Stick-slip Vibration Motion Simulation of Depth Well Drilling

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Abstract
In the drilling process, stick–slip friction between the drill bit and the rock trigger undesired the drill-string vibration, which exhibit drill bit intermittent stagnation and rotation. An elastic model and friction model of drill-string stick-slip vibration is established and analyzing nonlinear dynamics of the model. Based on the dynamic characteristics of the model, a structure block is set up to simulate the phenomenon of drill-string stick-slip vibration. The analysis and simulation result indicates that stick-slip vibration of drill-string is a nonlinear self-excited vibration, which is caused by the nonlinear friction. The instantaneous speed of drill bit exceeds twice the speed of drilling system.
Key words: DRILL-STRING, STICK-SLIP, VIBRATION, DYNAMIC SIMULATION

1. Introduction

When the drilling depth reaches 2-3 kilometers, the stiffness of drill-string torque decreased, drilling-bit affected by friction, may make periodic stagnation and rotating drill, producing stick-slip. The problems of drill-string oscillations has been perceived for many years as one of the prime causes of deterioration in drilling performance, and was subjected to some early investigations as reported in the literature[1]. The successive stick-slip oscillations of the drill-string seriously affected the drilling efficiency, which can damage the drilling equipment and is the main cause and assembly of the drill string fatigue or even the cause to fracture of the drill string [2]. In order to enhance the performance of the drilling, better control drilling running smoothly, study the mechanism of stick-slip oscillations of the drill-string is very important.

Many experts and scholars committed to the research of the stick-slip oscillations of the drill-string, many have insight into the results, published in the petroleum science journal [3]. Finite element method is used by Y.A.K hulief to derive the equations of the dynamic model of the drill string, explained the inertial combination of nonlinear bending of a reverse direction. He accounts for the torsional–bending inertia coupling and the axial–bending geometric nonlinear coupling and accounts for the gyroscopic effect, the effect of the gravitational force field, and the stick–slip interaction forces [4]. Millheim study of drilling directional control, attempts to use the finite element method in drill-string analysis, published a large number of articles, contains a lot of research data, related research has a great influence on the later [5,6]. Yigit and Christoforou based on Laplace transform, the introduction of high order model, calculating the drill string the elasticity of the degrees of freedom, construct the drill string mechanical model [7, 8]. Based on the method of free vibration twist, Richard and Detournay used with fixed quality and moment of inertia of rigid body to simulate the BHA, using linear spring to simulate the drill string, the drill string stick-slip model is set up [9]. After decades of tireless research, we gradually formed a relatively complete system of drill string dynamics theory, which include of the differential equation method and the finite element method. This article mainly committed to the mechanism analysis of stick-slip oscillations of the drill-string, through MATLAB simulation, studies the motion law of vibration and lays a foundation for restrain stick-slip. Section 2 mainly introduces the down-hole drilling system, and construction of the double degree of freedom model of drill string, and the friction model. The system structure of the drill string is established in Section 3 and the simulation based on MATLAB stick-slip oscillation phenomena of the drill-string. Section 4 respectively by time domain analysis and phase plane analysis and research the movement of the stick-slip oscillation of the drill string, discuss the causes of vibration. Section 5 includes the concluding remarks and discusses future research directions.

nomenclature section

J_1	drive moment inertia	J_2	the load inertia
b	damping coefficient	m	torque of drill-string
c	stiffness coefficient	m_f	torque of friction
D_1	the inner diameter of the drill-string	ω_1	the motor angular speed
d_1	the outer diameter of the drill-string	ω_2	the load angular speed
D_2	the inner diameter of the collar	φ_1	the motor angular displacement
d_2	the outer diameter of the collar	φ_2	the load angular displacement
L_1	the depth of drilling	J_{bit}	inertia of the bit
G	shear modulus of steel	M	torque of motor
ρ	the density of steel	Δm	torque-on-bit (TOB)

2. The drill-string mathematical model

2.1 The drill-string model of double degree of freedom

Oil drilling system is mainly divided into two parts, namely, the ground driving system and downhole drilling system. The ground driving system generally includes inverter, drive motor, gearbox, derrick and the turntable [10]. The bottom hole drilling system mainly consists of the drill-string and the BHA, which can be connected with the drill-string composed of a drill pipe. The oscillations are observed to become more severe in the Bottom Hole Assembly (BHA), which normally includes of the bit, the drill-collars and stabilizers, as shown in Fig. 1.

