Drill Bit Stick-Slip Vibration Experiment Research and Analysis of Influencing Factors

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Research Article

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Drill bit stick-slip vibration experiment research and analysis of influencing factors

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Abstract

Stick-slip vibration of the bit in ultra-deep wells will seriously affect drilling potency, increase extra costs, and even cause drilling accidents. The study of the inner mechanism and external influencing factors of stick-slip vibration is of nice significance to the analysis on the suppression of stick-slip vibration. During this paper, Firstly, the interaction between the bit and rock stratum is analyzed through theoretical analysis. Based on the principle of J. Boussinesq elastic theory solution and Coulomb-Navier criterion, the damage process of the rock and the critical conditions for the incidence of stick-slip vibration of the bit were analyzed. Next, an analysis of the axial force variation of the drill column was carried out based on the establishment of an equivalent axial force variation model of the drill column torque transmission system, and the placement most strongly affected by the stick-slip vibration was located. Then, from the perspective of energy transformation of stick-slip vibration, it's analyzed that the undamped state of the bit at the instant of rock breaking is an important factor leading to the incidence of stick-slip vibration. Finally, it's verified through semi-physical experiments that adding damping to the bit at the instant of rock breaking can directly and effectively suppress the incidence of stick-slip vibration.

Keywords: Stick-slip vibration, Coulomb-Navier criterion, Oil drilling, J.Boussinesq theory

1 Introduction

Stick-slip vibration is the main reason that affects drilling efficiency and increases drilling costs. Excessive stick-slip vibration can cause premature aging or abnormal damage to the drilling system [1]. Therefore, restraining the stick-slip vibration of the drilling system is a major problem in the current drilling engineering. At present, domestic and foreign scholars' research on stick-slip vibration mainly includes three aspects: nonlinear dynamic analysis when stick-slip vibration occurs during drilling, the establishment and solution of the mathematical model of stick-slip vibration, and the design of a soft torque controller to suppress stick-slip vibration [2-6].

Analysis of the dynamic model of the drill column shows that the main cause of stick-slip vibration is the interaction between the drill bit and the bottom hole rock. Huijuan Chen measured the vibration signal during rotary drilling in a deep well and analyzed the characteristics of the drill column stick-slip vibration and whirlpool through fast Fourier transform (FFT) and short-time Fourier transform (STFT) methods. It is determined that the stick-slip vibration is a low-frequency vibration, and then it is clear that the vibration excitation source is mainly the interaction between the drill bit and the rock layer, the stabilizer or the Power-V system, and the borehole wall friction [7]. Yuelin Shen et al. studied the origin and mechanism of stick-slip vibration and recorded the data of stick-slip vibration through a series of drilling experiments, including the interaction between a single cutting tooth and the rock, BHA, and the geometry of the borehole. Then, using the recorded data and three-dimensional transient technology, the state of stick-slip vibration was successfully reproduced. It reveals the coupling between the torsion, axial and lateral movement of the drilling system, and provides a new idea for alleviating stick-slip vibration [8]. D.M. Lobo et al. proposed a new stochastic process to simulate the change of rock strength in drill string interaction to analyze drill string vibration. The shear component of the bit torque is modeled into two different Ornstein-Uhlenbeck and Coupled random process models, and then the change of rock strength is considered. Then the statistical analysis concludes that the stick-slip vibration amplitude caused by the uncertainty of rock strength is larger than the prediction under the definite model [9]. Fabio F. Real et al. constructed a non-linear stochastic model of bit-rock interaction with hysteresis. The model data were calibrated through field parameters, and the related data of drill pipe stability were estimated through the model [10]. It can be seen that the interaction between the drill bit and the rock is the main cause of stick-slip vibration.

Constructing a torque transmission model and suppressing stick-slip vibration through an active controller is also an effective way. Meng Fu et al. estimated the nonlinear torque between the drill bit and the rock based on the state observer and introduced the governor to modify the control strategy to suppress the stick-slip vibration [11]. Mohammad Javad Moharrami et al. conducted a nonlinear analysis of the drill pipe under the state of stick-slip vibration, and proposed a finite element (FE) modeling method for the full drill string, and established a limited three-dimensional nonlinear FE model that can evaluate the entire response of the drill pipe system under different operating conditions [12]. Roya Sadeghimeh et al. proposed a sliding mode control algorithm based on the Smith predictor and studied the effect of delay parameters on system output [13]. Vahid Vaziri et al. made a parametric analysis of a sliding mode controller that can suppress stick-slip vibration. The analysis shows that the controller can work stably in a large parameter range without delay, and the controller will fail when there is a delay. Its application in actual drilling operations is limited [14]. Mohammed YAAlkaragoolee, based on the distributed-lumped parameter model (DLPM) of the drilling system, studied the changes of attenuation factors under static friction and Coulomb friction and selected appropriate drilling parameters to suppress stick-slip vibration through the changes of the model [15]. Zhiqiang Huang proposed a 4-DOF (degree of freedom) drill string system plus a segmented smooth torsion model of the PDC bit to simulate non-percussive drilling [16].

The impact of rock strength changes in different drilling areas to the drilling system cannot be ignored. The strength of the rock when the drill bit shears and destroys the rock will affect the strength of the stick-slip vibration. J. Yoshida et al. verified the relatively rough plane with a shear test machine, and the dynamic shear strength of the rock is greater than the static shear strength [17]. Through laboratory tests, T. Okada et al. found that the dynamic strength of the complete rock discontinuity is not much different from the static strength [18]. Reducing the strength of the rock can suppress the stick-slip vibration, and the drilling method of compound impact is conducive to the bit breaking the rock. Cai Can et al. proposed a new type of split impact-cutting compound bit, which effectively solves the adverse effect of impact load on the life of PDC teeth and reduces the strength of the rock in the impact pit area. It reveals the importance of the combination of impact and cutting methods for the design of impact rock-breaking tools [19]. Li Bo et al. practically applied composite percussion drilling tools in the Daqing Xushen Gas Field to conduct field tests. The experimental results showed that the composite percussion method increased the ROP and reduced the drilling cost [20]. Liu Weiji comparatively studied the rock-breaking mechanism of single-tooth compound impact and torsional impact [21]. Yumei Li et al. used the 3D FEM of a composite impact system with a load-unload cycle to simulate the dynamic single-tool-rock interaction [22]. Xie Zheng et al. proposed a control scheme considering the time-delay characteristics of the system [23]. In the process of industrial production, it is one of the simple and effective ways to suppress various vibrations through dampers [24-26]. It is more widely used in the cutting process of various machining processes. The purpose of this paper is to analyze the mechanism of stick-slip vibration of the drill bit and the force and deformation of the whole drill column during the process of stick-slip vibration. In turn, the unfavorable factors leading to stick-slip vibration are identified, and suitable vibration damping methods are sought to reduce the adverse effects of stick-slip vibration on the actual project.

