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RESEARCH ON STABILITY AND MINIMUM ORIFICE AREA OF HYDRAULIC SERVO POSITION CONTROL SYSTEM*

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Abstract: This paper reports results of research on the stability of a hydraulic servo position system using generalization pulse code modulation (GPCM) and common on/off valves for hydraulic servo control. The describing function was first used to analyze the system's stability, and based on the nonlinear theory, an equation calculating the minimum orifice area of GPCM valves was derived by applying results of analysis on the stability of the GPCM control system. In the end, aimed at developing a hydraulic servo position system to be used in a paint robot, simulation and experiment were carried out. The results show that the theoretical conclusions accorded with practical results.

Key words: stability, orifice area, nonlinear, hydraulic servo position control system, GPCM
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INTRODUCTION

The servo system presented here can control accuracy using cheap on/off valves by pulse code modulation technology. The on/off valve has simple structure and is insensitive to oil pollution. The hydraulic servo system with pulse code modulation using on/off valves is a cheap scheme and can satisfy many purposes. But the system minimal and maximal flow rates are defined by the quality of valves. So there is contradiction between the speed regulation range and control precision. The generalization pulse code modulation control strategy may overcome the contradiction. The basic principle of GPCM control is similar to that of PCM control.

Their difference is in the pulse code modulation method. The main idea of GPCM control is maintaining valves minimum opening S_0 determining by control precision and set the a series of valves opening area with special coding manner to increase maximum orifice area (Wang, 2000; Liu, 2001). This paper reports results of research on its stability and on determination of the minimum orifice area.

1. Stability analysis of the system

If the load of a hydraulic servo cylinder is small, its inherent frequency is high. But the frequency of as the GPCM system's input is low, the valve-controlling cylinder can be simplified as (Li, 1986)

$$\frac{Y(S)}{U_c} = \frac{k_q/A}{S} \tag{1}$$

Where, k_q, flow gain of on-off valves (m^3/s); S_0, the area of valve with minimum effective cross section; U_c, pulse code modulation output signal; A, action area of cylinder piston;

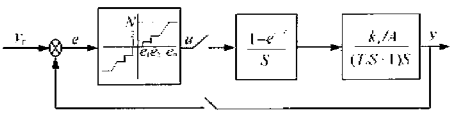

Fig.1　Block diagram of GPCM control system

The block diagram of GPCM control system is shown in Fig.1. Because the solenoid has

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hysteresis characteristic and common solenoid valve switching on/off time is long, the effects of valve delay can not be ignored. Regarding the solenoid valve as a first order link, its transfer function is $\frac{1}{T_v S + 1}$, and T_v is time constant.

Fig. 1 shows that the GPCM controller is a multi-step Bang-Bang controller, so the system is a multi-step Bang-Bang and nonlinear control system.

The describing function is one of the means for nonlinear system analysis. It is assumed that the only the fundamental harmonic component of the output is significant. Since the system has the characteristics of low-pass filters, compared with the fundamental harmonic component, the higher harmonics are very attenuated (Wu, 1992). Therefore, the assumption is valid for GPCM control system.

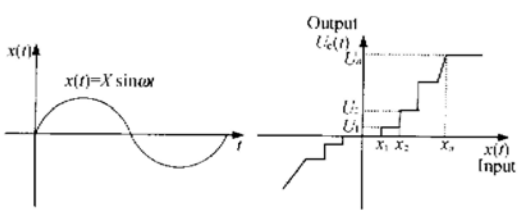

Fig.2 GPCM nonlinearity and the input-output relationship

Consider the sinusoidal input $x(t) = X \sin\omega t$ to the GPCM controller. From the input-output relationship shown in Fig. 2, the output function $U_c(t)$ is symmetric over the four quarters of a period. In the first quarter, it can be expressed as:

$$g(t) = \begin{cases} 0, 0 < \omega t \le \alpha_1; \\ U_1, \alpha_1 < \omega t \le \alpha_2; \\ \vdots \\ U_j, \alpha_j < \omega t \le \alpha_{j+1}; \\ \vdots \\ U_n, \alpha_n < \omega t \le \pi/2 \end{cases} \quad (2)$$

where $\alpha_j = \sin^{-1}(x_j/X)$.