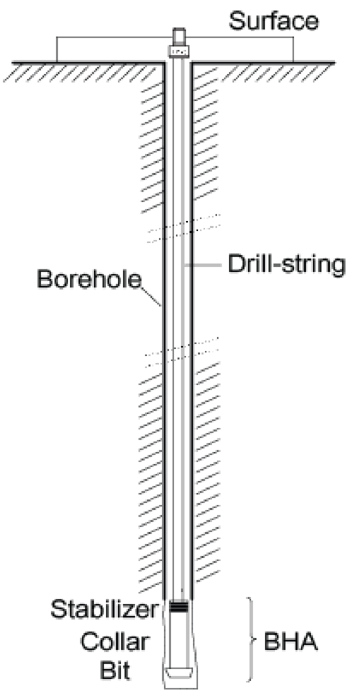


Figure 1. Down-hole drilling system

Arrived at thousands of meters, the drilling depth can be collected for down-hole information, and drill -string assembly and by the nature of the system itself and external force and boundary conditions, the influence of movement is very complicated. In order to carry out research, using mathematical methods needed for the system to set up a simplified model, in order to realize the simulation and analysis of stick-slip oscillation. Based on the principle of two-mass degree of freedom torsional oscillation, use a spring-mass system mechanics model to simulate the stick-slip oscillation of the drill-string, as shown in Fig. 2.

Establish a double degree of freedom model requires the following assumptions [11]:

·Transmission system only drill-string and bottom hole assembly (BHA);

·The drill string as the distortion of the whole root spring;

·Ignore assembly distortion characteristic, the whole the moment of inertia of down-hole drilling system focused on the flywheel;

·Ignore the damping of the drill string itself and the drill string internal and external mud drilling fluid damping and the friction between the drill string and borehole wall with viscous damping coefficient b;

According to the related mechanical knowledge, the system of effective moment of load inertia J_2 :

$$J_2 = \rho \frac{\pi}{32}\left[\frac{L_1}{3}\left(D_1^4 - d_1^4\right) + L_2\left(D_2^4 - d_2^4\right)\right] + J_{bit} \tag{1}$$

Damping coefficient b :

$$b = b_l \frac{L_1}{3} \tag{2}$$

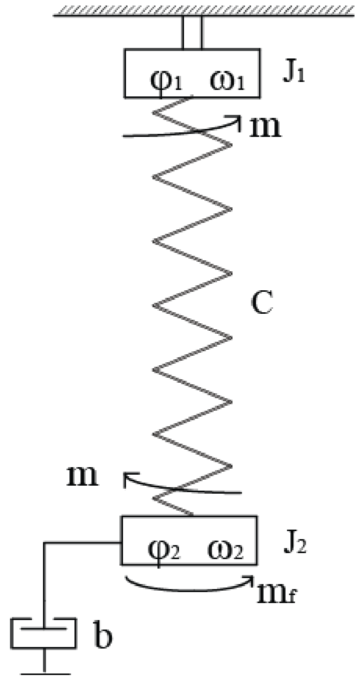


Figure 2. The drill-string structure model

Stiffness coefficient C :

$$C = G\frac{1}{L_1}\frac{\pi}{32}\left(D_1^4 - d_1^4\right) \tag{3}$$

Where G is the shear modulus for steel ($G = 7.96\times10^{10}\,N/m^2$), ρ is the density of steel and J_{bit} is moment of inertia of the bit, while the geometrical parameters φ_1, ω_1, φ_2, ω_2, m and mf are defined in nomenclature section.

