Research on stability of hydraulic system based on nonlinear PID control

Tong Liu*

Abstract: In order to avoid the interference of the excavator hydraulic control system by external factors, the output stability of the hydraulic control system has to be improved. The method introduces a nonlinear Proportional integral differentiation (PID) controller with deviation correction parameters through the simulation verification of the control effect and the creation of excavator hydraulic drive diagram. PID, whose full English name is proportional integral derivative, is a mathematical and physical term. The controller is modeled in Matlab/Simulink. Finally, the whole hydraulic system is co-simulated by the interface of AMESim and Matlab. The simulation results show that the system model realizes the co-simulation through the interface combination of the two software, which is more accurate than the traditional PID control, and the pressure and flow fluctuation are smaller, which can suppress the interference of external load mutation, and improve the stability of the hydraulic drive output of the excavator. The validity of the experiment is verified.

Keywords: hydraulic system, nonlinear PID control, stability of hydraulic system

1 Introduction

With the improvement of car design and manufacturing, the stability of car driving is getting better and better, which makes people drive faster and faster. The safety of vehicle driving has attracted much attention, and an excellent braking system is an important guarantee for the safety of vehicle driving [1]. There are many reasons for vehicle accidents, such as violation of road rules, drunk driving, uneven road surface, large traffic flow, brake system failure, etc. According to incomplete statistics, most of the major traffic accidents occur because of the brake system failure, brake system has become one of the main problems in the current automotive technology research. With the rapid development of electronics industry, control technology has also been widely used in automobile braking system [2]. Automobile brake control technology can respond quickly in an emergency, so as to avoid serious traffic accidents. The hydraulic system of large excavator mainly includes hydraulic cylinder, hydraulic pump, hydraulic motor, control valve, and oil pipe. Hydraulic drive takes oil as energy medium and converts mechanical energy into pressure energy through hydraulic pump to complete various driving actions [3]. With the rapid development of electro-hydraulic technology, the control methods of excavators are constantly improved, and gradually moved to the road of intelligent development. In the process of hydraulic drive of excavator, if the speed control is unstable, it not only causes excessive fuel consumption, but also leads to serious jitter of excavator. Therefore, the research on hydraulic drive control system of excavator plays a role in promoting the market competitiveness of excavator. In order to improve the stability of hydraulic control of excavators, researchers have conducted extensive research on hydraulic control technology of excavators [4]. This study establishes the hydraulic driving diagram model of excavator and deduces the piston motion equation. The nonlinear Proportional integral differentiation (PID) control method is used to design the hydraulic drive control system of excavator. In the case of no load mutation and load mutation interference, the PID control method and nonlinear PID control method of excavator are simulated, respectively, which provides theoretical basis for in-depth study on the stability of hydraulic control system of the excavator. In the process of hydraulic drive, if the speed control is unstable, it will not only cause excessive fuel consumption, but also cause the excavator to vibrate seriously. Therefore, the study of the hydraulic drive control system of the excavator has a promoting effect on improving the market competitiveness of the excavator.

Yan and Zhu studied the braking torque control method of electric vehicles, designed the simulation model of automobile braking, and conducted simulation verification of...
braking torque under different working conditions, so as to prevent vehicle side slip [5]. Su et al. studied the safety and comfort control system of automobile braking and designed the fuzzy control system. Through simulation, the effect of emergency braking was verified, which can appropriately improve the comfort under the premise of ensuring safety [6]. Zhao studied the fuzzy PID control method of hydraulic excavator, created a bucket hydraulic system model diagram, improved the traditional PID control, designed the fuzzy PID control process, and conducted simulation. The hydraulic system adopted fuzzy PID control not only has fast response speed, but also has high tracking accuracy [7]. Tan and Ha conducted some research on energy consumption of excavator hydraulic system. It was found that the efficiency of the hydraulic system of the excavator was lower when the compound action was performed than when the excavator was operated alone. The reason for the low efficiency of the system is that the outlet pressure of the load-sensitive pump is higher than the maximum load pressure by a certain value. In the circuit with low load, all the pressure is lost on the pressure compensation valve. Aiming at the problem of pressure loss in pressure compensation, a control method is proposed to realize pressure compensation, and the energy consumption of the load-sensitive hydraulic system that adopts the control method to realize pressure compensation is lower than that of the traditional load-sensitive hydraulic system [8].

