Research on Hydraulic Robot for Pipe Handling Based on Adaptive Fuzzy-PID Control

Rong Guo 1,* , Wei Ma 1, Haisheng Zhong 2, Yuchao Liu 1

1 School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China
2 Beijing Lapsen Intelligent Technology Co., Ltd, Beijing 100083, China

*Corresponding author e-mail: grustb@126.com

Abstract. In order to improve the control performance of the pipe handling robot and the tracking effect of manipulator trajectory, the adaptive fuzzy-PID algorithm was applied to the joint control of robot arm. According to the nonlinear and time-varying parameters of valve-controlled asymmetric hydraulic cylinders extending and retracting movement, considering the influence of hydraulic pipeline and oil compressibility, a mathematical model of valve-control asymmetric hydraulic cylinder system was established. The dynamic response of the system model was studied based on the co-simulation of AMESim and Simulink. The results showed that compared with regular PID, the adaptive fuzzy PID controller could effectively suppress the nonlinear effect caused by oil compressibility, and reduce the response time of the system. At the same time, it could enhance the anti-interference ability of the system, and improve the dynamic tracking performance of the pipe handling robot.

1. Introduction

In the drilling operation, a large number of pipe handling work is required. The use of hydraulic robot for the pipe handling avoids the direct participation of the workers, reduces the safety risk and greatly improves the work efficiency [1]. Asymmetric hydraulic cylinders as joint actuators are widely used in the field of hydraulic robots because of their large bearing capacity, small workspace, relatively simple structure and high response speed [2]. However, due to the asymmetry of its structure, the parameters of the extension and retraction motion process are time-varying. In addition, the hydraulic system itself has some non-linear factors such as leakage, friction and hydraulic compression, which aggravates the difference of dynamic performance when the robot attitude changes and the load changes, and seriously affects the motion response and stability of the robot [3].

In this paper, the mathematical model of the valve-controlled asymmetric hydraulic cylinder system was established [4]. The adaptive fuzzy PID algorithm was applied to the system to improve the tracking effect of the manipulator trajectory.

2. Main structure and function

As shown in Figure 1, the pipe handling robot is mainly composed of a manipulator assembly, a mechanical arm assembly, a pulley assembly, a running platform assembly, a longitudinal transmission system assembly and a two-layer pipe arrangement [1].
The function of the mechanical arm assembly is to achieve the actions of extending, retracting, and mentioning the lowering. The robot arm is driven by a boom cylinder and an arm cylinder. There is a specially designed plunger cylinder inside the manipulator, and the clamping part is fixed with a clamping plate for clamping the pipe body. A contact sensor is mounted on the manipulator for detecting the relative position between the pipe body and the manipulator. After the pipe body contacts the sensor probe, the system sends a signal to the manipulator to clamp the pipe body.

3. System Modelling
The motion trajectory of the manipulator is obtained by precise mathematical model and realized by electro-hydraulic proportional hydraulic control. Due to system characteristics such as hydraulic leakage and pressure loss, only an approximate mathematical model can be obtained. In addition, since the quality of the whole equipment is very large and the inertia of starting and braking is relatively large, the adaptive fuzzy PID control is used to correct the control system and achieve the optimal adjusting of the manipulator.

3.1. Mathematical model of valve-controlled asymmetric hydraulic cylinder system
The pipe handling system is simplified as a valve-controlled asymmetric hydraulic cylinder model [5]. Proportional valves are positively overlapped, and the load is three kinds of loads: mass, damping and elasticity, as shown in Figure 2.

When the spool moves to the right, the load pressure-flow characteristics of the valve can be obtained as follows:

$$Q_L = K_q x - K_c P_L$$

Where $Q_L$ is the load flow, $K_q$ is the valve orifice flow gain. $K_c$ is the pressure flow gain.
Formula (2) is the hydraulic cylinder load flow equation.

$$Q_L = C_{te} P_L + \frac{V_t}{4\beta_e} \dot{P}_L + A_1 \dot{y}$$

Where $C_{te}$ is the equivalent total leakage coefficient. $V_t$ is the equivalent volume of hydraulic cylinder. $K_c$ is the pressure flow gain. $\beta_e$ is volumetric elastic modulus of hydraulic oil.

