ADAPTIVE DISCRETE SLIDING MODE CONTROL OF AN ELECTRO-HYDRAULIC ACTUATOR SYSTEM

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To my lovely wife and son ...
Farhaana Yakop and Khalish Rozaimi

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ABSTRACT

This thesis presents system identification and development of an adaptive robust control strategy based on discrete sliding mode control (DSMC) with zero phase error tracking control (ZPETC) for an electro-hydraulic actuator (EHA) system. A linear type actuation of the EHA system using a single-ended cylinder controlled by a servo valve was considered in the experimental design. In the system identification process, EHA system was modelled using parametric linear time varying equations with parameters that were identified using recursive and non-recursive identification techniques. An identification process that recursively computes the dynamic model was performed using recursive least square with varying forgetting factors and the estimated linear model was validated through statistical approaches. From the identification process, a non-minimum phase model of EHA system with a high sampling time was obtained. To formulate the control algorithm for the EHA system, a robust feedback control theory with feedforward structure was employed to overcome the non-minimum phase problem in EHA system. The algorithm was also subjected to model uncertainty and non-linear characteristics. As a result, a new robust controller with an integrated design scheme based on DSMC and ZPETC was developed using a reaching law technique where parameters of the controller had been analytically determined. Subsequently, the new adaptive control strategy was improved by enhancing DSMC and ZPETC that are adaptable with variations in the parameters of EHA system. In simulation and experimental studies, an optimal linear-quadratic-regulator (LQR) and a proportional-integral-derivative (PID) were implemented in the position tracking control as comparisons with the proposed robust controller. A comprehensive performance evaluation with quantitative measures of the tracking performance is presented and the results show that the robust system performance was achieved with DSMC under different operating system conditions. The findings also demonstrated that the new adaptive DSMC with ZPETC structure has reduced the control effort and gave a better performance in terms of tracking accuracy as compared to the conventional DSMC, LQR and PID controllers.

ABSTRAK

Tesis ini mengemukakan pengenalpastian sistem dan pembangunan sebuah teknik kawalan tegap mudah suai berdasarkan kawalan ragam lincir diskret (DSMC) dengan teknik kawalan ralat penjejak fasa sifar (ZPETC) untuk sistem penggerak elektro-hidraulik (EHA). Sebuah penggerak jenis linear bagi sistem EHA menggunakan silinder berhujung tunggal yang dikawal oleh injap servo telah dipertimbangkan di dalam rekabentuk ujikaji. Di dalam proses pengenalpastian sistem, sistem EHA dimodelkan menggunakan persamaan linear berparameter masa berubah dengan parameter tersebut telah dikenalpasti menggunakan teknik pengenalpastian rekursif dan tidak rekursif. Sebuah proses pengenalpastian yang mengira secara rekursif model dinamik telah dijalankan menggunakan kuasa dua terkecil rekursif dengan faktor pemadaman berubah dan anggaran model linear tersebut telah disahkan melalui pendekatan statistik. Daripada proses pengenalpastian, sebuah model fasa tidak minima sistem EHA telah diperolehi dengan persampelan masa tinggi. Bagi perumusan algoritma kawalan untuk sistem EHA, teori kawalan suap balik tegap dengan struktur suap depan telah digunakan untuk mengatasi masalah fasa tidak minima di dalam sistem EHA. Algoritma tersebut juga mengalami ketidakpastian model dan ciri tidak linear. Hasilnya, sebuah pengawal tegap baru dengan skim rekabentuk berintegrasi berdasarkan DSMC dan ZPETC telah dibangunkan menggunakan teknik hukum mencapai di mana parameter pengawal telah ditentukan secara beranalitik. Kemudiannya, sebuah strategi kawalan mudah suai baru ditambah baik dengan peningkatan DSMC dan ZPETC yang boleh suai terhadap perubahan parameter di dalam sistem EHA. Di dalam kajian penyelakuan dan ujikaji, sebuah pengatur-kuadratik-linear (LQR) optima dan kadaran-kamiran-terbitan (PID) telah dilaksanakan di dalam kawalan penjejak kedudukan sebagai perbandingan dengan pengawal tegap yang dicadangkan. Penilaian prestasi komprehensif dengan sukatan kuantitatif bagi prestasi penjejak dikemukakan dan keputusan menunjukkan bahawa prestasi sistem tegap telah dicapai dengan DSMC bagi keadaan sistem yang berbeza. Penemuan ini juga menunjukkan bahawa DSMC mudah suai baru dengan struktur ZPETC telah mengurangkan usaha pengawal serta memberi prestasi yang lebih baik dalam terma ketepatan penjejakan berbanding pengawal konvensional DSMC, LQR dan PID.

