A FULL ORDER SLIDING MODE TRACKING CONTROLLER DESIGN FOR AN ELECTROHYDRAULIC CONTROL SYSTEM

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To my dearest father, mother and family for their encouragement and blessing

To my friends for their support and caring … … …

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ABSTRACT

Electrohydraulic control system are widely use in industry due to continuous operation, higher speed of response with fast motion etc. However, there is a drawback that it is difficult to control because of the highly nonlinear and parameters uncertainties. In this project, a Full Order Sliding Mode Controller is design to control the system. First, the mathematical model of the electrohydraulic servo control system is developed. Then the mathematic model will be transformed into state space representation for the purposed of designing the controller. The system will be treated as an uncertain system with bounded uncertainties where the bounded are assumed known. The proposed controller will be designed based on deterministic approach, such that the overall system is practically stable and tracks the desired trajectory in spite the uncertainties and nonlinearities present in the system. The performance and reliability of the proposal controller will be determined by performing extensive simulation using MATLAB/SIMULINK. Lastly, the performance of the controller is to be compared with Independent Joint Linear Control and advanced deterministic controller.

ABSTRAK

Sistem elektrohidraulik banyak digunakan secara meluas di industri kerana operasi yang berterusan, tindakbalas halaju yang lebih tinggi dengan gerakan yang pantas. Bagaimanapun kekurangan utama sistem ini ialah sukar untuk dikawal kerana kadar ketaklelurusan yang tinggi dan wujudnya ketidak pastian parameter. Dalam projek ini, sebuah pengawal ragam gelincir tertib penuh telah direkabentuk untuk mengawal sistem. Tahap pertama melibatkan pembangunan model matematik bersepadu yang mewakili sistem elektrohidraulik. Kemudian, model matematik tersebut ditukar kepada perwakilan dalam bentuk keadaan ruang bagi tujuan rekabentuk pengawal sepertimana telah dicadangkan. Sistem akan diperlakukan sebagai sistem tidak pasti dengan ketidak pastian sempadan dimana had maksimum sesetengah parameter dianggap diketahui. Pengawal yang dicadangkan akan direkabentuk berdasarkan pada kaedah deterministic, dimana keseluruhan sistem secara praktikalnya di anggap stabil dan mengikut kehendak trajektori. Walaupun wujudnya ketidak pastian dan ketaklelurusan dalam sistem. Perlakuan atau simulasi dan kebolehharapan cadangan kawalan akan ditentukan dengan bantuan perisian MATLAB/SIMULINK. Akhir sekali, keupayaan diantara pengawal ragam gelincir tertib penuh akan dibandingkan dengan kawalan lelurus bebas lipatan dan deterministic kawalan termaju.

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LIST OF SYMBOLS

SYMBOL	DESCRIPTION
1. UPPERCASE	
$A(*,*)$	N x N system matrix for the intagrated electrohydraulic control system
$B(*,*)$	N x 1 input matrix for the intagrated direct drive robot arm
$\Delta B(*,*)$	matrix representing the uncertainties in the input matrix
B_m	various damping coefficient of the load
β_e	effective bulk modulus of the system
C	1 x N constant matrix of the sliding surface
C_1	total leakage coefficient of the motor
C_d	the coefficient
D_m	volumetric displacement
$E(*)$	a continuous function related to ΔB(*,*)
$G(*)$	a continuous function related to ΔW(*,*)
$G_n\theta_m^3$	nonlinear stiffness of the spring
J_t	total inertial of the motor and load
K_c	flow pressure coefficient
K_q	flow gain which varies at different operating points
P_L	load pressure
P_s	supply pressure
Q_L	load flow
T_d	disturbance of the system
V_t	total compressed volume
$U(*)$	N x 1 control input vector for a N DOF robot arm
$X(*)$	$2N$ x 1 state vector for the intagrated direct drive robot arm
X_v	displacement of the spool in the servo valve
$Z(*)$	$2N$ x 1 error state vector between the actual and the desired states of the overall system

$(*)^T$	transpose of (*)
$\|(*)^T\|$	Euclidean norm of (*)

2. LOWERCASE

w	area gradient
t	time (s)

3. GREEK SYMBOLS

γ	norm bound of continuous function $H(*)$
β	norm bound of continuous function $E(*)$
ρ	fluid mass density
θ	joint displacement (rad)
$\dot{\theta}$	joint velocity (rad/s)
$\ddot{\theta}$	joint acceleration (rad/s^2)
θ_d	desired joint angle (rad)
$\dot{\theta}_d$	desired joint velocity (rad/s)
$\ddot{\theta}_d$	desired joint acceleration (rad/s^2)
σ	Integral sliding manifold
τ	time interval for arm to travel from a given initial position to a final desired position (seconds)

