

Research on load sensitive pressure control strategy of electro-hydraulic joint

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Abstract. In this paper, the mathematical and the state space model of the electro-hydraulic joint load sensitive pressure system are established. Combined with the perfect performance on optimization of RBF neural network and sliding mode variable structure control algorithm in the complex hydraulic system, this paper proposes a RBF neural network adaptive sliding-mode control algorithm. This paper designs a controller with the electro-hydraulic proportional overflow valve as the control object. The simulation results show that the RBF neural network adaptive sliding-mode controller has the advantages of high control accuracy, excellent dynamic response property and strong robustness in the complex electro-hydraulic system.

1. Introduction

Robot joints are the most important part of industrial robots. Its core components are the precision reducers, but the core technology of the precision reducer is occupied by enterprises in developed countries. Because of the lack of the core technology in precise reducer, the joints of high performance electric robots are controlled by others. Accordingly, the electro-hydraulic joints with simple structure, large power and easy control have attracted widely attention by many scholars.

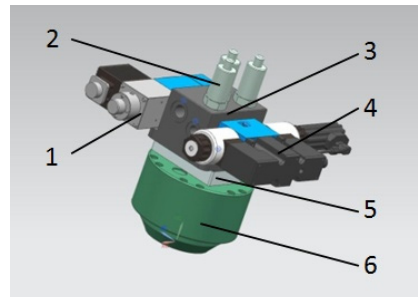
Yang Zhenzhong designed a new type motion-decoupling hydraulic servo shoulder joint and its control system^[1]. The shoulder joint had the characteristics of novel design, compact structure, rational layout, flexible movement, large torque and convenient control. Hiroshi Kaminaga et al. developed a kind of large torque and good flexibility of hydraulic knee joint^[2]. But the structure of knee joint is difficulty. Most of the above scholars have only designed the structure of electro-hydraulic joints, and have little researched on the control strategy of electro-hydraulic system. Liu Zonghong et al. in view of the load sensitive system pressure control, put forward to adjust the output pressure by setting damping in the variable pump LS feedback oil circuit^[3]. In view of the uncertainty of hydraulic system parameters of electro-hydraulic robot joint, Mohanty studied the indirect adaptive robust control algorithm to be based on the accurate estimation of the parameters and to realize robust control of system^[4]. But the time-variety of parameters made the method more difficult to estimate the parameters accurately. Therefore, it is very necessary to study the control strategy of the electro-hydraulic joint load sensitive pressure system. RBF neural network can approximate any complex nonlinear function under compact set and arbitrary precision^[5]. Sliding mode variable structure control has the advantages of fast response, excellent dynamic performance and strong robustness. In this paper, an adaptive sliding mode control strategy based on RBF neural network is designed for the load



sensitive pressure system of electro-hydraulic joint. The output pressure of electro-hydraulic system is controlled to adapt the change of load.

2. Introduction of load sensitive system on the electro-hydraulic joint

The structure model of electro-hydraulic joint is as shown in figure 1.



- 1-electro-hydraulic proportional relief valve
- 2- pressure sensor
- 3- integrated valve block
- 4- electro-hydraulic proportional reversing valve
- 5- connecting plate
- 6- steel ball hydraulic motor

Figure 1. The structure model of electro-hydraulic joint.

The principle of electro-hydraulic joint system is as shown in figure 2. The collected pressure of pressure sensors 1-1 is the output pressure, denoted by p_1 , of electro-hydraulic proportional relief valve, and the steel ball hydraulic motor front, back pressure, denoted by p_2 and p_3 , are collected by pressure sensors 1-2 and 1-3. The working pressure of the steel ball hydraulic motor, denoted by $\Delta p = |p_2 - p_3|$, is changed due to the changing load. The electro-hydraulic joint system controller receives real time pressure sensors to match the output pressure p_1 with the Δp . The purpose of control system is to achieve the self-adaptive regulation of hydraulic system pressure in the electro-hydraulic joint, so as to realize the load sensitive pressure control of the electro-hydraulic joint.

