Research on Safety Drilling Back Pressure Control Based on Fuzzy PID Control

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Abstract

Pressure control drilling technology through the precise control of the entire wellbore annular pressure profile, the bottom of the pressure can always maintain the safety density window, so as to achieve the purpose of safe operation. In the drilling process, the use of conventional drilling technology for drilling operations, easily lead to well, overflow and other drilling accidents. In this paper, the use of pressure control drilling technology, through the back pressure compensation system in the wellhead to apply back pressure, and thus to keep the bottom hole pressure balance. And the back pressure control model is established, the fuzzy immune PID adaptive control algorithm is designed, the speed and precision of the back pressure control response is improved, Which is of great significance to promote the development and popularization of controlled pressure drilling.

1. Introduction

As China's demand for oil and gas resources continues to grow, oil exploration and development continue to develop in deep and complex areas, narrow-density window formation safety drilling problem is more and more prominent, especially in the drilling operation, Once the bottom hole pressure exceeds the safety range of the design, prone to oil and gas intrusion, well blowout, leakage and other complex accidents [1]. As a modified drilling process, the pressure-controlled drilling can control the whole annular pressure profile of the wellbore in the safe drilling operation, so that the bottom hole pressure can be kept within a certain safe range, effectively preventing the formation fluid from penetrating the wellbore and reducing the pressure kick and circulation loss occur.

At present, for the pressure control drilling technology Weide Fu company developed the Secure Drilling system which is a relatively advanced foreign pressure control drilling technology. The Secure Drilling system was first known as Micro-Flux-Control [2-5]. Halliburton developed the MPD control system [6]. China Petroleum Drilling Technology Research Institute developed PCDS-Ⅰ fine pressure control drilling system [7,8]. Through a number of columns of literature research, in the pressure control drilling technology, how to improve the drilling process of the bottom of the pressure control ability to solve the existence of some problems are not high accuracy. In this paper, based on the PID control algorithm based on the throttle valve control valve caused by weak adaptive, poor robustness and other issues, based on the localization of the throttle valve equipment design a fast response, overshoot small, adaptive ability Throttle control algorithm, the goal of controlling the pressure of fine, effectively reduce the cost of pressure control drilling.

2. Composition and Mathematical Model of Back Pressure Control System

2.1 Back pressure control system

At present, the drilling construction site to use more electro-hydraulic proportional throttle control system, the system mainly by the method seven, electro-hydraulic proportional valve, hydraulic throttle and sensor components, as shown below. The workflow is the output of the control signal amplified by the amplifier to the electro-hydraulic proportional valve, according to the direction and size of the transmission signal, electro-hydraulic proportional valve through a different path to pump a certain amount of hydraulic oil into the throttle cylinder, to promote the spool movement , So as to adjust the throttle opening [9]. Wellhead back pressure system composition Figure 1 as follows:

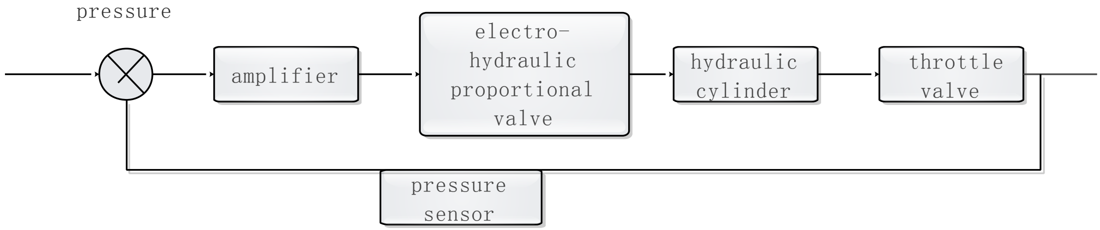


Figure 1. Wellhead back pressure system composition

The wellhead backpressure control system block diagram is shown in the figure. After the pressure sensor detects the wellhead back pressure, the control system compares the back pressure value set by the analysis decision system to obtain the deviation value, generates the control signal through the back pressure control algorithm, and transmits the control signal to the proportional directional control valve through the amplifier , and The control signal is transmitted to the proportional directional control valve through the amplifier. The proportional valve outputs the hydraulic oil flow proportional to the control current to push the distance required for the movement of the spool to change the opening degree of the throttle valve To achieve the purpose of wellhead back pressure control.

