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Observer-based State Feedback Control to Suppress Stick-slip Vibrations in Oil Well Drill-string

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Abstract: In drilling field, stick-slip vibrations of the drill-string are the main reason for the failure of the drilling system. To suppress the undesired stick-slip vibrations, an observer-based state feedback control method is proposed. The drilling system is described by a lumped parameter model including a Karnopp friction torque model. A state observer is designed to estimate the bit velocity in bottom hole and a state feedback controller is proposed to control the top drive velocity. By simulation, the performance of the control algorithm is demonstrated. Based on the control algorithm, a stick-slip vibration control system is developed. Test results show that the control system can effectively eliminate stick-slip vibrations of the drill-string and can be applied to the drilling field.

Keywords: drill-string; stick-slip vibration; state observer; state feedback controller; test

1 Introduction

Exploration and development of oil and gas wells is done by the drilling system, as shown in Figure 1.

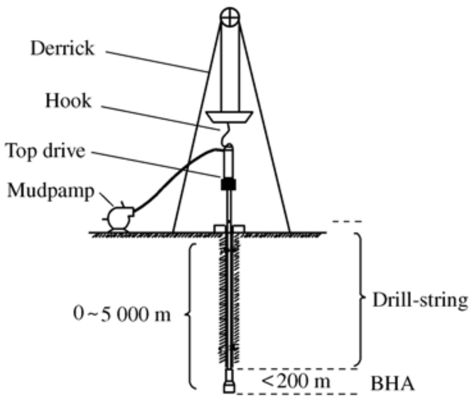

Figure 1 Basic structure of drilling system

The drilling system mainly includes the top drive, the drill-string and the bottom hole assembly (BHA). The driving force is provided by the top drive at surface. The drive torque transfer and the mud transmission from the rotary table to the bit are implemented by the drill-string[1]. The BHA is located at the lowest part of the drill-string and includes the drill-collar, the stabilizer and the bit. The rock is broken by the bit. Due to slenderness and small cross section of the drill-string, low inertia of the BHA, and the nonlinear interaction torque between the bit and the rock, it is easy prone to stick-slip vibrations of the drill-string[2]. It has been

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proved that stick-slip vibration of the drill-string belongs to self-excited vibration, which is caused by the nonlinear interaction torque between the bit and the rock[3].

The undesired stick-slip vibrations of the drill-string are very harmful. When these vibrations happen, the angular velocity of the drill bit can arrive many times of the angular velocity of the top drive[4]. Stick-slip vibrations may lead to failure in the drill pipe sections and connections or may lead to a mechanical failure of the bit. In extreme cases, stick-slip vibrations may lead to a complete standstill of the bit or may lead to fractures of the drill pipe[5].

In order to avoid the harm that comes from stick-slip vibrations of the drill-string, some control methods were proposed. Some different control approaches could be applied to suppress stick-slip vibrations of the drill-string, such as H_∞ control[1], PI controller[2, 5], active damping control strategy[6], sliding model control methods[7-9], output-feedback control[10], nonlinear control design[11], soft torque[12], modeling error compensation[13]. However, in drilling field, only the velocity and the torque of the top drive can be measured and other system variables cannot be detected. Therefore, these proposed control algorithms hardly be applied to actual drilling.

In order to eliminate stick-slip vibrations of the drill-string, in this paper, based on an established lumped parameter model, an observer-based state feedback control algorithm is proposed. The control algorithm includes a state observer and a state feedback controller. Only with the velocity and the torque of the top drive as input, the state observer can estimate the bit velocity. The state feedback controller can effectively eliminate the stick-slip vibrations of the drill-string with good dynamic performance. Furthermore, based on the proposed control algorithm, a stick-slip vibration control system is developed and is applied in drilling field.

In Section 2, a lumped parameter model is established to model the drilling system and a Karnopp friction model is built to model the nonlinear interaction torque. Section 3 presents the structure of the control algorithm. In Section 4, by simulations, the dynamic performance of the proposed control scheme is demonstrated. In Section 5, the test results of the control system are verified. Conclusions are given in Section 6.

