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A nonlinear dynamic model for characterizing downhole motions of drill-string in a deviated well

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ABSTRACT

In this article, a nonlinear dynamic model with four degree-of-freedom (DOF) was established to characterize the behavior of drill-string in a deviated well. It should be noted that the stick-slip phenomenon, the lateral and torsional deformations of the drill-string, meanwhile, the fluid damping effects were taken into account. The space-state analysis method was employed to obtain a reduced-order model which could be solved by the Runge-Kutta numerical method. Effects of different inclinations (α) on nonlinear motions were illustrated qualitatively. These investigations revealed that the contact area between drill-string and hole wall is increased due to the gravity in the horizontal section ($\alpha = 90^\circ$), thus leading to the increase of friction torque. Drill-string creeps along the hole wall towards its rotational direction range in a 30° fan-shaped region, which is located at the low-side of borehole. When the torque is built up to a certain level that is enough to overcome the friction torque, drill-string will suddenly tumble and go to the next irregular cycle. The local friction contact is reflected as the stick-slip ring and tumbling at low-side of borehole, which is one of the main reasons for causing drill-string wear out and key seating. With the decrease of the inclination, the stick-slip and tumbling motions are weakened gradually even transferred into pure rotational motion in wellbore eventually. Phase portrait projection of the rotor's lateral motion was introduced to identify different motion states such as creeping, stick-slip and tumbling. The study provides a theoretical understanding of the nonlinear motion of the drill-string in non-vertical well. It can help us rediscover the key seating and can be used to better understand the downhole working conditions so as to guide field drilling.

1. Introduction

Drill-string, as the key rotary drilling equipment, is used to provide the channel for drilling fluid circulation and delivering power from the ground to the bottom hole. As shown in Fig. 1, drill-string is comprised by specific pipes connected through joints. The diameter of pipe is generally smaller than the borehole, which provides space for deformation and movement of drill-string subjected to the weight on bit (WOB) and torque. The motion of drill-string is a multiple coupled nonlinear movement because of the bending and twisting. This complex motion is a combination of several kinds of movements, such as the rotation around its geometric axis, the rolling around the borehole axis and the whirl motion. Under such circumstance, the uncertainty of motion increases and it is more difficult to forecast the trajectory. Failing in getting the downhole motional trajectory, the drilling engineers find it hard to determine the well design scheme and optimize the drilling parameters. Failing in adopting positive measures to ameliorate the force environment will result in the premature failure of drill-string (Hakimi and Moradi, 2010; Moradi and Ranjbar, 2009) and will face the drilling accident (Hess, 2016). Fig. 2 illustrates the 'key seating' accident caused by the unusual movement of the drill-string. However, the scenarios discussed above are more prominent in deviated well because of the gravity effect.

The research on mechanical behavior of drill-string can be divided into two parts (Gao, 2006): static and dynamic analysis. The former concentrates on solving the problem of stress and deformation while the latter mainly concerns the characteristics of motion. There are numerous studies dedicated to the movement and vibration of drill-string. Jansen (1991), Leine and Campen (2002), Liao et al. (2011) and Melakhessou et al. (2003) made certain achievements in modeling and model development. Pavone

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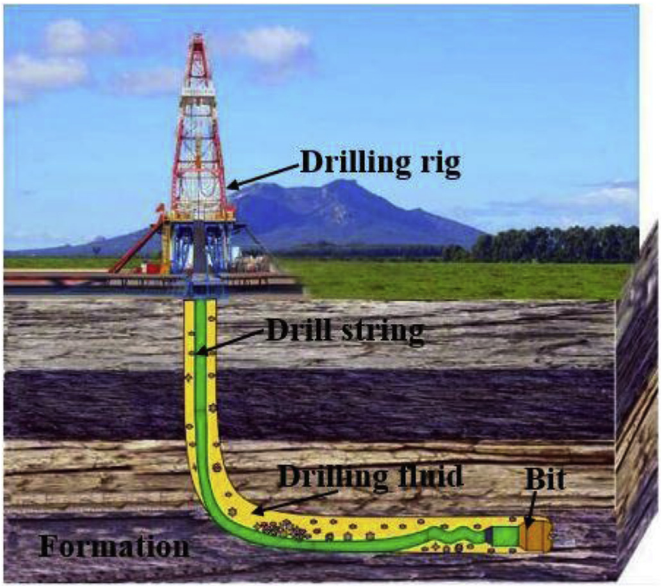

Fig. 1. The schematic of rotary drilling.

