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Stick slip vibration control of drill string based on torque feedforward and sliding mode controller

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Abstract: The drill string system in drilling engineering has significant geometric nonlinearity. Due to the frictional torque generated by the interaction between the drill bit and the rock and soil, it is easy to cause the drill string to fall into a sticky sliding vibration state. Based on the two lumped mass torsion pendulum model of the drill string, this paper establishes an observer of the bit speed, and designs a sliding mode controller (TF-SMC) considering the bit torque to suppress the stick slip vibration of the drill string. The simulation results show that compared with PID controller and sliding mode controller, torque feed-forward sliding mode controller can achieve better control effect on drill string at low speed. When torque feedforward sliding mode controller and PID controller are used in parallel, the control effect is better than the first three controllers.

Keywords: Stick slip vibration control of drill string; Torque feedforward; Sliding mode controller.

1. Introduction

The drill string system has a large aspect ratio, resulting in significant geometric nonlinearity of the drill string. During rotary drilling, the contact and collision between the drill string and the wellbore, as well as the rock breaking of the drill bit and the flow of drilling fluid, can cause vibration in the drill string system[1-3]. Among them, the vibration form that causes significant damage to the drill bit assembly (BHA) is the stick-slip vibration phenomenon[2]. When the drill string is in a stick-slip vibration state, the drill bit will enter a stationary high-speed sliding motion cycle. The speed of a drill bit in a general high-speed sliding state can be Several times the normal working speed, which can lead to high-speed wear, tooth skipping, and even drill string fracture accidents. Therefore, it is necessary to control the stick-slip vibration behavior of the drill string.

In order to suppress the stick-slip vibration of the drill string, researchers have studied methods such as increasing the rigidity of the drill string system and reducing impact vibration [4-5], but these methods require modification of the original control system. Without changing the basic structure of the drill string system, reference [6] studied a stick-slip vibration control system that directly controls the drilling speed of the drill bit. However, due to factors such as high-frequency vibration of the drill string itself, drilling fluid flow induced vibration, and the need for frequent single connections in the drill string system, there are great difficulties in measuring and transmitting the drilling speed at the bottom of the drill bit. Therefore, there are significant difficulties in the application of control strategies that directly use real drill bit drilling speed as signal feedback in engineering. When the physical quantities to be measured in the general control system cannot be measured accurately, the engineering personnel will use the state observer to estimate the physical quantities to be measured. Therefore, reference [7] designed a bit speed observer. Then, researchers designed observer-based SMC [8], H∞ [9] controller, etc. to control the bit speed and suppress the stick slip vibration behavior of the drill string. However, these controllers generally consider the frictional torque generated by the interaction between the drill bit and rock soil as interference, and there is not much research on incorporating the frictional torque of the drill string into the structural design of the controller.

The frictional torque generated by the interaction between the drill bit and the rock is the main cause of the stick-slip vibration of the drill string. Due to the fact that the input torque of the top drive in actual drilling engineering may lose its original control performance due to changes in the bottom layer or low top drive speed. In the study of control systems for drill strings, the friction torque at the drill bit is usually described using Stribeck and Karnopp models that consider the maximum static friction and viscous resistance. This paper will establish a dual mass torsion pendulum model of the drill string based on the Karnopp model, design the torque feedforward link of the drill string system, and combine SMC, torque feedforward controller, and PID controller to design a new stick-slip vibration controller for the drill string.

2. Dynamic model of drill string

According to the concentrated mass torsion pendulum model of the drill string used in reference [7], the dynamic model of the drill string established in this paper is shown in Figure 1.

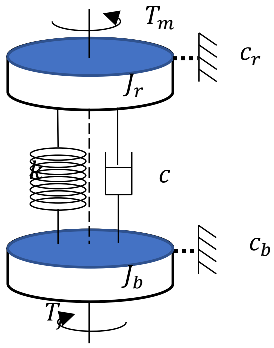

Figure 1. Drill string two concentrated mass torsion pendulum model.

