MODELLING OF AN ELECTRO-HYDRAULIC ACTUATOR USING EXTENDED ADAPTIVE DISTANCE GAP STATISTIC APPROACH

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requirements for the award of the degree of
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To my beloved parents, Ling Yen Chui & Wong Lang Chuo,
siblings, and my dearest wife, Jane Chua...

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ABSTRACT

The existence of high degree of non-linearity in Electro-Hydraulic Actuator (EHA) system has imposed a challenging task in developing its model so that effective control algorithm can be proposed. In general, there are two modelling approaches available for EHA system, which are the dynamic equation modelling method and the system identification modelling method. Both approaches have disadvantages, where the dynamic equation modelling is hard to apply and some parameters are difficult to obtain, while the system identification method is less accurate when the system's nature is complicated with wide variety of parameters, nonlinearity and uncertainties. This thesis presents a new modelling procedure of an EHA system by using fuzzy approach. Two sets of input variables are obtained, where the first set of variables are selected based on mathematical modelling of the EHA system. The reduction of input dimension is done by the Principal Component Analysis (PCA) method for the second set of input variables. A new gap statistic with a new within-cluster dispersion calculation is proposed by introducing an adaptive distance norm in distance calculation. The new gap statistic applies Gustafson Kessel (GK) clustering algorithm to obtain the optimal number of cluster of each input. GK clustering algorithm also provides the location and characteristic of every cluster detected. The information of input variables, number of clusters, cluster's locations and characteristics, and fuzzy rules are used to generate initial Fuzzy Inference System (FIS) with Takagi-Sugeno type. The initial FIS is trained using Adaptive Network Fuzzy Inference System (ANFIS) hybrid training algorithm with an identification data set. The ANFIS EHA model and ANFIS PCA model obtained using proposed modelling procedure, have shown the ability to accurately estimate EHA system's performance at 99.58% and 99.11% best fitting accuracy compared to conventional linear Autoregressive with External Input (ARX) model at 94.97%. The models validation result on different data sets also suggests high accuracy in ANFIS EHA and ANFIS PCA model compared to ARX model.

ABSTRAK

Kewujudan darjah ketaklinearan yang tinggi dalam Sistem Penggerak Elektrohidraulik (EHA) telah menjadikan penerbitan modelnya mencabar supaya algoritma kawalan yang efektif boleh dicadangkan. Secara umumnya, terdapat dua pendekatan pemodelan untuk sistem EHA, iaitu pemodelan berasaskan persamaan dinamik dan pemodelan melalui kaedah pengenalpastian sistem. Kedua-dua pendekatan ini mempunyai kelemahannya, di mana pemodelan persamaan dinamik adalah sukar untuk digunakan dan beberapa parameter sistem adalah sukar untuk diperolehi, manakala kaedah pengenalpastian sistem adalah kurang tepat apabila sistemnya mengandungi pelbagai parameter, ketaklinearan dan ketidaktentuan. Tesis ini membentangkan satu prosedur pemodelan baharu untuk sistem EHA dengan menggunakan pendekatan kabur. Dua set pembolehubah masukan telah diperolehi, di mana pembolehubah pertama dipilih berdasarkan pemodelan matematik sistem EHA. Pengurangan dimensi masukan dilakukan menggunakan kaedah Analisis Komponen Utama (PCA) untuk mendapatkan set masukan pembolehubah kedua. Satu statistik jurang yang baharu dengan pengiraan penyebaran dalam-kelompok baharu telah dicadangkan dengan memperkenalkan satu norma penyesuaian jarak dalam pengiraan jarak. Statistik jurang yang baharu itu menggunakan algoritma Gustafson Kessel (GK) untuk mendapatkan bilangan kelompok optimum untuk setiap masukan. Algoritma GK juga menyediakan lokasi dan ciri setiap kelompok yang dikesan. Maklumat pembolehubah masukan, bilangan kelompok, lokasi dan ciri kelompok, dan peraturan kabur digunakan untuk menjana Sistem Inferens Kabur (FIS) permulaan dengan jenis Takagi-Sugeno. FIS permulaan dilatih dengan algoritma latihan hibrid Rangkaian Sistem Mudah-suai Kabur Inferens (ANFIS) dengan satu set data pengenalan. Model ANFIS EHA dan model ANFIS PCA yang diperolehi dengan menggunakan prosedur pemodelan yang dicadangkan telah menunjukkan keupayaan untuk menganggar prestasi sistem EHA dengan tepat iaitu pada 99.58% dan 99.11% ketepatan kesesuaian terbaik berbanding dengan model konvensional Regresif Automatik lelurus dengan Masukan Luar (ARX) pada 94.97%. Pengesahan model dengan set data yang berbeza juga mencadangkan ketepatan yang tinggi dalam model ANFIS EHA dan model ANFIS PCA berbanding dengan model ARX.

