dr. Rozaimi Bin Ghazali,

To my beloved mother and father,

Mr Tan Lai Sia and Mrs Leong Kwee Ling,

To my supportive siblings,

Tian Lee and Tian Chuan,

To all my friends,

Lastly, to all the people who have helped me throughout the journey.

I would not have finished this project without all of you.

Thank you for all the supports and love.

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ABSTRACT

The electro-hydraulic system is a nonlinear system that consists of an electrical signal processing system and hydraulic components. The electrical signal control compartment is responsible for signal input, signal processing and signal output whereas the hydraulic compartment responsible to carry out mechanical action according to the specified output signal. An electro-hydraulic actuator (EHA) is a self-contained actuator powered by an electrical power signal instead of hydraulic energy. EHA leads to reliable and simple system architecture due to components such as hydraulic pumps and tubing is constructed together as a package. The design of a closed-loop electro-hydraulic actuator is necessary to cope with various plant variation such as noise, physical factors and internal factors that greatly reduce the productivity of the system. The robust design approach is important in a system in order to enhance engineering productivity as well as improve the performance of a control system. This study proposed the design of a robust controller for the closed-loop EHA model by using the PID controller and Variable Structure Control (VSC). The designed robust controller is implemented into the EHA system so that the mechanical output of the system is linear with the input electrical signal without affected by the disturbances. Graphical modelling of the system is constructed with the SIMSCAPE FLUID library of MATLAB software to evaluate the response of the system. The PID (Ziegler-Nichols with fine-tuning) system is proposed as the best system with the lowest Root-Mean-Square-Error (RMSE) value for all the evaluations and tests. The system also reduces the overshoot and settling time in the PID (Ziegler-Nichols) system by 63.7% and 30.3% respectively in the transient and steady-state analysis. Other than that, the system has the best performance in setpoint tracking evaluation with the fastest response and lowest RMSE value of $2.397 \times 10^{-7}\ m$.

ABSTRAK

Sistem elektro-hidraulik merupakan sistem tidak linear yang terdiri daripada sistem pemprosesan isyarat elektrik dan komponen hidraulik. Kompartmen kawalan isyarat elektrik bertanggungjawab untuk isyarat kemasukan, pemprosesan isyarat dan isyarat pengeluaran manakala kompartmen hidraulik bertanggungjawab untuk melakukan tindakan mekanikal mengikut isyarat pengeluaran tertentu. Penggerak elektro-hidraulik (EHA) adalah penggerak serba lengkap yang digerakkan oleh isyarat kuasa elektrik dan bukannya tenaga hidraulik. EHA membawa kepada seni bina sistem yang boleh dipercayai dan ringkas kerana komponen seperti pam hidraulik dan tiub dibina bersama sebagai pakej. Reka bentuk penggerak elektro-hidraulik gelung tertutup diperlukan untuk mengatasi pelbagai variasi seperti bunyi bising, faktor fizikal dan faktor dalaman yang akan mengurangkan produktiviti sistem. Pendekatan reka bentuk yang teguh penting dalam sistem untuk meningkatkan produktiviti kejuruteraan serta meningkatkan prestasi sistem kawalan. Kajian ini mencadangkan reka bentuk pengawal PID and VSC untuk model EHA gelung tertutup. Reka bentuk pengawal dimasukkan ke dalam sistem EHA sehingga pengeluaran sistem mekanikal selaras dengan isyarat kemasukan elektrik tanpa pengaruh ganguan isyarat. Pemodelan grafik sistem dibina dengan SIMSCAPE FLUID dalam perisian MATLAB untuk menilai prestasi sistem. Sistem PID (Ziegler-Nichols with fine-tuning) dicadangkan sebagai sistem terbaik dengan nilai Root-Mean-Square-Error (RMSE) terendah untuk semua penilaian dan ujian. Sistem ini juga mengurangkan masa overshoot dan masa menetap dalam sistem PID (Ziegler-Nichols) sebanyak 63.7% dan 30.3% dalam langkah analisis sementara dan keadaan tetap. Selain itu, sistem ini turut mempunyai prestasi terbaik dalam penilaian penjejakan setpoint dengan tindak balas terpantas dan nilai RMSE terendah iaitu $2.397\times 10^{-7}\ m$.

