Faculty of Electrical Engineering

PARAMETER TUNING OF SLIDING MODE CONTROLLER USING MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION IN ELECTRO-HYDRAULIC ACTUATOR SYSTEM

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**A thesis submitted
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DECLARATION

I declare that this thesis entitled "Parameter Tuning of Sliding Mode Controller using Multi-Objective Particle Swarm Optimization in Electro-Hydraulic Actuator System" 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 the candidature of any other degree.

Signature : …………………………….

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Date : …………………………….

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature : ……………………………………………….

Supervisor's Name : Associate Professor Dr. Rozaimi Ghazali

Date : ……………………………………………….

DEDICATION

To my supervisors,

Associate Professor Dr. Rozaimi Ghazali
Associate Professor Dr. Chong Shin Horng

To my beloved father and mother
Mr. Chai Ah Min and Mrs. Jong Nyong Kian

To my supportive siblings,
Chai Tsae Nyuk, Jonathan Lee Sze Chun
Chai Lien Chiew
Chai Cheen Shun

To all my lab mates and friends,

Lastly, to all the people who have helped me throughout the journey.
I would not have finished this project without all of you.
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ABSTRACT

Electro-Hydraulic Actuator (EHA) system is very popular and widely applied in the modern industry applications. This is because of its advantages on the high force to weight ratio, accurate positioning with fast motion and capability in generating large torque. Due to its increasing trends in modern applications, the research to control the EHA system has attract the attentions of many researchers around the world. However, the nonlinear characteristics in the dynamics of the EHA system such as internal leakage have make it difficult to control and hard to produce an accurate output such as position, force, and speed that are required in different applications. Internal leakage existed in the servo valve can degrade the overall performance of the EHA system. Commonly, a control system either open-loop or closed-loop is the key to overcome the aforementioned issue, where researchers had proposed many types of control strategies across the years ranging from classical to advanced controller to control the nonlinear EHA system so that it can suit into different industry applications. In this research, Sliding Mode Controller (SMC) is designed and proposed for the positioning control of the established EHA system. To obtain the optimum performance of the EHA system, Multi-Objective Particle Swarm Optimization (MOPSO) is implemented to the SMC to achieve the highest position output performance with least overshoot and steady-state error. In order to verify the effectiveness of the proposed SMC with MOPSO strategy, comparison study has been implemented to Proportional Integral Derivative (PID) and SMC controllers with conventional Particle Swarm Optimization (PSO) technique. The simulation results show that the proposed control strategy is able to improve the overshoot percentage of the EHA system by 99.78% and 99.64% as compared to the PSO-PID controller and PSO-SMC respectively. Robustness tests show the proposed control strategy achieved least overshoot percentage in all simulation case studies including the mass, pressure and internal leakage variations.

PENALAAN PARAMETER PENGAWAL RAGAM GELANGSAR MENGGUNAKAN PENGOPTIMUMAN PENGUMPULAN ZARAH PELBAGAI OBJEKTIF DI DALAM SISTEM PENGGERAK ELEKTRO-HIDRAULIK

