Sliding Mode Variable Structure Control of the Steerable Drilling Stabilized Platform Based on Disturbance Observer

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Abstract—A sliding mode variable structure control based on disturbance observer (SMVSCDOB) has proposed to tackle the uncertainty caused by friction in the stabilized platform on the rotary steerable drilling. Disturbance observer (DOB) is used to estimate the uncertainty in stabilized platform, and the estimated value is compensated by sliding mode variable structure control (SMVSC) to improve the control accuracy. The simulation experiment of control system is carried out with MATLAB, comparing the SMVSCDOB control method with proportional integral derivative (PID), PID+DOB, SMVSC. The simulation results show that the proposed method SMVSCDOB can better track the tool face angle, reduce the system error, suppress the friction interference, and enhance robustness of the system.

1. Introduction
The steerable drilling stabilized platform is a key link in the rotary steering drilling tool. Generally, traditional control methods have a good control effect on accurate mathematical models [1], but due to the complex and changeable downhole environment, there are many disturbances in the system, it is very difficult to establish an accurate stabilized platform. Therefore, it is very important to study how to eliminate the influence of disturbance on the system, accurately measure and quickly adjust the tool face Angle, and improve the control performance of the stabilized platform.

Huo Aiqing [2], Zhou Huilong et al. [3] combined fuzzy control and sliding mode variable structure control, and used fuzzy control to eliminate the jitter generated by sliding mode variable structure control on the switching surface. However, the structure of this method is complex and requires a large amount of computation. Ren Yan [4], Han Xiaokang et al. [5] introduced LuGre friction and Stribeck friction models respectively, and adopted SMVSC to realize friction compensation, which effectively suppressed friction and enhanced the anti-interference ability of the system. Yang Hualin [6], Zhang Jiaxu et al. [7] proposed a method based on nonlinear disturbance observer to eliminate the uncertainty disturbance in the nonlinear system. This method has strong robustness. Bhagyashri Tamhane et al. [8] designed a control method based on a sliding mode extended state observer to filter out nonlinear disturbances, and the system performance is greatly improved. However, considering the conversion form of speed disturbance to torque disturbance, there are problems such as dynamic modeling incompleteness, inadequate consideration of disturbance issue.
The disturbance observer (DOB) can suppress and estimate the disturbance in the system. The sliding mode variable structure control (SMVSC) has strong robustness, and has a good suppression effect on large-scale parameter fluctuations and external disturbance. Combining the disturbance observer with the sliding mode variable control structure not only inherits the rapidity of the sliding mode structure, but also suppresses external disturbance. For this reason, this paper proposes a sliding mode variable structure control based on disturbance observer (SMVSCDOB), and conducts simulation research and verification.

2. Establishment of the Steerable Drilling Stabilized Platform Model

2.1. Stablilized platform controlled object model

According to the working mode and principle of the stabilized platform \cite{9}, the generalized controlled object model of stabilized platform can be established, as shown in Fig. 1.

![Generalized controlled object model of stabilized platform.](image)

Where \( K_K \) is the PWM pulse modulation coefficient, \( K_E \) is the proportional constant between the armature current and the electromagnetic torque, \( K_W \) is the conversion coefficient of the gyro sensor, \( K_m \) is the motor transmission coefficient, \( T_m \) is the electromechanical constant of the motor, \( F_i \) is the external unknown interference torque, \( F_f \) is the friction torque.

Selecting the tool face angle \( \theta \) as \( x_1 \) and the stabilized platform angular velocity \( \omega \) as \( x_2 \), the generalized controlled object model of the stabilized platform can be expressed as:

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= \frac{K_m K_E K_m + 1}{T_m} x_2 + \frac{K_m K_f K_m + 1}{T_m} u - K_m F
\end{align*}
\]

(1)

Where \( F = F_f + F_i \), \( K_m = \frac{C_m}{J R_s + C_m} \), \( T_m = \frac{R_s J}{J R_s + C_m} \).

2.2. Analysis of friction characteristic

Due to the complex downhole environment, the control system of the steerable drilling stabilized platform will be affected by nonlinear friction. The Luger model can accurately describe the steady state and transient characteristics generated during the friction process. In addition, the model can also describe viscous friction, Coulomb friction, and Strubeck’s static friction and its negative slope effect, given its characteristics and the friction characteristics existing in the steering drilling stabilized platform rotation process have certain commonalities, so the Luger model is introduced into the steerable drilling stabilized platform for research.

