Position Control of a Pneumatic Rodless Cylinder Using Sliding Mode M-D-PWM Control the High Speed Solenoid Valves*

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The purpose of the paper is to apply 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 experimental results show that the pneumatic system has the advantages both good performance and low cost with the proposed controller.

Key Words: Sliding Mode PWM Control, Position Control

1. 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⁽¹⁾. Conventionally, a linearized mathematical model for the analysis and design of a pneumatic servo control system must be built up and, then, the modern control theory can be applied to design a suitable controller. In fact, the pneumatic system is a nonlinear and time variant system because of the compressibility of air, the friction force between the piston and the cylinder, the air mass flow rate through the servo valve, etc. The sliding mode control method is used widely to solve an imprecision problem⁽²⁾. Due to the external disturbance and the system uncertainties, the chattering phenomenon often happens in the application of sliding mode control system. To avoid the disadvantage, a sliding mode boundary control is introduced. Instead of using a servo valve, two cheap high speed solenoid valves are applied in the system. Noritsugu has used the

PWM method and a solenoid valve to control the velocity and the position of a pneumatic cylinder^{(3),(4)}; Yang, Wang and Lin⁽⁵⁾ have studied the characteristics of the PWM control with high-speed on/off valves; besides, Muto has used differential PWM method to control a hydraulic actuator⁽⁶⁾. In the paper, a sliding mode modified differential PWM (M-D-PWM) controller is designed and implemented in a microcomputer to control the position of a pneumatic rodless cylinder.

2. Layout of the Experimental Devices

The layout of the experimental devices for the pneumatic rodless cylinder position control system is shown in Fig. 1. An IBM 32 bit compatible microcomputer acts as a controller and is used for the experimental data acquisition. The displacement of the cylinder is measured by a pulse scale, the air pressures are also measured and fed back to the computer. The calculated control signal can be changed into pulse width modulated signal through the designed software in the microcomputer, then the on/off output signals control the solid state relay (SSR) and drive the high speed solenoid valves # 1 and # 2, which frequency is 100 Hz and was made by the company MAC, U. S. A., so that the air mass flow rate can be regulated and the pressure difference of the cylinder can be built up to

* Received 6th January, 1997

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Fig. 1 Layout of the experimental devices

drive the cylinder.

3. Sliding Mode M-D-PWM Controller Design

3.1 Principle of the PWM control method

The pulse width modulated signal can be produced by using a comparator to modulate the high frequency carrier wave to the desired modulated wave, as Fig. 2 described. The carrier wave is a periodical tooth wave, the modulated wave is also a periodical wave and has the same period T_c of the carrier wave. And, the duty ratio τ (or pulse width ratio) is defined as the ratio of the time of the switching state "on" to that of the period T_c . The higher the frequency of the carrier wave, the better the modulated wave. Generally, both the frequency and the amplitude of the carrier wave can not be smaller than those of the modulated wave⁽⁷⁾. Figure 3 shows that the pneumatic rodless cylinder is controlled by two normal closed solenoid valves. After switching the valves #1 and #2 according to the preset values of the duty ratio, the air flow rate through the valves can be regulated and the position of the cylinder can be controlled. If the desired motion of the cylinder is leftward, then the difference of the duty ratio should be larger than zero, i.e. $\Delta\tau = \tau_1 - \tau_2$, it could be $\tau_1 > 0$, $\tau_2 = 0$; similarly, if the desired motion of the cylinder is rightward, then the PWM control signal should have negative duty ratio, $\Delta\tau < 0$; it could also be $\tau_1 = 0$, $\tau_2 > 0$; one can let valve 1 closed and valve 2 open. After the pressure difference of the two chambers of the cylinder is built up due to the duty ratio difference

Fig. 2 Scheme of a pneumatic rodless cylinder PWM servo control system

Fig. 3 The actual motion of the solenoid valve

control, the cylinder can be controlled to make left- or rightward motion.

