

# Design of Adaptive Control System Based on Model Reference Stick Slip

## Vibration

**Abstract:** The stick-slip vibration is a common vibration mode of the drill string system during the drilling and it is extremely destructive. The drilling efficiency will be greatly reduced, the drill bit will be damaged and the drill rod will break when the stick-slip vibration occurs. In order to solve this problem, a two-degree-of-freedom focused mass model was established. The controller based on the model reference adaptive control method was designed. The simulation experiment was completed to prove the rationality of the established stick-slip vibration model and the correctness of the control method. The control equipment was development and the tests above on the well were completed. The experimental results show that the designed stick-slip vibration control system has the validity and stability.

**Key words:** stick-slip vibration of drill string, adaptive control, feedback control, Control system, mechanical model, model reference

### 1 Introduction

Stick-slip vibration of the drill string<sup>[1-4]</sup> is a vibration mode that "movement - still - moving again - and then stationary". Stick-slip vibration of the drill string leads to dramatically reduced the efficiency of the drilling, drill breakage, damage to the drill bit, drilling rate decreases, drilling fatigue failures<sup>[2]</sup> and other failures. In abroad there are many researches in the field of stick-slip vibration control about drill string. Among them, Lin et al.<sup>[5]</sup> adopted dynamic synovial control method to solve the problem of drill bit stuck. Eva et al.<sup>[6]</sup> designed a discrete control method based on the angular velocity of the upper part of the drill string, the torque of the bit and the weight-on-bit; Hiddabi et al.<sup>[7]</sup> designed a full-scale controller based on the elastic-mass model. However, there are few researches on stick-slip vibration control in drill string in China.

The oil well environment in the process of oil drilling is complicated and changeable, which leads to the model of the drill string system cannot be accurately obtained and brings difficulties to the stick-slip vibration control of the drill string. However, the adaptive control can handle the uncertainty of the model parameters well without completely knowing the model of the controlled object<sup>[8]</sup>. Model reference adaptive control and self-tuning regulator are two types of adaptive control systems which currently more mature<sup>[9]</sup>. In this study, the stick-slip vibration control system was designed based on the model reference adaptive control method<sup>[10]</sup>, the experiments were completed above on the well and the experimental results were satisfactory. The domestic research on stick-slip vibration control is still in the initial stage. Therefore, the development of stick-slip vibration control system of drill string has the important practical significance to improve the level of our country's oil drilling technology.

### 1 Drilling system dynamics model established

The drill string system is equivalent to a double focused mass-spring system, the top drive turntable and the drill assembly are considered as two upper and lower concentrated masses and established the drill string system model. Drill string system differential equations are as follows:

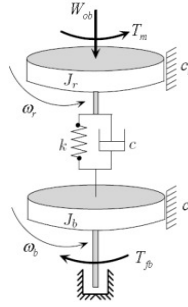


Fig. 1 Focused mass model with two degrees of freedom for drill string system

$$\begin{cases} J_r \ddot{\varphi}_r + c(\dot{\varphi}_r - \dot{\varphi}_b) + k(\varphi_r - \varphi_b) + c_r \dot{\varphi}_r = T_m \\ J_b \ddot{\varphi}_b + c(\dot{\varphi}_b - \dot{\varphi}_r) + k(\varphi_b - \varphi_r) + c_b \dot{\varphi}_b = -T_{fb}(x) \end{cases} \quad (1-1)$$

In formula (1)  $J_r$  is the top drive turntable moment of inertia;  $J_b$  is the bit moment of inertia;  $c_r$  is

the top drive damping coefficient;  $c_b$  is the drill damping factor;  $\varphi_r$  is top disc angle displacement;  $\varphi_b$  is

the bit angular displacement;  $c$  is the equivalent damping coefficient of two degree of freedom

concentrated mass model;  $k$  is the equivalent stiffness coefficient of two degree of freedom focused mass

model;  $T_m$  is the motor drive torque;  $T_{fb}$  is the nonlinear term for friction torque. Take the state variable

as:  $x = [\omega_r, \omega_b, \Delta\varphi]^T$ ,  $\Delta\varphi = \varphi_r - \varphi_b$ , As for the drill string system, its two degree of freedom focused

mass model becomes:

$$\begin{cases} \dot{\omega}_r = -\frac{c+c_r}{J_r} \omega_r + \frac{c}{J_r} \omega_b - \frac{k}{J_r} \Delta\varphi + \frac{1}{J_r} T_m \\ \dot{\omega}_b = \frac{c}{J_b} \omega_r - \frac{c+c_b}{J_b} \omega_b + \frac{k}{J_b} \Delta\varphi - \frac{1}{J_b} T_{fb} \\ \Delta\dot{\varphi} = \omega_r - \omega_b \end{cases} \quad (1-2)$$

