REAL TIME IMPLEMENTATION OF PID AND ACTIVE FORCE CONTROL FOR FEEDRATE CONTROL OF A SYRINGE FLUID DISPENSER

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A dissertation submitted in partial fulfilment of the
requirement for the award of the degree of
Master of Science (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

JANUARY 2017

To my dearest and loving parents Badar Sharif and Siti Fatimah,
my siblings and my fiancée Hilmy,
for their unending love, sacrifices, and moral support.

ACKNOWLEDGEMENTS

I would like to express my infinite gratitude to Allah SWT for His continuous blessings and mercy. With His grace, I was able to finish this study Alhamdulillah. I would also like to express my greatest gratitude to Professor Dr. Musa Mailah for his patience, advise and thorough supervision in helping me complete this study. I would also like to thank his never ending motivation and encouragement that helped me through hard times when the study was conducted. I would never be where I am without his help and guidance. I would also like to thank Dr. Tang Howe Hing for his guidance.

I would also like to thank my family for their infinite support and love. To my brother Asyraf Sharif b Badar Sharif, thank you for helping assemble the hardware. Without your help I would be crying rivers by now. To my fiancée, Hilmy Mustafa, I would like to thank you for your patience in dealing with my emotional rollercoaster throughout this study. My colleagues and friends especially Heng Eik Woei who helped me through this, thank you.

Special thanks to Mr. Fairuz for his guidance and advice. Thank you to Universiti Teknologi Malaysia (UTM) and MyBrain for their full support in this research work.

ABSTRACT

A method to control the flowrate of a syringe fluid dispenser using Active Force Control strategy (AFC) was carried out based on a simulation and experimental investigation. The AFC technique has been shown to compensate known and unknown disturbances in the system through the appropriate estimation of the inertia matrix of the physical system. The simplicity and effectiveness of the method in compensating the disturbances is demonstrated without relying on heavy mathematical computation. The objective of this study is to implement the AFC strategy to control the flowrate of the fluid in syringe feeding system. The performance of the AFC scheme was compared with the conventional proportional-integral-derivative (PID) controller to determine the robustness of the controllers in the dynamical systems. For sensitivity analysis purpose, AFC strategy was studied based on its performance with the value of the estimated inertia and the percentage of AFC applied to the system varied within a selected range. Simulation study was done to theoretically verify the model of the syringe fluid dispenser system. An experimental prototype of the syringe fluid dispenser system was then designed and developed to validate and complement the theoretical study. The development of the experimental rig was done by integrating the mechanical, electrical/electronic and computer software control. The results determined from both the simulation and experimentation works were analysed and compared to study the performance in terms of the proposed system robustness and accuracy against various operating and loading conditions. It is obvious that the AFC scheme performance is much superior in terms of both the robustness and accuracy even in the presence of introduced disturbances in comparison to the PID control scheme.

ABSTRAK

Satu kaedah untuk mengawal kadar aliran dispenser cecair picagari menggunakan strategi kawalan daya aktif (AFC) telah dijalankan berdasarkan simulasi dan penyiasatan eksperimen. Teknik AFC telah ditunjukkan untuk mengimbangi gangguan yang diketahui dan tidak diketahui dalam sistem menerusi anggaran matriks inersia yang sesuai dengan sistem fizikal. Kesederhanaan dan keberkesanan kaedah ini dalam memampas gangguan ditunjukkan tanpa bergantung kepada pengiraan matematik berat. Objektif kajian ini adalah untuk melaksanakan strategi AFC untuk mengawal kadar aliran bendalir dalam sistem picagari. Prestasi skim AFC telah dibandingkan dengan pengawal konvensional berkadar-integral-derivatif (PID) untuk menentukan keteguhan pengawal dalam sistem dinamik. Untuk kepekaan tujuan analisis, strategi AFC telah dikaji berdasarkan prestasinya dengan anggaran nilai inersia dan peratusan AFC digunakan untuk sistem yang berbeza-beza dalam julat yang dipilih. Kajian simulasi telah dilakukan secara teori untuk mengesahkan model sistem picagari cecair dispenser. Satu prototaip eksperimen sistem dispenser cecair picagari kemudiannya direka dan dibangunkan untuk mengesahkan dan melengkapkan kajian teori. Pembangunan pelantar eksperimen telah dilakukan dengan mengintegrasikan mekanikal, kawalan elektrik/elektronik dan perisian komputer. Keputusan ditentukan dari kedua-dua simulasi dan ujikaji dianalisis dan dibandingkan dengan mengkaji prestasi dari segi kemantapan sistem yang dicadangkan dan ketepatan terhadap pelbagai keadaan operasi dan muatan. Ia adalah jelas bahawa prestasi skim AFC adalah lebih unggul dari segi keteguhan dan ketepatan walaupun dalam kehadiran gangguan diperkenalkan berbanding dengan skim kawalan PID.

