Research on multi-cylinder synchronous control system of multi-directional forging hydraulic press

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Abstract—A master-slave synchronization control strategy based on RBF network adaptive sliding mode control is proposed to solve the problem of lack of effective control strategy and control accuracy in the process of synchronous motion of three horizontal cylinders of multi-directional die forging hydraulic press in VL ball cage forming process. According to the high-order nonlinear mathematical model of the single-cylinder electro-hydraulic servo system, the RBF network adaptive sliding mode controller is designed. The joint simulation model is established by using AMEsim and MATLAB to solve the tracking accuracy and synchronous control accuracy of the system, and the control effect is verified by comparing with the conventional PID control. The simulation results show that the RBF network adaptive sliding mode controller has strong robustness, and the three horizontal cylinder displacement synchronization controllers of the multi-directional die forging press designed in this paper have good synchronization performance.

1. Introduction
In the VL ball cage forming process, three horizontal cylinders of multi-directional die forging hydraulic press are required to move towards the shaft core at the same speed. Therefore, the research on the three-cylinder synchronous control of multi-directional die forging press is the premise for completing the forging experiment of this process.

At present, there are many studies on multi-cylinder synchronous control, mainly through the optimization of intelligent control algorithm and synchronous control strategy to improve the synchronous control accuracy. Xie Miao [1] of Liaoning University of Engineering and Technology proposed a cross coupling synchronous control strategy based on fuzzy PID, which realized synchronous control of multiple hydraulic cylinders in advanced support equipment; Guo Xiaosong [2] uses the improved single neuron PID control algorithm to improve the defects of master-slave control. The synchronization performance of the control method is verified by joint simulation, but this method is only for double cylinder master-slave synchronization control. Wang et al. [3] proposed to use adaptive genetic algorithm to optimize the control parameters under the deviation coupling control mode, and verified by simulation that the optimized control system had better synchronous control accuracy.
Most of the above studies on the synchronous control of hydraulic cylinders focus on the fixed load. In this paper, the three hydraulic cylinders are used to squeeze the blank. The stress of the blank will change in the process of plastic deformation, resulting in the change of the load on the hydraulic cylinder and the change of the nonlinear parameters in the hydraulic system, which reduces the synchronous performance of the hydraulic cylinder. Therefore, an adaptive sliding mode variable structure controller based on RBF network is designed. The RBF neural network is used to approximate the nonlinear function of the hydraulic system model. Combined with the sliding mode control, the system model is adjusted online to reduce the chattering in the sliding mode control and improve the synchronization accuracy of the three cylinder synchronization control.

2. Design of Three Cylinder Synchronous Controller

2.1 Hydraulic system model

In the multi-directional die forging press used in VL ball cage forming, the three horizontal hydraulic cylinders are symmetrically distributed at 120° angle, and the horizontal cylinder distribution diagram is shown in Fig.1. When forging VL ball cage, three horizontal hydraulic cylinders need to work synchronously.

Fig.1 Diagram of horizontal cylinder distribution

Due to the same execution mode of three hydraulic cylinders, the mathematical model of valve controlled asymmetric cylinder is established by analyzing a hydraulic cylinder. According to the servo valve load flow equation, the hydraulic cylinder flow continuity equation and the force balance equation between the hydraulic cylinder and the load, the transfer function of the valve-controlled asymmetric hydraulic cylinder system can be obtained [4].

$$X = \frac{K_g X_v - K_{ce}(1 + \frac{V_F}{4\beta e K_{ce}})}{mV_L A_1^3 + (\frac{mK_{ce}}{A_1^2} + \frac{PV_L}{4\beta e K_{ce}})x_v + (1 + \frac{BK_{ce}}{4\beta e K_{ce}})x_v + \frac{K_{ce}}{A_1^2} F \_1}$$

(1)

Where $K_g$ is flow gain coefficient; $K_{ce}$ is Pressure-flow coefficient; $V_F$ is Equivalent volume of rodless cavity; $\beta$ is Effective bulk elastic modulus of hydraulic oil; $A_1$ and $A_2$ is Rodless cavity area and rod cavity area of hydraulic cylinder; $m$ is Equivalent load mass; $B$ is Equivalent load damping; $K$ is Equivalent load stiffness; $x_v$ is Servo spool displacement; $F_1$ is Equivalent external load force.

