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Controller Design for Simulation Control of Intelligent Pneumatic Actuators (IPA) System

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Abstract

Intelligent Pneumatic Actuators (IPA) is a system for application that requires better control and accuracy. The purpose of this paper is to present a controller design for simulation control of an IPA system using Proportional-Integrative (PI) controller and pole-placement feedback controller. Before the controller is designed, a model identification is used to obtain the plant using transfer function. The flow for the controller design starts with the theory, mathematical calculation, procedures and the implementation of the simulation control by using MATLAB software. Furthermore, simulation results are compared and analyzed to illustrate the performance of the proposed controllers.

Keywords: Intelligent Pneumatic Actuator (IPA); System Identification (SI); PI controller; Feedback controller.

1. Introduction

Nowadays, pneumatic system is more complex which leads to the development of an intelligent pneumatic system. Although pneumatic actuators are adopted in many automation industries, it is not easy to control because has many nonlinear characteristics such as the valve dead zone problems, mass flow rate parameters and compliance variation [1]. Model identification is used to obtain the linear mathematical model (transfer function) of the plant system from the measured experimental data, L. A. Zadeh presented that there are multitude of identification processes techniques that can be utilized [2]. The application area of transfer function has become widespread to cover areas such as engineering, computer science, financial sector, industrial applications and many others [3-5].

Controller design for pneumatic system is more challenging to control the position, force, compliance, viscosity and etc. Proportional-Integral (PI) controller design was previously proposed to control pneumatic system [1, 6-8]. In addition, the position-controlled pneumatic actuator using pulse width modulation (PWM) valve pulsing algorithms is described by [6, 9]. The mechatronic system have the advantage of using on/off solenoid valves to replace more expensive servo valves and it may be applied to a variety practical positioning applications. Moreover, in most cases, the systems that have been described

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are linear process model which are obtained from experimental data using system identification and PI controller with position feedforward.

Another controller design such as feedback controller is proposed to control the pneumatic systems. A method of feedback linearization for a pneumatic actuator system was proposed by [10, 11]. The research shows that any single-input single-output (SISO) pneumatic system with a linearizable load and an isothermal pneumatic actuator is linearizable by state feedback. A method of feedback linearization with step type disturbance rejection is also proposed by measuring disturbances. In addition, feedback linearization with step-type disturbance rejection is proposed by measuring disturbances, which is useful for pneumatic systems with static friction. Pole-placement method generally has been used for the design of feedback controller. Pole-placement controller utilizing a low order linear approximation for a 2-axes Pneumatic Artificial Muscle (PAM) manipulator was presented by [12]. The parameters of Auto-Regressive with Exogenous Input (ARX) model used are estimated online from past input and output values by RLS system identification. Self-tuning pole-placement control can automatically accommodate wide changes in operating conditions, such as payload and time varying parameters of the 2-axes PAM manipulator. This novel proposed control scheme is initially applied to the independent control of the PAM manipulator joint angle position.

Therefore, the aim of this project is to develop IPA model and methodologies to overcome the limitations of the existing device and to improve the performance for IPA system. In this paper, model identification procedures and controllers design for simulation control of IPA system has been shown using MATLAB. Finally, the results of this system performances will be compared and discussed.