When it is in the speed control mode, taken  $\omega_r = \Omega$  as a fixed value, then equation (1-2) can be converted

into:

$$\begin{cases} T_m = c(\Omega - \omega_b) + c_r \Omega + k \Delta\varphi \\ \dot{\omega}_b = \frac{c}{J_b} - \frac{c+c_b}{J_b} \omega_b + \frac{k \Delta\varphi}{J_b} - \frac{T_{fb}}{J_b} \\ \Delta\dot{\varphi} = \Omega - \omega_b \end{cases} \quad (1-3)$$

## 2 Model reference adaptive control

The design of the control system structure shown in Figure 2. When the inverter works in the speed control mode, the feedback system (such as the current loop and speed loop in Figure 2) formed by the motor and the inverter is mainly used to adjust the motor torque so that the motor speed remains unchanged.  $I$  and  $W$  are the current real-time current and speed of the motor respectively, and they are used as the input of the stick-slip vibration control system. Top drive the existing electronic control system (PLC controller) output as the main given input speed of inverter, stick-slip vibration control system output as a speed of the inverter

62 given a given input. After the frequency converter control makes the speed of auxiliary given zero, thereby  
63 suppressing stick-slip vibration.

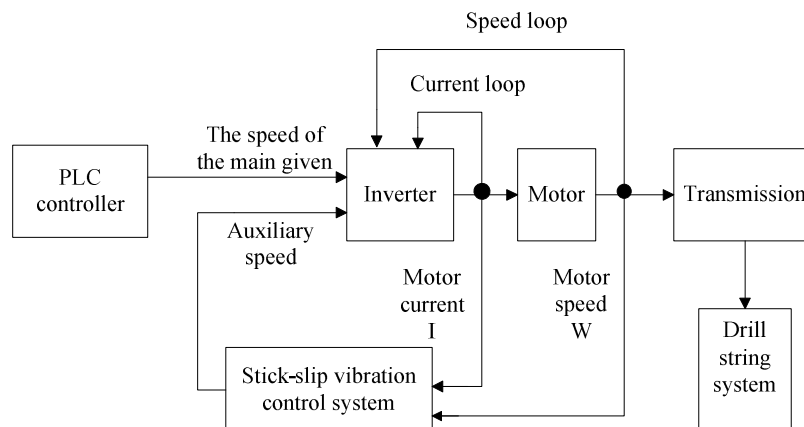


Fig. 2 Structure diagram of the control system

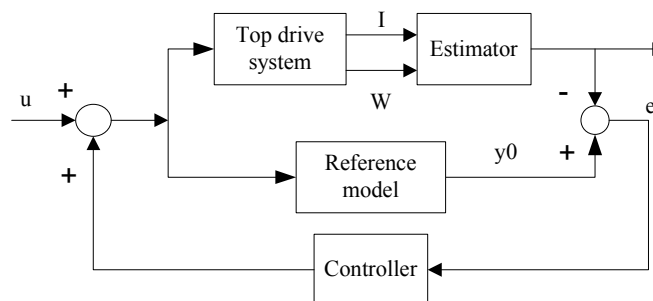


Fig.3 drilling model reference adaptive control system diagram of stick slip vibration

69 Drilling model reference stick-slip vibration adaptive control system shown in Figure 3: (1) The  
70 reference model is a physical model of the same nature as the system itself and is used to find the speed of the  
71 drill bit  $y_m$ ; (2) Top drive electric control system output current  $I$  and speed  $W$  as the input of the estimator  
72 to estimate the true bottom hole bit speed  $y_0$ . When stick-slip vibration does not occur, the value of  $y_0$   
73 equals the value of  $y_m$  equal to the system main setpoint speed  $u$ . When stick-slip vibration occurs, the  
74 force between the drill bit and the rock can vary, so the real bit speed  $y_0$  is a variable. When the true speed  
75 of drill bit  $y_0$  is not equal to model reference output  $y_m$ , the system has generalized error  $e = |y_m - y_0|$ ,  
76 using the controller to adjust the parameters of the drilling system, generalized error tends to zero, Finally,  
77 the true speed of the drill bit is approached to the output of the reference model, thereby suppressing  
78 stick-slip vibration.