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LIST OF ABBREVIATIONS

ANFIS	–	Adaptive Network Fuzzy Inference System
ARX	–	AutoRegressive with eXogenous
CE	–	Classification Entropy
DAQ	–	Data Acquisition
DI	–	Dunn’s Index
EHA	–	Electro-Hydraulic Actuator
EADGS	–	Extended Adaptive Distance Gap Statistic
EGS	–	Extended Gap Statistic
FCM	–	Fuzzy C-Means
FGS	–	Fuzzy Gap Statistic
FIS	–	Fuzzy Inference System
FSs	–	Fuzzy Systems
GK	–	Gustafson-Kessel
GS	–	Gap Statistic
MF	–	Membership Function
NNs	–	Neural Networks
PCA	–	Principal Component Analysis
PC	–	Principal Component
PCs	–	Principal Components
PC1	–	First Principal Component
PC2	–	Second Principal Component
PCI	–	Partition Coefficient Index
RMSE	–	Root Means Squared Error
S	–	Separation Index
SC	–	Partition Index
SI	–	System Identification
TS	–	Takagi-Sugeno
XB	–	Xie and Beni’s Index

LIST OF SYMBOLS

$\mathbf{A}$	–	norm-inducing matrix
$\mathbf{A}_j$	–	adaptive distance norm
A_1, A_2	–	cross section area of chambers of the cylinder
A_i	–	set of data point in the ith cluster
a_p	–	acceleration of the piston
a_i, b_i, c_i	–	parameters which determine the characteristic of membership function
$a_1 \dots a_n$	–	parameters to be identified (ARX)
$b_1 \dots b_n$	–	parameters to be identified (ARX)
β_e	–	effective bulk modulus of hydraulic oil
C_t	–	coefficient of internal leakage of the chamber
C_{v1}, C_{v2}	–	valve orifice coefficients
C_d	–	discharge coefficient
C_q	–	the indices of observation in cluster q
D_j	–	distance between data point
$D_{j\mathbf{A}}$	–	proposed adaptive distance
D_{jfuzzy}	–	distance proposed by Fuzzy Gap Statistic
$d_{i,i'}$	–	squared Euclidean distance
e	–	error signal
$\mathbf{F}_i$	–	the fuzzy covariance matrix of the ith cluster
F_a	–	hydraulic actuating force
F_f	–	hydraulic friction force
f_d	–	lumped uncertain nonlinearities due to external disturbance and other hard-to-model terms
$\mathbf{I}$	–	Identity Matrix
J_p	–	Fuzzy C-means functional
J_{GK}	–	GK functional
k_a	–	servo valve gain
m	–	fuzzy factor index

ms	–	milli seconds
N	–	the number data
n	–	total number of input-output data pairs in training data
$O_{1...5,i}$	–	ANFIS node functions
$\mathbf{PC}$	–	Principle Component
P_L	–	load pressure
p_1, p_2	–	fluid pressure in upper and lower cylinder chambers
p_r	–	hydraulic return pressure
p_s	–	hydraulic supply pressure
ρ	–	oil density
Q_1, Q_2	–	fluid volume flow rate from and to the cylinder
r, c, q	–	number of cluster
τ_v	–	time constant
$\mathbf{U}$	–	partition matrix
u	–	input signal
μ	–	fuzzy mebership function
V_1, V_2	–	total volume of first and second chamber
V_{i1}, V_{i2}	–	initial volume of both chambers including pipelines volume
v_i	–	mean of data point in cluster i
v_p	–	velocity of the piston
W_r	–	within cluster dispersions
W_{rEGS}	–	within cluster dispersions proposed by EGS
W_rnew	–	proposed within cluster dispersions
w_1, w_2	–	spool valve area gradients
$\omega_i, \omega_1, \omega_2$	–	ANFIS layer firing strength
$\mathbf{X}$	–	input data set
x_p, y	–	position of the piston
x_v	–	position of the spool valve