and Desplans (1994) and Jansen (1991) noted that the irregular motions of drill-string could result in severe lateral vibration. They simplified the Bottom Hole Assembly (BHA) as a rotor dynamics system with bearing constraints at both ends. The studies indicated that the complicated motion of drill-string contains forward and backward whirl movement. When the coupled vibration frequency was close to the natural frequency of drill-string, the larger the amplitude of shock, the greater the damage of drill-string. Leine and Campen (2002) studied on the nonlinear instability caused by discontinuity of the drill-string. They employed the bifurcation theory to explain the reduction of stick-slip vibration with the appearance of whirling vibration. Melakhessou et al. (2003) followed the unbalanced mass model proposed by Jansen (1991) to derive a four DOFs model. This model described drill-string as an unbalanced rotor supported by two bearings. Ignoring sliding effect, his study focused on a contact zone between the drill-string and the borehole wall. Motivated by the former study, Liao et al. (2011) developed the Melakhessou's model to a five DOFs model by increasing the tilt effect between the rotor and stator. In addition, an integrate contact model was introduced to characterize the overall contact behavior, such as stick-slip, sliding and rolling. Other researchers considered the interactions between bit and rock to study the drill-string's stick-slip vibration (Germay et al., 2009; Liu et al., 2013; Richard et al., 2007). The sharp difference among them is the way of handling fraction. Is it velocity-weakening friction model or Coulomb friction model? Time-delay effect was also taken into consideration. Kapitaniak et al. (2015) discretized the drill-string as a series of beam elements, of which each unit has twelve DOFs. Then these researchers used the Lagrange approach and Finite Element Analysis (FEA) to establish the motion equations considering the torsional bending inertia, the effects of gyroscopic effect and the gravitational force. The results revealed that the model can perfectly perform time-response of the drill-string system. Khulief and Al-Naser (2005) developed a high-dimension model based on the FEA and torsional pendulum method to demonstrate the predictive capabilities of mathematical models of stick−slip oscillations. At last, it should be particularly noted that the above studies were all for vertical well.

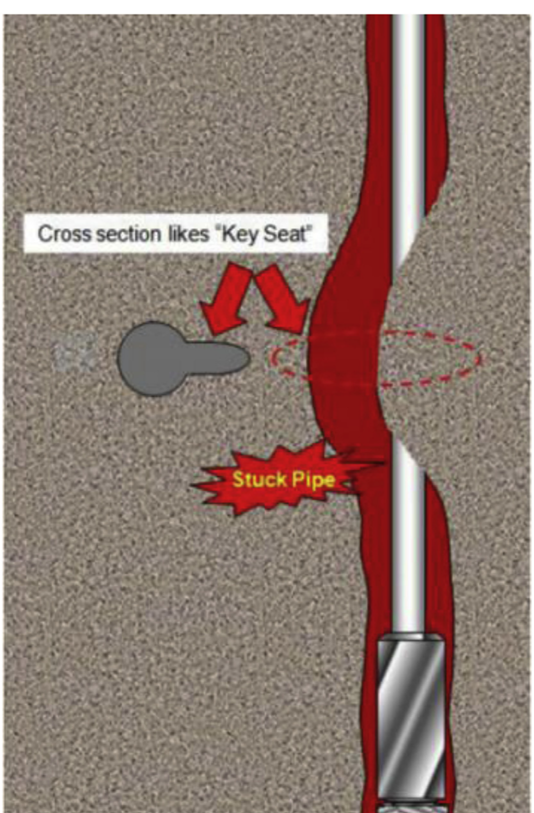

Fig. 2. Key seating (Hess, 2016).

The contact zone behavior between drill-string and hole wall is a critical factor to determine the motion trajectory. This behavior was further investigated in details by Batako and Piiroinen (2008), Leine et al. (1998) and Mihajlovic et al. (2006). Mihajlovic et al. (2006) employed the Lyapunov-based stability analysis method to clarify the effect of essential friction characteristics on the occurrence and nature of friction-induced limit cycling. They confirmed that the limit cycling was formed due to a subtle balance between negative damping at lower velocities and viscous friction at higher velocities. Leine et al. (1998) developed a switch model to simulate stick-slip vibration using shooting method to calculate the limit cycles. The alternate friction model was more efficient compared with the general smoothing method. Batako and Piiroinen (2008) set up a friction-driven vibro-impact system in order to introduce the impact effect at the contact moment. Although this study was limited to a mass ratio (<0.5), the analysis of phase portrait indicated that it was more approach to reality.

Apart from the wellbore confined, drilling fluid also influences the motion of drill-string. Three modes were proposed to describe the fluid damping effect on drill-string. Liu et al. (2013) introduced the Rayleigh's dissipation function to characterize the effects coming from fluid. Jansen (1991) treated the influence as an external force which is in proportion to velocity-squared. Fritz (1970) investigated the law that how fluid made a difference in a vibrating rotor surrounded by a thin annulus liquid. A complex model was obtained that not only contained damping factor but also reflected the feature of external generalized force.

This paper mainly focuses on the dynamic behavior of drill-string in horizontal and deviated well because it is quite different from that in the vertical well. Inspired by previous studies of the vertical well, a four DOFs nonlinear dynamic model was established based on the Lagrangian dynamics to describe the kinematic behavior of drill-string in deviated well. A comprehensive contact model was proposed so as to observe the contact behavior more