High Precision Pressure Control of a Pneumatic Chamber using a Hybrid Fuzzy PID Controller

Hao Liu[1], **Jae-Cheon Lee**[2,#] and **Bao-Ren Li**[3]
1 Department of Mechanical Engineering, Graduate School, Keimyung University, Sindang-Dong, Dalseo-Gu, Daegu, South Korea, 704-701
2 Faculty of Mechanical and Automotive Engineering, Keimyung University, Sindang-Dong, Dalseo-Gu, Daegu, South Korea, 704-701
3 FESTO Pneumatic Center, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, Wuhan, China, 430-074
Corresponding Author / E-mail: ljcds@kmu.ac.kr, TEL: +82-53-580-5921, FAX: +82-53-580-5115

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A hybrid fuzzy PID controller for a pneumatic chamber is proposed in this paper. First, a mathematical model of a pneumatic pressure servocontrol system was developed where separate implementations of a PID controller and a fuzzy controller were made. The experimental results using a step input signal revealed that the PID controller accurately controlled the steady-state pressure but did not robustly handle parameter variations in the system while the fuzzy controller provided a fast rise time and low overshoot of the pressure in the system. In order to attain the advantages of both the fuzzy and PID controllers, a hybrid control scheme was developed. The experimental results show that the hybrid fuzzy PID controller proposed in this study does indeed possess the advantages of both PID and fuzzy controllers. Hence, it can be concluded that the hybrid fuzzy PID controller is suited for high-precision control of pressure in a pneumatic chamber.

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1. Introduction

The word pneumatics is defined as working and controlling devices using compressed air. Today, pneumatic devices are used more frequently in industry because of their advantages including low cost, ease of maintenance, cleanliness, and low power requirements. Pneumatic servocontrol techniques use compressed air as a working medium[1] to implement transfer, transition, distribution, and control of energy.

Most of the current research on servocontrol systems has been focused on industrial applications using position or velocity control of actuators.[2-5] Research on servocontrol systems using pneumatic pressure control has been relatively rare.

Many pneumatic facilities require high-precision and high-speed control of pressure. A closed loop system consisting of a flow servovalve and a pressure sensor was mathematically modeled in this study. Then, a hybrid fuzzy PID controller was developed to overcome the individual disadvantages of PID and fuzzy controllers. A series of experiments was conducted to evaluate the performance of the proposed hybrid fuzzy PID controller. The experimental results show that the hybrid fuzzy PID is suited for high-precision and high-speed control of pressure in a pneumatic servocontrol system.

2. System Description and Modeling

2.1 System Description

The pneumatic pressure servocontrol system consisted of: (1) a computer with a user interface and a development platform; (2) a data acquisition system; (3) a servovalve; (4) a pressure sensor; (5) several closed chambers of different volume; and (6) an air compressor that supplies air at a pressure of 0.6 MPa. A schematic diagram of the system is shown in Fig. 1.

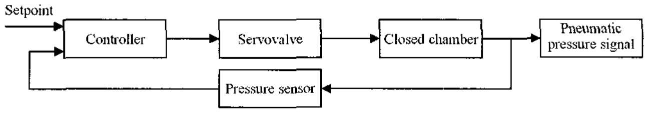

Fig. 1 Schematic diagram of the pneumatic pressure servocontrol system

In Fig. 1, the controller, which is embedded in a computer, estimates the output of voltage to the servovalve based on the error between the desired pressure defined by the setpoint and the actual pressure measured by the sensor. The voltage going into the servovalve causes the spool inside the valve to move away from its central point in order to proportionally increase the flow rate across the servovalve. This results in a charge or discharge of pressure in the closed chamber so that the pressure eventually becomes equal to the desired pressure defined by the setpoint.

The dynamic process of changing the pressure in the closed chamber from one value to another can be difficult to accomplish.

Also, it is difficult to mathematically model the nonlinearities in pneumatic systems due to the uncertain and time varying parameters in the system. Therefore, a control system must be developed in conjunction with a mathematical model to be able to more effectively control a pneumatic pressure system.