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Electro-Hydraulic Actuator System

An actuator is frequently referred to a mechanism that converts energy into motion. Actuators are commonly powered by either electric current, hydraulic fluid or air pressure, which are known as electric actuators, hydraulic actuators and pneumatic actuators, respectively. The actuators are important and fundamental parts in industrial processes and engineering practices. Among the available actuators, Electro-Hydraulic Actuator (EHA) system is one of the widely used actuator systems. An example of EHA system developed by Huanic Corporation [1], as shown in Figure 1.1, is an electrical controlled device where the flow of the hydraulic fluid ported to an actuator is controlled by an electrically operated valve.

Figure 1.1: EHA system [1]

EHA system has advantages over the rival actuator system because of its high power to weight ratio, smooth response characteristics and good power capability [3].

As a result, EHA system has wide applications, such as electro-hydraulic positioning systems [4, 5], industrial hydraulic machines [6, 7], and active suspension control [8, 9]. Figure 1.2 shows some of the popular applications that use EHA system.

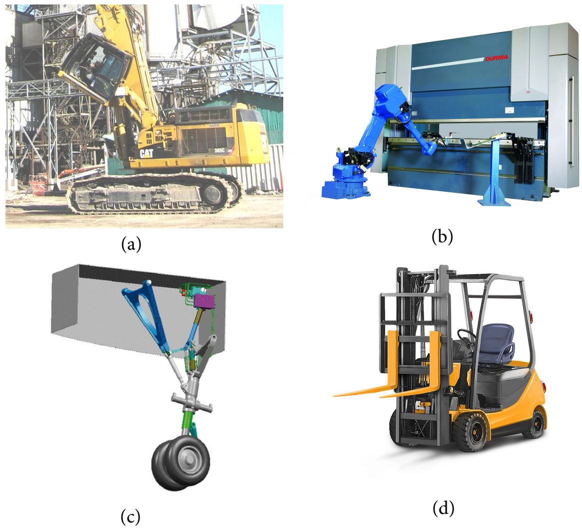

Figure 1.2: Applications with EHA system, (a) Crane system, (b) Positioning system, (c) Aircraft landing gear, (d) Forklift

An EHA system in the crane and forklift systems is responsible for the steering system of the vehicles [10, 11], whereas the landing gear, as well as the flaps, flight control surfaces and the brakes of an aircraft that are operated by an EHA system [12, 13].

1.2 Research Background

Most of the applications for EHA system, including the positioning system, have a common point, which is the precision in the desired position control. In order to achieve the desired position control of the EHA system, different methods of control strategies are proposed.

The control strategies proposed for position control of an EHA system can be grouped into three major categories, which are linear, nonlinear and intelligent approach. The proportional-integral-derivative (PID) and the pole placement controller are the examples of the linear controllers applied for position control in an EHA system. Variable structure controller (VSC), sliding mode controller (SMC), backstepping, feedback linearization, and adaptive technique are some of the common nonlinear controllers that are proposed to overcome nonlinearities or uncertainties of the EHA system. Other types of nonlinear controllers with intelligent approaches such as fuzzy logic control and neural network are also proposed for an EHA system. From the study, most of the controllers for an EHA system are nonlinear or intelligent controllers due to the uncertainties and nonlinearities of the system, whereas linear controllers are usually integrated with intelligent technique or nonlinear adaptive law to achieve similar control performance as nonlinear and intelligent controllers.

