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Article

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Posted Date: April 6th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1500559/v1

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Intelligent Control Strategy of Electro-hydraulic Drive System for Raising Boring Power Head

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Abstract: The power head is the key part of the rock breaking work of the raise boring machine. Because the power head cannot adjust speed in time with the change of complex rock stratum, it leads to high failure rate, low work efficiency and even accidents, so it is urgent to improve the controllability of the power head. In this paper, the electro-hydraulic coupling mathematical model of the power head is established by using the characteristic equations of dynamics and hydraulic components, and the control strategy of the fractional electro-hydraulic drive system of the power head is proposed; Genetic algorithm (GA), particle swarm optimization (PSO) and whale algorithm (WOA) are used to adjust the parameters of FOPID, so as to improve the control effect of electro-hydraulic system; The results show that the step response of WOA-FOPID control strategy is also better than that of genetic algorithm (GA) and particle swarm optimization (PSO). It can reach a stable state in 0.02 seconds, and the overshoot is only 0.12137%; The test verifies the correctness of the adaptive control and simulation results of the power head, which can effectively improve the adaptability of the power head to complex coal seams.

Key words: Raise boring machine; Power head; Electro hydraulic control; WOA-FOPID control algorithm; Parameter setting;

Due to the advantages of the high safety, relatively low cost and ensuring the safety of operators to the greatest extent, the reverse well drilling rig is widely used in underground roadway space, mine development, subway tunnel and other projects, and the drilling technology is also a fundamental change technology for well hole drilling. In recent years, with the improvement of intelligent control technology of the drive system of the reverse well drilling rig, it has not only accelerated the speed of excavation, but also greatly alleviated the labor intensity.

The power head is the key component of the reverse well drilling rig, and its control method and effect directly affect the safety and stability of the reverse well drilling rig in construction. At the same time, the intelligent control of the power head also has a positive role in promoting the intelligent construction of coal mines nationwide. Therefore, the intelligent control strategy of the electro-hydraulic drive system of the power head has attracted the attention of the majority of scientific researchers at home and abroad. For example, Xiu-kun Hu, Zhi-qiang Liu\textsuperscript{[1]} and others studied the relationship between the four parameters of drill pipe tension, torque, rotational speed and drilling speed in the power head control system. Shen Wei\textsuperscript{[2]} et al. formulated the mathematical modeling and robust integral adaptive controller of the power head valve-controlled hydraulic motor based on The Padde's theorem and the reverse step derivation method, which improved the accuracy and tracking speed of the system control. Yang Yanlin\textsuperscript{[3]} et al. proposed a fuzzy PID control algorithm based on the problem of synchronization of four hydraulic motors in the power head device, which improved the synchronization accuracy of the motor. Cheng Lilin\textsuperscript{[4]} Using AMESim and Matlab-Simulink to construct a joint simulation model of the test bench drilling simulation system, Cheng Lilin designed a fuzzy adaptive PID controller.
to analyze the control performance of the power head system. Zhang Yang[5] Using the method of co-simulation between AMESim and Matlab-Simulink, the adaptability of different control algorithms of traditional PID fuzzy and feedback linear synovial membrane structure to the position tracking control of valve-controlled asymmetrical hydraulic cylinders is analyzed, and the problems of nonlinearity and low control accuracy of the electro-hydraulic control system of the power head are solved. Foreign hydraulically driven reverse well drilling rig, power head drive using electro-hydraulic proportional PID control technology, control unit using PLC or engineering controller [6-9], due to the introduction of computer control technology, a variety of more complex control logic and PID control algorithms can be realized. The above literature research has made certain contributions to the intelligent control of the electro-hydraulic drive system of the power head of the reverse well drilling rig, and laid a certain foundation for the intelligent control algorithm of the power head. However, the research in the above article is based on the traditional PID control algorithm, especially in the downhole operation, the surrounding rock parameters, the drilling rig underground force complex these uncertain factors will make the driving head of the drilling rig can not adjust the control parameters in time, and eventually lead to low drilling efficiency, short life of the rock breaking hob, and even cause drill damage, jam drilling, etc. Under special working conditions, the traditional PID control effect is not ideal, even if the PID is re-parameter tuned, it still cannot achieve a good control effect, and it is essentially impossible to overcome the shortcomings of traditional PID control technology. Therefore, the complex system has a low control accuracy, reflecting the poor sensitivity and other issues, it is difficult to explore the intelligent control principle of the electro-hydraulic drive system of the power head from a deep level, and the parameter selection of the PID controller has a great impact on the control effect, the traditional parameter tuning method is still based on experience, it is difficult to find a set of parameters with good control effect in a short period of time.

Fractional order FOPID controller has 5-bit adjustable parameters. Compared with other control laws, it has better dynamic performance, parameter adjustment flexibility and control accuracy [10-12]. There is a great vacancy in the research and application of fractional order fopid in the research of electro-hydraulic system control method of raising boring. Based on the internal control principle of the reaming operation of the power head of the reverse well drilling rig, if the control effect is required to have good timeliness and reliability, the parameter adjustment research of the intelligent control algorithm is also indispensable, such as the particle swarm algorithm [13-15], the genetic algorithm [16], the gravity search algorithm [17], the neural network algorithm [18], the ILMI algorithm [19] and the whale algorithm [20], which are all applied in the PID controller, improving the control effect of the traditional PID controller. Got rid of the method of parameter tuning that relies on experience.

