Design Engineering

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550

Nonlinear Dynamics of Directional Drilling with Bit-rock Interactions

Jianwei Wang[1,2,*], Haoyu Le[2], Jin Shi[2]

[1]Institute of Mechanical and Electrical Engineering, Lingnan Normal University, Zhanjiang, Guangdong, China

[2]College of Mechanical Engineering, Dalian University, Dalian, Liaoning, China

*Corresponding Author: Jianwei Wang

Abstract:

For the sake of exploring the motion and vibration law of drilling system and its mechanical properties during the gas drainage process, the nonlinear dynamics model of drilling system taken into account the interaction between drill string and rock, the contacts between drill string and borehole is proposed. Firstly, the coal-rock effect and gradual evolution characteristics of drilling failure are deeply analyzed, the nonlinear dynamics and constitutive equation of drilling system based on the Drucker-Prager failure criterion is established. Furthermore, aim at studying of the performance and characteristics of the nonlinear dynamics model by using FEA method, the explicit and implicit combination algorithm is taken into account to deal with the dynamic model. Finally, the case imitation results demonstrate that the motion and vibration of drilling system presented the complex non-linear, the longitudinal, lateral and torsional vibration of drill bit increase with the increase of WOB and rotational speed. A technological basis is provided for drill strings dynamics and vibration analysis of kilometers directional rig.

Keywords*: Drill bit, Drill string, Modelling and simulation, Rock breaking mechanism, FEM.*

I. INTRODUCTION

As one of the most direct and effective technical means of coal mine accident prevention, treatment and service for safe and efficient coal mining, surface drilling and underground drilling in coal mine areas play a vital role in the development of coal bed methane (gas), water hazard prevention and control, channel construction for emergency rescue and so on [1]. The gas drainage technology is an effective means to reduce the disaster capacity of gas outburst. To develop directional drilling technology and equipment for soft coal seams in underground coal mines, meanwhile to improve borehole formation efficiency, drilling quality and borehole trajectory control accuracy in soft coal seams, it is of great significance to study the nonlinear dynamic characteristics between borehole system and coal rock.

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550

At present, there are two main research directions on drilling system dynamics, namely the dynamics of drill strings and the interaction between the drilling bit and coal rock [2-5]. The former is employed widely to optimize or control the trajectory of drill string, check the strength of drill string, optimize the structure, diagnose the drilling problems [6-8], etc. The methods, which were adopted to analyze the dynamics of drill strings, include differential equation method [9], gap-element method, formal stiffness method [10] and finite element method [11]. However in these aforementioned studies, the dynamics of drill strings is analyzed only for the drilling facility itself. In practice, the interaction between the drilling facility and rock should not be ignored. The latter includes different models in the literature for the bit–rock interaction. Theoretical models were established to evaluate weight on bit and the relationship between cutting speed and drilling processing conditions [12], an empirical relationship between the resistance of a single-edge PDC bit and rock type, cutting depth and bit wear state is derivated [13,14]. Some researchers proposed the model focuses on the dynamic behaviour of the drill stem considering the mud-drill stem interaction and the drill stem-borehole contacts [15].

However, a convincing theoretical formula taking comprehensively into account the drill stem dynamics and the bit-rock interaction is never reported. Based on reasonable assumptions, this paper aims at establishing a mathematical model of the coupling interaction between drilling tool and coal rock by adopting FEM. It is useful to effectively predict and control the dynamics and motion of drill bit and underground drills. In addition, the control of borehole trajectory is realized which can be a guidance to actual drilling operations.

The model presented hereafter focuses on the dynamic behaviour of the drill string taking into account the correlation between drill stem and coal rock, the contacts between drill stem and borehole. The nonlinear dynamic model of drilling system based on Drucker-Prager failure criterion is presented in Section 2. Section 3 is dedicated to the dynamic computation procedure. In Section 4, system simulation and performance analysis are analyzed. Finally, conclusions are given in Section 5.

