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Modeling and experimental investigations on the drag reduction performance of an axial oscillation tool

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A B S T R A C T

The high friction of a drill string against a wellbore is a concern during directional and horizontal drilling. An axial oscillation tool (AOT) is typically used to reduce drag and torque. This study examined the axial oscillation drag reduction mechanism using a specially designed laboratory test rig. An indoor simulation experiment was conducted, followed by model recognition and identification of the friction model parameters based on the experimental data. A torque/drag model and drilling string axial vibration model were used to establish the numerical model. Additionally, the boundary condition between the drill pipe and wellbore was based on a nonlinear dynamic friction model. Finally, the model was solved using a numerical method to gain an understanding of the drag reduction mechanism of the axial oscillation tool. The indoor experiment of the nonlinear friction model revealed that the Coulomb friction model appeared to disagree with the measured data of the experiment. The nonlinear dynamic friction model, however, which was based on the acquired parameters using particle swarm optimization (PSO), yielded results that were in good agreement with the experimental results. Comparisons with experimental setups, data and models from the literature were conducted. The simulation results clearly demonstrated that the friction reduction was effective when the amplitudes of the vibration velocities exceeded the drive velocity. Decreasing the slip velocity of drill strings and increasing the amplitude of the axial oscillation tool vibration force effectively lengthened the drilling-string vibration range. Furthermore, the optimal position of the axial oscillation tool corresponded to a highly deviated well section that was characterized by the existence of high friction resistance. Therefore, the oscillation motion of the drill pipe at a highly deviated well section could significantly decrease the total friction force of the entire drill string.

1. Introduction

An important issue in drilling engineering relates to the friction between the drill string tube and the wellbore. Excess friction is encountered in a long horizontal well that uses sliding drilling modes. Additional drag and torque result in low rates of penetration (ROP) and poor tool-face control in addition to preventing the transfer of weight to the drill bit. To modify this excessive drag problem, axial oscillation tools (AOT) are commonly used in the oil and gas industry, especially in coiled tubing string drilling (Newman et al., 2009; Sola and Lund, 2000; Wicks et al., 2014) and horizontal shale gas well drilling (Gee et al., 2015; Zhao et al., 2015a, b; Zhao and Liao, 2016). The extant literature, however, does not clarify the AOT drag reduction mechanism or adequately discuss its applications in the field of drilling engineering.

Friction performance is complex (Urbakh et al., 2004; Ou et al., 2016) and is highly dependent on the environment and materials. To date, a unified view of the vibration-induced friction reduction mechanism does not exist. Hess and Soom (1991) and Grudzinski and Kostek (2005) investigated the influence of vibration normal to the surface, and Qu et al. (2010) indicated that the effect of changing the normal pressure significantly reduced sliding friction. Grudzinski and Kostek (2005), however, indicated that normal contact micro-vibrations did not reduce the friction force. The extant literature discusses reductions in the friction force with respect to decreased values of the friction coefficient (Godfrey, 1967; Broniec and Lenkiewicz, 1982). Previous studies (Grudzinski and Kostek, 2005; Leus and Gutowski, 2008), however, have indicated that vibration-induced friction reduction primarily

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results from periodic dynamic processes that occur with frictional contact. Liu et al. (2016) suggested that the magnitude of friction forces could be dramatically modified using applied vibrations with high frequency and low amplitude. Wang et al. (2014, 2015) indicated the existence of an optimal amplitude and frequency in AOT friction reduction. Presently, most vibration-induced friction reduction studies have focused on ultrasonic vibrations and frequencies in the range of thousands of Hertz (Fridman and Levesque, 1959; Storck et al., 2002; Kumar and Hutchings, 2004; Grudzinski and Kostek, 2005). It is difficult for the maximum AOT operation frequency to exceed 30 Hz because of the limitations of manufacturing techniques. Additionally, studies have also focused on the steel-steel dry friction characteristic (Godfrey, 1967; Grudzinski and Kostek, 2005). Nevertheless, studies have seldom discussed the low frequency steel-rock vibration friction in oil-based mud (OBM). It is important to analyze the characteristics of the AOT mechanical behavior in shale gas drilling engineering.

The Dahl model (Dahl, 1968a, b) is one of the earliest dynamic friction models. It was designed to simulate symmetrical hysteresis loops that were observed in bearings subject to sinusoidal excitations with small amplitudes (Piatkowski, 2014; Lampaert et al., 2004). Dynamic models, such as the LuGre model, Leuven model, and GMS model, were derived from the Dahl model (Piatkowski, 2014). These friction models used the Dahl model's properties to describe preparatory displacement-slip friction and to predict friction hysteresis. The challenge of parameter identification, however, has limited the application of these models in drilling engineering (Liu et al., 2016). It is worth noting that the analysis of vibration-induced friction reduction was based on the relative motion of a pair of small rigid bodies (Pohlman and Lehfeldt, 1966; Grudzinski and Kostek, 2005; Piatkowski, 2014); in reality, the drilling string length extends several kilometers and its elasticity cannot be ignored. Thus, it is necessary to study the AOT drag reduction mechanism while considering the entire drilling string.

