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Design and Simulation Research of Active Heave Compensation Hydraulic Control System

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Abstract

According to the principle of active hydraulic waveform compensation control, a mathematical model of each module of the hydraulic components is constructed, and then integrated into the transfer function of the entire hydraulic system. The mathematical models of fuzzy PID and auto-disturbance control are established respectively, the control system simulation loop is constructed through Matlab/ Simulink, and the simulation experiment is carried out. The results show that the auto disturbance rejection control is more robust than fuzzy PID control, has higher control accuracy, and has good compensation performance, and its control can be given priority in actual production.

Keywords

ADRC, Fuzzy PID, Heave compensation, Ship Engineering.

1. Introduction

When a ship is operating at sea, it will be affected by the motion of the waves, which makes it difficult to maintain a stable posture in the vertical and horizontal directions. The dynamic positioning system can solve the problem of the ship's attitude and position control in the horizontal direction, and the influence of the ship's heave motion in the vertical direction on the offshore operations can be solved by the heave compensation system. The heave compensation system can be used for sonar detection system, offshore lifting operation platform and remotely operated submersible operation, etc[1]. . When the remotely operated submersible performs deep-sea operations, the armor cable bears the weight of the submersible and the repeater, and releases the submersible to a certain operating depth[2]. The heave compensation control system can effectively reduce the impact force formed on the armour cable due to the heave motion of the mother ship, and avoid the armour cable break due to the heave vibration of the mother ship when the submersible is docked with the repeater, and even the loss of the submersible Danger. In the current surface support system of advanced remotely operated submersibles, the heave compensation unit has also become a necessary configuration device. Therefore, it is very practical to design a heave compensation control system that can adapt to severe sea conditions and meet the safety of offshore operations.

According to the working mode of the control system, the heave compensation system can be divided into active and passive[3]. The passive heave compensation system mainly relies on a hydraulic or pneumatic buffer structure with greater damping to offset the heave displacement movement of the ship under the action of sea waves. The active heave compensation system obtains the information of the ship's heave movement through sensors, and actively controls the movement of the winch to retract and unwind the rope to offset the influence of the ship's heave movement on the underwater operation of the submersible. The passive heave compensation system is relatively mature at present, but the passive heave compensation system has disadvantages such as low compensation accuracy, limited compensation distance, and large area. The active heave compensation system not only has the advantages of small size and high control accuracy, but also adapts to complex sea conditions. At the same time, the compensation distance is not limited, and it is easy to transplant to the existing winch system. Therefore, the active heave compensation control system Has always been the main research direction in the field of ocean engineering

PID controller is widely used in industrial control field because of its simple structure and easy parameter adjustment. But when applied to the nonlinear and time-varying control objects such as heave compensation system using hydraulic winch, PID controller can hardly achieve satisfactory control effect. With the development of fuzzy control algorithms, many controllers that combine fuzzy control algorithms and conventional PID are used in many non-linear and large lag systems, and have achieved good control effects[4-6].

With the advent of Active Disturbance Rejection Control Technology (ADRC)[7], because it does not need to know the precise model of the controlled object, it has a certain degree of robustness and reliability and anti-disturbance ability for nonlinear unknown model system control, Especially for systems with non-linear dynamic changes, modeling errors and other factors, it has unique advantages, which has caused extensive research by scholars at home and abroad.

This article explores the pros and cons of fuzzy PID control and active disturbance rejection control for four-level sea conditions. Research shows that the control characteristics and robustness of active disturbance rejection are better than fuzzy PID.

2. Mathematical model of each element

During the offshore hoisting operation of cranes, the heave compensation system is more complicated due to the influence of environment, assembly accuracy and personnel operations. In order to analyze the working principle of the system more clearly, the following assumptions are made: the fixed pulley and winch are rigidly fixed on the crane, and the crane does not move relative to the hull; the influence of the movement of the weight on the reaction force of the hull is not considered; hydraulic cylinders and accumulators The seal is good and there is no leakage; the oil temperature is constant when the hydraulic cylinder is working; the balance position of the piston is in the middle of the cylinder; all the pipes are short and thick, regardless of the influence of fluid flow on the dynamic characteristics of the system, and the structure of the system is simple The picture is shown in Figure 1. The mathematical model of each component is established as follows.