ABSTRAK

Sistem Penggerak Elektro-Hidraulik (EHA) sangat popular dan banyak digunakan dalam aplikasi industri moden. Ini kerana kelebihannya pada nisbah daya tinggi kepada berat, kedudukan yang tepat dengan gerakan pantas dan keupayaan dalam menghasilkan daya kilas yang besar. Oleh kerana aliran dalam aplikasi moden yang semakin meningkat, penyelidikan untuk mengawal sistem EHA telah menarik perhatian banyak penyelidik di seluruh dunia. Walau bagaimanapun, ciri-ciri tidak lelurus dalam dinamik sistem EHA seperti kebocoran dalaman menjadikannya sukar dikawal dan sukar menghasilkan keluaran yang tepat seperti kedudukan, daya, dan kelajuan yang diperlukan dalam aplikasi yang berbeza. Kebocoran dalaman yang terdapat pada injap servo dapat menurunkan prestasi keseluruhan sistem EHA. Pada kebiasaannya, sistem kawalan sama ada gelung terbuka atau gelung tertutup adalah kunci untuk mengatasi masalah yang disebutkan di atas, di mana para penyelidik telah mencadangkan banyak jenis strategi kawalan selama bertahun-tahun dari pengawal klasik hingga lanjutan untuk mengawal sistem EHA yang tidak lelurus supaya sesuai digunakan dalam aplikasi industri yang berbeza. Dalam penyelidikan ini, Pengawal Ragam Gelangsar (SMC) telah direkabentuk dan dicadangkan untuk mengawal kedudukan sistem EHA yang telah dibangunkan. Untuk mendapatkan prestasi sistem EHA yang optimum, Pengoptimuman Pengumpulan Zarah Pelbagai Objektif (MOPSO) telah dilaksanakan kepada SMC untuk mencapai prestasi yang tertinggi dengan peratusan terlajak dan ralat keadaan mantap yang paling rendah. Untuk mengesahkan keberkesanan SMC yang dicadangkan dengan strategi MOPSO, kajian perbandingan telah dilaksanakan kepada Pengawal Kadaran-Kamiran-Terbitan (PID) dan SMC dengan teknik Pengoptimuman Pengumpulan Zarah (PSO) konvensional. Hasil simulasi menunjukkan bahawa strategi kawalan yang dicadangkan dapat menambahbaikan peratusan terlajak sistem EHA sebanyak 99.78% dan 99.64% berbanding pengawal PSO-PID dan PSO-SMC. Ujian ketegapan menunjukkan strategi kawalan yang dicadangkan telah mencapai peratusan terlajak yang paling sedikit dalam semua kes kajian simulasi termasuk variasi jisim, tekanan dan kebocoran dalaman.

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LIST OF ABBREVIATIONS

ABC	–	Artificial Bee Colony
µABC	–	Micro Artificial Bee Colony
ACO	–	Ant Colony Optimization
AFFFOPID	–	Adaptively Fast Fuzzy Fractional Order PID
AMESim	–	Advanced Modelling Environment Simulations
ASMC	–	Adaptive Sliding Mode Controller
BAS	–	Beetle Antennae Search
BCGSA	–	GSA with Bacterial Foraging Algorithm
BFA	–	Bacteria Foraging Algorithm
CGGSA	–	GSA combined with Cauchy and Gaussian Mutation
CGSA	–	Chaotic Gravitational Search Algorithm
CM-GPC	–	Characteristic Model-based Generalized Predictive Controller
CRS	–	Controlled Random Search
CSA	–	Cuckoo Search Algorithm
CSGA	–	Complex System Genetic Algorithm
DE	–	Differential Evolution
DLQR	–	Discrete Linear Quadratic Regulator
DOF	–	Degree of Freedom
DSMC	–	Discrete-Time Sliding Mode Controller
EHA	–	Electro-Hydraulic Actuator

EHA-CVT	–	Continuously Variable Transmission System based on Electro-Hydraulic Actuator
EHFLS	–	Electro-Hydraulic Force Loading System
EHFM	–	Electro-Hydraulic Flow Matching
EHLS	–	Electro-Hydraulic Load Simulator
EHS	–	Electro-Hydraulic Servo
EHSS	–	Electro-Hydraulic Servo System
FA	–	Firefly Algorithm
FASMC	–	Finite-time Adaptive Sliding Mode Controller
FLC	–	Fuzzy Logic Controller
FOPI	–	Fractional Order Proportional-Integral
FOPID	–	Fractional Order Proportional-Integral-Derivative
GA	–	Genetic Algorithm
GMS	–	Generalized Maxwell-Slip
GSA	–	Gravitational Search Algorithm
GSA-CW	–	GSA combined with Cauchy Mutation and Mass Weighing
GWO	–	Grey Wolf Optimizer
HOSMC	–	High Order Sliding Mode Control
HTGS	–	Hydraulic Turbine Governing System
HTRS	–	Hydraulic Turbine Regulating System
IACO	–	Improved Ant Colony Optimization
IAE	–	Integral Absolute Error
IFABC	–	Improved Fuzzy Artificial Bee Colony
IGSA	–	Improved Gravitational Search Algorithm
ISAE	–	Integral Squared Absolute Error

