The Research on the Position Control of the Hydraulic Cylinder Based on the Compound Algorithm of Fuzzy & Feedforward-feedback

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Abstract: This paper aims to research the position control of the hydraulic cylinder controlled by the high-speed on-off valve to realize the precise position control. The strategy combining the pulse width modulation with pulse frequency modulation is proposed to compensate the dead and saturated zones of the high-speed on-off valve, which is on the groundwork of the analysis of the flow characteristic of high-speed on-off valve. A compound algorithm of fuzzy & feedforward-feedback is put forward to realize the precise position control, which can be considered as the duty ratio is given ahead, and the fuzzy algorithm is designed and utilized to deal with the tracking error by adjusting to the frequency and duty ratio of the high-speed on-off valve. The mathematics modeling is analyzed and simulated with the proposed control algorithm using the finite chamber method. The hydraulic loop is established to verify the simulation result with experimental platform. The research finds that the proposed scheme is effective to make the flow linear of high-speed on-off valve and increase the position precision, and the position error can be limited within -0.6 mm ~ 0.6 mm. The application of pulse frequency modulation control method for high-speed on-off valve and the compound algorithm of fuzzy & feedforward-feedback for tracking can significantly improve the position control precision. The design methodology and control algorithm can be applied to other hydraulic system with position control requirement.

Keywords: High-speed on-off valve, Position control, Feedforward-feedback control, Pulse width modulation, Pulse frequency modulation, Fuzzy algorithm.

1. Introduction

High-speed on-off valve (HSV) is a new kind of electro-hydraulic digital valve, which has the advantage of fast switching capability, anti-pollution and high repeatability, and the past flow can be changed by adjusting the open and closed time of the valve [1]. HSV can be controlled by the pulse signal, and combines effectively the computer control technology and hydraulic fluid technology, and it is widely used in the speed, position, force control and other occasions [2].

The control methods for HSV can be ranked as 5 types, such as: pulse width modulation (PWM), pulse amplitude modulation (PAM), pulse code modulation (PCM), pulse frequency modulation (PFM), pulse number modulation (PNM), and the PWM control method is widely used [3], which is considered as
adjusting the duty ratio of HSV with the frequency fixed to change the past flow. On occasion of the mechanism and electromagnetism characteristics of the spool, the dead zone and saturated zone exists for the flow control. Many researchers have applied some methods to deal with dead zone: Mostafa Taghizadeh [4] uses the linear compensation method, which widens the duty ratio based on the switching parameters with the frequency fixed, to achieve closed loop position control. Shih and Maalso [5] use the modified differential PWM method to control the position of a pneumatic rodless cylinder. W. Q. Hua[6] researches the PFM control method to compensate the dead zone, and applied to the speed control for the hydraulic motor, which achieves the speed control. This paper analyzes and utilizes the control method of PWM-PFM to remedy the dead zone for HSV, and applies to the position control of the hydraulic cylinder.

On terms of the inherent nonlinear dynamic and uncertainties associated with the hydraulic system, many researchers have done some works. PID control is widely utilized for its agility, effect, and wide application, but it can’t be adjusted with the changing condition. As the computer technology develops the intelligent control methods including fuzzy control, adaptive control, and artificial neural network control are introduced to the position control applications. C. Jiefan [7] designs a PID controller based on the fuzzy algorithm which made use of the effect of PID control and intelligence of fuzzy control to achieve the position control of double cylinders by compensating the variants and no-linear characteristic. C. Xiaodong [8] proposes a new control algorithm based on Widrow-Hoff neural network learning algorithm, which can decrease the respond time. Mostafa Taghizadeh [4] applies the PD control based on the Kalman filter to the speed control system. Orhan Ekren [9] utilizes PID, fuzzy logic and artificial neural network (ANN) to the speed-changing control system, and compared with each others with simulation and experiment; Shih and Maalso [5] use the sliding mode control to control the position of a pneumatic rodless cylinder, but these control algorithms mentioned above belong to the feedback control, which compensates the effect brought by the interference to deal with the error between the realistic value and the reference value after detected. The control lags behind the interference, and it may leads to the dynamic error during the regulation process. While the feedforward control strategy is widely used in the occasions with much interference, which keeps the controlled parameters changeless to compensate the influence of the interference, and it is timely compared with the feedback control strategy, but with weak anti-interference ability. The feedforward control strategy should be combined with the feedback control strategy, which can be considered as the compound compensated control method based on the input. M. H. Dong [10] proposes the compound algorithm PD & feedforward-feedback, and utilized to the speed control for elevator. This paper combines the fuzzy control for its intelligent characteristic and the feedforward-feedback control to realize the position control.