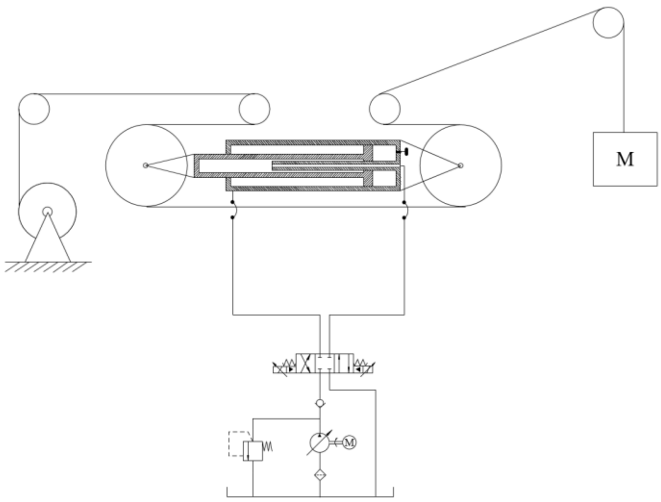

Fig. 1 Structure diagram of hydraulic system

Because the designed compensation system has a four-fold increase in distance, the equations of motion of the hull, load and piston can be expressed as:

$$x_G = 4x_h + x_s \tag{1}$$

In the formula, x_G represents the absolute displacement of the load; x_h represents the displacement of the piston rod relative to the cylinder; x_s represents the absolute displacement of the hull;

Considering that this system is a large inertia system, the external resistance is relatively small, and other external interferences can be ignored. Only the cable tension and load gravity are considered. The forces are as follows:

$$M_G\ddot{x}_G = T - M_G\mathrm{g} \tag{2}$$

In the formula, M_G represents the load mass; T represents the rope tension.

Considering that the compensation cylinder is placed horizontally, the weight of the piston can be considered. At this time, the hydraulic cylinder is subjected to the compensation force generated by the hydraulic oil provided by the oil pump and the servo valve, the cable pressure, the oil viscous damping force, and the friction force is relatively small. can be ignored. So there is the following formula:

$$P_dA_d - 4T = M_h\ddot{x}_h + B_h\dot{x}_h \tag{3}$$

In the formula, P_dA_d represents the active compensation force; $4T$ considers the effect of quadruple distance extension, at this time the cable pressure is four times the tensile force of the load; $M_h\ddot{x}_h$ represents the inertial force of the piston rod and pulley block; $B_h\dot{x}_h$ represents the oil of the compensation cylinder Damping force.

Considering the law of conservation of flow, and the internal and external leakage of the servo valve and compensation cylinder is small and can be ignored, and ignoring the impact of pipeline loss on the entire system, there are:

$$Q_d = A_d\frac{dx_h}{dt} + \frac{V_d}{4\beta_e}\frac{dP_d}{dt} \tag{4}$$

In the formula, Q_d represents the load flow; V_d represents the effective volume of the active compensation cavity; P_d represents the pressure of the active compensation cavity; β_e represents the effective volume modulus of hydraulic oil.

In order to simplify the mathematical model of the system to be built later, and without loss of generality, it is assumed that the return pressure is zero and the supply pressure is constant. According to the literature, the linear flow equation of the proportional valve can be expressed as:

$$Q_d = K_qx_v - K_cp_d \tag{5}$$

Where K_q represents the flow gain coefficient of the valve; K_c represents the pressure gain coefficient of the valve; x_v represents the spool displacement of the servo valve

Combining formulas (1)~(5) can get the mathematical model of the active compensation system as follows:

$$X_h(s) = \frac{\frac{K_q}{A_d}}{s[\frac{V_dM_t}{4\beta_eA_d^2}s^2 + (\frac{V_dB_h}{4\beta_eA_d^2} + \frac{K_cM_t}{A_d^2})s + (\frac{K_cB_h}{A_d^2} + 1)]}\Delta X_v(s) + \frac{\frac{V_dM_G}{\beta_eA_d^2}s^3 + K_c\frac{4M_G}{A_d^2}s^2}{s[\frac{V_dM_t}{4\beta_eA_d^2}s^2 + (\frac{V_dB_h}{4\beta_eA_d^2} + \frac{K_cM_t}{A_d^2})s + (\frac{K_cB_h}{A_d^2} + 1)]}X_s(s) \tag{6}$$

In the formula, the first term on the right side of the equation represents the change in the displacement of the piston rod caused by the displacement of the servo valve spool, and the second term represents the change in the displacement of the piston rod caused by the movement of the hull.