2.2 System Modeling

A pneumatic pressure servocontrol system is a basic process of charging or discharging the closed chamber. The complex aspects of pneumatic flow will be modeled with the following assumptions[6] to more easily analyze the system:

- The gas in the closed chamber is an ideal gas modeled by the ideal gas equation, $P = \rho RT$;
- The charging and discharging process is adiabatic where there is no thermal exchange;
- The flow of gas through the servovalve orifice is isoentropic and adiabatic;
- Leakage in the system is neglected.

The general energy equation of a control volume when applied to a closed chamber during the process of charging[6] can be simplified as

$$dm_f h_f = dU_i \tag{1}$$

where dm_f is the mass of the gas charged into the chamber, h_f is the specific enthalpy of the gas charged into the chamber, and dU_f is the internal energy change of the gas in the chamber. The subscript f indicates the parameters of the gas charged into the closed chamber while the subscript i indicates the parameters of the gas in the closed chamber. Equation (1) shows that the energy of the gas charged into the closed chamber is equal to the change in internal energy of the gas in the closed chamber.

By considering the specific heat parameter of the gas, Eq. (1) can be rewritten as

$$c_p T_f dm_f = c_v d(m_i T_i) \tag{2}$$

where c_p is the specific heat at constant pressure, T_f is the temperature of the gas charged into the chamber, c_v is the specific heat at constant volume, m_i is the mass of the gas in the chamber, and T_i is the temperature of the gas in the chamber.

The state equation of the gas in the closed chamber can be differentiated to obtain

$$\frac{V_i}{R} dp_i = d(m_i T_i) \tag{3}$$

where V_i is the volume of the gas charged into the chamber, R is the gas constant, and p_i is the pressure of the gas charged into the chamber.

Equations (2) and (3) are combined and divided by dt resulting in a differential equation between the charging time t_f and the gas pressure in the chamber p_i given by

$$dt_f = \frac{V_i}{kRT_f q_{mf}} dp_i \tag{4a}$$

where k is the isentropic index, 1.4 for air.

Similarly, the differential equation between the discharging time t_p and the gas pressure in the chamber p_i can be obtained as

$$dt_p = \frac{-V_i}{kRT_i q_{mp}} dp_i \tag{4b}$$

where q_{mf} and q_{mp} are the mass flow rate of the gas coming in and going out of the closed chamber, respectively.

The temperature T_i of the gas in the chamber changes during the charging process. An adiabatic isochoric charging process is dynamic having a changing polytropic exponent n. At the beginning of charging, the gas pressure in the chamber is as same as that of the outside environmental pressure p_b. The polytropic exponent is equal to the isentropic index, $n = k$, where the process at this moment is approximately equal to the isentropic change. The polytropic exponent decreases to $n \approx 1$ as the pressure increases in the chamber, showing that the charging process is approximately isothermal. During the discharging process, the polytropic exponent is equal to the isentropic index, $n = k$, where the process is adiabatic and isochoric as well as isentropic. The following equations relating temperature and pressure during charging and discharging can be used [6]:

$$\frac{T_f}{T_i} = \frac{p_i - p_b}{kp_i} + \frac{p_b}{p_i}\frac{T_f}{T_b} \quad \text{when charging and} \tag{5a}$$

$$\frac{T_i}{T_0} = \left(\frac{p_i}{p_0}\right)^{\frac{k-1}{k}} \quad \text{when discharging} \tag{5b}$$

where p_b and T_b are the environmental pressure and temperature and p_0 and T_0 are the pressure and temperature in the chamber at the beginning of the discharge.

