ANALYSIS ON THE DYNAMIC CHARACTERISTICS OF STICK-SLIP VIBRATION IN DEEP WELL DRILL STRING SYSTEM

by

Long WANG [a]***, Zhengbo HAN*** [a]***, Jinduo WANG*** [b, *]***, Liurui GUO*** [b]***, Rui LI*** [b]

[a] Petroleum Engineering Technology Research Institute of Sinopec Northwest Oilfield Company, Urumqi, 830011, China
[b] MOE Key Laboratory of Petroleum Engineering, China University of Petroleum (Beijing), Beijing, 102249, China

In this paper, based on the nonlinear mechanics theory of the drill pipe, a mechanical model of stick-slip vibration of the drill pipe has been established by considering the torsional properties of the drill pipe, kinetic energy and the motion law of the bit. The example calculations and sensitivity analysis of the parameters are carried out. The results show that increasing the rotational speed, viscous damping, length of the drill collar and de-creasing the weight of bit (WOB) have the effect of suppressing the stick-slip vibration.
Key words: *Deep well drilling, Drill string system, Stick-slip vibration, Viscosity reduction efficiency*

Introduction

During the drilling process of deep and ultra-deep wells, with the in-crease of formation depth, the geological conditions become more complicated and the drilling process faces more challenges. In addition, with the increase of drill string length, the equivalent torque stiffness of drill string decreases and the transfer torque is insufficient. Under the friction between drill string, drill bit, wellbore and bottom hole, the drill string system is prone to produce axial, transverse and torsional coupling vibration [1]. Among them, stick-slip vibration caused by torsional vibration is the most serious one, which is the main reason for the decline of drilling quality and the failure of drilling tools [2].The stick-slip vibration widely exists in the drilling process of deep wells, which not only affects the drilling cost and completion cycle, but also accelerates the fatigue failure of the drilling tools, and seriously threatens the drilling safety [3]. The study of the stick-slip vibration characteristics of the drill pipe is of great significance to improve the drilling efficiency of deep oil and gas resources.

Scholars noticed the "stick slip" phenomenon of the drill string during the drilling procedure of extended-reach wells. Richard, *et al.* [4] believe that the viscous vibration of drill string is a kind of self-excited vibration which is caused by the interaction between drill string and wellbore as well as between drill bit and formation. Jia, *et al.* [5] explained the basic principle of stick-slip vibration based on the rock breaking mechanism, and studied the

[*] Corresponding author; e-mail: wjd9412@163.com

influence of the interaction between bit and rock on the stick-slip vibration of the bit. Domestic research on stick-slip vibration of drill string started late. In 2001, analyzed the stability of the drill string system under the bit torque and frictional torque between the drill string and the wellbore, and gave the rea-sons of the stick-slip vibration of the drill string. Zhu, *et al.* [6] studied the stick-slip vibration characteristics of bit in deep formation and the motion law of drill bits by establishing the torsional pendulum model of drill string with concentrated mass. Ma, *et al.* [7] designed a test platform to explore the effects of parameters such as rotational speed, frictional resistance and drill string length on stick-slip vibration, which has certain reference significance for controlling drill string stick-slip vibration. Liu, *et al.* [8, 9] studied the stick-slip vibration characteristics of drill string system under different drilling parameters based on the axial and torsional coupled vibration model of drill string. The results showed that the influence of drill string stick-slip and bit runout could be minimized and the ROP could be in-creased by selecting appropriate parameters.

In this paper, based on the nonlinear mechanics theory of drill string, a mechanical model of stick-slip vibration of drill string has been established by considering the torsional mechanical properties of drill string, kinetic energy and the motion law of the bit. The influence law of the stick-slip vibration characteristics of the deep well drill string has been revealed.

Mechanical model

The drill string system is a complex system composed of multiple components, and it is very difficult to establish a complete dynamic model of the drill string. In this paper, in order to facilitate the study, the drill string system is simplified into a four-degree-of-freedom model, and the dynamic model is established for the rotating rotary table, drill pipe, bottom hole assembly (BHA) and bit, respectively. In order to simplify the model reasonably, the mechanical model of drill string system contains the assumptions as follows. The drill string system is in a vertical well. The lateral vibration and axial vibration of the drill pipe is not considered. The effect of frictional resistance between the drill pipe and the well wall on the drilling process is not considered. The influence of drilling fluid on the drill string is not considered. Neglect the change of strength of downhole rock.