The transfer function of the piston rod movement caused by ocean wave motion is recorded as $G_1(s)$:

$$G_1(s)=\frac{X_h(s)}{X_s(s)}=\frac{\frac{V_d M_G}{\beta_e A_d^2}s^3+K_c\frac{4M_G}{A_d^2}s^2}{s\left[\frac{V_d M_t}{4\beta_e A_d^2}s^2+\left(\frac{V_d B_h}{4\beta_e A_d^2}+\frac{K_c M_t}{A_d^2}\right)s+\left(\frac{K_c B_h}{A_d^2}+1\right)\right]} \tag{7}$$

The displacement of the piston rod caused by the displacement of the spool of the servo valve, and the transfer function of the active compensation mode between the two are recorded as $G_2(s)$:

$$G_2(s)=\frac{X_h(s)}{X_v(s)}=\frac{\frac{K_q}{A_d}}{s[\frac{V_d M_t}{4\beta_e A_d^2}s^2+(\frac{V_d B_h}{4\beta_e A_d^2}+\frac{K_c M_t}{A_d^2})s+(\frac{K_c B_h}{A_d^2}+1)]} \tag{8}$$

The relationship between the voltage signal input by the proportional valve and the displacement of the proportional spool is as follows:

$$X_v=K_e U_e \tag{9}$$

Where K_e is the input coefficient of the proportional valve,

From the above equations, the function block diagram of the transfer function of the heave compensation control system can be obtained, as shown in Figure 2.

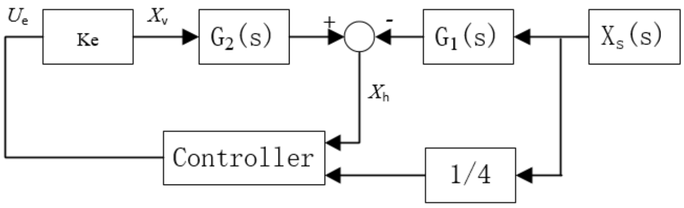

Fig. 2 Function block diagram of transfer function of heave compensation control system

3. Design of control program based on fuzzy PID

3.1. Fuzzy PID controller design

Since fuzzy PID has characteristics similar to traditional PID controllers, but can adjust PID parameters in real time according to system error and error rate[8], this proposes a new scheme for the heave compensation system to achieve better compensation effects. In this case, a fuzzy PID control scheme is proposed. The fuzzy PID controller has the characteristics of robustness and self-adaptation[9]. The structure of the controller is shown in Fig. 3. The heave compensation expected displacement and the displacement of the hydraulic cylinder piston The difference is regarded as the system deviation e, and the fuzzy controller adjusts the PID controller parameters in real time according to the system deviation e and the Δe deviation rate.

3.2. Various variables and membership functions are determined

The input of the fuzzy controller is the deviation e and the deviation rate Δe, and the output is the three parameters of the PID controller K_P, K_I, K_D. First, open the FIS editor in Matlab, configure a two-input three-output fuzzy rule controller, and map the variation range of deviation e and deviation rate Δe to the range of -0.5 to 0.5 on the fuzzy set, which is fuzzy The set is E, ΔE = {NB (negative large), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive medium), PB (positive large)}, domain of discourse The finer the

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division, the better the control effect. Their membership functions are shown in Figure 4. The same method maps the range of K_P, K_I and K_D to the range of -0.1 to 0.1 on the fuzzy set.