First, in Section 2, the interaction between the drill bit and the rock is studied. The damage process of the rock under two force conditions is analyzed. Several factors leading to the reduction of shear stress and the conditions under which stick-slip vibration occurs are obtained. In addition, the general method of suppressing stick-slip vibration is also summarized. In Section 3, an equivalent drilling column axial force variation model is established. The most affected parts of the stick-slip vibration process are analyzed according to the axial force diagram of the equivalent model and verified by simulation experiments. In Section 4, the most important factors leading to the occurrence of stick-slip vibration are analyzed according to the characteristics of the action of stick-slip vibration. A vibration damper principle is proposed through the energy conversion rate perspective. The influencing factors are changed through semi-physical experiments so that the stick-slip vibration is suppressed in principle. Finally, conclusions are drawn in Section 5.

2 Theoretical analysis

The drilling system consists of the top drive motor, drill pipe, drill collar, and drill bit. The essence of rock breaking by drill bit is that the torque generated by the motor is transmitted to the drill bit through the drill column system. The vertical movement of the drill bit generates a compressive stress perpendicular to rock formation, and the rotational movement of drill bit generates a shear stress parallel to rock formation. Under the action of double stress, the yield strength of the rock is reached and the rock is damaged. It showed the drilling system structures and rock breaking principle in Figure 1.

The types, shapes, and structures of rocks are different in different depths and geological conditions. Therefore, the uncertainty interaction between the drill bit and rocks makes it impossible to build an accurate mathematical model to predict this action. However, it is possible to analyze the influencing factors causing the vibration through the dynamics and vibration mechanism.

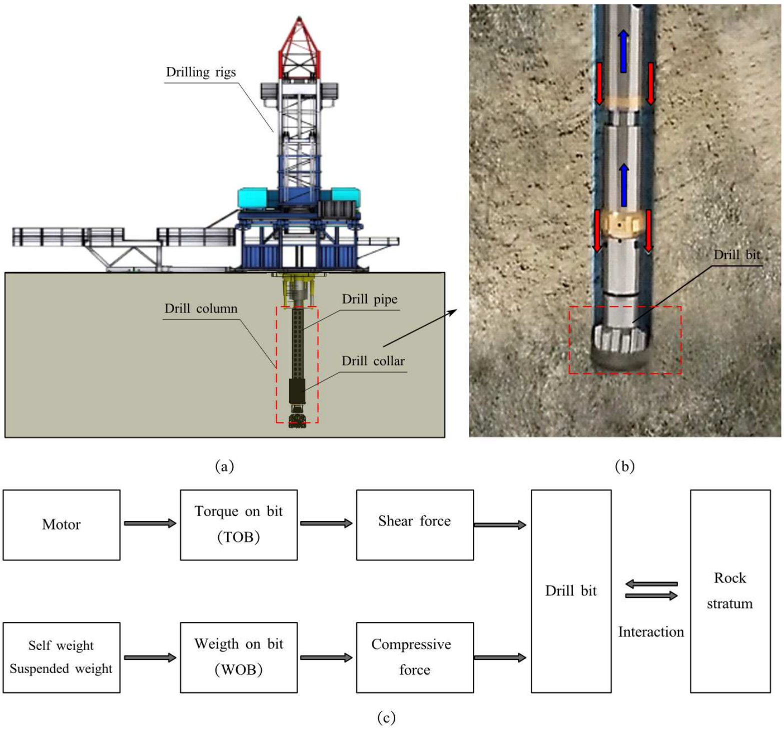

Fig. 1 (a)Structure of drilling system (b)Drilling run process (c)principle diagram of rock breaking action

2.1 Operation process analysis

Based on the definition of strain and shear Hooke's law, the equations for shear strain and shear stress during torsion of the drill column are derived.

$$\gamma(\rho) = \rho \frac{d\varphi}{dx} \tag{1}$$

$$\tau(\rho) = G\rho \frac{d\varphi}{dx} \tag{2}$$

Where $\frac{d\varphi}{dx}$ is the angle of twist per unit length of the shaft, $\gamma(\rho)$ is the torsional shear strain, $\tau(\rho)$ is the torsional shear stress, ρ is the distance from the torsional surface to the center of the section, and G is the shear elastic modulus. According to the equations of shear strain and shear stress, the shear strain and shear stress on the surface of the drill pipe are the largest during the torsion of the drill column. Taking a cross-section of a drill pipe as an example, the synthetic result of the shear stress in the cross-section is the torque in that cross-section, therefore.

$$T=\int_A \rho\tau_\rho dA = G\frac{d\varphi}{dx}\int_A \rho^2 dA = GI_p\frac{d\varphi}{dx} \tag{3}$$

Where $I_p = \int_A \rho^2 dA$ is the polar moment of inertia, and T is the torque. The relationship between the transmitted torque of the drill column and the shear stress and shear strain can be derived as follows.

$$\gamma(\rho)=\frac{T\rho}{GI_p} \quad \tau(\rho)=\frac{T\rho}{I_p} \tag{4}$$

$$I_P=\frac{\pi D^4\left(1-(d/D)^4\right)}{32} \tag{5}$$

$$W_P=\frac{\rho}{I_p}=\frac{\pi D^3\left(1-(d/D)^4\right)}{16} \tag{6}$$

Derive the formula for the maximum shear stress and the torsion angle of the drill column.

$$\tau_{\max}=\frac{T}{W_p} \tag{7}$$

$$\theta=\frac{T}{GI_p}\times\frac{180}{\pi}=\frac{\gamma T}{\tau I_p}\times\frac{180}{\pi} \tag{8}$$

Where Wp is the torsional section modulus of the cross-section, D is the outer diameter and d is the inner diameter of the drill pipe. θ is the torsion angle of the drill column. GIp is the torsional rigidity of the cross-section. The torsional rigidity of the entire drill column is obtained as.

$$K=\frac{GI_p}{l}=\frac{G\pi\left(D^4-d^4\right)}{32l} \tag{9}$$

Therefore, it can be seen that the inner diameter, outer diameter, wall thickness, length and material of the drill pipe determine the torsional rigidity of the drill column. It also determines the maximum deformation capacity and the maximum torque that can be transmitted to the drill bit without plastic deformation damage. The torsional rigidity of the drill column decreases as the well is drilled deeper and the drill column is longer.

