Research on Automatic Bit Feeding Control System with Constant Weight on Bit Based on Fuzzy Predictive Control

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Abstract—According to the automatic bit feeding system of oil drilling rig has basic characteristics such as multi-variable, time-varying and nonlinear, an automatic bit feeding control system with constant weight on bit (WOB) based on fuzzy predictive control is proposed. The fuzzy predictive controller of WOB is designed, and the future output of the system is predicted by predictive control, and the output value of the system is close to the given value of WOB as much as possible by fuzzy control. The simulation results show that the response speed of the system is improved, which meets the requirements of small error and high precision, and has a certain guiding significance for the actual design and application.

1. Introduction

The automatic bit feeding control system of oil drilling rig often adopts constant weight on bit (WOB) drilling control technology. At present, constant WOB control system mostly adopts PID control [1]. However, in the process of drilling, rock performance, mud properties, wellbore friction and other factors will affect the WOB, and many downhole factors make the automatic bit feeding system a multivariable, time-varying, time-delay and nonlinear system, so it is difficult to establish an accurate mathematical model of the hoisting system. For the automatic bit feeding system with large disturbance, the model-based PID control is difficult to achieve accurate and stable control effect. It leads to poor control and adaptability of drilling.

In this paper, an automatic bit feeding system with constant WOB based on fuzzy predictive control strategy is proposed. Fuzzy control and predictive control are two kinds of control methods developed independently. Fuzzy control is suitable for nonlinear systems or complex systems in which the mathematical model of the object is unknown, and it belongs to "ex post control". That is, the control quantity is determined according to the deviation information of the controlled quantity that can be measured at present. The predictive control realizes the control through the prediction of the future output of the controlled process, has a strong adaptive ability, and has a good control effect on complex systems such as large inertia and large delay [2-6].

In this paper, the constant WOB automatic bit feeding control system of AC frequency conversion electric drilling rig based on fuzzy predictive control is studied. According to the characteristics of WOB change, a fuzzy predictive controller is designed, and the simulation experiment is carried out. It is
verified that the WOB fuzzy predictive control has strong adaptability, with stable drilling rate response, and improves the dynamic control performance of the system.

2. Automatic bit feeding system with constant WOB

In the process of drilling, when the drilling reaches a certain depth, the weight of the whole drilling tool (the weight sum of the drill collar and drill pipe) will be very large, in order to keep the bottom hole WOB constant in the whole drilling process, the drawworks can be used to drive the wire rope to produce a certain lifting force on the drilling tool, so as to overcome the gravity of the drilling tool and keep the bottom hole WOB constant.

Constant WOB automatic bit feeding technology is that, in the normal drilling process, the drilling rig keeps the pressure of the bit to the bottom of the hole constant according to the requirements of drilling technology. By establishing the control relationship among bottom hole WOB, drawworks speed and brake, this technology controls the lowering of the drawworks, sends drilling tools to the bottom hole at the right time, and automatically adjusts WOB to realize automatic bit feeding.

The hook load acts on the tension sensor through the dead line, and then is converted into a standard voltage signal by the transmitter, and the actual WOB value is obtained. After the control algorithm is processed, compared with the given WOB value, the output signal of the controller is used as the given input signal of the frequency converter, and the frequency converter controls the electromagnetic torque and rotational speed of the drill feed motor. After the transmission devices such as gearbox and drawworks drum, the lowering speed of the hook is controlled, and the closed-loop control of constant WOB is realized [7-10].

3. Fuzzy predictive control system for automatic bit feeding

The block diagram of constant WOB automatic bit feeding control system based on fuzzy predictive control is shown in figure 1. The control system consists of two control loops, the outer loop is the WOB control, and the inner loop is the rate of penetrate control. This design helps to increase the stability of the system, improve the nonlinearity of the system, and improve the control accuracy of the rotate speed of the drawworks [1].