2.2 Synchronous control strategy

The control strategies adopted in the multi-cylinder synchronous control system mainly include parallel synchronous control strategy, master-slave synchronous control strategy, adjacent cross-coupling control strategy and mean-coupling control strategy [5]. Among them, the parallel synchronous control strategy will cause the hydraulic cylinder asynchronous problem when the partial load of a hydraulic cylinder changes greatly. The adjacent cross-coupling control strategy is based on the control idea of the minimum correlation axis, and the tracking error of the adjacent two cylinders is compensated to realize the synchronization control of multiple hydraulic cylinders. The mean coupling strategy is generally used for the synchronization control of more than three hydraulic cylinders. The use of adjacent cross coupling and mean coupling control strategy will greatly increase the difficulty of
controller design. Considering the practicability of equipment development, master-slave synchronization control strategy is selected. Set the expected displacement signal of hydraulic cylinder is \( r \), \( X_1 \) is active cylinder displacement, displacements of three driven cylinders are \( X_2, X_3 \) and \( X_4 \). \( E_1 \) is the error between the displacement of the active cylinder and the expected displacement, \( E_2, E_3, E_4 \) is the error between the displacement of the moving cylinder 1, 2, 3 and the displacement of the active cylinder, then the master-slave synchronous control strategy of the hydraulic system is shown in Fig. 2.

![Master-slave synchronous control block diagram](image)

Figure 2 Master-slave synchronous control block diagram

2.3 RBF network adaptive sliding mode controller

Sliding mode variable structure control is a kind of nonlinear control with discontinuous control variables. Its control mode is continuously adjusted according to the current state of the system, forcing the system to swing up and down in high frequency and small amplitude along the prescribed state trajectory. If the mathematical model of the controlled system is known, the sliding mode control can achieve better control effect. However, for the electro-hydraulic servo system, the model uncertainty is large, and the sliding mode control cannot play its best control effect. Neural networks have strong self-learning ability and can fully approximate any complex nonlinear function [6]. In this paper, RBF adaptive sliding mode controller is designed. RBF neural network is used to approximate the nonlinear function in the model. The structure diagram of RBF neural network sliding mode controller is shown in Fig.3.

![Structure Diagram of RBF Network Sliding Mode Controller](image)

Fig.3 Structure Diagram of RBF Network Sliding Mode Controller

Electro-hydraulic servo system is a third-order system. In order to facilitate the controller design, the displacement of a hydraulic cylinder is used as the state variable. The state space expression can be expressed as follows:

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= -a_0 x_1 - a_1 x_2 - a_2 x_3 + b_0 u + d(t) \\
y &= x_1
\end{align*}
\] (2)
for hydraulic cylinder displacement; \( x_2 \) is the speed of hydraulic cylinder; \( x_3 \) is the acceleration of the hydraulic cylinder; 
\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 \\
\dot{x}_3 &= f(x) + g(x)u + d(t)
\end{align*}
\] (3)

If the expected displacement is \( r \), the tracking error of the hydraulic cylinder \( e_1 = r - x_1 \), \( e_2 \) and \( e_3 \) are the velocity and acceleration of the tracking error \( e_1 \), respectively, and the error equation of state:
\[
\begin{align*}
\dot{e}_1 &= e_2 \\
\dot{e}_2 &= e_3 \\
\dot{e}_3 &= \ddot{r} - f(x) - g(x)u - d(t)
\end{align*}
\] (4)

where \( c_1 \) and \( c_2 \) are the sliding mode coefficients, \( k_i \) is the sliding mode integral coefficient, and the dynamic quality of the sliding mode is determined by it. The three coefficients can be solved by pole assignment. The tracking error controller \( u_g \) is composed of equivalent control rate \( u_{geq} \) and switching control rate \( u_{gs} \), which need to be designed separately.