This paper analyzes the flow characteristic of HSV and proposes the control method combining PFM and PWM to compensate the dead zone and saturated zone, which exists if only controlled by the current PWM control method. During the position control process, the compound algorithm of fuzzy & feedforward-feedback is researched and utilized for feedforward-feedback control strategy is utilized to solve the hysteresis characteristic of the pure feedback system, and fuzzy algorithm is designed to deal with the feedback error to realize the precise position control.

2. Design of Hydraulic Loop

Hydraulic position control loop designed in this paper as shown in Fig. 1 is mainly composed of the Lenovo computer with the data acquisition card PCI-6221, the displacement sensor for the hydraulic cylinder, HSV, and three position four-way reversing valve and so on.

The displacement sensor is installed to measure the hydraulic cylinder displacement which is gathered by the AI port of PCI-6221 data acquisition card (DAQ). HSV controls the flow to the hydraulic cylinder no-stem cavity by adjusting the open time of HSV. HSV is controlled by the amplified PWM signal, which was produced by the AO port of data acquisition card.

3. The Mathematics Modeling and Optimized Control of HSV

The relationship between the spool displacement and pulse width modulation signal is determined by the switching characteristics of HSV and its mathematical model.

The area of valve opening [11]:

\[ \bar{A}_{hsv} = \pi D_{hsv} \sin(2\theta) / 2, \] (1)
where \( A_{\text{avg}} \) is the average valve-port area of HSV; \( D \) is the diameter of valve ball; \( \theta \) is the half-angle of valve seat; \( A_{\text{avg}} \) is the average displacement of valve ball, which can be referred in [12-13].

The past flow of HSV:

\[
Q_{\text{avg}} = \frac{C_d}{D} (p_y - p_w)/\rho ,
\]

where \( Q_{\text{avg}} \) is the past flow of HSV; \( C_d \) is the flow coefficient; \( p_y \) is the pressure of rod cavity; \( p_w \) is the pressure of no-stem cavity; \( \rho \) is the oil density.

The list of switching characteristic parameters of HSV is shown in Table 1, and list of component parameters - in Table 2.

**Table 1.** List of switching characteristic parameters of HSV.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_1 )</td>
<td>2.00</td>
<td>( \tau_2 )</td>
<td>2.60</td>
</tr>
<tr>
<td>( \tau_3 )</td>
<td>0.50</td>
<td>( \tau_4 )</td>
<td>4.10</td>
</tr>
<tr>
<td>( T )</td>
<td>30/60/10</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

In this table \( T \) is the duty of the pulse signal; \( \tau_1 \) is the delay-closed time; \( \tau_2 \) is the move-closed time; \( \tau_3 \) is the delay-released time; \( \tau_4 \) is the move-released time.

**Table 2.** List of component parameters.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSV</td>
<td>Maximum displacement</td>
<td>0.0013 [m]</td>
</tr>
<tr>
<td></td>
<td>Diameter of valve ball</td>
<td>0.005 [m]</td>
</tr>
<tr>
<td></td>
<td>Half-angle of valve seat</td>
<td>20 [deg]</td>
</tr>
<tr>
<td>Cylinder</td>
<td>Effective stress area of piston in rod cavity</td>
<td>0.00012 [m²]</td>
</tr>
<tr>
<td></td>
<td>Effective stress area of piston in no-stem cavity</td>
<td>0.0002 [m²]</td>
</tr>
<tr>
<td></td>
<td>Effective displacement</td>
<td>0.2 [m]</td>
</tr>
<tr>
<td>Relief valve</td>
<td>Adjustment pressure</td>
<td>3.5 [MPa]</td>
</tr>
</tbody>
</table>

The mathematic analysis result shows that switching characteristic parameters and the frequency of pulse signal affect directly the flow characteristic of HSV in Fig. 2. On occasion of the mechanism and electromagnetism characteristics of the spool, as the frequency of the pulse signal becomes bigger, the linear zone decreases, and the flow of HSV magnifies, when the duty ratio of pulse signal becomes bigger. Dead zone, saturated zone, and non-linear zone become bigger as switching characteristic parameters of HSV getting bigger with frequency of pulse signal fixed.