When gas flows through the servovalve, the mass flow rate equations[7] are

$$q_{mf} = \begin{cases} Wx_v p_f \dfrac{F_1}{\sqrt{T_f}} f(\dfrac{p_i}{p_f}) & \dfrac{p_i}{p_f} \geq 0.528 \\ Wx_v p_f \dfrac{F_2}{\sqrt{T_f}} & \dfrac{p_i}{p_f} < 0.528 \end{cases} \tag{6a}$$

$$q_{mp} = \begin{cases} Wx_v p_i \dfrac{F_1}{\sqrt{T_i}} f(\dfrac{p_b}{p_i}) & \dfrac{p_b}{p_i} \geq 0.528 \\ Wx_v p_i \dfrac{F_2}{\sqrt{T_i}} & \dfrac{p_b}{p_i} < 0.528 \end{cases} \tag{6b}$$

where

$$F_1 = [\frac{2k}{R(k-1)}]^{\frac{1}{2}} \tag{6c}$$

$$F_2 = (\frac{2}{k+1})^{\frac{1}{k-1}} [\frac{2k}{R(k+1)}]^{\frac{1}{2}} \tag{6d}$$

$$f(b) = [b^{\frac{2}{k}} - b^{\frac{k+1}{k}}]^{\frac{1}{2}} \tag{6e}$$

Here, W is the spool perimeter and x_v is the spool displacement. The servovalve is considered as a linear system in which the spool displacement is proportional to the control voltage U,

$$x_v = K_v U \tag{7}$$

where K_v is the gain.

Therefore, Eqs (4) through (7) describe a mathematical model of the pneumatic pressure servocontrol system.

3. Control System Logic

There are various types of control system logic used in classical control, modern control and intelligent control systems, each having been studied and implemented in many industrial applications. Every control system method has its advantages and disadvantages. Therefore, the trend is to implement hybrid systems consisting of more than one type of control technique.[8-9] This section describes the logic of conventional PID control and fuzzy control.

3.1 PID Control

The PID control method has been widely used in industry during last several decades because of its simplicity.[10-11] The implementation of PID control logic, as shown in Eq. (8), requires finding suitable values for the gain parameters K_P, K_I and K_D. To tune these parameters, the model is linearized around different equilibrium points,

$$u(k) = K_P e(k) + K_I \sum_{i=0}^{k} e(i) + K_D [e(k) - e(k-1)] \tag{8}$$

where $e(k)$ is the error signal. However, the PID method is not suitable for controlling a system with a large amount of lag, parameter variations, and uncertainty in the model. Thus, PID control logic cannot accurately control pressure in a pneumatic system.

3.2 Fuzzy Control

Fuzzy control has found many applications in a variety of fields since Prof. Zadeh introduced fuzzy set theory in 1965.[12] Among the most successful applications of this theory has been the area of fuzzy logic control (FLC) initiated by the work of Mamdani and Assilian.[13]

FLC has the advantage that it does not require an accurate mathematical model of the process. It uses a set of artificial rules in a decision-making table and calculates an output based on the table.[14-16] Figure 2 shows a schematic diagram of a fuzzy control system. Input variables go through the fuzzification interface and are converted to linguistic variables. Then, a database and rule base holding the decision-making logic are used to infer the fuzzy output. Finally, a defuzzification method converts the fuzzy output into a signal to be sent out.

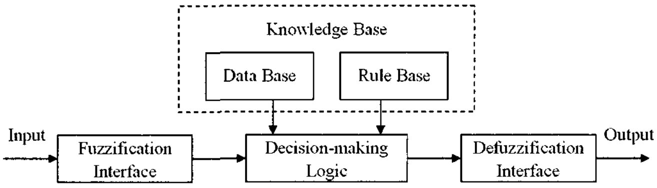

Fig. 2 Schematic diagram of a fuzzy control system

When used in a control system, FLC is robust since it provides a fast rise time and a small amount of overshoot. However, some difficulties can occur when designing the FLC. One problem is that the complexity of fuzzy controllers increases exponentially with respect to the number of input variables. Furthermore, fuzzy controllers are similar to that of standard PD controllers in that the steady-state error of the controlled variable is difficult to eliminate.[17]