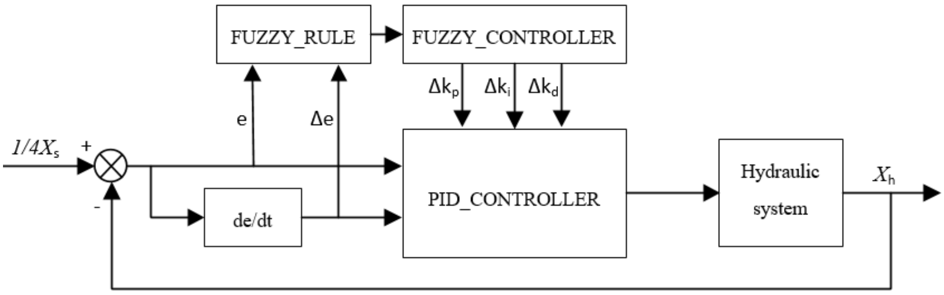

Fig. 3 Fuzzy PID control system

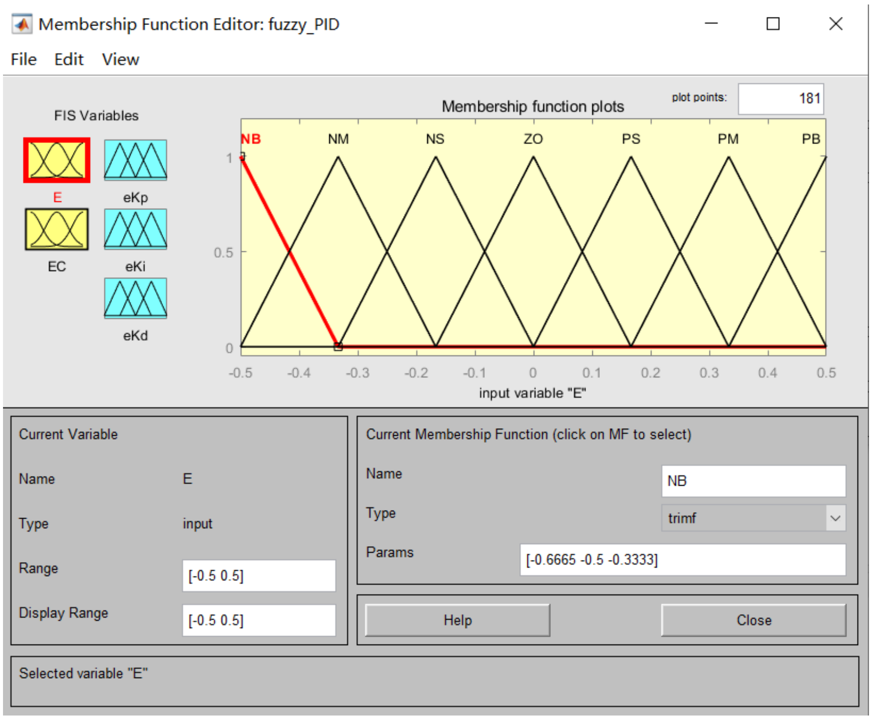

Fig. 4 Error membership function graph

3.3. Establish fuzzy control rules

The establishment of fuzzy control rules is based on the experience of experts. It can also be found through multiple simulations or online debugging to find out the appropriate control rules. Here, the expert fuzzy rule table[10] is used. The fuzzy rule table is obtained by experts through theoretical analysis and practical application. The principle is to adjust the three parameters of K_P, K_I and K_D in real time according to the changes of deviation e and deviation rate Δe. The rules are shown in Tables 1, 2, and 3, which are completed in the FIS editor according to the rule table. Input of expert rules. After completing the input of the fuzzy rules, use the export to file option to export the entire set of rules to the specified directory and save them as FIS files for Simulink control program call.

Table 1 K_P fuzzy rule table

ΔE	E						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS

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NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

Table 2 K_I fuzzy rule table

ΔE	E						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	ZO	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NB	NM	NS	NS	ZO	PS	PS
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PS	PM	PB
PM	ZO	ZO	PS	PS	PM	PB	PB
PB	ZO	ZO	PS	PM	PM	PB	PB

Table 3 K_D fuzzy rule table

ΔE	E						
	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	PM	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	ZO
NS	ZO	NS	NM	NM	NS	NS	ZO
ZO	ZO	NS	NS	NS	NS	NS	ZO
PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

3.4. Build Simulink/Fuzzy PID control program

Using Simulink in Matlab to build an active fuzzy PID compensation control program diagram is shown in Figure 5.

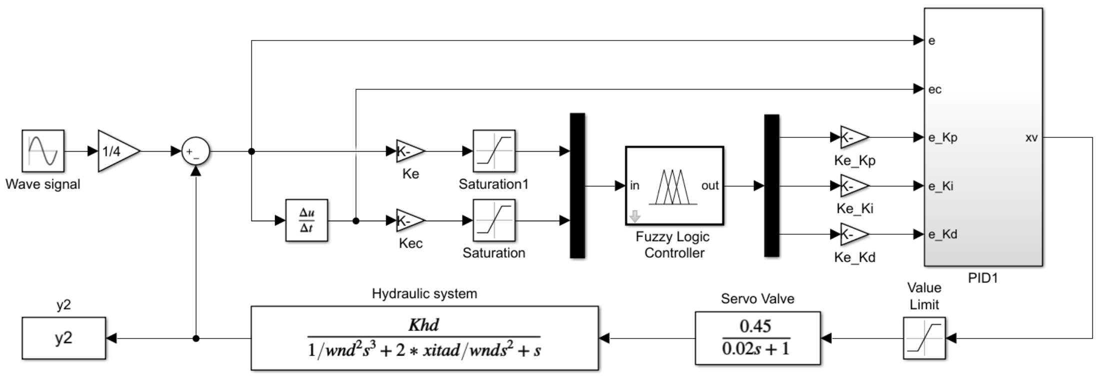

Fig. 5 Fuzzy PID heave compensation control program diagram

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4. Design of Active Disturbance Rejection Control System