II. NONLINEAR DYNAMIC MODEL OF DRILLING SYSTEM

2.1 Basic Assumptions

Due to the motion, deformation and vibration of drilling system are more complex, factors are more difficult to detailed descript during the drilling process, specific assumptions are proposed to establish the nonlinear coupling vibration model of drill bit-string-rock. The following assumptions are specified in advance for the modeling:

(1) The direct contact between drill bit and borehole is random elastic impact.

(2) Duing to the fact that the drill bit has a noticeably higher elasticity modulus than coal rock and its minimal deformation, so it can be taken as a rigid body.

(3) The geometry size and material properties of the drill string are constants.

(4) Coal rock is assumed as an elastic-plastic material.

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550

(5) The friction coefficient between drill bit and coal rock is constant.

2.2 The Dynamic Model of Drill Bit

During the process of gas drainage borehole, the force of the drill bit is one of the direct factors affecting the drilling efficiency and probability of borehole formation. Studies show that the force of the drill bit is closely related to its mechanical motion state. The drill bit force mainly includes weight on bit (WOB), the reaction force of coal rock and the longitudinal force generated by torque. The cutting process is similar to metal cutting. The rake face of bit cuts into the coal rock by imposing WOB through drill stem. Then the drill bit is driven by the torque transmitted by the drill pipe to cut the coal rock on the side of the bit. Therefore, the process is mainly included the penetrating and cutting two main motion. Basing on the force equilibrium conditions, the longitudinal force equation between the drill bit and coal can be expressed as follows.

$$WOB(t)+M_b a(t)+F_z(t)=0 \tag{1}$$

where $WOB(t)$ is the WOB acting on the drill bit at time t, M_b is the mass of drill bit, $a(t)$ is the acceleration of the drill bit at any moment, $F_z(t)$ is the longitudinal counter force of coal rock at any moment. At any time, the horizontal force of the drill bit is the sum of all horizontal force on tooth surface contacting with coal rock at this moment. It can be decomposed in the X and Y direction, the force decomposition formula is as follows:

$$\begin{cases} F_x(t)=\sum_i F_{xi}(t)\cos\left(\pi+T_i(t)\right) \\ F_y(t)=\sum_i F_{yi}(t)i\sin\left(\pi+T_i(t)\right) \end{cases}, i\in[1,4] \tag{2}$$

where $F_x(t)$ and $F_y(t)$ are the horizontal force of drill bit along X and Y direction, $F_{xi}(t)$ and $F_{yi}(t)$ are the component horizontal force on the ith cutter tooth at the tth time along X and Y direction respectively, $T_i(t)$ is the direction of the ith cutter tooth at tth time.

Other than the above-mentioned forces, the drill bit is also affected by the resistance moment $M_R(t)$ generated by the cutting resistance, which should be meted the moment equilibrium with the actuating torque on the bit. The moment equilibrium equation of drill bit is given:

$$M_R(t)=\sum_i l_{xi}(t)f_{l_{xi}}(t)+\sum_i l_{yi}(t)f_{l_{yi}}(t) \tag{3}$$

where $l_{xi}(t)$ and $l_{yi}(t)$ is the distance of the ith cutter tooth's surface between x axis and y axis at the tth time in drill bits coordinate system respectively. $f_{lxi}(t)$ and $f_{lyi}(t)$ is the component horizontal force on the ith cutter tooth at the tth time along X and Y direction, respectively.

The average force on the cutting surface during drilling can be expressed as:

$$F=F_S+F_M \tag{4}$$

where F_S is the static cutting force, F_M is the dynamic cutting force.