3.3 Hybrid of Fuzzy and PID Control

While conventional PID controllers are sensitive to variations in the system parameters, fuzzy controllers do not need precise information about the system variables in order to be effective. However, PID controllers are better able to control and minimize the steady-state error of the system. Hence, a hybrid system, as shown in Fig. 3, was developed to utilize the advantages of both PID controllers and fuzzy controllers.[9]

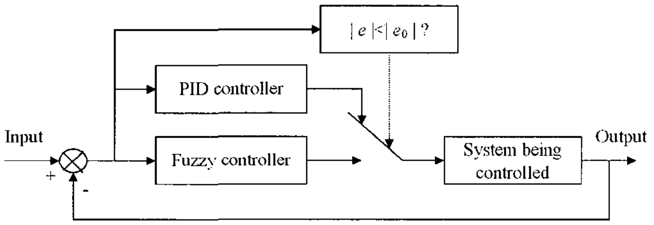

Fig. 3 Block diagram of a hybrid fuzzy PID controller

Figure 3 shows a switch between the fuzzy controller and the PID controller, where the position of the switch depends on the error between the actual value and set point value. If the error in pressure reaches a value higher that that of the threshold e_0, the hybrid system applies the fuzzy controller, which has a fast rise time and a small amount of overshoot, to the system in order to correct the pressure with respect to the set point. When the pressure in the closed chamber is below the threshold e_0 or close to the set point, the hybrid system shifts control to the PID, which has better accuracy near the set pressure.

4. Designing the Controller and Simulation

The control parameters and set of terms that describe each linguistic variable must be determined when designing a FLC. Obviously, the pressure in the closed chamber is the parameter to be controlled in the system. A two-dimension structure will be used to produce fast calculations. The two input linguistic variables are the error of the pressure E and the error change of the pressure EC. The output is the voltage signal to control servovalve spool U. Thus, the FLC has two antecedences and one consequence.

First, the two input variables must be defined in terms of linguistics. The error in pressure is expressed by a number in the interval from –5 to 5. There are eight linguistic terms of the error in pressure: negative big (NB), negative medium (NM), negative small (NS), negative zero (NZ), positive zero (PZ), positive small (PS), positive medium (PM) and positive big (PB). Similarly, the fuzzy set of the error change of the pressure is represented as {NB NM NS ZE PS PM PB} over the interval from –5 to 5. Finally, the fuzzy set of the output signal is represented as {NB NM NS ZE PS PM PB} over the interval from 0 to 10.

The knowledge base for a fuzzy controller consists of a rule base and membership functions. It is reasonable to represent these linguistic terms by triangular-shape membership functions, as shown in Figs. 4, 5 and 6.

A fuzzy control knowledge base must be developed that uses the linguistic description of the input variables. In general, there are four methods[15] used to build a rule base:

- An expert's experience and knowledge,
- Modeling the operator's control actions,
- Modeling a process, and
- Self organization.

The first method is the most widely used. The rule base consists of a set of linguistic IF-THEN rules containing two antecedences and one consequence, as expressed in the following form:

$R_{i,j,k}$: IF $E=A_i$ and $EC=B_j$ THEN $U=C_k$,

where $1 \leqslant i \leqslant 8$, $1 \leqslant j \leqslant 7$ and $1 \leqslant k \leqslant 7$. The total number of IF-THEN rules is 56 and is represented in matrix form, called a fuzzy rule matrix, as shown in Table 1.