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LIST OF SYMBOLS AND ABBREVIATIONS

EHA	-	Electro-Hydraulic Actuator
PID	-	Proportional–Integral–Derivative
VSC	-	Variable Structure Control
P	-	Proportional
I	-	Integral
D	-	Derivative
FOPDT	-	First Order Plus Dead Time
RMS	-	Root Mean Square
RMSE	-	Root Mean Square Error
ZN	-	Ziegler-Nichols
y	-	Error Signal
ydot	-	Integral of Error Signal
i	-	Variable
N	-	Number of Samples
Predicted i	-	Setpoint value at particular variable
Actual i	-	Observed or output value at particular variable

CHAPTER 1

INTRODUCTION

1.1 Background

The electro-hydraulic system is the combination of electrical and mechanical components with compressed fluid. Scientist around the world has started to study electro-hydraulic control system for hydraulic supports since mid of the 1970s. The concept for hydraulic cylinders come from Blaise Pascal who studies fluids and pressure. Pascal proposed that pressure act on every point inside a closed container is the same. For a fluid in equilibrium condition, the net force acting any part of the fluid is equal to zero as proposed by Pascal in Treatise on the Equilibrium of Liquids [1]. Pascal had conducted a hydrostatic experiment known as Pascal's barrel. The experiment was conducted with a 10-meter tube that connected to a barrel. As the water was being transferred to the tube, the barrel burst from the large static pressure that develops from the moving fluid.

The hydraulic systems transmit energy by taking advantage of the pressure of fluid within a closed system. The common mechanism that utilizing the hydraulic system consists of the hydraulic brake inside a car, gasoline pumps, aeroplanes, and cranes. The major advantage of the hydraulic system is it able to transmit large power output and is able to create a constant force on moving a large load. Moreover, hydraulic components are less likely to suffer from breakdown due to their simple and robust design. The hydraulic system also more economical than an electrical or mechanical system due to minimal and simple maintenance is required to maintain the functionality of the hydraulic system. Simple maintenance such as replacement filters and fluid sample testing are carrying out on certain occasion to ensure the efficiency of the system. Other than that, the operation of the hydraulic system does not cause a spark which makes it suitable to be applied on the various field. This makes hydraulic system actively applied on chemical plants, mines, and aircraft industries [2].

A robust design consists of a system or process that able to maintain performance in various conditions and disturbances. The robust design is intended to improve engineering productivity. The robust design focuses on enhancing the fundamental function of the process and leads to facilitating flexible designs and concurrent engineering. Robust design will bring advantages to the current system in term of serving life, reliability and consistency as temperature and other conditions change. This rapid development and application of robust controller are because it is relevant to the practical problems of an automation engineer. The system or process is said to be robust when they exhibit the following properties [3]:

i. independent of the particular values of the constant disturbances or references
ii. independent of the initial conditions of the plant and controller and
iii. independent of whether the plant and controller are linear or nonlinear.

Nowadays, a robust design is necessary to make the control system insensitive to factors of noise, develop formulas and processes of a product to achieve the desired performance at a reduced cost and simplify the whole design.

Robust PID design is widely used in industrial control application to regulate the parameters such as temperature, pressure, speed, and flow. PID is the combination of three factors which comprises proportional (P) which provide the gain that is proportional to the error reading while comparing input and output value, integral (I) which introduce gain to the integral of the error signal and derivative (D) which introduce gain the derivative of the error signal. The PID control applies a closed-loop or feedback system with the setting coefficient of proportional gain (Kp), integrator time (Ti) and derivative time (Td) to achieve ideal or targeted output [4]. Ziegler-Nichols method is one of the tuning methods for a robust PID design. Ziegler-Nichols method is introduced in the year 1942 by John G. Ziegler and Nathaniel B. Nichols who work in Taylor Instruments [4]. This method is intended to enhance the performance of a system, save cost and ease of use. Three of the performance parameters that used as an indicator of an efficient robust PID design are immunity to disturbance, setpoint tracking and robust stability [5].

Aside from PID controller, there is another control theory known as Variable Structure Control (VSC). The VSC system has the same function as the PID controller, which is to provide robustness and enhance the existing control system. The state-feedback of the control law constantly shifts from one satisfactory condition to another and it is not a continuous function of time [6]. Moreover, VSC also able to produce output response that has satisfactory transient performance and fast response.

1.2 Problem statement

In real working conditions, an electro-hydraulic system will always suffer from interference and disturbance such as noise, internal breakdown, humidity, and many others. This will greatly reduce the efficiency of the system and leads to undesired or inconsistent output. According to Brenda L. Reichelderfer which is senior vice president of the ITT Corporation (an American worldwide manufacturing company that produces speciality components for the aerospace, transportation, energy and industrial markets), design directly influences more than 70% of the product life cycle cost and companies with high product development effectiveness to have earnings three times the average earnings [7].

