An ADRC-based Stick-slip Vibration Control Method for Drill String

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Abstract. For complex deep wells, the drill string stick-slip vibration is an intensive destructiveness torsional vibration caused by twisting vibration and down hole drag. This phenomenon can be explained that the bit is motionless for some time, and when the torque on drill string is large enough, the bit suddenly rotate at a high-speed. The stick-slip vibration has become a major problem to be solved urgently in the exploration and exploitation of deep and ultra-deep wells. In drilling operations, the stick-slip will occur in drilling for more than half of the time. Usually, the stick-slip vibration leads to the decrease of penetration rate and the increase of completion cycle. In serious cases, it leads to drill string fracture, bit failure, and even serious downhole accidents. In this thesis, the drill string torsion model is established, the drill string stick-slip vibration mechanical model is proposed, the equation of stick-slip vibration motion is analyzed and the general laws of drill string stick-slip vibration are acquired. In order to effectively suppress stick-slip vibration, an auto-disturbance rejection control (ADRC) method is adopted. Result of experiment shows that the soft-torque control method can make the actual speed of motor changed according to the torque, so as to decrease the motor torque fluctuations, eliminate stick-slip vibration and achieve the drill string soft-torque control.

1. Introduction

Stick-slip phenomenon is a movement between complete adhesion contact and sliding contact (ultimate rubbing contact). Displaying in the drill string drilling process, this phenomenon is a stick-slip vibration. This vibration can be explained that the bit is motionless for some time, and when the torque on drill string is large enough, the bit will rotate at a high-speed. The stick-slip vibration of the drill string is an intensive low-frequency vibration, and the instantaneous speed of bit is high during the vibration, which maximum value can be even more than 2 times of the turntable.

As the down hole measurement while drilling (MWD) data shows, there are a variety of vibration during the drilling process, which include axial, horizontal, torsional and some unusual vibration, such as stick-slip. As the drill string increases, the torsional stiffness will be reduced and the drag torque will be grater, these factors will make the underground drill string rotation very difficult and cause the phenomenon of stick-slip\(^1\). During the drill string stick-slip vibration, the bit speed can instantly achieve to a great value, which is likely to cause the drill string damage. In addition, the torque fluctuates very greatly in this process, which not only affects the efficiency of drilling operation, but also threats the drilling safety, and the too large actual torque may exceed the limits of the device, resulting in the drilling operation not be carried out.
To eliminate the process of drilling the stick-slip vibration of the drilling system for drilling performance, many experts and scholars have done lots of research, mainly to solve the stick-slip vibration of drilling system modeling and control problem. In this thesis, drill string torsion model is established[3], drill string stick-slip vibration mechanical model is proposed and the equation of stick-slip vibration motion is analyzed, the general laws of drill string stick-slip vibration are acquired[3], and an ADRC-based control method for drill string soft-torque control system is proposed. Independent of the exact model of the system, ADRC can estimate the state of the system and compensate the "total disturbance" directly by using the input and output information of the controlled object, and maintain good control performance even when there are many uncertainties. By comparing the experimental results, the proposed stick-slip vibration control method based on ADRC can make the actual speed of the motor change with the change of the torque, thus reducing the fluctuation of the motor torque, eliminating the influence of stick-slip vibration, and realizing the flexible torque control of the drill pipe.

2. Self-excited Vibration and Stick-slip Phenomena

The vibration is a common phenomenon in nature. Vibration can be divided into deterministic vibration and random vibration according to whether it can be expressed by deterministic time function. Deterministic vibration can be divided into periodic vibration and non-periodic vibration, while self-excited vibration is a kind of periodic vibration. Self-excited vibration does not require external force excitation or external action to change the structural parameters of the system, but depends on the interaction of various components of the system to maintain steady-state periodic motion. The self-excited vibration phenomena caused by friction in mechanical systems are mainly manifested in system flutter, system pursuit (stick-slip) and asymmetric inertial coupling. The chasing phenomenon of mechanical system generally exists in the low-speed transmission system with strong frictional force, which is mainly manifested in the phenomenon of non-uniform motion of the object's stopping interaction. Drill string system is a kind of low-speed transmission system with strong frictional force, so it is easy to produce stick-slip phenomenon.

