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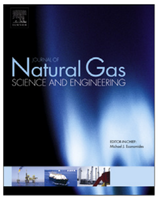

Modeling friction-reducing performance of an axial oscillation tool using dynamic friction model

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ABSTRACT

An axial oscillation tool (AOT) is an effective means to solve the problem of high friction observed in structurally complex wells during sliding drilling. However, the classical Coulomb model does not explain the mechanism of friction reduction caused by the AOT. To solve this problem, a theoretical model for the analysis of frictional force is proposed based on the dynamic friction model and microscopic contact deformation theory. The Dahl model, an innovative dynamic friction model, is used in this model to determine the friction force changes during slide drilling with an imposed axial vibration. A computational program is developed in the Matlab/Simulink environment. The results indicate that the calculation results using the present model and the experimental results are in good agreement (the average error is only 5.09%), verifying the accuracy of the present model and method. The reduction of friction increases with the vibration frequency and tangential contact stiffness coefficient; it first increases with vibration amplitude and then tends to decrease before reaching the optimal amplitude, but it decreases with increasing relative sliding velocity. The instantaneous frictional force does not exhibit an abrupt phenomenon. The prerequisites for reducing friction caused by the AOT are that the relative sliding velocity should be less than the maximum velocity of the axial vibration. The present model can quantitatively characterize the axial vibration and the relationship between the frictional force and asperity deformation during sliding drilling, and it also can be utilized to analyze the variations of frictional force in real-time. In addition, this model can provide a quantitative calculation to predict the frictional resistance in horizontal drilling.

1. Introduction

Examining the drag and torque between a drill-string and borehole rock is a basic research topic in drilling engineering. High frictional resistance is encountered when structurally complex wells (such as horizontal wells, extended reach wells, and multilateral wells) are drilled using the sliding mode, resulting in a low rate of penetration (ROP) and ultimate extension distance (Li, 1998). Tribology research has moved toward a combination of analysis and control and has even been extended to control tribological properties (Wen and Huang, 2002). Using experiments and theoretical methods, many studies have indicated that the value and direction of friction forces can be dramatically modified using applied vibrations with high frequency and low amplitude (Pohlman and Lehfeldt, 1966; Godfrey, 1967; Hess and Soom, 1991; Grudziński and Kostek, 2005). Researchers have concluded that friction force is more effectively reduced using axial vibrations than lateral vibrations. Therefore, stimulating an axial vibration to address the high friction caused by drilling complex structural wells in the sliding mode has become an effective technical tool in complex oil and gas development (Newman et al., 2009; Barton et al., 2011; Alali and Barton, 2011; McCarthy et al., 2009).

The axial oscillation tool (AOT), a downhole tool, is often used to generate axial vibrations to improve the transmission efficiency of the weight-on-bit (WOB) and reduce the friction between the bottom hole assembly (BHA) and borehole during drilling. In recent years, use of AOT tools has been spread rapidly in the major oil fields domestically and abroad (McCarthy et al., 2009; Xu et al., 2013; Liu and Li, 2012; Li, 2014). However, drilling engineers are most interested in exploiting the effect of friction reduction caused by vibration and its field applications and may not emphasize a thorough understanding of the mechanism behind vibration

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induced friction reduction. National Oilwell Varco (NOV) and China's domestic reports indicate that the ability of an AOT to convert the static friction to dynamic friction was the key to reducing friction (Xu et al., 2013; Liu and Li, 2012; Skyles et al., 2012; Gee et al., 2015; Dong et al., 2014). However, Matunaga and Onoda (1992), Kumar and Hutchings (2004), and Leus and Gutowski (2008) concluded that vibration changes the direction of instantaneous friction, thereby reducing the total friction experienced during a single oscillation cycle. Olofsson (1995) experimentally observed a micro-slip phenomenon between dry contacting surfaces during oscillating motion. Tani (1996) noted that the Coulomb friction model cannot be directly adopted for analyzing contact problems with micro-slippage. Broniec and Lenkiewicz (1982), Littmann et al. (2001a, b), and Kumar and Hutchings (2004) experimentally studied the mechanism of friction reduction caused by tangential vibration. They found that the results acquired in experimental research exhibit obvious discrepancies when compared with the calculated friction force for static friction models. These static friction models are generally based on the classic Coulomb model, in which the contact deformation between two bodies moving in relation to one another is not taken into account. However, Tsai and Tseng (2006) reported that the results determined by the Dahl model correlated well with the experimental results mentioned above. Dahl (1976) proposed a dynamic friction model, which took into account actual elastic-plastic contact characteristics. The Dupont model (2002) and LuGre model (Canudas de Wit et al.,1995) are extensions of Dahl's model, but the challenge of parameter identification has limited the application of these models in drilling engineering. Furthermore, none of these reports has included a comprehensive study on the axial vibration, sliding processes and the micro-contact problem.