According to the definition of the describing function, the GPCM controller's describing function is given by:

$$N(X) = \begin{cases} 0, 0 < X < x_1; \\ \frac{4}{\pi X}\left[\sum_{i=1}^{j}(U_i - U_{i-1})\sqrt{1-(x_i/X)^2}\right], \\ \quad x_{j-1} < X < x_j; \\ \frac{4}{\pi X}\left[\sum_{i=1}^{n}(U_i - U_{i-1})\sqrt{1-(x_i/X)^2}\right], \\ \quad x_n < X. \end{cases} \quad (3)$$

Using the describing function to replace the nonlinear GPCM component, the characteristic equation of the feedback control system shown in Fig. 1 is

$$1 + N(X)G(j\omega) = 0 \quad (4)$$

From the Eq. (3) the describing function $N(X)$ can be considered as a varying real magnification chain. Its amplifying coefficient relates to input signal amplitude. When the $n \to \infty$, $N(X)$ tend to a constant. On the condition that there are many flow rate steps, the $N(X)$ varying range is narrow and can be considered to a proportional constant.

Making use of describing function, we analyze the GPCM control system and draw the conclusion: that the GPCM controller is similar to the varying gain proportional controller, and that the gain coefficient increases with the input signal; has no essential influence on the system stability, and just influences the transient state (Liu, 2001).

2. Determination of minimum orifice area of GPCM valve

Before using the GPCM control system, the orifice areas of the GPCM switching valves must be determined. The GPCM valve flow rate is also decided by valves operation pressure and opening areas. The minimum control flow rate determines the stability and control precision of the system, and the maximum opening area determines the drive speed. Usually the maximum flow rate can be directly quantified from the maximum speed. But the minimum control flow rate is influenced by several factors, such as control precision and sampling period. So how to obtain an appropriate minimum orifice area is a key problem in the use of GPCM control. Following decreasing error, the controller outputs reduce. Because there is a minimum flow rate corresponding to minimum cylinder piston's moving speed, the position system has an error threshold. The minimum flow affects the position precision, so error limit is a dominant factor determining the minimum opening area of the GPCM valve.

The position precision and stability depend on the lowest piston speed determined by the minimum flow rate. Therefore we just take into account the situation when the system runs at in the minimum flow rate, and the system can be regarded as a single step Bang-Bang system. The Bang-Bang actuator has hard nonlinearity, so the feedback control system will encounter a limit cycle that tends to cause poor position accuracy and stability, because the limit cycle results in constant oscillation. Therefore, a deadband is used to avoid the problem of the limit cycle. The dead zone inevitably brings about steady-state position error, so the deadband is set according to position accuracy. The reduced block diagram of the system is shown in Fig.3. Here, ε is the maximum permissible error, and T is sampling period of the digital control system. When the position error is less than , the GPCM controller outputs zero and the cylinder stop moving.

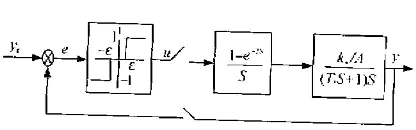

Fig.3 Block diagram of the reduced system

For the nonlinear system, it is difficult to obtain a analytic answer, so the phase portrait is used to analyze qualitatively nonlinear system. The dead zone can be described as:

$$u = 1, e > \varepsilon; \quad u = -1, e < -\varepsilon; \quad u = 0, |e| < \varepsilon. \tag{5}$$

The phase portrait for the system is given in Fig.4 divided into three parts by two switching lines. All points in c-c' line in area III are singular point. According to the phase portrait shown in Fig. 4a, the system will stop at a certain point in c-c' after it started from any point. But the system response lags behind input, so the phase portrait changes. Besides the hysteresis, there is sampling time influence. During a period the controller output is invariable, so when the system enter the deadband the output may not equal zero and the system maintains movement status. If the sampling period is too long, the system will jump over the dead zone from area I to area II. This exerts heavy influence on the stability and will induce a limit cycle. Therefore, the control accuracy and stability of the GPCM system relate to the deadband, position accuracy range, velocity decided by flow rate, hysteresis, and sampling frequency. Theoretical study on minimum orifice area is conducted on the basis the phase portrait.