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LIST OF ABBREVIATIONS

AFC	-	Active Force Control
ANN	-	Artificial Neural Network
DAQ	-	Data Acquisition
DC	-	Direct Current
EMF	-	Electromotive Force
HFM	-	Hollow Fibre Membrane
HIL	-	Hardware-in-the-Loop
I/O	-	Input-Output
MOSFET	-	Metal-Oxide-Semiconductor Field-Effect Transistor
PC	-	Personal Computer
PI	-	Proportional Integral
PID	-	Proportional-Integral-Derivative control

LIST OF SYMBOLS

A	-	area	m^2
d_c		collar diameter	m
D_m	-	frictional constant of the motor	-
D_n	-	nominal major diameter	m
D_p	-	minimum pitch diameter	m
e	-	efficiency	-
f	-	friction	-
F	-	force	N
I	-	mass moment of inertia	kgm^2
I_a	-	armature current	A
J_m	-	moment of inertia of the motor	kgm^2/rad
K_{crit}	-	critical value	-
K_b	-	constant of the back EMF	-
K_d	-	gain of the derivative term	-
K_i	-	gain of the integral term	-
K_p	-	proportional gain	-
K_s	-	switch of the AFC scheme block	-
K_t	-	torque constant	-
L,p	-	pitch	m
L_a	-	armature inductance	H
l_s	-	length of the syringe	cm
$\dot{m}$	-	mass with respect to time	kgs^{-1}
n	-	threads per inch	-
P_{crit}	-	critical period	-

q	-	flowrate	
r	-	radius	m
R_a	-	armature resistance	Ω
r_n	-	radius of the nozzle	m
r_s	-	radius of the syringe	m
T	-	torque	Nm
T_d	-	derivative time constant	-
T_i	-	integral time constant	-
T_m	-	torque of the motor	Nm
v	-	velocity	ms^{-1}
V_a	-	armature voltage	V
V_b	-	back EMF	V
τ_d	-	torque disturbance	Nm
$\tau_d{}^*$	-	estimated disturbance toque	Nm
$\dot{\theta}$	-	angular velocity	$rads^{-1}$
$\ddot{\theta}$	-	angular acceleration	$rads^{-2}$
ω	-	angular velocity	$rads^{-1}$
ρ_{water}	-	density of water	kgm^{-3}

CHAPTER 1

INTRODUCTION

1.0 General Introduction

The combination of high chemical, thermal and mechanical resistance has made hollow fibre membranes an attractive alternative to polymeric varieties as it has a high surface area/volume ratios achieved by hollow fibre configurations. Hollow fibre membrane (HFM) performance may greatly exceed that of other membrane systems (Benjamin *et al.*, 2009). Due to its structure, HFM has the ability to operate at high temperatures and pressures, and in corrosive environments. Due to its impressive behaviour, it is used in a variety of applications including filtration for corrosive fluids (Weber *et al.*., 2003), high temperature membrane reactors (Keuler and Lorrenzen, 2002) solid oxide fuel cells (Wei and Li, 2008) and membrane contactors (Koonaphapdeelert and Li, 2006). The main goal in membrane technology is to control the structure and performance of the membrane (Mustaffar *et al.*., 2004). However, to achieve this goal, a wide number of parameters need to be considered as the membrane structure and performances depends on various factors which includes flowrate of the bore fluid and polymeric solutions, temperature of the solution, coagulant, polymer choice etc (Darton *et al.*., 2012). This study will study the control methods used to control the flowrate of the bore fluid in spinneret for the preparation of the bore fluid.

1.1 Research Background

Membrane has made significant advancement due to its flexibility, performance reliability, increased environmental awareness which results in an increase of its demand and cost competitiveness (Mustaffar et al., 2004). Porosity prediction is crucial before applying the membranes in real applications. This is because porosity will affect the structure of the membrane as well as the membrane’s performance. Various factors need to be considered as these factors will be affecting the performance of the membranes. Plus, varying these factors could cause the membrane structure to be significantly affected as these factors may be dependent to one another. In this present study, the focus will be on controlling the flowrate of the bore fluid in the spinneret.