2.2 The drill-string friction torque model

The friction torque of bit is continuous nonlinear drill, which can be expressed as the function of bit speed as the independent variable [12]. As traditional friction model only describes the friction and velocity between the static characteristic, the speed zero point is discontinuous. In order to illustrate the friction force in the state of zero velocity, using Stribeck friction model simulation tool by the friction torque, as shown in Figure 3.

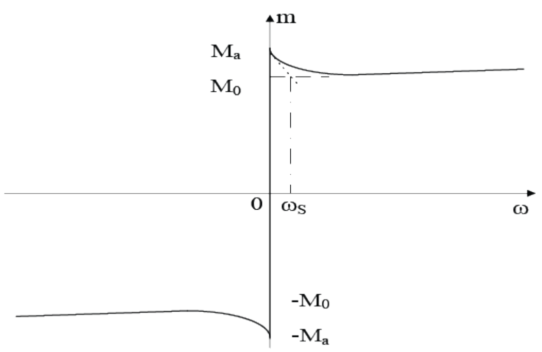


Figure 3. The friction model

From Fig.3, M_0 is the coulomb friction torque, M_a is the maximum static friction torque and ω_s is known as Stribeck speed. When the speed of drill-bit is zero ($\omega_2 \in [-\omega_s, +\omega_s]$), the friction with other force balance effect on the system, until the driver more than maximum static friction force into the sliding state. Stribeck friction model is a simplified between the static friction and dynamic friction model, the biggest benefit of can stipulate its static range. The expression of the Stribeck friction model can be described by

$$m_f = \begin{cases} M(\omega_2) & \omega_2 \neq 0 \\ M_e & \omega_2 = 0\ \&\ |M_e| \le M_a \\ M_a\,\mathrm{sgn}(M_e) & \omega_2 = 0\ \&\ |M_e| > M_a \end{cases} \tag{4}$$

In order to accurately describe the continuity of the zero speed area friction, exponential decay function is selected to describe here:

$$m_f(\omega_2) = \left[M_0 + (M_a - M_0)e^{-|\omega_2/\omega_s|\sigma}\right]\mathrm{sgn}(\omega_2) \tag{5}$$

Where σ is the Stribeck friction coefficient, $\sigma \in [0.5, 2]$.

2.3 The structure of drill-string system

In Fig. 2, analyzing the drill-string model, the closed-loop control system can be described by the following differential function:

$$\begin{cases} J_2\dot{\omega}_2 + b\omega_2 + C(\varphi_2 - \varphi_1) = -m_f(t) \\ J_1\dot{\omega}_1 + b\omega_2 - C(\varphi_2 - \varphi_1) = M(t) \end{cases} \tag{6}$$

For the damping spring mass model, tool movement state equation, the torque of the drill string m and torque-on-bit (TOB) Δm are obtained:

$$\begin{aligned} m &= c\int(\omega_1 - \omega_2)dt + b\omega_2 \\ \Delta m &= m - m_f(\omega_2) = J_2\ddot{\varphi}_2 \\ \omega_1 &= \dot{\varphi}_1 \\ \omega_2 &= \dot{\varphi}_2 \end{aligned} \tag{8}$$

Structural diagram of mechanical system is built based on the differential equations, as shown in Fig. 4. Closed-loop system structure lay the foundation for the realization of stick-slip vibration simulation of the drill-string.