Active disturbance rejection control is a new type of control algorithm. It regards the unmodeled parts and unknown disturbances in the controlled object as system disturbances. It is estimated by the extended state observer and compensated in the feedback. Multi-variable and strongly coupled systems have better control effects[11-12]. Figure 6 is the basic structure diagram of the ADRC. It can be seen that the ADRC algorithm is mainly composed of three parts: the arranging transition process module, the nonlinear feedback module, and the extended state observer module.

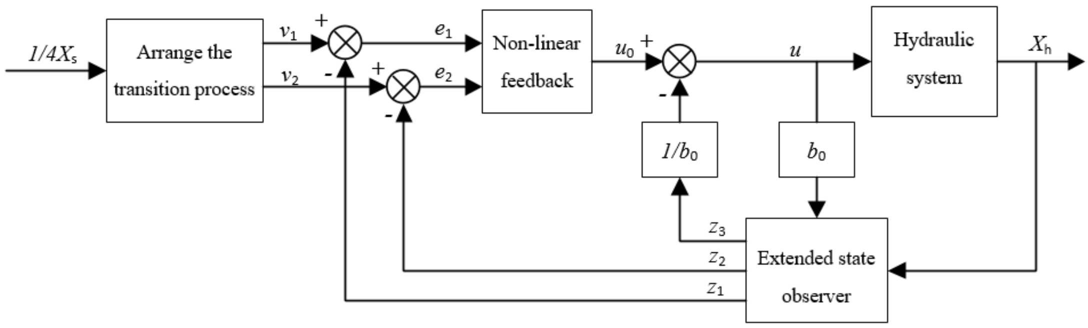

Fig. 6 Active disturbance rejection control structure diagram

4.1. Arrange the transition process module

The function of this module is to use the tracking differentiator to arrange the transition process and extract its differential signal. Its discrete formula is[13]

$$\begin{cases} x_1(k+1) = x_1(k) + Tx_2(k) \\ x_2(k+1) = x_2(k) + Tfst(x_1(k), x_2(k), u(k), r, h) \end{cases} \tag{10}$$

In the formula, T is the sampling period, u(k) is the input signal at the k-th moment, r is the parameter that determines the tracking speed, and h is the parameter that determines the filtering effect when the input signal is contaminated by noise. The fst function can be determined by the following Formula calculation

$$\delta = rh, \quad \delta_0 = \delta h, \quad y = x_1 - u + hx_2, \quad a_0 = \sqrt{\delta^2 + 8r|y|} \tag{11}$$

$$a = \begin{cases} x_2 + y/h, & |y| \le \delta_0 \\ x_2 + 0.5(a_0 - \delta)sign(y), & |y| > \delta_0 \end{cases} \tag{12}$$

$$fst = \begin{cases} -ra/\delta, & |a| \le \delta \\ -rsign(a), & |a| > \delta \end{cases} \tag{13}$$

4.2. Extended state observer module

The function of the extended state observer is to treat the unknown external disturbance and the internal disturbance of the system as the total disturbance of the system, and to observe the extended state of the nonlinear uncertain object to realize feedback control and disturbance compensation. Its discrete mathematical model is

$$\begin{cases} e(k) = z_1(k) - y(k) \\ z_1(k+1) = z_1(k) + T[z_2(k) - \beta_{01}e(k)] \\ z_2(k+1) = z_2(k) + T[z_3(k) - \beta_{02}fal(e(k), 1/2, \delta) + bu(k)] \\ z_3(k+1) = z_3(k) - T\beta_{03}fal(e(k), 1/4, \delta) \end{cases} \tag{14}$$

$$fal(e, a, \delta) = \begin{cases} e\delta^{a-1}, & |e| \le \delta \\ |e|^a sign(e). & |e| > \delta \end{cases} \tag{15}$$

In the formula: e is the system error; u, y, b are the control quantity of the system, the output of the system, and the coefficients respectively; β_{01}, β_{02}, β_{03} are the output error correction gains; a is the non-linear factor; δ is the filter factor; z_1, z_2 and z_3 are respectively the y tracking signal, the differential signal, and the tracking signal of the system disturbance.