The static cutting force F_S can be calculated as follows:

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550

$$F_S = \sigma_t S \tag{5}$$

$$\sigma_t = \frac{2}{f+1}\tau_J \frac{\cos\varphi}{1-\sin\left(\varphi - 0.75\theta + 22.5\right)} \tag{6}$$

where σ_t is the cutting stress, S is the cutting area, τ_J is the shear strength of material, φ is the shear angle, θ is the rake angle of bit, f is the stress distribution coefficient, its value relates with the rake angle, f=11.3-0.18θ. The dynamic cutting force F_M can be computed according to Eq.7.

$$F_M = \frac{\pi^3}{\sqrt{3}} nV\rho R^3 \tag{7}$$

where n is the rotational speed of bit, V is the feed rate of bit, ρ is the density of coal rock, R is the radius of bit.

The average cutting force, which is applied on the coal rock by the drill bit, can be expressed according to the following equation.

$$F = \frac{2}{f+1}\tau_J \frac{\cos\varphi}{1-\sin\left(\varphi - 0.75\theta + 22.5\right)} \times S + \frac{\pi^3}{\sqrt{3}} nV\rho R^3 \tag{8}$$

The equation show that the longitudinal force of bit increases with the increase of feed speed under the rotational speed of bit is constant, the longitudinal force of bit increases with the increase of the rotational speed of bit under the feed speed is constant. Meanwhile, the equation reveals the interaction between the longitudinal force of bit with the strength of coal rock, the shear angle, the rake angle and radius of bit.

2.3 Constitutive Equation of the Bit and Rock Interaction

Considering the gas effect on the mechanical properties of coal rock, the constitutive equation and failure criterion subjected to Drucker-Prager temperature field is established. The failure criterion subjected to Drucker-Prager temperature field are given as follows:

$$F = t - p\tan\beta - d = 0 \tag{9}$$

$$t = \frac{1}{2} q\left[1 + \frac{1}{K} - \left(1 - \frac{1}{K}\right)\left(\frac{r}{q}\right)^3\right] \tag{10}$$

where p is the equivalent stress, β is the frictional angle of rock, d is the cohesive force of rock, q is Von Mises equivalent stress, K is the stress triaxiality, r is the deviator stress.

It is assumed that only the uniaxial compression is considered, the constitutive equation can be expressed as follows:

$$\sigma = E\varepsilon \exp\left\{-\left[\frac{\varepsilon}{\varepsilon_{pk} m^{\frac{1}{m}}}\right]^m\right\} = E\varepsilon \exp\left\{-\frac{1}{m}\left[\frac{\varepsilon}{\varepsilon_{pk}}\right]^m\right\} \tag{11}$$

where E is the elasticity modulus of rock, ε is the strain, ε_{pk} is the maximum strain, m is the homogeneity of rock.

Design Engineering

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550

2.4 The Dynamic Model of Bit and Rock

During in the drill processing, the nonlinear Timoshenko beam theory is employed to the drill column. The column vibrations couple longitudinal, lateral and torsional vibrations. The finite element method is applied to discretize the drill column to establish finite spatial beam elements and constitute a multiple degrees of freedom system. The basic dynamics equation of the system can be expressed as follows:

$$M\ddot{q}^e + C\dot{q}^e + \left(K_L + K_N\right)q^e = F \tag{12}$$

where M is the mass matrix, $\ddot{q}^e$ is the acceleration vector of integral joints, C is the damping matrix, $\dot{q}^e$ is the velocity vector of integral joints, K_L is the elastic stiffness matrix, K_N is the geometric stiffness matrix, q^e is the displacement vector of integral joints, F is the external load vector of the system. Both energy method and finite element method are adopted to deduce mass, damping and stiffness matrices in local coordinates, the dynamics model of drill column can be established in the global coordinate system by coordinate transforming.

III. NUMERICAL METHODS FOR COMPUTING THE NONLINEAR RESPONSE

Due to the complex nonlinear systems of drill bit and rock, its dynamics problem includes not only the random contact problem which is suitable for the explicit algorithm but also the dynamic response problem of its own structure. Meanwhile, the drill string is an assembly of pipes with different diameters and shows a slender structure, it is more advantageous to adopt the large-step implicit algorithm to solve its own structural response. If the small-step explicit algorithm is adopted, it will significantly increase the computation complexity. For the abovementioned reasons, just one algorithm alone is difficult to analyze comprehensively the model of drilling system, the explicit and implicit combination algorithm is taken into account to solve the dynamic model.