2. Plant

The Intelligent Pneumatic Actuator (IPA) plant used in these real-time studies is referred from [13-16] where A. A. M. Faudzi *et al.* developed intelligent actuators and applied them to Pneumatic Actuator Seating System (PASS) as an application. The linear actuator type is a double acting (KOGANEI: HA Twinport Cylinders) driving pneumatic actuators with two air inlets and one exhaust outlet. The general IPA has five extensive elements realizing *all-in one* system of actuator. The five elements are optical encoder (AEDR: 8300), laser stripe code, Programmable System on a Chip (PSoC) board (CYPRESS: CY8C27243-24PVXI), pressure sensor (KOGANEI: PSU-EM-S) and valves (KOGANEI: EB10ES1-PS-6W). Pressure sensor is used to check the chamber pressure to perform control action of the cylinder. The cylinder applies two on/off valves (two ports two positions) for driving the cylinder. A miniature valve is attached at the end of the cylinder and a microcontroller board which consists of PSoC as the central processing unit that is fixed at the top of the actuator, in a single device. The advantage of this actuator is that it can decide the target output based on the feedback inputs with real-time communication capability locally. The actuator has 200mm stroke and force up to 100N. The 0.169mm laser stripe pitch can give high accuracy for position control. An optical reflective surface mount encoder chip is implemented on the bottom part of the PSoC circuit board. This encoder chip consists of three parts; an LED light source, a photo detector IC and optical lenses. The lenses focus the LED light onto the code strips on the guide rod and reflected light on the photo detector IC.

3. Model Identification

This research implements model identification to obtain plant in mathematical model of IPA. Mathematical model will be approximated using MATLAB software such as System Identification Toolbox from open-loop input-output experimental data. Through experimental setup, the hardware and PC communicates using Data Acquisition (DAQ) card over MATLAB software. Experimental setup for this research consists of National Instrument (NI) DAQ card PCI/PXI-6221 (68-Pin) board connected with Personal Computer (PC) motherboard, PCI slot and SCB-68 M series devices with SHC68-68-EPM cable connector. Fig. 1(a) shows overall parts of the intelligent actuator and Fig. 1(b) shows the real experiment setup. During experimental setup, data will be gathered and analyzed to support model identification and observed the system dynamic. Then, model identification will go through the model estimation, model structure selection, and model validation. Proper parameters identification requires the usage of input signal that rich in frequencies. There are several methods in generating the signals such as PRBS (Pseudo-Random Binary Sequences), sinusoidal, step etc. This research used the step signal as it is one of the most commonly used excitation signals for model identification. Step signal can be generated by operation such as on/off of power and open/close of valve [17]. Fig. 2(a) shows the proposed design of step signal implemented to IPA. This step signal is specially designed for the on/off valve on the IPA system. This signal is preferable compared to original step signal in order to capture the dynamic characteristic of the system. The signal is generated using three different frequencies based on maximum operating frequency (width actuator movement) to step signals for valve 1 (references), valve 2 and reset (offset). Fig. 2(b) shows the relationship between the input, u_1 (voltage) and the output, y_1 (position) of the IPA system for model identification. This signal is injected to the IPA system and the output of the system is recorded. Several sets of 1000 numbers of input and output data with sampling time of 0.1s are collected for model estimation and validation. Equations (1) to (4) represent the step signal followed by the number of width, N_{Width} which can determine the displacement according to time of an on/off valve.

$$T_{V1} = N_{Width} = T_{V2} + T_R \tag{1}$$

$$T_{V2} = T_{V1}^{-1} - T_R \tag{2}$$

$$T_R = T_{V1}^{-1} + T_{V2}^{-1} \tag{3}$$

where,

$$Period = (Period_{V1,\ V2,\ Reset})T_{\max_{valve}} \tag{4}$$

T_{V1} is time valve 1 on (air inlet), T_{V2} is time valve 2 on (air outlet), T_R is time reset counter or offset and $T_{\max_{valve}}$ is maximum operating time for the valve. This research implement the $N_{Width} = 4$ for the step signal.