Past studies have utilized the usage of a syringe pump to control the flowrate of bore fluid on the spinneret (Mohammad *et al.*, 2004; Mustaffar *et al..*, 2004). Although federate control is a powerful tool which is used in various fields, syringe pump is known to cause fluctuations in flowrate (Zida et al., 2014). This is due to the mechanical oscillations within the syringe pumps (Wen et al., 2014). Therefore, this present study attempts to control the flowrate of a syringe fluid dispenser by utilizing DC motors combined with control methods.

DC motors are dominantly used in industries where accurate speed and position control is required. DC motors is a motor which is used for speed or position control in closed loop control systems (Akar and Temiz, 2007). They are widely used in a wide range of applications that includes precise positioning as well as speed control (Bindu and Namboothiripad, 2012). DC motors have been dominantly used at computers, numeric control machines, industrial equipment, weapon industry, and speed control of alternators, control mechanism of full automatic regulators as the first starter (Akar and Temiz, 2007). This is generally due to DC motor having characteristics such as the wide rotation speed adjustment range, the linear mechanical character and the regulated character and the fast dynamical response (Huang *et al.*, 2013). Plus, research works mostly focuses on DC motors in the field of control of mechanical linkages and robots (Akar and Temiz, 2007). The study of controlling a

DC motor has been done extensively by a wide range of researchers. Some recent control method of the DC motor which will be included in this study are the Proportional-Integral-Derivative (PID) control (Noshadi *et al.*, 2010; Jamal and Zhu, 2010; Bindu and Namboothiripad, 2012), Fuzzy Control (Akar and Temiz, 2007; Dipraj and Pandey, 2012), Fuzzy PI dual mode control (Yang *et al.*, 2013), Neuro Fuzzy control (Kang and Kim, 2001) and Active Force Control (AFC) (Jahanabadi *et al.*., 2011; Dehkordi *et al.*, 2012). The present study focuses on controlling a DC motor by using PID control and AFC.

A DC motor exhibits wide rotation speed adjustment range, the linear mechanical character and the regulated character and the fast dynamical response characteristics (Huang *et al.*, 2013). PID is a common used control method for controlling DC motor in industries. Although PID control could generally perform excellently for a system with no or little disturbances and operating at a low speed, however at the adverse conditions, the performance of a PID control degrades considerably (Jahanabadi *et al.*., 2011). Therefore, a need of a controller that could provide robustness and a stable performance in the presence of disturbances is needed. In the present study, a control method that is able to secure systems stability and robustness and minimize the presence of known and unknown disturbances is proposed and applied to the motion control of a DC motor. This controller is called Active Force Control (AFC) which is pioneered by Johnson (1971) and later by Davidson (1976) (Ramli *et al.*, 2013). Through the works of Hewit and Burdess (1981), AFC has been proven to be simple, robust and effective compared to conventional methods in controlling dynamical systems, both in theory and in practice (Jahanabadi *et al.*., 2011). In this study, AFC is used to accurately control the speed of a DC motor which will then control the feedback rate of a syringe fluid dispenser through drive mechanism. Both theoretical and experimental approach shall be used in the undertaken research. The AFC controller applied to the DC motor will be tested vigorously with different operating conditions.

1.2 Problem Statement

A wide range of application utilizes the control of flowrate. These applications include medical applications as well as various chemical process control. Crucial control of flowrate is needed to ensure that the desired operation is achieved. An example of a crucial control of flowrates is medical applications, in which the control of the flowrate of the vaccines and medications is needed. The operation in which vaccines are produced requires precise flowrates as well as precise volumes. A slight error occurred could cause a huge amount of economic lost as the vaccines may be needed to be thrown away to not affect the health of its consumer as well as risking the lives of others as the vaccines produced may give side effects to the patients. Control of flowrate has been done extensively using a wide range of approach ranging from manual control to electronic control such as pumps and the utilization of motors. Therefore, this study is needed to assess and study the control of a flowrate. However, the flowrate considered in this study is the flowrate of a syringe fluid dispensing system.

Controlling a DC motor is important to ensure that desired performance is achieved. From the literature survey, extensive research was done by many researchers to control the speed and position of a DC motor by various controller approach. The control of the DC motor could be done by utilizing the conventional PID controller, adaptively controlling the DC motor by applying intelligent system and by using other methods such as the AFC. This study therefore aims to precisely control the speed of a DC motor to determine the flowrate of fluids in small pipe or cylinder or syringes.

1.3 Research Objective

Present study involves the real time implementation of PID and AFC to control the feed rate of a syringe fluid dispenser. Therefore, the objectives of this study includes:

(i) To model, simulate and control the volumetric flowrate of a syringe fluid dispensing fluid using PID and AFC,

(ii) To develop a real time experimental rig, and

(iii) To validate the proposed control scheme.