The explicit and implicit combination algorithm, which is consist of the central difference method and Newmark-β method, is proposed. The displacement and acceleration formulas with correction-prediction format are given as follows:

$$\begin{aligned} \tilde{q}^e_{n+1} &= q^e_n + \dot{q}^e_n \Delta t + (\frac{1}{2}\text{-}\beta)\Delta t^2 \ddot{q}^e_n \\ \tilde{\dot{q}}^e_{n+1} &= \dot{q}^e_n + (1\text{-}\alpha)\ddot{q}^e_n \Delta t \end{aligned} \tag{13}$$

And the deduced dynamic equation with prediction can be written:

$$M\ddot{q}^e_{n+1} + \tilde{C}\dot{q}^e_{n+1} + K q^e_{n+1} = {}_{n} \tag{14}$$

Substituting of Eq. (13) into Eq. (14), the acceleration $\ddot{q}^e_{n+1}$ can be given:

$$\ddot{q}^e_{n+1} = M^{-1}F_{n+1} - M^{-1}C\left[\dot{q}^e_n + (1-\alpha)\ddot{q}^e_n\Delta t\right] - M^{-1}K\left[q^e_n + \dot{q}^e_n\Delta t + (\frac{1}{2}-\beta)\Delta t^2\ddot{q}^e_n\right] \tag{15}$$

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550

where α and β are the parameters that can be adjusted according to the accuracy and stability of the integral, $\alpha \geq 0.5$, $\beta \geq \frac{\left(0.5+\alpha^2\right)}{4}$, respectively.

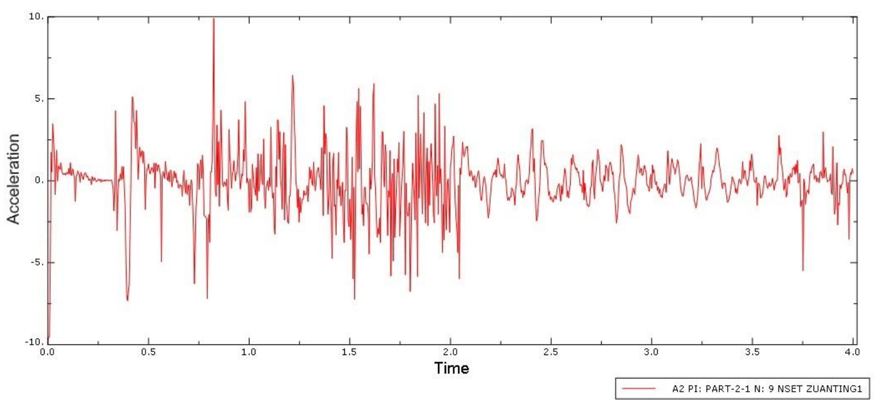
IV. SYSTEM SIMULATION AND ANALYSIS

In order to simulate a realistic drilling dynamic behaviour in operation, the engineering software ABAQUS is adopted to simulate and verify the nonlinear dynamics of the drilling system. The drill string material, drill string and borehole contacts parameters are given in TABLE I.

TABLE I. The simulation parameters

Young modulus	E(N/m^2)	1.7E11
Poisson's coefficient	v	0.3
Drill string density	ρ(kg/m^3)	6800
Weight on bit	WOB(N)	1.2E5
Rotational speed of bit	n(r/min)	60
Angle of friction	θ(º)	30
Stiffness	K(N/m)	1E7