2 Dynamics of the drilling system

A lumped parameter model with two degree of freedom is established for the drilling system, as shown in Figure 2. Serrarens et al[1] pointed that simplified 2DOF model in Figure 2 is accurate enough for the description of the stick-slip phenomenon and can be used as the model for the controller design.

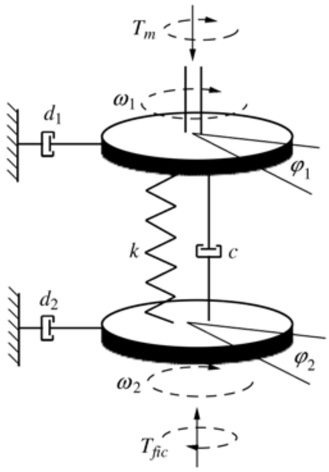

Figure 2 Lumped parameter model of drilling system

The dynamics of the 2DOF model can be described by the following equations:

$$\begin{cases} J_1\ddot{\varphi}_1 + c(\dot{\varphi}_1 - \dot{\varphi}_2) + k(\varphi_1 - \varphi_2) + d_1\dot{\varphi}_1 = T_m \\ J_2\ddot{\varphi}_2 - c(\dot{\varphi}_1 - \dot{\varphi}_2) - k(\varphi_1 - \varphi_2) + d_2\dot{\varphi}_2 = - T_{fic} \end{cases} \tag{1}$$

With the top drive (the inertia J_1, the damping coefficient d_1, the angular displacement φ_1 and the angular velocity $\omega_1 = \dot{\varphi}_1$), the drill-string (the structural damping coefficient c and the stiffness coefficient k), the BHA (the inertia J_2, the damping coefficient d_2, the angular displacement φ_2 and the angular velocity $\omega_2 = \dot{\varphi}_2$), the top drive torque T_m, the nonlinear interaction torque T_{fic}. Stability of the 2DOF model was analyzed[14]. The 2DOF model can be described by the following block diagram in Figure 3.

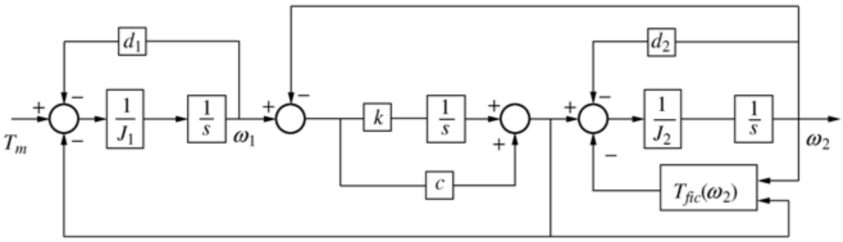

Figure 3 Block diagram of the drilling system

The nonlinear interaction torque between the bit and the rock is called Torque-on-Bit (TOB). In order to describe more accurately the interaction between the drill bit and the rock, the Karnopp friction model is applied here[15]. The Karnopp model was also used[2, 4-5]. Based on the Karnopp friction model, the nonlinear interaction torque T_{fic} can be described by the following equations:

$$T_{fic} = \begin{cases} M & \text{if } |\omega_2| \leqslant \Delta\omega \text{ and } |M| < M_a \\ M_a \mathrm{sgn}(\omega_2) & \text{if } |\omega_2| \leqslant \Delta\omega \text{ and } |M| \geqslant M_a \\ [M_o + (M_a - M_o)\mathrm{e}^{-\xi|\omega_2|}]\mathrm{sgn}(\omega_2) & \text{if } |\omega_2| > \Delta\omega \end{cases} \tag{2}$$

With the torque applied to the BHA by the drill-string M, the maximum static friction torque M_a, the sliding friction torque M_o, an empirical constant $\xi \in [0,1]$ and the threshold value $\Delta\omega$. The friction drop M_a-M_o causes stick-slip vibrations of the drill-string[3]. The nonlinear interaction torque T_{fic} is proportional to the Weight-on-Bit (WOB).