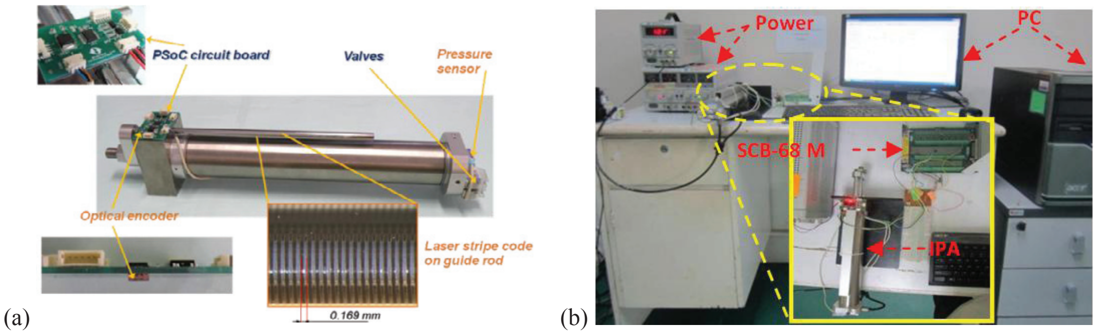

Fig. 1. (a) Intelligent actuator and its parts [13]; (b) Real experimental setup

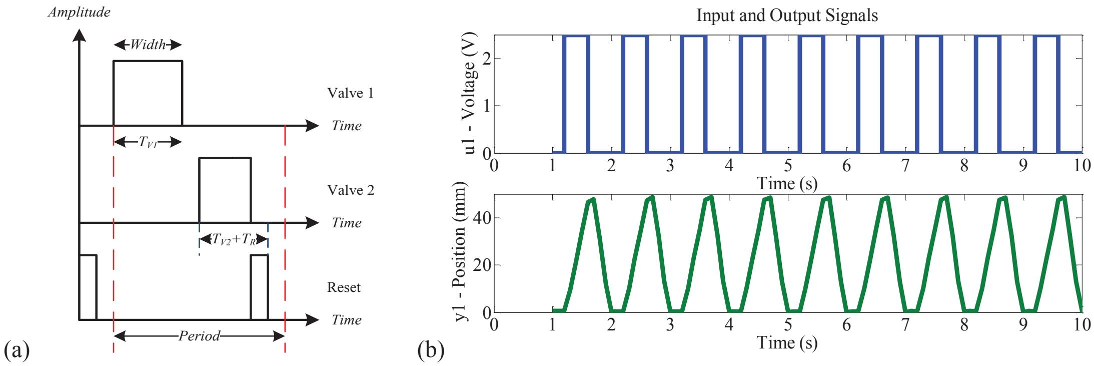

Fig. 2. (a) Step signals; (b) Input and output signal

Normally, the models obtained from SI are limited to second and third order. Higher-order models may produce unstable output. In this case, the third-order model will represent the nearest model of the true plant. From the MATLAB System Identification Toolbox, Auto-Regressive Moving Average with Exogenous Input (ARMAX) model from input-output data will be obtained. The following ARMAX model in the form of discrete-time open-loop transfer function is identified for third order system as shown in Equation (5).

$$\frac{B_o\left(z^{-1}\right)}{A_o\left(z^{-1}\right)}=\frac{4.406z^{-1}+0.6648z^{-2}+1.633z^{-3}}{1-1.87z^{-1}+1.696z^{-2}-0.7961z^{-3}} \tag{5}$$

In addition, MATLAB System Identification Toolbox also show the model views such as model output, model residual, zeros and poles and etc. Fig. 3(a) shows the model output and Fig. 3(b) shows the zeros and poles of an IPA system.