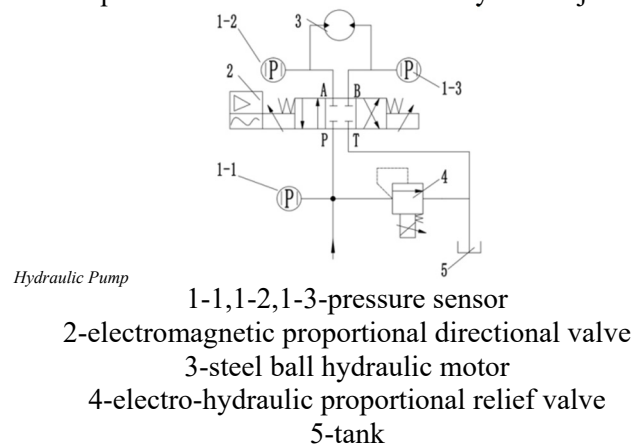
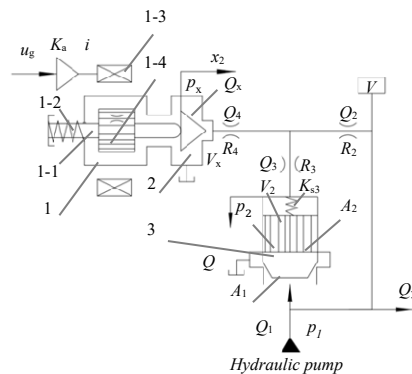


Figure 2. The principle of electro-hydraulic joint system.

3. Establish mathematical model of electro-hydraulic joint pressure system

3.1. The working principle of electro-hydraulic proportional relief valve

The working principle of electro-hydraulic proportional relief valve is as shown in figure 3.



1-proportional electromagnet (1-1-push rod 1-2-spring
1-3-coil 1-4-armature)

2-pilot valve 3- main valve

Figure 3. The working principle of electro-hydraulic proportional relief valve.

The electro-hydraulic proportional relief valve is mainly composed of proportional electromagnet, pilot valve and main valve. When the oil pressure p_x of acting on the pilot valve is smaller, the pilot valve core is closed. When the hydraulic pressure p_1 and p_2 of both cavity of the main valve are equal, the main valve core is also kept closed. When the pressure value corresponding to the set value of the proportional electromagnet is less than the system pressure p_1 , the main valve core will open to achieve the overflow effect.

3.2. The mathematical model of proportional electromagnet

As shown in figure 3. When the armature of the proportional electromagnet drives the pilot valve movement, it needs to overcome inertial force, damping force and spring force of the load, The force balance equation of the proportional electromagnet is as follows:

$$f_m = m \frac{d^2x}{dt^2} + B \frac{dx}{dt} + K_s x \quad (1)$$

where m is the total mass of the armature, the push rod and the pilot valve core, B is the combined damping parameter of the proportional electromagnet, K_s is the equivalent spring stiffness on the armature assembly. x is the displacement of the proportional electromagnet push rod.

The electromagnetic force generated by the proportional electromagnet drives the armature movement, causing the magnetic flux in the coil to change. The coil generates back electromotive force that is opposite to the direction of the current change. The input voltage equation of the proportional electromagnet is as follows:

$$u = L \frac{di}{dt} + (R_c + r_p)i + K_e \frac{dx}{dt} \quad (2)$$

where u is integrated electronic controller output voltage, L is the inductance of proportional electromagnet coil, i is the size of the input current of the proportional electromagnet, R_c and r_p are coil resistance and amplifier internal resistance, K_e is back electromotive force coefficient.

3.3. The mathematical model of the pilot valve of the electro-hydraulic proportional relief valve

The pilot valve is a hydraulic amplification link connecting the proportional electromagnet and the main valve in the electro-hydraulic proportional relief valve. The function of the pilot valve is to convert the mechanical quantity output of the proportional electromagnet to control the hydraulic quantity of the main valve. The pilot valve's force balance equation is as follows:

$$f_m - p_x A_x = m \frac{d^2 x_2}{dt^2} + B \frac{dx_2}{dt} + K_s x_2 \quad (3)$$

where p_x is the oil pressure on the side pressure surface of the pilot valve, A_x is the action area of the oil pressure on the side pressure surface of the pilot valve, x_2 is the pilot valve core displacement.

Flow balance equation of the electro-hydraulic proportional relief valve cavity V_x is as follows:

$$Q_2 = Q_4 + Q_3 + \frac{V_x}{\beta_e} \frac{dp_x}{dt} \quad (4)$$

where Q_2 is flow through the throttle R_2 , Q_4 is flow through the throttle R_4 , Q_3 is load flow of pilot valve, β_e is bulk elastic modulus of oil, V_x is volume of control chamber.

