Faculty of Electrical Engineering

POSITIONING CONTROL OF A 1-DOF PNEUMATIC MUSCLE ACTUATOR (PMA) SYSTEM WITH MODIFIED PID PLUS FEEDFORWARD CONTROLLER

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POSITIONING CONTROL OF A 1-DOF PNEUMATIC MUSCLE ACTUATOR (PMA) SYSTEM WITH MODIFIED PID PLUS FEEDFORWARD CONTROLLER

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DECLARATION

I declare that this thesis entitled "Positioning Control of a 1-DOF Pneumatic Muscle Actuator (PMA) System with Modified PID plus Feedforward Controller" 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 candidature of any other degree.

Signature : ……………………………

Name : Vasanthan A/L Sakthi velu

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 Mechatronics Engineering.

Signature	:	……………………………………
Supervisor's Name	:	Dr. Chong Shin Horng
Date	:	……………………………………

DEDICATION

To my beloved parents, Sakthivelu A/L Muniandy and Kanmani A/P Vanniaraju,

For taking good care of me and giving me guidance in my life and academic.

To my dear wife, Sangeetha A/P Ramanujam,

For the love, strength and continues support.

To my siblings, Karthikesan, Thinesh and Nanthini,

For giving me the continues moral support.

And also to those who guided and gave me education.

ABSTRACT

The pneumatic muscle actuator (PMA) is a novel actuator which carries numerous advantages such as high strength and power/weight ratio, low cost, compact, clean and easy to maintain features. However, pneumatic muscle actuator has notable nonlinear characteristics, which makes it difficult to control. The purpose of this research is focused on experimental system development and parameter characterization of phenomenological modelling for commercially available Festo Fluidic Muscle Actuator. The model and parameters obtained from the characterization are validated in simulation and experimental platform. The major part of the research is focused on the framework of the modified PID plus feedforward control system, and its effectiveness in a 1 degree-of-freedom PMA system is experimentally demonstrated in comparison with a classical PID controller. The overall control system comprises of a feedforward controller and a modified PID controller in the feedback loop which designed based on the exact PMA system characteristics. The design procedure of the modified PID plus feedforward controller is practical and features easy design procedures. The usefulness and advantages of the proposed controller are shown via positioning and tracking motion experimental studies. Besides, this study also highlights the robustness of the modified PID plus feedforward controller by examining its performance in point-to-point and tracking motions in the presence of extra mass. In the robustness performance, the modified PID plus feedforward controller is compared with a classical PID control systems. The comparative experiments results illustrate that modified PID plus feedforward controller shows the significant motion performances as compared to the PID controller by maintaining steady state error between ±50µm. The framework used to develop the proposed controller is generally enough for further investigation in PMA motion control system, further improvement in terms of positioning accuracy and tracking motion could extend the usefulness of the proposed controller into other type of rehabilitation applications.

ABSTRAK

Penggerak pneumatik bercirikan otot (PMA) adalah penggerak unik yang mempunyai banyak kelebihan seperti daya mengangkat dan kuasa / nisbah berat yang tinggi, kos yang rendah, padat, bersih dan mempunyai ciri-ciri yang mudah untuk diselengerakan. Walaubagaimanapun, penggerak pneumatik bercirikan otot ini mempunyai ciri-ciri tidak linear yang sangat ketara, yang menjadikan pergerakannya sukar untuk dikawal. Tujuan utama penyelidikan ini dijalankan adalah tertumpu kepada pembangunan sistem eksperimen dan pencirian parameter pemodelan matematik "phenomenological" terhadap penggerak pneumatik bercirikan otot komersial berjenama Festo sedia ada. Model matematik dan parameter yang diperolehi daripada pencirian parameter disahkan dengan memgunakan landasan simulasi dan eksperimen. Sebahagian besar daripada penyelidikan ini tertumpu kepada rangka kerja sistem kawalan PID yang diubahsuai ditambah dengan pengawal suap depan, dan keberkesanannya diuji ke atas sistem PMA 1 darjah kebebasan dan dibandingkan dengan pengawal klasik PID secara eksperimen. Keseluruhan sistem kawalan ini terdiri daripada pengawal suap depan dan pengawal PID yang diubahsuai dalam gelung suap balik yang telah direka berdasarkan ciri-ciri sistem pergerakan PMA yang tepat. Prosedur reka bentuk pengawal PID yang telah diubahsuai ditambah dengan pengawal suap depan ini adalah sangat praktikal dan mempunyai prosedur reka bentuk yang sangat mudah. Kegunaan dan kelebihan pengawal yang dicadangkan ini ditunjukkan melalui pengerakan kedudukan tertentu dan pergerakan jenis penjejakan secara kajian eksperimen. Selain itu, kajian ini juga menegaskan keteguhan (robustness) pengawal PID yang telah diubahsuai ditambah pengawal suap depan dengan memeriksa prestasinya dalam pergerakan ke kedudukan tertentu dan pergerakan jenis penjejakan. Dalam prestasi keteguhan, pengawal PID yang telah diubahsuai dicampur pengawal suap depan dibandingkan dengan sistem kawalan klasik PID. Keputusan perbandiangan eksperimen menggambarkan bahawa pengawal PID yang telah diubahsuai dicampur pengawal suap depan menunjukkan prestasi gerakan yang ketara dan bagus berbanding dengan pengawal klasik PID dengan mengekalkan keadaan mantap dalam lingkungan ±50µm. Rangka kerja yang digunakan untuk membangunkan pengawal yang dicadangkan ini umumnya cukup untuk menjalankan kajian/siasatan yang lebih lanjut ke atas sistem kawalan gerakan PMA, penambahbaikan dari segi ketepatan kedudukan dan pengesanan gerakan boleh melanjutkan kegunaan pengawal ini ke dalam aplikasi pemulihan yang lain.