3.2 Modified differential PWM (M-D-PWM) method

For the PWM control, the on/off switching actions are operated instantly, but, the actual motion

of the solenoid valves are delayed and even only half-opening due to the magnetic hysteresis and the mechanical motion of the spool valve. For the pneumatic cylinder control, the dead zone will happen due to the above stated reason, as Fig. 3 shows. The time t_n is equal to the summation of t_1 and t_2 , t_1 is the required time of the electromagnetic response and t_2 is the required time of the motion of the pneumatic spool valve. And, the time t_f can be divided into the time of the magnetic action t_3 and the closing time of the spool valve t_4 . To avoid the above nonlinear characteristics, one can find the suitable switching time of the solenoid valve or the duty ratio to compensate it. From the literature, Muto⁽⁶⁾ has developed a D-PWM (differential PWM) method to modify it. In the paper, a M-D-PWM (modified differential PWM) is applied⁽⁸⁾ to improve the nonlinearity in the neighborhood of the original point. Figure 4 shows the switching diagram of the D-PWM and the M-D-PWM method. For the D-PWM control law, if the modified time t_p is equal to zero, then the duty ratio difference $\Delta\tau$ is equal to zero. If the switching time S_1 is the summation of T_{on} and t_p , $t_p > 0$, and S_2 is the difference of $T_{on} - t_p$, then the difference of the duty ratio

difference $\Delta\tau$ is larger than zero. But, the nonlinearity characteristic will happen due to D-PWM control law for the larger value of $\Delta\tau$. By using M-D-PWM control law, to achieve the on/off switching operation completely, one must find the suitable time t_n and t_f ; the time t_n must be larger than the switching time from the state "off" to "on"; and the value of t_f must be larger than the switching time from the state "on" to "off." And, the valves # 1 and # 2 must be switched to the state "on" at the end of every period simultaneously. Therefore, the operation time of the state "on" and the period T_c must satisfy the following condition

$$t_n \leq T_{on} \leq (T_c - t_f) \quad (1)$$

Therefore, one can insure that the "on/off" switching operation of the valves # 1 and # 2 can be executed completely. And $\Delta\tau$ is defined as the equation (2)

$$\Delta\tau = \tau_1 - \tau_2 = \left[\frac{T_{on}/\text{valve}\#1 - t_n}{T_c - t_n - t_f} - \frac{T_{on}/\text{valve}\#2 - t_n}{T_c - t_n - t_f} \right] \times 100\% \quad (2)$$

In Fig. 4 II-(a) and (b), one can see the switching operation for the duty ratio $\Delta\tau > 0$ and $\Delta\tau < 0$, with M-D-PWM control, respectively.

Fig. 4 Scheme of the D-PWM and the M-D-PWM control

3.3 Realization of M-D-PWM with software

Generally, the PWM control signal can be realized with hardware or software. The later can be realized by microcomputer and 8254 counter and the interruption process. To find the linear relationship between the control signal and the duty ratio, a tooth wave signal is chosen as the carrier wave. If the periods of the sampling and the carrier wave are the same, then the control signal $u(k)$ can be changed to be the pulse width and control the opening time of the high speed solenoid valve. Assuming the maximum value of the control signal $u_{\max}$, which is also the maximum amplitude of the carrier wave, the following equations can be derived from Fig. 5.

$$k_t = \frac{u_{\max}}{T_c} \quad (3)$$

$$T_{on}(k) = \frac{1}{k_t} u(k) \quad (4)$$

$$\tau(k) = \frac{T_{on}(k)}{T_c} \quad (5)$$

To compensate the delay time of the solenoid valve, the time t_n and t_f must be reduced from the period T_c . Figure 6 has shown the time compensated PWM signal, which relations are as follows:

$$k'_t = \frac{u_{\max}}{T_c - t_n - t_f} \quad (6)$$

$$T_{on}(k) = \frac{1}{k'_t} u(k) + t_n \quad (7)$$

$$\tau(k) = \frac{T_{on}(k) - t_n}{T_c - t_n - t_f} \quad (8)$$

Owing to different on/off delayed time of different valves, one can use valve #1 as the base

Fig. 5 Scheme of the signal with PWM control software

Fig. 6 Scheme of the signal with the time compensated M-D-PWM control software

valve, so that the opening time of the valve #1 and valve #2 can be modified as

$$\begin{cases} t_{1n} = T_{on}|_{valve\#1} \\ t_{2n} = T_{on}|_{valve\#2} + \Delta t \end{cases} \quad (9)$$

where Δt is the compensated time of the valve #2.