The stick-slip vibration is caused by the friction between moving objects. To be exact, it is caused by the difference of static and dynamic friction coefficients between moving objects. Viscous-slip vibration is characterized by the alternation of viscous and slippage phenomena of vibrating objects. For most objects, due to the high frequency of this alternation, it is difficult to be clearly captured, but the existence of viscous-slip phenomena is beyond doubt. In the process of drilling, drill string motion will occur periodically "rotation-stop-rotation-stop", which we call stick-slip vibration of drill string. The stick-slip vibration of drill string is mainly caused by the periodic accumulation and release of energy in drill string when the bit overcomes the frictional torque at the bottom of the well. The stick-slip vibration will bring a series of negative effects on drilling work, mainly in the following aspects[4-5]:

1. With the increase of well depth, the drill string is also increasing, and the equivalent torsional stiffness of the drill string decreases. When the torque transmitted by the drill string is insufficient to drive the bit to break rock, the bit stops rotating, and the system is in the sticky stage. In the slippage stage, the bit accelerates rotation at a great instantaneous speed, and then slows down to zero gradually. In this process, the bit is subjected to alternating stress and friction resistance with the formation. Periodic friction change between drill bit and formation will accelerate the passivation process of drill bit, which will lead to the decrease of penetration rate and the increase of completion cycle.

2. During drilling, the energy provided by the power drive system is transmitted to the bit through the drill string to break the rock. When the bit sticks, the accumulated torque in the drill string can neither break the rock, but also accelerate the failure of the drill string. When the bit slips, the collision friction between the drill string and the borehole wall and the interaction with the drilling fluid will waste the energy provided by the wellhead, which not only affects the drilling cycle, but also increases. The cost of drilling is high.

3. The stick-slip vibration is a special form of torsional vibration, which is very destructive. The stick-slip vibration is accompanied by more than 50% of the drilling time in deep formation. In the actual drilling process, the stick-slip vibration often accompanies other forms of vibration at the same
time, forming a variety of forms of coupling vibration, which has a great impact on the damage of drilling tools, seriously affecting drilling speed and completion cycle. At the same time, the irregular rotation of the drill bit and the vibration of the drill string system will reduce the wellbore quality.

3. Dynamic Model Of Drilling String’s Stick-Slip Vibration

3.1.3-DOF Model

The drill string rotating mechanical model mainly includes: turntable, drill pipe, the drill collar, drill bits, four parts, drill bits and drill collars known collectively as downhole assembly (BHA). According to the actual well drilling technology, considering the drill collar and the drill between the rigid very large, and in order to facilitate the analysis of drill string system, merge the drill bits and drill collars together, at the same time, by further simplifying the structure of the drill string system, a 3-DOF model of the rotary disc-drill string-drill tool assembly is obtained, as shown in Fig.1.

![Figure 1. Simplified drill string structure](image)

It includes three units: 1) turntable system; 2) drill pipe; 3) drill bits. $J_r$, $J_p$, $J_b$ are the inertia belong to turntable, drill pipe, drill bits. Inertia is connected with linear spring, linear spring has the torsional rigidity ($k_r$, $k_p$) and rotating damping ($c_r$, $c_p$). $T_{ar}$ is damper torque of the top drive system, $T_{ab}$ is damper torque of the drill bits, $T_{fb}$ is friction torque of the drill bits, $T_m$ is driver torque. The mathematical models of the drill string system are

$$J_r\ddot{\varphi}_r + C_r(\dot{\varphi}_r - \dot{\tau}_r) + k_r(\varphi_r - \varphi_b) + T_{ar}\ddot{\tau}_r = T_m$$