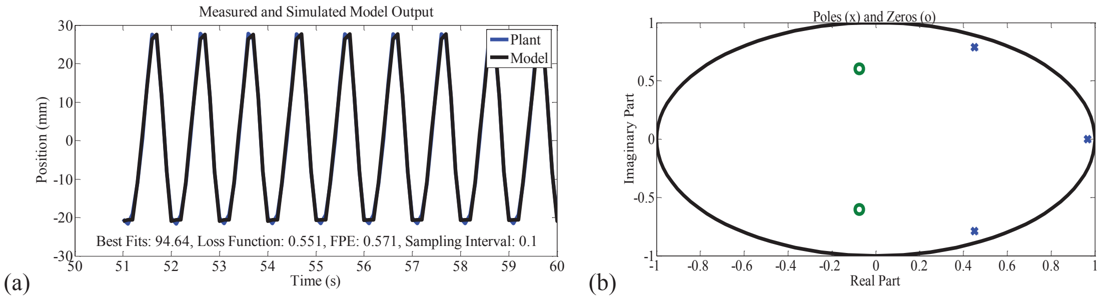

Fig. 3. (a) Model output; (b) Zeros and poles

4. Controllers Design

This research proposed two controllers design. The first design is the Proportional-Integrative (PI) controller as the same controller implemented on the existing research [13-16]. The second controller design is the feedback controller using pole-placement technique to validate position tracking control of IPA system with the former controller.

4.1. PI controller

This research used discrete PI controller where it considers the basic ideal PID controller written in the continuous time domain form:

$$U(t)=K_p\left(e(t)+\frac{1}{T_i}\int_0^t e(\tau)d\tau+T_d\frac{d}{dt}e(t)\right) \tag{6}$$

Sampling time of discretisation is Δt. The integral term can be considered discrete via a trapezoidal approximation. Where $e(t_i)$ is the error of the continuous time system at the i_{th} sampling instant. Thus, the discrete time control laws or positional algorithm becomes,

$$U(t_k)=K_p\left(e(t_k)+\frac{\Delta t}{T_i}\sum_{i=1}^{k}e(t_i)\right) \tag{7}$$

The parameters of PI can be obtained from the calculation based on Ziegler-Nichols tuning method and manual adjustment using MATLAB. The block diagram of a PI controller is shown in Fig. 4(a).

4.2. Feedback controller (Pole-Placement)

The feedback controller design will be based on pole-placement technique. The block diagram of a feedback control system using pole-placement technique is shown in Fig. 4(b). This technique enables all poles of the closed-loop to be placed at desired location and providing satisfactory and stable output performance. The transfer function of the closed-loop system is given as:

$$\frac{Y(z^{-1})}{U(z^{-1})}=\frac{K_f B_o(z^{-1})}{A_o(z^{-1})F(z^{-1})+B_o(z^{-1})G(z^{-1})} \tag{8}$$

where:

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} + \ldots + a_n z^{-n}$$
$$B(z^{-1}) = b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3} + \ldots + b_m z^{-m}$$
$$F(z^{-1}) = 1 + f_1 z^{-1} + f_2 z^{-2} + f_3 z^{-3} + \ldots + f_m z^{-m-1}$$
$$G(z^{-1}) = g_0 + g_1 z^{-1} + g_2 z^{-2} + g_3 z^{-3} + \ldots + g_n z^{-n-1}$$

A Diophantine equation derived from Equation (8) is given as follows:

$$A(z^{-1})F(z^{-1}) + B(z^{-1})G(z^{-1}) = T(z^{-1}) \tag{9}$$

where, $K_f = \dfrac{Sum(T)}{Sum(B)}$ and $T(z^{-1}) = 1 + t_1 z^{-1}$. K_f is forward gain, T is the location of poles that we required, which is by selecting a pole position at t_1=-p which is inside a unit circle and let all other poles at the origin. The range of p is 0<p<1. For slow response, p is set large and for fast response, p is set small. The method of solving Equation (9) can be referred to [18]. From Equation (9) the following matrix equation can be derived and referred to [19]. Let $E.M$=D where E is a Sylvester Matrix given by:

$$E = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & b_1 & 0 & 0 & 0 & 0 & 0 & 0 \\
a_1 & 1 & 0 & 0 & 0 & 0 & b_2 & b_1 & 0 & 0 & 0 & 0 & 0 \\
a_2 & a_1 & 1 & 0 & 0 & 0 & b_3 & b_2 & b_1 & 0 & 0 & 0 & 0 \\
a_3 & a_2 & a_1 & 1 & 0 & 0 & b_4 & b_3 & b_2 & b_1 & 0 & 0 & 0 \\
a_4 & a_3 & a_2 & a_1 & 1 & 0 & b_5 & b_4 & b_3 & b_2 & b_1 & 0 & 0 \\
a_5 & a_4 & a_3 & a_2 & a_1 & 1 & \vdots & b_5 & b_4 & b_3 & b_2 & b_1 & 0 \\
\vdots & a_5 & a_4 & a_3 & a_2 & a_1 & b_m & \vdots & b_5 & b_4 & b_3 & b_2 & b_1 \\
a_n & \vdots & a_5 & a_4 & a_3 & a_2 & 0 & b_m & \vdots & b_5 & b_4 & b_3 & b_2 \\
0 & a_n & \vdots & a_5 & a_4 & a_3 & 0 & 0 & b_m & \vdots & b_5 & b_4 & b_3 \\
0 & 0 & a_n & \vdots & a_5 & a_4 & 0 & 0 & 0 & b_m & \vdots & b_5 & b_4 \\
0 & 0 & 0 & a_n & \vdots & a_5 & 0 & 0 & 0 & 0 & b_m & \vdots & b_5 \\
0 & 0 & 0 & 0 & a_n & \vdots & 0 & 0 & 0 & 0 & 0 & b_m & \vdots \\
0 & 0 & 0 & 0 & 0 & a_n & 0 & 0 & 0 & 0 & 0 & 0 & b_m
\end{bmatrix} \tag{10}$$

$$M = \begin{bmatrix} f_1 & f_2 & f_3 & f_4 & \cdots & f_{m-1} & g_0 & g_1 & g_2 & g_3 & g_4 & \cdots & g_{n-1} \end{bmatrix}^T \tag{11}$$

$$D = \begin{bmatrix} t_1 - a_1 & -a_2 & -a_3 & -a_4 & -a_5 & \cdots & -a_n & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{12}$$

Therefore, vector F and G can be computed from vector M that is given by M=$E^{-1}.D$. Table 1 shows the controller parameters that have been computed using MATLAB software are shown as follows.

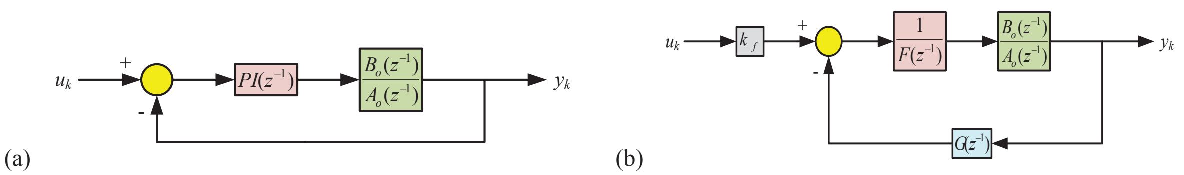

Fig. 4. (a) PI controller; (b) Feedback controller using pole-placement technique

Table 1. Comparison between PI controller and feedback controller analysis results

t_1	K_f	$T(z^{-1})$	$F(z^{-1})$	$G(z^{-1})$
-0.25	0.1119	$1-0.25z^{-1}$	$1+0.2650z^{-1}+0.4436z^{-2}$	$0.3075-0.4195z^{-1}+0.2162z^{-2}$
-0.5	0.0746	$1-0.5z^{-1}$	$1+0.3189z^{-1}+0.4366z^{-2}$	$0.2386-0.3847z^{-1}+0.2129z^{-2}$
-0.75	0.0373	$1-0.75z^{-1}$	$1+0.3728z^{-1}+0.4297z^{-2}$	$0.1696-0.3498z^{-1}+0.2095z^{-2}$

5. Result and Discussion

The result of PI controller design using square wave input is shown in Fig. 5(a). From the result, PI controller give better response but the time response is slow. This problem is the same as the existing experiment results [13]. This is due to the abilities of on/off valve to open and close at its capabilities rate [19]. In addition, the starting result of step response has a small overshoot and small friction.