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LIST OF ABBREVIATIONS

2-DOF – two-degree-of-freedom
APA – absolute positioning accuracy
CSMC – continuous sliding mode control
DAQ – data acquisition system
DSMC – discrete sliding mode control
EHA – electro-hydraulic actuator
FPE – final prediction error
LQG – linear quadratic Gaussian
LQR – linear quadratic regulator
MPA – mean positioning accuracy
MRAC – model reference adaptive control
NMSE – normalized-mean-square-error
PID – proportional-integral-derivative
PRBS – pseudo-random-binary-sequence
PRMS – pseudo-random-multiple-sequence
PTC – perfect tracking control
QFT – quantitative feedback theory
RI – robustness index
RIV – recursive instrumental variable
RLS – recursive least square
RMSE – root-mean-square-error
SISO – single-input-single-output
SMC – sliding mode control
VSC – variable structure control
WPA – weight positioning accuracy
ZPETC – zero phase error tracking control

LIST OF SYMBOLS

α_0 – Coulomb friction
α_1 – Stribeck friction
α_2 – viscous friction parameter
β_e – effective bulk modulus
ΔP_v – pressure difference in servo valve
$\dfrac{dz_f}{dt}$ – rate of bristle deflection
$\hat{\theta}(k)$ – estimated system parameters
λ – forgetting factor
ω_v – servo valve natural frequency
ϕ – matrix regression
σ_0 – bristle-spring constant
σ_1 – bristle-damping coefficient
σ – control weighting factor
$\theta(k)$ – system parameters
$\varepsilon(k)$ – residual
ζ_v – servo valve damping ratio
A_1, A_2 – the area of each chamber
A_p – surface area of the piston
B_s – damper coefficient
C_{tp} – total leakage coefficient
$e(k)$ – white noise of the system with zero mean
F_a – force of the actuator
F_f – friction force
I_v – current signal to the servo valve
$J(\theta)$ – quadratic loss function
K_c – flow-pressure coefficient
K_q – flow-gain coefficient
K_s – spring coefficient

K_v, K_{v1}, K_{v2} – servo valve gain

L_c – coil inductance

M_p – moving mass

$P(k)$ – covariance matrix

P_L – load pressure

P_s – supply pressure

Q – volume flow rate

q_1, q_2, q_{12}, q_{21} – external and internal leakages in the hydraulic actuator

Q_L – volume flow rate that used in the servo valve

Q_{pump} – constant volume flow rate

R_c – coil resistance

T_s – sampling time

$u(k)$, $y(k)$ – system input and output for linear discrete-time model

V_1, V_2 – volume of each chamber in hydraulic actuator

V_{line} – the volume of the pipeline

V_t – volume in the piping between servo valve and the pump

V_v – voltage signal to the servo valve

x_p, y – current position of the hydraulic actuator

x_s – total stroke of the hydraulic actuator

x_v – spool valve position

z^{-1} – backward shift operator

z_f – average bristle deflection

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Electro-hydraulic Actuator System

Electro-hydraulic actuator (EHA) system emerge in fluid power technology was greatly developed from the beginning of the 20^{th} century where the works were first introduced by French physicist, Blaise Pascal in 1663. Brief but very interesting histories of fluid in technology or known as hydraulic system can be referred in various books such as in Merritt (1967). Tracked back to the invention of the water clock by Alexanderian inventor Ctesibios in about 250 B. C., this is a great invention based on the principle of hydraulic mechanisms back to several centuries ago. Following the invention, the idea was widely used in early 1763 for industrial applications using water as the working fluid after the invention of steam engine by James Watt. It was written in histories, the importance and advantageous of fluid control systems which are very crucial in the development of modern technology.

