DESIGN AND CONTROL FOR THE PNEUMATIC CYLINDER
PRECISION POSITIONING UNDER VERTICAL LOADING

Ming-Hung Tsai, Chi-Neng Cheng, and Ming-Chang Shih
Department of Mechanical Engineering,
National Cheng Kung University
Tainan, Taiwan, R.O.C

INTRODUCTION
The pneumatic control systems have played the important roles in the industrial automation equipments owing to the following advantages - low cost, clean of the working environments, easy in power transfer, and so on. In recent years, high accuracy and high speed systems are growing up rapidly, and are important in high-tech industry. However, the precise position control of a pneumatic cylinder is very difficult due to the compressibility of air, nonlinear behavior of the air flow rate through the servo valve, the friction force between the cylinder and the piston, and the stick slip effect at the low speed of the system. The traditionally pneumatic control systems are only controlled to carry out simple on-off position and speed control by using programmable logic controller. The high precision control cannot be reached through on-off logic controller so that the modern control strategies are essential. Pandian et al [1] proposed practical design for the position and trajectory control of pneumatic actuators based on the sliding mode control approach. Shih and Ma [2] developed a control law which combines the sliding mode and modified differential PWM (M-D-PWM) control method to control the position of a pneumatic rodless cylinder. The control accuracy of the pneumatic cylinder is always under 0.1 mm. Furthermore, K.R. Pai and M.C. Shih [3] designed velocity compensator to overcome the stick-slip effect of the pneumatic table and the pneumatic table has the positioning accuracy of 20 nm. Piezoelectric actuators have been developed in recent years and already applied in pneumatic precision positioning control. Chiang et al [4] investigated pneumatic-piezoelectric hybrid positioning control system and the positioning accuracy can reach 100 nm. These papers mainly research horizontal precision positioning control, but fewer papers study the vertical precision positioning control under loading effect. This paper is mainly to study the precision performance of positioning to the vertical pneumatic cylinder under vertical loading. In this paper, the friction force and the vertical loading have the great effect on the positioning accuracy. The hybrid fuzzy sliding mode controller with loading compensator is developed and implemented in the microcomputer to control the position of the vertical pneumatic cylinder under vertical loading in the study. Regarding the simulation of loading force, it can be accomplished by controlling the pressure of the load cylinder using pneumatic proportional valve.

LAYOUT OF THE EXPERIMENTAL DEVICES
The layout of the experimental devices for the servo pneumatic vertical position control system is shown in Fig.1. A microcomputer is applied as a controller and to get the experimental data. The displacement of the cylinder is measured by a pulse scale and the air pressure of the load cylinder is also measured and feedback to the computer. The control input signals are calculated in the microcomputer through the designed software and passed to the servo valve by the D/A capability of the data acquisition and the control card. So that the air mass flow rate can be regulated and the pressure difference of the cylinder can be built up to drive the cylinder. The simulation of loading force can be accomplished by controlling the pressure of the load cylinder using pneumatic proportional valves.

CONTROLLER DESIGN
It is difficult to obtain the accurate mathematical modal of the pneumatic system because of the strong nonlinearities, high air compressibility and significant mechanical friction. In this paper, the hybrid fuzzy sliding mode controller with loading compensator is implemented in the microcomputer to control the position of the vertical pneumatic cylinder. The fuzzy sliding mode controller is designed on the basis of human experience without accurate mathematical modal. And the stability of the fuzzy sliding mode controller can be guaranteed by using the Lyapunov approach.
Hybrid fuzzy sliding mode controller

The differential equation describing the piston-load dynamics is given by:
\[
m\ddot{y} + b\dot{y} = (P_a A_a - P_b A_b) + mg - F_f \cdot \text{sgn}(\dot{y}) - P_L A_L
\]  
where \( m \) is the piston and rod assembly mass, \( y \) is the piston position, \( b \) is viscous friction coefficient, and \( F_f \) is friction force. \( P_a \) and \( P_b \) are the absolute pressures in cylinder chambers, \( A_a \) and \( A_b \) are the piston areas. \( P_L \) is the absolute pressures in load cylinder chamber and \( A_L \) is the piston area. The downward direction is defined as positive direction.

The actuator output force \( F_{\text{applied}} \) can be controlled using servovalve and expressed as:
\[
F_{\text{applied}} = P_a A_a - P_b A_b
\]

The load force \( F_L \) is expressed as:
\[
F_L = P_L A_L
\]

The Eq. (1) can be rewritten as:
\[
m\ddot{y} + b\dot{y} = F_{\text{applied}} + mg - F_f \cdot \text{sgn}(\dot{y}) - F_L
\]  
(2)

The position error is
\[
e = \tau - y
\]  
(3)

where \( \tau \) is the command input. If the absolute position error \( |e| \) is larger than the control boundary of error \( E_M \), the control signal is set to be the maximum value \( +U_M \) or \( -U_M \); if the absolute position error is smaller than the control boundary of error, the fuzzy sliding mode controller is implemented to control the position of the pneumatic cylinder. The sliding surface \( S \) is defined as:
\[
S = \dot{e} + \alpha e, \quad \alpha > 0 \]  
(4)

Differentiating above equation yields:
\[
\ddot{S} = \ddot{e} + \alpha \dot{e}
\]  
(5)

The triangular membership functions for the input \( S \), \( \dot{S} \) and output \( u_f \) were shown in Fig. 2 and the center-of-gravity method was used for defuzzification. The fuzzy control law \( u_f \) can be determined from the rule table which was shown in Table 1.