According to the above five assumptions, the simplified model of the dynamics of the drill string system is shown in Figure 1.

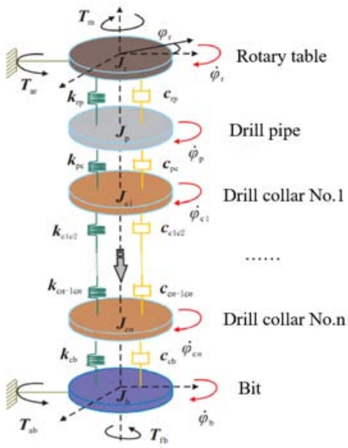


Fig. 1. Simplified model of drill string system.

In the simplified model of the drill string, the rotary table, drill pipe, BHA and bit are connected by linear springs with torsional stiffness and torsional damping. During the drilling process, the drive system drives the rotary table to rotate, and the rotary table drives the square drill pipe to rotate the BHA, which in turn drives the bit to rotate to break up the rock and drill into the well. From the simplified model of the drill string system in Figure 1, the governing equations of the drill string system can be obtained as follows:

$$\begin{cases} J_r \ddot{\varphi}_r + c_{rp}(\dot{\varphi}_r - \dot{\varphi}_p) + k_{rp}(\varphi_r - \varphi_p) = T_m - T_{ar} \\ J_p \ddot{\varphi}_p + c_{pc}(\dot{\varphi}_p - \dot{\varphi}_c) + k_{pc}(\varphi_p - \varphi_c) - c_{rp}(\dot{\varphi}_r - \dot{\varphi}_p) - k_{rp}(\varphi_r - \varphi_p) = 0 \\ J_p \ddot{\varphi}_c + c_{cb}(\dot{\varphi}_c - \dot{\varphi}_b) + k_{cb}(\varphi_c - \varphi_b) - c_{pc}(\dot{\varphi}_p - \dot{\varphi}_{pc}) - k_{pc}(\varphi_p - \varphi_c) = 0 \\ J_b \ddot{\varphi}_b + c_{cb}(\dot{\varphi}_c - \dot{\varphi}_b) + k_{cb}(\varphi_c - \varphi_b) = T_{ab} - T_{fb} \end{cases} \quad (1)$$

where J_r, J_p, J_c, and J_b are the equivalent moment of inertia of the rotary table, drill pipe, drill collar and bit, respectively. k_{rp}, k_{pc}, and k_{cb} are the equivalent torsional stiffnesses of the springs connected to the neighboring drill pipes, respectively. c_{rp}, c_{pc}, and c_{cb} are the equivalent damping of the springs connected to the neighboring drill pipes, respectively. T_m is the torque of the rotary table; φ_{r}, φ_p, φ_{c}, and φ_{b} are the rotation angles at the rotary table, the drill pipe micro-element section, the drill collar micro-element section, and the bit, respectively. $\dot{\varphi}_{\mathrm{r}}$, $\dot{\varphi}_p$, $\dot{\varphi}_{\mathrm{c}}$, and $\dot{\varphi}_{\mathrm{b}}$ are the angular velocities at the rotary table, the drill pipe micro-element section, the drill collar micro-element section, and the bit, respectively. $\ddot{\varphi}_{\mathrm{r}}$, $\ddot{\varphi}_p$, $\ddot{\varphi}_{\mathrm{c}}$, and $\ddot{\varphi}_{\mathrm{b}}$ are the angular accelerations at the rotary table, the drill pipe micro-element section, the drill collar micro-element section, and the bit, respectively.

The frictional torque at the rotary table T_{ar} can be expressed as:

$$T_{\mathrm{ar}} = c_{\mathrm{r}}\dot{\varphi}_{\mathrm{r}} \quad (2)$$

where c_{r} is the viscous damping coefficient of the rotary table.

The viscous friction moment T_{ab} at the bit can be given as:

$$T_{\mathrm{ab}} = c_{\mathrm{b}}\dot{\varphi}_{\mathrm{b}} \quad (3)$$

where c_{b} is the viscous damping coefficient of the bit.