Based on this, this paper establishes the electro-hydraulic coupling model of the power head of raise boring machine from the dynamic principle, electro-hydraulic coupling properties and the characteristic equation of hydraulic components, and puts forward the control method of the power head electro-hydraulic drive system based on fractional FOPID. In order to further improve the control effect of the system, the genetic algorithm (GA), particle swarm algorithm (PSO), whale algorithm (WOA) three groups of intelligent optimization algorithms are used to adjust the FOPID and PID controller parameters, and the influence of the above different combination algorithms on the control system is evaluated, so as to provide theoretical guidance for the reliability of the reaming operation of the reverse well drilling rig [21-24]. Finally, field experiments were conducted in Liuqiao Town, Suixi County, Anhui Province, to prove the effectiveness of WOA-FOPID control strategy in electro-hydraulic drive control system. It further provides new theoretical guidance for the intelligent control strategy of the electro-hydraulic drive system of the power head.

1 Mathematical modeling
This article takes a deep well lane full-section test drilling rig (raising boring) as an example to study, which is the most widely used [25] and belongs to the lower lead upward expansion type. In order to make the intelligent drilling technology be applied in the reverse well drilling rig, with the power head as the research object, the PLC combined with the HMI design rock breaking control system, four variable piston pump A11VLO130LRDS are connected in series into two groups, driven by 132kw motors, driving four MCR15A1500W80Z32A0M2L4 2S The 506U two-speed radial piston motor, hydraulic motor also controls the rotation of the power head [26-27]. The overall idea of the structure composition, construction process and control scheme of the reverse well drilling rig and the power head is shown in Fig. 1.

In order to facilitate the theoretical modeling and analysis, the basic assumptions of hydraulic motor modeling are made. On this basis, the proportional amplifier, electro-hydraulic proportional control valve, power head electro-hydraulic coupling model and the transfer function of power head hydraulic motor speed are established respectively.

The signal output by the controller is a voltage signal or a current signal, which is a component that amplifies its input signal, and simplifies this model to a proportional link because of its input and output characteristics, and its transfer function is:

$$G_i = \frac{I(s)}{U_i(s)} = K_b$$

(1)

where $K_b$ is the gain of the proportional amplifier.

The current signal output by the proportional link is based on dynamics and electromagnetic induction to drive the proportional solenoid movement, and then the valve spool generates motion, thereby controlling the size of the valve opening and the direction of the liquid in and out. The working principle of the electro-hydraulic proportional control valve is established, and the following expressions are established for the relationship between the coil current in the electromagnet, the driving force of the electromagnet, and the displacement of the valve core:

$$\begin{cases}
u = L \frac{di}{dt} + (R_i + r_p) i \\
F_s(t) = K_p U(t) \\
F_M(t) = m \frac{dx}{dt}^2 + c \frac{dx}{dt} + k_s x
\end{cases}$$

(2)

The transfer function obtained by pulling the change of equation (2) is:

$$G_2 = L(s) = \frac{K_s}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

(3)

In the formula, $\omega_n$ is the natural frequency of the spool, $\zeta$ is the damping ratio of the spool, and $K_{sm}$ is the gain of the electro-hydraulic proportional valve.

The electro-hydraulic coupling model of the power head is composed of the hydraulic motor connected to the power head through the deceleration device, so the following relationship is established according to the flow continuity of the hydraulic motor valve, the static characteristic equation, the dynamic balance equation of the shaft and $\omega_n(s) = s \theta_m(s)$:

Fig.1 Overall train of thought block diagram
\[
q_L = C_d \Delta x \sqrt{\frac{1}{\rho} (p_L - p_t)} \\
q_L = D_m \frac{\theta_m}{dt} + C_m p_L + \frac{V_i}{4} \frac{dp_L}{dt} \\
T = D_m P_L = J \frac{d^2 \theta_m}{dt^2} + B_m \frac{d\theta_m}{dt} + G \theta_m + T_f \\
T_f = J_s \omega_s(s) + B_s \omega_s(s) + T_d(s)/i
\]

(4)

As can be seen from the Fig., the hydraulic motor and the power head are connected through the deceleration device, and the angular velocity exists: \( \omega_m(s) = i \omega_s(s) \). Perform a pull transform on equation (4) to get the following equation:

\[
T = D_m P_L(s) = (iJ_s + J_s)s \omega_s(s) + (iB_m + B_s) \omega_s + T_d(s)/i
\]

(5)

From equation (5) can be known the equivalent inertia of the power head \( J_e = iJ_s + J_s \), equivalent viscous damping coefficient \( B_e = iB_m + B_s \), The transfer function of the electro-hydraulic coupling power head model under no-load state is sorted out:

\[
G_{d}(s) = \frac{\omega_d(s)}{U_i(s)} = K_d \frac{s^2 + 2 \omega_d \xi_d s + \omega_d^2}{(s^2 + 2 \omega_d \xi_d s + \omega_d^2)(s + 1)}
\]

(6)

where, \( K_d = \frac{K_u K_m K_f D_m}{iD_m^2 + B_d (C_m + K_f)} \)

\( \omega_d = \sqrt{\frac{\beta_e \sum_{i=1}^{n} D_m^2 + B_d (C_m + K_f)}{V_i J_d}} \)

\( \xi_d = \frac{J_d \beta_e (C_m + K_f) + B_d V}{2 \sqrt{\beta_e V_i J_d [iD_m^2 + B_d (C_m + K_f)]}} \)