79 The controlled object can be described as:

$$\begin{cases} \dot{x}_p = A_p x_p + b_p u \\ y_p = h^T x_p \end{cases} \quad (2-1)$$

In formula (2-1)  $x_p$  is the dimensional state vector,  $A_p$  is the  $n \times n$  matrix;  $b_p$  is the  $n \times 1$  input vector;  $y_p$  is the output;  $h^T = (1 \ 0 \ \dots \ 0)$  is the  $1 \times n$  matrix; the corresponding transfer function is:

$$W_p(s) = h^T (sI - A_p)^{-1} b_p = \frac{k_p N_p(s)}{M_p(s)} \quad (2-2)$$

In formula (2-2)  $M_p(s)$  and  $N_p(s)$  for the  $n$ -order and  $m$ -order polynomial,  $k_p$  is the controlled object gain. According to equation (1-2) take the state variable is:  $x = [\omega_b, \Delta\varphi]$ ,  $T_m$  is the output variable, equation (1-3) changes to:

$$\dot{x} = \begin{bmatrix} \dot{\omega}_b \\ \Delta\dot{\varphi} \end{bmatrix} = \begin{bmatrix} -\frac{c+c_b}{J_b} & \frac{k}{J_b} \\ -1 & 0 \end{bmatrix} \begin{bmatrix} \omega_b \\ \Delta\varphi \end{bmatrix} + \begin{bmatrix} \frac{c}{J_b} \\ 1 \end{bmatrix} \Omega + \begin{bmatrix} -\frac{T_{fb}}{J_b} \\ 0 \end{bmatrix} \quad (2-3)$$

Since the friction torque is constant at steady state, the equation of state can be transformed into:

$$\dot{x} = \begin{bmatrix} \dot{\omega}_b \\ \Delta\dot{\varphi} \end{bmatrix} = \begin{bmatrix} -\frac{c+c_b}{J_b} & \frac{k}{J_b} \\ -1 & 0 \end{bmatrix} \begin{bmatrix} \omega_b \\ \Delta\varphi \end{bmatrix} + \begin{bmatrix} \frac{c}{J_b} \\ 1 \end{bmatrix} \Omega \quad (2-4)$$

Among them  $A = \begin{bmatrix} -\frac{c+c_b}{J_b} & \frac{k}{J_b} \\ -1 & 0 \end{bmatrix}$ ,  $B = \begin{bmatrix} \frac{c}{J_b} \\ 1 \end{bmatrix}$ , the transfer function is:

$$W_p(s) = \frac{s+k}{J_b s^2 + sc + sc_b + k} \quad (2-5)$$

Substituting the values in [11] into (2-5), then  $W_p(s) = \frac{23.2s+473}{374s^2+73.2s+473}$ . The corresponding controller structure shown in Figure 4:

Figure 4 shows that the controlled object can be expressed as:

adjustable parameter vector of the controller respectively. Making  $x = (x_p \quad v_1 \quad v_2)^T$  then:

$$\dot{x} = \begin{bmatrix} \dot{x}_p \\ \dot{v}_1 \\ \dot{v}_2 \end{bmatrix} = \begin{bmatrix} A_p & 0 & 0 \\ 0 & G & 0 \\ bh^T & 0 & G \end{bmatrix} \begin{bmatrix} x_p \\ v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} b_p \\ b \\ 0 \end{bmatrix} \theta^T \varphi(t) \quad (2-7)$$

$$\theta^T \varphi = k_0^* y_r + (c^*)^T v_1 + d_0^* h^T x_p + (d^*)^T v_2 + \tilde{\theta}^T \varphi \quad (2-8)$$
$$\begin{cases} \dot{x}_p = A_c x + b_c [k_0^* y_r + \tilde{\theta}^T \varphi] \\ y_p = h_c^T x = h^T x_p \end{cases} \quad (2-9)$$
$$\begin{cases} \dot{x}_{mc} = A_c x_{mc} + b_c k^*_0 y_r \\ y_m = h_c^T x_{mc} = h^T x_m \end{cases} \quad (2-10)$$