Formula (3) is the force balance equation of hydraulic cylinder.

$$p_1 A_1 - p_2 A_2 = M\ddot{y} + C \dot{y} + K y + F$$

By Laplace transformation of formulas (1), (2) and (3), the mathematical model of valve-controlled asymmetric hydraulic cylinder can be expressed as formula (4), which is related to the displacement $x$ of valve spool and external load $F$ of the system.
\[
Y(s) = \frac{K_a K_{uc} x - K_{ue} \frac{V}{A_h} (1 + \frac{1}{2 \xi_h s + 1}) F(s)}{s^{\frac{1}{2}} + 2 \xi_h s + 1}
\]

Where \(K_a\) is the gain of proportional amplifier. \(K_{uc}\) is the gain of proportional directional valve. \(K_{ce}\) is the pressure flow gain. \(A_h\) is the effective working area of the hydraulic cylinder, take \(A_1\) when the piston rod is extended, and take \(A_2\) when the piston rod is contracted; \(\xi_h\) is the damping ratio of hydraulic cylinder-load mass system; \(\omega_n\) is the natural frequency of hydraulic cylinder-load mass system.

Ps- system pressure; P0- return pressure of oil; P1- rodless cavity pressure; A1- piston action area of rodless cavity; P2- rod cavity pressure; A2- piston action area of rod cavity; PL- load pressure; M- total mass of piston rod and load; F- external load; B- viscous damping coefficient; K- load elasticity coefficient; x- displacement of spool; y- displacement of piston rod

Figure 2. Schematic diagram of controlled asymmetric hydraulic cylinder

3.2. Adaptive fuzzy PID control

The principle of adaptive fuzzy PID algorithm is shown in Figure 3. The universe of the deviation \(e\) and the deviation change rate \(ec\) are set to \{-3, -2, -1, 0, 1, 2, 3\}; The universe of \(\Delta kp\), \(\Delta ki\), and \(\Delta kd\) is set to \{-3, -2, -1, 0, 1, 2, 3\}; The seven quantization levels of the fuzzy subset \{NB, NM, NS, ZO, PS, PM, PB\} correspond to \{-3, -2, -1, 0, 1, 2, 3\}. NB adopts Z-type membership function, NM, NS, ZO, PS and PM adopt triangular membership function, and PB adopts S-type membership function. Taking \(\Delta kp\) as an example, the membership function of \(\Delta kp\) is shown in Figure 4.

Figure 3. Schematic diagram of adaptive fuzzy PID control
According to the fuzzy control rule shown in Table 1, the fuzzy rule table is built in the fuzzy toolbox of MATLAB, and the input/output membership curve of the fuzzy system of $\Delta k_p$ can be obtained as shown in Figure 5.

**Table 1. Fuzzy control rule table of $\Delta k_p$**

| $e$  | $e_c$ | NB | NM | NS | ZO | PS | PM | PB |
|------|-------|----|----|----|----|----|----|----|
| NB   | PB    | PB | PM | PM | PS | ZO | ZO |
| NM   | PB    | PB | PM | PM | PS | ZO | NS |
| NS   | PM    | PM | PM | PS | ZO | NS | NS |
| ZO   | PM    | PM | PS | ZO | NS | NM | NM |
| PS   | PS    | ZO | NS | NS | NM | NM | NM |
| PM   | PS    | ZO | NS | NM | NM | NM | NB |
| PB   | ZO    | ZO | NM | NM | NM | NB | NB |

Figure 4. Membership curve of $\Delta k_p$

Figure 5. Fuzzy system input and output characteristic surface of $\Delta k_p$

### 4. Simulation analysis

#### 4.1. Co-simulation model of AMESim and MATLAB/Simulink

As shown in Figure 6, the dynamic response simulation model of the valve-controlled hydraulic cylinder of the pipe handling robot is built by the Hydraulic Component Design module in the simulation software AMESim [6]. As shown in Figure 7, the adaptive fuzzy PID control model is built by software MATLAB/Simulink [7]. Through the interface technology between the two softwares of MATLAB/Simulink and AMESim, the data transmission is realized, which not only exerts the powerful data processing capability of MATLAB, but also highlights the advantages of AMESim in the field of
fluid machinery simulation [8]. The main physical parameters of the simulation model are shown in Table 2.

![Co-simulation model in AMESim environment](image)

**Figure 6. Co-simulation model in AMESim environment**

![Co-simulation model in MATLAB/Simulink environment](image)

**Figure 7. Co-simulation model in MATLAB/Simulink environment**

**Table 2. Simulation model physical parameters and values**

| Parameter                                      | Value  |
|------------------------------------------------|--------|
| System oil supply pressure $p_s$/ MPa          | 16     |
| System flow $Q$/ L·min$^{-1}$                   | 30     |
| Oil density $\rho$/ kg·m$^{-3}$                 | 850    |
| Oil temperature $T$/°C                           | 40     |
| Hydraulic oil modulus $E_0$/ MPa               | 700    |
| Rodless cavity area $A_1$/ m$^2$                | 0.0123 |
| Rod cavity area $A_2$/ m$^2$                    | 0.0059 |
| Total mass of load and hydraulic actuator $M$/ kg | 1500   |
| Viscous friction coefficient $B$/ N·s·m$^{-1}$  | 200    |
| Load elasticity coefficient $K$/ N·m$^{-1}$     | 0      |
4.2. System response analysis
A group of satisfactory conventional PID parameters are obtained by trial and error method and set to the initial value of adaptive fuzzy PID. The values are: P=26.9, I=1, D=0.018.