ISE	–	Integral Squared Error
ITAE	–	Integral Time Absolute Error
ITSE	–	Integral Time Squared Error
LBAS	–	Lévy-flight Beetle Antennae Search
LQR	–	Linear Quadratic Regulator
LSSA	–	Lévy-flight Salp Swarm Algorithm
MATLAB	–	Matrix Laboratory
MGSA	–	Modified Gravitational Search Algorithm
MOFPA	–	Multi-Objective Flower Pollination Algorithm
MOPSO	–	Multi-Objective Particle Swarm Optimization
MPC	–	Model Predictive Controller
MS-GSA	–	Mixed-Strategy based Gravitational Search Algorithm
NMP	–	Non-Minimum Phase
OS	–	Overshoot Percentage
PD	–	Proportional-Derivative
PFC	–	Predictive Functional Controller
PHHV	–	Parallel Hydraulic Hybrid Vehicle
PI	–	Proportional-Integral
PID	–	Proportional-Integral-Derivative
PI-FL	–	PI-like Fuzzy Logic
PSO	–	Particle Swarm Optimization
RASMC	–	Robust Adaptive Sliding Mode Controller
RHP	–	Right-Half-Plane
RMSE	–	Root Mean Squared Error
SACO	–	Standard Ant Colony Optimization

SCA	–	Sine Cosine Algorithm
SGLSSA	–	Self-Growing Lévy-flight Salp Swarm Algorithm
SMC	–	Sliding Mode Controller
SQP	–	Sequential Quadratic Programming
SSA	–	Salp Swarm Algorithm
ZN	–	Ziegler-Nichols

LIST OF SYMBOLS

A_n, B_n, C_n	–	Nominal system parameters obtained from the system identification
A_p	–	Difference between the piston rod area and the piston area
B_L	–	Viscous damping ratio
B_m	–	Bulk modulus
$c1$, $c2$	–	Acceleration constants
dim	–	Number of the dimensions
e	–	Error of the EHA system
F	–	Force produce by the piston in the electrohydraulic cylinder
G_{BEST}	–	Global best
I	–	Current
IAE	–	Integral Absolute Error
$iter$	–	Current iteration
K	–	Gain of the servo valve
k	–	Leakage coefficient
K_{ex}	–	Exterior leak coefficient
K_{in}	–	Interior leak coefficient
K_L	–	Stiffness of the spring
k_s	–	Positive constant
lb	–	Lower boundary of the searching space
L_{sv}	–	Inductance of the servo valve coil

maxiter	–	Total number of the iteration
M_L	–	Mass of the load
N	–	Number of random particles
n	–	Order of the EHA system
OS	–	Overshoot Percentage
P_A	–	Pressure in chamber A
P_B	–	Pressure in chamber B
P_{BEST}	–	Personal best
P_R	–	Tank way pressure
P_S	–	Pump pressure
q_a	–	Exterior leaking flow rate in the hydraulic cylinder
Q_A	–	Volume flow rate of the hydraulic fluid from the electrohydraulic servo valve to the electrohydraulic cylinder
q_{ab}	–	Interior leaking flow rate in the hydraulic cylinder
q_b	–	Exterior leaking flow rate in the hydraulic cylinder
Q_B	–	Volume flow rate of the hydraulic fluid from the electrohydraulic cylinder back to the electrohydraulic servo valve
q_{ba}	–	Interior leaking flow rate in the hydraulic cylinder
rand	–	Random number between 0 and 1 generated by using MATLAB
R_{sv}	–	Resistance of the servo valve coil
s	–	Sliding surface of the sliding mode controller
u	–	Voltage
ub	–	Upper boundary of the searching space
u_{eq}	–	SMC switching control signal
u_{smc}	–	SMC control signal

u_{sw} – SMC equivalent control signal

V – Current velocity of the particles

V_A – Volume of the hydraulic fluid in chamber A

V_B – Volume of the hydraulic fluid in chamber B

V_{line} – Volume of the pipeline

V_{new} – Updated velocity of the particles

w – Inertia weight

w_{max} – Upper limit for the inertia weight

w_{min} – Lower limit for the inertia weight

X – Population of particles

x_0 – Flow rate of the hydraulic fluid leakage in a leaking electrohydraulic servo valve