In this study, the hydraulic system is further studied by introducing a nonlinear PID controller with deviation correction parameters. The controller is modeled in Matlab/ Simulink. Finally, the whole hydraulic system is co-simulated by the interface of AMESim and Matlab.

2 Hydraulic system

2.1 Calculation of formation earth pressure

Before the construction of shield tunnel, different tunnel construction methods shall be considered and proposed in advance based on the earth pressure and groundwater pressure, the foundation earth pressure theory and the actual construction experience. First, the tunnel is divided into shallow tunnel and deep tunnel according to the depth of tunnel construction. Then, according to the different performance indexes of local soil composite, different methods are finally determined to calculate the construction earth pressure. The excavator PID control and nonlinear PID control methods are simulated, respectively, which provides a theoretical basis for the in-depth study of the stability of the excavator hydraulic control system.

According to whether the soil covering the top of the tunnel can form a natural arch, the tunnel is divided into deep-buried tunnel and shallow-buried tunnel. The loose pressure value of soil surrounding rock in deep-buried tunnel is determined by the equivalent load height of construction. According to experience, 2–2.5 times of the equivalent load height is used to divide deep-buried tunnel and shallow-buried tunnel, namely:

$$\text{Hp} = (2 ~ 2.5) \text{hp},$$

where $\text{Hp}$ is the boundary depth between deep- and shallow-buried tunnels; $\text{hp}$ is the average height of construction collapse, $\text{hp} = 0.45 \times 2^b \omega$; $S$ is the type of surrounding rock, such as class III surrounding rock, $S = 3$; $\omega$ is the influence width factor, and $\omega = 1 + i(B - 5)$; $B$ is the net width of the tunnel, in m; $j$ is based on $B = S_m$, and $B$ is the increase/decrease rate of surrounding rock pressure when increasing/decreasing 1 m. When $B < 5$ m, $I = 0.2$ when $b > 5$ m, $I = 0.1$.

In the construction of deep buried tunnel, the loose earth pressure before shield construction can be calculated more accurately based on the theoretical formula. In the actual construction project, according to the railway tunnel design code, the vertical distribution of the loosening pressure $q$ must also be calculated. The calculation formula is:

$$q = 0.45 \times 2^b \gamma \omega,$$

where $\gamma$ is the surrounding rock density.

The lateral pressure is produced with the vertical pressure, and the lateral horizontal loosening pressure can be calculated by empirical formula $\sigma a$:

$$\sigma a = Ea \times az.$$  

The calculation formula of $Ea$ is shown in Table 1.

2.2 Mathematical model of hydraulic system

The working principle of hydraulic drive is as follows: When the hydraulic system is working, the power supply of the motor is turned on, and the motor rotates and drives the hydraulic pump to work. The hydraulic pump pumps the hydraulic oil out of the tank, and pumps the hydraulic oil out of the one-way throttle valve $Q$ [9]. Under the action of the hydraulic oil to two-way solenoid valve inlet P
location, the electromagnetic valve opens the oil outlet A (valve on the left side of the battery power), the hydraulic oil flows into the hydraulic cylinder from A to rodless cavity, and the rodless cavity filled with hydraulic oil pushes forward the hydraulic pole; after the drive, its connected structure does a clockwise motion. When the solenoid valve at oil outlet A closes (battery valve left power), and the one at B opens (battery valve right power), the hydraulic oil flows from P to B and into the rod chamber of the hydraulic cylinder. After the rod cavity is filled with hydraulic oil, the oil outlet A will be opened again. The hydraulic oil in the rodless chamber flows out from A to T and through port P, and then returns to the tank through one-way throttle valve [10].

The relationship between load displacement and piston displacement is as follows:
\[ x(t) = K_x \delta(t). \]  
(4)

Taking the derivative of Eq. (4), the load speed can be obtained:
\[ v(t) = dx(t)/dt. \]  
(5)

2.3 Hydraulic system control

2.3.1 PID control

PID control consists of a proportional unit P, integral unit I, and differential unit D, and its control principle is shown in Figure 1.