LIST OF ABBREVIATIONS

IJC	Independent Joint Control
LHP	Left Half Plane
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
SMC	Sliding Mode Control
VSC	Variable Structure Control

CHAPTER 1

INTRODUCTION

1.1 Introduction

Hydraulic servo system are widely used in industry due to their capabilities of providing large driving force or torques, higher speed of response with fast motion and possible speed reversals and continuous operation. Many industrial applications of electrohydraulic servo systems are in a load condition application such as suspension of electrohydraulic servo system, fly by wire system of aircraft, sheep steering gear system and numerical machine tools. Electrohydraulic servo system combine together the versatile and precision available from electrical technique of measurement and signal processing with the superior performance which high pressure hydraulic mechanism can provide when moving heavy loads and applying large forces. Servos of this type are commonly used to operate the control surface of aircraft with actuators which are very compact because they operate at high pressure.

The control of hydraulic system is difficult because of the nonlinear dynamics, load sensitivity and parameter uncertainties due to fluid compressibility, the flow pressure relationship and internal leakage. In addressing this problem, many advanced control approaches have been proposed. The other methods employed variable structure control is sliding mode control. Sliding Mode Control has been known as an efficient and robust approach to control the nonlinear system with uncertainties.

Hydraulic system can always be made to responds quickly than electrical devices of the same power rating. The electrical signal processing take place almost instantaneously and occurs at a very low power level. There is thus rapid response even with large distance between the source of the control signal and the actual mechanism. And its including servo valve itself. The hydraulic system also good in moving a large mass and its responds must inevitably be relatively slow.

Electrohydraulic system uses low power electrical signals for precisely controlling the movements of large power pistons and motors. The interface between the electrical equipment and the hydraulic (power) equipment is called 'hydraulic servo valve'. These valves that use in the system must responded quickly and accurately. One of the examples is in aircraft controls. Many mechanism which use other methods of control particularly if they are already employed hydraulic could benefit from incorporating electrohydraulic technique.

The physical model of a nonlinear electrohydraulic servo motor shown in Figure 1.1.The inertial-damping with a nonlinear torsional spring system is driven by an hydraulic motor and the rotation motion of the motor is controlled by a servo valve. Higher control input voltage can produce larger valve flow from the servo valve and fast rotation motion of the motor.

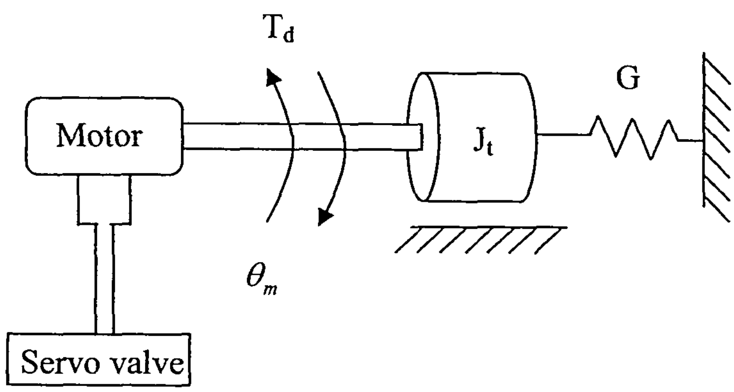

Figure 1.1 : Physical model of nonlinear electrohydraulic servo control system

There are many unique feature of hydraulic control compared to other types of control. Some of the advantages are the following [Herbett E. Merrit, 1967]:

1. Heat generated by internal loses is a basic limitation of any machine. Lubricants deteriorate, machine parts seize, and insulation breaks down as temperature increase. Hydraulic components are superior to others in this respect since the fluid carries away the heat generated to a convenient heat exchanger. This features permits smaller and light components.

2. The hydraulic fluid also acts as a lubricants and makes possible long components life.

3. There is no phenomena in hydraulic components comparable to the saturation and loses in magnetic materials of electrical machine. The torque developed by an electrical is proportional to currents and is limited by magnetic saturation. The torque developed by hydraulic actuators (examples motor and piston) is proportional to pressure difference and is limited only by safe stress levels.

Therefore hydraulic actuators developed relatively large torques for comparatively small devices.

4. Electrical motors are basically a simple lag device from applied voltage to speed. Hydraulic actuators are basically a quadratic resonance from flow to speed with a high natural frequency. Therefore hydraulic actuators have a higher speed of response with fast start, stop and speed reversal possible. Torque to inertia ratios are large with resulting high acceleration capability. On the whole, higher loop gains and bandwidths are possible with hydraulic actuators in servo loops.

5. Hydraulic actuators may be operated under continuous, intermittent, reversing and stalled condition without damage. With relief valve protection, hydraulic actuators may be used for dynamics breaking. Larger speed range are possible with hydraulic actuators. Both linear and rotary actuators are available and add to the flexibility of hydraulic power elements.