The process of rock breaking by the drill bit is not a pure shearing process, but a uniaxial compressive shearing breaking process under the action of WOB. While bearing the shear stress generated by the drill bit, the rock formation is also subjected to axial drilling pressure generated by the self-weight of the drilling column system and auxiliary drilling tools.

$$\sigma=\frac{WOB}{A}=\frac{(m_{sw}+m_{suw})\,g}{A} \tag{10}$$

Where WOB is the weight on bit, σ is the compressive stress on the rock surface, m_{sw} is the quality of the drilling column, m_{suw} is the quality of auxiliary drilling tools, and A is the action area. The action area of the drill bit on the rock is small. Multiple drill teeth action can be considered as multiple vertical concentrated forces on the rock surface, as shown in Figure 2b. The study of the force acting on the rock surface by a single drill tooth is shown in Figure 2c. Under the action of the concentrated force of drilling teeth, intermediate cracks, lateral cracks and radial cracks are generated inside the rock, as shown in Figure 2e. The area of action of a single drill tooth can be considered as an elastic semi-infinite space surface. According to the principle of J. Boussinesq solution, the stress components at any point M (x, y, z) in the half-space when a vertical concentrated force is applied to the elastic semi-infinite space surface are as follows.

$$\sigma_{ij} = \begin{pmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{pmatrix} \tag{11}$$

The six stress states are.

$$\sigma_x = \frac{3P}{2\pi}\left[\frac{x^2 z}{R^5} + \frac{1-2\mu}{3}\left(\frac{R^2 - Rz - z^2}{R^3(R+z)}\right) - \frac{x^2(2R+z)}{R^3(R+z)^2}\right] \tag{12}$$

$$\sigma_y = \frac{3P}{2\pi}\left[\frac{y^2 z}{R^5} + \frac{1-2\mu}{3}\left(\frac{R^2 - Rz - z^2}{R^3(R+z)}\right) - \frac{y^2(2R+z)}{R^3(R+z)^2}\right] \tag{13}$$

$$\sigma_z = \frac{3Pz^3}{2\pi R^5} \tag{14}$$

$$\tau_{xy} = \tau_{yx} = -\frac{3P}{2\pi}\left[\frac{xyz}{R^5} - \frac{1-2\mu}{3} \cdot \frac{xy(2R+z)}{R^3(R+z)^2}\right] \tag{15}$$

$$\tau_{yz} = \tau_y = \frac{3P}{2\pi}\frac{yz^2}{R^5} \tag{16}$$

$$\tau_{xz} = \tau_x = \frac{3P}{2\pi}\frac{xz^2}{R^5} \tag{17}$$

The three displacement components are.

$$u = \frac{P(1+\mu)}{2\pi G}\left[\frac{xz}{R^3} - (1-2\mu)\frac{x}{R(R+z)}\right] \tag{18}$$

$$v = \frac{P(1+\mu)}{2\pi G}\left[\frac{yz}{R^3} - (1-2\mu)\frac{y}{R(R+z)}\right] \tag{19}$$

$$w = \frac{P(1+\mu)}{2\pi G}\left[\frac{z^2}{R^3} - 2(1-\mu)\frac{1}{R}\right] \tag{20}$$

Where P is the axial load, μ is the Poisson ratio, $\tau_{xy}, \tau_{yz}, \tau_{xz}$ are shear stress, and $\sigma_x, \sigma_y, \sigma_z$ are positive stress, $\sigma_z = \frac{3Pz^3}{2\pi R^5}$ is of great significance, the strength of σ_z determines the depth of the bit embedded in the rock formation and the degree of the rock deformation. It can be seen that as the axial load increases, the axial stress becomes larger and the shear depth increases.

Rock's compressive strength is the highest, shear strength is in the middle, and tensile strength is the lowest[27]. Therefore, the rock is mainly damaged by

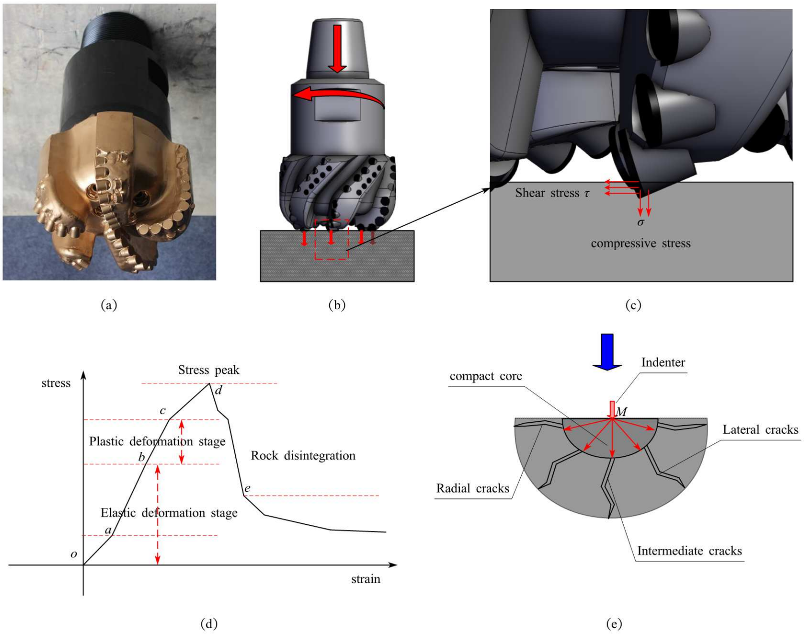

Fig. 2 The principle of rock breaking by the drill bit and the change of rock strength (a)the PDC drill bit (b)PDC drill bit model (c)Drill bit and rock action proess (d)Complete stress-strain curve of rock (e)Internal changes in the rock under normal stress

the shear force of the drill bit during the rock breaking process. The complete stress-strain curve of the rock from bearing the load to deformation damage is shown in Figure 2d. From the figure, it can be seen that there is a peak strength of the rock destruction process, and when the shear force cannot reach this peak, it is difficult to achieve the rock-breaking purpose. The WOB can reduce the rock strength to assist in rock-breaking. Under the action of the WOB of the drill bit, cracks are produced inside the rock and keep expanding. The number of small cracks is increasing. Small cracks join to form larger cracks, reducing the rock's strength. At this point, the rock is more likely to break under the shear action.

2.2 Rock failure principle

When a rock fails, it is related not only to the shear stress on the surface but also to the magnitude of the normal stress on the surface, according to the Coulomb-Navier criterion[28]. The damage to the rock is produced along the most unfavorable side of the combination of shear stress and normal stress. The principle expression of which is:

$$\tau = [\tau] + f(\sigma) \tag{21}$$

The conditions for the occurrence of stick-slip vibration in the drill column are derived using the Coulomb-Navier criterion:

$$\begin{cases} \tau_{MAX} \gg [\tau] & \text{No vibration} \\ \tau_{MAX} \approx [\tau] & \text{Vibration (Low amplitude)} \\ \tau_{MAX} \ll [\tau] & \text{Vibration (High amplitude)} \end{cases} \tag{22}$$

Where $[\tau]$ is the rock's shear yield strength, τ_{MAX} is the maximum shear stress at the drill bit. According to the Mohr rupture criterion, rock damage occurs along a face when the shear and positive stresses on that face satisfy a functional relationship[29], the principle expression of which is:

$$\tau = f(\sigma) \tag{23}$$

The functional relationship is difficult to get precisely because of the complex environment of drilling wells and the wide range of rock types.