For the system in Figure 1, the dynamic equation of the system can be established based on the theory of rigid body dynamics. The dynamic equation at the top drive turntable is:

$$J_r\dot{\omega}_r = T_m - T_{ar} - T_t \tag{1}$$

$$T_{ar} = \omega_r c_r \tag{2}$$

$$T_t = c(\omega_r - \omega_b) + k(\varphi_r - \varphi_b) \tag{3}$$

The dynamic equation of the drill bit part:

$$J_b\dot{\omega}_b = T_t - T_{ab} - T_f \tag{4}$$

$$T_{ab} = c_b\omega_b \tag{5}$$

where, J_r and $\mathrm{J_b}$ is the rotational inertia of the top drive rotary table and the equivalent drill bit; φ_r, ω_r, φ_b, ω_b is the torsional angle and rotational speed of the top drive rotary table and drill bit, respectively; T_m is the input speed of the top drive, T_{ar} is the viscous torque of the top drive rotary table; T_t is the coupling torque of the drill string; T_{ab} is the viscous torque of the drill bit; T_f is the friction torque of the drill bit. c_r, c_b, c is the damping coefficient of the top drive rotary table, drill bit, and equivalent drill string, respectively; k is the torsional stiffness of the drill string.

Take the state variable $x = (\omega_r, \omega_b, \varphi_r - \varphi_b)^T$, The friction torque T_f of the drill bit is represented by the Karnopp model in Equation 6.

$$T_f(x) = \begin{cases} T_{eb}(x)\,, & |\omega_b| < D_v, |T_{eb}| < T_{sb} \\ T_{sb}sgn(T_{eb}(x)), & |\omega_b| < D_v, |T_{eb}| \geq T_{sb} \\ f_b(\omega_b)sgn(\omega_b), & |\omega_b| \geq D_v \end{cases} \tag{6}$$

where sgn(…) is the sign function, D_v is the Karnopp velocity boundary layer.

$$T_{eb} = T_t - T_{ab} \tag{7}$$

$$T_{sb} = \mu_{sb}W_{ob}R_b \tag{8}$$

$$f_b = \mu_b(\omega_b)W_{ob}R_b \tag{9}$$

$$\mu_b(\omega_b) = \mu_{cb} + (\mu_{sb} - \mu_{cb})e^{-\gamma_b|\omega_b|/v_f} \qquad)$$

where, T_{eb} is the static equilibrium torque of the drill string; T_{sb} is the maximum static friction torque; f_b is the dynamic friction torque; μ_b (...) is the dynamic friction coefficient function; μ_{cb} and μ_{sb} is the coefficient of viscous friction and the coefficient of dynamic friction; γ_b and v_f are karnopp empirical constants.

In summary, the dynamic equation of the drill string system is:

$$\begin{cases} J_r\ddot{\varphi}_r + c(\dot{\varphi}_r - \dot{\varphi}_b) + c(\varphi_r - \varphi_b) + c_r\dot{\varphi}_r = T_m \\ J_b\ddot{\varphi}_b + c(\dot{\varphi}_r - \dot{\varphi}_b) + c(\varphi_r - \varphi_b) + c_b\dot{\varphi}_b = -T_f(x) \end{cases} \tag{11}$$

$$\Rightarrow \begin{bmatrix} \dot{\omega}_r \\ \dot{\omega}_r \\ \Delta\dot{\varphi} \end{bmatrix} = \begin{bmatrix} -\frac{c+c_r}{J_r}\omega_r + \frac{c}{J_r}\omega_b - \frac{k}{J_r}\Delta\varphi + \frac{1}{J_r}T_m \\ \frac{c}{J_b}\omega_r - \frac{c+c_b}{J_b}\omega_b + \frac{k}{J_b}\Delta\varphi - \frac{1}{J_b}T_{fb} \\ \omega_r - \omega_b \end{bmatrix} \tag{12}$$