Lugre model can be expressed as:

\[
T_f = \sigma_0 z + \sigma_1 \frac{dz}{dt} + B \dot{\theta}
\]

(2)

\[
\frac{dz}{dt} = \dot{\theta} - \frac{\dot{\theta}}{g(\theta)} z
\]

(3)
\[ g(\dot{\theta}) = T_r + (T_c - T_s) e^{-\frac{\theta}{\sigma_c^2}} \] (4)

Where \( T_f, T_c, T_s \) are friction torque, Coulomb friction torque and maximum static friction torque respectively. \( \sigma_c, \sigma_l, B \) are stiffness coefficient, viscous damping coefficient and viscous friction coefficient respectively. \( \theta \) is friction surface angular velocity.

3. Controller Design

On the basis of establishing the controlled model of the steerable drilling stabilized platform, the controller is systematically designed, and the disturbance observer and the sliding mode variable structure control are designed respectively to realize the control of the stabilized platform.

3.1. Controller overall design

Sliding Mode Variable Structure Control based on Disturbance Observer mainly uses DOB to compensate and estimate the system's uncertain disturbance items, so that the design of the controller is no longer affected by the precise mathematical model of the controlled object, which can better reduce the jitter of SMVSC. By SMVSC reduce the error caused by DOB to the system. The block diagram of the sliding mode variable structure control based on the disturbance observer is shown in Fig. 2.

![Figure 2 Block diagram of sliding mode variable structure control based on disturbance observer.](image)

3.2. Design of disturbance observer

The basic idea of the disturbance observer designed in this paper is to equivalent the external torque interference and the difference between the actual object and the nominal model output to the control input, that is, to measure the equivalent disturbance and introduce equal compensation into the control to realize the complete suppression of the disturbance. Fig. 3 shows the block diagram of the disturbance observer.

![Figure 3 The principle diagram of disturbance observer.](image)

Where \( G_p(s) \) is the transfer function of the control object. \( G_i^{-1}(s) \) is the inverse of the nominal model. \( Q(s) \) is the low-pass filter. \( d \) is the equivalent disturbance. \( \tilde{d} \) is the estimated value of disturbance \( d \). \( \xi \) is measurement noise. \( u \) is the control input of the system. \( y \) is the control output of the system. \( c \) is the output of the controller.
The output of the controller is:

\[ c = u - \hat{a}_f + d \]  \hfill (5)

According to Fig. 3, the transfer function of output control signal \( U(s) \), interference signal \( D(s) \) and measurement noise \( N(s) \) when they act respectively is as follows:

\[ G_{Uy}(s) = \frac{Y(s)}{U(s)} = \frac{G_p(s)G_n(s)}{G_r(s) + Q(s)[G_p(s) - G_n(s)]} \]  \hfill (6)

\[ G_{Dy}(s) = \frac{Y(s)}{D(s)} = \frac{G_p(s)G_n(s)[1 - Q(s)]}{G_r(s) + Q(s)[G_p(s) - G_n(s)]} \]  \hfill (7)

\[ G_{Ny}(s) = \frac{Y(s)}{N(s)} = \frac{G_p(s)Q(s)}{G_r(s) + Q(s)[G_p(s) - G_n(s)]} \]  \hfill (8)

According to (6)-(8), when \( Q(s) = 1 \), \( G_{Dy}(s) = 0 \), the disturbance signal can be eliminated. When \( Q(s) = 0 \), \( G_{Ny}(s) = 0 \), the system can eliminate measurement noise. Since disturbances are generally low-frequency signals, measurement noise is generally high-frequency signals. Therefore, \( Q(s) \) is designed as a low-pass filter in the paper, so that the system has the ability to eliminate disturbance and measure noise at the same time.

It can be seen from the transfer function of the controlled object of the stabilized platform that the relative order of the system is 2. In order to make \( G(s)G^{-1}(s) \) regular, take \( N = 3 \) and \( r = 2 \), then the low-pass filter \( Q(s) \) is designed as follows:

\[ Q(s) = \frac{3\tau s + 1}{(\tau s)^3 + 3(\tau s)^2 + 3\tau s + 1} \]  \hfill (9)

The value of the time constant \( \tau \) in the formula can be selected according to the actual situation.