There are many unique elements and advantages of EHA system over rival actuators such as pneumatic and electrical motor. The main advantages of fluid power, which led to its prominent feature, is the good ratio between forces delivered by the actuator over the weight and its size. The lighter and smaller compact structure of the EHA system has made this actuator very suitable to be used especially in transportable industrial field. The combination between electrical and hydraulic devices also rendered EHA system to be more flexible by implementing in real application with advanced control strategies.

1.2 Research Background

The source of power in the EHA system which distributed fluid under pressure is used to generate the necessary movements in different applications particularly for the linear and rotary machines which are typically referred as cylinders or motors, respectively. The movement is the desired end function to lift, shift, press, orient and clamp depending on the type of applications. As the reasons and advantages as discussed by Merritt (1967), the increased usage of EHA system has brought demands of high performance for position and force control to diverse of applications. The EHA system is particularly used in applications where high response, linear movements and accurate positioning with heavy weight or load are usually required. Recently, EHA system has become progressively popular in various types of engineering equipment. The typical engineering application fundamentals such pulling or pushing are employed in earth moving equipment, manufacturing equipment and flight applications. Moreover, these actuators are also widely used in industrial field that involved textile industries, automotive engineering, agricultural machinery and military equipment in defence technology.

In the literatures, intensive works have been found concerning EHA system in the construction applications. As stated in Cetinkunt *et al.* (2004), the size of the world market in EHA system is estimated about 30 to 35 billion dollars per year. It is approximately thirty percent of that market belongs to the construction equipment industry. The construction equipment has started developing progressively in heavy engineering industry these days. The uses of EHA system in construction equipment increased the operator safety and reduced its physical effort in handling such applications that were formerly required to manipulate bulky valve handles. There are two major types of construction machinery equipped with EHA system operating in huge numbers which are the wheel type loader and the excavator.

In general, the main purpose of the wheel type loader is to load material from a pile to a truck at a construction area. In the development of wheel loader as reported in Fales *et al.* (2005), virtual reality based human-in-the-loop real-time simulation for a wheel loader control system is implemented in the simulator which consists of hydraulic actuator acts as a main part in the wheel loader application. More recent works has been studied by Fales and Kelkar (2009) in simulation environment which are concerning on wheel loader applications as an automatic bucket levelling mechanism. Alaydi (2008) also implemented the hydraulic actuator with pump-controlled system which is operated in a single bucket excavator. The employment of EHA system in the high power mining excavators and forestry equipments are generally to increase the efficiency of its performance.

In the initial works of EHA system for industrial machine tools, Lee and Srinivasan (1989) implemented the hydraulic actuator in mechanical material testing machine. As discussed in Renn and Tsai (2005) and Pluta (2008), press machines are the most commonly utilised in industrial machine tools especially for metal forming. It was also clarified by Chiang *et al.* (2005) the importance of using EHA system in moulding machines in order to simultaneously achieve high energy efficiency and also high accuracy of the force control response. The experimental works by Tsai *et al.* (2009) presented an ultra high-speed plastic injection moulding machine by controlling the injection speed with hydraulic actuator.