The drill column has two motions throughout the drilling process: a linear movement along the axial direction and a rotational movement. The primary cause of stick-slip vibration is a change in the state of rotation. The rotational state of motion and thus the stick-slip vibration is affected by the axial state of motion. The equation of axial linear motion of the drilling column is.

$$\Delta d = v_{\text{asp}}\, t + kt^2 \frac{F_N - F_T}{m} = v_{\text{asp}}\, t + kt^2 \frac{A\sigma - F_T}{m} \tag{24}$$

Where F_N is the axial force of drilling column, F_T is the opposite acting force of rock, v_{asp} is the axial drilling speed. When the drill bit is drilling at a constant speed, there is no stick-slip vibration; as the drilling depth increases, more drill pipes are strung together, and the axial positive pressure increases. The depth of the drill bit embedded in the rock, which is the shear depth of the drill bit, increases at this point. The positive pressure applied to the drill correlates positively with the shear depth.

$$F_N \propto d \tag{25}$$

And the positive pressure exerted by the drill column is proportional to the number of accessed drill pipes.

$$F_N \propto l \tag{26}$$

As a result, as the drilling depth increases, so does the shear depth. The shear area grows. The relationship between shear stress and normal stress is as follows:

$$\tau = \frac{T}{S(d)} = \frac{T}{S\left(kt^2 \frac{A\sigma - F_T}{m}\right)} \tag{27}$$

$$\tau = f(t, d, Q, T) \tag{28}$$

Where Q is the rock factor, T is the bit torque, d is the shear depth, and t is the time of action. Shear stress is related to several variables in a non-linear relationship. When the bit torque is constant, the shear stress decreases as the drilling depth increases. The shear stress cannot quickly overcome the shear strength of the rock during the rotational shear breaking process, resulting in the phenomenon of the bit "sticking". Drill speed slows or even stops at this point. The deformation of the drill column increases when it is "sticking" and the elastic potential energy of the drill column is converted into torque at the drill bit. The expression for the synthesis of torque at the drill bit is as follows.

$$T = T_0 + |T| = T_0 + T(\Delta\theta) \tag{29}$$

Where $\Delta\theta$ is the deformation of the drill column, T_0 is the torque transferred from the motor, and $|T|$ is the additional torque generated by the deformation of the drill column. The elastic potential energy generated when the drill column is deformed produces an additional torque on the drill bit. The greater the deformation of the drill column, the greater the shear stress until it overcomes the shear strength of the rock. Subsequently, the rock is instantly damaged, the drill column resumes deformation, and the elastic potential energy is rapidly released as rotational kinetic energy at the drill bit, causing the drill bit to reach a high speed in an instant. A reverse angular velocity is produced because of inertia. At this point, the drill bit is "slipping" and the torque is rapidly reduced, resulting in a reduction in shear stress, until the next "sticky" state is reached. The "sticky-slip-sticky" state occurs repeatedly, and the drill column's deformation shows a periodic change of increasing-decreasing-increasing state, which is externally expressed as a periodic stick-slip vibration.

2.3 Influencing Factors

Based on the analysis of the above study, it can be concluded that there are three main factors for the occurrence of stick-slip vibration.

(1) The strength of the rocks varies from depth to depth. As the depth increases, the degree of weathering of the rock layer decreases, and the strength gradually increases. The rock layers with different degrees of weathering are as shown in Figure 3a below. The shear moments in the strongly weathered and moderately weathered layers cannot meet the strength of the rocks in the weak weathered layers. Therefore, stick-slip vibration occurs [30]. The strength variation of rocks in different weathering layers is shown in Table 1 below.

(2) As the drilling depth increases, the drilling pressure of the bit on the rock formation increases. According to the previous analysis, it is known that the shear depth of the drill bit increases and the shear area per unit time increases, leading to a decrease in shear stress, as shown in Figure 3b. The shear stress of the drill bit cannot overcome the yield strength of the rock quickly, resulting in a mismatch between the speed of the drill bit and the

Table 1 Strength of different weathered rock masses

Degree of weathering	Rock mass BQ	Cohesion (MPa)	Internal friction angle
Mw_s[1]	301-396	0.46-1.07	33.5-44.6
$Mw_a s$[2]	259-336	0.25-0.63	28.2-37.5
Mw_m[3]	231-321	0.18-0.56	25.2-35.9
W_w[4]	415-515	1.22-1.89	46.6-57.1

[1]Moderately weathered sandstone

[2]Moderately weathered siltstone

[3]Moderately weathered argillite

[4]Weak weathering

drive motor. The deformation of the drill column accumulates until it reaches the slippage state and stick-slip vibration occurs.

(3) At a constant drive torque T_D, the frictional area of the well wall increases as the drilling depth increases. The torque T_f used to overcome the frictional damping of the well wall increases, leading to a decrease in the output torque T_{out} of the drill bit, as shown in Figure 3c. The shear stress decreases and stick-slip vibration occurs.

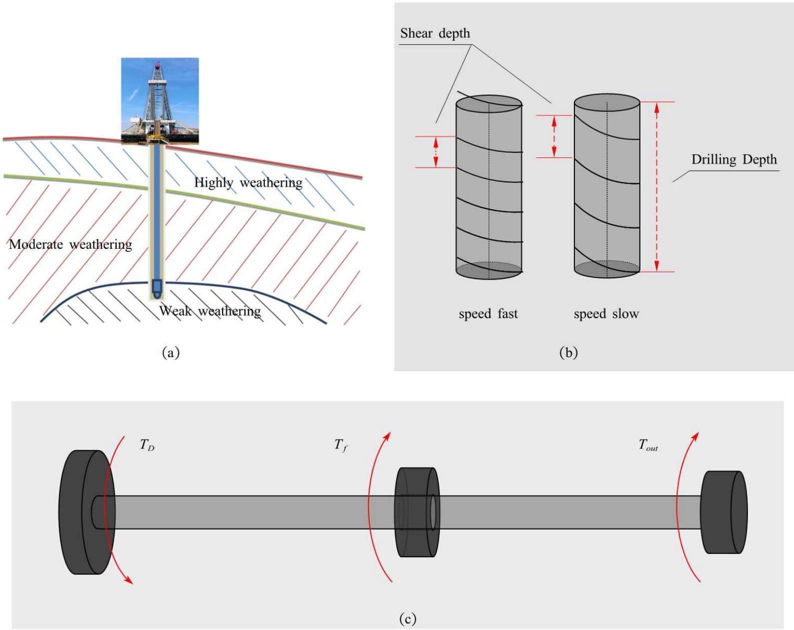

Fig. 3 Influencing factors(a)Structure diagram of weathering layer (b)Shear trajectory diagram (c)Torque distribution diagram

(4) The sticking state occurs before the peak rock strength is overcome and the slipping state occurs after the peak rock strength is overcome. According

to the complete stress-strain curve of rock damage, it can be seen that the rate of change of stress before the peak strength is smaller than the rate of change of stress in the rapid damage phase. From the energy point of view, the elastic potential energy accumulated in the sticking state is rapidly released into the kinetic energy of the drill bit in the rock destruction stage. The angular velocity of the drill bit increases at the moment of slipping, resulting in stick-slip vibration. And as the deeper the drilling the stronger the rock is. The greater the difference in the rate of stress changes between the sticking and slipping states. The vibration amplitude is more dramatic. Compared with sticking damping, the slipping moment has less damping. The drill bit can be regarded as being in an undamped state at the moment of slipping. This undamped state is the direct cause of the stick-slip vibration.

Based on the above analysis, the study of the suppression of stick-slip vibration can be carried out from the following two perspectives. One aims to reduce the shear yield strength of the rock. Breaking the internal structure of the rock through a compound impact drilling method to achieve rock breaking. The other aims to increase the maximum shear stress of the drill bit. Ensure that there is enough torque at the drill bit, which can easily overcome the yield strength of the rock to achieve the purpose of rock breaking. For the above analysis, three control strategies are proposed to suppress the stick-slip vibration.