Based on the 2DOF model, the state vectors $\boldsymbol{X}$ of the drilling system are defined as

$$\boldsymbol{X} = [\dot{\varphi}_1 \quad \varphi_1 - \varphi_2 \quad \dot{\varphi}_2]^{\mathrm{T}} = [x_1 \quad x_2 \quad x_3]^{\mathrm{T}} \tag{3}$$

Then the state space model of the simplified system can be given by

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} -\dfrac{c + d_1}{J_1} & -\dfrac{k}{J_1} & \dfrac{c}{J_1} \\ 1 & 0 & -1 \\ \dfrac{c}{J_2} & \dfrac{k}{J_2} & -\dfrac{c + d_2}{J_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \dfrac{1}{J_1} \\ 0 \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ 0 \\ -\dfrac{1}{J_2} \end{bmatrix} T_f \tag{4}$$

Where, u is the control input, $u = T_m$.

3 Control algorithm

In this section, a linear active damping control algorithm is presented. It has been proved that the linear controller can suppress the non-linear stick-slip vibrations of the drill-string[2]. If the original reference input Ω_{ref} of the top drive velocity is given, the control objective can be described as $x_3 \to x_1 \to \Omega_{ref}$. It means that the bit velocity converges to the top drive velocity which should be close to the original reference input. To achieve the control goal, an observer-based state feedback control algorithm is proposed, as shown in Figure 4.

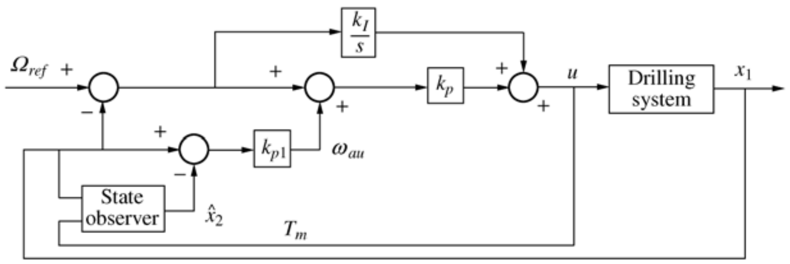

Figure 4 Control strategy

In Figure 4, the symbol ω_{au} is an auxiliary velocity command. In practice, the D/A converter has an interface to receive the auxiliary velocity command. Based on surface measurement (i. e. the velocity and the torque of the top drive), a state observer is developed to estimate the bit velocity x_3. And a state feedback controller is proposed to suppress stick-slip vibrations of the drill-string.

The damping coefficient of the drilling system is very small. If system damping is not considered, the dynamics of the top drive can be described by

$$J_1 \ddot{\varphi}_1 = T_m - M \tag{5}$$

The torque M is represented by a second-order disturbance model. With the estimation error $e=\hat{x}_1 - x_1$, the designed state observer can be constructed as

$$\begin{cases} \dot{\hat{x}}_1 = \dfrac{T_m - \hat{M}}{J_1} + k_{o1}(\hat{x}_1 - x_1) \\ \dot{\hat{M}} = \hat{\dot{M}} + k_{o2}(\hat{x}_1 - x_1) \\ \dot{\hat{\dot{M}}} = k_{o3}(\hat{x}_1 - x_1) \end{cases} \tag{6}$$

With $K_o = [k_{o1} \quad k_{o2} \quad k_{o3}]$ are observer gains. Based on $\dot{M} = k(x_1 - x_3)$, the estimated value of the bit velocity can be then estimated as

$$\hat{x}_3 = \hat{x}_1 - (\hat{\dot{M}}/k) \tag{7}$$

The advantages of the state observer are as follows:

1) It does not need to consider the effect of the nonlinear friction on the drilling system.

2) Its structure is simple, which only need to obtain the inertia of the top drive and the stiffness coefficient of the drill-string.

As the bit velocity x_3 can be estimated and the top drive velocity x_1 can be measured, for the control goal $x_3 \to x_1$, the auxiliary velocity command ω_{au} can be described as

$$\omega_{au} = k_{p1}(x_1 - \hat{x}_3) \tag{8}$$

Based on Equation (8), for the control goal $x_1 \to \Omega_{ref}$, the state feedback controller is proposed, which has the law

$$u = k_p(\Omega_{ref} + \omega_{au} - x_1) + k_I \int_0^t (\Omega_{ref} - x_1)\,\mathrm{d}\tau \tag{9}$$

Where, K_c is control gains, $K_c = [k_{p1} \quad k_p \quad k_I]$.