5

$$W_m(s) = \frac{Y_m(s)}{Y_r(s)} = h_c^T (sI - A_c)^{-1} b_c k_0^*, \quad (2-11)$$

$$\text{Making } e = x - x_{mc} = \begin{bmatrix} x_p - x_m \\ v_1 - v_{m1} \\ v_2 - v_{m2} \end{bmatrix} \text{ and } e_1 = y_p - y_m, \text{ the extended state equation as:}$$

$$\begin{aligned} \dot{e} &= A_c e + b_c [\tilde{\theta}^T(t) \phi(t)] \\ e_1 &= h_c^T (x - x_{mc}) = h_c^T e \end{aligned} \quad (2-12)$$

Let  $e_1$  and  $\tilde{\theta}^T(t) \phi(t)$  are the output and input of the error model, the transfer function of augmented error model is :

$$W_e(s) = h_c^T (sI - A_c)^{-1} b_c \quad (2-13)$$

Because  $k_0^* k_p = k_m$  and  $W_e(s) = \frac{k_p}{k_m} W_m(s)$ , then  $e_1 = \frac{k_p}{k_m} W_m(s) \tilde{\theta}^T(t) \phi(t)$ . Lyapunov function that is selected as this:

$$V = \frac{1}{2} (e^T P e + \tilde{\theta}^T \Gamma^{-1} \tilde{\theta}) \quad (2-14)$$

In formula (2-14)  $P$ ,  $\Gamma$  are positive definite matrix. Derive t from (2-14), combined with extended state equation has:

$$\frac{dV}{dt} = \frac{1}{2} e^T (P A_c + A_c^T P) e + \tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}} + \tilde{\theta}^T \phi_c^T P e \quad (2-15)$$

Making  $(P A_c + A_c^T P) = -Q$  and  $\tilde{\theta}^T \Gamma^{-1} \dot{\tilde{\theta}} + \tilde{\theta}^T \phi_c^T P e = 0$ , in that formula  $Q$  is a non-negative symmetric matrix, then  $\frac{dV}{dt} = \frac{1}{2} e^T Q e \leq 0$ , adaptive regulation law is:

$$\dot{\tilde{\theta}} = \dot{\tilde{\theta}} = -\Gamma \phi_c^T P e \quad (2-16)$$

$b_c^T P = h_c^T$ , so adaptive law is:

$$\dot{\tilde{\theta}} = -\Gamma \phi_c^T e = -\Gamma \phi e_1 \quad (2-17)$$

In formula (2-17)  $e_1$  is measurable;  $\phi$  is the semaphore is also known, so the adaptive law can be achieved.

### 3. Simulation

The simulation system structure (Figure 5) was established according to the model reference adaptive control law and the literature <sup>[11]</sup> in the parameters. When the main given speed is 21 rad / s, the simulation results of motor torque, bit speed and control speed are shown in Figure 6 (a), 6 (b) and 6 (c) respectively.