The result shows that \( \tau_1 \) decides the dead zone, \( \tau_4 \) decides the saturated zone and \( \tau_2 , \tau_4 \) decide the linear zone in Fig. 2(b). It is shown the relationship between the frequency and dead dot, saturated dot, linear zone in Fig. 3, Fig. 4. The dead dot comes to 0.25, which implies that HSV keeps on closed when the duty ratio is less than 0.25, and the saturated dot comes to 0.75, which implies that HSV keeps on the largest flow when the duty ratio is bigger than 0.75.
The flow control of HSV can’t reach the demand, when the duty ratio is smaller than the least responding time or larger than the most responding time. In order to compensate the dead zone and saturated zone of HSV controlled by PWM control mode, this paper proposes the control mode for HSV, which combines PWM and PFM (Fig.5).

The PWM and PFM control mode deal with the dead and saturated zone by adjusting the frequency as the duty ratio changes, which changes the frequency with the same width of pulse signal. The frequency can be changed as Eq. 3.

\[
\begin{cases}
\text{zhan} / (t_1 + t_2), & \text{zhan} \in [0, \frac{t_1 + t_2}{T}]
\\
1/T, & \text{zhan} \in \left[\frac{t_1 + t_2}{T}, \frac{t_1 + t_2}{T} \right]
\\
(1-\text{zhan}) / (t_1 + t_2), & \text{zhan} \in \left[\frac{t_1 + t_2}{T}, 1\right]
\end{cases}
\]

The equation can be adjusted with the on-off parameters, which \(t_1 = 2.5\ ms\), \(t_2 = 1\ ms\), \(t_3 = 2.5\ ms\), \(t_4 = 1\ ms\), \(T = 1/60\). The frequency is shown in Eq. 4.

\[
\begin{cases}
zhan / 0.0035, & \text{zhan} \in [0, 0.21]
\\
lz = 60, & \text{zhan} \in (0.21, 0.79)
\\
(1-\text{zhan}) / 0.0035, & \text{zhan} \in [0.79, 1]
\end{cases}
\]

The mathematics modeling result of the flow characteristic of PWM-PFM control shows that the control method for HSV can make the flow linear on the bound of \([0 \sim 100\%]\).

4. The Mathematics Modeling of the Hydraulic System

The flow equation can illuminate the relationship between the pressure and the total flow with the bulk-cavity-node method [14], which is shown in Eq. 5.

\[
P = \int \frac{E}{V} \sum Q dt,
\]

where \(\sum Q\) is the total flow of the cavity; \(P\) is the pressure of the cavity; \(E\) is the elastic modulus of oil; \(V\) is the volume of rodless cavity.

The hydraulic system model is established with the finite chamber method according to hydraulic system schematic diagram, and the application is modeling respectively, as shown in Eq. 6-9.

The flow equation of rodless cavity:

\[
\frac{d\psi}{dt} = -\frac{\beta_\psi}{V_{\psi} + A_\psi x} (Q_{\psi0} - \psi - A_\psi \dot{x})
\]

where \(\beta_\psi\) is the elastic modulus of oil, \(Q_{\psi0}\) is the flow that flow into the rod cavity; \(\psi\) is the flow that leakage from rod cavity to rodless cavity; \(V_{\psi0}\) is the initial volume of rodless cavity; \(A_\psi\) is the effective stress area of piston in rodless cavity.

The equation of rod cavity:

\[
\frac{d\psi}{dt} = -\frac{\beta_\psi}{V_{\psi0} + A_\psi x} (Q_{\psi} + A_\psi \dot{x} - Q_{out})
\]

where \(A_\psi\) is the effective stress area of piston in rod cavity; \(V_{\psi0}\) is the initial volume of rod cavity, \(Q_{out}\) is the flow that flow out of rodless cavity.

The equation of force balance:

\[
m \dot{x} = p_{\psi0} A_\psi - p \dot{x} - mg - \beta_\psi \dot{x}
\]

where \(m\) is the equivalent mass of piston; \(\beta_\psi\) is viscous damping coefficient of oil; \(g\) is the gravity acceleration.

The equation of the leakage flow:
\[ Q_c = k_c(p_r - p_a), \]  \hspace{1cm} (9) \]

where \( k_c \) is the leakage flow coefficient; \( p_r \) is the pressure of system.

The list of component parameters of the hydraulic system is adduced in Table 3.