(1) Adjustment of rotational speed: the faster the rotational speed, the smaller the depth of shear per unit time, the greater the shear stress, and its shear schematic diagram is shown in Figure 3b. Therefore, there exists a critical speed at which stick-slip vibration does not occur, and when the speed is lower than the critical speed, the more severe the vibration is as the speed increases. When the speed is greater than the critical speed, the smaller the vibration amplitude is as the speed increases [31-32].

$$\begin{cases} |A| > 0, \dot{A} < 0 \ \dot{\theta} \geq [\dot{\theta}] \\ |A| > 0, \dot{A} > 0 \ \dot{\theta} < [\dot{\theta}] \end{cases} \tag{30}$$

Where $|A|$ is the stick-slip vibration amplitude, $[\dot{\theta}]$ is the critical angular velocity.

(2) Increase torque: control the motor output torque to increase. Ensure that the drill bit torque can overcome the rock strength and the mismatch between the drill bit and the drive motor speed is reduced. At this time, the drill column will not undergo large deformation, avoiding the instantaneous release of elastic potential energy that causes the drill bit to slip off.

(3) Controlled WOB: By controlling the weight on the bit, it can ensure that the shear depth of the drill bit will not increase due to the increase in the self-weight of the drill column. Ensure that the shear stress will not be affected by the change of shear depth. Thus, the stick-slip vibration can be suppressed to a certain extent.

3 Analysis of Drill column Torque Transmission System

Domestic and foreign scholars have established many torque transfer models for the drilling column system. At present, it mainly divided them into two types: one is an integrated parametric model, which equates the whole drilling column system as a mass-spring-damper system; the other is a distributed model, which characterizes the drilling column system by continuous partial differential equations. In this paper, to better study the structural changes of the drill column system when deformation occurs, a single drill pipe is equated to an extra-long torsion spring, as shown in Figure 4a below.

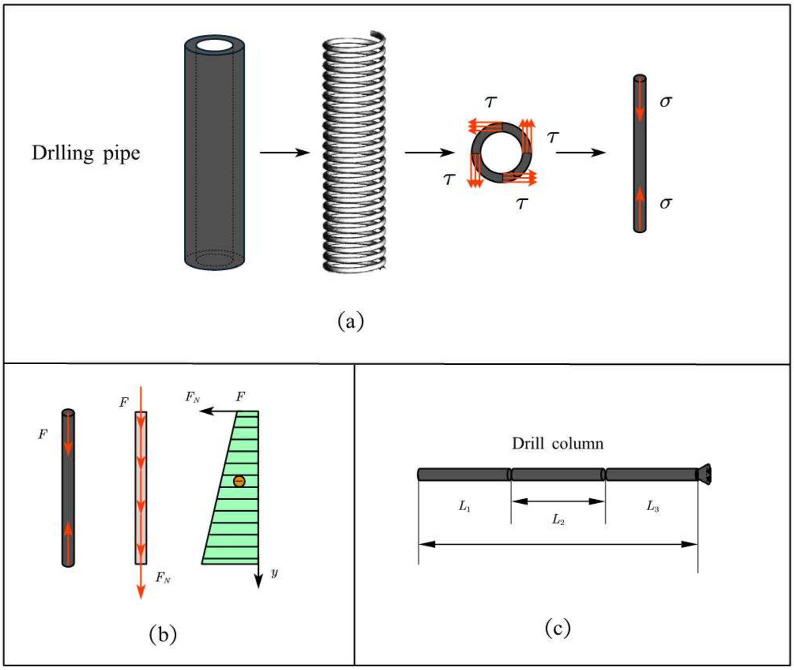

Fig. 4 (a)Equivalent schematic of drill column (b)Axial force diagram (c)Drill column division diagram

The shear force direction is always along the tangential direction of the drill pipe arc. The shear force transmitted by system can be equated to the axial force applied to a single straight shaft. Therefore, the effect of stick-slip vibration on the drill column can be equated to the effect of a single straight shaft under the vibration axial force. The maximum compressive stress that the equivalent straight shaft can withstand is the maximum rock-breaking shear stress transmitted by the drilling column.

$$[\tau] \approx [\sigma] = \begin{cases} \sigma_s/n_s & \text{Plastic materials} \\ \sigma_b/n_b & \text{Brittle materials} \end{cases} \tag{31}$$

Among them n_s, n_b is the safety constant. Figure 4b showed the axial force diagram of the straight shaft. As the length of the straight shaft increases, the internal force will also increase. Under the condition of transmitting the same torque, the internal force of different positions of the drill string is different. The strength conditions are as follows:

$$\sigma_{\max} = \frac{F_{N\max}}{A} = \frac{F}{A} + \gamma l < [\sigma] \tag{32}$$

Where l is the equivalent length, γ is the unit weight, related to the material of the drill pipe, A is the cross-sectional area, which is related to the inner diameter, outer diameter, and wall thickness of the drill pipe.

The longer the drill column, the greater the internal force on the bottommost drill pipe, the positive pressure is also greater. The corresponding deformation will be greater, and even plastic deformation will occur. The amplitude of stick-slip vibration will also increase, and the system will easily lose balance. To verify this conclusion, the whole drilling column system is divided into three parts, as shown in Figure 4c. The variation amplitude intensity of each part under the applied load is shown in Fig. 5-6.

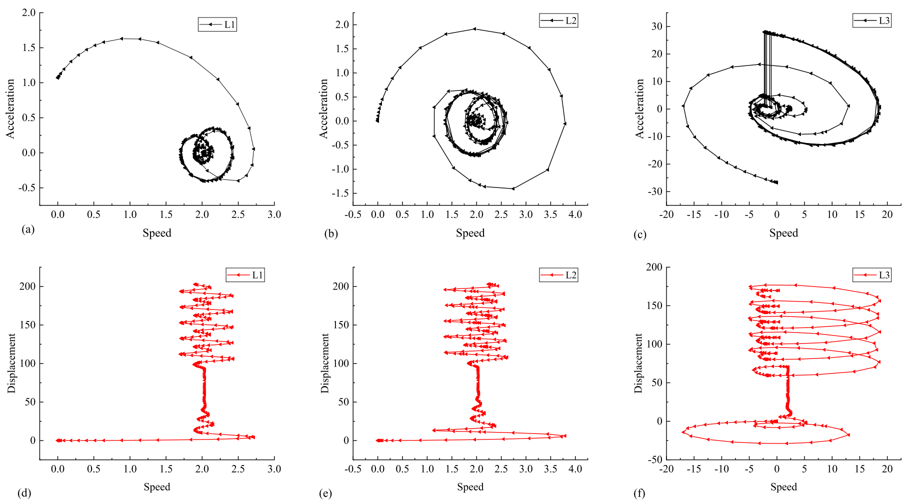

Fig. 5 Acceleration-speed curves of L1(a) L2(b) L3(c),Displacement-speed curves of L1(d) L2(e) L3(f)