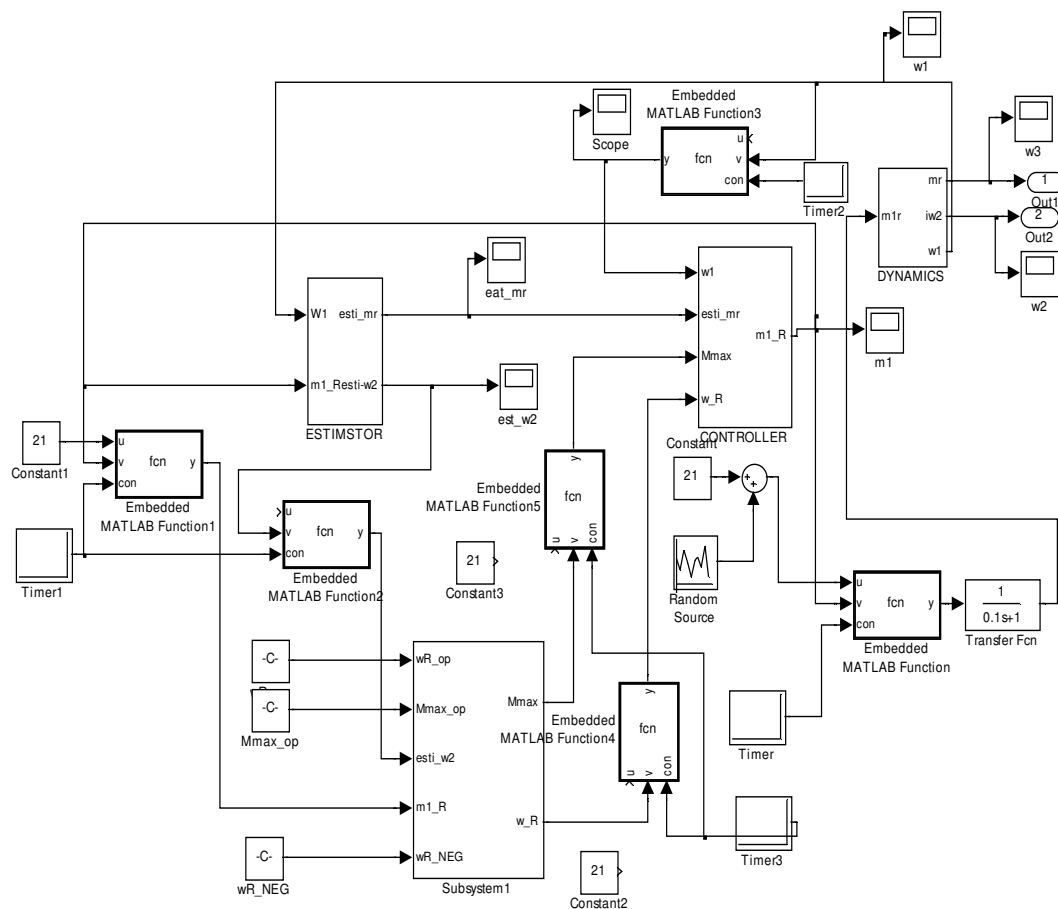


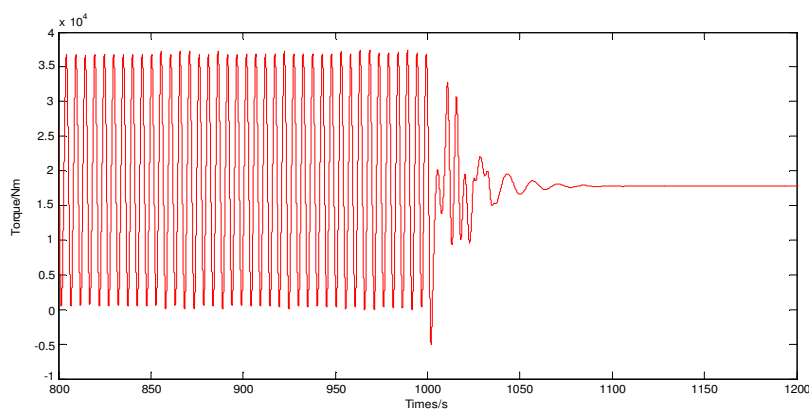
Fig.5 simulation model

The analysis of Figure 6 is summarized in Table 1:

153

Table 1 Summary of simulation results

| Times<br>Picture order | Before 1000 s                                                                                                                                    | 1000 s-1050 s                                                                                                                           | 1050 s-1150 s                                                                                                                                    |
|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Figure 6 (a)           | Stick-slip vibration caused the motor torque fluctuations more intense.                                                                          | After starting the stick-slip vibration control, the fluctuation of the motor torque gradually decreases during the control transition. | The motor torque gradually tends to be stable, and it is approximately equal to the desired torque 17548Nm.                                      |
| Figure 6 (b)           | Stick-slip vibration causes bit speed fluctuations more intense, stick-slip vibration frequency of about 0.2 Hz.                                 | The stick-slip vibration frequency of the drill bit was gradually reduced, and the stick-slip vibration was controlled.                 | Drill speed gradually stabilized, equal to the main given speed 21 rad/s.                                                                        |
| Figure 6 (c)           | Since the stick-slip vibration control was not activated, the speed control was zero, the speed was maintained at 21 rad/s of the main setpoint. | The gradual decrease of speed control was the same with the change of bit speed.                                                        | After stick-slip vibration was controlled, the speed control was zero and the speed was approximately equal to the main given speed of 21 rad/s. |