The error equation of PID control is:
\[ e(t) = r(t) - y(t), \]  
(6)
where \( r(t) \) is the theoretical input value; and \( y(t) \) is the actual output value.

The error \( e(t) \) is added after the proportion, integral, and differential adjustment, and the output of PID controller is obtained, so as to realize the online control of the actuator. PID control equation interface is:
\[ u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt}, \]  
(7)
where \( K_p \) is the proportionality coefficient; \( K_i \) is the integral coefficient; and \( K_d \) is the differential coefficient.

| Table 1: Lateral horizontal loosening pressure gauge |
|-----------------------------------------------|
| Surrounding rock classification | VI | V | IV | III | II | I |
| Level of loosening pressure | 0 | (0–1/6)q | (1/6–1/3)q | (1/3–1/2)q | (1/2–1)q |

2.3.2 Nonlinear P control

The output control quantity \( u(t) \) of traditional PID control is affected by the linear combination of the proportional coefficient, integral coefficient, and differential coefficient of error \( e(t) \), \( r(t) \) is generally non-differentiable and discontinuous, and the output control result \( y(t) \) is also affected by the external noise environment [11]. Therefore, the deviation signal is not differentiable, and its differential control signal is difficult to be collected. In order to overcome the above shortcomings, the nonlinear P control method is used to replace the traditional PID control.

The variable equation of the hydraulic control system is:
\[ e(t) = Z_{11}(t) - Z_{22}(t), \]  
(8)
\[ e(t) = Z_{12}(t) - Z_{22}(t), \]  
(9)
\[ e(t) = \int_0^t (r(t) - y(t)) dt, \]  
(10)
where \( e_1, e_2, \) and \( e_0 \) are the errors; \( Z_{11} \) and \( Z_{12} \) are the input signals; \( Z_{21} \) and \( Z_{22} \) are the feedback signals.

The nonlinear group is used to process the error differentiable and integral of the traditional PID control to produce the control quantity \( u(t) \). Different from traditional PID control, the nonlinear PID control adopts the nonlinear to process the input and output signals to obtain the new error differential and integral.

The nonlinear P control equation is:
\[ u(t) = \beta_0 f_a(e_0, a_0, \delta) + \beta_1 f_a(e_1, a_1, \delta) + \beta_2 f_a(e_2, a_2, \delta). \]  
(11)

2.4 Establishment of AMESim model of hydraulic system

AMESim is a multi-domain system simulation integration platform developed by Malting Company, which can create and run multi-physical field simulation model to analyze complex system characteristics and support control system design, from early technical parameter determination to subsystem testing. Users can store and manage
mechanical and control models and data across different departments: configuration management, system integration, and architecture verification can be supported through AMESim [12].

As a standard platform for system simulation, AMESim has the following characteristics:

1) AMESim system engineering modeling and simulation standard environment enables modules of different fields to directly connect physically.

2) Multidisciplinary system engineering modeling and simulation can be realized by AMESim on its own single platform in one day. AMESim provides an intelligent solver for users, which can automatically select the optimal algorithm according to the system model. In the simulation process, it can automatically adjust the integral step size and switch the optimal integral algorithm according to the dynamic characteristics of the system at different moments, which greatly reduces the system simulation time and improves the simulation accuracy.

3) AMESim improves complete basic elements for users, which are the minimum elements extracted from the physical system. When building a complex model, users can establish a detailed engineering system with as few elements as possible.

4) AMESim uses engineering technology language as modeling language, so its user needs to be an engineering and technical personnel in the automotive aerospace and other engineering research and development department, first choosing the physical model of graphics as modeling method, which is the most ideal modeling simulation.

5) AMESim provides a secondary development platform for users, and users can carry out standardized and graphical secondary development through AMESet in AMESim during the secondary development, users can embed the C or Fortran language codes written by themselves in the form of graphics into the AMESim software package. In addition, users can directly call the model source code in AMESim.

6) AMESim provides users with four different modeling methods: basic element level, block graph level, mathematical equations level, and component level. Users, according to their own special skill, when modeling can make flexible use of these modeling ways, while at the same time, can also comprehensively use several methods.