3.4. The mathematical model of the main valve of the electro-hydraulic proportional relief valve

The force analysis is performed on the main valve, which is subjected to the system pressure, the output pressure of pilot valve, the main valve core inertia force, the equivalent spring force, the damping force, and the steady-state flow force. Force balance equation of the main valve is as follows:

$$p_1 A_1 - p_2 A_2 = m_3 \frac{d^2 x_3}{dt^2} + K_{s3} (x_3 + x_0) + B_3 \frac{dx_3}{dt} + F_{f3} \quad (5)$$

where p_1 is system pressure, p_2 is the output pressure of the pilot valve, m_3 is the mass of main valve core, x_3 is the displacement of main valve core, K_{s3} is the equivalent spring stiffness acting on the main valve core, B_3 is the viscous damping coefficient of the main valve core.

The flow continuity equation at the main valve port is as follows:

$$Q_1 - Q_y = A_1 \frac{dx_3}{dt} + \frac{V_1}{\beta_e} \frac{dp_1}{dt} + Q + Q_2 \quad (6)$$

where Q_1 is the flow at the bottom of the main valve core, Q_y is the load flow, V_1 is volume of the main valve core lower chamber, Q is flow through the main valve core.

The pressure-flow equation of the main valve is as follows:

$$Q = K_{q2} x_3 - K_{c2} p_1 \quad (7)$$

where K_{q2} is the flow gain coefficient of the main valve port, K_{c2} is the flow-pressure gain coefficient of the main valve port.

4. Pressure control strategy of electro-hydraulic joint system based on RBF neural network sliding mode controller

4.1. Algorithm design

The model of the electro-hydraulic joint pressure system has great uncertainty and complexity of external interference. The traditional PID control algorithms are not only difficult to eliminate this effect in practical application, but also the adjustment and response time is not ideal. This paper designs an pressure control algorithm based on RBF neural network adaptive sliding mode. The principle of the control system is as shown in figure 4.

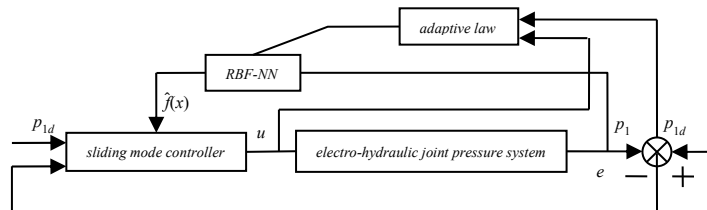


Figure 4. The principle of RBF neural network adaptive sliding mode control.

The definition of systematic error is $e = p_{1d} - p_1$. The sliding mode function is as follows:

$$s = c_1 \dot{e} + c_2 \ddot{e} + \ddot{e} \quad (8)$$

where p_{1d} is the ideal pressure signal, c_1 and c_2 are the sliding surface parameters to be designed. The values of c_1 and c_2 determine the dynamic performance of the system state on the sliding surface.

Because RBF neural network has very good approximation properties, it is adopted to approximate the uncertainties. The network algorithm is as follows:

$$h_i = \exp\left(-\frac{\|x - c_i\|^2}{2b_i^2}\right) \quad (9)$$

$$f(x) = W^{*T} h(x) + \varepsilon \quad (10)$$

where x is the input of network, i is network hidden layer node, $h = [h_i]^T$ is the output of Gauss function, W^* is the ideal weight of the network, ε is network approximation errors, $\varepsilon \leq \varepsilon_N$.

The input of the network is $X = [x_1 \ x_2 \ x_3]^T$. The output of the network is as follows:

$$\hat{f}(x) = \hat{W}^{*T} h(x) \quad (11)$$

$$f(x) - \hat{f}(x) = W^{*T} h(x) + \varepsilon - \hat{W}^{*T} h(x) = -\tilde{W}^T h(x) + \varepsilon \quad (12)$$

The Lyapunov function is defined as:

$$V = \frac{1}{2} s^2 + \frac{1}{2\gamma} \tilde{W}^T \tilde{W} \quad (13)$$

where $\gamma > 0$, $\tilde{W} = \hat{W} - W^*$.

$$\dot{V} = s(c_1 \dot{e} + c_2 \ddot{e} + f(x) + u - \ddot{p}_{1d}) - \frac{1}{\gamma} \tilde{W}^T \dot{\hat{W}} \quad (14)$$

The derivatives of sliding mode control rate and Lyapunov function are as follows:

$$u = -c_1 \dot{e} - c_2 \ddot{e} - \hat{f}(x) + \ddot{p}_{1d} - \eta \operatorname{sgn}(s) \quad (15)$$

$$\dot{V} = \varepsilon s - \eta |s| + \tilde{W}^T \left[\frac{1}{\gamma} \dot{\hat{W}} - s h(x) \right] \quad (16)$$

When $\eta > |\varepsilon|_{\max}$, the adaptive law is as follows:

$$\dot{\hat{W}} = \gamma s h(x) \quad (17)$$

$$\dot{V} = \varepsilon s - \eta |s| \leq 0 \quad (18)$$

It can be seen that the closed-loop system based on RBF neural network sliding mode control is asymptotically stable.