Proportional amplifier, electro-hydraulic proportional valve, hydraulic motor related parts of the parameters are as follows: the inertia of the motor shaft \( J \) is 67kg\( \cdot \)m\(^2\), \( J_s \) is 0.4755kg\( \cdot \)m\(^2\), the total volume \( V_i \) of the connecting pipe is \( 3 \times 10^{-4} \) m\(^3\), the elastic modulus of the system is \( 6.9 \times 10^8 \) N/m\(^2\), the flow gain \( K_q \) is 2.42m\(^3\)/s, the motor displacement is \( 2.39 \times 10^{-4} \) m\(^3\)/rad, the gear ratio of the reducer is \( i \) of 6.817, and the open-loop transmission function of the power displacement signal by calculating the angular velocity of the power head is:

\[
G_m(s) = \frac{\omega_m(s)}{U_i(s)} = K_f \frac{1}{(s^2 + 2 \omega_m \xi_m s + \omega_m^2)(s + 1)}
\]

(7)

\[
= \frac{8.476 \times 10^4}{5.478 \times 10^7 s^4 + 0.0252 s^3 + 2.85 s^2 + 432.59 s + 10000}
\]

By formula (7) to obtain the system without interference and control Bode diagram as shown in Fig. 2.

From Fig. 2, it can be seen that when the amplitude-frequency characteristics reach zero decibels, the phase frequency characteristics are below -180 ° line, and the phase lag point has a negative stability margin at the 180 ° point, so there is a stability problem in the system, but due to the stability of the system itself and the dynamic characteristics, to make the system have a stable margin, it is necessary to add a controller to adjust to meet the stability requirements.

2 Fractional order FOPID controller design

As a branch of the control field, fractional order (FOPID) control has many advantages such as flexible and precise parameter adjustment, large system stability margin, and strong system robustness, and has
been widely used in different types of controller design\cite{28-30}. Fractional-order $P^{\mu}D^\nu$ control was first proposed by Igor Podlubny, and its superiority over traditional PID control was demonstrated through response analysis\cite{31-41}. Fractional order $P^{\mu}D^\nu$ controller of the order of parameters $\lambda$, $\mu$, can take any real number, in the $P\cdot I\cdot D$ plane, according to the different controller parameters to take the value, FOPID control system structure as shown in Fig. 3. Compared with traditional PID control, fractional $P^{\mu}D^\nu$ control can more subtly reflect the transition process from proportional control to integral control and differential control, so as to achieve a control effect with higher accuracy, better stability and stronger anti-interference ability.

$$C(s) = \frac{U(s)}{R(s)} = K_p + \frac{K_i}{s^\lambda} + K_d s^\mu$$ \hfill (8)

Where $K_p$ is the proportional gain, $K_i$ is the integral gain, $K_d$ is the differential gain, and $\lambda$, $\mu$ is the fractional and integral order, respectively.

3 Whale optimization algorithm

Based on the advantages of Fractional Order PID control algorithm, this paper proposes a control strategy based on WOA-FOPID algorithm. There are many kinds of parameter tuning methods for FOPID. According to the regulation characteristics of the algorithm itself, it is mainly divided into traditional method tuning and intelligent optimization algorithm tuning, and intelligent optimization algorithm is widely used because of its self adaptability. In this paper, genetic algorithm (GA), particle swarm optimization (PSO) and whale algorithm (WOA), three intelligent optimization algorithms are combined with PID and FOPID respectively, and the speed control effect of power motor is further analyzed through different control strategies. The flow chart of setting FOPID parameters by the developed intelligent optimization algorithm is shown in Fig. 5.

4 Parameter setting and optimization process of real analysis and optimization flow simulation analysis
There are many kinds of parameter tuning methods for FOPID. With the development of intelligent and control technology, according to the regulation characteristics of the algorithm itself, it is mainly divided into traditional method and intelligent optimization algorithm. Intelligent optimization algorithm is widely used because of its self-adaptability. Whale optimization algorithm (WOA) has been widely used because of its simple optimization mechanism and fast solution speed. The algorithm searches for the optimal solution by simulating the predation behavior of humpback whales[^42-43], and solves the D-dimensional optimization problem in control parameter optimization under the ITAE index, which can be expressed as:

$$\min \ f(x) \ \text{s.t.} \ 1 \leq x \leq u$$  \hspace{1cm} (9)

In servo control, the ITAE performance index weights the error so that the error signal converges to zero as soon as possible. Therefore, the optimization objective function generates the objective function of control parameter optimization under the ITAE index, which is defined as:

$$f_y = \sum_{t=0}^{N} L(t) e(t)$$  \hspace{1cm} (10)

As shown in Fig.6, the contents and steps of WOA algorithm are summarized.

In this paper, genetic algorithm (GA), particle swarm optimization (PSO) and whale algorithm (WOA) are combined with PID and FOPID respectively. Through different combined control strategies, the control effect of raising boring power head is further analyzed and compared. The specific parameter settings of each algorithm are shown in Table 1 below.

| Table 1. Specific parameter setting table of each algorithm |
|-------------------|-----------------|---------------------|
|                  | PSO              | GA                | WOA-FOPID | WOA-PID |
| Max_er           | 200              | 200                | 50        | 50       |
| N                | 20               | 50                 | /         | /        |
| C1               | 1.49             | /                  | /         | /        |
| C2               | 1.49             | /                  | /         | /        |
| Variation parameters | 0.8             | /                  | /         | /        |
| Variation probability | 0.75            | /                  | /         | /        |
| dim              | /                | 5                  | 3         |          |
| Search Agents No | /                | 100                | 100       |          |

See Table 2 for comparison of different combination strategies and control indicators; The dynamic response curve comparison diagram of each combination strategy of the regulation system is shown in Fig.7. Fig.7(a) is the step response diagram of each intelligent optimization algorithm and PID combination strategy, and Fig.7(b) is the step response diagram of each intelligent optimization algorithm and FOPID combination strategy; The comparison of PID and FOPID combined control strategies based on WOA algorithm is shown in Fig.8.