The object of the inner ring is mainly composed of frequency converter, AC variable frequency speed regulation motor, speed measuring encoder and so on. This part is not affected by geological structure, rock properties and other external environmental factors. In the control process, the speed and current of the variable frequency motor are controlled by double closed-loop vector control, and finally the rotate speed of the drawworks is controlled. The speed of the motor is detected by the speed encoder and fed back to the input of the speed control unit of the frequency converter to form a negative feedback loop, which can improve the response speed, increase the stability of the system and improve the speed control accuracy of the variable frequency motor.

The fuzzy prediction algorithm is used in the WOB control of the outer loop. According to the time-delay, time-varying and nonlinear characteristics of the automatic bit feeding system, a fuzzy prediction controller is designed. The control algorithm has a good control effect in the automatic bit feeding control system with constant WOB.

![Figure 1](image-url) Figure 1 Block diagram of automatic bit feeding control system with constant WOB.
4. Design of fuzzy predictive controller with constant WOB

According to the nonlinear, uncertain and time-varying characteristics of automatic bit feeding system, fuzzy predictive control system is adopted by combining fuzzy strategy with predictive strategy. The system is mainly composed of fuzzy control and predictive control, in which the predictive control adopts dynamic matrix control (DMC) algorithm, which mainly predicts the future output of the system, which is used to predict the future, adjust the strength of control and maintain good dynamic control performance; fuzzy control is mainly to make the output predictive value of the controlled object close to the given value of WOB as far as possible. The structure of the fuzzy predictive control system for automatic drill feeding is shown in figure 2.

![Figure 2 The principle diagram of disturbance observer](image)

As can be seen from figure 2, the system consists of three parts: fuzzy control, predictive model and on-line correction. First of all, the future output WOB $P_p$ of the system is estimated by the prediction model through on-line correction, and compared with the given WOB $P^*$, the error value $e$ and error change rate $\dot{e}$ obtained are used as the input of the fuzzy controller. Through fuzzy reasoning, the output $u$ function of the fuzzy controller acts on the drilling system, which controls the operation of the automatic bit feeding and outputs the WOB $P$. The main function of the control system is to make the predicted output $P_p$ of the drilling system as close as possible to the given WOB $P^*$, so that the WOB can follow the given WOB.

4.1. Prediction model

The prediction model is to predict the future output value of the system according to the historical data and future input of the system. The prediction model adopts dynamic matrix control (DMC) algorithm, which is an incremental algorithm based on system step response and adopts multi-step prediction technology, so that the problem of time delay can be solved effectively and controlled according to the index that minimizes the deviation between the estimated output and the given value. Suppose $\alpha = [\alpha_1, \alpha_2, ..., \alpha_l]^T$ is the predictive model vector based on the step response of the controlled object, and $l$ is the time domain length of the model. During time of $k$, a control increment $\Delta u(k)$ is applied to the system, and the $n$ predicted output value vectors of the future moment under the action of $\Delta u(k)$ can be obtained.

\[
P_m = P_0 + A\Delta U
\]

\[
P_m = [P_m(k + 1), P_m(k + 2), \cdots, P_m(k + n)]^T
\]

\[
P_0 = [P_0(k + 1), P_0(k + 2), \cdots, P_0(k + n)]^T
\]

\[
\Delta U = [\Delta u(k), \Delta u(k + 1), \cdots, \Delta u(k + m - 1)]^T
\]
4.2. On-line correction

Due to the influence of time-varying, nonlinear, environmental interference and other factors in the actual drilling process, the predicted value obtained by formula 1 may deviate from the actual value, so the predicted value must be corrected on-line to improve the accuracy of the predicted value. The method of correction is to compare the actual output value of the object with the predicted value obtained by formula 1 at the next sampling time to get the prediction error.

$$e(k+1) = P(k+1) - P_m(k+1)$$ (6)

Then the output predicted value is corrected by online scrolling.

$$P_p = P_m + He(k+1)$$ (7)

In the formula: $H = [h_1, h_2, ..., h_r]^T$ is the error correction vector and $P_p$ is the predicted value after correction. After shift, it is used as the initial predicted value of the next time.