6. Hydraulic actuators have higher stiffness, that is inverse of slope of speed-torque curves, compared to other drive deices since leakage are low. There is a little drop in speed as loads are applied. In closed loop system, this results in greater positional stiffness and less position error.

7. Open and closed loop control of hydraulic actuators is relatively simple using valve and pumps.

8. The transmission of power is moderately easy with hydraulic line. Energy storage is relatively simple with accumulators.

Although hydraulic offers many distinct advantages, several advantages tend to limit their use. Major disadvantages are the following [Herbett E. Merrit, 1967]:

1. Hydraulic power is not so readily available as that if electrical power. This is not a serious threat to mobile and airborne application but most certainly affect stationary application.

2. Small allowable tolerance results in high cost of hydraulic components.

3. The hydraulic fluid imposes an upper temperature limit. Fire and explosion hazard exists if a hydraulic system is used near a source of ignition. However, these situation have improved with the available of high temperature and fire resistant fluids. Hydraulic systems are messy because it is difficult to maintain a system free from leaks and there is always a possibility of complete loss of fluid if a break in the system occurs.

4. It is impossible to maintain the fluid free of dirt and contamination. Contaminated oil can clog valve and actuators and, if the contaminant is abrasive, cause a permanent loss in performance and failure. Contaminated oil is the chief source of hydraulic control failure. Clean oil and reliability are synonymous terms in hydraulic control.

5. Basic design procedure are lacking and difficult to obtain because of the complexity of hydraulic control analysis. For example, the current flow through a resistors is described by a simple law – Ohm's law. In contrast, no single law exists which describe the hydraulic resistance of passages to flow. For this seemingly simple problem there are almost endless details of Reynolds number, laminar or turbulent flow, passage geometry, friction factors and discharge coefficients to cope with. This factor limits the degree of sophistication of hydraulic control devices.

6. Hydraulics are not so flexible, linear, accurate and inexpensive as electronics and electromechanical computation, error detection, amplification, instrumentation and compensation. Therefore, hydraulic devices are generally not desirable in the low power portions of control systems.

The outstanding characteristic of hydraulic power elements have combined with their comparative inflexibility at low power levels to make hydraulic control attractive primarily in power portions of circuit and systems. The low power portions of systems are usually accomplished by mechanical and electromechanical means.

All control system can be reduced to a few basic groups of elements, the elements of each group performing a specific function in the system. The division into group of elements can be carried out in a number of different ways, but selecting the following four groups forms a convenient structure for the deviation of hydraulic and electro-hydraulic system.

i) The power source.
ii) The control elements.
iii) The actuators.
iv) The data transmission elements.

The power source consists invariable of a pump or combination of pumps and ancillary equipments, examples accumulators, relief valves, producing hydraulic energy which is processed by the control elements to achieve the required operation of the actuators. In system which have the supply pressure maintained at a constant level, the hydraulic power source can be either a fixed or variable displacement pump.

The control elements control the output variable by manipulating the hydraulic variables, pressure and flow. The input variable to the control elements are usually in the form of mechanical, pneumatic, hydraulic or electrical signal. The input variable is mostly a low power electrical or digital signal.

The actuator convert the hydraulic energy generated by the power source and processed by the control elements into useful mechanical work. The actuator have either a linear or rotary output, can be classified into cylinders or jacks, rotary actuators and motors. The actuator producing linear output is referred as a cylinder or jack.Cylinder can be either single acting or double acting. Single acting cylinders are power driven in one direction only, while double acting cylinders are power driven in both direction. Cylinder can be constructed as an single ended or double ended. Double ended symmetric cylinder are frequently used for high performance servo system, but have greater overall length and more expensive than single-ended actuators. Single ended cylinder widely used for industrial and aerospace control system cause of smaller size and lower cost.

Hydraulic motors are essentially hydraulic pumps in which the sense of energy conversion has been reversed. While a pump converts mechanical energy supplied to its drive shaft by a primary mover into hydraulic energy.The motor reconverts the hydraulic energy provided by the pump into mechanical energy at its output shaft.

The control elements act on information received from the data transmission elements. In a simple hydraulic control system the data transmission elements are mechanical linkage or gears. But in complex systems data transmission can take at many form for examples electrical, electronic, pneumatic and optical or combination of these types of data transmission. The function of the data transmission elements is to sense he controlled output quantity and to convert it to a signal which can be used to either monitor the output or to act as a feedback devices in a closed loop control system. The control output variable in a hydraulic operated force motion can be force, velocity, position acceleration, pressure and flow.