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PMA	-	Pneumatic muscle actuator
DOF	-	Degree of freedom
PID	-	Proportional Integral Derivative
FF	-	Feedforward
PAM	-	Pneumatic Artificial Muscle
ROMAC	-	Robotic Muscle Actuator
PD	-	Proportional Derivative
PI	-	Proportional Integral
P+ID	-	Proportional plus Integral Derivative
P+	-	Proportional plus
MPC	-	Model Predictive Control
PPR	-	Proportional Pressure Regulator
PT	-	Pressure Transducer
LVDT	-	Linear Variable Differential Transducer
LC	-	Load Cell
DC	-	Direct current
P	-	Proportional
PC	-	Personal computer
PID	-	Proportional integrated derivative
OS	-	Overshoot

LIST OF SYMBOLS

Mathematical Symbol:

N	-	Newton
mm	-	Millimetre
Kg	-	Kilogram
µm	-	Micrometre
kPa	-	Kilopascal
±	-	Plus or minus
L	-	Litres
%	-	Percentage
/	-	Divide
+	-	Plus
=	-	Equal
A	-	Ampere
HP	-	Horsepower
PSI	-	Pounds per square inch
Hz	-	Hertz
V	-	Volts
Hz	-	Hertz
kg	-	Kilogram
m	-	Meter
e	-	exponential

lb - Pounds

mV - millivolts

s - Second

t - Time

Ns - Newton second

x_e - Experimental PMA contraction

x_s - Simulation contraction

e_{max} - Maximum peak error

e_{rms} - Root mean square error

e - Error

t_r - Rise time

t_s - Settling time

System Model Symbol:

M - Mass

$\ddot{x}$ - Acceleration of PMA (system)

B_m - Damping coefficient

$\dot{x}$ - Velocity of PMA (system)

K_m - Spring coefficient

F_{ce} - Contractile force

x - Contraction displacement of PMA

F_L - External force

F_K - Spring force

F_B - Damping force

P - Pressure

g - Gravity

$x_{\max}$ - Maximum displacement

Control System Symbol:

C_{PV} - Compensator pressure to voltage

B - Damping coefficient

x_r - Reference input

x - Displacement

$X_r(s)$ - Input displacement in s-domain

$X(s)$ - Output displacement

K_p - Proportional gain (PID controller)

K_d - State-feedback gains (LQR controller)

K_i - Integral gain

K_u - Ultimate gain

K_c - Critical gain

T_u - Ultimate period

T_i - Integral time constant

T_d - Derivative time constant

Inf - Infiniti

CO - Controller output

e - Error

dt - Differentiate over time

LIST OF PUBLICATIONS

Journal:

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1. S.Vasanthan, and Shin-Horng Chong., 2013. Motion Control of Pneumatic Muscle Actuator: Experimental Setup and Modeling. *Proceedings of the IEEE student Conference on Research and Development (SCOReD)*, pp. 60-64.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.0 Introduction

Pneumatic muscle actuator (PMA) is a new type of actuator which carries an unique type of characteristics compared to the traditional pneumatic actuators. It is a man-made artificial muscle that consists of an inflatable rubber tube sheathed by a braided mesh. The pneumatic muscle actuator features numerous advantages such as simple structure, cleanliness and high safety, cost effective, and also free from electrical and hydraulic leakage. Pneumatic actuator is a commercial actuator that holds an unique advantage as compared to electric motor and hydraulic systems. The most significant advantage of this actuator is a high power-to-weight ratio and high power-to-volume ratio. Industrial machines and rehabilitation applications always require low cost actuators with high force and power output. In addition, medical systems also require an actuator that has features that is safe to handle and clean, where there are limited actuators that can bridge both types of demands. These demands have increased the need of PMA as an actuator that fit above requirements. However, PMA has nonlinearity, creep phenomenon, and hysteresis problem. These characteristics cause the difficulties to model and control the system that actuated by PMA accurately.