$$J_p\ddot{\varphi}_p + C_p(\dot{\varphi}_p - \dot{\tau}_p) + k_p(\varphi_p - \varphi_b) + T_{ab}(\dot{\tau}_b - \dot{\tau}_c) = 0$$

$$J_b\ddot{\varphi}_b + T_b(x) = C_b(\dot{\varphi}_b - \dot{\tau}_b) + k_b(\varphi_b - \varphi_s)$$

where $\varphi_i$, $\dot{\varphi}_i$ [$i \in \{r, p, b\}$] are the angular displacements and angular velocities of drill-string elements respectively, $T_m$ is the torque coming from the electrical motor at the surface. The actuator dynamics is not considered, and $T_m = u$, with $u$ the control input. $T_{ar} = c_r\dot{\varphi}_r$, with $c_r$ the viscous damping coefficient, $x$ is the system state vector defined as

$$x = (\varphi_r, \varphi_p, \varphi_b, \dot{\varphi}_r, \dot{\varphi}_p, \ddot{\varphi}_b)^T = (x_1, x_2, x_3, x_4, x_5)$$

Finally, $T_b$ is the torque on the bit, $T_b(x) = T_{ab}(x) + T_{fb}(x)$, $T_{ab} = c_b x_5$ approximates the influence of the mud drilling on the bit behavior. $T_{fb}(x)$ is the friction modeling the bit-rock contact. Karnopp friction model is adopt,

$$T_b(x) = \begin{cases} T_{ab}(x), & |x| \leq D, |T_a| \leq T_a \\ T_{ab}\text{sgn}(T_a(x)), & |x| \leq D, |T_a| > T_a \\ W_{ar}R_{ar}|X_r|\text{sgn}(X_r), & |x| > D \end{cases}$$

where $W_{ar}R_{ar}$ is the torque on the bit, $X_r$ is the position of the bit, $D$ is the摆动滑移阈值.
When \(|x_5|<D_v|T_{eb}|<T_{sb}\), drill pipes in a stagnation stage, when \(|x_5|<D_v|T_{eb}|>T_{sb}\), drill pipes in a stage of stick-slip, when \(|x_5|<D_v\), drill pipes in a sliding stage.

With \(D_v>0\), \(T_{eb}\) the reaction torque, that is, the torque that the static friction torque \(T_{sb}=W_{ob}R_{b}\mu_{sb}\) must overcome so that the bit moves. \(R_{b}\) is the bit radius and \(W_{ob}>0\) is the WOB. \(\mu_{ob}(x_5)\) is the bit dry friction coefficient considered as

\[
\mu_{ob}(x_5) = \mu_{oa} + (\mu_{oa} - \mu_{eb})e^{-\frac{x_5}{r_f}}
\]  

(6)

With \(\mu_{ob}(x_5) = \mu_{eb} + (\mu_{eb} - \mu_{cb})e^{-\frac{x_5}{r_f}}\) \(\mu_{eb}, \mu_{cb} \in (0,1)\) the static and Coulomb friction coefficients associated with \(J_{eb}^b\), \(0<\gamma_b<1\) and \(V_f>0\), \(T_{eb}\) is

\[
T_{oa} = C_{oa}(x_1-x) + k_{oa}x + -T_{oa}x
\]  

(7)

According to equation (1)~(7), the state equation of the drill string system can be described as follows

\[
\begin{align*}
\dot{x}_1 &= \frac{1}{J} \left[-(C_r+C_r)x_1-k_{r}x_2+C_sx_3+u\right] \\
\dot{x}_2 &= x_1-x_3 \\
\dot{x}_3 &= \frac{1}{J_p} \left[C_sx_1+k_xx_2-(C_r+C_r)x_3-k_{r}x_4+C_sx_5\right] \\
\dot{x}_4 &= x_3-x_5 \\
\dot{x}_5 &= \frac{1}{J_p} \left[C_{ib}x_3+k_{ib}x_4-(C_p+C_{ib})x_5-T_{fb}(x)\right]
\end{align*}
\]

(8)

3.2.2-DOF Model

In order to facilitate the model analysis and algorithm implementation, the drill string system structure shown in Fig. 1 is further simplified by combining two-thirds of the drill string inertia with the rotary table inertia and one-third of the drill string inertia with the bit. The simplified structure of the drill string system is transformed from the original 3-DOF to 2-DOF (shown in Fig.2).