Table 2 Comparison of different combination strategies and control indicators

| combination | Standard deviation | Overshoot /% | Stabilization time / S |
|-------------|--------------------|--------------|-----------------------|
| PSO-PID     | 0.06309            | 30.1721      | 0.84                  |
| GA-PID      | 0.06309            | 30.1217      | 0.84                  |
| WOA-PID     | 0.03624            | 8.35         | 0.1                   |
| PSO-FOPID   | 0.06349            | 2.8197       | 0.51                  |
| GA-FOPID    | 0.03778            | 6.9309       | 0.16                  |
| WOA-FOPID   | 0.03535            | 0.12137      | 0.02                  |
As can be seen in Fig.7, after adding PID and FOPID controllers, the system can quickly tend to a stable state. Comparing Fig.7 (a) with Fig.7 (b), in the control based on the same algorithm, the FOPID control is significantly better than the PID control in terms of response time and dynamic response; In Fig.7(a), the step response of WOA-FOPID control strategy is obviously better than the control strategy based on GA and PSO algorithm, and the overshoot is 8.35%, only 0.5% Stable state is reached in 1s; In Fig. 7(b), the step response of WOA-FOPID control strategy is also better than the control strategy based on GA and PSO algorithm, at 0.5% It reaches a stable state within 0.2s, and the overshoot is only 0.5% 12137%. The simulation results in Fig. 7 (a) and Fig. 7(b) show that in the PID/FOPID combination strategy, the whale algorithm (WOA) has more advantages than the genetic algorithm (GA) and particle swarm optimization algorithm (PSO) in the process of intelligent parameter adjustment.

Fig.8 compares the two controllers based on WOA algorithm. The results show that WOA-FOPID is more dominant, which further verifies the superiority of FOPID controller. In these combination strategies, it is concluded that the optimal controller is the FOPID controller based on WOA algorithm, and the parameters of the controller is:

$$G_c = 15.2654 + 20s^{-1.0039} + 9.5963s^{1.1118}$$  \hspace{1cm} (11)

5 Experiment

In order to verify the correctness and effectiveness of WOA-FOPID control strategy in the electro-hydraulic drive control system of the power head of raise boring machine, the performance test of the power head of raise boring machine was carried out in Liuqiao Town, Suixi County, Anhui Province. The on-site commissioning layout is shown in Fig. 9.
power head motor, the stepless speed regulation of the power head output shaft, the lifting/lowering action of the thrust cylinder, the pressure, displacement, stroke, constant pressure/constant torque drilling mode switching Precise control of temperature control and automatic operation of pump station. At the same time, the rock breaking control system is equipped with a remote control function to facilitate remote operation. S7-1200 series PLC and large screen display form the control core in the control cabinet, and each working condition monitoring and input/output drive unit cooperate with each other to ensure the stable operation of various control functions of the system. The general scheme of electric control system of raise boring machine is shown in Fig. 10.

5.1 Power head speed control scheme

Power head speed regulation control model in the process of power head speed adjustment potentiometer from minimum to maximum, adjust the displacement of variable pump from 0 ~ 145ml /R and variable motor from 215 ~ 65ml /R in turn. That is, in the first half of the speed regulation process, the displacement of the motor remains unchanged, and only the displacement of the variable pump is adjusted to meet the requirements of speed adjustment. In the second half, the maximum displacement output of the variable pump is maintained, and only the displacement of the variable motor is adjusted to meet the requirements of speed adjustment. In this way, no matter at any speed, the output torque is the maximum torque corresponding to the speed.

(1) Remote control and valve group control of hydraulic pump station. Before the remote control of hydraulic pump station operates the control system, the pump station motor must be started first to make the pump station in working state. In order to avoid starting the pump station in another place, the system adds the start and stop button of the pump station motor on the control cabinet, and the start signal sent by the button acts on the soft starter remotely to realize the start and stop function of remote control motor.

Control scheme: the main pump motor is started by soft starter, and the start / stop signal of soft starter is controlled through the console button to realize the start/stop control function of corresponding motor. Control process: as shown in Fig. 11 and Fig. 12 below.

The valve group control system sends the control command to PLC through the knob on the operation panel or the virtual button on HMI, and the output signal drives the corresponding solenoid valve action through the relay to realize the corresponding functions.

(2) The power head is driven by 160ml/R variable pump and variable motor. In order to realize the adjustable steering and speed, the system designs a
three position knob to control the action of the electromagnetic directional valve, so as to realize the steering control of the power head. At the same time, the potentiometer is designed to input 0 ~ 5V analog signal, and then through the calculation of PLC speed regulation model, output the first conductive signal of 0~10V driving proportional amplifier, control the proportional amplifier to output 200~600mA current, and then control the speed of power head.

Forward/reverse control scheme of power head: forward/reverse switching control is realized through three position four-way solenoid directional valve. That is, the control of the electromagnetic directional valve is realized through the console knob or the remote controller knob, so as to realize the control of the forward/reverse switching function. Control flow: as shown in Fig.13.

![Fig.13 Flow chart of forward / reverse control of power head](image)

Stepless speed regulation control scheme of power head output shaft: adjust the flow by controlling the swing angle of variable pump, so as to realize the function of stepless speed regulation of power head output shaft. That is, the proportional electromagnet is controlled by the knob potentiometer, and then the swing angle of the variable pump is controlled to realize the function of stepless speed regulation of the output shaft of the power head. Control flow: as shown in Fig.14.