Both the parameters K_o and the parameters K_c are obtained by the damping optimum procedure[2, 16]. Based on the damping optimum procedure, the closed-loop system has a step response characterized by an overshoot of approximately 6% and the rise time of approximately 1. 8 T_e, where, T_e is the time constant[2, 16].

4 Simulations

In this section, the simulation results are presented. The dynamic performance and the ability to suppress stick-slip vibrations of the proposed state feedback control algorithm are demonstrated. In simulation, the drilling system is described by Equation(1) (or Equation(4)) with parameters taken from Ref. [2] as $J_1 = 1\,440$ kg · m^2, $J_2 = 432$ kg · m^2, $k = 525$ Nm/rad, $c = 23.2$ Nms/rad, $d_1 = d_2 = 0$. The parameters of the nonlinear friction model are taken from Ref. [7] as $M_a = 13\,200$ N · m, $M_o = 7\,800$ N · m, $\xi = 0.9$ s/rad, $\Delta\omega = 0.001$ rad/s. The reference input is set to $\Omega_{ref} = 15$ rad/s.

The top drive torque T_m, the angular velocity (i. e. the top drive velocity x_1, the bit velocity x_3 and the bit velocity estimate $\hat{x}_3$), the angular difference x_2 and the interaction torque T_{fic} are shown in Figure 5. It can be seen that the bit velocity x_2 shows a cyclical "sticky-slip-sticky", which means that stick-slip vibrations at the bit happen. Therefore, the 2DOF model of the drilling system can reflect stick-slip vibrations of the drill-string. From Figure 5b), the state observer can provide good estimate of the bit velocity (the red line). In fact, the state observer also can be extended to the multi-DOF models.