Considering the different static and dynamic friction torque between the bit and the formation, combining the Karnopp friction model and the Stribeck curve to express the dynamic friction torque in the process of rock breaking of the bit, we can get the expression of friction torque $T_{fb}(\mathbf{x})$ between the drill bit and the formation as follows:

$$T_{fb}(\mathbf{x}) = \begin{cases} T_{eb}(\mathbf{x}) & \text{if } |\dot{\varphi}_{\mathrm{b}}| < D_v, |T_{eb}| \le T_{sb} \\ T_{sb}\,\mathrm{sgn}(T_{eb}(\mathbf{x})) & \text{if } |\dot{\varphi}_{\mathrm{b}}| < D_v, |T_{eb}| > T_{sb} \\ W_{ob} R_{\mathrm{b}} \mu_b(\dot{\varphi}_{\mathrm{b}})\,\mathrm{sgn}(\dot{\varphi}_{\mathrm{b}}) & \text{if } |\dot{\varphi}_{\mathrm{b}}| \ge D_v \end{cases} \quad (4)$$

where T_{sb} is the maximum static friction torque, $T_{\mathrm{eb}}(\mathbf{x})$ is the torque accumulated by the drill string due to torsion driven by the rotary table when the bit sticks, D_v is the critical rotational speed between dynamic friction and static friction of the bit, W_{ob} is the weight of bit, R_b is the radius of the bit, and $\mu_b(\dot{\varphi}_{\mathrm{b}})$ is the dry friction coefficient.

Here, T_{sb} can be given by

$$T_{\mathrm{sb}} = R_{\mathrm{b}} W_{\mathrm{ob}} \mu_{\mathrm{sb}} \quad (5)$$

Here, $\mu_{\mathrm{b}}\left(\dot{\varphi}_{\mathrm{b}}\right)$ can be expressed as:

$$\mu_{\mathrm{b}}\left(\dot{\varphi}_{\mathrm{b}}\right)=\mu_{\mathrm{cb}}+\left(\mu_{\mathrm{sb}}-\mu_{\mathrm{cb}}\right)\mathrm{e}^{-\gamma_{\mathrm{b}}\dot{\varphi}_{\mathrm{b}}} \tag{6}$$

When the torque is larger than the maximum static friction torque, $T_{\mathrm{eb}}\left(\mathbf{x}\right)$ can be expressed as

$$T_{\mathrm{eb}}\left(\mathbf{x}\right)=c_{\mathrm{cb}}\left(\dot{\varphi}_{\mathrm{cn}}-\dot{\varphi}_{\mathrm{b}}\right)+k_{\mathrm{cb}}\left(\varphi_{\mathrm{cn}}-\varphi_{\mathrm{b}}\right)-T_{\mathrm{ab}}\left(\dot{\varphi}_{\mathrm{b}}\right) \tag{7}$$

Here,

$$\operatorname{sgn}\left(T_{\mathrm{eb}}\left(\mathbf{x}\right)\right)=\begin{cases}1 & T_{\mathrm{eb}}\left(\mathbf{x}\right)>0\\ 0 & T_{\mathrm{eb}}\left(\mathbf{x}\right)=0\\ -1 & T_{\mathrm{eb}}\left(\mathbf{x}\right)<0\end{cases} \quad \text{and} \quad \operatorname{sgn}\left(\dot{\varphi}_{\mathrm{b}}\right)=\begin{cases}1 & \dot{\varphi}_{\mathrm{b}}>0\\ 0 & \dot{\varphi}_{\mathrm{b}}=0\\ -1 & \dot{\varphi}_{\mathrm{b}}<0\end{cases} \tag{8}$$

During the drilling process, in order to make the rotary table rotate at a stable speed, the driving torque of the rotary table should be adjusted according to the real-time speed of the rotary table and the bit. There are classical PID control and linear robust control, etc., but simple reduced order closed-loop control is often used to control rotary speed in drilling string system of oil and gas wells.

The closed-loop governing equation of rotary speed can be expressed as:

$$T_{\mathrm{m}}=K_1\left(\omega_{\mathrm{d}}-\dot{\varphi}_{\mathrm{r}}\right)+K_2\int\left(\omega_{\mathrm{d}}-\dot{\varphi}_{\mathrm{r}}\right)dt-K_3\left(\dot{\varphi}_{\mathrm{r}}-\dot{\varphi}_{\mathrm{b}}\right) \tag{9}$$

where ω_d is the rotational speed of the rotary table, K_1 K_2 K_3 are the gain coefficients of the control system.