![2-DOF rotation model](image)

The dynamic equation of the 2-DOF model is

\[
\begin{align*}
T_m &= c(\omega_r-\omega_b) + c,\omega_r + k\Delta \phi \\
\dot{\omega}_b &= \frac{c}{J_b} \omega_r - \frac{c + \mu_c}{J_b} \omega_b + \frac{c}{J_b} \Delta \phi - \frac{1}{J_b} T_{fb} \\
\Delta \phi &= \omega_r - \omega_b
\end{align*}
\]

(9)
From the simulation results of Fig.3 and Fig.4, it can be seen that when the rotary table runs at a constant speed, the speed of the bit and the torque of the main motor oscillate sharply up and down with the fluctuation of the non-linear torque, resulting in Stick-Slip vibration.

There are angular displacements and angular velocities in Eq. (5)~(7). In order to simplify the experimental structure without affecting the structural model analysis, the non-linear formula in literature \[7\]

\[
\begin{aligned}
T_{OB}=T_{OB_{dyn}} = \frac{2}{p}(\alpha W_{i}e^{-\alpha r_{i}}) + \alpha \tau_{e} \left( \frac{1}{1+\tau_{e} \alpha} \right)
\end{aligned}
\]

\[\alpha_1 = 9.5, \alpha_2 = 2.2, \alpha_3 = 35\]

is adopted to replace Eq. (5). Two different non-linear simulation curves are shown in Fig.5. It can be seen from the figure that the two kinds of non-linear curves are very close and the properties of non-linearity are identical. It shows that the non-linear formula in literature [7] can be used in the 2-DOF drill string system model instead of Eq. (5).

4. ADRC Control Strategy
Active disturbance rejection control (ADRC) does not depend on the exact model of the system. It can estimate and compensate the state and total disturbance of the system directly by using the input and output information of the controlled object. When there are many kinds of uncertainties, ADRC can still maintain good control performance. Its structure is shown in Fig.6, including tracking differentiator TD, nonlinear state error feedback control law NLSEF, expansive form. State observer ESO and disturbance compensation part. \[8,9\] Tracking differentiator can track input signal quickly and generate approximate differential signal of input signal. The total disturbance of the system is regarded as a new extended state of the system, and the state observer for the expanded new system is called the extended state observer. The extended state observer estimates the total disturbance of the system in real time. The disturbance compensation part compensates the estimated total disturbance reasonably. The original system can be approximated as an integral series system. Error signals \(e_i\) based on tracking differentiator and ESO and error differential signals \(e_2, e_3, \ldots, e_n\), different nonlinear error feedback control laws can be selected.
Taking the second-order uncertain controlled object as an example, the typical second-order ADRC algorithm for unknown object is as follows:

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= f(x_1, x_2, w(t), t) + bu \\
y &= x_1
\end{align*}
\]  

(10)

Arrange the transition process:

\[
\begin{align*}
\dot{v}_1 &= v_2 \\
\dot{v}_2 &= f\text{han}(v_1 - v, v_2, r_0, h)
\end{align*}
\]  

(11)

The extended state observer is:

\[
\begin{align*}
e &= z_1 - y \\
e_1 &= f\text{al}(e, 0.5, h) \\
e_2 &= f\text{al}(e, 0.25, h) \\
z_1 &= z_2 - \beta_0 e \\
z_2 &= z_3 - \beta_0 e_1 + bu \\
z_3 &= -\beta_0 e_2
\end{align*}
\]  