Equivalent control rate section:
\[
\dot{s} = k_1 e_1 + c_1 e_2 + c_2 e_3 + \ddot{r} - f(x) - g(x)u - d(t)
\] (5)

\[
\dot{s} = 0, \quad \text{then:}
\]
\[
u_{geq} = \frac{1}{g(x)} \left[ k_i e_1 + c_1 e_2 + c_2 e_3 + \ddot{r} - f(x) \right]
\] (6)

The switching control rate part: Because the symbolic function has 'switching characteristics', the system will produce a small range of chattering. In order to weaken the influence of chattering on the system, the saturation function exponential reaching law is designed [7]:
\[
\dot{s} = -\phi sat(s) - k_{si} s
\] (7)

The switching control rate is:
\[
u_{si} = \frac{1}{\phi(s)} \left[ \phi sat(s) + k_{si} s \right]
\] (8)

The tracking error controller \( u_g \) is:
\[
u_g = \frac{1}{g(x)} \left[ k_i e_1 + c_1 e_2 + c_2 e_3 + \ddot{r} - f(x) + \phi sat(s) + k_{si} s \right]
\] (9)

In the electro-hydraulic servo system, there are many nonlinear factors, \( f(x) \) and \( g(x) \) can not be accurately solved in the system state equation. RBF neural network can accurately approximate any function. The network output function of the approximation function is:
\[
\begin{align*}
\begin{cases}
\hat{f}(x) = W^T h_f(x) + \varepsilon_f \\
\hat{g}(x) = V^T h_g(x) + \varepsilon_g
\end{cases}
\end{align*}
\] (10)

\( W^\ast \) and \( V^\ast \) are ideal weights of the network, \( h_f(x) \) and \( h_g(x) \) are Gaussian basis functions of \( f(x) \) and \( g(x) \) respectively, \( \varepsilon_f \) and \( \varepsilon_g \) are approximation errors of the network. The input of RBF neural network is defined as \( X = [x_1, x_2, x_3] \), then the output expression is:
\[
\begin{align*}
\begin{cases}
\hat{f}(x) = \tilde{W}^T h_f(x) \\
\hat{g}(x) = \tilde{V}^T h_g(x)
\end{cases}
\end{align*}
\] (11)
\( \hat{W} \) and \( \hat{V} \) are the estimated weights of the network, \( \hat{f}(x) \) and \( \hat{g}(x) \) are the estimated values of \( f(x) \) and \( g(x) \), respectively. The control rate of RBF neural network approximation is:

\[
\hat{u}_a = \frac{1}{\hat{g}(x)} \left[ k_1 e_1 + c_1 e_2 + c_2 e_3 + \hat{r} - \hat{f}(x) + \phi \text{sat}(s) + k_{si} s \right]
\]  

(12)

2.4 Stability proof

Lyapunov function is designed as follows:

\[
L = \frac{1}{2} s^2 + \frac{1}{2\gamma_1} \hat{W}^T \hat{W} + \frac{1}{2\gamma_2} \hat{V}^T \hat{V}
\]  

(13)

\( \hat{W} = W - \hat{W}, \hat{V} = V - \hat{V}, \gamma_1 > 0, \gamma_2 > 0. \)

Defining \( \hat{f}(x) = \hat{f}(x) - f(x), \hat{g}(x) = \hat{g}(x) - g(x) \), and inserting Equation (9) and Equation (10) into:

\[
\begin{align*}
\hat{f}(x) &= \hat{W}^T h_f(x) - e_f \\
\hat{g}(x) &= \hat{V}^T h_g(x) - e_g
\end{align*}
\]  

(14)

Derivation to (13) and derivation to (10), (11), (12), (14) with:

\[
L = \hat{W}^T \left( s h_f(x) - \frac{1}{\gamma_1} \hat{W} \right) + \hat{V}^T \left( s h_g(x) u - \frac{1}{\gamma_2} \hat{V} \right) + s \left( -e_f - \phi \text{sat}(s) - k_{si} s - e_g u - d(t) \right)
\]  