### Table 3. List of component parameters of the hydraulic system.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Elastic modulus of oil ( \beta_e )</td>
<td>750</td>
<td>MPa</td>
</tr>
<tr>
<td>2</td>
<td>The pressure of system ( p_r )</td>
<td>3.5</td>
<td>MPa</td>
</tr>
<tr>
<td>3</td>
<td>The density of oil ( \rho )</td>
<td>850</td>
<td>kg/m³</td>
</tr>
<tr>
<td>4</td>
<td>Maximal displacement ( x_c )</td>
<td>200</td>
<td>mm</td>
</tr>
<tr>
<td>5</td>
<td>The area of the rod cavity ( A_z )</td>
<td>120</td>
<td>mm²</td>
</tr>
<tr>
<td>6</td>
<td>The area of the rodless cavity ( A_w )</td>
<td>200</td>
<td>mm²</td>
</tr>
<tr>
<td>7</td>
<td>The mass of piston ( m )</td>
<td>9</td>
<td>kg</td>
</tr>
<tr>
<td>8</td>
<td>Viscous damping coefficient of oil ( \beta_v )</td>
<td>250</td>
<td>N·s/m</td>
</tr>
<tr>
<td>9</td>
<td>The initial volume of rod cavity ( V_{y0} )</td>
<td>2827.5</td>
<td>mm³</td>
</tr>
<tr>
<td>10</td>
<td>The initial volume of rodless cavity ( V_{w0} )</td>
<td>5696.5</td>
<td>mm³</td>
</tr>
<tr>
<td>11</td>
<td>The leakage flow coefficient ( k_c )</td>
<td>0.0033</td>
<td>m³/(Pa·s)</td>
</tr>
</tbody>
</table>
5. The Compound Algorithm of Fuzzy and Feedforward-Feedback

5.1. The Feedforward-Feedback Control Algorithm

This paper proposes the compound algorithm of fuzzy & feedforward-feedback, which is shown in Fig. 10.

![Fig. 10. The compound algorithm of fuzzy & feedforward-feedback.]

The feedforward value is referred as the control signal, and the fuzzy algorithm is utilized to compensate the error between the reference input and the realistic output to deal with the uncertainties associated with the hydraulic system. The feedforward input signal is multiplied by the feedforward control so that the final control voltage can be expressed in Eq. 10:

$$ u(t) = k_2[k_1 \times v_{\text{ideal}}(t) + u_{\text{fuzzy}}(t)], $$(10)

where $k_1$ is the control coefficient, which is set as 1 in this paper; $k_2$ is the feedforward coefficient, which is set as 5 in this paper; $u_{\text{fuzzy}}(t)$ is the feedback output based on the fuzzy algorithm.

5.2. The Design of the Fuzzy Controller

The fuzzy controller is the core of the position control system, which is composed of fuzzifier, fuzzy inference engine and defuzzifier etc. [15], which is shown in Fig. 11.

![Fig. 11. The fuzzy controller.]

1) Structure of fuzzy controller.

The structure of the fuzzy controller determines the control performance and the complexity of the system [16], and this paper designs MISO type fuzzy control: multi-input and single output. The error between desired position set point and the realistic output and the derivation of error are the input of the fuzzy controller, and the duty ratio of the HSV is the output of the fuzzy controller, which is shown in Fig. 12.

![Fig. 12. The structure of fuzzy controller.]

2) Fuzzification of input and output variables.

The fuzzy inference system is established on the base of fuzzy set theory. At first it is necessary to carry out fuzzification of the input and output variables, which transforms the input and output data into proper semantic value. In this paper, the basic ranges of input and output variables are $e \in [-0.03, 0.03], ec \in [-3, 3], u \in [-3, 3]$. The fuzzy range of input and output is both separated into 7 semantic variables respectively, and the corresponding fuzzy subsets are:

- $e, ec = [NB, NM, NS, ZO, PS, PM, PB]$;
- $u = [NB, NM, NS, ZO, PS, PM, PB]$;

where NB is negative big; NM is negative middle; NS is negative small; ZO is zero; PS is positive small; PM is positive middle; PB is positive big.

Let NB and PB be gauss membership functions and others are triangular membership functions. All variables of the membership functions are shown in Fig. 13.

![Fig. 13 (a). The memberships of the input and output for the fuzzy algorithm.]

$$ e, ec = [NB, NM, NS, ZO, PS, PM, PB]; $$

$$ u = [NB, NM, NS, ZO, PS, PM, PB]; $$

where NB is negative big; NM is negative middle; NS is negative small; ZO is zero; PS is positive small; PM is positive middle; PB is positive big.
3) Establishment of fuzzy inference rule.

The key to realize fuzzy control is to establish appropriate fuzzy inference rules by using the experience of experts. Although a great deal of achievements have been obtained in the research of using fuzzy logic based the expert knowledge, there is no systematic method to design and examine the number of rules, input space partitions and membership functions at present. In this paper, the influence laws that the duty ratio of HSV acts on the stability, response frequency and steady-state precision of the electro-hydraulic system are studied by simulation and experiment. The fuzzy inference rules between input $e$, $ec$ and output $u$ are summarized in Table 4 and Fig. 14.