### 3.3. Design of sliding mode variable structure control

The state equation of the stabilized platform is:

\[ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -A \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ B \end{bmatrix} u - \begin{bmatrix} 0 \\ D \end{bmatrix} F \]  \hfill (10)

Where \[ A = \frac{K_uK_xK_m}{T_n} + 1, B = \frac{K_uK_xK_m}{T_n}, D = \frac{K_u}{T_n}. \]

Taking \( x_1 \) as \( \theta \), \( \theta_d \) is the predetermined tool face angle signal, the tracking error can be defined as:

\[ e = \theta_d - \theta \]  \hfill (11)

The switching function is designed as:

\[ s = \dot{e} + ce (c > 0) \]  \hfill (12)
Taking the derivative of the above equation:
\[
\dot{s} = c\dot{e} + \ddot{e} + \ddot{\theta} - \ddot{x}_z = c\dot{e} + \ddot{\theta} - \left[-A\dot{x}_z + Bu - DF\right]
\]  

(13)

Using the method of exponential approach law can obtain:
\[
\dot{s} = -\varepsilon \text{sgn}(s) - ks \quad (\varepsilon > 0, \ k > 0)
\]  

(14)

Where \( \dot{s} = -ks \) is an exponential approach term;
The expression of the total control quantity \( u \) can be described by:
\[
u = -\frac{1}{B}\left[\dot{\theta}_d + ce + A\dot{x}_z + DF + \varepsilon \text{sgn}(s) + ks\right]
\]  

(15)

4. Simulation Experiment and Analysis

According to the \[10\], the model parameters of the stable platform are obtained as follows:
\[K_u = 3.44 \text{ (A/V)}, \quad K_\varepsilon = 0.22 \text{ (N \cdot m/A)}, \quad K_n = 5.74 \text{ (V/rad/s)}, \quad J = 0.03 \text{ (kg \cdot m^2)}, \quad f = 0.270, \quad R_n = 12.500(\Omega), \quad C_s = 0.400, \quad C_n = 3.820. \]  

Based on the static parameter identification of literature \[11\], the four static parameters involved in the Lugre model are obtained as follows:
\[T_s = 2.4440, \quad T_\varepsilon = 0.5991, \quad \dot{\theta}_r = 0.0103, \quad B = 0.0049. \]  

For dynamic parameters \( \sigma_0 \) and \( \sigma_1 \), neural network method is used to identify, and \( \sigma_0 = 0.4766, \quad \sigma_1 = 0.2701 \) are obtained.

Use MATLAB/SIMULINK to simulate the control system described in (15). The model of the controlled object adopts (1). Design of disturbance observer adopts Fig.3, where the low-pass filter adopts (9), the time constant \( \tau = 0.005 \).

4.1. Simulation analysis of tool face angle tracking control system

The initial state of the system is \( x = [0 \ 0]^T \), the given input signal is \( \theta_d = \sin(2\pi t) \), and the external interference signal is \( F_u = 2\sin(t + \pi) \). The simulation results of the comparative tracking control system using proportional integral derivative (PID), PID+DOB, SMVSC and SMVSCDOB four controllers are shown in Fig. 4.

It can be seen from Fig. 4(a) that SMVSCDOB and SMVSC have better tracking effects than PID and PID+DOB control. SMVSCDOB can suppress the interference very well, enhance the robustness of the system, and the tracking effect is also obvious better. Fig. 4(b) that SMVSCDOB error is the smallest, which is significantly lower than error of PID and PIDDOB controllers.
4.2. Robustness

J and R are reduced by 50%, and external interference $F = 2\sin(t + \pi)$ is fixed, the tool face angle tracking error curve are shown in Fig.5.

When the stabilized platform parameters J and R are reduced by 50%, the SMVSCDOB control method still has the best tracking effect among the four control methods, with the maximum error is 1%. In SMVSC control method, parameter perturbation has little effect on the control performance of the system, which proves that the sliding mode variable structure can improve the robustness of the system. For the two control methods of PID and PIDDOB, the influence of parameter perturbation on the system error is obvious, with the error reaching 19% and 16% respectively. Therefore, SMVSCDOB method can effectively reduce the error caused by parameter perturbation of stabilized platform control system.
5. Conclusion
In this study, sliding mode variable structure control method based on disturbance observer is proposed for the uncertainty caused by friction in the downhole operation of the steerable drilling stabilized platform. This method uses the disturbance observer to compensate and estimate the interference, and uses the sliding mode variable structure to improve the robustness of the system. Based on the stabilized platform control system for rotary steerable drilling, the disturbance observer and controller with sliding mode variable structure are designed, and simulation experiments are carried out with MATLAB/SIMULINK. Experimental results prove that the control algorithm can effectively suppress the impact of friction disturbance, reduce jitter and ensure that the system tool face angle quickly stabilizes within a certain range of time. Compared with PID, PID+DOB and SMVSC found that its tracking accuracy is high, the error is small, it can effectively restrain the influence of parameter perturbation, and it can meet the control requirement of the steerable drilling stabilized platform.

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