1.4 Research Scope

The research mainly focuses on the control of the DC motor to provide the flow or feed rate regulation of the syringe fluid dispensing system. The research scope is as follows:

a. The study is limited to a small DC motor and the modelling of the DC motor will be done on its linear range only.
b. The fluid in the syringe considered in the study is water.
c. The reference or targeted fluid flow/feed rate is based on the production of the hollow fibre membrane production system.
d. The simulation study is performed using MATLAB/Simulink software package based on PID and AFC control methods.
e. The drive mechanism implemented in the study to change the drive from rotational motion to translational motion involves rack and pinion, ball screw and lead screw, in order to control the feedrate of the syringe fluid dispenser. However for the experimental work a ball screw mechanism shall be employed.
f. An experimental is fully designed and developed based on mechatronic approach considering both the PID and AFC control schemes. A microprocessor-based system (microcontroller, data acquisition system, I/O devices) will be applied to the hardware in-the-loop system to control the DC motor.
g. The sensitivity analysis shall consider a number of varied loading and operating conditions pertaining to the controller gains, estimated inertia matrix and AFC percentage.

1.5 Research Methodology

This study methodology is summarized into four major tasks; literature review, modelling and simulation, design and development of the experimental test rig, experimentation and analysis. Integration of the mechanical, electrical/electronics, and software control as well as hardware-in-the-loop (HIL) test configuration is the fundamental component of this study.

1.5.1 Literature Review

The overview of the syringe fluid dispenser system was described at length based on the previous research related. A detailed description of the control techniques applied to speed control of a DC motor was then discussed. The control techniques discussed are categorised into two categories; intelligent feedback controllers and robust controllers. The theories related with AFC and a DC motor was then explained in detail.

1.5.2 Modelling and Simulation

The modelling is done by considering the principles related to the physical system. This includes derivation of mathematical equations that explains the dynamics and kinematics of the system. The modelling of the syringe fluid dispenser was done by integrating the DC motor, the drive mechanism and the syringe fluid dispenser. Three different drive mechanisms were proposed for this system.

PID as a robust technique has been implemented with AFC for comparison. The simulation study was performed by implementing the presence of disturbance due to the unwanted vibration from the hardware as well as environmental conditions. A comparison of the control methods was conducted as a benchmarking for the performance of the two controllers. Analysis of the effect on varying the estimated inertia of the AFC strategy was also performed. The simulation was conducted using MATLAB/Simulink software as the primary tool for developing the syringe fluid dispenser experimental rig.

1.5.3 Design and development of the experimental rig

Development of the experimental rig utilizes the integration of the mechanical, electrical and software control components. All the important aspects associated with the mechanism of the system and related environmental conditions are taken into consideration.

i. Mechanical

The development of the mechanical design is based on the physical concept of a syringe fluid dispenser system driven by a ball screw. The design steps will include suitability of the structural system, efficiency, and consideration of various factors, which includes cost, availability, etc. A complete design of the test rig was developed by addressing the friction of its components, the viscosity and density of the fluid.

ii. Electrical and electronics

The electrical and electronics component are associated with the input and output (I/O) devices. Quadrature and rotary encoder are suitable to be used in this system to track the position of the shaft of the DC motor hence measuring the speed of the DC motor. Transistors as well as diodes are also suitable to be used as the electrical components for this system. Installation of the electrical and electronics component requires knowledge in mechatronics experience in this stage of the study.

iii. Software Control

This stage includes interfacing the computer and control panel including data acquisition procedure using Arduino MEGA 2560 microcontroller and a PC for software control. The actuators were all linked and integrated with the Arduino MEGA 2560 microcontroller and were later tested prior to the experimentation. MATLAB/Simulink was employed as an instrumental linkage between the physical mechanical, electrical and software control components through the Arduino MEGA 2560 microcontroller hence forming a hardware-in-the-loop simulation and test platform.

iv. Experimentation

In order to achieve the objective of the study, the development of an adequate model that represents the system is crucial. The study will be done in two parts, which includes experimental and simulation. The results of the two approach will be assessed and compared, and a validation process will be made in which the results of both methods will be compared and analysed. Figure 1.1 represents the flowchart of the model development of controlling the feedrate of a syringe fluid dispensing system.