![Fig.14 Flow chart of stepless speed regulation control of power head output shaft](image)

5.2 Implementation plan

Field commissioning stage: speed regulation of power head under shunt state. The experimental parameters are shown in Table 3, Table 4 and Table 5.

(1) Stage I: keep the displacement of the power head motor unchanged and adjust the displacement of the hydraulic pump from \(0 \sim 145 (ml/r)\). at this time, the driving current of the power head motor is about \(43mA\) (the corresponding digital quantity is 2000). According to the driving characteristic curve, the maximum displacement of the power head motor is \(216.5ml/r\).

(2) Stage II: keep the displacement of the power head motor unchanged, adjust the discharge of the hydraulic pump to the maximum value of \(145ml/r\) (theoretical value), the actual control driving current is about \(586mA\) (corresponding to the digital quantity of 27000), and the flow of the corresponding pump is \(140ml/r\). at this time, the displacement of the power head motor remains at the maximum value of \(216.5ml/r\).

(3) Stage III: keep the maximum displacement of the hydraulic pump unchanged at \(145ml/r\), and adjust the displacement of the power head motor from \(216.5ml/r\) to \(V_s_{min}\). When the software controls the minimum displacement of the power head motor, the corresponding driving current is about \(526mA\), \(V_s_{min}\) is 0.185 times,
\[ V_{\text{max}} = 216.5 \text{ml/r} \times 0.185 = 40.0525 \text{ml/r} \]

(4) Stage IV: the rotating speed of the power head is the maximum and the Baote remains unchanged.

Table 3 Experimental parameters (Relationship between displacement and current of power head motor)

| Serial number | 1   | 2   |
|---------------|-----|-----|
| Electric current | 200 | 600 |
| Displacement | 216.5 | 0  |
| Maximum speed | 2900 | 5500 |

Table 4 Experimental parameters (Relationship between pump displacement and current)

| Serial number | 1   | 2   |
|---------------|-----|-----|
| Electric current | 200 | 600 |
| Displacement | 145 | 0  |
| Maximum speed | 1450 | 1450 |

Table 5 Experimental parameters

| (Electromagnet at technical data EP1, EP2) |
|-----------------------------------------|
| Voltage                                 |
| EP112V                                  |
| ±20%                                    |
| EP212V                                  |
| ±20%                                    |
| Initial control value at displacement   |
| 400mA                                   |
| 200mA                                   |
| Control current value at displacement   |
| 1200mA                                  |
| 600mA                                   |

5.3 Empirical conclusion

- Compared with 《the power head parameter table of enhanced TD2000 drilling rig under shunting state and turning into working condition》, there is an error in the maximum displacement control of hydraulic pump station, with an error of about 5 ml/r. There is still a little room for optimization, which can be optimized on site.
- Compared with 《the power head parameter table of enhanced TD2000 drilling rig under shunting condition and turning into working condition》, the minimum displacement control of power head motor has error, and the error is about 2 ml/r, so the optimization needs to be careful (during in plant commissioning, when the speed regulation exceeds a certain position, the speed of power head decreases instead).

In the whole speed regulation process, the trend is basically consistent with the table of power head parameters under shunting condition of enhanced td2000 drilling rig, but there is a little error at the two end points. The error is as described in points □ and □ above. The position number described in the table is included in the whole speed regulation process and does not need to be corrected separately. Only the corresponding speed identification needs to be carried out on site, Mark the corresponding position.

6 Conclusion

Aiming at the problem of whether the power head of raise boring machine can be driven in complex environment during reaming operation, using the fine-tuning characteristics of FOPID control to apply to the nonlinear control object, a method of adjusting FOPID control parameters based on whale algorithm (WOA) is proposed. Through the establishment of the electro-hydraulic coupling model of the power head of the raise boring machine and the simulation analysis in MATLAB software, the following conclusions are obtained:

1. From the simulation results of six different combined control strategies, it can be seen that the overall control effect of FOPID is much better than PID control in the overshoot and response time in the frequency response curve. In PID control, the overshoot is at least 8.35%, while the overshoot of FOPID control is at most 6.9309%. The results show that FOPID is more suitable for the electro-hydraulic control of raising boring than PID, and the overall response time is shorter. It can adjust the angular speed of the power head in time, and then control the fast and slow switching of the power head, which shows that
FOPID control has a better application prospect in the electro-hydraulic drive control of raising boring.

(2) Among the six combined control strategies, the combined strategy based on WOA algorithm has obvious advantages in each control method. The overshoot of WOA-PID control strategy in PID control is at least 8.35% and takes 0.1s; The overshoot of WOA-FOPID control strategy in FOPID control is at least 0.12137%, with a time of 0.02s. From the numerical iteration process of WOA objective function, it can be found that WOA has good optimization ability and convergence performance, which verifies the excellent performance of WOA in control parameter tuning. The experimental data show that the WOA-FOPID combined control strategy studied in this paper can respond to the input in time, and the FOPID parameters are adjusted through WOA algorithm, which has a good effect on the optimization of control parameters and can effectively improve the control accuracy of FOPID.

(3) After the design of the control system is completed, it is debugged and applied on the raise boring rig. The control system realizes various functions including remote pump station start and stop control and single / double drive motor switching control, and meets the requirements of process operation. Experiments show that the WOA-FOPID control strategy is effective in the electro-hydraulic drive control system. The control strategy can make the electro-hydraulic drive control have good real-time, accuracy and rapidity, and can realize fast power head Slow switching and high-precision control can be used as the exclusive control system of raise boring rig.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal elation-ships that could have appeared to influence the work reported in this paper.