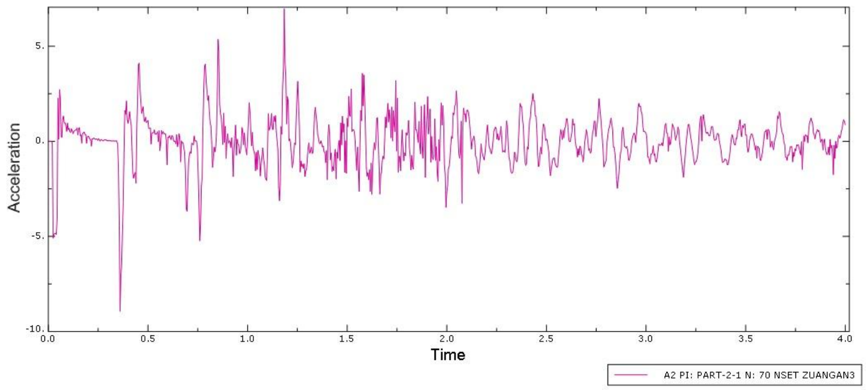
The simulation results are obtained after running 4.0s, as shown in Fig.1-3. The longitudinal acceleration of drill strings is manifested in Fig. 1. Fig. 2 shows the lateral acceleration of drill strings. Fig. 3 demonstrates the torsional acceleration of the drill strings.