In the present flight technology, most of the modern high-performance aircraft commonly used fly-by-wire in their flight control systems. In these aircraft systems, the pilot send electrical signals through flight control computers to achieve the desired trajectory. Di Rito *et al.* (2008) has performed hardware-in-the-loop simulations of the fly-by-wire flight control systems. In that works, EHA system was mainly used in designing the simulator platform. In Guo *et al.* (2008), a parallel robot manipulator was constructed as a spatial platform mechanism. This type of manipulator was originally used as a flight simulator. Karpenko and Sepehri (2009) also had applied EHA system in their research works mainly in hardware-in-the-loop simulator for flight control applications. Then, the research was continued in a year later by Karpenko and Sepehri (2010b) where the hydraulic actuator was operated as a flight surface actuator of a high-performance aircraft.

Some applications especially in automotive industry is very crucial where the actuators are used as an active part in the system in order to drive the passive part. Chen and Zeng (2003) used the hydraulic actuator in torsion bar suspension systems where in the test rig, the EHA system was used to generate several road disturbances. Sam *et al.* (2004) implemented the hydraulic actuator in the active suspension system where a quarter-car model was adopted in the simulation studies. Similar concept has been revealed by Ayalew (2008) in the development of the road simulators which enable the in-laboratory evaluation of vehicle structural durability and vehicle dynamics for ride comfort without having to run the vehicle's drive train on an actual road surface. It can also be used in the assessment of pavement damage and the study of road-vehicle interaction. It was found in Witters and Swevers (2010), that they started to develop the continuously variables using the electro-hydraulic semi-active dampers in improving the suspension technology.

From the discussions and motivation in the current applications of the EHA system, it was found that the importance of hydraulic actuator is really significant in the technology development nowadays. In the engineering design approach, modelling and control are the most important processes in realizing the advanced technology. In general, it is difficult to establish or identify an accurate dynamic models where the EHA system inherently have many uncertainties, highly non-linear and time-varying which makes the modelling and controller designs becoming more complicated. Non-linear flow and pressure characteristics, backlash in control valve, actuator friction, variations in the trapped fluid volume due to piston motion and fluid compressibility are major sources of non-linearity in the actuation system (Jelali and Kroll, 2003). These difficulties have motivated the researchers and academia to conduct further investigations on the actuator performance before the implementation of various potential applications in the industries. To solve those engineering issues, several research works focusing on the hydraulic actuator have been carried out.

According to Merritt (1967), a typical EHA system consists of a pump, control valve and a hydraulic actuator. The actuator can be either a cylinder providing linear motion or hydraulic motor providing rotary motion. EHA system combines together with the versatile and precision available from electrical technique of measurement and signal processing with the superior performance which high pressure hydraulic mechanism can be provided when moving heavy loads and applying large forces. Hence, the EHA system control problem might be grouped into force and position control as an innermost loop of control systems.

There are few numbers of work discussing the problem of force control in EHA system (Alleyne and Liu, 1999, 2000; Sohl and Bobrow, 1999). This type of control is very useful for certain applications that required force as an output from the hydraulic actuator. Furthermore, some applications only need certain amount of force to be exerted to the applied system. In recent works by Truong and Ahn (2011), force control of EHA system was applied in press machine operation. Another example on application that required force as an output from the EHA system is an active suspension system (Sam *et al.*, 2004). However, in contrast, hydraulic positioning control is more attractive due to its wide range of applications. From the discussion above, construction machinery, machine tools, aircraft systems and robotic applications usually need an accurate positioning control from the actuator. It can be seen from the literature that several number of publications have been published among academia and researcher regarding the problem of position control using EHA system. Therefore, the research study will be focused on various types of control strategies of EHA system particularly in position tracking control.

1.3 Problem Statement

The problem statement of this study is expressed as follow:

"an identification process and adaptive robust controller are necessary to control the EHA system due to its nonlinearities and uncertain characteristics".

1.4 Research Objectives

The objectives of this research are as follows:

(i) To obtain a dynamic model of the EHA system in state space form using system identification technique.

(ii) To design a robust controller based on discrete-time sliding mode control with feed-forward approach that will overcome non-minimum phase problem in EHA system.

(iii) To design an adaptive control strategy based on the discrete-time sliding mode control with feed-forward approach that will overcome the time-varying in EHA system's parameters.