Commonly, there are two types of approach used in the motion control of PMA system which is the classical approach and the advanced approach. The classical approach that widely used in the PMA motion control is the PID controller. The PID controller presents advantages such as simple structure, easy design procedure and high adaptability characteristics. Although PID controller is easy to design, the classical approach has the weakness such as the need of exact model parameters about the system and it frequently exhibits stick slip problem. Since then, the researcher has devoted themselves into a new type of approach in the field of research and motion control of PMA system. The advanced controller approach that has been widely used is the feedback linearization controller (Su, 1982), gain scheduling controller (Leith and Leithead, 1999), adaptive controller (Tonietti and Bicchi, 2002), fuzzy controller (Balasubramaniam and Rattan, 2005) and also neural network controller (Thanh and Ahn, 2006). These advanced controllers provide advantages such as robust, high adaptability, and high positioning performance characteristics. However, the advanced controller presents disadvantages such as time consuming, deep understanding of considered system, low adaptability and mathematically complex. As a result, these have created a need for a controller that has robust, easy to design, fast and adaptable characteristics for better performance of the PMA system in position control.

This research aims to propose a practical and simple design procedure for the positioning control of PMA system. As a solution, controller with the combination of modified PID plus feedforward controller for positioning control of 1-DOF pneumatic muscle actuator system is proposed and its usefulness is demonstrated experimentally. The design, development and dynamic modelling of the 1-DOF pneumatic muscle actuator system are focused on the early part of this thesis. The dynamic model of the 1-DOF PMA system was validated via simulation and experimental results. In comparison to the classical controller, the proposed controller has been proved to achieve better positioning accuracy. Future works will be focused on reducing the overshoot effect of the PMA system, faster response and higher positioning accuracy. In addition, future works will focus on improving the tracking performance of the proposed controller on the 1-DOF PMA system. Future works also will focus on precision positioning control.

1.1 Problem Statement

The PMA system poses highly nonlinear characteristics which are caused by the existence of pressurized air, elastic-viscous material, viscous friction and the PMA geometric features. Due to this, system modelling, controller design and system real-time implementation are a prime challenge. Besides that, the lack of accurate mathematical model parameters to predict the PMA motion contributes to the PMA system positioning performance challenge. Many researchers have devoted themselves to develop a control system for the PMA system. However, the proposed controllers are either mathematical complex (advanced), classical features, not easy to design or has low adaptability to be utilized in a nonlinear system.

In order to overcome this problem, a phenomenological model will be characterized and the effectiveness of the model will be validated in simulation and experimental environment. The phenomenological model approach is less theoretical and it is understood to better capture the motion of the PMA (able to predict the PMA motion in simulation environment). This model is more adaptable as compared to the geometrical approach, where the geometrical approach might limit its application for real-time control due to its structure complexity and requires too many parameters that are difficult to obtain during experimentation. To deal with the complex nonlinear dynamics of the PMA system, a modified PID plus feedforward PID controller is proposed. The detail of the proposed controller will be discussed comprehensively in Chapter 3.

1.2 Objectives of the Research

This research is focused on the following objectives:

(a) To develop a pneumatic muscle actuator system and model its dynamic characteristics using phenomenological model.

(b) To design a Modified PID plus Feedforward controller for the 1-DOF pneumatic muscle actuator system.

(c) To validate the effectiveness of the proposed controller in point-to-point and tracking motions experimentally.

1.3 Scopes

This research is focused on the 1-DOF pneumatic muscle actuator system only. In order to achieve the goals of the research, several scopes have been outlined.

(a) The pressure tested on the PMA system is from 0-550kPa only.

(b) The working range of the PMA system is set to below 60mm and the maximum load tested is below 60kg.

(c) The PMA system is examined in point-to-point and tracking motions only.

(d) The scope of positioning accuracy for the proposed controller is set to be between ±100µm.

(e) The system numerical analysis and validation are performed in MATLAB Simulink environment.

(f) The proposed modified PID plus feedforward controller is focused on the idea of practical and easy design procedure approach. Hence, the proposed controller performance is compared with a classical PID controller only.

1.4 Contribution of Research

This research contributes to the field of control system engineering and medical applications (rehabilitation robot). In this research, an advanced controller is designed for a 1-degree of freedom (DOF) pneumatic muscle actuator system. It involves designing a nonlinear feedback controller and a feedforward controller to minimize the steady-state error of the system and improving the positioning performance in term of rise time, overshoot and settling time. This thesis contributes as a complete cycle in control system engineering design and development. Specifically, the contributions of this research are as follows:

(a) An experimental setup for positioning control of a 1-DOF pneumatic muscle actuator system has been developed.

(b) Then, a phenomenological model for the 1-DOF PMA system is characterized and its effectiveness has been validated.

(c) Most significantly, a practical and easy design procedure control system is proposed and validated experimentally. The developed 1-DOF pneumatic muscle actuator system will contribute towards the design and development of a bionic arm application and also serves as a preliminary result for various types of exoskeleton robot applications (motion control).

(d) The practical and easy to design controller is the key contribution of this research and will serve in the PMA system motion control. The easy design procedure proposed in this research can be embedded into other types of nonlinear PMA system with different type of configurations.