154

155

Fig.6 (a) motor torque

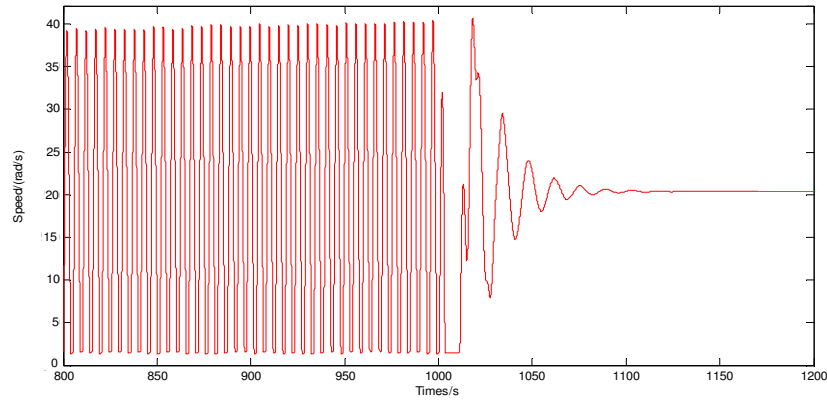


Fig.6 (b) bit rotation speed

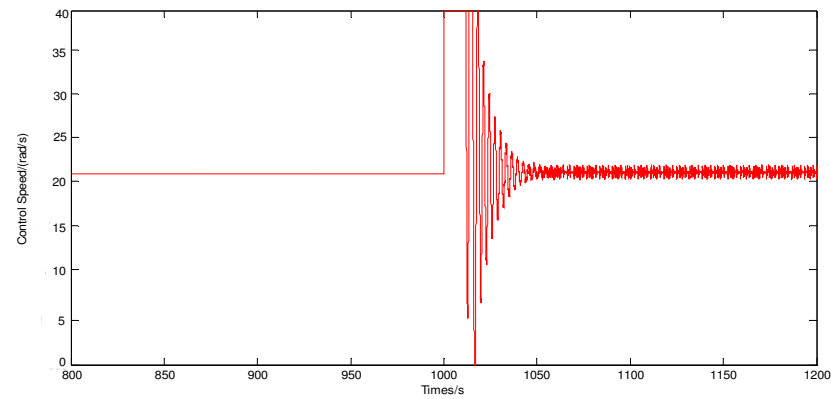


Fig.6 (c) control speed

## 4 Experiment

### 4.1 System Design

The experimental system was that made the drill string stick slip-vibration control system accessed to top drive electronic control system controlled the stick-slip vibration of drill string system. Stick-slip vibration control system (including human-computer interaction unit and control algorithm unit) was connected with external inverter through CAN bus which could realize the data exchange between inverter and control algorithm unit. The data exchange process was as follows : the actual motor speed and actual torque data acquired by the inverter were sent to the control algorithm unit through the CAN bus in time, the related parameters of the drill string system set in the display unit were transmitted to the control algorithm unit through the network cable. The speed control amount processed by the control algorithm unit was transmitted to the frequency converter through the CAN bus in a speed-assisted manner. Setting the speed which has set in the PLC controller as the main speed of the inverter. At the same time, the main setting of speed and the auxiliary setting of speed will act on the inverter to adjust the motor speed so as to restrain the stick-slip vibration .