(a) longitudinal acceleration of No.9 node

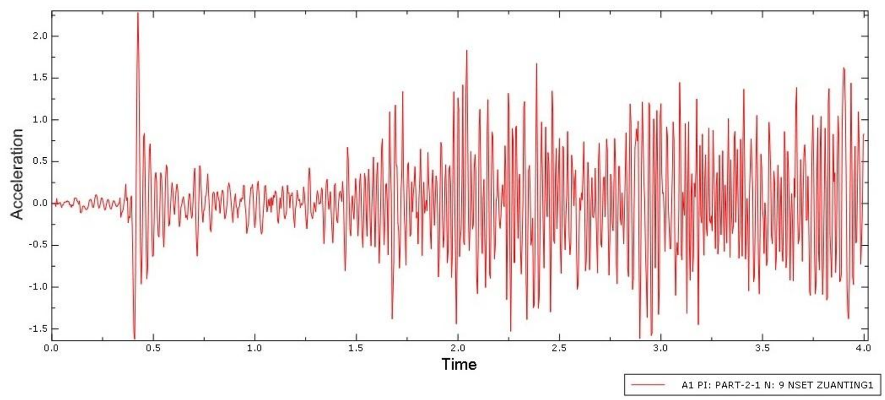
Design Engineering

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550

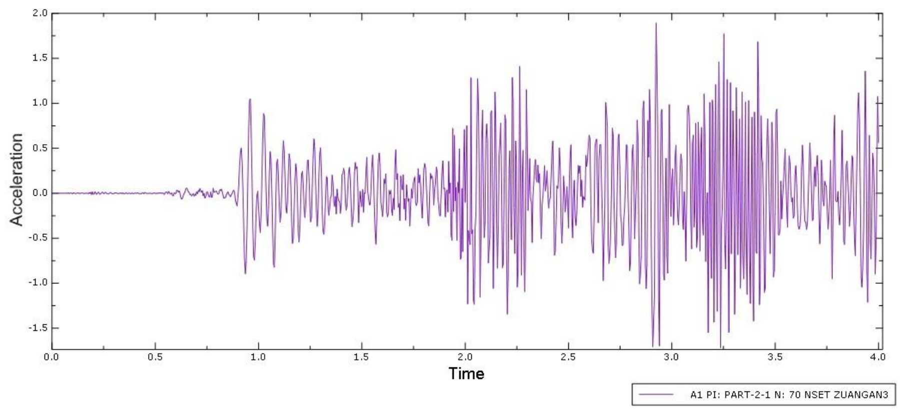


(b) longitudinal acceleration of No.70 node

Fig 1: longitudinal acceleration of drill strings



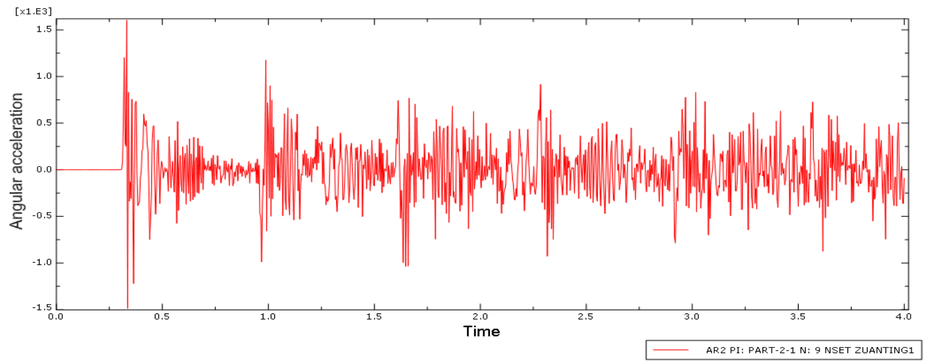
(a) lateral acceleration of No.9 node



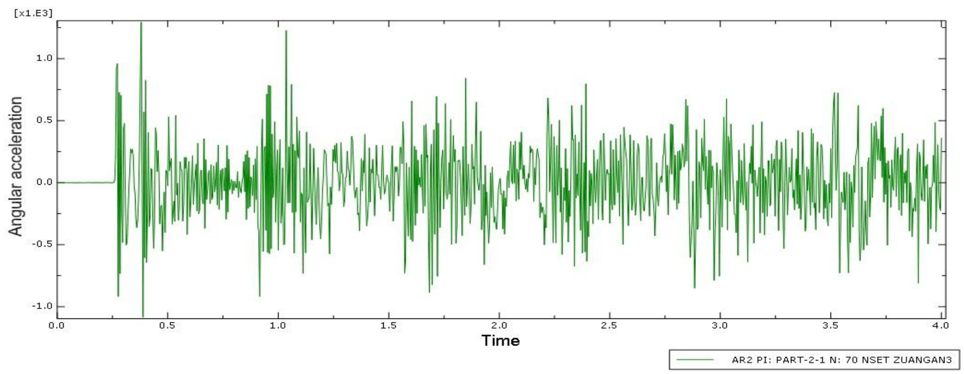
(b) lateral acceleration of No.70 node

Fig 2: lateral acceleration of drill strings

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550



(a) torsional acceleration of No.9 node



(b) torsional acceleration of No.70 node

Fig 3: torsional acceleration of drill strings

According to the obtained results as shown in Figures 1-3, it demonstrates the distinction among longitudinal acceleration, lateral acceleration and torsional acceleration of the drill strings. The extreme longitudinal vibration of drill string is mainly concentrated in the initial cutting state. The maximum lateral vibration is mainly focused on the stable continuous cutting situation. The extreme torsional acceleration are evenly distributed ever once in 0.5s, as shown in Figure 3 (a) and (b). It can be found that the maximum accelerations in the three figures are around 1.5deg/s2 and the main variable interval locates on [-1.0deg/ s2, 1.0 deg/s2]. It illustrates that the torsional acceleration of drill string is mainly caused by the intermittent rock breaking of bit scraping teeth and the uneven stiffness of coal and rock in the bottom hole, the reasons mainly rely on drilling speed, WOB and stiffness of drill string itself, but it is little influenced on drill sting length.

The simulation results indicate that there are different degrees of coupling among the longitudinal, lateral and torsional vibrations of drill string, it demonstrates that the vibration coupling of drill strings is fully coupled. Any one of three vibration forms will be affected by the coupling effect of the other two, and the vibration in other directions will be affected at the same time. The results illuminated that the longitudinal vibration affords the chief effect to the service life of drill string owing to its obvious nonlinear and greater amplitude than the other two. In order to avoid fracture accidents of drill string, it should be taken into account the drillability grade of coal rock and the reasonable drilling parameters.

V. CONCLUSION

(1) Aiming at researching on the interaction between drill bit and rock, the nonlinear dynamic equation of drilling system is established, which is considered comprehensively the dynamic and stiffness coupling among longitudinal, lateral and torsional movements of drill strings.

