CONTROLLER DESIGN OF HYDRAULIC ACTUATOR SYSTEM USING SELF-TUNING AND MODEL REFERENCE ADAPTIVE CONTROL

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For my beloved family...

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ABSTRACT

Nowadays, hydraulic actuator system has become a major drive system in industrial sector especially when involving motion control or position tracking applications. However, due to its natural behaviour which is highly nonlinear, associated with many uncertainties and having parameters that change with time-variation, handling and controlling a hydraulic actuator system is a challenging task. The purpose of this study is to model and to design a controller for hydraulic actuator system. Thus, in order to develop a system that meets the desired performance such as a highly-accurate trajectory tracking, a special knowledge about the system togather with a suitable modelling and control design for the system is mandatory. In this research, Self-tuning Controller using Generalized Minimum Variance Control Strategy and Model Reference Adaptive Controller using Gradient Method has been designed to improve the performance of hydraulic actuator system. System Identification technique with the aid of System Identification Toolbox in MATLAB is used to estimate the mathematical model of the system. System Identification is chosen because it only requires a set of input and output data without the prior knowledge about the system, in order to obtain the system's transfer function. Auto Regressive with exogeneous input (ARX) model was selected as system's model structure and the best model among ARX orders was selected based on the analysed result of fitting percentage, loss function and Akaike's Final Prediction Error. The obtained model was then used to develop the controller for hydraulic actuator system. The output performance was analysed and it has been shown that the output of controlled system successfully tracked the given input signal for both simulation and experimental modes. It has also been observed that Model Reference Adaptive Controller using Gradient Method demonstrates a better output performance compared to Self-tuning Controller using Generalized Minimum Variance Control Strategy in terms of having a minimum phase lagging and a better transient response in terms of rise time, settling time and steady state error.

ABSTRAK

Pada masa kini, sistem penggerak hidraulik telah menjadi satu sistem pemacu utama dalam sektor perindustrian terutamanya apabila melibatkan aplikasi kawalan gerakan atau pengesan kedudukan. Walau bagaimanapun, disebabkan oleh tingkah laku semula jadi yang sangat tak linear, mempunyai ketidaktentuan yang tinggi dan mempunyai parameter yang berubah dengan masa yang berbeza-beza, ini telah menyebabkan pengendalian dan mengawal sistem penggerak hidraulik satu tugas yang mencabar. Tujuan kajian ini adalah untuk memodel dan untuk mereka bentuk pengawal bagi sistem penggerak hidraulik. Oleh itu, dalam usaha untuk membangunkan satu sistem yang memenuhi prestasi yang dikehendaki seperti trajektori menjejak yang sangat tepat, pengetahuan khas mengenai sistem berserta dengan pemodelan dan kawalan reka bentuk yang sesuai untuk sistem ini adalah mandatori untuk difahami. Dalam penyelidikan ini, Pengawal Sendiri Penalaan menggunakan Strategi Pengawalan Minimum Varian Umum dan Pengawal Model Rujukan Adaptif menggunakan Kaedah Kecerunan direkabentuk untuk meningkatkan prestasi sistem penggerak hidraulik. Teknik Pengenalan Sistem dengan bantuan Kotak Perkakasan Sistem Pengenalan dalam MATLAB diguna untuk menganggarkan model matematik sistem. Sistem Pengenalan dipilih kerana ia hanya memerlukan satu set input dan output data tanpa pengetahuan terlebih dahulu tentang sistem, untuk mendapatkan rangkap pindah sistem. Auto regresif dengan input luaran (ARX) dipilih sebagai struktur model sistem dan model yang terbaik dalam kalangan peringkat ARX dipilih berdasarkan keputusan analisis peratusan yang sesuai, kehilangan fungsi dan Ralat Ramalan Akhir Akaike. Model yang diperolehi kemudiannya digunakan untuk mereka pengawal untuk sistem penggerak hidraulik. Prestasi keluaran dianalisis dan ia menunjukkan bahawa keluaran sistem kawalan berjaya mengikut isyarat input yang diberikan untuk kedua-dua mod iaitu simulasi dan eksperimen. Daripada kajian didapati Pengawal Model Rujukan Adaptif menggunakan Kaedah Kecerunan terbukti memberikan prestasi yang lebih baik berbanding dengan Pengawal Sendiri Penalaan menggunakan Strategi Pengawalan Minimum Varian Umum dari segi mempunyai fasa ketinggalan yang minimum dan sambutan fana yang lebih baik dari segi masa naik, penetapan masa dan ralat keadaan mantap.