4.3. Non-linear state error feedback controller module

This part of the module can use the nonlinear combination of the error between the transition process and the state estimation and the compensation of the disturbance estimator to generate the control signal. Compared with the linear controller, the controller can have higher control quality, and its expression is

$$\begin{cases} e_1 = v_1(k) - z_1(k), \ \ e_2 = v_2(k) - z_2(k) \\ u_0 = \beta_1 fal(e_1, a_1, \delta_1) + \beta_2 fal(e_2, a_2, \delta_1) \\ u(k) = u_0 - z_3(k)/b \end{cases} \tag{16}$$

4.4. Build Simulink/ADRC Program

Using Simulink in Matlab to build an active ADRC compensation program diagram is shown in Figure 7

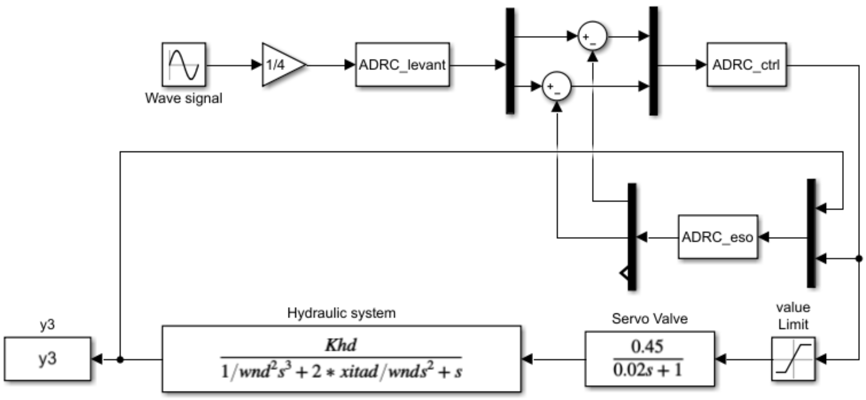

Fig. 7 ADRC heave compensation control program diagram

5. Simulation research

MATLAB/Simulink is used to build the simulation model of the system, and the simulation parameter design is shown in Table 4.

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Table 4 Main parameters of hydraulic system simulation

Symbol	Numerical value	Unit
M_G	900	kg
M_h	100	kg
A_d	2.59×10^{-3}	m^2
V_d	3.24×10^{-3}	m^3
β_e	700	MPa
K_q	0.2	m^2/s
K_c	1.43×10^{-10}	$m^3/(s \cdot Pa)$
B_h	1639	$N/(m/s)$
K_P	0.457	
K_I	0.077	
K_D	0.2	
β_{01}	100	
β_{02}	30	
β_{03}	1000	

Under different sea conditions, the displacement and period of the mother ship heave motion correspond to the amplitude and period of the sine function, respectively. Therefore, this paper uses a sine function to represent the curve of the mother ship's heave motion. According to the literature[14], it can be known that the amplitude of the heave direction of the fourth-level sea state reaches 2.5m, and the period reaches 4s.

In this paper, the advantages and disadvantages of fuzzy PID and active disturbance rejection control are studied through step signals and four-level wave signals. The simulation results are shown in Figure [8-10]