2.2 Back pressure control mathematical model

(1) proportional amplifier

Proportional amplifier can be seen as a proportion of links, according to the selected amplifier model can be derived from the transfer function:

$$K_a = I(s)/U(s) = 0.244\,(A/V) \tag{1}$$

$U(s)$—— the amplifier input voltage, V;

$I(s)$——Amplifier output current, A.

(2) electro-hydraulic proportional valve

The mathematical model of the electro-hydraulic proportional valve can be expressed by the first-order inertia [10]. According to the flow rate characteristic curve of the proportional directional control valve used in combination with the amplifier, the flow gain coefficient can be obtained. After obtaining the sample may query the bandwidth, and then come to valve transfer function:

$$G_{pv} = \frac{Q_l(s)}{I(s)} = \frac{K_{pv}}{\dfrac{s}{\omega_{pv}}+1} = \frac{6.6\times10^{-4}}{2.7\times10^{-2}s+1}\,(m^3/A) \tag{2}$$

$Q_l(s)$——Electro - hydraulic proportional valve for no - load flow, m^3/s, $Q_l(s)=K_vX_v(s)$;

$X_v(s)$——Spool displacement of electro - hydraulic proportional valve, m.

(3) hydraulic cylinder

The hydraulic cylinder controlled by the electro-hydraulic proportional valve is the hydraulic power part of the throttle valve [11]. Since the piston rod of the throttle cylinder used in this paper is relatively thick, the influence of the elastic deformation of the hydraulic cylinder on its displacement can be neglected, It is simplified after the transfer function can be:

$$X_p(s) = \frac{\dfrac{K_q}{A_p}Q(s) - \dfrac{K_{ce}}{A_p^2}\left(\dfrac{V_t}{4\beta_e K_{ce}}s+1\right)F_l(s)}{s\left(\dfrac{s^2}{\omega_h^2}+\dfrac{2\zeta_h}{\omega_h}s+1\right)} \tag{3}$$

K_q——Flow - Displacement Gain of Electro - hydraulic Proportional Valve, $K_q = 2.51\, m^2/s$;

A_p——Effective working area of hydraulic cylinder, $A_p = 4.644\times10^{-2}\, m^2$;

V_t——Effective working volume of the piston chamber, $V_t = 3.11\times10^{-3}\, m^3$;

β_e——Effective modulus of hydraulic oil modulus, $\beta_e = 690\, MPa$;

$F_l(s)$——Hydraulic cylinder load force, N;

K_{ce}——Pressure flow coefficient;

$$K_{ce} = \frac{\pi\omega c_r^2}{32\mu} = 9.2\times10^{-12}\ (m^3/Pa\cdot s) \tag{4}$$

ω_h——Hydraulic cylinder natural frequency;

$$\omega_h = \sqrt{4\beta_e A_p^2 / M_t V_t} = 4891\,(rad/s) \tag{5}$$

ζ_h——Hydraulic damping ratio;

$$\zeta_h = \frac{K_{ce}}{A_p}\sqrt{\frac{\beta_e M_t}{V_t}} = 8.3\times10^{-7} \tag{6}$$

As in the general case, the calculated damping ratio is very small, the value is generally in the range of 0.10 ~ 0.20, therefore, take this article. At the same time, considering the existence of a hydraulic flow line between the electro-hydraulic proportional valve and the hydraulic cylinder, there is a certain time delay between the operation of the proportional valve and the generation of the hydraulic cylinder. Therefore, this paper in the transfer function model in series with a time delay link, then after a simplified hydraulic cylinder transfer function:

$$X_p(s) = \frac{54Q(s) - 4.27\times10^{-9}(1.22\times10^5\cdot s+1)F_l(s)}{s\cdot(4.18\times10^{-8}\cdot s^2 + 4.09\times10^{-5}\cdot s+1)} \tag{7}$$

(4) pressure sensor

Since the time constant of the pressure sensor is usually small, the detection feedback link can be regarded as a proportional link, the scale factor is:

$$K_f = U(s)/P(s) = 0.18 \tag{8}$$

$U(s)$——Feedback voltage, V;

$P(s)$——The pressure of check point, MPa.