### 4.2 Results and Analysis

During the experiment, the stick-slip vibration control system of the drill string was connected to the inverter for research, made Starter third-party online monitoring software to monitor the actual motor speed and actual torque detect the actual effect of the stick-slip vibration control system of the drill string. As shown in table 2, the actual drilled drill string data, drilling depth 2948 m, the main speed of converter was

given at 600 rpm, top drive motor gearbox reduction ratio of 12.5. In order to ensure the reliability of the experimental data, the experimental results of the motor actual speed, actual torque and auxiliary given speed (Table 3, Figure 7) were obtained by the starter third-party online monitoring software.

Table 2 structural parameters setting of drill string

| Drill column components | Length /m | Outer diameter /m | Inside diameter /m |
|-------------------------|-----------|-------------------|--------------------|
| Drill pipe              | 2680      | 0.127             | 0.108              |
| Increase the drill pipe | 120       | 0.127             | 0.0762             |
| Drill collar            | 148       | 0.2096            | 0.0715             |

The analysis of Figure 7 is summarized in Table 3:

Table 3 summary of experimental results

| Times<br>Picture order | Before 130 s                                                                                                      | 130 s-180 s                                                                                                                                                                               | After 180 s                                                                                                                                                                                                                                                |
|------------------------|-------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                        |                                                                                                                   |                                                                                                                                                                                           |                                                                                                                                                                                                                                                            |
| Figure 7 (a)           | The motor's actual speed fluctuation was small and vibration between 590 and 610 RPM.                             | Start stick-slip vibration control, controlled the actual motor speed during the transition large fluctuations in the vibration range of 580 ~ 640 RPM.                                   | The motor speed fluctuates within the range of 590 ~ 610 RPM. After the control was applied, the trend of the motor speed and the auxiliary given speed was the same and equal to the speed of the motor before starting the stick-slip vibration control. |
| Figure 7 (b)           | Stick-slip vibration caused the motor torque fluctuations more obvious, the value of about 600 ~ 1000 Nm between. | Start the stick-slip vibration control, the actual torque of the motor began to converge to the preset torque of 900 Nm, and the stick-slip vibration of the drill string was controlled. | The actual motor torque in the 800 ~ 1000 Nm within a small range, tended to the center value of 900Nm.                                                                                                                                                    |
| Figure 7 (c)           | The stick-slip vibration control was not started so the auxiliary given output was zero.                          | Start stick-slip vibration control, auxiliary given speed was between -30 ~ 40 RPM vibration.                                                                                             | Auxiliary speed was equal to the total output motor speed minus the main given speed 600 RPM, the fluctuations in the vicinity of zero.                                                                                                                    |