1.3 Motivation

A well-designed system is important to ensure higher engineering productivity and lower operating cost. Nowadays, the electro-hydraulic system is widely used in aeronautics, heavy industrial application, and civil application. The advantages of the electro-hydraulic system include a long lifespan, high power density, flexible motion control, high reliability, and a customizable system. By applying appropriate robust design to the system, external and internal disturbances such as noise can be tackled easily, and this greatly increases the productivity and consistency of the system.

1.4 Objectives

The objectives of this project are:

i. To demonstrate an electro-hydraulic actuator system with the pipeline blocks in MATLAB Software.

ii. To design a robust controller based on PID and Variable Structure Control (VSC) system.

iii. To evaluate the performance of the designed controller and system via MATLAB simulation.

1.5 Scope

The scopes of this project are:

i. The electro-hydraulic actuator system is modelling in graphical mean only using pipeline blocks in MATLAB SIMSCAPE.

ii. The external disturbances or loads are limited to translational spring load, viscous friction, step load disturbance and mechanical translational mass load.

iii. The robust design is via PID and Variable Structure Control (VSC) system.

iv. The PID tuning methods are limited to trial-and-error tuning, Ziegler-Nichols tuning, and Ziegler-Nichols with fine-tuning.

v. The performance evaluation via step response analysis, root-mean-square error (RMSE) analysis, disturbances analysis and setpoint tracking will be based on MATLAB simulation and no hardware involve in this study.

1.6 Thesis Organization

This study is about the Robust Controller Design for Closed-Loop Electro-Hydraulic Actuator Model. It is divided into five chapters which are included as follows:

Chapter 1 discusses the general background for electro-hydraulic system and robust controller that gives an idea to implement a robust controller as a solution for this project. Next, it will explain details about the motivation, project scope and objectives.

Chapter 2 covers the literature review related to the electro-hydraulic actuator (EHA), closed-loop hydraulic system, and controller (PID and VSC) design. The literature is based on the previous study and focusing more on robust design in the hydraulic system.

Chapter 3 discuss the modelling of the hydraulic system which includes various external load and the design of (PID and VSC) system with performance evaluations.

Chapter 4 presents the result that has been conducted throughout the whole process of the controller design and evaluation. Then, the output result will be discussed in detail. PID controller design via Ziegler-Nichols with fine-tuning will be proposed as the best system for this project.

Chapter 5 gives a summary of this study and gives a clear view of the study. In this chapter, the conclusion has been made based on the study findings along with the recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses previous studies related to the robust controller design for the closed-loop system. Literature on the robust controller design approach is explained thoroughly with references from previous studies focusing more on controller design on electro-hydraulic actuator (EHA) system.

2.2 History of Electro-Hydraulic Actuator (EHA)

The linear actuator was being used in various fields such as manufacturing, transportation, scientific research, and many other fields. Initially, the actuator is powered by pure hydraulic energy. To meet new functional requirements, various manufacturer has begun to combine pure hydraulic with the electrical control system.
Starting in the 1940s, hydraulic was introduced in aircraft manufacturing industries to provide sufficient output for high-speed aircraft. In the early stage, the function of hydraulic pumps that attached to the engines is to supply high-pressure fluid to multiple control components via enclosed tubes. The control cables were attached with small valves to control the flow of oil into the corresponding actuator that connected to the control component. The system is then undergoing further modification which utilizes electrical control system to replace the conventional mechanical linkages to the valve. The addition of electrical control system leads to the new system known as “fly-by-wire” and “fly-by-light” design [8]. However, all the system comprised of three separate systems which are hydraulic supply, control network and actuators. If one of the subsystems undergo failure, the whole component will suffer from malfunction.

The primary development of the electro-hydraulic actuator (EHA) system was the feedback control method of conventional motor and stepper motor. With EHA, the application of a high-power motor becomes possible to drive a reversible pump that linked to a hydraulic cylinder. The whole system consists of the pump, hydraulic reservoir and the cylinder is packed as a single component. The energy needs to move the actuator is come from an electrical signal instead of a conventional hydraulic supply. The speed of the motion is now controlled via pulse-code modulation which results in a “power-by-wire" system developed by Lockheed Martin JSF team [8]. In the system, both the control and energy are sent through a single set of wires to the small and compact EHA component.