Fuzzy logic controller is an intelligent control approach that attracts attention from researchers in the control of an EHA system. A fuzzy logic controller is applied on the EHA system with nonlinear state space model [14], mathematical model with internal leakage [15] and fuzzy inverse model control of fuzzy model [16, 17]. A state feedback controller with fuzzy state controller [18] and a generic fuzzy tuning algorithm [19] are added into the family of fuzzy logic control on the EHA system. Neuro-fuzzy controller is the variation of a fuzzy controller that is proposed to control an EHA system [20, 21]. On the other hand, an artificial neural network controller is applied on an EHA system with a large dead zone model in the control design [22] and trained using Levenberg-Marquardt back-propagation [23]. The fuzzy logic and neural network controls are also integrated with other types of control theory to achieve the desired control performance.

Various PID controllers are proposed for the EHA system such as model reference adaptive PID control [24], integrated PID controller with fuzzy controller [18, 25, 26, 27, 28, 29], PID optimization using generic algorithm (GA) [30, 31], PID parameter tuning with differential evolution algorithm [32], and PID parameter optimization using Nelder-Mead approach [33]. The application of pole placement as a system controller performs in the position tracking and adapts to changes in load stiffness and supply pressure [34, 35].

Variable structure control (VSC) is one of the nonlinear controllers that have been proposed for position control of an EHA system. VSC is applied to achieve zero steady-state error [36, 37] in the position tracking of the system. VSC is also designed to overcome effects by disturbances such as lumps friction and load [38], unknown dead zone [39] and system's parameter variation [36]. Sliding model controller (SMC) is the subfamily of VSC and is widely applied for the position control of an EHA system. SMC is designed to deal with different nonlinearities, such as flexible load [40], parameter variation, load disturbance and spring stiffness [41, 42]. SMC is also designed with varying boundary layers [43] and fuzzy boundary layers [44]. The integration of SMC with fuzzy tuning is proposed in several literature studies [39, 45, 46, 47].

Backstepping controller, which is based on Lyapunov function is proposed for the control of an EHA system in several studies [38, 48, 49, 50]. Adaptive law is introduced with a backstepping controller to compensate the parametric uncertainties in system dynamics [51, 52]. The backstepping controller is designed to improve the tracking performance with disturbance [53], variations of effective bulk modulus, friction and external disturbance [54, 55], and constant force as external disturbance [51]. Feedback linearization is developed for several types of control, such as position, velocity and differential pressure of the EHA system [56, 57]. Feedback linearization is also designed by several methods, such as neural network [58], Lyapunov approach [59], and robust H_∞ control [60].

Another control technique for the position control of an EHA system is adaptive control [61]. Discrete-time adaptive controller [62] and continuous-time adaptive control [63] are developed to deal with the tracking performance of a system with parametric uncertainties, unmodeled dynamics and disturbances. Model reference adaptive control [64] and indirect model reference adaptive control [65] are also proposed as the control schemes for EHA system's position tracking. Adaptive control is applied to deal with nonlinear electro-hydraulic with disturbance due to variations in system parameters [66].

From the study of the various types of controllers proposed for the position control on the EHA system, it is noticed that most of the controller designs require a system model. For example, for the PID controller design, the model of the system is required either in the transfer function form [24, 25, 26, 28, 29] or in the state-space form [27, 30, 31, 67]. On the other hand, the pole placement method requires the model in transfer function form for a controller design [34, 35]. Mostly, the models required for designing VSC and SMC are in the state-space form [37, 38, 40, 42], and some are in the form of transfer function [36]. The same model requirement appears in the backstepping and feedback linearization controller design, which is in the state-space form [50, 56, 57]. Either the transfer function model [64] or the state-space model [61, 63] is used in designing the adaptive control. Neural network model [68] and fuzzy model [17] are used for the control of an EHA system using neural network controller and fuzzy controller.

It can be seen that various types of modelling forms and methodologies have been proposed in several publications in developing a model for an EHA system. Therefore, this research study focuses on proposing an alternative modelling procedure for an EHA system, particularly in fuzzy modelling.

1.3 Problem Statement

The problem statement of this study is expressed as follows:

"*how to effectively model a highly nonlinear EHA system by using fuzzy approach based on experimental data set*"

1.4 Research Objectives

The objectives of the study are:

1. To develop a representation model of an EHA system using fuzzy approach based on the simplified mathematical model and identification data set.
2. To optimize the number of membership function based on input and output data of the fuzzy model.
3. To validate the newly developed fuzzy model at different operating conditions of the EHA system.