3. The simulation and analysis of the stick-slip vibration of the drill-string

3.1 The simulation of the stick-slip vibration

The theoretical research of vibration of drill string began in the 1950s, mainly from the perspective of statics for drill string vibration prediction, the intro-

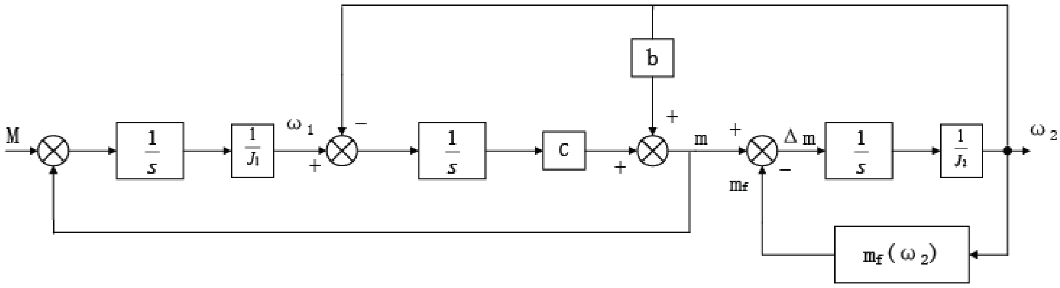


Figure 4. Structural diagram of mechanical system

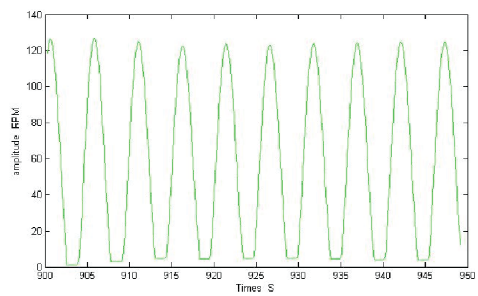
duction of the theory of digital opened a direction for the study of drill string vibration. Through the analysis of drill string dynamics, builds the mathematical model of drilling string system, under the MATLAB implements the simulation of the stick-slip vibration of the drill string. According to the drill pipe, drill collar and the specifications of the drill bit, the simulation parameters Settings such as table 1.

Table 1. Specification of drilling unit

the inner diameter of the drill-string D_1	$127mm$
the outer diameter of the drill-string d_1	$108mm$
the inner diameter of the drill-collar D_2	$180mm$
the outer diameter of the drill-collar d_2	$103mm$
the depth of drilling L_1	$2500m$
shear modulus of steel G	$7.96\times10^{10} N/m$
the density of steel ρ	$7800kg/m^3$

According to the formula (1), formula (2) and formula (3), you can learn hat the effective moment of load inertia $J_2 = 388kg\cdot m^2$, damping coefficient $b = 18N\cdot ms/rad$ and stiffness coefficient $C = 432N\cdot m/rad$. Set the maximum static friction torque M_a in the friction model for 57950N·m and the coulomb friction torque M_0 for 37000N·m. Set motor driving speed ω_1 for 50rad/s, based on the MATLAB simulation graph was obtained for the stick-slip vibration of the drill string, as shown in Figs below.

Figs.5 show the drill-string angular speed at 2500-m above the bit. If the system is great disturbance, the drill-string can produce stick-slip vibration. Bit speed fluctuations is very big, amplitude can be reduced to zero, the most substantial value will be more than twice as much. Figs. 6 describe the changes of the torque of the drill-string at bottom of the cave. Under the effect of damping system itself and friction of the hole, the drill-string torque unable to maintain smooth, cyclical fluctuations. Figs. 12 and 13 show the simulation of drill-bit torque and the simulation of Stribeck friction torque, respectively. Angular velocity according to the bit, drill pipe, drilling torque on the torque and friction torque in the time domain waveform figure shows that in sliding cycle, the bit of friction for sliding friction, torque and rotational speed in the same direction, if the bit drilling speed increases; If the bit torque and rotational speed in the opposite direction, drill speed decreases gradually. Peak bit rate more than double the rotational speed of the drill string system, the drill string easy to be damaged. When bit into the stick on demurrage, bit of friction for static friction, the friction torque torque balance with drill pipe, drilling torque is zero at this time and bit rotation speed is zero.