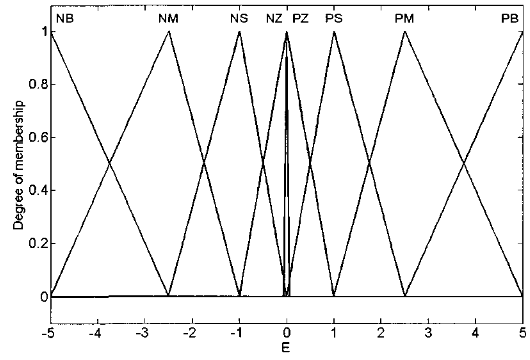

Fig. 4 Membership function of the pressure error

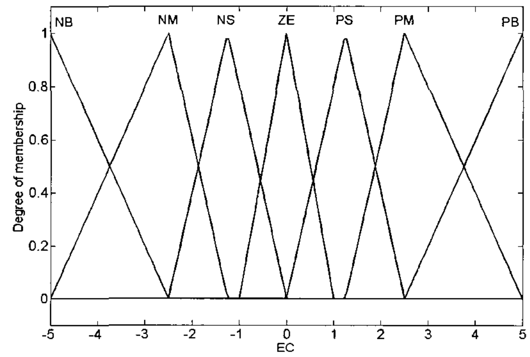

Fig. 5 Membership function of the pressure error change

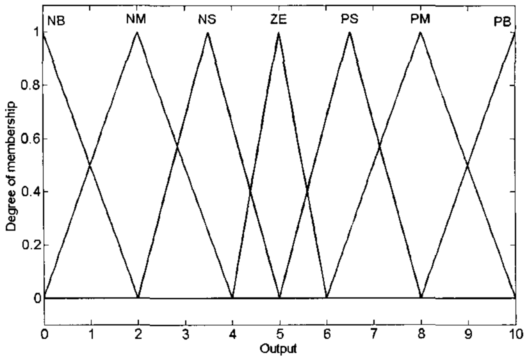

Fig. 6 Membership function of the control output

Table 1 Fuzzy rule matrix

	EC						
E	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PB	PB	PM	ZO	ZO
NM	PB	PB	PB	PB	PM	ZO	ZO
NS	PM	PM	PM	PM	ZO	NS	NS
NZ	PM	PM	PS	ZO	NS	NM	NM
PZ	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NM	NM	NM	NM
PM	ZO	ZO	NM	NB	NB	NB	NB
PB	ZO	ZO	NM	NB	NB	NB	NB

The decision-making output can be obtained using a max-min fuzzy inference where the crisp output is calculated by the center of area (COA) method.

In order to validate the hybrid fuzzy PID controller, a simulation of the response of the system was performed using a square wave input. Figure 7 shows the simulation response of the hybrid system compared to that of the PID and fuzzy systems used individually. The PID controller produced a response with a slow rise time and the fuzzy controller produced a response with steady-state error. The fuzzy PID controller (with $e_0 = 0.01$ MPa) had a response that made an abrupt turn during the transient period, which can be considered as two intervals. In the first interval, the pressure in the closed chamber approached the set pressure value with high speed. This was due to the fuzzy controller and also resulted in minimum overshoot. In the second interval, the pressure change was slower than that of the first interval. This was due to the fact that the PID controller was implemented to minimize the steady-state error of pressure with respect to the set point.

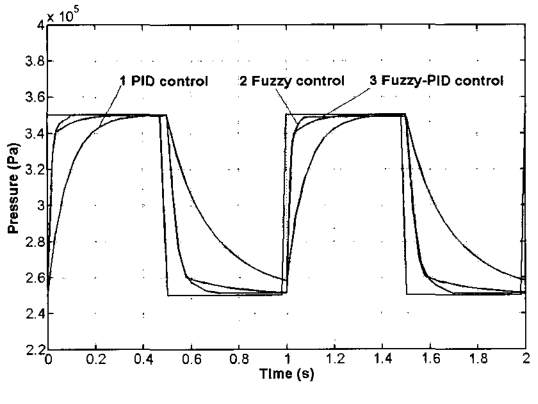

Fig. 7 Square wave response simulation

5. Experiment

The control algorithms described in Section 4 were applied to the pneumatic pressure servocontrol system shown in Fig. 1 using LabVIEW by National Instruments as the development platform.