It can be seen that the L3 part is undergoes the largest fluctuations in torque and velocity changes and the most violent vibration amplitude when

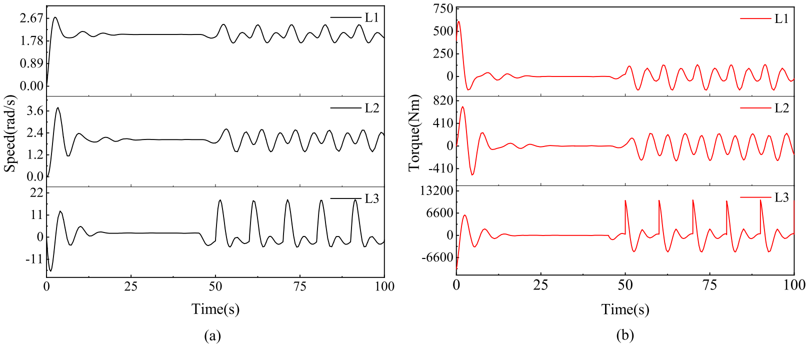

Fig. 6 (a)L1 L2 L3 speed curves (b)L1 L2 L3 torque curves

stick-slip vibration occurs. Here, the drill bit and drill pipe are most easily plastic deformed and damaged.

The drill column is mainly composed of multiple drill pipes and drill collars. The proportion of drill collars within the whole drill column length is little. The material density, inner and outer diameter and wall thickness of the drill collar are much larger than those of the drill pipe. Therefore, the deformation of the drill collar during stick-slip vibration is much smaller than that of the drill pipe. Table 2 is the API drill pipe specification table, and Table 3 is the API drill collar specification table.

Table 2 API drill pipes specification

Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)	Linear density (kg/m)
114.3	100.53	6.88	18.23
114.3	97.18	8.56	22.31
114.3	92.48	10.92	27.84
127	111.96	7.52	22.15
127	108.62	9.19	26.71
127	108.62	9.19	26.71
127	101.6	12.70	35.79
127	101.6	12.70	35.79
139.7	121.36	9.17	29.51
139.7	118.62	10.54	33.57
168.3	151.54	8.38	33.05
168.3	149.92	9.19	36.06

Source:https://www.api.org/products-and-services/standards/important-standards-announcements

The wall thickness of the drill pipe is about 6-13mm and the linear density is about 18-36kg/m, that is far smaller than the wall thickness of drill collar 47-102mm and linear density 123-446 kg/m. The main function of the drill collar is to stabilize the drill bit and provide drilling pressure. With stick-slip vibration, the deformation of the drill collar relative to the drill pipe can be neglected, but because of its big quality, the moment of inertia of the drill collar

Table 3 API drill collar specifications

Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)	Linear density (kg/m)
152.4	57.2	47.6	123.7
158.8	57.2	50.8	135.6
177.8	71.4	53.2	163.9
203.2	71.4	65.9	223.5
228.6	71.4	78.6	290.6
254.0	76.2	88.9	362.0
279.4	76.2	101.6	445.5

Source:https://www.api.org/products-and-services/standards/important-standards-announcements

during rotation is cannot negligible. The cross-sectional torsional rigidity and wall thickness of the drill pipe and drill collar are shown in Figure 7 below.

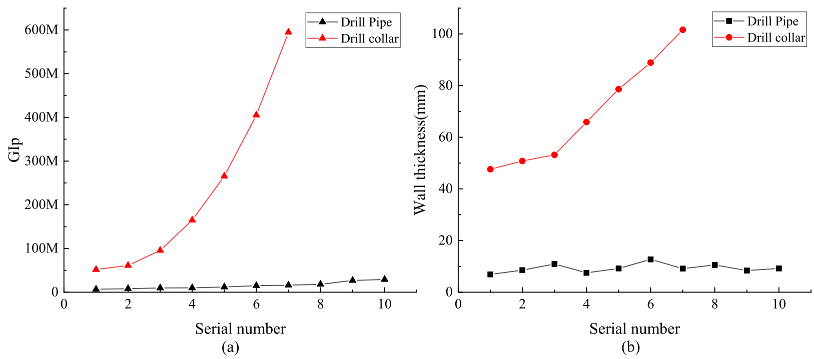

Fig. 7 (a)Torsional rigidity of cross-section (b) Wall thickness of drill pipe and drill collar

From the above analysis, it can be seen that the drill collar and the upper part of the drill column are less affected when stick-slip vibration occurs. The most easily damaged position is at the bottom drill column and drill bit. Therefore, stick-slip vibration can cause damage and dislodgement of the bottom drill pipe and drill bit, which has a great impact on the actual engineering operation.

4 Torsional damper design and simulation experiment

4.1 Torsional Damping Damper design

During the drilling operation, motors generate torque that is transmitted to the drill bit through the drill pipe and collar. Similarly, the action of the rock on the drill bit transmits to the drill pipe through the collar, thus affecting the drill bit and the drill pipe. The drill collar between the drill pipe and the drill bit is less affected by the stick-slip vibration because of its large wall thickness and short length, not considering its deformation. For the general active control to suppress stick-slip vibration, the lag time of the whole control system needs to be considered. As the drilling depth increases, the lag time will be larger, which requires the active control to be highly adaptive. In this paper, based on the analysis of stick-slip vibration mechanism, a torsional tuned mass damper is proposed in principle, as shown in Figure 8.

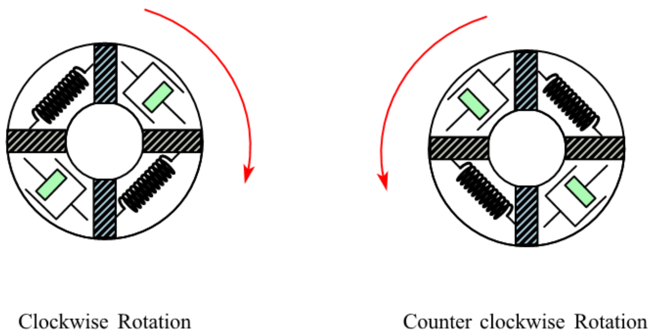

Fig. 8 Schematic diagram of Torsional Tuned Mass Dampers structure

When stick-slip vibration occurs, the spring element undergoes different degrees of deformation, which can replace the deformation of the drill column and protect the drill column. In the sticking state, as the rock load increases, the deformation of the spring increases and the corresponding elastic potential energy increases, which compensates the rock-breaking torque of the drill bit and plays the role of regulating the torque. At the moment of slipping, the damper comes into play and generates a damping force to prevent the momentary kinetic energy conversion rate being too large. The damper absorbed the elastic potential energy released by the spring and converted into internal energy. Therefore, the kinetic energy when the drill bit slips off is reduced, and the stick-slip vibration is suppressed.

4.1.1 Model simulation and result analysis

Simulated the interaction between the load and the drill bit through direct coupling with the two motors. The experimental equipment is shown in Figure 9.

Motor A simulates the output speed and torque of the drill bit; motor B simulates the rock load. The direct coupling of the two motors, A and B, simulates the drill bit insertion into the rock formation. By changing the load torques, it can simulate the stick-slip vibration of the drill bit and measure the vibration speed and torque. Adjusting different load torques can better simulate the running process of the drill bit in different rock formations.