(5) Throttle valve

During the actual drilling construction, the drilling fluid in the annulus is often in the form of gas, liquid and solid multiphase flow. The throttle pressure drop of the throttle valve is a nonlinear function relationship with the spool displacement and the drilling fluid flow:

$$\Delta p = f(x_p, q) \tag{9}$$

By the fluid mechanics hole over-current analysis principle [43] shows that the throttle flow section at the flow rate:

$$V_c = \frac{1}{(\alpha_c + \xi_0)}\sqrt{2\frac{p_1 - p_2}{\rho}} = C_V\sqrt{\frac{2\Delta p}{\rho}} \tag{10}$$

Δp——Effective pressure difference of throttle valve, MPa;

α_c——The kinetic energy correction coefficient at the end of the overcurrent section shrinkage is basically uniform due to the flow rate of the throttle overcurrent shrinkage section, so there is $\alpha_c = 1$;

ξ_0 ——The local loss coefficient of the throttle overcurrent calculated by the average velocity of the contraction section;

$C_V = \dfrac{1}{(\alpha_c + \xi_0)}$ ——The flow rate coefficient of the throttle valve, such as no flow loss, $\xi_0 = 0$, $\alpha_c = 1$, $C_V = 1$.

Therefore, the flow through the throttle valve is:

$$q = S_c V_c = C_c S\ C_V \sqrt{\frac{2\Delta p}{\rho}} = CS\ \sqrt{\frac{2\Delta p}{\rho}} \tag{11}$$

The effective pressure drop of the throttle valve is:

$$\Delta p = \frac{q^2 \rho}{2C^2 S^2} \tag{12}$$

S ——Throttle flow area;

S_c ——The flow cross section of the flow head at the end of the throttle;

C ——Throttle valve flow coefficient.

With W said throttle valve flow area gradient, X said throttle valve spool displacement, the throttle flow area S is:

$$S = w \cdot x_p \tag{13}$$

$$\Delta p = 0.5 \frac{\rho q^2}{C^2 w^2 x_p^2} \tag{14}$$

Δp ——Throttle pressure drop, MPa;

ρ ——Drilling fluid density, g/cm3;

q ——Drilling fluid flow, L/s;

C ——Flow coefficient, the general value of 0.9;

x_p ——Spool displacement;

w ——Flow area gradient.

From the equation (1-13) shows that the throttle pressure drop p and its spool displacement and drilling fluid flow presents a serious non-linear relationship,, Therefore, when it is linearized, the equation (1-9) is expanded into a Taylor series at a predetermined operating point. there are

$$p = f(x_0, q_0) + \frac{\partial f(x,q)}{\partial x}\Big|_{(x_0, q_0)} \Delta x + \frac{\partial f(x,q)}{\partial q}\Big|_{(x_0, q_0)} \Delta q \tag{15}$$

(1-14) and (1-9) subtraction available

$$\Delta p = K_{px} x_p + K_{pq} q \tag{16}$$

K_{px} ——Throttle valve pressure - displacement coefficient, $K_{px} = \left.\dfrac{\partial p}{\partial x}\right|_{(x_0, q_0)}$, (x_0, q_0) is the value of the scheduled operating point, MPa/m;

K_{pq} ——Throttle valve pressure - flow coefficient, $K_{pq} = \left.\dfrac{\partial_p}{\partial_q}\right|_{(x_0, q_0)}$, MPa s/m3.

(6) System open-loop transfer function

As the inherent frequency of the hydraulic cylinder is high, the mathematical model can be simplified as an integral link and a delay link in series. Therefore, the comprehensive analysis of the transfer function of each link can be obtained wellhead back pressure control system transfer function block diagram shown in Figure 2.

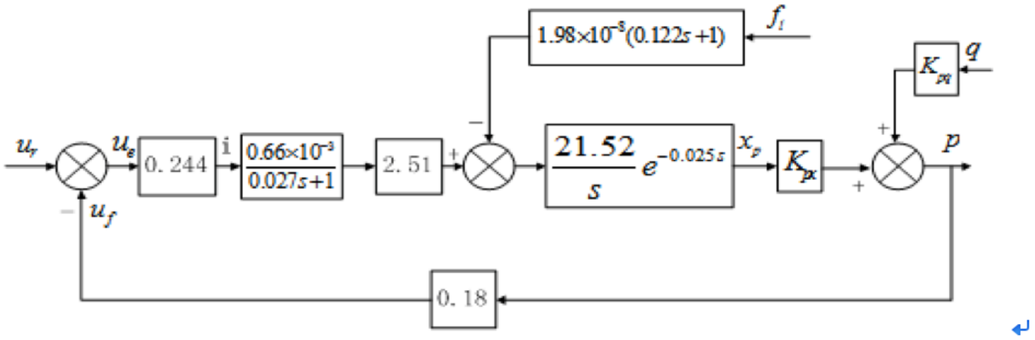


Figure 2. Transfer function block diagram

From Figure 2, the open-loop transfer function of the system is:

$$G_p(s)=\frac{1.57\times10^{-3}K_{px}}{0.027s^2+s+0.5}e^{-0.025s}$$

3. Design of Fuzzy Immune PID Controller

Based on the mechanism of immune feedback algorithm, fuzzy PID control principle and fuzzy PID control parameter tuning rules, this paper designs a fuzzy immune PID adaptive controller. Based on the principle of immunization, the number of antigens in the kth generation is assumed to be $\varepsilon(k)$, and the output of the T_h cells after stimulation by the antigen is $T_h(k)$ [12,13].

$$T_h(k)=k_1\varepsilon(k) \tag{17}$$

k_1——The incentive factor is positive

Assuming that the effect of suppressing cells on B cells is $T_s(k)$,then

$$T_s(k)=k_2 f(\Delta s(k))\varepsilon(k) \tag{18}$$

k_2——Suppression factor, the symbol is positive;

$f(\cdot)$ is a non-linear function that shows the inhibition of cell inhibition, the output range of [0,1].

Thus, the total stimulus received by B cells is

$$S(k)=T_h(k)-T_s(k)=(k_1-k_2 f(\Delta s(k)))\cdot\varepsilon(k) \tag{19}$$

The primary function of the immune response is to respond quickly to the invading antigen while ensuring the stability of the immune system. The overall goal is to minimize the total amount of damage to the organism. In the process of dynamic adjustment of the control system, it is also required to quickly eliminate the deviation under the premise of ensuring the stability of the system, which is consistent with the goal of the immune system. The comparison of the immune system with the control system is shown in Table 1.

The discrete form of the commonly used incremental PID controller is:

$$u_{PID}(k)=u(k-1)+K_P(e(k)-e(k-1))+K_Ie(k)+K_D(e(k)-2e(k-1)+e(k-2)) \tag{20}$$

The control law of the proportional coefficient P controller is:

$$u(k)=K_Pe(k) \tag{21}$$

According to Table 1, the mechanism of immune feedback is applied in the control, the design control law is

$$u(k)=K(1-\eta f(u(k),\Delta u(k)))\cdot e(k)=K_{P1}e(k) \tag{22}$$

$K_{P1} = K(1-\eta f(u(k),\Delta u(k)))$, $K = k_1$ is the speed of reaction control.

Table 1. Comparison of immune system and control system

immune system	Control System
(Antibody, antigen, etc) The breeding of the K generation	The kth sampling time of the discrete system
The antigen concentration of K generation $\varepsilon(k)$	The deviation of the given value at the kth sampling time $e(k)$
K-generation B cells received total stimuli $S(k)$	The kth sampling time of the controller output $u(k)$

When l increases, the system will increase the response speed; for the control of stability, if increased, the system will reduce the overshoot. Therefore, reasonable adjustment and, can improve the response speed of the control system, reduce the system overshoot. $f(\cdot)$ is a nonlinear function $f(u(k),\Delta u(k))$ of $u(k)$, $\Delta u(k)$

It can be seen that the controller based on the principle of immune feedback is actually a nonlinear P controller, the proportion coefficient is with the controller output changes, and has a strong ability to adapt. However, P-type immune controller also has shortcomings, can not compensate for control error caused by the non-linear interference. Therefore, the use of PID-type immune controller, the PID controller output as the amount of antigen, the immune PID controller output is:

$$u(k) = u(k-1) + K_{P1}(e(k)-e(k-1)) + K_I e(k) + K_D(e(k)-2e(k-1)+e(k-2)) \qquad (23)$$

$K_{P1} = K(1-\eta f(u(k),\Delta u(k)))$

It can be seen from the control theory that the appropriate scaling factor can improve the adjustment precision of the system, and the reasonable integral control can reduce the steady-state error of the system. Reasonable differential control can improve the dynamic characteristics of the system. Therefore, the fuzzy immune principle can be used to adjust the proportional coefficient K_{P1}, and the K_I and K_D parameters can be modified online by the fuzzy control principle, so as to realize the adaptive adjustment of PID parameters. The structure of the fuzzy immune adaptive PID control system is shown in Fig. 3 [14,15].