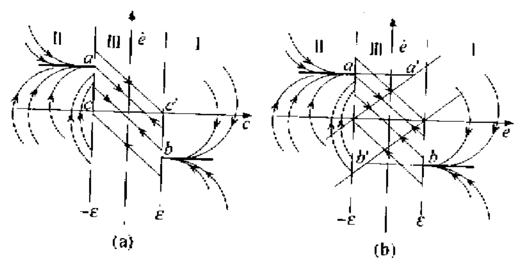

Fig.4 The system phase portrait
(a) The phase portrait; (b) The phase portrait to reflect the system's stability

For simplifying the deductive procedure, the first order inertial link is regarded as pure delay, and delay time is T_s. It is feasible because the time constant is small. When the system operates near the setpoint, the GPCM controller output is ± 1 and the running speed of piston is the minimum. Here the velocity is

$$V = V_{min} = \frac{k_q}{A} \tag{6}$$

From the phase portrait in Fig.4b, we can obtain a necessary condition for stability, which is that there be a sampling point during deadband when trajectories move from zone I to zone II or from II to I. Obviously, if this condition is not satisfied the system will constantly oscillate between area I and II. So we draw the conclusion:

$$V_{min} T < 2\varepsilon \tag{7}$$

It is supposed that there is a switching signal at the time when the trajectories of the system drop into the dead area in the phase plane. The switching will lag the output signal due to the response delay of time T_s. The displacement of the piston in the course of switching is $V_{min} T_s$. As the system will ultimately stop in the deadband to the avoid limit cycle, the essential condition for stability is

$$V_{min} T_s < \varepsilon \quad (8)$$

The sampling period of the system is must larger than the valve switch on/off time. Otherwise the valve can not work normally. Here the period is determined to be equal to twice the switching time T_s. Regarding the condition $T = 2T_s$, from the above two inequalities we derive a formula:

$$V_{min} T_s < \varepsilon$$

Because and $V_{min} = \frac{k_q}{A}$ and $k_q = C_d S_0 \sqrt{\frac{2P}{\rho}}$, the formula changes to

$$C_d S_0 T_s \sqrt{\frac{2P}{\rho}} \Big/ A < \varepsilon \quad (9)$$

So we draw the conclusion that the minimum orifice area should satisfy:

$$S_0 < \frac{A\varepsilon}{C_d T_s \sqrt{\frac{2P}{\rho}}} \quad (10)$$

3. Simulation

In order to verify the formula for minimum orifice, we use MATLAB SMULINK to simulate the system working state. According to the experimental system, the simulation parameters are set as:

$A = 8.76 \times 10^{-4} m^2$, $\varepsilon = 0.1 mm$, $C_d = 0.65$, $T_s = 50 ms$, $P = 7 MPa$, $\rho = 883 kg/m^3$

Substituting these parameters into inequality Eq.(7), yields get to $S_0 < 2.14 \times 10^{-3} mm$, For $S_0 = 2 \times 10^{-3} mm$, the simulation result is shown in Fig.5. The results indicated that the GPCM control system can satisfy the requirement of permission error if its minimum opening area complies with the inequality Eq.(10). On condition that control precision ε is unvaried and valve opening S_0 becomes larger, the limit cycle appeared and the system turned to unstable (Figs.5a 5b and