4.2. Simulation of electro-hydraulic joint pressure system based on RBF neural network adaptive sliding mode control

Sinusoidal signal $p_{1d} = \sin(x)$ is selected as an expected output signal of the system. c_1 and c_2 is determined by pole collocation method. The simulation model of electro-hydraulic joint pressure system is shown figure 5.

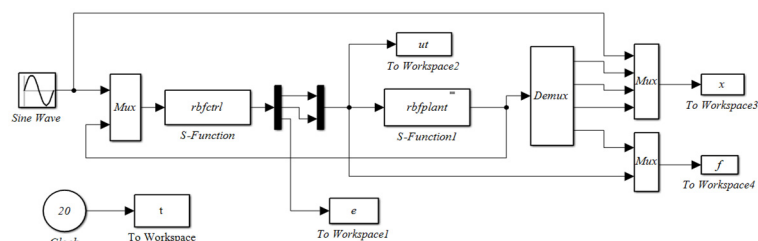


Figure 5. RBF neural network adaptive sliding mode control of pressure system

As shown in figure 6-7, the initial state value of the ideal expected pressure at $t = 0s$ is inconsistent with the actual value, resulting tracking error. However, the tracking error decreases rapidly after adjustment by the RBF neural network adaptive sliding mode controller. The actual pressure signal can quickly track the desired signal. The dynamic response performance and robustness of the system are better and the adjustment effect is obvious.

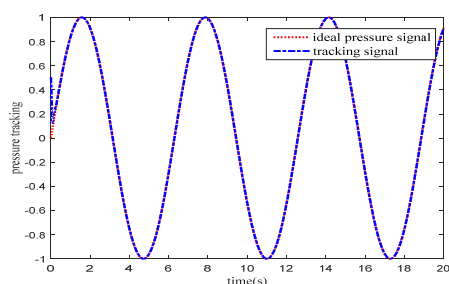


Figure 6. Pressure tracking curve.

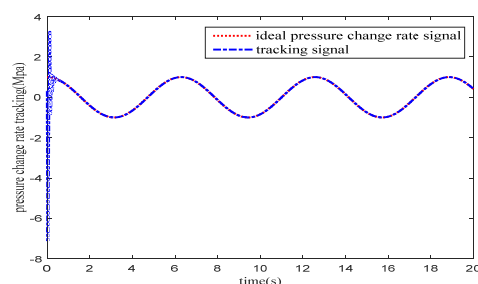


Figure 7. Rate tracking curve.

As shown in figure 8-9, at the initial time of system, because of the initial condition of the actual pressure signal and the desired signal are different, the pressure of system is larger. But the error signal is reduced in a short time due to the adjustment of the RBF neural network adaptive Sliding mode controller. Finally, the error signal has been small change near $e=0$. It shows that the control algorithm has good effect on the electro-hydraulic proportional relief valve system.

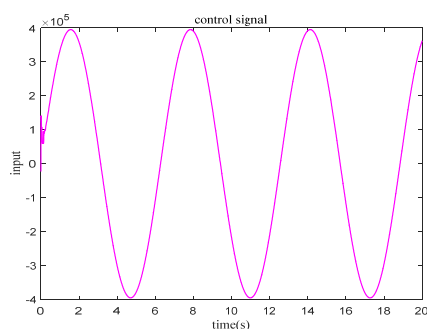


Figure 8. Control signal.

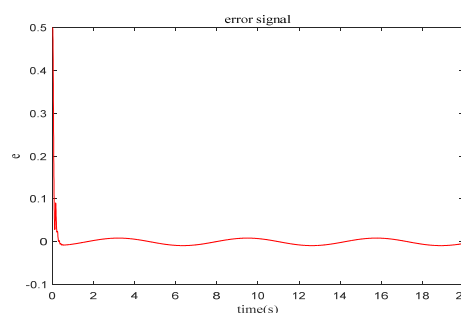


Figure 9. Error signal.

5. Conclusion

In view of the complexity of the typical load sensitive electro-hydraulic proportional relief pressure system, in this paper RBF neural network is used to approximate the uncertainties and the variable structure control rate is used to design sliding mode controller. The simulation analysis in Matlab shows that the output pressure curve approximates the expected curve and has good following performance. The simulation results show that the RBF neural network adaptive sliding mode

controller designed for electro-hydraulic joint system in this paper has high control precision, strong stability and robustness

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