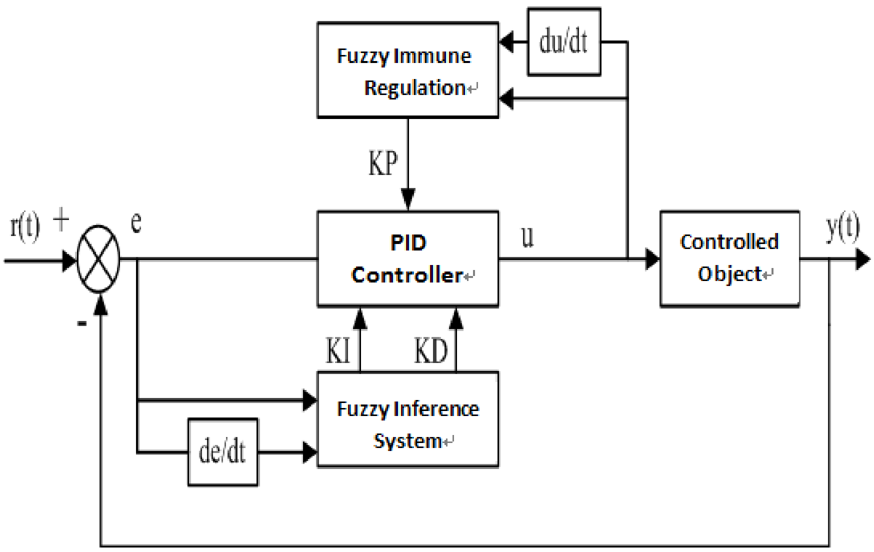
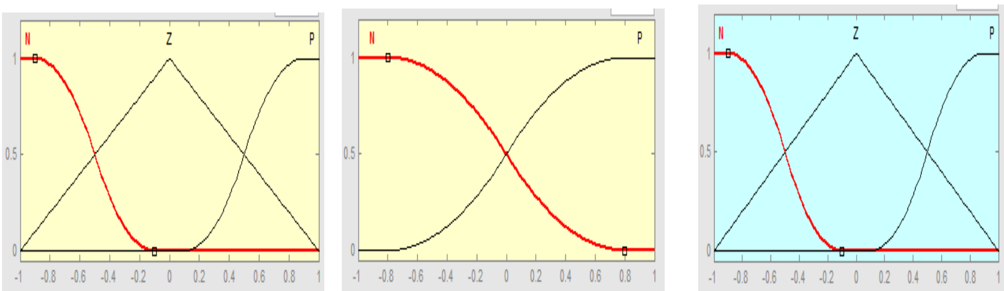


Figure 3. Fuzzy immune adaptive PID control system structure

3.1 Fuzzy adaptive adjustment of immune feedback rule

Because the nonlinear function $f(\cdot)$ in the immune PID controller has a great influence on the control performance of the system, it is usually difficult to select. Therefore, this paper uses a two-dimensional fuzzy controller to adjust the immune function of the nonlinear function $f(\cdot)$.

The input of the fuzzy controller is the amount of blur of the change in the output and output of the immune feedback controller, and its fuzzy subsets are {positive (P), zero (Z), negative (N)} and {positive (P) negative (N)}; The output is a fuzzy quantity of the nonlinear function $f(\cdot)$, and the fuzzy subset is {positive (P), zero (Z), negative (N)}. The input and output membership functions of the immune controller are shown in Fig. 4 (a), (b) and (c), respectively.



(a) (b) (c)

Figure 4. Input and output variables u, uc and membership function curve of $f(\cdot)$

According to the stability of Lyapunov, the fuzzy reasoning rules of the controller are obtained. At the same time, the fuzzy control rules of approximating nonlinear functions are shown in Table 2.

Table 2. The fuzzy control rules of $f(\cdot)$

U / UC	P	Z	N
P	N	N	Z
N	Z	P	P

Zadeh's fuzzy logic AND operation is used in each fuzzy rule, and the output $f(\cdot)$ of the fuzzy controller is obtained by Mamdani reasoning method.

3.2 PID controller integral and fuzzy adaptive adjustment of differential parameters

(1) setting of fuzzy rule set

According to the structure of the two-dimensional fuzzy controller, the input fuzzy language variable of the fuzzy controller is taken as E (fuzzy language variable of deviation) and EC (fuzzy language variable of deviation change rate), and its fuzzy domain is taken as [-6 , 6]. At the same time, the two outputs of the fuzzy controller are defined as [-10,10].The fuzzy subsets of variable E, EC, ΔK_I and ΔK_D are all defined as {Negative Big (NB), Negative Median (NM), Negative Small (NS), zero (ZO), Positive Small (PS), Positive Median (PM) Positive Big (PB)}. According to the deviation, the different state of the deviation rate and the basic principle of the fuzzy PID controller parameter tuning and the continuous simulation and debugging optimization, the fuzzy control rules for tuning two parameters are obtained, as shown in Table 3 and Table 4.