7) After their model is set up using AMESim, users can also use the AMESim complete analysis tools for the optimization analysis of their own system model, such as system solution of the eigenvalue Bode graph, Nichols graph, Nyquist graph root locus analysis, modal analysis tools, frequency general analysis tools such as fast Fourier Transform order analysis spectrogram, and model simplification tools such as activity index.

3 Simulation analysis

In order to compare the effect of traditional PID control and nonlinear PID control, Matlab software is used to simulate the speed response of the hydraulic servo system, and the simulation parameters are set as follows: $A_1 = 0.08 \text{m}^2$, $K_{qs} = 1.32 \text{m}^2/\text{s}$, $K_{cs} = 3.22 \times 10^{-9} \text{m}^5/(\text{N} \cdot \text{s})$, $M = 13,000 \text{kg}$, $\beta = 1.0 \times 10^9 \text{Pa}$, $\alpha = 0.8$, $\delta = 5$, $\beta_1 = 9.5$, $\beta_2 = 40$, and $\beta_3 = 1.2$. Hydraulic cylinder piston reference movement speed is $\beta = 0.2 \cos(n \cdot t) \text{m/s}$. Under the condition of no load, the simulation results of hydraulic cylinder piston speed response curve are shown in Figure 2.

In MATLAB7.0, the fuzzy toolbox can be seamlessly connected with Simulink through the fuzzy logic toolbox to establish the fuzzy reasoning system, and can immediately be simulated in Simulink simulation environment.

---

![Figure 1: PID control process.](image-url)
for its simulation analysis. Simulink has the corresponding fuzzy logic block diagram (Fuzzy LogicBlock), the block diagram is copied to the Simulink simulation model established by the user, and the fuzzy inference matrix name of the fuzzy logic controller block diagram is the same as the name of the fuzzy inference system established by the user in Matlab workspace, and the connection between the fuzzy inference system and Simulink can be completed in Matlab command. The fuzzy rule editor can be activated by typing rule Edit “in the window” or selecting the menu of fuzzy rules in the editor of the fuzzy reasoning system [13]. The fuzzy rule editor provides a graphical interface for adding, modifying, and deleting fuzzy rules. The fuzzy rule editor provides a text editing window G-1 for the input and modification of rules. There are three forms of fuzzy rules, namely, linguistic ones, symbol type 1, and type index. In the bottom of the window there is a drop-down list box, for the user to choose a certain rule type to establish rules. Fuzzy rules editor should first define the editor to use all of the input and output variables, and then select the input/output variables on the window and the connection between the different input variables and the value of the weight, finally click on add rule button to display the rule in the editor’s display area.

Under the condition of no load interference, both traditional PID control and nonlinear PID control method can realize the tracking of hydraulic cylinder piston speed response. Under the condition of load (load mass is 100 kg), the simulation results of hydraulic cylinder piston speed response curve are shown in Figure 3.

According to Figure 3, under the condition of load interference, when the transport time is 3 s, the traditional PID control speed will have a large jitter phenomenon, and the speed decreases from 0.2 to 0.025 m/s, while the nonlinear PID control speed basically remains unchanged without mutation. Therefore, nonlinear PID control can suppress the disturbance of sudden load and keep the stability of hydraulic drive system.

In this chapter, the fuzzy adaptive PID controller is designed by adding the popular fuzzy control into the control of the hydraulic propulsion system of shield tunneling machine. The fuzzy PID controller has faster response speed and anti-interference ability through simulation comparison. When there is interference from the outside, fuzzy PID control can quickly eliminate the disturbance and make the output fluctuate in a small range, and quickly reach a stable state. It can be seen from the simulation curve that the fuzzy PID controller adjustment time is short and the system response curve is stable.