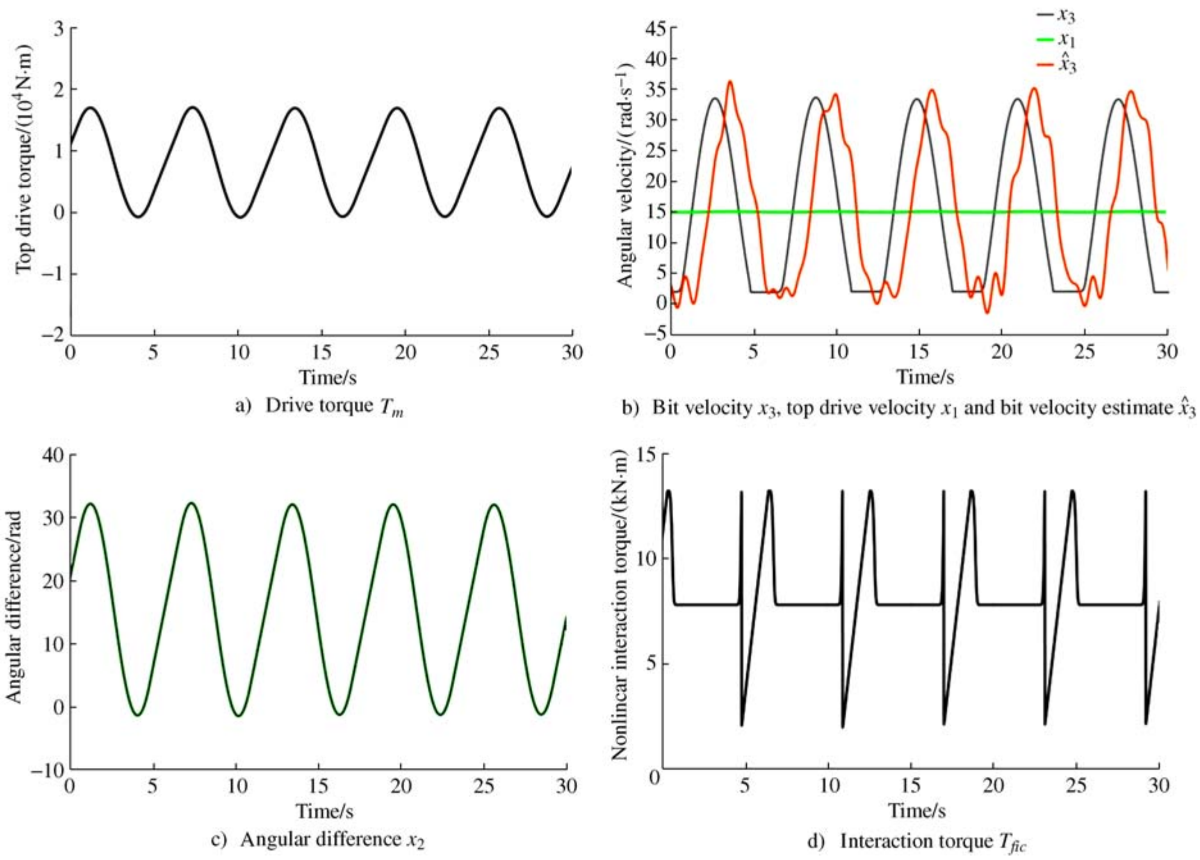

Figure 5 Time domain response of the drilling system

The simulation results of the top drive torque T_m, the angular velocity (including auxiliary velocity command ω_{au}), the angular difference x_2 and the interaction torque T_{fic} using the proposed control algorithm Equation (9) are shown in Figure 6. It can be seen that stick-slip vibrations of the drill-string is eliminated with quick response (the settling time is less than 20 s) and no steady-state errors. The proposed control algorithm Equation (9) has a strong ability to overcome the nonlinear interaction torque, which can be applied in drilling field.

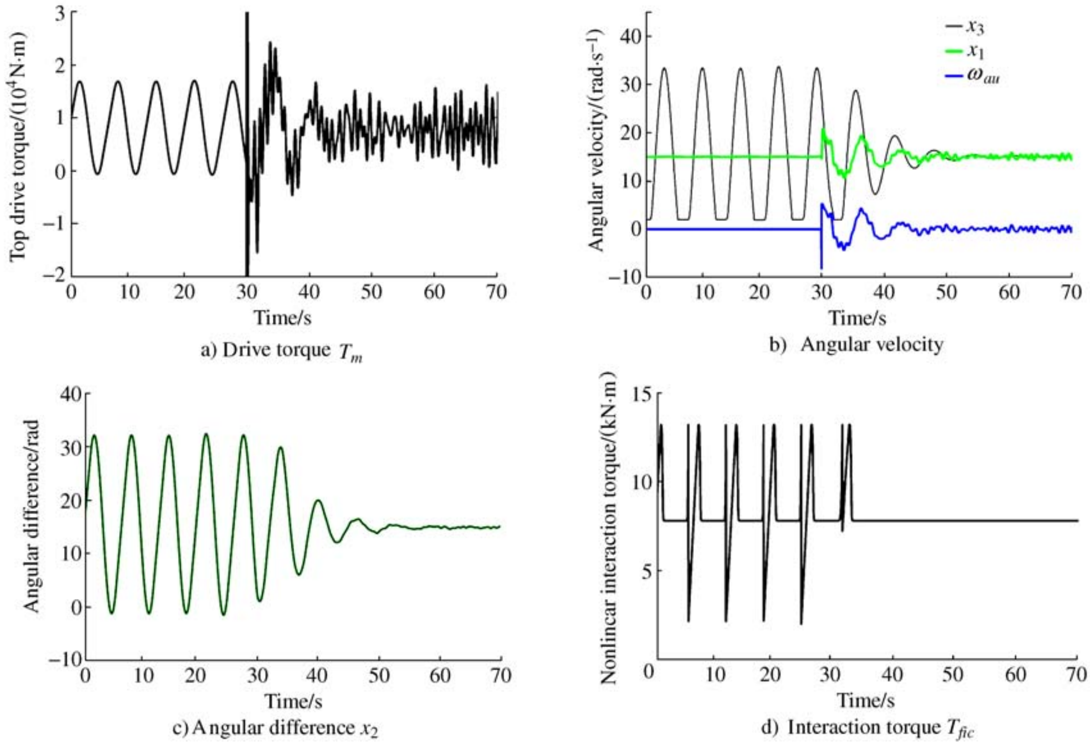

Figure 6 Time domain response of the closed-loop control system

5 Drilling field test

Based on the control algorithm, a stick-slip vibrations control system is developed, as shown in Figure 7. In this section, the performance of the control system is verified.