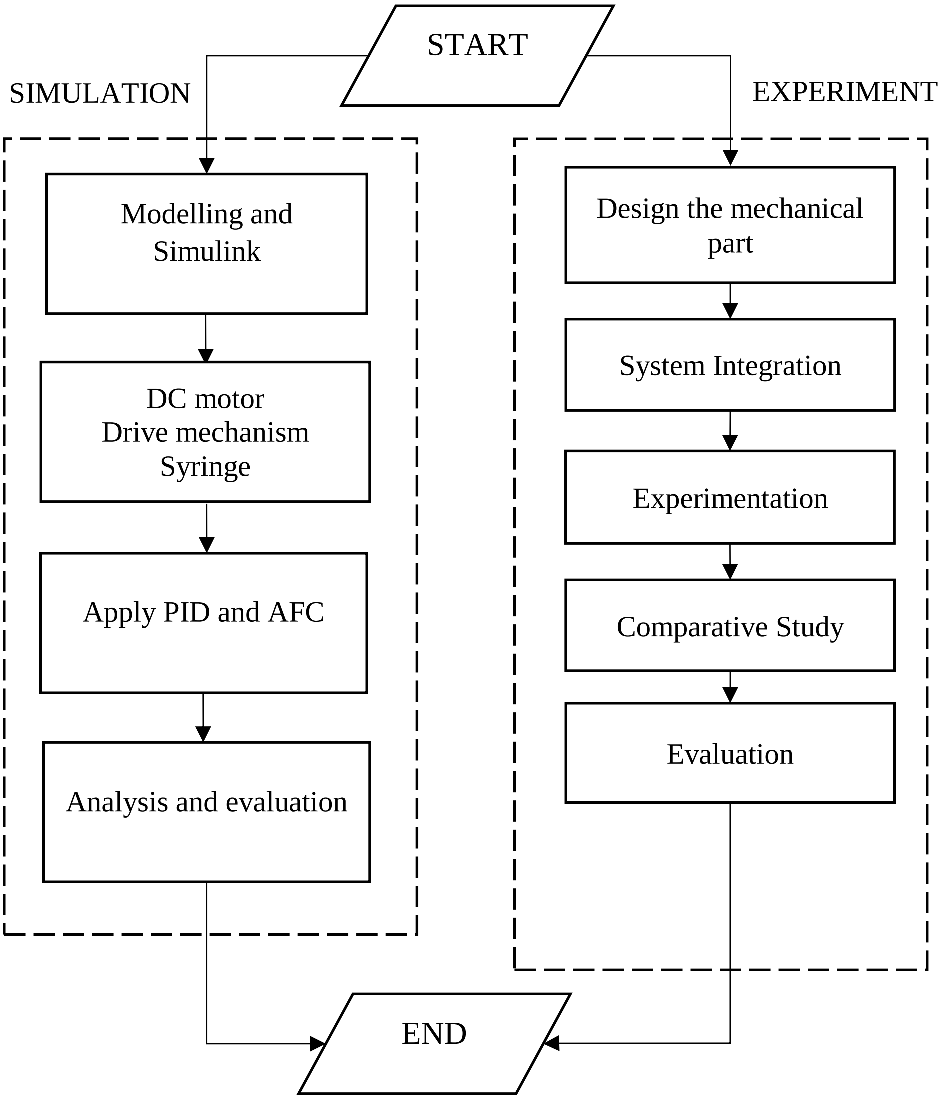

Figure 1.1 Flowchart of the development of feedrate control of a syringe fluid dispensing system

1.6 Thesis Outline

This paper is organised into five chapters. The general introduction in chapter 1 introduces the recent research done in using various type of controllers to control a DC motor. Research background discusses the challenges faced by a conventional PID controller in the presence of disturbances which is then the reason of the AFC scheme being implemented in controlling the DC motor. Problem statement discussed the significance of the study which is then followed by research objectives and scopes of this study which describes the objective and limitations of the present study.

Chapter 2 discusses the theory and fundamental behind the PID control and AFC. It also discusses the different control methods available and previously used which includes fuzzy control, fuzzy-PI dual mode control and neuro fuzzy control to control the speed of the DC motor based on past research. The different drive mechanisms were discussed and compared in this chapter.

Chapter 3 describes the modelling and simulation study of the syringe fluid dispenser. The application of the AFC method in simulation was discussed in this chapter. PID and AFC were both implemented into the system to study the performance of the control methods theoretically. Analysis and evaluation of the results were done.

Chapter 4 discusses the design and development of the experimental rig. The incorporation and integration of the mechanical, electrical and electronics and software control components were discussed in this chapter. This chapter demonstrates the practical application of both PID and AFC in real world situations. The experimentation results obtained were analysed and evaluated. The results were also used as a verification and validation of the simulation result.

Chapter 5 concludes the recent study which has been implemented. Future works that are expected to be implemented are also addressed in this chapter.

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