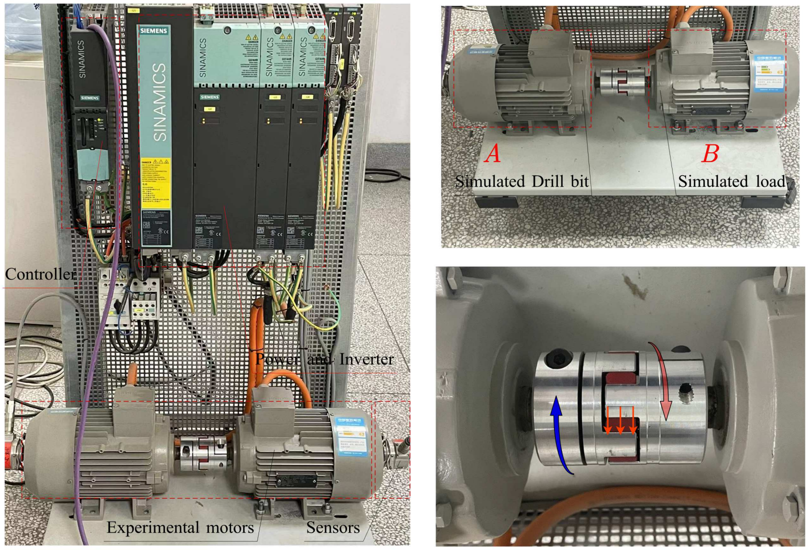

Fig. 9 Simulation experimental equipments

Oil drilling speed is about 120 r/min=2 rad/s. When stick-slip vibration occurs, the slipping speed can reach 330 r/min=5.5 rad/s, which is 2 times or even higher than the normal speed. Its torque fluctuation is about 13.0-27.0kNm. The data on different drilling platforms may be different. In the simulation experiment, the set speed is 120 r/min. Because the power of the experimental motor is small, and ensures the safety of the experimental equipment, reducing the experimental torque. the simulated stick-slip vibration curves as shown in Figure 10-13.

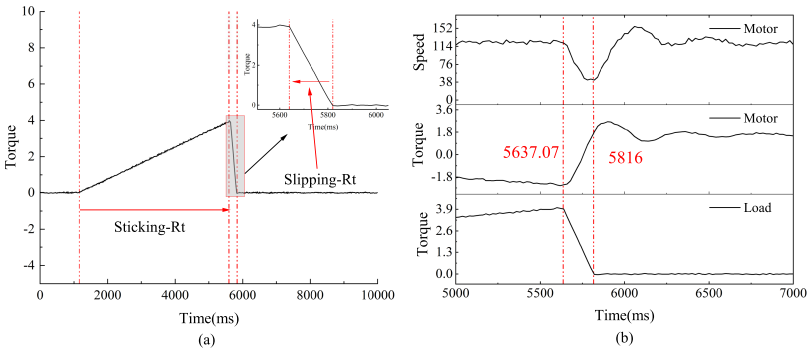

Fig. 10 (a)Simulation of rock damage loads (b)Single stick-slip vibration speed-torque curve

Setting different torque change rates, the load damping changes of the drill bit in sticking and slipping states can be simulated, respectively. Sticking-Rt indicates the sticking change rate and Slipping-Rt indicates the slipping

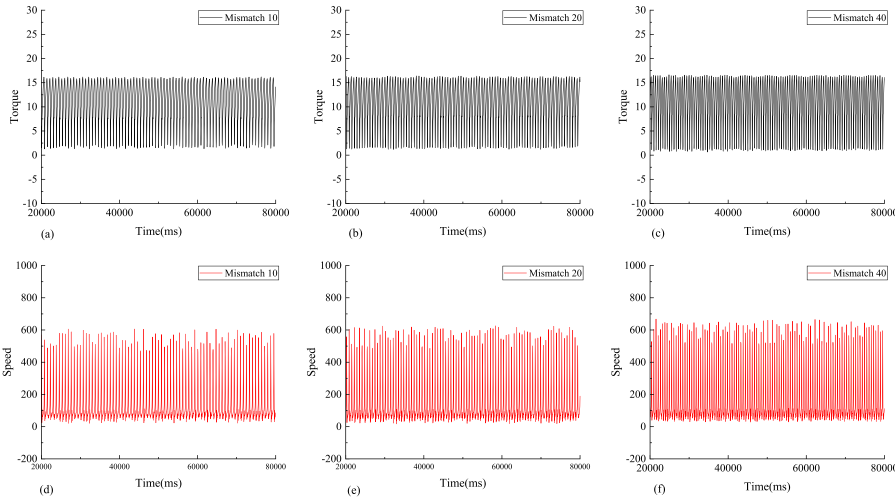

Fig. 11 Stick-slip vibration Torque variation curves: Mismatch 10(a) Mismatch 20(b)Mismatch 40(c), Speed variation curves: Mismatch 10(d) Mismatch 20(e) Mismatch 40(f)

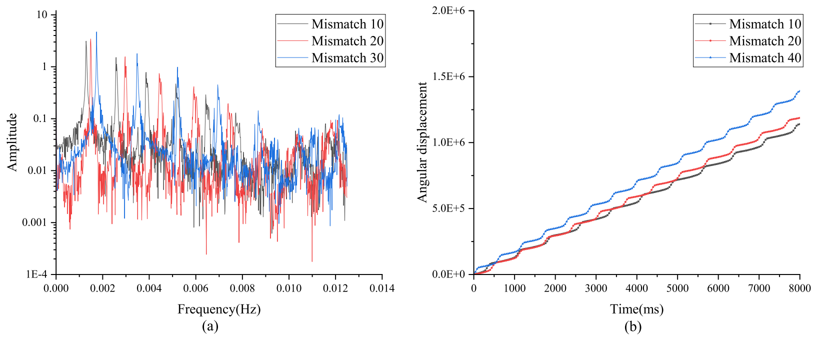

Fig. 12 (a)Amplitude and frequency characteristics curves (b)Angular displacement curves

change rate in Figure 10(a). In the sticking state of the bit, the load torque gradually increases. The rate of load torque change is relatively small. After the drill bit torque reaches the rock yield strength, the rock breaks in a very short time. And the torque change rate at the slipping moment is the largest. The drill bit is almost undamped at the slipping moment. The results of three experiments under different conditions are as shown in Figures 11-12. The vibration intensity and frequency change as the conditions change, which shows that stick-slip vibration is not a fixed frequency vibration, but changes with the change of load intensity.