![Image](image-url)
Figure 3: Scheme of the servo pneumatic positioning control system.

Loading compensator
The actuation of pneumatic cylinder is obviously influenced by the vertical loading. Moreover, the states of the position control system cannot slide along the surface to track the specific time-varying state $\dot{y}$, and the position accuracy is decreased if the vertical loading cannot be compensated well. Therefore, the loading compensator is designed to decrease the effect of the vertical loading and improve the position accuracy. The loading compensator can be written as:

$$u_L = k \int (\dot{y}_L - \dot{y}) dt$$

where $k$ is the controller gain. Because the permissible speed of the linear scale is 40 mm/s, the specific time-varying state $\dot{y}_L$ should be lower than permissible speed of the linear scale and is defined as:

$$\begin{align*}
\dot{y}_L &= \alpha \cdot E_L \quad ; \quad \left| \dot{y}_L \right| > E_L \\
\dot{y}_L &= \alpha \cdot e \quad ; \quad \left| \dot{y}_L \right| \leq E_L
\end{align*}$$

(7)

In order to get better position accuracy, the maximum value of $|\dot{y}_L|$ is set to be 20 mm/s.

Dead-zone compensator
The position accuracy is decreased owing to the dead-zone of the control system. The dead-zone of the control system is caused by the friction force and the dead-zone of the servo valve. Therefore, the compensation signal $u_d$ is used to compensate the dead-zone of the control system.

$$u_d = \begin{cases} a & \text{if } e > 0 \\ -b & \text{if } e \leq 0 \end{cases}$$

(8)

Then combine the fuzzy sliding mode control law with compensators, the control law is redefined as:

$$u(t) = u_{act} - u_L - u_d$$

(9)

And the block diagram of the control system is shown in Fig. 3.

EXPERIMENTAL RESULTS
In this study, the sampling time is chosen to be 10 ms, the air supply pressure is set to be 5 bar. The piston diameter and the stroke of the pneumatic cylinder are 16mm and 50mm, and the load cylinder is the same size. The scaling factors of the fuzzy sliding mode controller are decided according to the experience and the reasonable mapping range into the membership function. In order to compare the experiment results between precision positioning and precision positioning with vertical loading, the various experimental results are shown below.

Step input
For nanometer step displacements, Fig. 4 shows the time response of the multi-step positioning control. The experimental results have shown that steady state errors are within $\pm 10 nm$.

Step input under constant load
Fig. 5 shows the time responses of the vertical positioning control under 4kgf upward loading force. In the experiment, the reference input is set to be 10mm and the steady state error is within $\pm 30nm$.

CONCLUSIONS
In this paper, the hybrid fuzzy sliding mode controller with loading compensator is applied to
control the vertical position of the pneumatic
cylinder successfully. From the experimental
results, one can make conclusions as follows:
(1) The positioning accuracy would be
decreased owing to the dead-zone of the
servo valve, friction force, and loading effect.
(2) From the experimental results, the vertical
positioning accuracy of the pneumatic
cylinder is within $\pm 30\text{mm}$, i.e. the control
performance with or without loading effect is
satisfactory.

Fig. 4: Time response of the multi-step
positioning control.

Fig. 5: Time responses of the vertical positioning
control under 4kgf upward loading force.

ACKNOWLEDGEMENTS
The support provided by National Science
Council of Taiwan (NSC 94-2212-E-006-033) is
greatly appreciated.

REFERENCES
1. S.R. Pandian, Y. Hayakawa, Y. Kanazawa, Y.
Kamoyama, and S. Kawamura, 1997,
Practical design of a sliding mode controller
for pneumatic actuators, Transactions of the
ASME, Journal of Dynamic Systems,
Measurement., and Control, v119, pp. 666–
674.
2. M.C. Shih and M.A. Ma, 1998, Position control
of a pneumatic rodless cylinder using sliding
mode M-D-PWM control the high speed
solenoid valves, JSME International Journal,
position control of a pneumatic cylinder driven
table, International Journal of JSME, Series C,
4. M.H. Chiang, C.C. Chen and T.N. Tsou, 2005,
Large stroke and high precision pneumatic-
piezoelectric hybrid positioning control using
adaptive discrete variable structure control,
Mechatronics, v 15, n 5, June, p 523-545.