Acknowledgment

The author wishes to thank 1. Youth fund of National Natural Science Foundation of China, Project Name: Research on uncertain motion characteristics and compound control mechanism of drilling and anchor manipulator based on Chebyshev interval algorithm, No. 52104165; Free exploration general fund of Shanxi Provincial Department of science and technology, Project Name: Motion uncertainty analysis and closed-loop feedback control mechanism of drilling anchor manipulator, No.: 20210302123123; State Key Laboratory of robotics and systems, Project Name: Research on motion uncertainty characteristics and compound control mechanism of manipulator of anchor drilling robot, No.: SKLRS-2021-KF-16.

Reference

[1] Wang Hai, Yang Yongjun Hydraulic system design of raise boring machine using cartridge valve [J] Mechanical design and manufacturing engineering, 2019, 48 (07): 71-73
[2] Shen Wei, Liu Shuai, Wu Yi Adaptive robust integral control of hydraulic motor servo position system based on network [J] Journal of Shanghai University of technology, 2021, 43 (04): 325-331
[3] Yang Yanlin Research on control algorithm of electro-hydraulic proportional valve controlled four cylinder synchronization [D] Lanzhou University of technology, 2019
[4] Cheng Lilin Design and Research on electro-hydraulic control system of rotary steering drilling tool test bench [D] Xi’an University of petroleum, 2021
[5] Zhang Yang Research on key technology of performance optimization of electromechanical hydraulic integrated system of drilling rig [D] General Coal Research Institute
[6] Xing Tong Research on hydraulic drive and control system of shield cutterhead [D] Zhejiang University, 2008
[7] Xu Yanying, Bao Songjian Fractional Order PID controller of five link robot optimized by improved particle swarm optimization [J] Chinese Journal of construction machinery, 2018, 16 (05): 431-435
[8] Xue Dingyu, Zhao Chunna Design of Fractional Order PID controller for fractional order system [J] Control theory and application, 2007 (05): 771-776
[9] Dai Yizong, Zhao De’an Research on PID control of semi-active suspension based on particle swarm
optimization [J] Tractors and agricultural transporters, 2013 (4): 4

[14] Yuan Chunyuan, Cai Jinkang, Wang Xinyan Research on PID controller of vehicle suspension based on particle swarm optimization algorithm [J] China Journal of agricultural machinery chemistry, 2019 (5): 7

[15] Yan Haijing, Yang Qian, Yan Tianyi, et al Research on particle swarm optimization control strategy of vehicle semi-active suspension [J] Journal of Qingdao University: Engineering Technology Edition, 2013 (1): 6

[16] Meng Jie, Yang Haipeng, Chen Qingzhang, et al Simulation Research on PID control of automotive semi-active suspension based on genetic algorithm optimization [J] Modern manufacturing engineering, 2013 (6): 5

[19] Wen Guilin, Gong Xu, Li Zhenlei, et al Static output feedback control of vehicle semi-active suspension based on ILMI algorithm [J] Automotive Engineering, 2007, 29 (6): 4

[24] Xue Dingyu Fractional calculus and fractional control [M] Science Press, 2018

[25] Liu Zhiquiang, song Chaoyang, Cheng Shouye, Hong Wenhao, Jing Guoye, Li Xinhua, Wang laisuo, Zhao Junxian Development history and current situation of drilling technology and equipment of raise boring rig in China [J] Coal science and technology, 2021,49 (01): 32-65

[26] Feng Jingpu, Chen Yun, Ma Kefeng, Xu kuifu, Tu Wei Design of electric control system for td2000 / 1200 top drive drilling rig [J] Coal mining machinery, 2021,42 (08): 18-21

[27] Mirjalili, Seyedali, Lewis, et al. The Whale Optimization Algorithm[J]. Advances in engineering software, 2016,(95):51-67.

[28] RI A , Jc B , Cx C , et al. Quasi-stability and quasi-synchronization control of quaternion-valued fractional-order discrete-time memristive neural networks[J]. Applied Mathematics and Computation, 395.

[29] Dalir M , Bigdeli N . The design of a new hybrid controller for fractional-order uncertain chaotic systems with unknown time-varying delays[J]. Applied Soft Computing, 87.

[30] Sdna B , Bao D , Sbc C . Smart dampers-based vibration control – Part 2: Fractional-order sliding control for vehicle suspension system[J]. Mechanical Systems and Signal Processing, 148.

[31] Bushnaq S , Saeed T , Torres D , et al. Control of COVID-19 dynamics through a fractional-order model[J]. Alexandria Engineering Journal, 2021.

[32] Musarrat M N , Fekih A . A fractional order sliding mode control-based topology to improve the transient stability of wind energy systems[J]. International Journal of Electrical Power & Energy Systems, 2021, 133(107306):1-12.

[33] I. Podlubny, Fractional order systems and $PI^D$ controller, IEEE Trans. on Autom. Control, 1999, 442:208-214, 1999.

[34] Wu X , Huang Y. Adaptive fractional-order non-singular terminal sliding mode control based on fuzzy wavelet neural networks for omnidirectional mobile robot manipulator - ScienceDirect[J]. ISA Transactions, 2021.

[35] RI A , Jc B , Cx C , et al. Quasi-stability and quasi-synchronization control of quaternion-valued fractional-order discrete-time memristive neural networks[J]. Applied Mathematics and Computation, 395.

