Stability of the Cone Probe Driven by Hydraulic Motor Based on Fuzzy PID

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Abstract. In the test of mechanical properties of deep-sea sediments, hydraulic cylinders are often used to drive the probe into the sediment. However, due to the limitation of the stroke of the hydraulic cylinder, there is a limit to the depth of penetration of the probe. In order to solve the problem of limited travel, a penetration device that relies on hydraulic motor to drive the probe is designed. Through the co-simulation of AMESim and Simulink, the valve-controlled hydraulic motor system is analysed under the control of conventional PID control strategy and fuzzy PID control strategy. Simulation results: In terms of step response, the fuzzy PID control is 7.12% faster than the traditional PID control, and the overshoot is reduced by 44.4%. Under the step interference signal, the fuzzy PID control has an anti-interference ability improved by 60.7% compared with the traditional PID control. In terms of energy consumption, fuzzy PID control saves 1.08% energy compared to traditional PID control.

1. Introduction
In the measurement of the mechanical characteristics of seabed sediments, most hydraulic cylinders are used as actuators to drive probe rods to penetrate the sediments. However, due to the limited volume and mass of the deep-sea lander, the stroke of the hydraulic cylinders cannot be too large, and its penetration depth is limited. Therefore, a penetrating device using a hydraulic motor instead of a hydraulic cylinder is designed. As a commonly used actuator, hydraulic motor is quite common in hydraulic transmission systems. Its control methods mainly include pump-controlled motors and valve-controlled motors [1] Because the sediments on the deep ocean floor are saturated and easy to disturb, high-power penetration equipment is not needed [2]. Coupled with the limited energy carried by deep sea landers, it cannot support high-power equipment to work for a long time, so it is required to reduce the power of the actuator as much as possible. Therefore, the valve-controlled motor system with the advantages of fast response frequency, short adjustment time, good dynamic characteristics, high efficiency, and suitable for low power conditions can be applied to the detection system of mechanical
properties of submarine sediments. The stability of the speed of the valve-controlled motor directly affects the stability of the penetration speed of the probe. The disturbance torque generated by the gear transmission mechanism and the load force fluctuation caused by the unevenness of the sediment on the sea floor will make the speed of the hydraulic motor unstable [3]. Therefore, it is extremely important to improve the stability of the rotation speed through reasonable design control methods. The principle of PID control algorithm is simple, easy to adjust, and has good adaptability. Based on the above advantages, PID control is widely used in automation systems [5]. Combining the PID controller in Simulink with the valve-controlled hydraulic motor system in AMEsim simulation software to build an accurate system model, making the simulation results more realistic and reliable [7].

2. Design of penetration device and modelling of valve-controlled motor system

2.1. Penetration device

The schematic diagram of the penetrating device is shown in FIG. 1. The hydraulic motor drives the gear 1 to rotate. The gear 1 meshes with the gear 2. The gear 2 is coaxial with the timing pulley 1 and drives the timing pulley 1 to rotate. The specific connection method is shown in FIG. 2. The guide rod is inserted into the slide rest to ensure that the tapered probe rod penetrates vertically when it works.

The maximum working load is set to \( F = 2000 \) N, and the penetration speed is set to \( v = 0.08 \sim 0.085 \) m/s. Therefore, the power should be \( P = 160 \) W. Because the transmission efficiency between the gear and the timing belt is 80%, the minimum output power of the hydraulic motor should be \( P_{\text{motor}} = 200 \) W.

The diameter of gear 1 is \( d_1 = 50 \) mm, the diameter of gear 2 is \( d_2 = 300 \) mm, and the diameter of the two synchronous pulleys are \( d_3 = 80 \) mm. Finally, get the motor speed according to Eq. (1).

\[
v = n_1 \times \frac{d_1}{d_2} \times \pi d_3
\]

Bring the value into formula 1 to get \( n_1 = 114 \sim 121 \) r/min, so we set the motor speed as \( n_{\text{motor}} = 120 \) r/min.
2.2. Model of valve-controlled motor system
The schematic diagram [10] of the four-way valve valve-controlled motor system is shown in FIG. 3. The valve control system is designed, and a three-position four-way proportional solenoid valve is used instead of the on-off valve. The valve orifice area is changed by controlling the valve core displacement, and then the flow and pressure entering the hydraulic motor are controlled, thereby achieving the control of the hydraulic motor speed.