Table 3. fuzzy control of ΔK_I rules table

E / EC	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NM	NS	ZO
NM	NB	NB	NM	NS	NS	ZO	ZO
NS	NM	NM	NS	NS	ZO	ZO	PS

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

Table 4. Fuzzy control of ΔK_D rules table

E / EC	NB	NM	NS	ZO	PS	PM	PB
NB	PM	PM	ZO	ZO	ZO	PM	PB
NM	PS	PS	NS	NS	ZO	NS	PM
NS	NS	ZO	NM	NS	PS	PS	PM
ZO	NB	NM	NS	NS	PS	ZO	PS
PS	NB	NM	NS	NS	PS	PS	PS
PM	NB	NS	NM	NS	ZO	PM	PB
PB	NM	ZO	ZO	ZO	ZO	PB	PB

(2) the determination of quantization factor and scale factor

The quantization factor of the deviation can be set according to the actual domain of the deviation of the controlled quantity and the allowable error limit. According to the design index, the dynamic response error of backpressure control wellhead backpressure control system is less than 0.1MPa. Therefore, the actual physical domain of the deviation e is [-1,1], then the deviation quantization factor $k_e = \frac{6-(-6)}{1-(-1)} = 6$. According to the requirements of the control system response speed, the basic domain of the initial change rate ec is [-1,1], then the quantization factor is $k_{ec} = \frac{6-(-6)}{1-(-1)} = 6$.

As the fuzzy controller output adjustment integral coefficient K_I and differential coefficient K_D on the system stability and overshoot has a great impact. Therefore, the range of the theoretical domain of the increment ΔK_I of the integral coefficient K_I and the increment ΔK_D of the differential coefficient K_D can be set to [-1, 1], and the actual scale factor of the fuzzy controller is set to $k_{u1} = \frac{1-(-1)}{10-(-10)} = 0.1$, $k_{u2} = \frac{1-(-1)}{10-(-10)} = 0.1$.

4. Back pressure fuzzy immune PID control system simulation

Based on the design of the fuzzy immune PID controller, the simulation model ofBack Pressure Fuzzy Immune PID Control System and PID Control System is established by using Matlab / Simulink simulation software, as shown in Figure 5.

The Z-N (Ziegler-Nichols) method is used to set the PID control parameter as $K_P = 5$, $K_I = 6.8$, $K_D = 0.9$.

Setting the system simulation parameters and mathematical model parameters and running the simulation, comparative simulation Results of Square Wave Response Curve between fuzzy immune PID control and PID control in different open-loop gain k value can be available, as shown in Figure 6.