[36] Dalir M , Bigdeli N . The design of a new hybrid controller for fractional-order uncertain chaotic systems with unknown time-varying delays[J]. Applied Soft Computing, 87.

[37] Sdna B , Bao D , Sbc C . Smart dampers-based vibration control – Part 2: Fractional-order sliding control for vehicle suspension system[J]. Mechanical Systems and Signal Processing, 148.

[38] Bushnaq S , Saeed T , Torres D , et al. Control of COVID-19 dynamics through a fractional-order model[J]. Alexandria Engineering Journal, 2021.

[39] Musarrat M N , Fekih A . A fractional order sliding mode control-based topology to improve the transient stability of wind energy systems[J]. International Journal of Electrical Power & Energy Systems, 2021, 133(107306):1-12.

[40] Cuong H M , Dong H Q , Trieu P V , et al. Adaptive fractional-order terminal sliding mode...
control of rubber-tired gantry cranes with uncertainties and unknown disturbances[41]. Mechanical Systems and Signal Processing, 154.

[41] Sh A., Jie W A., Chen H C., et al. A fixed-time fractional-order sliding mode control strategy for power quality enhancement of PMSG wind turbine[41]. International Journal of Electrical Power & Energy Systems, 134.

[42] Chu Dingli, Chen Hong, Wang Xuguang. Whale optimization algorithm based on adaptive weight and simulated annealing [J] Electronic news, 2019,47 (05): 992-999

[43] Butti D., Mangipudi S K., Rayapudi S R. An improved whale optimization algorithm for the design of multi-machine power system stabilizer[43]. International Transactions on Electrical Energy Systems, 2020, 30(5).

**Attached table:**

| Symbol | Parameter meaning | Parameter value or unit |
|--------|-------------------|-------------------------|
| $d_C$  | Flow coefficient of solenoid proportional directional valve |  |
| $\rho$ | Hydraulic oil density | $kg/m^3$ |
| $A$    | Area of solenoid proportional directional valve port | $m^2$ |
| $p_s$  | Outlet oil supply pressure | $MPa$ |
| $x$    | Spool displacement of solenoid proportional directional valve | $m$ |
| $p_L$  | Outlet flow or load flow of solenoid proportional directional valve | $m^3/s$ |
| $C_{on}$ | Total leakage coefficient of hydraulic motor |  |
| $V_t$  | Total volume of oil inlet chamber, oil return chamber and connecting pipe of hydraulic motor |  |
| $\beta_e$ | Effective bulk modulus of elasticity |  |
| $D_m$  | Volume displacement per radian of hydraulic motor |  |
| $\theta_m$ | Angular displacement of output shaft of hydraulic motor |  |
| $J_e$  | Equivalent inertia of reducer |  |
| $B_e$  | Equivalent damping coefficient of reducer |  |
| $U$    | Input voltage |  |
| $F_d$  | Wire coil |  |
| $i$    | Current in coil |  |
| $R_e$  | Coil internal resistance |  |
| $c$    | Damping coefficient of valve core armature assembly |  |
| $r_p$  | Internal resistance of amplifier |  |
| $K_f$  | Voltage force gain of proportional electromagnet |  |
| $m$    | Quality of valve core armature assembly |  |
| $L$    | Displacement of valve core |  |
| $k_s$  | Spring stiffness of armature assembly |  |
| $F_m$  | Current magnet driving force |  |
| $J_{cm}$ | Quality of valve core armature assembly |  |
| $L$    | Displacement of valve core |  |
| $k_s$  | Spring stiffness of armature assembly |  |
| $F_m$  | Current magnet driving force |  |

**Enclosure:**

**Program code**

% Using fminsearchbnd function to design controller

clear;

ww=[1e-13 1e13];N=20;

n=9;
s=fotf('s');

%G=1/(7.38e-4*s^3.0214+1.48e-3*s^1.9731+1.99e-2*s);

G=1/(6.4736e-10*s^4+2.97e-07*s^3+3.36e-05*s^2+0.005*s+0.118);

xm=zeros(5,1);xM=[30;30;30;2;2];x0=rand(5,1)';

t=0:0.01:8;

x=fminsearchbnd(@fpidfun,x0,xm,xM,[]',G,t,1);

Gc1=fopid(x);

step(feedback(G*Gc1,1),t);