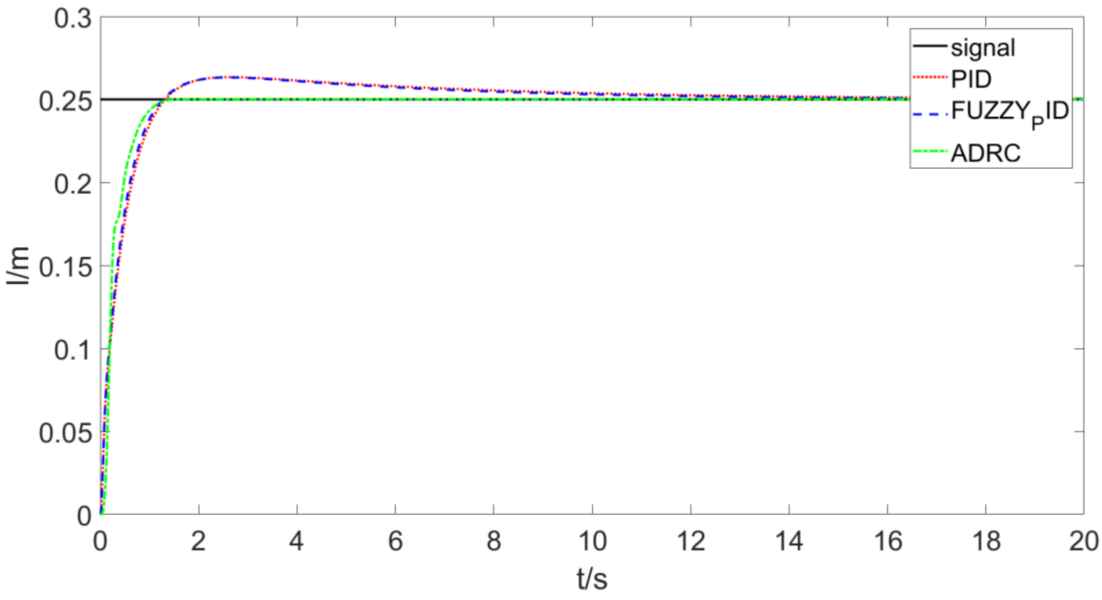

Fig. 8 Step response

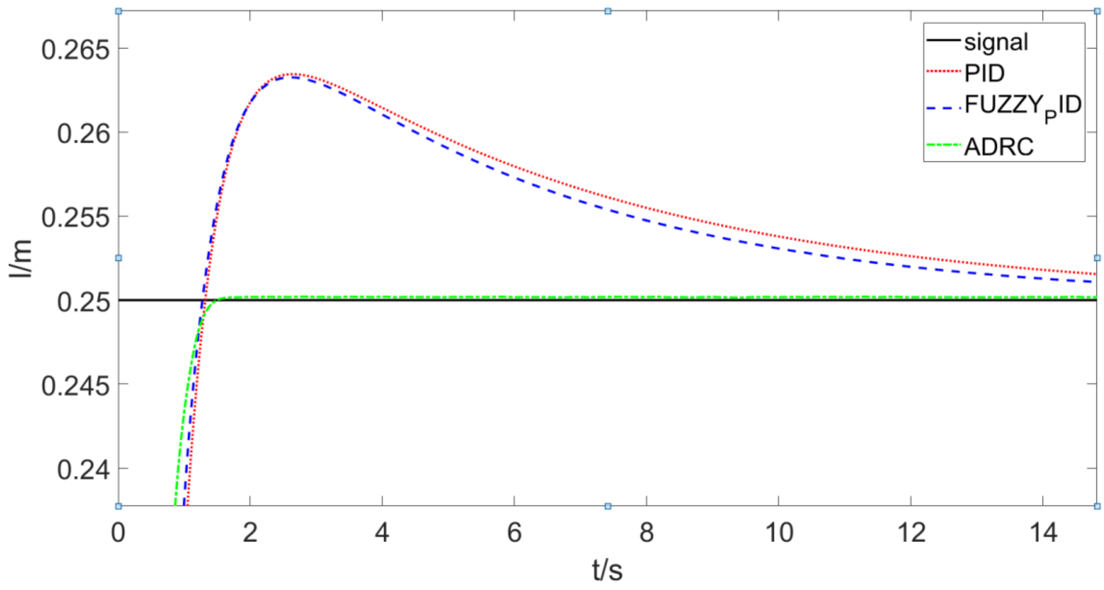

Fig. 9 Partial enlarged view of step response

According to Figure [8-9], it can be seen that the rise time and adjustment time of fuzzy PID are not much different from ordinary PID, the overshoot is lower, the steady-state error is smaller than that of ordinary PID, and the dynamic response and stability of active disturbance rejection Compared with fuzzy PID, the performance of the state error is significantly improved, and the overshoot is basically zero.