1.2 Objective

The objectives of this research are as follows:

1. To transform the integrated nonlinear dynamic model of the Electrohydraulic control system into a set of nonlinear uncertain model comprising the nominal values and the bounded uncertainties. These structured uncertainties exist due to the limit of the angular positions, speeds and accelerations.

2. To design a controller using the Full Order Sliding Mode Controll approach and prove the stability of the system using Lyapunov approach.

3. To simulate the Electrohdraulic control system controlled by the Full Order Sliding Mode Controller and to compare its performance with other conventional controllers.

1.3 Scope of Project

The scopes of work for this project are

- The electrohydraulic system considered is as described in [Rong-Fong Fung, 1997].

- Design a controller using Full Order Sliding Mode Controller and prove that the system is stable using Lyapunov approach.
- A simulation study using MATLAB/Simulink as platform to prove the effectiveness of this controller.
- The performance of the Full Order Sliding Mode Controller is to be compared with Independent Joint Linear Control (IJC) and advanced controller in [Yeoh Aik Seng, 1998].

1.4 Research Methodology

The research work is undertaken in the following five developmental stages:

a) Decomposition of the complete model into an uncertain model.

b) Determination of the system dynamics during Sliding Mode.

c) Design a controller using Full Order Sliding Mode Control approach.

d) Prove the stability of the Full Order SMC controlled electrohydraulic system using Lyapunov stability approach.

e) Perform simulation of this controller in controlling electroydraulic control system. This simulation work will be carried out on MATLAB platform with Simulink as it user interface.

f) Compare of the performance of Integral Sliding Mode Controller with other controllers.

1.5 Literature Review

Electrohydraulic servomechanism is highly nonlinear with inherit parameter uncertainties. Various type of Sliding Mode Control based on Variable Structure Control has been proposed by researchers to control such a system. Some of the existing results will be briefly outlined in this section.

In [Rong-Fong Fung, 1997] a new technique of the variable structure control is applied to an electrohydraulic servo control system which is described by third-order nonlinear equation with time-varying coefficient. A two-phase variable structure controller is designed to get the precise position control of an electrohydraulic servo system. A reaching law method is implements to the control procedure, which make fast response in the transient phase and good stability in the steady state of a nonlinear hydraulic servo system.

Sliding mode control with time-varying switching gain and a time-varying boundary level has been introduced in [L-C.Huang, 1996] to modify the traditional sliding mode control with fixed switching gain and constant width bounded layer to enhance the control performance of electrohydraulic position and different pressure. Under certain condition, for a time-varying switching gain and boundary layer, the combination of weighted position error and differential pressure can be asymptotically tracked even when the system is subject to parameters uncertainties. One of the important feature is to use only one input to simultaneously controls the angular position and torque the electrohydraulic servo system in a different load condition.By using this technique, the high frequency and large amplitude of control input are attenuated.

An approach using variable structure control (VSC) with integral compensation for an electrohydraulic position servo is presented in [Tzuen-Lih Chern,1992]. The design involves the choice of the control function to guarantee the existence of a sliding mode.The procedure include the determination of the switching function and the control gain such that the system has an optimal motion with respect to a quadratic performance index and the elimination of chattering of the control input.

[Miroslav Mihajlov, 2002] introduced a new technique of the sliding mode control which is enhanced by fuzzy Proportional-Integral (PI) controller. The position control problem in the presence of unmodelled dynamics, parametric uncertainties and external disturbances was investigated. Fuzzy controller is added in the feedforward branch of the closed loop in parallel with the Sliding Mode Controller with boundary layer to improved the performance of the system.

1.6 Thesis Layout

This thesis contains five chapters. Chapter 2 deals with the mathematical modelling of the Electrohydraulic control system. The formulation of the integrated dynamic model of this electroydraulic is presented. The nonlinear differential equation of the dynamics model of the system are derived then transform into state space representations.

Chapter 3 presents the controller design using Full Order sliding mode control. The Electrohydraulic control system is treated as an uncertain system. The model comprising the nominal and bounded uncertain parts is computed, based on the allowable range of the position, velocity and acceleration of the electrohydraulic servo system. It is shown mathematically that Full Order SMC is practically stable using Lyapunov stability approach.

Chapter 4 shows some of the simulation results. The performance of the Full Order sliding mode controller is evaluated by simulation study using Matlab/Simulink.

Chapter 5 conclude the work undertaken, suggestions for future are also presented in this chapter.

CHAPTER 2

MATHEMATICAL MODELLING

2.1 Introduction

An important initial step in designing the controller for electrohydraulic servo control system is to obtain a complete and accurate mathematical model. This model mathematical is useful for computer simulation of the electrohydraulic servo system and synthesis processes before applied into real application.

Basically, this chapter deals with the formulation of a mathematical model of the electrohydraulic servo control system in state space form for the purpose of deriving a control algorithm for controlling the system.

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