Case Study and Parameter Sensitivity Analysis

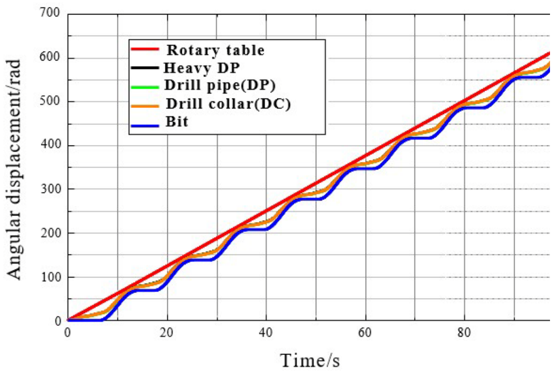
Case Study

A deep well is selected for example calculation, and the basic parameters of the drill string system are shown in Table 1.

Table 1. Basic operating parameters

Well depth	Drill pipe length(DP)	Heavy DP length	Drill collar length	Drill pipe external diameter
2841m	2609m	135m	97m	139.7mm
Drill pipe internal diameter	Heavy DP external diameter	Heavy DP internal diameter	Drill collar external diameter	Drill collar internal diameter
118.6mm	139.7mm	76.2mm	203.2mm	71.45mm
Radius of bit	Rotational speed	WOB	Coefficient of static friction	Coefficient of kinetic friction
203.2mm	80r/min	80000N	0.8	0.5

As shown in Figs. 2 and 3, when the rotary table is moving at the initial rotational speed, there is stick-slip vibration below the rotary table. Although the rotary table moves well, the drill pipes, heavy drill pipes, and drill collars have the tendency of stick-slip vibration, and the bit has completely occurred stick-slip vibration. From the angular displacement curve, it can be clearly seen that the rotary table curve is relatively smooth, with a linear trend of increase, and the angular velocity does not appear 0, indicating that the rotary table does not have a stick-slip vibration phenomenon similar to that of the drill bit. Combined with the curves of angular displacement and angular velocity, stick-slip vibration has occurred at the bit.



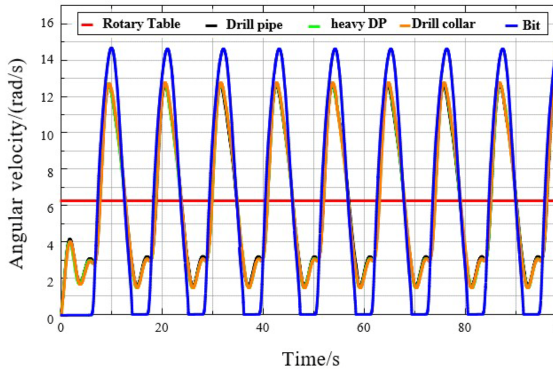


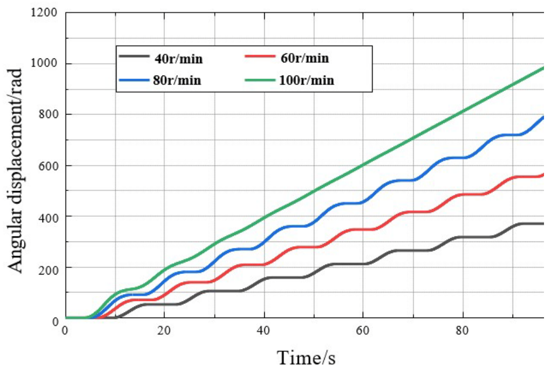
Figure 2. Changes of angular displacement of each component of drill string

Figure 3. Changes of angular velocity of each component of drill string

Parameter sensitivity analysis

Rotational speed of rotary table

When the rotational speed of the rotary table are 40r/min, 60r/min, 80r/min and 100r/min respectively, the motion of the bit is shown in Figure 4 and Figure 5.