(2) To improve the computing efficiency, the explicit and implicit combination algorithm is proposed to solve the nonlinear dynamics of drilling system.

(3) The simulation results highlight that the longitudinal, lateral and torsional coupled vibration affected directly the drill bit and drill string, the longitudinal vibration is the main cause of the drill strings fatigue and fracture.

ACKNOWLEDGEMENTS

This project is financially supported by the National Natural Science Foundation of China (51275061, 61672121), the Scientific Research Project of Lingnan Normal University (No. ZL2025).

REFERENCES

[1] Jianwei Wang (2018) Structural modeling and performance analysis of rotary circuit in directional drilling rig based on load sensing technology. International Journal of Wireless Information Networks 25(3): 269-278

[2] Kai Wang, Zhen Lou, Lianhe Guan, et al (2020) Experimental study on the performance of drilling fluid for coal seam methane drainage boreholes. Process Safety and Environmental Protection 138(6): 246-255

[3] Yucai Shi, Zhixiang Teng, Jing Bai, et al (2019) Analysis on the weight-on-bit transmission efficiency of the static push-the-bit rotary steerable system. Natural Gas Industry B 6(3): 250-256

[4] Weiji Liu, Xudong Qian, Tao Li, et al (2019) Investigation of the tool-rock interaction using Drucker-Prager failure criterion. Journal of Petroleum Science and Engineering 173(2): 269-278

[5] Sajjad Kalantari, Hamid Hashemolhosseini, Alireza Baghbanan (2018) Estimating rock strength parameters using drilling data. International Journal of Rock Mechanics and Mining Sciences 104(4): 45-52

[6] Kuilin Huang, Yingxin Yang, Yang Liu, et al (2020) Study on rock breaking mechanism of PDC bit with rotating module. Journal of Petroleum Science and Engineering 192: 107312

[7] D.G. Gromakovsky, L.V. Kudyurov, S.V. Shigin (2018) Improving the working capacity resource for a roller cone-drill rod joint of a drill bit. Journal of Friction and Wear 39: 528-534

[8] M.K. Das, S. Sarkar, B.S.Choudhary (2018) Experimental and numerical analysis of rotary tricone drill bit and its wear prediction. Journal of the Brazilian Society of Mechanical Sciences and Engineering 40: 366-374

ISSN: 0011-9342
Issue: 11 | Pages: 541 - 550

[9] Yijin Zeng, Lianzhong Sun, Kai Wei, et al (2020) Numerical simulation of the pressing of polycrystalline diamond compact cutter into the rock based on arbitrary Lagrangian-Eulerian algorithm. Alexandria Engineering Journal 59(3): 1381-1390

[10] H. M. Panayirci (2015) Modeling contact of pipes within elliptic and spiralled wellbores using finite element analysis. Finite Elements in Analysis and Design 107: 1-12

[11] Jiayi Xu, Abdul Hamid Sheikh, Chaoshui Xu (2017) 3-D Finite element modelling of diamond pull-out failure in impregnated diamond bits. Diamond and Related Materials 71: 1-12

[12] Yingjian Xiao, Charles Hurich, Stephen D. Butt (2018) Assessment of rock-bit interaction and drilling performance using elastic waves propagated by the drilling system. International Journal of Rock Mechanics and Mining Sciences 105: 11-21

[13] F.F. Real, A. Batou, T.G. Ritto, et al (2018) Hysteretic bit/rock interaction model to analyze the torsional dynamics of a drill string. Mechanical Systems and Signal Processing 111: 222-233

[14] Luc Perneder, Emmanuel Detournay, Geoff Downton (2012) Bit/rock interface laws in directional drilling. International Journal of Rock Mechanics and Mining Sciences 51: 81-90

[15] Quang-Thinh Tran, Khac-Long Nguyen, Lionel Manin, et al (2019) Nonlinear dynamics of directional drilling with fluid and borehole interactions. Journal of Sound and Vibration 462: 114924