4 Conclusion

Relevant tests are carried out on the hydraulic test bench, and the test and simulation results are consistent, which verifies the correctness of the simulation model. Finally, the stability of the load-sensitive hydraulic system of the synchronous gravel-sealing truck is further studied when the two circuits work at the same time, and the displacement of the main valve spool of the multi-way valve, the spring stiffness, and load of the pressure compensation
valve are quantitatively studied by means of simulation. When the two circuits of the hydraulic system work at the same time, the effects of the spring stiffness, the length and inner diameter of the feedback pipe and the diameter of the damping hole on the stability of the hydraulic system are also studied. The speed of the piston remains basically unchanged, and the tracking error is small. Using nonlinear PID to control the hydraulic drive system of the excavator can suppress the disturbance of the sudden change in the external load and improve the stability of the excavator hydraulic drive output of the excavator.

In this study, on the basis of pressure and flow compound control, a nonlinear PID controller with deviation correction parameters is introduced, and the control model is established in Matlab/Simulink, and the nonlinear PID parameters are optimized and analyzed by NCD Block toolbox. Finally, the hydraulic system model in AMESim and the nonlinear PID control model in Simulink are combined to achieve co-simulation through the interface of the two software. Aiming at the unstable response speed of excavator hydraulic drive, a nonlinear PID control method is designed. The main conclusions are as follows:

1. Using the traditional PID control method, the piston movement of the hydraulic drive system of the excavator is unstable, can be easily affected by the load interference, and the jitter range is large.

2. The nonlinear PID control method can adjust the parameters of the controller adaptively online, suppress the interference of sudden load, and the piston movement of the hydraulic cylinder is relatively stable.

3. Using Matlab software to simulate non-linear PID control, the piston speed response curve that can be obtained can improve the irrationality of PID control in time, thus improving the design efficiency.

Funding information: The author states no funding involved.

Conflict of interest: Author states no conflict of interest.

References

[1] Wang R, Man F, Yan D, Hu B, Wang J. Research on multi-loop nonlinear control structure and optimization method of PMLSM. IEEE Access. 2019;7:165048–59.

[2] Sang Y, Sun W. Study on the compensation control of electro-hydraulic servo force loading in nonlinear variable load condition. Proc Inst Mech Eng. 2019;233(6):677–88.

[3] Xiang L, Zhu ZC, Rui GC, Dong C, Gang S, Yu T. Force loading tracking control of an electro-hydraulic actuator based on a nonlinear adaptive fuzzy backstepping control scheme. Symmetry. 2018;10(5):155.

[4] Sun C, Fang J, Wei J, Bo H. Nonlinear motion control of a hydraulic press based on an extended disturbance observer. IEEE Access. 2018;6(99):18502–10.

[5] Yan B, Zhu L. Research on milling stability of thin-walled parts based on improved multi-frequency solution. Int J Adv Manuf Technol. 2019;102(1):1–11.

[6] Su L, Wang Q, Qin X, Shan Y, Zhou B, Wang J. Analytical solution of the one-dimensional nonlinear richards equation based on special hydraulic functions and the variational principle. Eur J Soil Sci. 2018;69(6):980–96.

[7] Zhao LH, Jiao KF, Li DJ, Zuo S. System reliability analysis of seismic pseudo-static stability of rock wedge based on nonlinear Barton–Bandas criterion. J Cent South Univ. 2020;27(1):3450–63.

[8] Tan VN, Ha C. Experimental study of sensor fault-tolerant control for an electro-hydraulic actuator based on a robust nonlinear observer. Energies. 2019;12(22):4337.

[9] Sharma A, Kumar R. A framework for pre-computed multi-constrained quickest QoS path algorithm. J Telecommun Electron Comput Eng. 2017;6:73–7.

[10] Shiriram S, Jaya J, Shankar S, Ajay P. Deep learning-based real-time AI virtual mouse system using computer vision to avoid COVID-19 spread. J Healthc Eng. 2021;2021:8133076.

[11] Liu X, Ma C, Yang C, Diao Y. Power station flue gas desulfurization system based on automatic online monitoring platform. J Digital Inf Manag. 2015;13(6):480–8.

[12] Huang R, Zhang S, Zhang W, Yang X. Progress of zinc oxide-based nanocomposites in the textile industry. IET Colab Intell Manuf. 2021;3(3):281–9.

[13] Guo E, Jagota V, Makhattha M, Kumar P. Study on fault identification of mechanical dynamic nonlinear transmission system. Nonlinear Eng. 2021;10(1):518–25.