3. Design of speed observer and controller

Based on the proportional integral observer design method, this paper considers T_f as an observable interference. The observer structure of the drill string rotary speed is as follows [7]:

$$\begin{cases} \dot{\widehat{\omega}}_r = -\frac{c+c_r}{J_r}\widehat{\omega}_r + \frac{c}{J_r}\widehat{\omega}_b - \frac{k}{J_r}\Delta\widehat{\varphi} + \frac{1}{J_r}T_m + K_1(\omega_r - \widehat{\omega}_r) \\ \dot{\widehat{\omega}}_b = \frac{c}{J_b}\widehat{\omega}_r - \frac{c+c_b}{J_b}\widehat{\omega}_b + \frac{k}{J_b}\Delta\widehat{\varphi} - \frac{1}{J_b}T_f + K_2(\omega_r - \widehat{\omega}_r) \\ \Delta\dot{\widehat{\varphi}} = \widehat{\omega}_r - \widehat{\omega}_b + K_3(\omega_r - \widehat{\omega}_r) \\ \dot{\widehat{T}}_f = K_4(\omega_r - \widehat{\omega}_r) \end{cases} \tag{13}$$

Due to the observation of four physical quantities by the observer, according to the optimal damping principle, the optimal damping polynomial corresponding to the observer is of order 4. The gain coefficients of the observer are:

$$K_1 = \frac{1}{D_2D_3D_4T_e} - \frac{c+c_r}{J_r} - \frac{c+c_r}{J_b} \tag{14}$$

$$K_2 = \frac{k(-J_rc_b + K_1J_rJ_b - c_bD_2T_e^2K_4 + c_rJ_b + J_bT_eK_4)}{c_b(c_bc - kJ_b)} \\ \frac{-c_b^2(c_r + c + K_1J_r) + c(c_bc_r + c_bK_1J_r + J_bK_4)}{c_b(c_bc - kJ_b)} \tag{15}$$

$$K_3 = \frac{k^2(J_r + J_b + D_2T_e^2K_4) + k(c_bc_r + K_1J_rc_b - cK_4T_e) + K_4c^2}{k(-c_bc + kJ_b)} \tag{16}$$

$$K_4 = \frac{J_rJ_b}{kD_4D_3^2D_2^3T_e^4} \tag{17}$$

where D_2, D_3, D_4 Take as 0.5; the time coefficient T_e is taken as 0.2.

In order to suppress stick slip vibration of drill string, an observer-based torque feedforward sliding mode controller (TF-SMC-PID) is designed in this paper. The controller structure is shown in Figure 2.

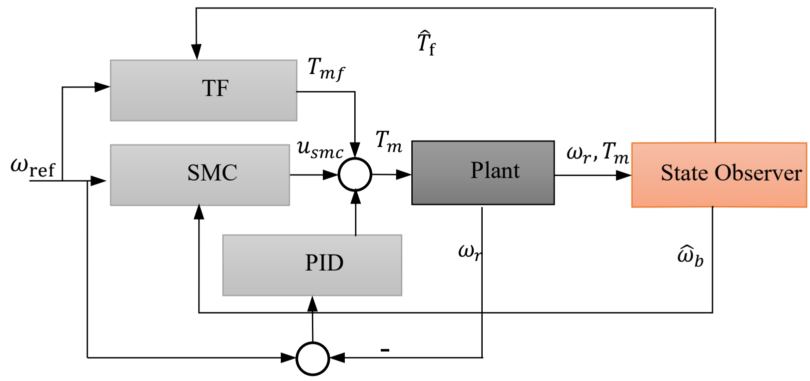

Figure 2. Controller Structure

According to equation 12, when the drill string system does not experience stick-slip vibration, $\dot{x}$=0. The top drive torque T_{ms} of the system is:

$$T_{ms} = \omega_{ref}(c_r + c_b) + \hat{T}_f \tag{18}$$

Therefore，this paper uses T_{ms} as the output of the torque feedforward controller and refers to it as T_{mf}.