3.4 Sliding mode M-D-PWM controller design

If the pneumatic control system is assumed to be a second order nonlinear system, x_1 , x_2 are the state variables, y is the system output, u is the control signal, d is the disturbance signal and f is the system dynamic function, then

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f + u + d \\ y = x_1 \end{cases} \quad (10)$$

where $f = \hat{f} + \Delta f$, $\hat{f}$ is the evaluated system dynamic function and Δf is the difference between f and $\hat{f}$. If r is a step input, and the error signal e is also defined as $e_1 = r - y$, then

$$\begin{cases} \dot{e}_1 = e_2 \\ \dot{e}_2 = -f - u - d \end{cases} \quad (11)$$

where $e_1 = e$ and $e_2 = \dot{e}_1 = \dot{e}$

And the sliding hyperplane is

$$s = \left(\frac{d}{dt} + \lambda \right) e = \dot{e} + \lambda e = 0 \quad (12)$$

where λ is the weighting factor.

The scheme of the phase e vs. $\dot{e}$ with sliding mode control is shown in Fig. 7

The design procedure of the sliding mode M-D-PWM controller is as follows:

(1) Choice of the parameter λ

According to the Ref. (9), the value of the parameter is less than one fourth of the sampling frequency, therefore $\lambda < (2\pi \times 50)/4 = 78.5$. The value λ is chosen to be 10 according to the experiment.

(2) Choice of the type of the controller

There are three different controller type for the sliding mode control, i.e. relay type, state variable feed back type and equivalent control type. Figure 7 shows that the phase plane of e and $\dot{e}$, the control signal $u = u_{eq} + \Delta u^{(10)}$ can make the system trajectory along the sliding hyperplane by using "on-off" control and reached the original point. The control signal can be

$$u(t) = k_p e(t) + k_d \dot{e}(t) \times \text{sgn}(s) \quad (13)$$

Fig. 7 Scheme of the phase plane with sliding mode control

(3) Choice of the boundary layer

In order to reduce the chattering phenomenon, a suitable boundary layer is introduced for the control signal. The control signal can be

Fig. 8 Block diagram of a sliding mode M-D-PWM control system

Fig. 9 Time response of the position control of cylinder with square wave input under sliding mode M-D-PWM control

$$u(t) = k_p e(t) + k_d \dot{e}(t) + \text{sat}\left(\frac{s}{\phi}\right) \quad (14)$$

But, a boundary layer is a saturated function, the on-off operation in the boundary is still not very smooth, therefore the control signal is modified as

$$u(t) = k_p e(t) + k_d \dot{e}(t) + k \times \tanh\left(\frac{s}{\phi}\right) \quad (15)$$

(4) Combination of sliding mode and M-D-PWM
The block diagram of the sliding mode M-D-PWM control the pneumatic cylinder as shown in Fig. 8

4. Experimental Results

In the following experimental results, the system pressure is set to be 5 bar, the sampling time is chosen to be the same as the period of the pulse width modulated signal 20 ms, shown in Fig. 9(a). Figure 9(b) shows the time response of the control input signal; Fig. 9(c) shows the response of the error signal. The phase plane of $\dot{e}$ vs. e is shown in Fig. 9(d), and the hyperplane is also shown in Fig. 9(d).

Fig. 10 Time response of the position control of cylinder with load change

Fig. 11 Experimental results of the reliability test of sliding mode M-D-PWM control

a. Square wave position control without load

Figure 9 shows the time response of the position of the pneumatic rodless cylinder. The command signal is a square wave type. The steady state error is 0.005 mm.

b. Step input signal with load change

The time response of the position of the cylinder with load change is shown in Fig. 10, where at the time instant 2.5 sec the load pressure is changed to be 0.5 bar. The steady state error is increased to be 0.01 mm under the loading effect.

c. Reliability of the control performance

Owing to the experimental condition, the results may be different. In the study, the experiments have been done 50 times, and the distribution diagram of the steady state errors is shown in Fig. 11, which indicates that the reliability and accuracy of the control system with such a controller is very good.

5. Conclusions

Through the above experimental study, one can make the short conclusions in the following:

1. Using the sliding mode PWM controller, one can get the precision under 0.01 mm.
2. The designed controller is verified by using the software, instead of using the external electric circuit for the PWM controller. It's flexible to design and

easy to maintain.

Acknowledgment

The support provided by National Science Committee of R. O. C. (NSC 85-2212-E 006-006) is greatly appreciated.

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