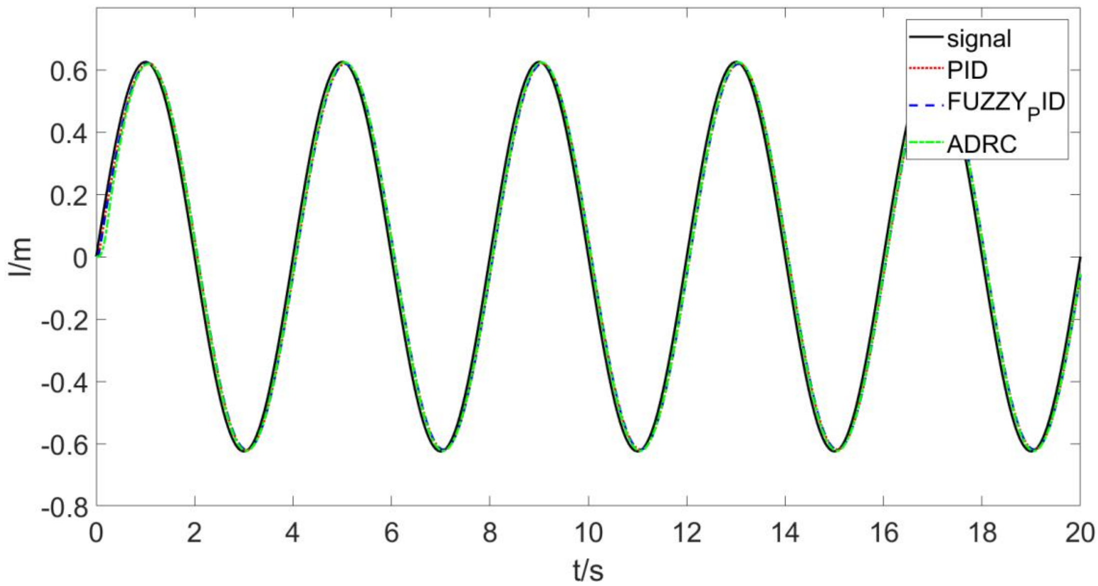

Fig.10 Tracking curve of five-level sea state control system

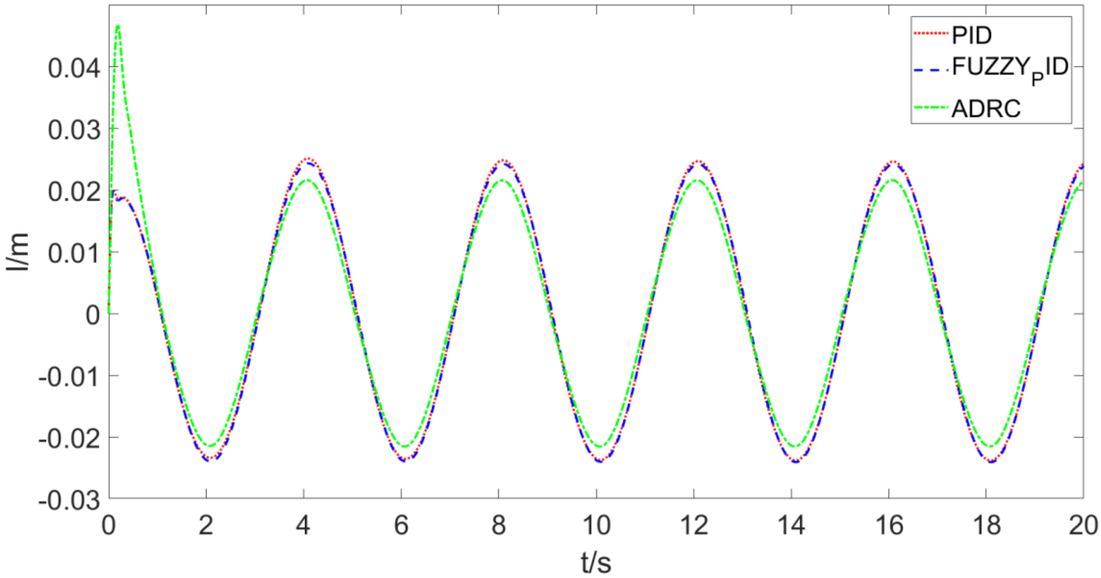

Figure 11 Five-level sea state hydraulic compensation system error

According to the figure [10-11], under the four-level sea condition with an amplitude of 2.5m and a period of 4s, the PID compensation error reaches 24.78mm, the fuzzy PID compensation error reaches 24.14mm, and the auto disturbance rejection compensation error reaches 21.5mm. It can be seen that under severe conditions, the compensation effect of fuzzy PID and ordinary PID is not much different, and the compensation effect of auto disturbance rejection is relatively good.

6. Conclusion

In the actual situation, there will always be uncertain factors, and the established mathematical model will always have deviations. Based on this, the fuzzy PID and active disturbance rejection control are designed. Considering the influence of sea waves, harsh environmental conditions are adopted, that is, the wave amplitude reaches 2.5m and the period is 4s for discussion. The results show that in harsh environments, fuzzy PID has little effect on the hydraulic compensation system, and auto disturbance rejection has a good control effect. In actual production operations, auto disturbance rejection control can be given priority.

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