An Improved Digital PID Algorithm for Angle Position Electric-hydraulic Servo System

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Abstract

PID control algorithm is widely used in servo control system. Because of the non-symmetrical structure of the hydraulic cylinders in the angle position electric-hydraulic servo system of plant converter, the conventional PID control has low control precision and bad flexibility. To solve the problem, an improved digital PID control algorithm with variable sampling periods is proposed. Based on the analysis of the system control principle, the system transfer function is built, and the system response curves are simulated with Matlab. The result indicates that the improved digital PID algorithm with variable sampling periods can reduce the response time, and decrease the overshoot of the system at the same time. In the application, it is proved with the improved digital PID control algorithm, the overshoot, the rise time and the settling time meet the requirements for the angle position control system.

Keywords: Digital PID Algorithm, Electric-hydraulic Servo System, Angle Position Control

1. Introduction

Angle position servo system is widely used in high-speed, heavy-duty, high-precision automation equipments, such as steel-making facilities, iron facilities, rolling equipment, hydroelectric facilities, large-scale high-precision valve control and a variety of high-power electromechanical integration products. PID (proportional-integral-derivative) control is one of the developed strategies for control system. Because of its simple implement, robustness, reliability, PID control still occupies an important position in hydraulic servo control systems.

Digital PID control is the PID control in which the input-output signal is digital signal. With the development of computer technology and microelectronics technology, digital PID control gradually become the main PID control method in the automatic control field [1-2]. In this field there are many research papers in recent years. Dou Xiumin etc. designed a precise digital control system to improve the performance of the Fourier transform spectrometer [3]. Song Xiaoyan etc. presented a compound digital control system combining the conventional PID control and the fuzzy control to improve the performance of the PID controller [4]. Chang Pyung Hun and Jung Je Hyung proposed a systematic method to select gains of a discrete PID controller to robustly control nonlinear MIMO plants in a second-order controller canonical form [5]. Truong Dinh Quang etc. studied the structure, the parameters setting and the combined strategy of PID controller with fuzzy method, particle swarm and evolutionary algorithm [6-12]. From the searched papers, the research is mainly concentrated on the combination of PID control method and fuzzy theory, genetic algorithm and immune evolutionary algorithm to intelligently determine the PID control parameters. However, in the angle position servo system, the adjustment of the PID parameters is realized by the adjustment of the control signals and the non-symmetrical hydraulic cylinders control signals. If the PID control parameters are inputted using the above method, the system will have large overshoot or long settling time, which will cause the great shock or poor stability for working process.

In this paper, the angle position servo system of plant converter is studied. According to the control principle of the angle position servo system, an improved digital PID algorithm based on variable sampling periods is proposed. Compared with the conventional digital PID control, the improved digital PID control has a better stability and flexibility for the angle position servo system.

The structure of this paper is organized as follows. Section 2 introduces the control principle of the angle position servo system and establishes the signal transfer function. Section 3 analyzes the
conventional digital PID control algorithm and discusses its limitation in the angle position servo system. Section 4 presents the improved algorithm and its simulation. Section 5 contains the application of the improved PID control algorithm. Section 6 is devoted to the conclusions.

2. The control principle of angle position electric-hydraulic servo system

Plant converter is the key equipment in steel industry. Figure 1 shows the control principle of angle position electric-hydraulic servo system in some plant converter. The hydraulic oil source is composed of the hydraulic pumps, relief valves, unloading valves and precision filters. The hydraulic pump is used of dual-pump which is driven by the motor. The oil is pressured by the dual-pump and goes through the filter to the servo valve. The system pressure is set by the relief valve and instructed by the pressure gauge. When the system pressure reaches to the pressure controlled by the unloading valve, the unloading valve connects the manifold to unload pressure. The oil from the first pump of the dual-pump goes back to the tank when its pressure overcomes the atmospheric pressure. If the system pressure drops quickly, the unloading valve is closed, and the first pump of the dual-pump offers oil to the system automatically. The electro-hydraulic servo valve controls the action of the hydraulic cylinder according to the control signal. A pair of check valve is adopted at the output port of the servo valve, which is used to prevent system malfunction when the unexpected loss of system pressure. In this case, the check valves close the import and export of oil line to lock the hydraulic cylinder piston, and then the output shaft will be fixed.