(12)

The non-linear combination is:

\[
\begin{align*}
e_1 &= v_1 - z_1, e_2 = v_2 - z_2 \\
u_0 &= f\text{han}(e_1, ce_2, r, h_1)
\end{align*}
\]  

(13)

The control quantity generated by disturbance compensation is:

\[
u = \frac{u - z_3}{b_0}
\]  

(14)

Where, \(r_0, \beta_{01}, \beta_{02}, \beta_{03}, c, h_1, b_0\) are the parameters of ADRC, \(r_0\) is influenced by both the speed of transition and the endurance of the controlled system. The parameters \(\beta_{01}, \beta_{02}, \beta_{03}\) are determined by the sampling step of the system. So the only parameters that need to be adjusted in the final controller are control gain \(r\), damping coefficient \(c\), precision factor \(h_1\) and compensation factor \(b_0\).

In actual drilling process, the structure of stick-slip vibration control system of drill string is shown in Fig.7. The greatest advantage of this control strategy is that it overcomes the problem that it is difficult to detect the bit state in technology, but estimates the bit state through the existing data and the data that can be detected, thus indirectly incorporating the bit into the controlled object category, and realizes the closed-loop control of the bit.

5. Experimental Study

For further analyzing the stick-slip vibration and control performance, an experimental structure platform is established. It main includes control, nonlinear and display segments shown in Fig.7. [10]
In the diagram, control part is made up of ①②③, ① check upper turntable speed and torque, ③ user input parameters, the data of ① and ③ sent to the controller, calculated control volume by the controller and send to AC frequency conversion motor to control motors speed by ②; Nonlinear part is made up of ④⑤⑥ detect the lower turntable speed to the PLC, calculated non-linear control volume by the PLC and send to AC server motor to control the output torque of the motor by ⑤; Display part is composed of ⑥ and ⑦, ⑥ and ⑦ collect all data needed to be displayed to the HMI, HMI displays collected data, and running curve.

When the stick-slip state of the bit is monitored and calculated, the soft torque control system starts to work: the control input can be obtained from the given control parameters of the system, such as $\alpha$, $\beta$ and the torque $T$ of the main motor. When the system is in the initial stage, the control input and output are all zero. When the control system is not in the initial stage, the control output is discretized. The compensation input voltage is gradually calculated by iteration principle and used as the main motor so that the whole drill string system is in normal working state.

**Figure 7.** Experimental structure platform of drill system

![Diagram](image)

**Figure 8.** Running curve with no input controls

**Figure 9.** Running curve with input control

Fig.8 is the lower turntable speed curve when no input controls, Fig.9 is control curves when input control. As can be seen from the diagram, when no input controls, under non-linear torque in the lower, lower turntables speed alone with the fluctuations in nonlinear oscillation sharply up and down, which shows the drill system settled up by the experimental structures in Fig.8 has produced a lot of stick-slip vibration phenomena. When input the controller, turntables speed becomes substantially from the original oscillation range and tend to be gentle, nonlinear curve wave also disappear as controller...
inputs. That explains that after the controller into operation, the controller role to overcome the effects of nonlinear friction torque on the running drill system, improving the operational status of turntables in the lower, thus absorbing the stick-slip vibration.

The theoretical simulation proves that the simplified mathematical model can accurately represent the physical characteristics of the actual drill string system. It also shows that the ADRC proposed in this paper can effectively improve the operation status of drill string system and make the bit run smoothly. Through the construction of the test-bed and its operation effect, the actual manifestation of stick-slip vibration and the performance of the control scheme in practical application are further explained.

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Acknowledgments

This research was supported by the school enterprise cooperation practical education base project in Anhui (2018sjjd079), the emergent engineering research and practice project in Anhui (2020xgkxm32), and National Innovation and Entrepreneurship Training Program for College Students (201910375009, 201910375042).