![Figure 3. Valve-controlled motor system schematic diagram](image)

A valve-controlled hydraulic motor system model as shown in FIG. 4 is created in AMESim software. Through the interface interaction module in the software, the input speed of the speed sensor is used as the feedback signal, and the signal output by the fuzzy PID controller is used as the control signal. In the AMESim software, input the desired value of the speed signal through the interface interaction module, and input the interference torque signal at the load. The most important thing is to ensure that the names of the AMESim model and Simulink model are exactly the same, so that the simulation can be performed smoothly [11].

![Figure 4. AMESim hydraulic system model](image)
During the simulation, the expected speed was set to 120 r/min, the disturbance torque was 50 N\cdot m, and the hydraulic motor displacement was set to 100 ml/r. In order to meet the flow rate requirements of the speed, the volume flow of the three-position four-way solenoid valve port is uniformly set to 20 L/min. The displacement of the hydraulic pump is set to 25 ml/r, and the motor speed is set to 600 r/min.

3. Control method

3.1. Traditional PID control

The incremental PID control method [12] constructs a PID controller by inputting three constant values of $K_p, K_i,$ and $K_d$. The difference $e(t)$ between the desired speed and the actual speed is used as the input signal, and the Spool displacement of proportional solenoid valve is used as the output signal. The designed PID control law is shown in Eq. (2).

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$  \hspace{1cm} (2)

As shown in FIG. 5, in order to achieve the AMESim-Simulink co-simulation [13] the hydraulic system model established in AMESim is imported into Simulink, and a PID control system was established in Simulink.

![Figure 5. Traditional PID control system](image)

3.2. Traditional PID control

The schematic diagram [14] of fuzzy control is shown in FIG. 6. The fuzzy PID control method is based on the traditional PID control method and uses fuzzy logic to adjust the PID parameters.

![Figure 6. Fuzzy PID parameter control](image)
The actual speed of the hydraulic motor detected by the speed sensor is subtracted from the desired speed to obtain the speed deviation $E$, and further obtain the deviation change rate $E_c$, and then input the obtained deviation $E$ and the deviation change rate $E_c$ to the fuzzy controller. The parameters are adjusted, and finally the correction values $\Delta K_p, \Delta K_i$ and $\Delta K_d$ of the PID parameters are output. The control signal output by the PID controller prompts the hydraulic motor to perform the corresponding action.

As shown in FIG. 7. The discrete universe of deviation $E$ and the rate of change of deviation $E_c$ is [-6, 6]. Membership function uses triangular membership function, and {PB, PM, PS, ZO, NS, NM, NB} as fuzzy subsets. As shown in FIG. 8. The discrete universe of $\Delta K_p, \Delta K_i, \Delta K_d$ is [-3, 3]. The membership function also uses a triangular membership function, and {PB, PM, PS, ZO, NS, NM, NB} as fuzzy subsets.

The center of gravity method [15] is used to solve the ambiguity to obtain $\Delta K_p, \Delta K_i$ and $\Delta K_d$, then adjust the PID parameter through Eq. (3), Eq. (4) and Eq. (5).

$$K_p = K_{p1} + \Delta K_p \cdot K_1$$ (3)

$$K_i = K_{i1} + \Delta K_i \cdot K_2$$ (4)

$$K_d = K_{d1} + \Delta K_d \cdot K_3$$ (5)

In the equation: $K_1, K_2$ and $K_3$ are the adjustment factors of the parameters $K_p, K_i$ and $K_d$; $K_{p1}, K_{i1}$ and $K_{d1}$ are the initial values.

The parameter adjustments $\Delta K_p, \Delta K_i$ and $\Delta K_d$ are obtained by Mamdani fuzzy reasoning method [16]. Fuzzy control rules are shown in table 1, table 2 and table 3.

**Table 1. Fuzzy control rule of $\Delta K_p$**

| $E_c$ | NB | NM | NS | ZO | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| E    |    |    |    |    |    |    |    |
| NB   | PB | PM | PS | ZO | NS | NM | NB |
| NM   | PB | PB | PM | ZO | PS | ZO | NS |
| NS   | PM | PM | PM | ZO | PS | PS | NM |
| ZO   | PM | PM | ZO | PS | PS | PS | NM |
| PS   | PS | PS | ZO | PS | PS | PS | NM |
| PM   | PS | ZO | NS | NM | NM | NM | NB |
| PB   | ZO | ZO | NM | NM | NM | NB | NB |
Table 2. Fuzzy control rule of $\Delta K_i$