The PID control method was applied to a system with three different volumes V of the closed chamber and a dynamic response due to a step input signal of pressure ranging from 0.3 MPa to 0.4 MPa, as shown in Fig. 8. The rise times of the response curves were less than 0.3 seconds and the steady-state errors were close to zero. However, there was a large overshoot in the response, resulting in a slow approach to the steady-state value. The larger the volume of the closed chamber, the longer it took the system to reach the steady-state value. The percentages overshoot with V=0.1L, 0.3L and 0.5L were 4.79, 5.27 and 8.69 respectively. Also, the overshoot for V=0.5L was greater than 15%. This means that the control parameters need to be adjusted to different values than those used for V=0.1L or V=0.3L due to the fact that a larger volume also induces more lag between the output pressure and the set point. The PID controller also led to overshoot in the system. A large value of overshoot leads to vibrations and noise that could harm the pneumatic components and shorten their life cycles.

Figure 9 shows that the dynamic response of the system using a fuzzy controller was better than that of the PID controller. The rise

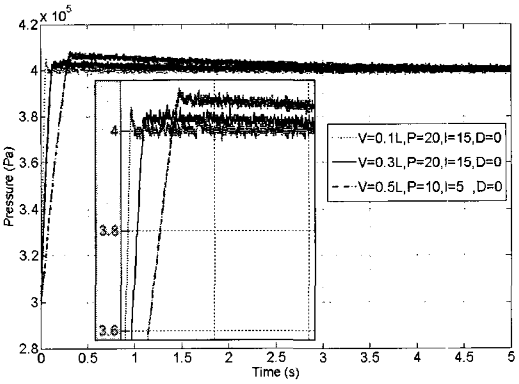

Fig. 8 Step signal response curves of the PID controller

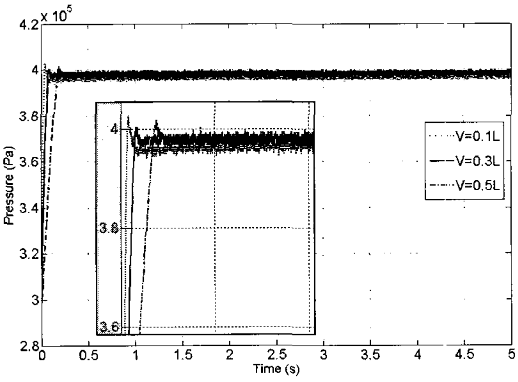

Fig. 9 Step signal response curves of the fuzzy controller

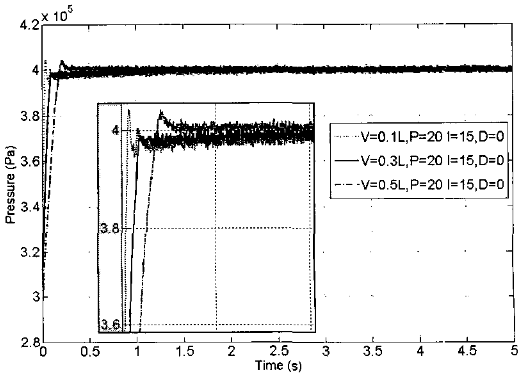

Fig. 10 Step signal response curves of the hybrid fuzzy PID controller

times of the three curves for the three different volumes of V=0.1L, 0.3L and 0.5L were 0.038, 0.081 and 0.182 s, respectively, and the largest overshoot was 2.83%. However, the steady-state error of the fuzzy controller was at least 0.002 MPa, which was much larger than that of the PID controller.

Figure 10 verifies the advantages that the hybrid fuzzy PID controller has over the individual PID and fuzzy controllers. The value of the error threshold e_0 in Fig. 3 was experimentally determined to be 0.02 MPa.

Figure 10 indicates that the average rise time and steady-state error of the system controlled by the hybrid fuzzy PID controller were less than 0.2 seconds and 0.001 MPa, respectively. The hybrid fuzzy PID controller also had a faster rise time than that of the PID controller, showing the effect that the fuzzy part had on the control scheme. Since the PID controller was applied when the pressure was below the threshold value and near the set point, the hybrid fuzzy PID controller had the same steady-state error as that of the PID controller.