1.5 Research Methodology

The process of fuzzy model identification of an EHA system in this thesis is performed in several steps. Firstly, the input variable for the fuzzy model is determined by two approaches. The first approach determines the input variable by obtaining a simplified mathematical model of the EHA system. The second approach obtains another set of input variable by reducing the dimension of input variable identified in the first approach by performing Principal Component Analysis (PCA).

The next element in the fuzzy modelling is the determination of the number of membership function for each identified input. In order to obtain the optimal number of membership function, a new gap statistic is proposed. The new gap statistic is the extension of Extended Gap Statistic (EGS), which introduces an adaptive distance norm in the cluster distance calculation. The initial locations and shape's parameters of the membership functions are identified by the clustering algorithm.

The third element for the fuzzy model is the rule base, which is developed based on the number of input variables and the number of membership functions. The input variable identified with both approaches, the number of membership function with the initial locations and shape's parameter, as well as the rule base, are used to generate the initial fuzzy model for the EHA system.

The initial fuzzy model of the EHA system is trained by Adaptive Network Fuzzy Inference System (ANFIS) using the identification data set obtained from the system. The trained fuzzy model is later validated with the real EHA system using the validation data set and different operating regions of the system.

1.6 Research Scopes

The experimental study and data collection process for this research took place at the laboratory, using the established EHA system workbench. The workbench includes an electro-hydraulic actuator system, a computer with MATLAB, Simulink, System Identification and Fuzzy Logic Toolbox installed, and a data acquisition card for communication between EHA system and computer.

The scopes of the study are:

1. The model identification is conducted on the EHA system with a single-ended cylinder and controlled by a servo valve.
2. The bandwidth of the EHA system for the model identification and validation process is limited to 1Hz due to the limitation of the hardware construction.

3. The maximum supply pressure is regulated to 75 bar, which is assumed to be the nominal operation pressure of the EHA system.
4. Fuzzy model is used to model the EHA system.
5. The identification scheme for the fuzzy model is the series-parallel method.

The model of the system is generated with the aid of System Identification and Fuzzy Logic Toolbox. The accuracy verification of the developed fuzzy model is accomplished by using the best fitting percentage and Root Means Squared Error (RMSE). The generation and accuracy validation of the fuzzy model is performed using MATLAB and Simulink software and analysed by computer simulation.

1.7 Organization of the Thesis

The overall structure of the thesis takes the form of six chapters, including this introductory chapter. The remaining chapters are literature review, research methodology, experimental set-up of the system, results and discussion, as well as conclusion of the work.

Chapter 2 begins with the literature review on EHA system. Different types of modelling approaches that are used to model the EHA system are reviewed. Besides, other types of available modelling approaches are also reviewed. The challenges exist in all the modelling approaches are explained and the possible alternatives to solve the problems are reviewed. The applications of fuzzy modelling are widely reviewed in this chapter, especially the ANFIS. The studies on the construction of an ANFIS model are performed on subjects, such as input selection, optimal number of membership function determination, clustering algorithm and cluster validation.

Chapter 3 shows the methodology of the research. The input selection of the model is done by the derivation of the simplified mathematical modelling of the EHA system based on the dynamic equation of the system. PCA method which is used to reduce the input data dimension, is also explained. The gap statistic used to obtain the optimal number is shown, and a new gap statistic that applies the fuzzy clustering algorithm and new distance calculation is proposed in this chapter. The rule base generation for the ANFIS model is also explained, as well as the ANFIS parameter training algorithm.

In Chapter 4, the experimental setup of the EHA system, including hardware and software, as well as the communication between the hardware and the computer system is covered. Steps to obtain the identification data set are explained. Apart from that, the modelling process of the autoregressive with exogenous (ARX) and different ANFIS models including heuristic and proposed ANFIS modelling procedures are shown in the chapter.

Chapter 5 presents the results of different modelling steps. The effects of different modelling conditions are analysed. The advantages of EHA modelling using the proposed methods are observed and discussed.

Finally, chapter 6 summarises the total results of the study and the contributions of the research. The recommendations for further study are also included in this chapter.

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