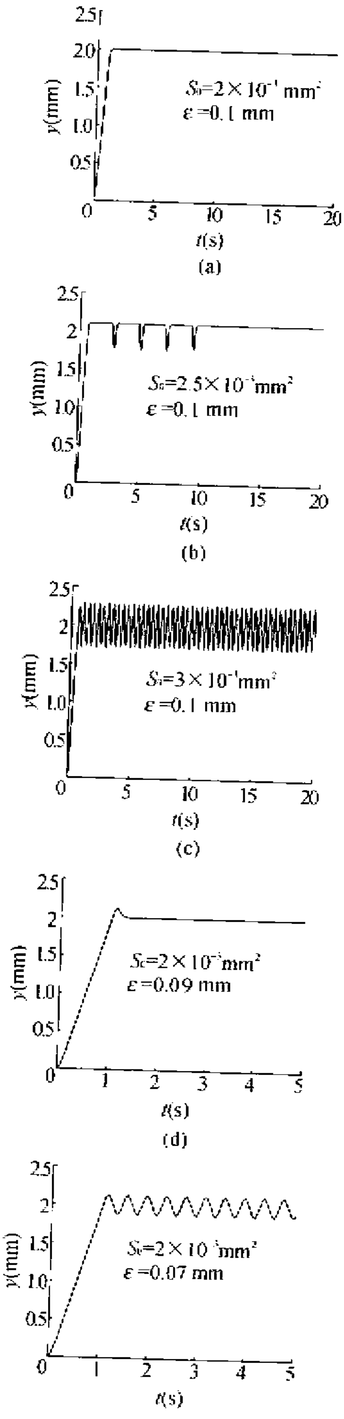

Fig.5 Simulation results of the step responses
(a) $S_0 = 2.0 \times 10^{-3} mm^2$, $\varepsilon = 0.1$ mm;
(b) $S_0 = 2.5 \times 10^{-3} mm^2$, $\varepsilon = 0.1$ mm;
(c) $S_0 = 3.0 \times 10^{-3} mm^2$, $\varepsilon = 0.1$ mm;
(d) $S_0 = 2.0 \times 10^{-3} mm^2$, $\varepsilon = 0.09$ mm;
(e) $S_0 = 2.0 \times 10^{-3} mm^2$, $\varepsilon = 0.07$ mm

5c). On the other hand, unvaried opening area S_0 and reduction of the maximum permission error ε affect the instability of the system and brings about the limit cycle. All these indicate Eq.(10) is suitable for determining the minimum orifice area of the GPCM valve. Furthermore, the control accuracy is changed depending on it.

EXPERIMENTAL DETAILS

The experimental device is a paint robot. Because it is a light load system, we set the system pressure as 2 MPa and change the dead zone ε from 1 to 0.7 mm during the experiment. The other parameters are same as the simulation parameter.

A series of the system experiment curves of the step responses are shown in Fig.6. Following the deadband decrease, the adjustment time to stable state increases. This accords with theoretical research results. The actual position precision is up to 0.2 – 0.3 mm.

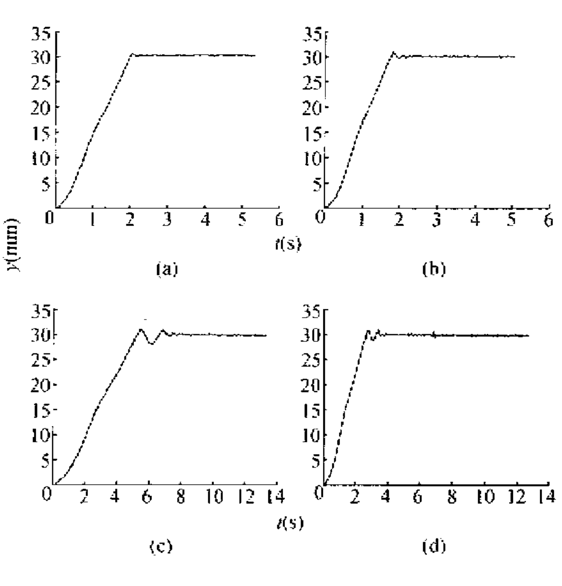

Fig.6 Experimental results of the step responses
(a) $\varepsilon = 1.0$ mm (b) $\varepsilon = 0.9$ mm
(c) $\varepsilon = 0.8$ mm (d) $\varepsilon = 0.7$ mm

CONCLUSIONS

The stability of the GPCM control system was studied on the basis of nonlinearity theory and obtain a method for deciding the minimum opening area of the GPCM valve. The simulation and experimental results showed that the GPCM control is feasible and satisfy stability and control accuracy requirements.

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