(15)

the adaptive rate is:

\[
\begin{align*}
\dot{\hat{W}} &= -\gamma_1 s h_f(x) \\
\dot{\hat{V}} &= -\gamma_2 s h_g(x) u
\end{align*}
\]  

(16)

Since the approximation errors \( e_f \) and \( e_g \) of RBF network are very small, then:

\[
L = s \left( -e_f - \phi \text{sat}(s) - k_{si} s - e_g u - d(t) \right) = \left( -e_f - e_g u - k_{si} s - d(t) \right) s - \phi |s| \leq 0
\]  

(17)

When \( L = 0, s = 0 \). According to LaSalle invariant set principle, the closed-loop system is asymptotically stable, and when \( t \to \infty, s \to 0 \). Therefore, when the control rate is Equation (12), it can be made to ensure the stability of the system.

3. AMESim and MATLAB co-simulation analysis

In this paper, the co-simulation method of AMESim and MATLAB is used to build the simulation model of RBF network adaptive sliding mode control based on master-slave synchronous control. AMESim can build the hydraulic system model through the component library in the software. Through the cooperation of various modules, it can intuitively reflect the working principle and characteristics of the hydraulic system. MATLAB can process a large number of data, and Simulink in MATLAB can build a complex controller structure, which is connected through the SimuCosim joint simulation interface. The AMESim model of the three-cylinder hydraulic cylinder system is built in this paper. The model adopts the structure of one valve and one cylinder. The displacement of the hydraulic cylinder is detected by the displacement sensor. The displacement sensor inputs the detected displacement signal into the Simulink controller. After the controller calculates, the corresponding voltage signal is fed back to the electro-hydraulic servo valve. The electro-hydraulic servo valve changes the size of the valve port, so as to control the displacement of the hydraulic cylinder. In this simulation, the control effects of RBF network adaptive control and PID control are compared and analyzed. In the experiment, three hydraulic cylinders are set with 3KN random interference signals.

\[
\hat{W} \text{ and } \hat{V} \text{ are the estimated weights of the network, } \hat{f}(x) \text{ and } \hat{g}(x) \text{ are the estimated values of } f(x) \text{ and } g(x), \text{ respectively. The control rate of RBF neural network approximation is:}
\]

\[
\hat{u}_a = \frac{1}{\hat{g}(x)} \left[ k_1 e_1 + c_1 e_2 + c_2 e_3 + \hat{r} - \hat{f}(x) + \phi \text{sat}(s) + k_{si} s \right]
\]  

(12)
Fig. 4 shows the tracking error control effect diagram of hydraulic cylinder. It can be seen from the diagram that the tracking error of RBF network adaptive sliding mode control is 1mm after the system reaches steady state, and the tracking error of PID control is 2.9mm after the system reaches steady state. It can be seen from Fig. 5 that on the basis of using master-slave synchronization control, the synchronization error of adaptive sliding mode control algorithm based on RBF network is smaller than that of PID control algorithm, and the maximum synchronization error does not exceed 1.73 mm, while the maximum synchronization error of PID control algorithm does not exceed 3.51 mm. Table simulation results show that the adaptive sliding mode control algorithm based on RBF network not only has better tracking accuracy, but also has better synchronous control accuracy and robustness.

4. Conclusion
In view of the problem that the control accuracy is not high due to the unknown parameters of the horizontal cylinder of the multi-directional die forging hydraulic press during operation, an adaptive sliding mode control strategy based on RBF network with master-slave synchronous control is designed, and a design method of the controller of the electro-hydraulic servo system with uncertain model parameters and external disturbance is proposed. Through the co-simulation test of AMESim and MATLAB, it is concluded that RBF network adaptive sliding mode controller can better realize multi-cylinder synchronous control compared with traditional PID controller, which provides an effective way for multi-cylinder synchronous control.
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