Figure 10(b) shows the curves of load torque, drill torque, and speed variation. It can be seen from the graph that there is a certain lag in the drill bit torque relative to the load torque change. The function of the torsional damper is to produce an additional damping effect on the drill bit at the moment of

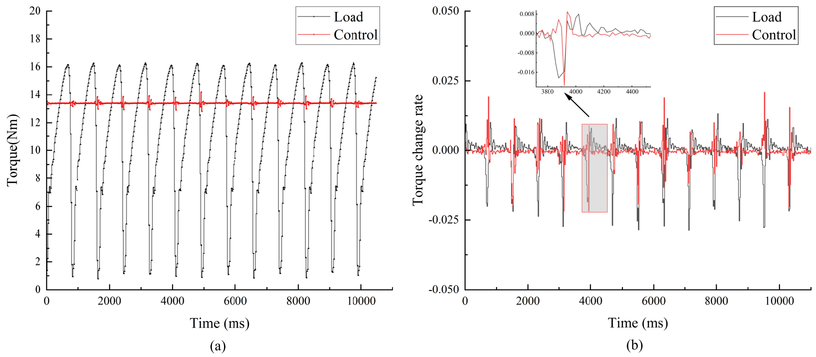

Fig. 13 (a)Stick-slip vibration torque curves(b) Stick-slip vibration torque variation rate curves

rock breaking. Through the damping effect of the damper, the slippage of the drill bit is suppressed and the undamped state at the moment of rock crushing is compensated. The following Figs. 14-15 simulate the change curves of speed and torque at the drill bit under different torque change rates of soft torque control, respectively.

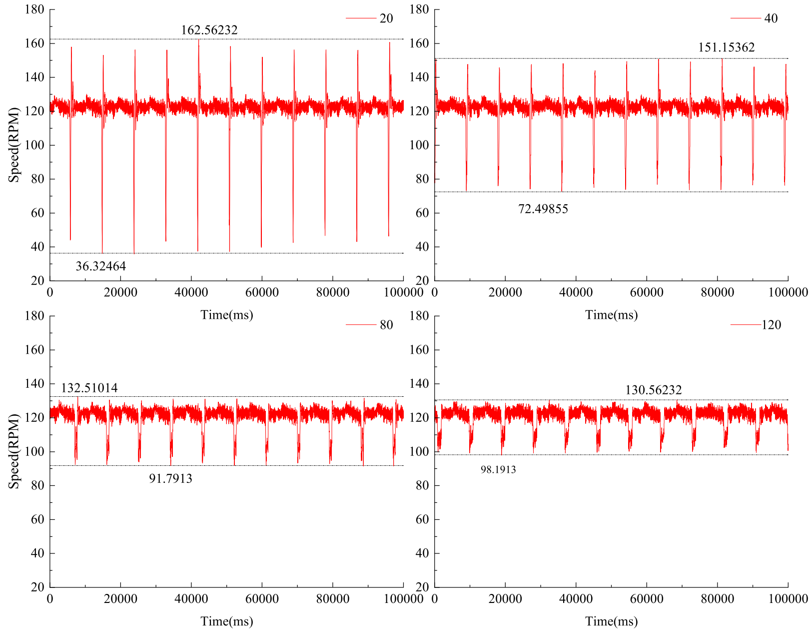

Fig. 14 Speed variation curves. The damage time is 20ms, 40ms, 80ms, and 120ms respectively

As seen in Figure 14-15, with the addition of soft torque control, the motor output torque increases as the load increases during the sticking process, and

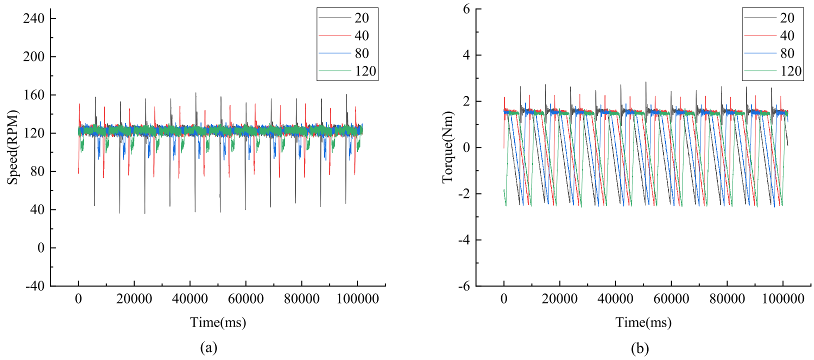

Fig. 15 (a)Vibration speed change comparison curves (b)Vibration torque change comparison curves

the speed of the drill bit is stable. In the slipping state, the smaller the damping force on the drill bit at the moment of slipping, the greater the fluctuation of the drill speed. The soft torque control method does not directly and effectively change this slipping state. The slipping instant state is only related to the rock strength and action damping force. Therefore, applying a damping effect to the drill bit can theoretically suppress the problem of excessive energy at the slipping moment. A reasonably designed torsional damper can reduce the stick-slip vibration of the drill bit, while effectively protecting the drill column and drill bit.

5 Conclusion

This paper studies the vibration mechanism of stick-slip vibration in the bit and analyzes qualitatively the various influencing factors of stick-slip vibration. Summarized the indirect and direct causes of stick-slip vibration and the general methods to suppress stick-slip vibration. The torsional vibration damper is proposed in principle according to the vibration characteristics. And the effect of the drill bit embedded in the rock is simulated by the direct coupling experiment of the dual motors. The simulated fluctuation curves of torque and speed of stick-slip vibration are obtained, and the following conclusions are obtained.

1. The indirect causes of stick-slip vibration from the operation condition analysis are with the increase of drilling depth, the drilling pressure increases leading to an increase in shear depth. The rock yield strength increases because of the reduced weathering of the rock formation. And the effective shear torque decreases due to the increase in friction area of the well wall. The direct cause of stick-slip vibration from the vibration mechanism analysis is that the drill pipes deformation in the sticking state accumulates huge torque, and the drill bit becomes "undamped" at the moment of slipping so that the energy in the sticking state is quickly converted into kinetic energy and stick-slip vibration occurs.

2. Three methods of suppressing stick-slip vibration are summarized. Through the compound impact drilling method to destroy the internal structure of the rock and reduce the yield strength to achieve the aim of rock breaking. By soft torque control method, increase the output torque to ensure that the bit can overcome the rock yield strength to achieve the aim of rock breaking. By controlling the drilling parameters to reduce the separation of the effective output torque with the change of well depth, the ineffective torque and shear stress loss at the drill bit is reduced to achieve the aim of rock breaking.

3. The equivalent axial force model is established to find out the location of the dangerous section where the stick-slip vibration occurs in the bit. The design of a torsional damper at the location of the dangerous section and the introduction of the damping effect to improve the undamped state of the drill can theoretically solve the vibration effects caused by the excessive rate of change of torque in the slipping state and suppress the stick-slip vibration.

Future work will design a torsional tuned mass damper by adding a rigid spring and a damper to match the drill collar characteristics. Absorb vibration energy at the vibration source location. Suppress stick-slip vibration, effectively protect drilling equipment and improve drilling efficiency.

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Declarations

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- The authors have no relevant financial or non-financial interests to disclose.
- The datasets generated during the current study are available in the [American Petroleum Institute(API)]repository,[https://www.api.org/products-and-services/standards/important-standards-announcements]
- All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Guangwu Chen], [Peng Li] and [Kexin An]. The first draft of the manuscript was written by [Dejun Ba].Experimental equipment provided and directed by [Xiaobao Liu] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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