2.3 Working Principle of Electro-Hydraulic Actuator

The pressure of the hydraulic cylinder (single-acting or double-acting) is controlled by a flapper-nozzle system via a high-pressure hydraulic valve until the desired position of the valve stem is achieved. The flapper nozzle is the main component for pneumatic devices to convey a measurement into a pneumatic pulse or signal. The system able to detect very small displacement of the flapper and then converts that displacement into a variation of the output pressure. A constant pressure of 20 psi usually supplies at one end of the pipeline. The air will pass through the restriction and leads to a pressure drop. Eventually, the pressure will pass through the nozzle and flapper of another end. The position of the flapper will determine the pressure within the pipeline between the restriction and flapper. Figure 2.1 illustrate the pneumatic flapper nozzle system.

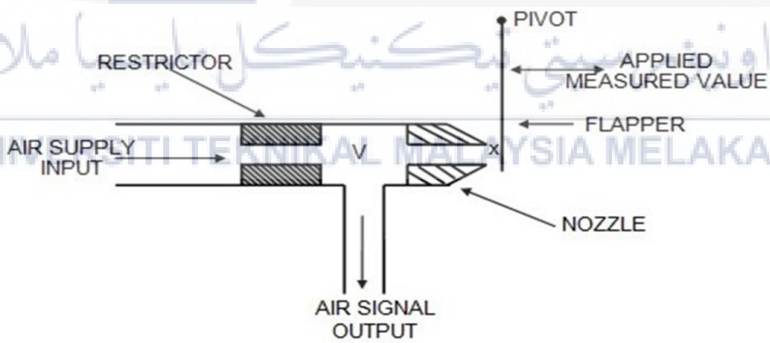

Figure 2.1: A pneumatic flapper nozzle system

When the flapper is closer to the nozzle, the higher the pressure inside the pipeline. The pressure is equal to the atmospheric pressure as the flapper is fully open and the pressure is equal to the difference between supplied pressure and pressure drop in restriction when the flapper is fully closed. The orifice plate and nozzle are usually very small so that minor change in displacement of flapper will lead to a large variation in output pressure. For example, with the flapper’s displacement of 0.0001 inches, the pressure can be changed to 1 psi [9].

2.4 Closed-Loop Hydraulic System

There are two types of the hydraulic system which is known as open-loop and closed-loop hydraulic system. It is important to consider which system to use when designing a hydraulic system. Figure 2.2 illustrate the open-loop hydraulic and closed-loop hydraulic system.

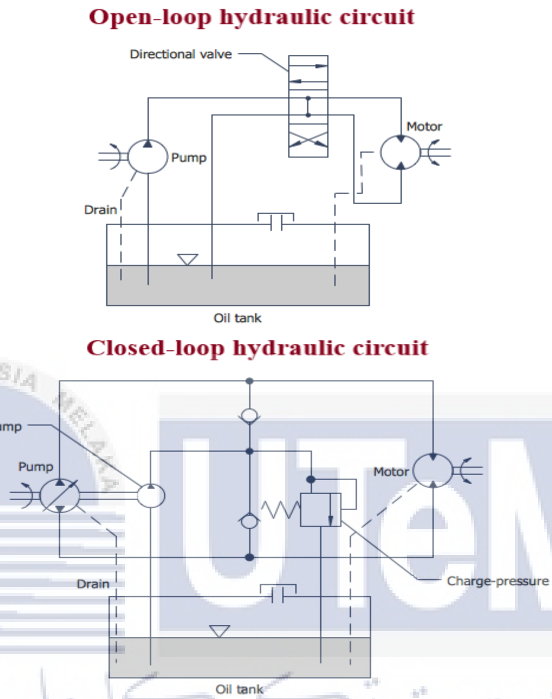

Figure 2.2: Open-loop and closed-loop hydraulic system

Closed-loop hydraulic systems are known as hydrostatic drive and normally applied on skid-steer loaders, bulldozer, and conveyor. In hydrostatic drive, fluid flows from a piston pump to a valve directly and returns to the pump without passing through a reservoir. The closed-loop system is usually smaller and lighter than an open-loop system which makes them ideal for mobile design. A closed-loop system has an input value that depends on variation on the output value. The output value will be fed into the system via a feedback loop to identify the variation with the targeted value. The variation will be adjusted by the selected controller. Hydraulic system engineers usually apply closed-loop system for control related to force and pressure [10,11]. There are many advantages of utilizing a closed-loop system which include systems that can run at higher pressures with less fluid flow which result in smaller hydraulic lines, the direction can be reversed without the use of valves and a wide range of control solutions are available.