4.3. Fuzzy control

After comparing the given WOB value with the predicted WOB value in the constant WOB automatic feeding system, the given WOB value is input to the fuzzy controller for corresponding fuzzy processing, and then the fuzzy processing result is sent to the frequency converter to realize the control of the drill feed motor, in order to control the lowering speed of drilling tools to achieve the purpose of constant WOB drilling.

In the fuzzy controller designed in this paper, the input variables are the WOB error $e$ and the rate of change of the WOB error $\dot{e}$, and the output is the lowering speed $u$ of the drilling tool. Drilling technology requires that the WOB should be kept constant in the process of drilling, and the variation range of WOB $P$ is $-5 \sim 5$ kN[7], which is the basic domain of WOB error $e$. Try not to have negative deviation in the actual control, because the negative deviation means that the actual WOB is too large, which will shorten the service life of the bit, increase the additional drilling cost, and increase the vibration of the system. The basic domain of error change rate $\dot{e}$ is $-1 \sim 1$ kN/s. According to the drilling experience, when the formation is uniform and the hydraulic parameters are constant, the bit wear is the smallest when the drill bit is drilled for about $5 \sim 6$ mm per second. The lowering speed $u$ of drilling tools in drilling starts from zero, so its variation range is $0 \sim 6$ mm/s. Because the domain of the theory $u$ is asymmetric, in order to facilitate the calculation, it is transformed into a symmetrical weight $-6 \sim 6$ mm/s. The fuzzy domain of error $e$ and error change rate $\dot{e}$ is quantized to 13 levels, and the fuzzy domain of output control variables $u$ is quantized to 15 levels. The quantization factors were $K_1 = n/e = 6/5 = 1.2$, $K_2 = m/e = 6/1 = 6$, $K_3 = u/l = 6/7 = 0.857$. 

\[
A = \begin{pmatrix}
    a_1 & 0 & \cdots & 0 \\
    a_2 & a_1 & \cdots & 0 \\
    \vdots & \vdots & \ddots & \vdots \\
    a_n & a_{n-1} & \cdots & a_{n-m+1}
\end{pmatrix}
\] (5)
The WOB error $e$, the change rate $\dot{e}$ of WOB error and the lowering speed $u$ of drilling tool all take 7 language values, which are NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), PB (positive big).

After the fuzzy set domain of fuzzy input variable error $e$, error change rate $\dot{e}$ and output control quantity $u$ is determined, the membership degree of elements in the domain to fuzzy language variables must be determined. The membership functions of the fuzzy controller designed in this paper are all in the form of trigonometric functions, and the membership functions of input variables $e$ and $\dot{e}$ and output variables $u$ are shown in figure 3 respectively.

![Figure 3 Membership function of variable](image)

Table 1  Fuzzy control rule table

| E   | NC | NM | NS | ZE | PS | PM | PB |
|-----|----|----|----|----|----|----|----|
| NB  | NB | NB | NB | NB | NM | NS | ZE |
| NM  | NB | NB | NB | NM | NM | NS | ZE |
| NS  | NB | NM | NM | NS | NS | NS | ZE |
| ZE  | NB | NM | NS | ZE | PS | PM | PB |
| PS  | ZE | PS | PS | PS | PM | PM | PB |
| PM  | ZE | PS | PM | PM | PB | PB | PB |
| PB  | ZE | PS | PM | PB | PB | PB | PB |

According to the requirements of drilling technology, expert knowledge and driller's operation experience, fuzzy control rules can be summarized, as shown in Table 1.