4.2.1. Square wave signal response. Set the frequency of the square wave signal to 1 Hz, and add 3kN interference force in the 1~2s time period. The direction of the force is the same as the retraction movement direction of the hydraulic cylinder. The simulation result is shown in Figure 8. The adjusting time of the system response is shown in Table 3.

| Control method          | Adjusting time /s |
|-------------------------|-------------------|
|                         | 0~0.5s | 0.5~1s | 1~1.5s | 1.5~2s |
| Regular PID             | 0.052   | 0.045  | 0.064  | 0.040  |
| Adaptive fuzzy PID      | 0.039   | 0.037  | 0.041  | 0.035  |

![Figure 8. The system responds in the square wave signal](image)

As can be seen from Figure 8 and Table 3, the two control algorithms were not over-tuned. Compared with the regular PID control, the adaptive fuzzy PID control effectively suppresses external interference, reduces the adjust time of the system response, and improves the tracking speed of the system.

4.2.2. Sinusoidal signal response. As shown in Figure 9, the response of the system is excited by a sinusoidal signal with a frequency of 2 Hz.

![Figure 9. The system responds in the sinusoidal wave signal](image)
As can be seen from Figure 9, the amplitude of the sinusoidal tracking of the regular PID control is 99.28% of the amplitude of the input signal, and the phase lag is 0.1 rad; the amplitude of the sinusoidal tracking of the adaptive fuzzy PID control is 99.95% of the input signal and the phase lag is 0.06 rad. Adaptive fuzzy PID control effectively improves the accuracy and speed of trajectory tracking.

5. Conclusion

The adaptive fuzzy PID control algorithm was applied to the valve-controlled asymmetric hydraulic cylinder to control the movement of the joint of the hydraulic robot arm, and the AMESim-Simulink co-simulation model of the system was built. The effects of adaptive fuzzy PID control and conventional PID control on the square wave signal and sinusoidal signal of the system were compared and analyzed. The simulation results showed that the adaptive fuzzy PID control effectively suppressed the influence of system nonlinearity and time-varying parameters, improved the anti-interference ability of the system, had better robustness, and improved the tracking performance of the end of the hydraulic robot manipulator.

Acknowledgments

This work was financially supported by the National Key Research and Development Program of China (Grant No. 2016YFC0802905).

References

[1] Tong Zheng, Zheng Lichen, Niu Haifeng. Design of Racking Board Pipe System for Land Rig [J]. China Petroleum Machinery, 2011, 39(8): 27-29+1.
[2] Chen Bin, Pei Zhongcai, Tang Zhiyong. Self-tuning Fuzzy-PID Control for Hydraulic Quadruped Robot [J]. Journal of Harbin Institute of Technology, 2016, 48(09): 140-144.
[3] Ding Wensi, Liu Kun, Ding Yunke. Fuzzy PID Controller Optimized by Particle Swarm Optimization for Valve Controlled Asymmetric Servo Cylinder [J]. Chinese Hydraulics & Pneumatics, 2017(9): 17-23.
[4] Wang Guiyun, Wang Yongqin, Yan Xingchun. Mathematics Modeling and Simulation Analysis of Dynamic Characteristics for Hydraulic Cylinder Controlled by Servo-valve [J]. Advanced Engineering Sciences, 2008, 40(05): 195-198.
[5] Rahmat M. F, Zulfatman, Husain A R, et. al. Modeling and controller design of an industrial hydraulic actuator system in the presence of friction and internal leakage [J]. International Journal of the Physical Science. 2011, 6(14): 3502-3517.
[6] Bai Yanhong, Quan Long, Hao Xiaoxing. Modeling of Hydraulic Valve-controlled Cylinder Power Mechanism Based on Flow Approximation [J]. Journal of Mechanical Engineering, 2014, 50(24):179-185.
[7] Jiang Changhong, Zhang Yongheng, Wang Shenghui. PID Parameter Optimization of the Grate Cooling Electro-hydraulic Position Servo Systerm Based on Adaptive Particle Swarm Optimization Algorithm [J]. Chinese Hydraulics & Pneumatics, 2016, (7):44-49.
[8] Meng Fanhu, Zhao Susu, Yu Zipeng. Single Neural Element PID Control Based on AMESim and Simulink Co-simulation for Seed Governing System of value-controlled Motor [J]. Chinese Hydraulics & Pneumatics, 2016, (7):83-88.