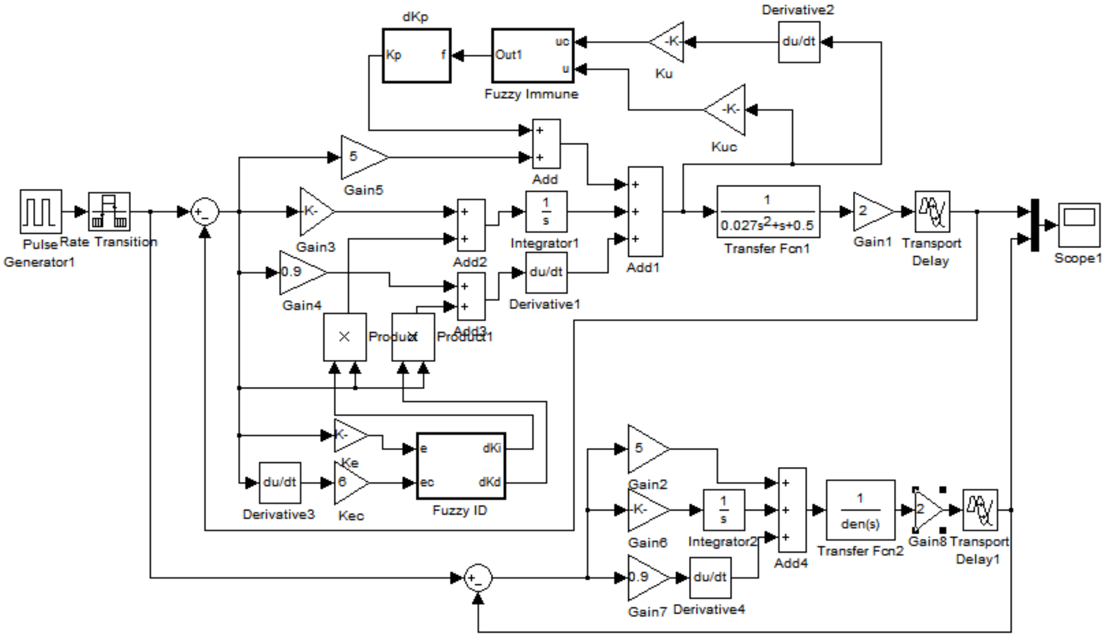
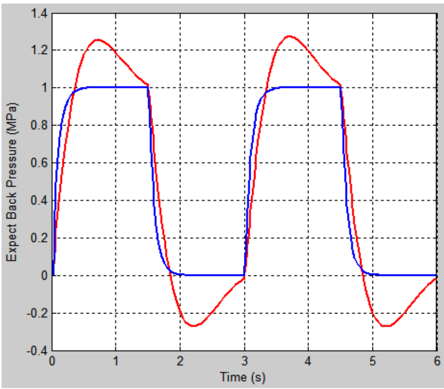
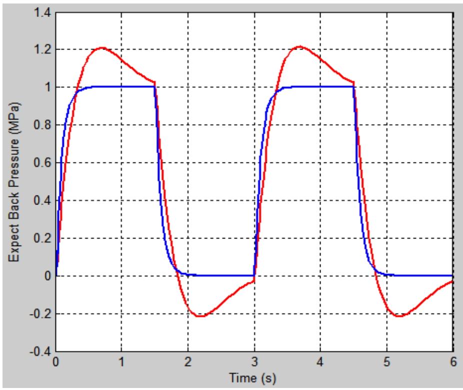


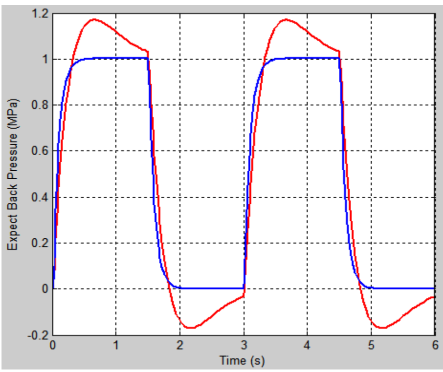
Figure 5. Back pressure fuzzy immune PID control system simulation