The principle of selecting the change of the output control quantity is that when the error is large or larger, the output should eliminate the error as soon as possible; when the error is small, the output should prevent overshoot and maintain the stability of the system. As can be seen from Table 1, when the error $E$ is negative, it shows that the bottom hole WOB is greater than the given WOB. If the error change rate $EC$ is negative, then the error tends to increase negatively, so that the bottom hole WOB continues to increase. In order to eliminate the existing negative large error and restrain the error from increasing as soon as possible, it is necessary to reduce the output WOB and make the output $U$ negative big. If the error change rate $EC$ is positive big, the output $U$ should be zero in order not to cause positive error caused by overshoot of the control system. When the error $E$ is positive big, it shows that the bottom hole WOB is less than the given WOB, and if the error change rate $EC$ is positive, the error tends to increase, so that the bottom hole WOB continues to decrease. In order to eliminate the existing
positive error and restrain the error as soon as possible, it is necessary to increase the output WOB and make the output U large, that is, it is necessary to accelerate the lowering of drilling tools.

5. Simulation experiment

According to figure 1, the structure block diagram of the drilling system is shown in figure 4, where, the AC vector control is the motor driven by the vector control frequency converter, \( G_v(s) \) is the transfer function of the hoisting system, H is the proportional coefficient of the speed of the drawworks drum and the drilling speed, and \( G_p(s) \) is the transfer function of drilling speed and WOB.

\[
W = \frac{s^2}{s^2 + \frac{M_r}{I_2} + \frac{C_1}{I_2} + \frac{C_3}{I_3}} \frac{s}{s^2 + \frac{C_1}{I_3}}
\]

The motion structure block diagram of the hoisting system is shown in figure 5, which is the moment of inertia of the drum, is the total converted moment of inertia of the other parts, is the static resistance torque, and is the torque acting on the drum axis after the motor passes through the gearbox. According to the working manual of the relevant drilling engineer [14-15], it can be concluded that: \( I_2 = 619.985 \text{kg} \cdot \text{m}^2 \), \( I_3 = 169.652 \text{kg} \cdot \text{m}^2 \), \( M_r = 1.88 \times 10^4 \text{N} \cdot \text{m} \), \( C_{12} = 1.301 \times 10^6 \text{kg} \cdot \text{m} / \text{rad} \), \( C_{23} = 6.361 \times 10^6 \text{kg} \cdot \text{m} / \text{rad} \).

The relationship between drilling speed and WOB of drilling system is as follows:

\[
G_p(s) = \frac{P(s)}{V(s)} = \frac{-M_2s^2 + C_1}{s} = \frac{-1.826 \times 10^6 s^2 + 9.01 \times 10^6}{s}
\]

Formula: M is the torque of the steel rope on the drum; \( C_1 \) is the stiffness of the drilling tool.

According to the principle of fuzzy predictive control, the simulation model of the system is established in the Simulink of MATLAB. The structure diagram of the simulation experiment is shown in figure 6.
According to the working experience of oil field drilling, when the WOB is about 20t, the drilling speed is proportional to the square of the WOB [1], so the step signal is used as the input signal of the controller in the simulation process, and the amplitude is 20. The parameters of predictive control are as follows: $l=50$, $n=20$, $m=10$. The simulation results are shown in figure 7.

The Abscissa of the output response curve in figure 7 represents the time, and the ordinate represents the WOB. As can be seen from figure 7, the response time of the system is fast, the overshoot of the system is 10% lower than the engineering requirements, the stable state is fast, and the steady-state error is less than 5% of the engineering requirements, which can meet the requirements of system control.

6. Conclusion
Through the research on the constant WOB automatic bit feeding control system of AC frequency conversion electric drilling rig, the constant WOB fuzzy predictive controller of the automatic bit feeding system of electric drilling rig is designed in this paper. The simulation results show that the control system can realize the automatic bit feeding process with constant WOB, has good follow-up performance, shortens the transition time and improves the control stability of the system. This control method has a certain guiding significance for the design and application of the actual system.

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