The Coulomb friction model is usually adopted in the drilling string dynamic analysis of the friction between the drill pipe and wellhole rock (Johancsik, 1984; Li, 1999; Aadnøy and Andersen, 2001; Mitchell and Samuel, 2009, Mitchell et al., 2015; Mirhajmohammadabadi et al., 2010; McCormick and Chiu, 2011). Extant studies have also conducted stiff-string dynamic analysis using Dahl's elasto-plastic model (Tikhonov and Safronov, 2009; Tikhonov et al., 2013). These studies, however, did not report details related to the model solution process or AOT drag reduction mechanism.

The present study designed an indoor test rig to simulate the vibration friction between steel and shale rock in a down hole based on the Hertz contact theory. The experimental results indicated that the Dahl model was more suitable than the Coulomb model for metal/rock vibration friction in oil-based mud. Parameter identification in the Dahl model was addressed using experimental data. The drilling string axial vibration model used in the study in combination with the Dahl model was established and solved. The AOT drag reduction mechanism during the sliding drilling mode was investigated using the established model while considering the entire drilling string. According to the mechanism of friction reduction axial vibrations, the optimal position of AOT was determined.

2. Indoor experiment

This section describes the experimental setup and plan.

2.1. Experimental setup

Fig. 1 shows the experimental setup that was used to investigate the friction force characteristics between the rock and steel friction pair in an oil-based mud environment. The experiment was designed to determine the quantitative variations in the support force of the steel specimen during rock vibrations in the direction of the achieved motion.

A rock was cut into a rectangular shape with a face of the rock polished into an arc shape to maintain good contact with the steel specimen. To apply relative vibration, the rock was fixed into a cubic opening in a pillar by using a bolt (Figs. 1 and 2). The pillar was attached to the table of an electro-dynamic vibration shaker (Suzhou Sushi Testing Instrument Co. Ltd., DC-1000-15). This enabled the vibration motion to pass to the shale rock through the pillar. The electro-dynamic vibration shaker measured the displacement from peak to peak. The amplitude of the vibration motion was influenced by the power of the vibration table.

The main component involved a fixed steel square plate that was connected to a force sensor (Hangzhou Meacon Automation

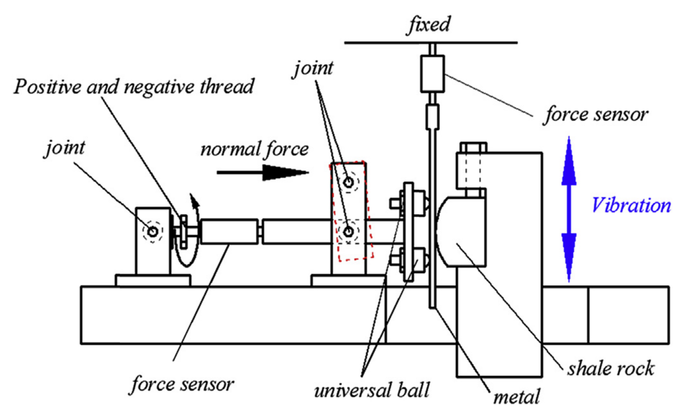

Fig. 2. Schematic of the indoor experimental rig.

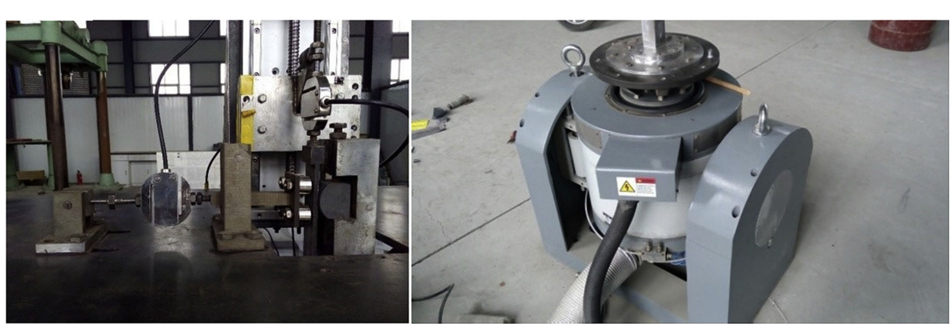

Fig. 1. Photograph of the experimental rig.