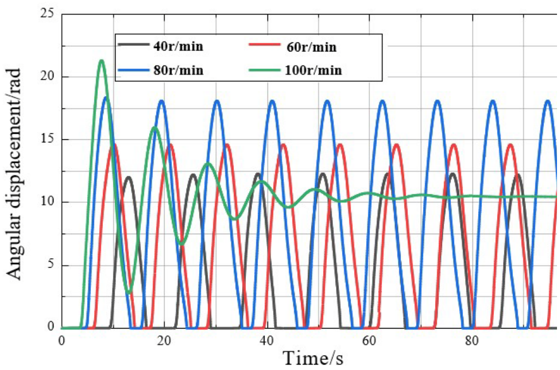


Figure 4. Change of bit angular displacement under different rotational speed

Figure 5. Change of bit angular velocity under different rotational speed

As shown in Figs. 4 and 5, the smaller the rotational speed is, the longer stick-slip period of the bit is, the longer the stick-slip time is, and the fluctuation amplitude of the angular velocity of the bit is smaller. With the increase of rotational speed, the angular velocity of the bit increases and the sticking time is shortened. When the rotational speed reaches 100r/min, the bit has no stick-slip vibration phenomenon, which indicates that increasing the rotational speed is beneficial to inhibit the occurrence of stick-slip vibration.

WOB

When the WOB are 60KN, 80KN, 100KN and 120KN, respectively, the motion of the bit is shown in Figure 6 and Figure 7.

As shown in Figs. 6 and 7, when the WOB is larger than 80kN, the bit exhibits stick-slip vibration phenomenon. With the reduction of WOB, the stick-slip vibration phenomenon of the bit disappears, and the smaller the WOB, the shorter the sticking period is. When the WOB exceeds a certain value, the bit appears obvious jamming phenomenon, and the larger the WOB, the longer the jamming period is, which shows that the reduction of the WOB can inhibit the stick-slip vibration.

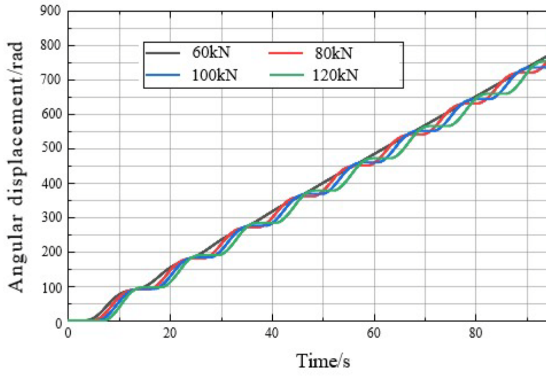


Figure 6. Change of bit angular displacement under different bit pressure

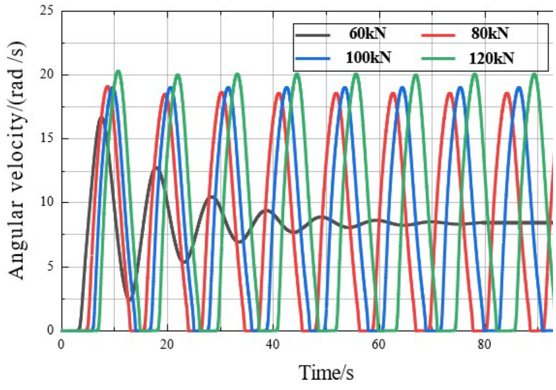


Figure 7. Change of bit angular velocity under different bit pressure

Length of drill collar

When the length of drill collar are 100m, 200m, 300m and 400m, respectively, the motion of the bit is shown in Figure 8 and Figure 9.

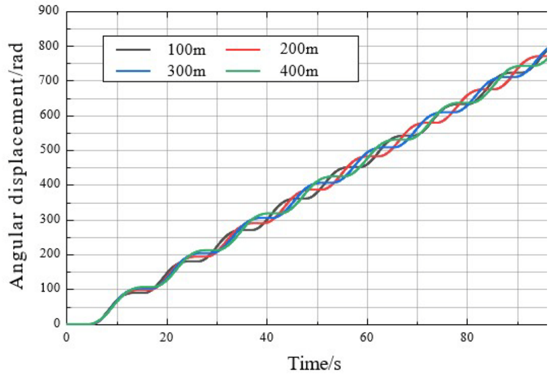


Figure 8. Change of bit angular displacement under different drill collar lengths