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LIST OF ABBREVIATIONS

MATLAB	–	Matrix Laboratory
STC	–	Self-tuning Controller
GMVC	–	Generalised Minimum Variance Controller
MRAC	–	Model Reference Adaptive Controller
ARX	–	Auto Regressive Exogenous
ARXMAX	–	Auto Regressive Moving Average
BJ	–	Box Jenkins
OE	–	Output Error
FPE	–	Akaike's Final Prediction Error
PID	–	Proportional Integral Derivative Controller
FPE	–	Akaike's Final Prediction Error
DAQ	–	Data Acquisition System
RAM	–	Read Access Memory

LIST OF SYMBOLS

R_c	–	Resistance
L_c	–	Coil Inductance
ξ_v	–	Servo Valve Damping Ratio
ω_v	–	Servo Valve Natural Frequency
Q	–	Liquid Flow in Chamber
x_v	–	Spool Valve Position / Displacement
K_v	–	Servo Valve Gain
P_v	–	Servo Valve Pressure Different
P_s	–	Power Supply
β_e	–	Effective Bulk Modulus
V_t	–	Piping Volume
Q_{pump}	–	Constant Flow Rate
Q_L	–	Load Flow Rate
u_n	–	Negative Limit of Dead Zone
u_p	–	Positive Limit of Dead Zone
$g_z(u)$	–	Negative Slope Of Output
$h_z(u)$	–	Positive Slope Of Output
u_z	–	Output
u	–	Input
P_a	–	Hydraulic Supply Pressure
P_r	–	Hydraulic Return Pressure
Q_1	–	Fluid Flow from Cylinder
Q_2	–	Fluid Flow to Cylinder
P_1	–	Fluid Pressure in Lower Cylinder Chamber
P_2	–	Fluid Pressure in Upper Cylinder Chamber
x_p	–	Piston Displacement
v_p	–	Piston Velocity
d_u	–	External Disturbance

F_a	–	Actuating Force
F_f	–	Hydraulic Friction Force
P_L	–	Load Pressure
A_L	–	Hydraulic Cylinder Cross Section Area
V_t	–	Actuator Volume
C_t	–	Total Leakage Coefficient
C_s	–	Discharge Coefficient
x_d	–	Spool Valve Area
ρ	–	Oil Density
k	–	Discrete Time Index
$y(k)$	–	Measured System Output in Discrete Time Index
$\Phi(k)$	–	Vector of Input and Output Signals
j	–	Cost Function
$L(k)$	–	Least Square Weighting Factor

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CHAPTER 1

INTRODUCTION

1.1 Background

The hydraulic actuator system was briskly developed starting from the era of the 20th century. The principle of hydraulic was first introduced by Blaise Pascal, who is a French Physicist in the year of 1993. Starting from the introduction, many books [1] has been published to discuss and share about the histories, principle and application of the hydraulic actuator system. Tracing back the history of invention that applied the principle of hydraulic mechanisms there is the invention of water clock by Ctesibios in about 250 B.C and the invention of the steam engine by James Watt in the year 1763. As time flies, the importance and advantages of the hydraulic actuator system have become crucial, especially for the development of modern technology.

There are a number of advantages in the hydraulic actuator system compared to other actuators such as pneumatic and electrical motors that are available nowadays. One of the important advantages of the hydraulic actuator system is to have a good ratio between hydraulic actuator size and weight over the force delivered by the actuator. This means that a small and compact structure of the hydraulic actuator system is capable of producing a great actuator force. This has made hydraulic actuator system suitable to use, especially in the transportable industrial field. Furthermore, the combination between electrical and hydraulic system can make the hydraulic actuator system becomes more flexible, especially when applied in advance control strategy. Apart from this, another advantage of the hydraulic actuator system is, it manages to perform a self-cooling activity as the fluid is driving away from the actuator and other control element. Besides that, hydraulic fluid also can act as a lubricant that helps to make the component more durable [1]. The hydraulic actuator system can also be operated under continuous, intermittent, large speed range and in an immediate stop situation without damaging the system. This is due to the combination of valve and pumps that help to make the open and closed-loop control of the hydraulic actuator system become much easier.

In previous research, many works have been done concerning the hydraulic actuator system. As mentioned in by Cetinkunt *et al.* [2], about thirty percent of the world market is possessed to industrial equipment which is related to the hydraulic system. By relating hydraulic actuator system in industrial equipment, this will help to increase the safety of workers together with the decreasing of the physical effort when handling a big and bulky work. One example of application of the hydraulic actuator system is in automotive industries. In automotive industries the active part which is the actuator is used to drive the passive part. Some research had been done that relates hydraulic actuator system to the automotive field [3] where the hydraulic actuator is used to activate the suspension bar system test rig. Meanwhile, the research by Sam *et al.* [4] used a hydraulic actuator system to operate the suspension system of a quarter-car model. Similarly in the work by Ayalew [5] , an in-laboratory road simulation that used a the hydraulic actuator system was developed to test the vehicle structure and durability without the need to test the vehicle on the actual road.