% Numerical optimization solution

clear

global G t key1 key2;
\( s = \text{fotf}(s); \)
\( G = \frac{1}{(9.7 \times 9 \times s^4 + 4.0015 \times 2.69e-7 \times s^3 + 1.3143 \times 2.7e-5 \times s^2 + 2.0253 + 1.4e-4 \times s^1 + 0.0031 + 0.0058)}; \) % Fractional order of model
\( x_m = \text{zeros}(5,1); x_M = [30; 30; 30; 2; 2]; \)
\( x_0 = \text{rand}(5,1)\); % 0:0.01:8;
\( \text{key1} = \text{fpid}('y2=\text{itae}([Gc,x]) - \text{fpidtune}(x_0, x_m, x_M, 1)); \)
\( \text{step(feedback}(G*Gc,1),t,'*r'); \) % Fractional order controller
\( x_m = \text{zeros}(3,1); x_M = [1; 10; 1.2]; x_0 = [1; 1; 1].'; \)
\( \text{key1} = \text{fpid}('y2=\text{itae}([Gc1,x]) - \text{fpidtune}(x_0, x_m, x_M, 1)); \)
\( \text{step(feedback}(G*Gc1,1),t,'*r'); \) % Integer order controller
% Open loop Bode diagram of hydraulic system
% Clear
\( \text{num} = [173]; \)
\( \text{den} = [1.69e-6 8.146e-5 0.0049 0.0241 1]; \)
\( w = \text{logspace}(0, 5, 500); \)
\( [\text{mag}, \text{pha}] = \text{bode}(\text{num}, \text{den}, w); \)
\( \text{magDB} = 20 \times \text{log10}(\text{mag}); \)
\( \text{subplot}(211); \)
\( \text{semilogx}(w, \text{magDB}); \)
\( \text{grid on}; \)
\( \text{title}(\text{`Bode Diagram'}); \)
\( \text{xlabel}(\text{`Frequency(red/sec)'}); \)
\( \text{ylabel}(\text{`GaindB'}); \)
\( \text{subplot}(212); \)
\( \text{semilogx}(w, \text{pha}); \)
\( \text{grid on}; \)
\( \text{xlabel}(\text{`Frequency(red/sec)'}); \)
\( \text{ylabel}(\text{`phase deg'}); \)
% Uncontrolled unit step response
% Clear
\( s = \text{fotf}(s); \)
\( G = \frac{173 \times (1.69e-6 	imes s^4 + 8.146e-5 	imes s^3 + 0.0049 	imes s^2 + 0.0241 	imes s + 1)}{t = 0.01:8; \}
\( \% G1 = \frac{7.24e4(s^3 + 427.5 	imes s^2 + 2.899 	imes s + 2.826)}{y = \text{step}(G, t); \)
\( \% y1 = \text{step(feedback}(G1, 1), t); \)
\( \% \text{PID based on numerical optimization} \)
\( \text{clear} \); \}
\( \% \text{Uncontrolled unit step response} \)
\( \% \text{Clear} \); \}
\( s = \text{fotf}(s); \)
\( G = \frac{1}{(9.7e-9 \times s^4 + 4.716e-7 \times s^3 + 2.8e-5 \times s^2 + 2.0253 + 1.4e-4 \times s^1 + 0.0031 + 0.0058)}; \) % Integer order of own model
\( \% G = \frac{1}{(9.7e-9 \times s^4.0015 + 2.69e-7 \times s^{3.1343} + 2.7e-5 \times s^{2.0253} + 1.4e-4 \times s^{1.0031} + 0.0058)}; \) % Fractional order of own model
\( x_m = \text{zeros}(3,1); x_M = [1; 10; 1.2]; x_0 = [1; 1; 1].'; \)
\( \text{key1} = \text{fpid}('y2=\text{itae}([Gc1,x]) - \text{fpidtune}(x_0, x_m, x_M, 1)); \)
\( \text{step(feedback}(G*Gc1,1),t,'-b'); \) % Change the last digit, GPS \ GA \ pso-3, 4, 5
\( y = \text{step(feedback}(G*Gc1,1),t,'-b'); \)
\( [\text{ys}, \text{tr}, \text{ts}, \text{tm}, \text{ov}] = \text{Fun_Step_Performance}(t, y, 1); \)
% Fopid based on numerical optimization
\( \% \text{Clear global G t key1 key2; \}
\( s = \text{fotf}(s); \)
\( G = \frac{1}{(9.77e-9 \times s^4 + 4.716e-7 \times s^3 + 2.8e-5 \times s^2 + 1.39e-4 \times s^1 + 0.0058)}; \) % Integer order of own model
\( \% G = \frac{1}{(9.77e-9 \times s^4 + 4.716e-7 \times s^3 + 2.8e-5 \times s^2 + 1.39e-4 \times s^1 + 0.0058)}; \) % Fractional order of own model
\( x_m = \text{zeros}(3,1); x_M = [1; 10; 1.2]; x_0 = [1; 1; 1].'; \)
\( \text{key1} = \text{fpid}('y2=\text{itae}([Gc1,x]) - \text{fpidtune}(x_0, x_m, x_M, 1)); \)
\( \text{step(feedback}(G*Gc1,1),t,'*r'); \) % Change the last digit, GPS \ GA \ pso-3, 4, 5
\( y = \text{step(feedback}(G*Gc1,1),t,'*r'); \)
\( [\text{ys}, \text{tr}, \text{ts}, \text{tm}, \text{ov}] = \text{Fun_Step_Performance}(t, y, 1); \)
% Stability judgment
\( \text{Fractional transfer function of controlled object} \)
\( a = [2.1409, -2.9408, -0.8069, 0.1308, 0.00000004]; na = [0.0912, 0.4277, 1.0731, -0.9786, 0]; \)
\( b = [-4.7434, -4.6477, 5.1276, 3.8868, -4]; nb = [3.5512, 3.3388, 3.3836, 3.8590, 0]; \)
\( G = \text{fotf}(a, na, nb); \)
% \%
-3.8686*s^3.859-4.7434*s^3.5512-5.1276*s^3.3836-
4.6477*s^3.3388-4

-0.8069*s^1.0731-2.9408*s^0.4277+2.1409*s^0.0912+4e-
08+0.1308*s^{-0.9786}

WOA-fopid controller

s=fotf('s');Ge=15.2654+20*s^{-1.0039}+9.5963*s^1.118

9.5963*s^{2.1219}+15.2654*s^{1.0039}+20

s^0.1039

G3= Ge*G

GG=feedback(G3,1)

determine the stability of the

Frequency domain analysis of FOTF object: Bode diagram and Nyquist
diagram of the system are drawn

bode(G3,w);Fig.;uere,w=logspace(-2,4,400);nyquist(G3,w);grid