1-Motor, 2-Tank, 3-Dual-pump, 4-Check valve, 5-Unloading valve, 6-Relief valve, 7-Pressure Gauge, 8-Precision filter, 9-Electrohydraulic servo valve, 10-Pilot-controlled type valve, 11-Hydraulic cylinder, 12-Storage capacitor, 13-Cut-off valve, 14-Change valve, 15-Pilot-controlled change valve, 16-Hand-operated direction valve, 17-Manual pump

Figure 1. The control principle of angle position servo system

When considering only the flow characteristics, the two hydraulic cylinders can be equivalent to a symmetric cylinder. Assume that the input signal is the servo valve displacement $x_v$, the output signal is the hydraulic cylinder displacement $x_p$. Under normal circumstances, the
flow compressibility and hydraulic cylinder leakage must be taken into account, and the elastic load can be ignored because it is very small. The resultant transfer function is as follows:

\[
x_p = \frac{\frac{K_q}{A_c} - \frac{K_{ce}}{A_c^2} \left( \frac{V_p}{4\beta K_{ce}} s + 1 \right)}{s^2 + \frac{2\beta}{\omega_h} s + 1} F_L
\]

(1)

\[
\omega_h = \sqrt{\frac{4\beta A_c^2}{V_m}}
\]

(2)

\[
\xi_h = \frac{K_{ce}}{A_c} \sqrt{\frac{\beta m_v}{V_i} + \frac{B_p}{4A} \sqrt{\frac{V_i}{\beta m_i}}}, \quad K_{ce} = K_c + C_{ip}
\]

(3)

\[
m_t = 2m_p + m_{eo} + m_{od} \left( \frac{A_c}{a} \right)^2 + m_v, \quad m_{od} = \rho La
\]

(4)

where \( \omega_h \) is the free-running frequency, \( \xi_h \) is the damping coefficient, \( A_c \) is the effective area of hydraulic cylinder, \( \beta_c \) is the elastic modulus, \( K_c \) is the flow-pressure coefficient of servo valve, \( C_{ip} \) is the leak coefficient, \( K_{ce} \) is the total pressure-flow coefficient, \( m_t \) is the total mass of the conversion from the load, \( m_p \) is the mass of the piston and piston rod, \( m_{eo} \) is the oil mass in oil control cavity, \( m_{od} \) is the mass of the oil pipeline, \( m_v \) is the mass of the mechanical linkage, \( \rho \) is the oil density, \( L \) is the pipe length from servo valves to control oil chamber, and \( a \) is the overflow area.

Assumed the angular displacement is \( \phi \), the radius of shaft movement is \( R \). When the shaft angle range is small, the cylinder displacement can approximately be linear with the shaft angle, and the relationship between the hydraulic cylinder displacement and the shaft angle can be described as:

\[
\frac{\phi}{x_p} = \frac{1}{R}
\]

(5)

### 3. The conventional digital PID control algorithm

The PID algorithm includes proportional part (P), integral part (I), and differential part (D). In conventional PID control algorithm, the input signal is continuous in the timeline and the general expression is as follows:

\[
u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int_0^t e(t) dt + \frac{T_d}{T_i} \frac{de(t)}{dt} \right]
\]

(6)

where \( u(t) \) is the output signal, \( e(t) \) is the bias signal, \( K_p \) is proportional coefficient, \( T_i \) is integral time constant, and \( T_d \) is differential time constant.

Assumed the discrete sampling period is \( T_s \), (6) can be discretized as follows:
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\[
\begin{align*}
    u(k) &= K_p e(k) + K_i \sum_{j=0}^{k} e(j) + K_D \left[ e(k) - e(k-1) \right] \\
    K_i &= K_p T / T_I, \quad K_D = K_p T_D / T
\end{align*}
\]

where \( k \) is the sample number, \( u(k) \) is the output digital value in the \( k \) sampling time, \( e(k) \) is the input bias value in the \( k \) sampling time, \( K_p \) is the proportional coefficient, \( K_i \) is the integral coefficient, and \( K_D \) is the differential coefficient.

From (7) and (8), it can be seen the proportional coefficient \( K_p \), the integral coefficient \( K_i \), and the differential coefficient \( K_D \) are the main parameters in digital PID algorithm. Many approaches can be used to adjust the three parameters, such as fuzzy theory, genetic algorithm and immune evolutionary algorithm, which are researched in many papers. Based on the electrical signals given by the PID control algorithm, the system changes the flow to control the location of hydraulic cylinder according to the servo valve spool position, and then drives the institutions to convert the cylinder displacement to the angular position. However, in the angle position of the servo system, the angular displacement often changes in a wide range at startup with these approaches. This is because the two hydraulic cylinders in Figure 1 are actually non-symmetrical hydraulic cylinders. When the external load changes, the adjustment of \( K_i \) and \( K_D \) will amplify the hydraulic cylinder displacement \( x_p \). In this case, the angle position \( \phi \) will change unsteadily.