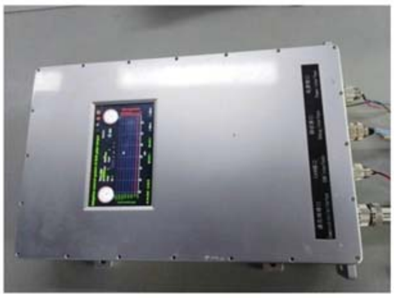

Figure 7 Carrier of the stick-slip vibrations control system

In drilling field, the inertia of the top drive is 1 430 kg · m^2 and the drilling depth reaches 3 600 m. The stick-slip vibration control system is activated at 45 s and the test results are shown in Figure 8. Figure 8a) shows the top drive torque T_m before and after control. Figure 8b) shows the top drive velocity ω_1, the bit velocity estimate $\hat{\omega}_2$ and the auxiliary velocity command ω_{au}. Figures 8c) and Figures 8d) show the spectrum analysis of the top drive torque and the bit velocity before and after control, respectively. The experimental results show that the fundamental frequency amplitude of the top drive torque and the bit velocity are effectively suppressed.

Based on the above analysis, the developed stick-slip vibrations control system can eliminate stick-slip vibrations of the drill-string and it should be applied in drilling field.

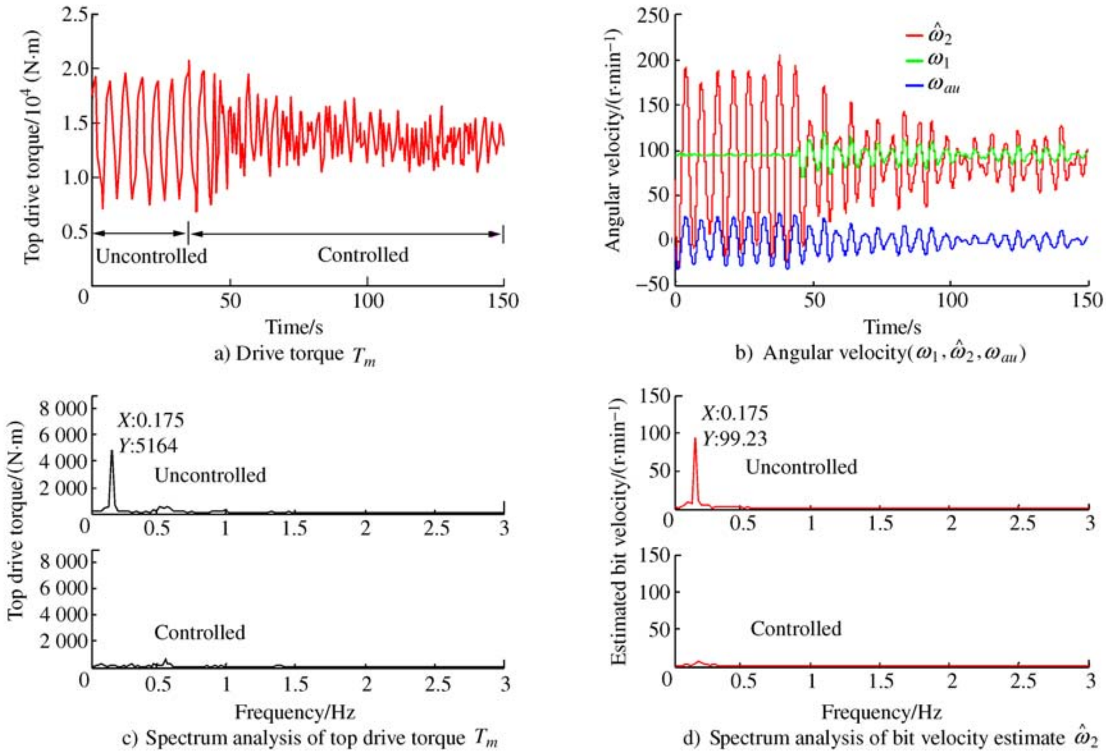

Figure 8 Experimental results of the stick-slip vibrations control system

6 Conclusions

In this paper, an observer-based state feedback control algorithm is proposed to suppress stick-slip vibrations. Based on this idea, a stick-slip vibration control system is developed and is tested in drilling field. Simulation results indicate that the proposed control algorithm has a strong ability to overcome the nonlinear interaction torque. The experimental results show that the control system can effectively eliminate stick-slip vibrations of the drill-string.

7 Acknowledgments

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References

[1] Serrarens A F A, van de Molengraft M, Kok J J, et al. H_∞ control for suppressing stick-slip in oil well drill strings [J]. IEEE Control Systems, 1998, 18(2): 19-30

[2] Pavkovic D, Deur J, Lisac A. A torque estimator-based control strategy for oil-well drill-string torsional vibrations active damping including an auto-tuning algorithm [J]. Control Engineering Practice, 2011, 19 (8): 836-850

[3] Brett J F. The genesis of torsional drillstring vibrations [J]. SPE Drill Engineering, 1992, 7 (4): 168-174

[4] Fu M, Li J, Wu Y, et al. Characteristic simulation and mechanisms analysis for drill-strings stick-slip

vibration[J]. Journal of Northwestern Polytechnical University, 2016, 34 (3): 467-472 (in Chinese)