2.5 PID Controller

The first PID type controller is developed by Elmer Sperry in 1911 which used to automate the mechanism of ship steering. The model manages to demonstrate the capability of aircraft to maintain specified level under disturbance with the application of gyroscope and ailerons [12]. In the year 1940, the first pneumatic PID controller is introduced with additional derivative action into the existing proportional-Integral (PI) controller that intended to remove the steady-state error. The PID controller is designed to deal with the overshooting problem. A PID controller is a controller that includes the proportional, integral, and derivative elements [5]. The nature of the output associated with the respective element is as below:

i. P action : proportional to the error at the instant (present error)
ii. I action : proportional to the integral of error up to the present instant, (accumulation of past error)
iii. D action : proportional to the derivative at the instant (prediction of future)

Therefore, a PID controller can be known as a controller that considers the error that introduces in past, present and future [13]. PID control is the method of feedback that mainly utilize the PID controller as the main component. The objective of the control is to ensure that the process variable follows the trajectory of set-point or reference.

2.5.1 Ziegler-Nichols Tuning

In the year 1942, John G. Ziegler and Nathaniel B. Nichols of Taylor Instruments introduced the new tuning rule that enables fast and stable closed-loop step response. Their first proposed method was used for non-First Order Plus Dead Time (FOPDT) condition and involved intense manual calculations [14]. A line is drawn tangent to the response curve (S-Shaped) at the steepest point to determine the response of the system to the step input. The S-Shaped reaction curve is represented by two constant which are delay time and time constant. From the information on delay time and time constant, the parameter of PID can be identified.

The second classical method proposed by Ziegler-Nichols is the frequency-domain method. The second method is performed on a closed-loop system based on the initial adjustment for gain for proportional (P) element only [15]. From the sustained oscillate response obtained, the information of ultimate period (Pu) and ultimate gain (Ku) can be determined. They determine that the best setting for the PID controller can be computed based on the value of ultimate period (Pu) and ultimate gain (Ku). The setting for Ziegler-Nichols continuous cycling method is shown in Table 2.1 [4]:

Table 2.1: Ziegler-Nichols continuous cycling tuning formula

Controller Parameter	Kp	Ki	Kd
Formula	0.6 Ku	2Kp/Tu	KpTu/8

2.5.2 Trial-and-Error Tuning

In trial-and-error tuning, the proportional action act as the main control. The integral and derivative action act as a secondary controller to refine the response. This method is an easy way to tune a controller, but satisfactory performance is not guaranteed and it consumes a lot of time due to multiple iteration steps [16]. Normally, the performance of the controller will be determined based on the square wave or step response. A high stability margin indicates that the output response has a low overshoot with step response input. This method is more convenient to use for process operator because only a little knowledge is required in this controlled process.

2.6 Robust Control

A revolution in control theory happens in the early 1970s where the major focus on the research and development of controller is shift from optimality to robustness [17]. The robust controller is introduced to overcome the drawback and limitation of optimal control theory which is unable to deliver feedback control designs that capable to sustain normal differences between design models and reality. In other words, the performance of the existing optimal controller is greatly affected by the disturbances that exist during actual application. This rapid development and application of robust controller are because it is relevant to the practical problems of an automation engineer. The plant or system is said to be robust when it responds without considering:

i. constant disturbances
ii. initial conditions of the plant and controller and
iii. the type of plant and controller whether it is linear or nonlinear.

With the given specification of desired response and frequency estimates of the magnitude of uncertainty, the controller able to evaluate the best suitable control law and produce the desired output response which is insensitive to noise or disturbances [3].

The theory of robust controller is said to be the combination of dominant frequency and Automatic Modern dominated state variables. From the dominant frequency, it is enhancing the performance parameter in term of monitoring or regulation and bandwidth based on the frequency analysis system. Other than that, it inherits the simplicity and systematic synthesis method from the Automatic Modern dominated state variables [3,18]. With the systematic analysis and synthesis algorithm, the engineer can introduce complex frequency specifications and evaluate the feasibility of the designed system with appropriate control law.

2.7 Variable Structure Control

In recent years, much research related to control theory focused on the design of discontinuous feedback which shifts the structure of the system according to the progression or deviation of its state vector. One of the nonlinear controls with discontinuity is known as variable structure control (VSC). The idea of implementation of the VSC began in the Soviet Union by Stanislav Emelyanov in the early 1950s. During the pioneering work, the system is considered as a second-order linear system that modelled in phase variable form. Since then, the VSC developed into a general design method that is analyzed for a wide variety of systems including multiple-input multiple-output (MIMO) system, non-linear system, stochastic system, discrete-time system, and large-scale infinite-dimensional systems [19]. The state-feedback of the control law constantly shifts from one satisfactory condition to another, and it is not a continuous function of time. The major advantages of the VSC approach include the dynamic response of the system can be customized with a specific switching function and the closed-loop response of the system will be unsusceptible to a