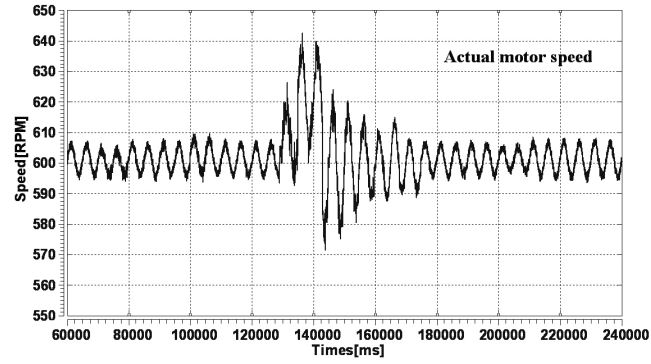


Fig.7 (a) actual speed of motor

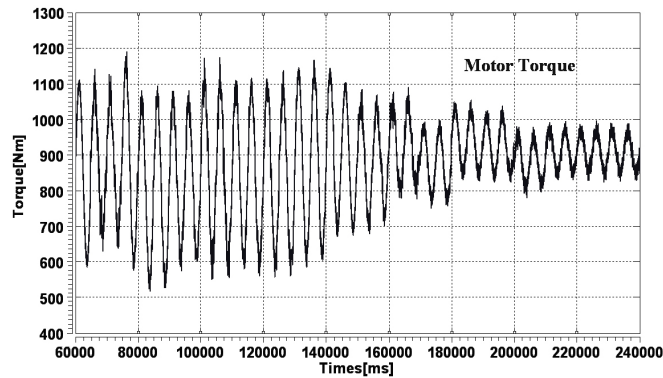


Fig.7 (b) motor torque

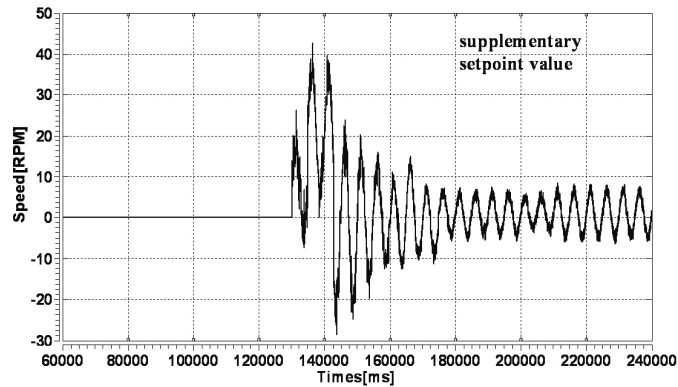


Fig.7 (c) auxiliary given rotation speed

It can be seen from the experimental results that the control system can give the auxiliary given speed in time when the stick-slip vibration control system is started. The combination of the given speed and the auxiliary given speed can effectively improve the stick-slip vibration, restrain the drastic fluctuation of the top drive motor torque, and restore the drill string system to a balanced state in a short period of time. The results show that the stick-slip vibration control system designed in this paper can effectively restrain the stick-slip vibration of drill string.

## 5 Conclusion

In this study, a dual-degree-of-freedom mass model of drill string system was established. An adaptive control system based on model reference was designed and simulated. Simulation results show that the proposed control method can effectively suppress stick-slip vibration effectively. Finally, the actual control system works on a well was developed and the well site test was completed. The actual drilling data obtained from the third-party on-line monitoring software of starter showed that the designed control system can follow the changing rules of speed and torque, adjust the output speed of the inverter in time, and has better performance on the stick-slip vibration of the drill string inhibition. It plays a good guiding role in reducing the damage of drilling tools, increasing the drilling speed, improving the drilling efficiency and reducing the drilling accidents.

## References

- [1] Fu Meng, Li Jianghong, Wu Yafeng, et al. Analysis of drill string stick slip vibration simulation and mechanism[J]. Journal of Northwestern Polytechnical University, 2016, 34(3):467-472.
- [2] Wang Jianping, Wang Dingfeng, Wang Xiongfei, et al. Analysis of stick slip phenomenon of drilling tools and application of soft torque system in Chang Bei gas field[J]. Petrochemical application, 2012, 31(12):51-55.
- [3] Feng Chengbao, Jia Xiaoli, Liu Shuhai, et al. Research progress on stick slip vibration of drill string in oil and gas wells[J]. Oil field equipment, 2016, 45(11):78-87.
- [4] Han Chunjie, Yan tie. Study on the stick slip law of drill string in extended reach well[J]. Natural gas industry, 2004; 24(11):58-60.
- [5] Yao-Qun Lin and Yu-Hua Wang, Stick-Slip Vibration of Drill Strings, Transactions of the ASME, Vol. 113, FEBRUARY 1991.
- [6] Eva M. Navarro-L'opez and Domingo Cort'es. Sliding-mode control of a multi-DOF oil well drill string with stick-slip oscillations, Proceedings of the 2007 American Control Conference Marriott Marquis Hotel at Times Square New York City, USA, July 11-13, 2007.
- [7] Al-Hiddabi, S.A., Samanta.B., &Seibi. A.(2003). Non-linear control of torsional and bending vibrations of oil well drill strings. Journal of Sound and Vibration, 265(2), 401-415.
- [8] Li Junling, Yang Guanghong. Development and Prospect of adaptive fault-tolerant control[J]. Control and decision making, 2014, 29(11):28-33.
- [9] Liu Xing, Liu Xiao. The development and application of adaptive control system[J]. Internet of things technology, 2011, (9):61-63.
- [10] Zhang Hongshuai, Wang Ping, Han Bangcheng. Rotor position detection of high speed permanent magnet synchronous motor based on fuzzy PI model reference adaptive[J]. Chinese Journal of Electrical Engineering, 2014, 34(12):1889-1896.
- [11] Gong Quancheng. Nonlinear characteristics analysis and robust control of stick slip vibration of drill string[D]. Shannxi, Northwestern Polytechnical University, 2015, 23-24.