(iv) To implement and evaluate the tracking performance of an EHA system with proposed control strategy through simulation and experimental study.

1.5 Scope of Work

This thesis addresses the position tracking problem for the developed EHA system workbench in the laboratory. The scope of this research are as follows:

(i) The position tracking is conducted for the linear type of motion using single-ended cylinder and controlled with a servo valve.

(ii) Due to the limitation of hardware construction, bandwidth of the EHA system for the identification process and tracking control is limited to 1 Hz.

(iii) The maximum supply pressure is regulated at 8×10^6 Pa which is assumed to be the nominal operation of the EHA system.

(iv) The robustness and adaptive tests are conducted at 8×10^6 Pa and limited to $50\ \%$ of nominal pressure which is 4×10^6 Pa.

(v) Robustness of the PID and LQR controllers with the zero phase error tracking controller based on the discrete sliding mode control technique is analysed in a comparative manner by considering the tracking error and control signals.

Theoretical verification of the discrete sliding mode controller on its stability and reachability condition will be accomplished by using the reaching law method. The performance of the EHA system will be analysed by using extensive computer simulation and experimental studies that will be performed using MATLAB and SIMULINK software.

1.6 Contributions of the Research Work

From the literature study, it is evidenced that there are significant outstanding issues related to the identification and control of EHA system particularly for positioning that need to be further investigated. From the problem statements and the importance of the research as discussed previously, several contributions can be made in the vicinity of identification and control strategy. These are also reflected in several journal and conference papers arising from this research study as detailed in Appendix A. The main research contributions from this study are as follows:

(i) A new robust controller with integrated design scheme based on discrete-time sliding mode control and zero phase error tracking control for the non-minimum phase EHA system.

(ii) A new adaptive control strategy with the enhancement of discrete-time sliding mode control and zero phase error tracking control that adaptable to the variation in the EHA system's parameters.

1.7 Organization of the Thesis

Chapter 2 presents the literature study on the EHA system particularly for trajectory position tracking control. The discussion based on control strategies that have been implemented by the prominent researchers ranging from the linear control to non-linear control as well as intelligent control strategies. The review is discussed in details with the comprehensive exploration to the main contributions as proposed in the methodology section.

Chapter 3 deals with the modelling of an EHA system. Firstly, the physical representation of the dynamic model of the EHA system is outlined. Secondly, the mathematical representation of the dynamic model and its assumptions for position tracking control are composed. Then, the state space representation of the dynamic model of the hydraulic actuators will be presented. Based on the dynamic models of the actuators, the state space representation of the hydraulic actuator will be derived. Finally, variations in load and supply pressure that represent the uncertainties and disturbances in the EHA system will be presented.

In Chapter 4, the system identification theory and parameter estimation process are presented. The design of the non-recursive and recursive identification with the selection of the input signals and effects on forgetting factor will be discussed. Results on the identification process also will be presented in this chapter before the implementation of the developed model in proposed controller design. Lastly, the experimental design of the developed workbench for EHA system will be presented.

Chapter 5 presents the proposed new control strategy for EHA system based on the sliding mode control approach. Theory of SMC will be discussed first in this chapter. The discrete-time sliding mode controller is proposed to improve the EHA system and the proposed controller will be evaluated to determine its stability and reachability condition. Then, the two-degree-of-freedom structure will be presented for minimum and non-minimum phase EHA system. With the same control structure, an adaptive scheme is then introduced with the proposed robust controller design.

Chapter 6 presents the results and discussion based on the adaptive DSMC approach. This single-input-single-output model which suffers from the non-minimum phase condition due to the slow sampling time will be analysed. It will be shown that the proposed adaptive DSMC is able to overcome such conditions and improve the performance of the EHA system. The stability and reachability conditions of the sliding surface and controller also will be discussed. Several simulation and experimental results will be presented and discussed based on this chapter to study and verify the performance of the proposed controller.

The summary of the research findings and the recommendation of future research based on this study will be presented in Chapter 7.

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