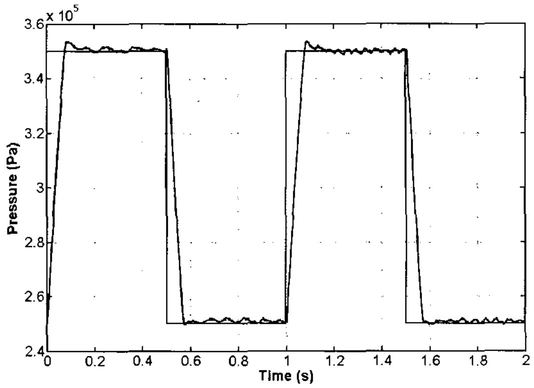

Fig. 11 Square wave signal response curve of the PID controller

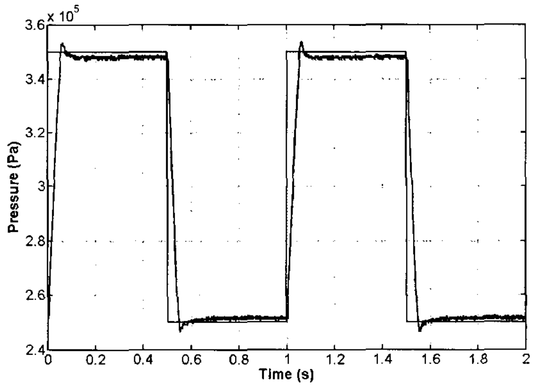

Fig. 12 Square wave signal response curve of the fuzzy controller

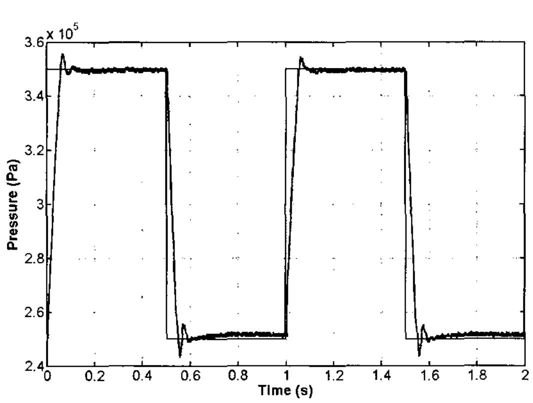

Fig. 13 Square wave signal response curve of the hybrid fuzzy PID controller

Figures 11, 12 and 13 show the square wave response for the PID, fuzzy and hybrid fuzzy PID controllers, respectively. These simulation results yield a different response than those shown in Fig. 7. The actual pressure response shown here is faster than that of the PID control simulation using the model presented in Section 2. Thus, the model presented in Section 2 is not accurate enough for a simple PID control, which requires a more accurate model than that of the more complicated fuzzy control. From Figs. 10 and 13, the hybrid fuzzy PID is suited for the high-precision control of pressure in a pneumatic chamber.

6. Conclusions

The objective of this study was to develop a control scheme for a pneumatic pressure servocontrol. First, a PID controller and a fuzzy controller were individually applied to a pneumatic pressure servocontrol system. The responses of the system with the PID controller had a larger overshoot and lower steady-state error while those with the fuzzy controller had a shorter rise time and larger steady-state error. Then, the hybrid fuzzy PID controller proposed in this study was tested experimentally and the results were compared with that of individually applied PID and fuzzy controllers. The experimental results showed that the hybrid fuzzy PID controller gave the most satisfying results of rise time, overshoot, and steady-error.

The nonlinear nature of pneumatic systems and the uncertainty in the system parameters do not allow accurate simulations using only mathematical models. In practice, a fuzzy controller can improve the results without adding too much complexity to the design. The hybrid fuzzy PID controller can obtain high-precision results for the steady-state error in a pressure servocontrol system. A better model of the pneumatic system must be formed to improve its accuracy. The transfer function of the system should be redefined and used as a reference for adjusting the parameters used in PID control.[18]

The pressure source, system parameters including control parameters, volume of the closed chamber and pressure of the air supply must all be considered for a given application. Further research will be conducted in the future to refine the method of selecting the control parameters based on a wider range of system values.

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