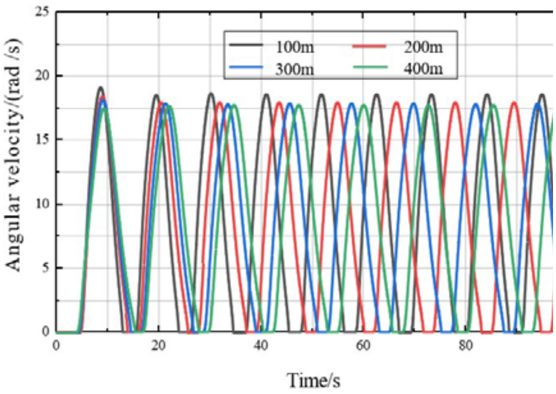


Figure 9. Change of Angle velocity under different drill collar lengths

As shown in Figure 8 and Figure 9, when the length of drill collar are 100m, 200m, 300m and 400m, respectively, the drill bit has obvious stick-slip vibration phenomenon. And the shorter the stick-slip vibration period of the bit as the drill collar length increases. It indicates that increasing the drill collar length can shorten the sticking time of the drill bit with a certain viscosity reduction effect.

Conclusions

This paper establishes a mechanical model of stick-slip vibration of the drill pipe by considering multiple parameters. Besides, the response law of stick-slip vibration characteristics of the deep-well drill pipe has been obtained. The sensitivity analysis of parameters reveals that increasing rotational speed and decreasing WOB are conducive to suppressing the occurrence of stick-slip vibration, and at the same time, increasing the length of drill collar can shorten the sticking time of the bit with a certain viscosity reduction effect. The length of the drill collar is the main factor affecting viscosity reduction efficiency. The smaller the difference between the dynamic and static friction coefficients, the longer the collar is, the higher the rotational speed of the rotational speed, and the smaller the WOB are more conducive to the improvement of viscosity reduction efficiency.

Nomenclature

T_{fb} -friction torque, [N·m]

T_{eb} - torque exerted on the bit, [N.m]

W_{ob} - weight of bit, [N]

u_{sb} - coefficient of static friction, [-]

γ_b - conversion factor, [-]

c_{rp} - equivalent damping, [(N·m·s)/rad]

T_m - torque of the rotary table, [N.m]

φ_b - rotation angles at the bit, [rad]

D_v - critical rotational speed, [rad/s]

T_{sb} - maximum static friction torque, [N.m]

R_b - radius of the bit, [m]

T_{ab} - viscous friction moment, [N·m]

ω_d - rotational speed, [rad/s]

c_{rp} - equivalent damping, [(N·m·s)/rad]

φ_r - rotation angles at the rotary table, [rad]

T_{ar} - frictional torque, [N·m]

Acknowledgments

This research was funded by the scientific research projects of petroleum engineering technology research institute of Sinopec northwest oilfield company (Grant No. 34400007-22-ZC0613-0067).

References

[1] Wang, H., *et al*., Progress and Prospect of Oil and Gas Drilling Technology in Deep Wells and Ultra-Deep Wells, *Natural Gas Industry*, *41*(2021), 8, pp. 163-177

[2] Wang, D., *et al*., Research on Deep Rock Mechanics and Deep Well Drilling Technology, *Drilling Technology*, *2006*(2006), 3, pp. 6-10

[3] Dong, G., *et al*., A Review of the Evaluation, Control, and Application Technologies for Drill String Vibrations and Shocks in Oil and Gas Well, *Shock and Vibration*, *2016*(2016), 1, Article ID 7418635

[4] Richard, T., *et al*., Self-Excited Stick-Slip Oscillations of Drill Bits, *Comptes Rendus Mecanique*, *332*(2004), 8, pp. 619-626

[5] Jia, X., *et al*., Characterization of Viscous Slip Vibration of Deep Well Drill String, *Petroleum Mining Machinery*, *47*(2018), 6, pp. 1-7

[6] Zhu, X., *et al*., Analysis of Stick-Slip Vibration Mechanism of PDC Drill Bit, *Petroleum Mining Machinery*, *41*(2012), 4, pp. 13-16

[7] Ma, S., *et al*., Research on Vibration and Regulation Characteristics of Downhole Drill String System, *Petroleum Machinery*, *50*(2022), 10, pp. 20-28

[8] Liu, J., *et al*., Analysis of Coupled Vibration of Drill String and Drilling Fluid Pressure in Downhole Section, *Petroleum Machinery*, *49*(2021), 7, pp. 16-22

[9] Tian, J., *et al*., Characterization of Viscous Slip Vibration of Drill String under Longitudinal-Torsional Coupling, *Mechanical Science and Technology*, *41*(2022), 4, pp. 511-516

Paper submitted: July 21, 2023
Paper revised: Doctor 16, 2023
Paper accepted: November 13, 2023