X_{new} – Updated position of the particles

x_p – Displacement of the piston in the hydraulic cylinder

x_r – Desired piston displacement

x_s – Total stroke of the hydraulic cylinder

x_{sv} – Spool displacement of the servo valve coil

α – Weight combination between two objective functions

β – Weight combination between two objective functions

λ – Positive constant

ξ_{sv} – Damping ratio of the servo valve coil

φ – Boundary of the hyperbolic tangent function

ω_{sv} – Natural frequency of the servo valve coil

LIST OF PUBLICATIONS

Journal:

1. Chai, M.S., Ghazali, R., Chong, S.H., Soon, C.C., Ghani, M.F., Sam, Y.M., and Has, Z., 2021. The Effects of Weightage Values with Two Objective Functions in iPSO for Electro-Hydraulic Actuator System. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 81(2), pp. 98–109.
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CHAPTER 1

INTRODUCTION

1.1 Introduction to electro-hydraulic actuator system

The word “hydraulics” originates from the Greek word (hydraulikos), which means the study of liquids at rest and in motion (Das et al., 2013). A hydraulic system is a technology that converts the pressurized fluid into kinetic energy and produces a motion such as pushing, pressing, clamping and lifting. Electro-Hydraulic Actuator (EHA) system is a combination of the hydraulic system and the electrical system. The pressurized fluid flows from the pump to the electro-hydraulic servo valve, which controlled using the electrical signal and then to the hydraulic cylinder to produce the necessary movement designed by the engineer.

EHA system involves in most science and engineering disciplines due to its advantages over other actuators such as pneumatic and an electric motor which have the same function. Truong et al. (2019) emphasized that the electro-hydraulic actuator system is a good choice to replace both electric and pneumatic actuators due to its high stiffness and high power to weight ratio. The EHA system can produce large torque and force output which has been proven by a French mathematician Blaise Pascal using Pascal’s law. The high power to weight ratio in a hydraulic system has made it played an indispensable role in this modern era of advanced technology.

Recently, it was reported that the global hydraulic cylinder market size was valued at USD 13.4 Billion in 2020 and is expected growth to USD 15.8 Billion by 2025

(MarketsandMarkets, 2020). It shows that the EHA system is widely implemented in various applications and has huge potential in the future.

The exclusive elements and advantages in EHA system have made it very popular in many advanced technology applications (Guo et al., 2015a; Shen et al., 2019), such as manufacturing industries, robotic manipulator, aerospace technologies, construction vehicles and medical applications (Yoon et al., 2019).

In manufacturing industries, the EHA system is used to perform heavy-duty machinery works such as bending, clamping, pressing, and lifting. Salloom and Abdulqader (2016) have implemented the EHA system in a hydraulic press for different thickness of copper alloy. In automotive industries, Yoon and Sun (2016) applied the EHA system in a camless engine valve actuator. Another study on active car suspension by Wang et al. (2017a) applied the EHA system in the car suspension system to transmit the torque and force between the frame and wheel.

In recent aerospace technology, almost all aircraft uses the fly-by-wire in their flight control system. The pilot sends electrical signals through the flight control system to the hydraulic actuators to move the respective part of the aircraft such as rudders and the ailerons (Garg et al., 2013). An electro-hydraulic control loading system of a flight simulator is proposed to guarantee robust stability and improve the force tracking accuracy (Zhao et al., 2016). Another study on robotic manipulators, EHA has been applied in robotic manipulator joints to perform different tasks such as push recovery and stair climbing (Semini et al., 2017).

Furthermore, Wang et al. (2018b) proposed a novel electro-hydraulic flow matching (EHFM) steering system into wheel loader to reduce the energy consumption of the load sensing system. A similar application in construction vehicle by Ge et al. (2017), EHA is applied in a hydraulic excavator. The energy consumption characteristic of the electro-