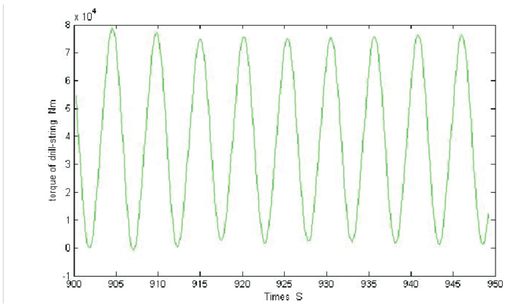


Figure 6. Stick-slip vibration drill-string torque simulation

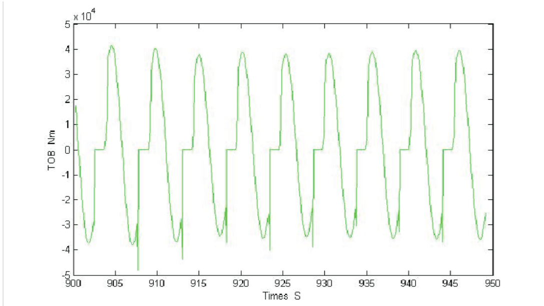


Figure 7. stick-slip vibration drill-bit torque simulation

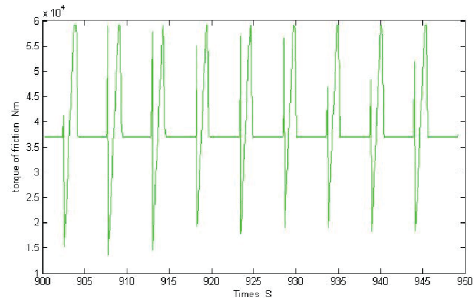


Figure 8. stick-slip vibration friction torque simulation

3.2 The phase plane analysis of the stick-slip vibration

Figs. 8 show the stick-slip vibration of the drill-string, the horizontal axis as the relative angular displacement and the vertical axis for bit angular velocity. The figure 8 shows that the primary stage bit by sticking at point a, the drill string continues to bit transmission energy, friction torque and the drill rod torque balance, until the point b. Point b exceed the maximum static friction torque, bit started sliding, the friction torque moment decreases, and reached the maximum bit speed up until the point d. Started sliding speed drop from point d to point a, again by adhesive. In c and e, drill speed is equal to the top of the drill string speed, speed and point d more than twice the point c speed. Drill string system to produce a certain frequency and amplitude of periodic motion, movement before and after the disturbance in the system still keep the original frequency and amplitude.

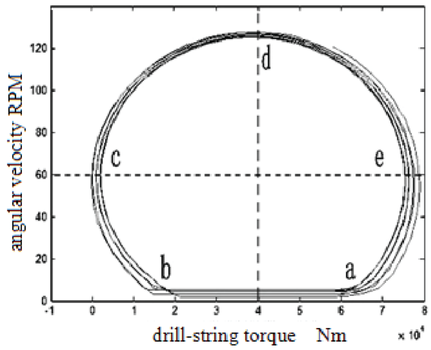


Figure 9. stick-slip vibration phase plane simulation

4. Conclusion

The paper has presented the design of an oil-well drill-string model aimed for the simulation and analysis of drill-string torsional vibrations. By analyzing the motion law, can know the mechanism of stick-slip vibration of the drill string. Under the effect of its damping, the disturbance will gradually weaken, system restore the original state of equilibrium. In case of stick-slip vibration, bit instantaneous speed more than double the rotational speed of the top of the string. That is to say, the stick-slip vibration of drill-string is a kind of periodic self-excited, self sustaining vibration, and the nonlinear vibration is caused by nonlinear friction.

The method developed in this paper is intended to furnish the basic building block for further development of more comprehensive drilling vibration mechanism that can easily improve drilling efficiency and ensure the drilling efficiency. The future research is going to be directed towards the study of the production of stick-slip vibration, as well as the method to restrain stick-slip.

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Analysis of Blood Pressure Variability Based on Frequency Spectrum

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