4) Fuzzy inference and defuzzification.

The Mamdani min operators and max operators are adopted to carry out fuzzy implication and synthesis calculation [17] respectively. Thus, the result of $u$ is:

$$
\mu_{u_j}(u) = \bigvee_{i,j=1} \left[ \mu_i(e) \wedge \mu_{j}(ec) \wedge \mu_j(u) \right]
$$

The centroid method is used to implement defuzzification after the output fuzzy set $u$ is acquired from the fuzzy operation. The duty ratio $u$ is obtained as follows:

$$
u(e, ec) = \frac{\sum_{n=1}^{N} u_n \mu_{C_n}(u)}{\sum_{n=1}^{N} \mu_{C_n}(u)} , \quad (12)
$$

5) Proportion Coefficient of the Fuzzy Range.

The proportion coefficient of the fuzzy range can influence the dynamic characteristic of the system, and is regulated with the off-line regulation method, which is shown in Table 5.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>e (Error)</th>
<th>ec (The derivation of error)</th>
<th>$u$ (The duty ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linguinal Parameters</td>
<td>[−0.03, 0.03]</td>
<td>[−3, 3]</td>
<td>[−0.03, 0.03]</td>
</tr>
<tr>
<td>The Basic Range</td>
<td>[−0.03, 0.03]</td>
<td>[−3, 3]</td>
<td>[−3, 3]</td>
</tr>
<tr>
<td>The Fuzzy Range</td>
<td>1</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>Proportion Coefficient</td>
<td>1</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>Fuzzy Subset</td>
<td>NB, NM, NS, ZO, PS, PM, PB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6. Validation and Discuss

6.1. Validation of the Compound Algorithm of Fuzzy & Feedforward-Feedback

The feedback control and feedforward-feedback control based on the fuzzy algorithm is verified by simulation and experiment. In the simulated environment, the configuration parameters are that the type of the solver is variable-step and the solver is ode23tb. The mathematic modeling is simulated after the parameters are given, and the simulation result is shown in Fig.15.

The simulation result shows that the feedforward-feedback control strategy can decrease effectively the maximal tracking error from 4 mm to 1.6 mm. The experiment is done to verify the simulation with the feedforward-feedback control strategy, which is based on the FESTO experimental platform, and the experimental result is shown in Fig. 16.
Fig. 16 (c). The simulation and experiment results of the compound algorithm of fuzzy & feedforward-feedback.

The simulation result and the experiment result verify the mathematic modeling and the validity of the feedforward-feedback control strategy, which decreases the tracking error from 4 mm to 1.5 mm, but it also shows obviously that the tracking error of the starting and stopping process is larger than the other process, which results from the dead zone of the flow for HSV.

6.2. Validation of the Optimized PWM-PFM Control Method for HSV

In order to compensate the dead zone and the saturated zone, the PWM-PFM control method is proposed and validated, which makes the flow linear on the bound of \([0 \sim 100\%]\). The PWM-PFM control method based on the feedforward-feedback control and fuzzy algorithm is verified by simulation and experiment. In the simulated environment, the configuration parameters are that the type of the solver is variable-step and the solver is ode23tb. The mathematic modeling is simulated after the parameters are given, and the simulation result is shown in Fig. 17.

The simulation result shows that the feedforward-feedback control strategy can decrease effectively the maximal tracking error from 1.6 mm to 0.2 mm during the starting and stopping process. The experiment is done to verify the simulation with the feedforward-feedback control strategy, which is based on the FESTO experimental platform, and the experimental result is shown in Fig. 18.

Fig. 17. The figure of the PWM control and the PWM-PFM control for HSV.
Fig. 18. The simulation and experiment results of the PWM-PFM control.

The simulation result and the experiment result verify the validity of the feedforward-feedback control strategy, which is used to compensate the dead zone and saturated zone, which decreases the tracking error from 1.6 mm to 0.6 mm, realizing the precise position control.

7. Conclusions

The research result shows HSV can achieve effectively the precise position control of the hydraulic cylinder. In order to compensate the dead zone and the saturated zone, the PWM-PFM control method is researched and utilized to decrease the tracking error during the starting and stopping process, which results from the dead zone. The compounded fuzzy algorithm & feedforward-feedback control strategy is used to achieve the precise position control by adjusting the duty ratio and the frequency, and the tracking error of the compounded fuzzy algorithm & feedforward-feedback control strategy and PWM-PFM control strategy is limited to $0.6 \text{ mm} \sim 0.6 \text{ mm}$.

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