From the discussion above, it is clear that the hydraulic actuator system is important for the development of current and future technology. For the purpose of engineering design approach, modelling and control of the system play important roles in realizing and enhancing the advance technology. Unfortunately, for the hydraulic actuator system, it is difficult to establish or identify the exact dynamic model as the system is naturally highly non-linear and have many uncertainties. With the nonlinearities and uncertainties property that existed in the system, this makes the modelling and control design of the hydraulic actuator system hard and complicated. Some of the nonlinear properties in the hydraulic actuator system are caused by non-linear flow of fluid, backlash in control valve, actuator friction, variation in the trapped fluid, external disturbance [6–10] and others. In the work done by Loukianov *et al.* [8], external load, that was modelled as a parallel spring and damper attached to the piston and considered as an interference to the system where the friction happened was taken as an external disturbance. Meanwhile, in some previous researches [7, 9, 10] an unknown, but bounded signal and deterministic signal was considered as external disturbance. Regarding the non-linear behaviour in hydraulic actuator system, some works [11–14] considered that it happened due to the friction while some [15–22] some considered variation of fluid, unknown dead zone, bulk modulus of fluid and leakage that caused the system to become non- linear. With the difficulties that complicate the modelling and control design process, it has motivated the researchers and academia to further study and investigate on the hydraulic actuator system performance. In hydraulic actuator system, from electrical technique and signal processing coupled with high pressure in HSA itself when moving loads generate a combination of flexible and accurate system.

Several research had been carried out discussing about the force control problem that occured in the hydraulic actuator system [4, 23–25], where this type of control is useful in some application that requires an output force from hydraulic actuator system. However, not all applications require the same amount of force, some applications only require a certain amount of force to be applied to hydraulic actuator system. In contrast, position control of the hydraulic actuator system is also becoming a popular research subject as it is used in a wide range of application such as in construction machinery, robotic application and machinery tools that normally require an accurate actuation position control. This is further enhanced by the increase in the number of publications that have been published concerning about the position control of the hydraulic actuator system.

1.2 Problem Statement

From the earlier discussion, it is proven that the hydraulic actuator system has many uncertainties and is highly non-linear that cause inaccurate performance, especially when an accurate position tracking that is desired is hard to achieve. This situation has attracted many researchers and academia to propose a different technique of control design to improve the tracking performance of the hydraulic actuator system, and these conditions cause the modelling and controller design process for the hydraulic actuator system to become a challenging task

Thus, to increase the tracking performance of the hydraulic actuator system, a proper method should be implemented in designing and modelling a hydraulic actuator system. In this research, a dynamic model for hydraulic actuator system test bed was developed in order to be used in controller designing process part. Two types of adaptive controller, which is STC with GMVC strategy and MRAC using MIT method were designed to help increase the tracking performance of the hydraulic actuator system. Adaptive controller was chosen because this type of controller is widely used for controlling hydraulic actuator system . Another reason for choosing an adaptive controller is because the scheme will assist the controller to adapt to any changes that occur in the system and at the same time this will help to reduce the effort to achieve the best tracking performance for hydraulic actuator system.

The most important part in this research is the validation process that is done to support the theoretical work that had been done and need to be realized in the real system. From the previous work, many researches are lacking in experimental validation. Thus, in this research, an experimental procedure is compulsory to be done in order to validate that the proposed controller is manageable to control the hydraulic actuator system and which controller from these two controllers is able to give the best performance when it is applied in the real hydraulic actuator system test bed.

1.3 Research Objectives

The objectives of this research are:

1. To determine the mathematical model that represents the hydraulic actuator system by using system identification technique and parameter estimation method approach.

2. To design STC with GMVC strategy and MRAC using MIT method based on the mathematical model obtained from the experiment and system identification technique.

3. To analyze the tracking performance of the complete control system that consists of hydraulic actuator system with servo valve and the controllers.

1.4 Research Scope and Limitation

To achieve the objective of this research, there are several scopes and limitation that need to be outlined:

1. MATLAB's System Identification Toolbox was used with linear ARX model structure to estimate the system's model and also to test for the model's suitability.

2. Hydraulic actuator system was assumed as a linear system to reduce the complexity in developing the hydraulic actuator system model.

3. STC with GMVC strategy and MRAC using MIT method were designed to control hydraulic actuator system.

4. Electro hydraulic actuator system with servo valve test bed was used in experimental mode to verify the tracking performance of the designed controller.

5. NI PCI 6221 DAQ card was used as an interface between MATLAB program in the PC and electro hydraulic actuator system with servo valve test bed.

1.5 Contribution of the Research Work.

From the problem statement, it is proven that there is a significant outstanding problem concerning of identification and controlling of the hydraulic actuator system especially in position control that required a further investigation. Thus, the contribution of this research is to choose the best designed controllers between STC with GMVC strategy and MRAC using the MIT method that give a better transient response and phase difference performance in both simulation and experimental mode.

1.6 Thesis Outline

This thesis consists of five chapters. The first chapter describe a brief introduction about the project in terms of objective, problem statement, scoped of work and summary of work.

Chapter two focuses on the theory of the project and literature review that has been done, as well as quoting other previous research which will help to support the project.

Chapter three focuses on the methodology of the project where the idea on the project flow, method involved together with the software used are explained and discussed.

Chapter four presents the result and discussion of the project where the simulation and experimental results are presented together with the detailed descriptions and discussions on the obtained result are also made.

Chapter five summarised the conclusion and findings of the project together with the future recommendation that may be done to improve the project in the future.

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