The present study combines micro-contact theory with the Dahl friction model to analyze the friction reducing performance of the AOT during sliding drilling. The actual contact state between the AOT and borehole rock is addressed. The mechanism of friction reduction caused by AOT vibrations is investigated using the present model, and the operating characteristics of the AOT are also discussed.

2. Modeling the reduction in friction induced by an AOT

2.1. Surface forms and contacts

The microscopic contact deformation theory proposes an asperity hypothesis for the real contact surface, which assumes that the friction force is generated by the tangential deformation of asperities on the contact surface. Microscopic contact models, such as the G-W model (Greenwood and Williamson, 1966) and M-B model (Majumdar and Bhushan, 1991) models, assume that the interface consists of a plane on one side, with the other side consisting of a rough surface containing a large number of asperities. The friction coefficient between two contact surfaces is defined as the Coulomb friction coefficient. Considering that the real contact is between the AOT and the borehole rock, we make the same assumption for the contact surface. This implies that the tool surface is a smooth plane and the wellbore is a rough surface composed of a large number of asperities. The simplified model is shown in Fig. 1.

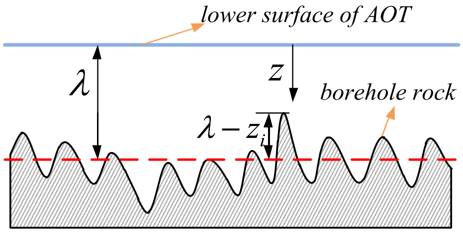


Fig. 1. Micro contact model between the AOT and the borehole rock.

2.2. Basic assumptions

To simulate the real working conditions of the AOT, the following assumptions are made: (1) The surface of the AOT is relatively smooth and the wellbore is composed of a large number of asperities, the shape of the asperities is ellipsoidal, the height distribution of the asperities is uniform and the contacting asperities have the same ovality ratio. (2) The contacted surface is elastic, and each asperity follows the Hertz theory for elliptical contacts. (3) The AOT tools slide with a constant velocity in the direction of the borehole extension. (4) The vibrating motion of the borehole rock is harmonic and takes the form $u = u_0 sin(\omega t)$, and the amplitude of vibration velocity is defined as $v_a = u_0\omega$.

2.3. Modeling the reduction in friction

Based on the above assumptions, the AOT's actual working conditions can be simplified into the interaction model, as shown in Fig. 2 (a). Put simply, the AOT's actual motion can be resolved into a combination of sliding motion and simple harmonic vibration. The distribution of the forces acting on a sliding body is given in Fig. 2(b).

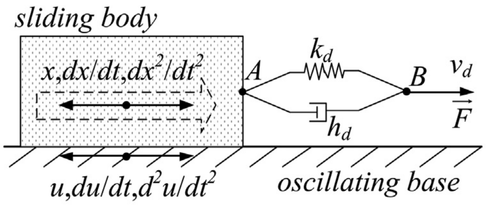
The vector equation for the sliding motion of a body moving on an oscillating base in a stationary reference system *oxy* [Fig. 2(b)] has the form

$$m\vec{a} = \vec{F_d} + \vec{F_g} + \vec{F_e} + \vec{F_F} + \vec{F_N} \tag{1}$$

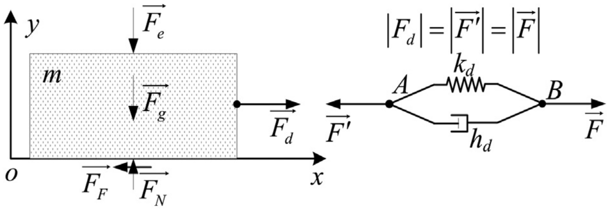
If we suppose that the borehole extension direction is along the *ox*-axis [Fig. 2(b)], Eq. (1) can be simplified to

$$m\frac{d^2x}{dt^2} = F_d - F_F \tag{2}$$

For motion over the oscillating base, the sliding body is



(a) Interaction model of the sliding-vibration system



(b) Distribution of forces acting on the sliding body

Fig. 2. Simplified model for the analysis of friction in the presence of axial sliding and vibration.