This paper takes $\omega_b \rightarrow \omega_r$, $\omega_r \rightarrow \omega_{\mathrm{ref}}$ is the control target of the sliding mode controller, and an integral sliding mode surface is selected for the sliding mode controller. The structure of the sliding mode surface is:

$$s = (\omega_r - \omega_{ref}) + \lambda\int_0^t(\omega_r - \omega_{ref}) + (\omega_r - \omega_b)d\tau \tag{19}$$

where λ is the sliding mode area partition coefficient?

The control law of sliding mode controller is

$$u_{smc} = J_r\left(\frac{c+c_r}{J_r}\omega_r - \frac{c}{J_r}\omega_b + \frac{k}{J_r}\Delta\varphi + \dot{\omega}_{ref} - \lambda\big(2\omega_r - \omega_b - \omega_{ref}\big) - \varepsilon\, sat(s) - \eta s\right) \tag{20}$$

where, sat(…) is the saturation function; ε, η is a sliding mode controller parameter.

The PID controller in Figure 2 indirectly controls the bit speed only with the top drive speed as the feedback signal.

4. Controller performance analysis

The parameters of the system are shown in Table 1. Set Expected Torque T_{mref}=12000N·m. According to equation 12, when the system is stable, $\dot{x}$=0, the relationship between the expected speed and the expected torque is

$$\omega_{\text{ref}} = \omega_r = \omega_b = \frac{T_{\text{m}} - T_{fs}}{c_r + c_r} \tag{21}$$

The expected speed of the system is obtained from equation 21. ω_{ref}=9.32rad/s. The performance of the system is shown in Figure 3.

Table 1. Parameters

Parameter	Value	Parameter	Value	Parameter	Value
J_r	2122 kg·m^2	c_b	50 N·m·s·rad^{-1}	W_{ob}	97533 N
J_b	374 kg·m^2	μ_{cb}	0.5	R_b	0.156 m
c	23.2 N·m·s·rad^{-1}	μ_{sb}	0.8	c_r	425 N·m·s·rad^{-1}
k	473 N·m·rad^{-1}	γ_b	0.9	v_f	1
D_v	0.001 m·s^{-1}				

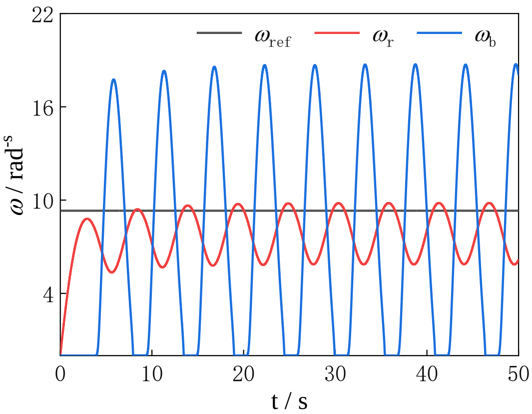

Figure 3. Raw system performance

From Figure 3, it can be seen that there is a periodic oscillation in the top drive rotary table speed, and the drill bit speed is in a stagnant, high-speed sliding periodic vibration state, that is, a stick-slip vibration state. At the same desired speed, this paper studies the influence of PID, SMC, torque feedforward sliding mode controller (TF-SMC), torque feedforward sliding mode controller and PID parallel controller (TF-SMC-PID) on the performance of the drill string system. The system performance is shown in Figure 4.

From Figure 4, it can be seen that the time when the top drive speed of the system reaches stability is basically the same, and the speed vibration peak value of the PID controller scheme is relatively low. In terms of drill speed control, compared to PID controllers, the other three controllers have significantly better control effects. The drill bit speed can basically reach a steady state within 20 seconds. Among them, the TF-SMC-PID controller has significantly better overshoot indicators for drill bit speed, and the peak to peak oscillation is significantly lower compared to other controllers.