[5] Monteiro H L S, Trindade M A. Performance analysis of proportional-integral feedback control for the reduction of stick-slip-induced torsional vibrations in oil well drillstrings [J]. Journal of Sound and Vibration, 2017, 398: 28-38

[6] Jansen J D, Van den Steen L. Active damping of self-excited torsional vibrations in oil well drillstrings[J]. Journal of Sound and Vibration, 1995, 179 (4): 647-668

[7] Navarro-López Eva M, Cortés D. Sliding-mode control of a multi-DOF oil well drillstring with stick-slip oscillations [C]//Proceedings of the 2007 American Control Conference, New York City, USA, 2007, 3837-3842

[8] Liu Y. Suppressing stick-slip oscillations in underactuated multibody drill-strings with parametric uncertainties using sliding-mode control [J]. IET Control Theory Application, 2015, 9(1): 91-102

[9] Ghasemi M, Song X Y. Control of a vertical drilling system using a cascade sliding mode controller[C]// Proceedings of the American Control Conference, IEEE, 2017: 5830-5835

[10] Vromen T G M, Van de Wouw N, Doris A, et al. Observer-based output-feedback control to eliminate torsional drill-string vibrations [C]//Proceedings of the 53rd Conference on Decision and Control, IEEE, Los Angeles, 2014: 872-877

[11] Al-Hiddabi S A, Samanta B, Seibi A. Nonlinear control of torsional and bending vibrations of oil well drillstrings [J]. Journal of Sound and Vibration, 2003, 265 (2): 401-415

[12] Tucker R W, Wang C. On the effective control of torsional vibrations in drilling systems [J]. Journal of Sound and Vibration, 1999, 224(1): 101-122

[13] Puebla H, Alvarez-Ramirez J. Suppression of stick-slip in drillstrings: a control approach based on modeling error compensation [J]. Journal of Sound and Vibration, 2008, 310 (4): 881-901

[14] Nandakumar K, Wiercigroch M. Stability analysis of a state dependent delayed, coupled two DOF model of drill-string vibration [J]. Journal of Sound and Vibration, 2013, 332 (10): 2575-2592

[15] Karnopp D. Computer simulation of stick-slip friction in mechanical dynamic systems [J]. ASME Journal of Dynamic Systems, Measurement and Control, 1985, 107(1): 101-103

[16] Zäh M, Brandeburg G. The extended damping optimum [J]. Automation Technology, 1987,35(1):275-283

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