To overcome this problem, feedback controller is designed and the result of feedback controller design for that used square wave input is shown in Fig. 5(b). The result of feedback controller are compared with three variable of t_1, such as t_1=-0.75, t_1=-0.5 and t_1=-0.25. Using t_1 is -0.75, the time response is slow. When t_1 decreases to –0.5, the simulation time response is a bit faster. When t_1 decreases to –0.25, the time response is a very bit faster but the starting of step response has the small overshoot. The comparison of PI controller and feedback controller using t_1=-0.5 with square wave input is shown in Fig. 6. The performance of feedback controller gives a good response and more stable compared to PI controller. Table 2 shows the comparison for step responses position tracking between PI controller and Feedback controller analysis.

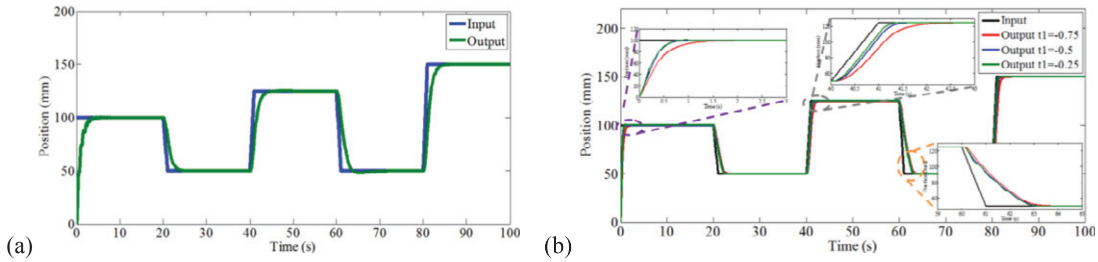

Fig. 5. (a) PI controller result; (b) Feedback controller results

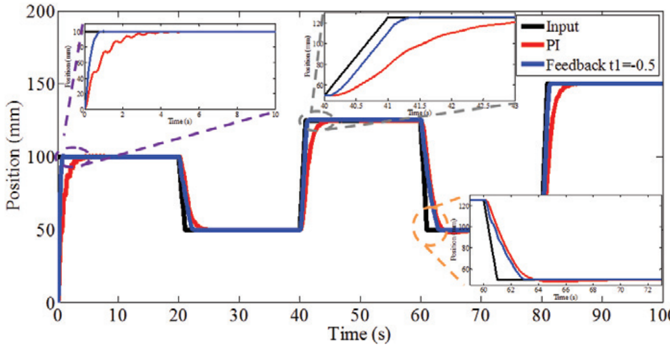

Fig. 6. PI controller versus feedback controller results

Table 2. Comparison for step responses position tracking between PI controller and feedback controller analysis results

Analysis	PI Controller	Feedback Controller (t_1=0.5)
Percent Overshoot (*%OS*)	0%	0%
Dead Time (T_U)	0.45s	0.25s
Peak Time (T_P) = Settling Time (T_S)	4s	1.25s
Rise Time (T_R)	2.05s	0.8s
Percent Steady State error ($\%e_{ss}$)	0.01%	0.01%

6. Conclusion

Controller design using PI controller and pole-placement feedback controller have been analyzed. To perform comparison between both controllers, the criterion for measuring the response is identified. The most common are compare the percent overshoot (*%OS*), dead time (T_U), peak time (T_P), settling time (T_S), rise time (T_R) and percent steady state error ($\%e_{ss}$), feedback controller is more stable than PI controller to control the IPA system. In addition, the sampling period of the real embedded controller (PSoC) has an important influence upon the control performance. From the simulation result, the sampling period is short (0.1 samples per second) and it can be realized with the previous experimental work in [13-16] based on the theoretical model. This research will provide greater opportunities for future work such as development of other controllers, validation process and comparison with the real system including disturbance.

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