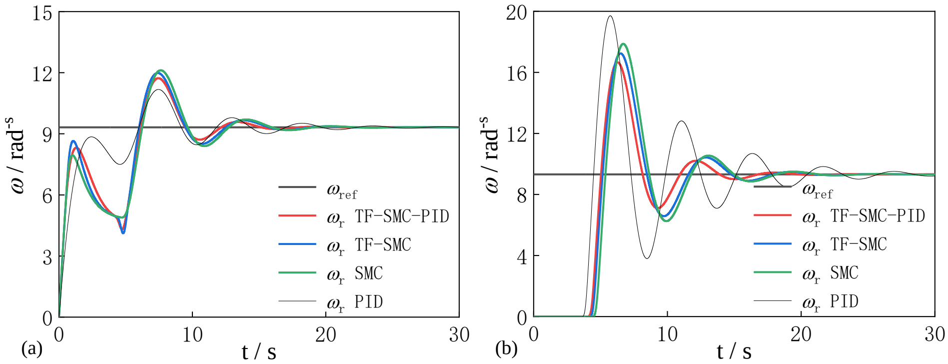

Figure 4. The Influence of several controllers on system performance

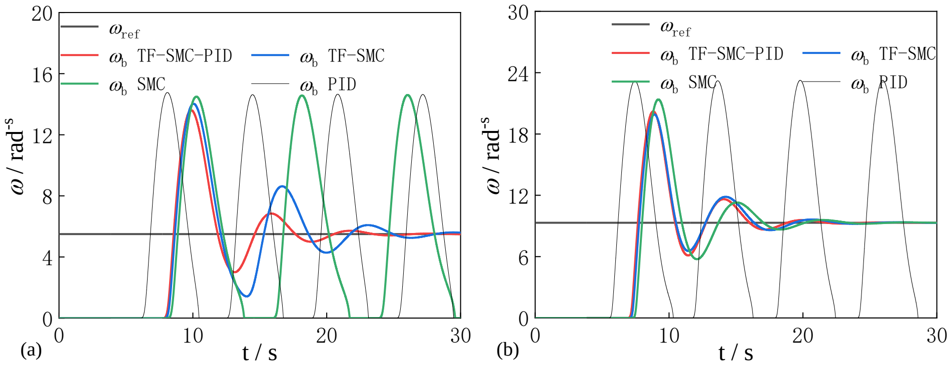

Figure 5. System performance: (a) low speed (b) high bit pressure

Set the expected speed ω_{ref} =5.5rad/s, and the performance of each controller is shown in Figure 5(a). After setting the expected speed ω_{ref} =9.32rad/s and increasing the W_{ob} to 150000N, the performance of each controller is shown in Figure 5.2(b).

From Figure 5.1(a), it can be seen that TF-SMC-PID and TF-SMC can still achieve effective control of the drill string at low rotational speeds. SMC and PID controllers cannot effectively control the drill string system at low speeds. From this, it can be seen that the torque feedforward link can significantly increase the lower limit of the system's operating speed. From Figure 5.1(b), it can be seen that as the drilling pressure increases, the PID controller is no longer able to effectively control the drill string system. TF-SMC-PID, TF-SMC, and SMC can all suppress the stick-slip vibration behavior of the drill string. Among them, TF-SMC-PID and TF-SMC have faster response speed and lower peak to peak vibration compared to SMC.

5. Conclusion

This paper establishes a dual mass torsion pendulum model for the drill string and a drill bit drilling speed observer. Based on the drill speed observer, this paper studies the control effect of torque feedforward sliding mode controller (TF-SMC), PID controller and torque feedforward sliding mode controller and PID parallel controller (TF-SMC-PID) on the drill string. The research shows that both PID controller and torque feedforward sliding mode controller can effectively control the stick slip vibration of the system. After the torque feedforward is added, the system can guarantee the normal operation of the system at a lower speed or a higher WOB. Compared to PID controllers, TF-SMC-PID controllers significantly increase the response speed of drill bit speed, shorten the adjustment time, significantly reduce overshoot, and significantly lower the peak value of vibration when controlling the drill string system.

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