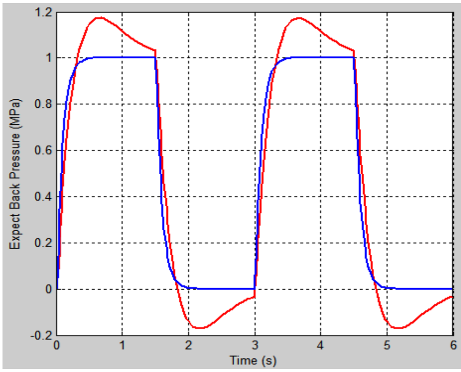
(a) the simulation results in K =0.5



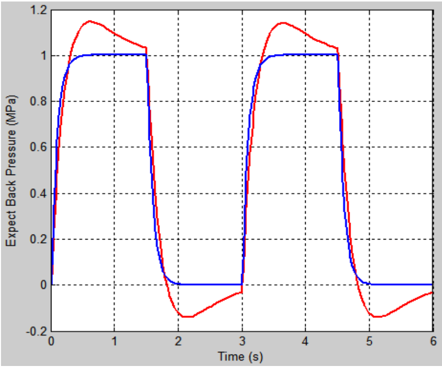
(b) the simulation results in K =1

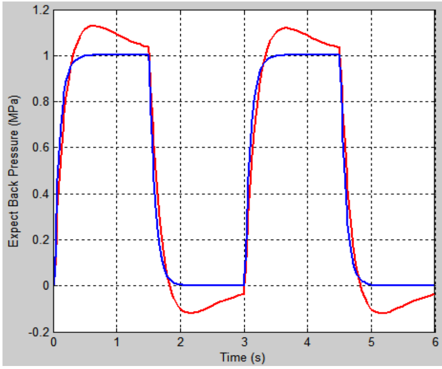


(c) the simulation results in K =2



(d) the simulation results in K =3





(e) the simulation results in K =4 (f) the simulation results in K =6

Figure 6. Comparison and analysis of simulation results

Analysis of the simulation results show that when the set pressure value changes, control system appeared a large overshoot after tuning by the conventional PID and had a larger range of variation under the different K values. (K =0.5h, σ =25%; K =6h, σ =11.4%), While the fuzzy immune PID control algorithm for simulation, the system does not produce overshoot, and when the K value changes when the system no overshoot generation. With the fuzzy immune PID parameter control, the system response speed is faster, the response time is 0.5s. At the same time, we can see that the conventional PID control should adapt to the change of the model parameters when the adaptive capacity is weak, the overshoot will change to varying degrees and it is difficult to reach the stable value quickly, While the fuzzy immune PID parameter control should adapt to the change of the model parameters when the adaptive capacity is strong, and the adjustment time and overshoot of the system are basically the same.

5. Conclusion

In this paper, Aiming at the problems such as the weak self-adaptability of the valve and the poor robustness of the throttle control based on the PID control algorithm, a set of fuzzy immune PID controller is designed through the establishment of wellhead back pressure model and combination with fuzzy immune algorithm to realize a fast response to the wellhead pressure throttle valve, and the overshoot is small and the adaptive ability is strong. So it can effectively reduce the cost of pressure control drilling.

References

[1] Meipeng Ren, Xiangfang Li, Qintao Ma etc.. A new method for design of well density in wellbore injection during drilling [J]. Petroleum Drilling Technology, 2013, 41(1): 25-30.

[2] Helio Santos, Erdem Catak, et al.: Microflux control MPD improves understanding of downhole events, worldoil, Vol. 229 No. 3.

[3] Santos H, Reid P, Leuchtenberg C, et. Micro – Flux Control Method Combined with Surface BOP Creates Enabling Opportunity for Deepwater and Offshore Drilling.OTC 17451, 2005.

[4] Santos H, Reid P.Deepwater Drilling Made More Efficient and Cost-Effective: Using the Microflux Control Method and an Ultralow-Invasion Fluid To Open the Mud-Weight Window. OTC 17818 , 2006.

[5] Santos H,Leuchtenberg C,Shayegi Sara. Micro–Flux Control: The Next Generation in Drilling Process.SPE 81183, 2003.

[6] Saponja J, Adeleye A, Hucik B. Managed pressure drilling (MPD) field trials demonstrate technology value[R]. IADC/SPE 98787, 2006.

[7] Chao Sun, Gensheng Li, Yanjun Kang,etc. Application of Pressure Control Drilling Technology in Tazhong Block and Its Effect Analysis [J]. Petroleum Machinery, 2010, 38(5): 27-29.

[8] Xiongwen Yang, Yingcao Zhou, Shiliang Fang, etc. Analysis of Pressure Control Drilling System and Key Process Realization Method [J]. Petroleum Machinery, 2011 39(10): 39-43.

[9] Yang Yang. Research and Design of Throttle Pressure Control System for Fine Pressure Control Drilling [D]. Southwest Petroleum University, 2012.

[10] Deyu Wang, Cailiang Li, Qiyan Wang, etc. Dynamic analysis of electro - hydraulic proportional throttle control system [J]. Special Oil and Gas Reservoirs, 2006, 13(6): 101-104

[11] Yong Tian, Changyin Gao, Zongcai Wang. Hydraulic and pneumatic transmission technology and application [M]. Beijing: Electronic Industry Press, 2011.

[12] Sergei Gutnikov, Yuri Melnikov. A simple non-linear model of immune response[J]. Chaos, Solitons and Fractals. 2003, 17(7): 125-132.

[13] Chunhua Yang, Min Wu, Deyao Shen, etc. Hybrid intelligent control of gas collectors of coke ovens[J]. Control Engineering Practice, 2001, 47(9): 725-733.

[14] Quancheng Dong, Xianying Feng . Automatic control system based on adaptive fuzzy immune PID [J]. Journal of Agricultural Engineering, 2013, 29(23): 30-37.

[15] Liping Feng,Huaitong Ma,Yi Liu. Automatic Control of Hydraulic Position of Rolling Mill Based on Fuzzy Immune PID [J]. Electrical Transmission, 2015, 45(2): 58-62