| $E_c$ | NB   | NM   | NS   | ZO   | PS   | PM   | PB   |
|-------|------|------|------|------|------|------|------|
| NB    | NB   | NM   | NS   | ZO   | PS   | PM   | PB   |
| NM    | NB   | NB   | NM   | NS   | NS   | ZO   | ZO   |
| NS    | NB   | PM   | NS   | NS   | ZO   | PS   | PS   |
| ZO    | NM   | NM   | NS   | ZO   | PS   | PM   | PM   |
| PS    | NM   | NS   | ZO   | PS   | PS   | PM   | PM   |
| PM    | ZO   | ZO   | PS   | PS   | PM   | PM   | PB   |
| PB    | ZO   | ZO   | PS   | PS   | PM   | PB   | PB   |

Table 3. Fuzzy control rule of $\Delta K_d$

| $E_c$ | NB   | NM   | NS   | ZO   | PS   | PM   | PB   |
|-------|------|------|------|------|------|------|------|
| NB    | PS   | NS   | NB   | NB   | NB   | NM   | PS   |
| NM    | PS   | PS   | NM   | NM   | NM   | NS   | ZO   |
| NS    | ZO   | PS   | NS   | NS   | NS   | NS   | ZO   |
| ZO    | ZO   | PS   | NS   | NS   | NS   | ZO   | ZO   |
| PS    | ZO   | ZO   | PS   | ZO   | ZO   | ZO   | ZO   |
| PM    | PB   | NS   | NS   | PS   | PS   | PS   | PB   |
| PB    | PB   | PM   | PM   | PS   | PS   | PS   | PB   |

The simulation model of fuzzy PID built in Simulink is shown in FIG. 9. The fuzzy controller is constructed by using the integration module in the fuzzy logic toolbox [17]. The fuzzy controller can automatically perform complex operations. The desired fuzzy controller can be obtained by setting the corresponding parameters.

Figure 9. Fuzzy PID simulation model

4. Simulation and results
As shown in the FIG. 10 and FIG. 11, the simulation time is set to 10 seconds, the expected speed is 120r/min, and the disturbance torque is 50 N·m.
The comparison of simulation curve between the traditional PID controller and the fuzzy PID controller is shown in FIG. 12, and the step response comparison curve is shown in FIG. 13.

The response time of traditional PID is 1.545 seconds and the overshoot is 9 r/min. The response time of fuzzy PID is 1.435 seconds and the overshoot is 5 r/min. In terms of step response speed, the response time of fuzzy PID control is reduced by 7.12%, and the overshoot amount is reduced by 44.4%.

In order to further analyze the control performance of the two control methods, a step disturbance signal is set to the hydraulic system when the system simulation time reaches 6 seconds. The enlarged simulation curve is shown in FIG. 14. In FIG. 14, we can see the minimum speed of the hydraulic motor controlled by the traditional PID is reduced to 92 r/min under the step interference signal, and the minimum speed of the hydraulic motor is reduced to 103 r/min under the fuzzy PID control. The anti-interference ability has increased by 60.7%.
Unlike onshore operations with continuous and continuous energy supply, deep-sea landers are completely isolated from the outside world, and are limited by their own masses. So the energy they could carry is restricted and it is essential to research their energy consumption. Further, the energy consumption of the hydraulic motor will be simulated and compared by AMESim software under the control of fuzzy PID and traditional PID.

The output power $P(w)$ of the hydraulic motor is equal to the product of the actual output torque $T$ (N·m) and speed $w$ (rad/s). As shown in FIG. 15, the energy consumption curve is obtained in AMESim. The hydraulic motor under the fuzzy PID control consumes $2617.968j$ energy, while the hydraulic motor under the traditional PID control consumes $2646.4j$ energy. The fuzzy PID control saves $1.08\%$ energy, which shows that the fuzzy PID is more energy-saving than the traditional PID.

5. Conclusion
In this paper, the deep-sea hydraulic penetration device with hydraulic motor as the actuator and the model of valve controlled hydraulic motor speed regulation system based on AMESim and Simulink are designed. Step response of desired speed and step disturbance signal are set in AMESim software. The results show that the fuzzy PID control scheme has a faster response speed than the traditional PID.
control scheme. It can make the probe reach the desired speed before touching the sediment, suppress the overshoot and improve the control accuracy. And in the case of external disturbance torque, it has better anti-interference ability, its control performance is better than traditional PID control, and fuzzy PID control system is more energy-saving.

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