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The vibration characteristics of drillstring with positive displacement motor in compound drilling Part 2: Transient dynamics and bit control force analysis☆

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ABSTRACT

The transient dynamics of a drill string and the dynamic characteristics of bit control force during compound drilling have not been elucidated yet. A numerical simulation model of drill string with a positive displacement motor was established to analyze the transient dynamics of drill string. The calculation model of dynamic bit control force was proposed based on the results of the transient dynamics of drill string. The results show that, when compared with conventional drilling, the impact frequency and the mean and peak values of drill string–wellbore interaction were larger. The effect of compound drilling on the lateral vibration acceleration of drill string was greater than that on the longitudinal vibration acceleration. A heightened build-up effect was caused by the increase of weight on bit. The larger bend angle and higher position of the stabilizer were not conducive to the stable control of the well trajectory. The increased outer diameter of the stabilizer could reduce the build-up effect of the bottom hole assemble to a certain extent. The driller in the field control of a well trajectory should be based on the complex dynamics of the numerical model of the bottom hole assemble during compound drilling.

Introduction

Compound drilling can effectively improve the transportation of cuttings, rate of penetration (ROP), wellbore quality, and well trajectory control. However, the accurate analysis of transient dynamics of drill string and bit control force is still difficult because there are too many factors influencing the drilling operation. The frequent switching of drilling modes further increases the difficulty of controlling the well trajectory and wellbore quality [1–6].

Drilling technology is used to establish a deep wellbore by using a drilling rig, drill string, and drilling tools. The well

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trajectory control is mainly based on bottom hole assemble (BHA), drilling modes, and drilling parameters. The BHA is a component of a drilling rig and is the lowest part of the drill string, extending from the bit to the drill pipe. The BHA consists of a drill bit, positive displacement motor (PDM), drill collar, stabilizer, and drill pipe. The characteristics of the BHA help to determine the drill bit force, borehole shape, direction, and other geometric characteristics. The PDM generally consists of a stator, rotor, and rubber ling. The two ends of the stator are connected to the drill collar and bit, and the rotor is connected to the bit. The rotating speed of the rotary table is delivered to the bit by the stator shell, and the rotating speed of PDM is delivered to the bit by the rotor. The drilling modes include slide drilling mode, compound drilling mode, and conventional drilling mode. The realization of drilling modes can refer to the analysis of previous part [7].

Numerous studies have been carried out on the dynamics analysis of drill string and bit control force. The early studies were related to the static mechanical analysis of BHA. The representative research methods of drill string include the finite element method, continuous beams method, energy method, and weighted residual method [8–11]. The characteristics of these methods have been described in previous reports. These methods were mainly used to analyze the bit control force and the friction of drill string–wellbore interaction. The analysis focused on the quasi-dynamics and statics problems, but did not consider the PDM and rock fragmentation. Other scholars have also studied the transient dynamics of drill string with PDM during compound drilling. The rotor dynamics method and beam element method can simulate the dynamic contact of drill string–wellbore interaction, but do not consider the bit structure and rock damage. The rigid drill string model does not consider the mechanical properties of the rock. The improved finite element method can solve the lateral force of bit in rotating state, but still ignores the bit and rock fragmentation [12–14]. Although many scholars studied the coupling between the drill string, bit, and formation, the main objective of these studies was to study the dynamic behavior of drill string. These studies did not investigate the capability of dynamic deviation control. In a previous study [7], a numerical simulation model of drill string with PDM was established by considering the bit–rock interaction, rock failure behavior, drill string–borehole interaction, and drill string structure. The axial force and torque of the bit was calculated using the simulation model, and the dynamic stress and movement state of the drill string were investigated.

However, there have been no studies on the accurate analysis of transient dynamics of drill string with PDM and bit control force by considering the actual working conditions of compound drilling. The structure of this paper is as follows. Section 2 is a simple description of simulation model. Section 3 analyzes the transient dynamics of BHA with PDM, which mainly focuses on the axial and lateral acceleration and impact force between the drill string and borehole wall. Section 4 discusses the bit control force. The calculation model of dynamic bit control force is proposed based on the results of the transient dynamics of drill string. The effective factors of drill string with PDM include the weight on bit (WOB), bend angle, stabilizer installation position, and stabilizer size.

Simple description of simulation model

This work establishes a nonlinear dynamic model of the BHA with a single bend PDM. Most of the equations and calculation methods used herein have been described in a previous report [7]. Therefore, we only provide a general overview of the model, and highlight the changes from the previous report. The nonlinear dynamic model of the entire drill string increases the number of elements and computing time, and reduces the accuracy of the dynamic characteristics of BHA [15–18], as shown in Fig. 1 (a). The upper boundary of the nonlinear dynamic model of BHA with PDM during compound drilling is the neutral point, as shown in Fig. 1 (b). The numerical model is established under the following assumptions. The drill string of BHA is a beam element; the circular wellbore and the full-scaled Polycrystalline Diamond Compact (PDC) bit is simplified as a rigid body. The rock pore pressure, temperature, and flow field are ignored. The modeling progress of BHA with PDM during compound drilling is shown in Fig. 2.

Motion equation of wellbore–drill string–bit–rock system

As many factors are considered in the simulation model of a bit–rock–drill string–wellbore system herein, the substructure method is adopted to establish the motion equation. The substructure method can obtain the solution using the reduced-order method. The bit–rock–drill string–wellbore system includes the string–wellbore substructure and bit–rock substructure, as shown in Fig. 1. Using the standard finite element assembly procedure, the equation of motion for BHA with PDM can be written in the assembled general form as [19].

$$[\overline{K}]_R^{Sub1}\begin{Bmatrix} q_{Sub1} \\ q_{Sub2} \\ \zeta_B \end{Bmatrix} + [\overline{M}]_R^{Sub1}\begin{Bmatrix} \ddot{q}_{Sub1} \\ \ddot{q}_{Sub2} \\ \ddot{\zeta}_B \end{Bmatrix} + [\overline{C}]_R^{Sub1}\begin{Bmatrix} \dot{q}_{Sub1} \\ \dot{q}_{Sub2} \\ \dot{\zeta}_B \end{Bmatrix} = \begin{Bmatrix} F_{Sub1} \\ F_{Sub2} \\ f_B \end{Bmatrix} \tag{1}$$

where q_{Sub1} and q_{Sub2} are the displacement matrices considering modal transformation; F_{Sub1} and F_{Sub2} are the force vector matrices considering modal transformation; $[\overline{M}]$ is the global assembled mass matrix of the drilling system; $[\overline{C}]$ is the global assembled damping matrix of the drilling system; $[\overline{K}]$ is the global assembled stiffness matrix of the drilling system.

In this numerical analysis, it is assumed that the rock yields according to the Drucker–Prager yield criterion. The criterion of estimating rock damage is defined by the equivalent plastic strain [20–22]. The determination of mechanical and structure parameters has been described in the previous report [7]. The simulation model of a full-sized bit worked under WOB and rotations per minute (RPM). The WOB was applied to the top of the full-sized bit, and the value of RPM mainly depended on the specific research problem, as shown in Fig. 3.

Many explanations of the rock material have been provided in the previous report [7]. The study field is located in Longmaxi shale formation, which extends vertically from a depth of 2400 m to a depth of 2479 m. This paper focuses on a depth of 2425 m, and the confining pressure is 25 MPa. The

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