4. The improved digital PID control algorithm

From Section 3, it is known the angle position servo system is a nonlinear time-varying system. In order to obtain satisfactory control performance, we proposed an improved digital algorithm where \( K_p \) varies with the sampling period \( T_s \), as (9) shows.

\[
    K_p = \sum_{i} K_{pi} / T_{si}, \quad i = 1, 2, 3, 
\]

To decrease the influence of the adjustment of \( K_i \) and \( K_D \), the integral part and the differential part are ignored at startup when the angle position servo system works. Then (7) can be simplified as (10).

\[
    u(k) = \sum_{i} K_{pi} / T_{si} e(k), \quad i = 1, 2, 3, 
\]

To analyze the results of the proposed PID algorithm, the SIMULINK module in MATLAB software is used to build the angle position servo system model described by (1)–(10), and the selected input signal is step signal. In the simulation with the conventional PID control, the proportional coefficient \( K_p \) is 2000, the integral time constant \( T_I \) is 0.5, the differential time constant \( T_D \) is 0.25. In the simulation with the improved PID control, the resampling times \( i \) is 3, the variable sampling periods \( T_s \) are respectively selected as 5ms, 1ms and 0.5ms. The response simulation curves are shown in Figure 2.
Table 1. The results under variable sampling periods

<table>
<thead>
<tr>
<th>Sampling period (ms)</th>
<th>Overshoot (%)</th>
<th>Rise time (s)</th>
<th>Settling time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 0.65</td>
<td>6.32</td>
<td>11.26</td>
<td></td>
</tr>
<tr>
<td>1 1.34</td>
<td>5.94</td>
<td>10.03</td>
<td></td>
</tr>
<tr>
<td>0.5 3.84</td>
<td>5.02</td>
<td>10.21</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 shows the overshoot, the rise time and the settling time of the three curves in Figure 2. According to the requirement of the plant converter control process, the rise time should be no more than 7 s. From Table 1, then the maximum sampling period is 5 ms. With the reduction of the sampling period, the system overshoot is increased, the rise time is reduced, and the stable time firstly decreases and then increases. This indicates we can improve the system sampling frequency to reduce the system rise time, which means the system response faster and more sensitive. However, the improvement of the system's sampling frequency also increases the adjustment time. Meanwhile, the high sampling frequency will extend the stability time of the system and make the system tend to be unstable. Therefore, the minimum sampling period is selected as 0.5 ms in this system.

Figure 3 is the simulation result with the conventional digital PID control, in which the system overshoot is 5%, the rise time is 1.2 s and the settling time is 13.4 s. Figure 4 is the simulation result with the improved digital PID control, in which the system overshoot is 3.5%, the rise time is 0.7 s and the settling time is 3.9 s. Obviously all the overshoot, the rise time and the settling time with the improved digital PID control are less than those with the conventional digital PID control. This indicates the system has better stability and the flexibility under the improved digital PID control with variable sampling periods.
5. Application

In order to study the actual effects of the proposed digital PID algorithm, we designed an angle position servo system of plant converter, as Figure 5 shows. The improved digital PID control algorithm is developed by Visual C++ and loaded in the embedded computer. The hardware of the embedded computer is ARM9, and the operating system is Windows CE. The PID control parameters can be adjusted in the software interface of the embedded computer. After the PID control parameters are set up and the “Begin” button is pressed, the step signal is sent to the angle position servo system as input current, and the system output current is sampled at the same time. The angle position indicator is rotated around the axis to indicate the system angle.
Figure 5. The angle position servo system

Figure 6 and Figure 7 show the input and the output curves using the conventional algorithm and the improved PID control algorithm in the embedded computer controller. It is tested that when the input current is 10 mA, the responding time is 10s with the conventional PID control. While in the same condition, it is 6s with the improved PID control. This indicates the system can respond to the control commands more quickly. On the other hand, the overshoot of the system with the conventional PID control is 20%, much higher than that with the improved PID control, which is less than 2%. This indicates the system is not stable enough under conventional PID control. According to above analysis, it is known the conventional digital PID control with single sampling period can not reach the working process requirements of the angle position servo system, but the improved digital PID control with variable sampling periods is a good way to realize a better control effect.

6. Conclusions

Digital PID control can easily implement the flexible control of the servo system by adjusting PID parameters. In this paper, the angle position servo system of the plant converter is studied, and the system response speed and its stability under variable sampling periods are simulated and analyzed. Based on it, an improved digital PID control algorithm is proposed. The actual application shows that with the improved digital PID control algorithm, a better control effect of the rapid response and the working stability for the angle position electric-hydraulic servo system can be reached.
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8. References