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The friction-reducing principle and application of the drill string with a hydro-oscillator

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ABSTRACT

In order to solve the problem related to effective weight on bit (WOB) transition during shale gas long departure horizontal well drilling, the hydro-oscillator has been applied more and more both in China and abroad to reduce drill string drag and enhance the rate of penetration (ROP) for the horizontal section drilling, which can greatly reduce the cost of shale gas horizontal well drilling. This paper presented a theoretical relation between axial vibration velocity and friction coefficient of drill string, analyzed the principle of reducing friction by the use of the hydro-oscillator. On the basis of principle that axial vibration can reduce drag and taking well bore trajectory, drill string combination, the hydro-oscillator structure, etc. into account, a dynamics analysis model for full-well drill string with the hydro-oscillator was established. The effects of installation location, maximum vibration force and vibration frequency of the hydro-oscillator on drag reduction were simulated, and comparison and analysis had been carried out by using field data, with the calculation results providing a theoretical basis for the field application of hydro-oscillator and the optimization of structure parameters.

1. Introduction

With the rise of the shale gas exploitation and exploration in recent years, the long departure horizontal well drilling has also been widely applied for the shale gas development. However, it is getting harder to apply the weight of drill string on drill bit as horizontal departure gets more and more far away from the vertical. In the process of slide drilling below curved well sections of a horizontal well, WOB transition is getting more and more difficult due to greater friction between drill string and wellbore (McCormick and Chiu, 2011; Hilling et al., 2012). A lot of researches and trials have been made both in China and abroad based on the ideas of initiative mechanical excitation in order to solve the problem related to effective WOB transition caused by a high friction in shale gas long departure horizontal well, and a series of tools used to reduce friction have been developed, among which the hydro-oscillator has been widely used by drill string axial vibration excited by hydraulic oscillation.

The use of the hydro-oscillator can reduce friction coefficient between the drill string and the wellbore, the weight of drill string can be effectively transmitted to the bit, ROP and bit footage can be improved (Li and Wang, 2017). For acquainting the effects of application of the hydro-oscillator during shale gas long departure horizontal well drilling, a lot of field applications of the hydro-oscillator have been mentioned both in China and abroad. Taking the 5 shale gas wells drilled on the same platform in Barnett Shale reservoir, Tarrant county, U.S. as example (Baez and Barton, 2011; Barton et al., 2011), the hydro-oscillator had been applied in buildup sections of two of these wells, and the actual drilling results indicated that using of the hydro-oscillator had increased the ROP by 19% at the buildup section and reduced the cost of drilling by 17% per foot. The actual drilling effects showed that the hydro-oscillator could effectively solve such problems as sticking drill string and WOB transition during drilling highly deviated hole section. Taking the Xinsha 21–28H Well drilled in Xinchang Gas Field in China as example, the hydro-oscillator had been applied to the drilling buildup section, and the application results indicated that use of the hydro-oscillator had increased the ROP in slide drilling by 45.16% and increased the ROP in rotating drilling for more than 30% (Xu et al., 2013).

In recent years, various research on vibration induced friction reduction between tubulars (i.e., drill pipe or coiled-tubing) and wellbores have been published (Livescu and Watkins, 2013; Gee et al., 2015; Liu et al., 2016, 2017; Jones et al., 2016; Livescu et al., 2017; Livescu and Craig, 2017). However, drilling engineers are most interested in exploiting the field applications and may not emphasize a thorough understanding of the mechanism behind vibration induced friction

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reduction. In order to explain the principle to reduce friction by use of the hydro-oscillator, Q.C. Sun had analyzed the effects of friction on ROP in the slide drilling, and explained the structure and mechanism of action of hydro-oscillator (Sun et al., 2015). R.Q. Ming had established a non-linear friction model and explained the mechanism of action of hydro-oscillator, specifically as follows: (1) hydro-oscillator could change the frictional states during slide drilling and could further reduce the friction of the whole drill string; (2) the high-frequency and low-amplitude vibration of hydro-oscillator could change the dynamic properties of drill string around and reduce the possibility of drill string buckling (Ming et al., 2015).

Some scholars had established an instantaneous dynamic model for drill string under axial excitation and a theoretical model for torque/drag of drill string with hydro-oscillator, the reasonable installation location of hydro-oscillator in drill string was determined by simulation and application results was analyzed, (Wu et al., 2014; Zhang et al., 2016; Liu et al., 2017). C.B. Yu had analyzed the law of change of key parameter of hydro-oscillator such as pressure drop, flow area and total axial forces in different static valve holes and flow rate (Yu et al., 2017). J.L. Tian had established the vibration analysis method of hydro-oscillator. taking the diameter of static valve, location of hydro-oscillator and friction coefficient of well wall into account, the vibration property of hydro-oscillator was analyzed (Tian et al., 2017).

From now on, various study about the effects of friction reduction on drill string with hydro-oscillator on the condition that the friction coefficient is fixed have been published. With reference to friction calculation and analysis method based on Dieterich-Ruina friction law (Ruina, 1983; Popov, 2010), this paper presented a theoretical relation between axial vibration velocity and friction coefficient of drill string, and established a dynamic model of drill string with hydro-oscillator by Finite Element Method, the effects of installation position of hydro-oscillator, maximum vibration force and frequency of hydro-oscillator on friction reduction had been simulated, simulation results provided an important reference for hydro-oscillator filed applications.

2. Principle of reducing friction with hydro-oscillator

Plenty of studies pointed out that the friction reduction caused by axial vibration occurs as a consequence of cyclical, instantaneous changes in the sign of the friction force vector (Matunaga and Onoda, 1992; Leus and Gutowski, 2008; Gutowski and Leus, 2012). Littmann et al. (2001), and Kumar and Hutchings (2004) experimentally studied the mechanism of friction reduction generated by axial vibration and suggested that the results acquired in experimental research exhibit significant differences when compared with the calculated friction force for static friction models. Therefore, it is necessary to establish a dynamic friction model to analyze the friction reduction principle of the hydro-oscillator. Dieterich's (1979) experimental study shows that the static friction coefficient increases slowly with time, and the friction coefficient is related to the velocity. Ruina (1983) summarized it as the law of friction related to velocity and state.

The Dieterich-Ruina friction law referenced in this paper was applied to calculate sliding friction in generalized friction law, i.e.:

$$F_R = \mu F_N \tag{1}$$

In the Dieterich-Ruina friction law, friction coefficient is related to velocity and state:

$$\mu = \mu_0 - a\ln\left(\frac{v^*}{|v|}+1\right) + b\ln\left(\frac{v^*\theta}{D_c}+1\right) \tag{2}$$

For state variables, the following dynamic equation is valid:

$$\dot{\theta} = 1 - \left(\frac{|v|\theta}{D_c}\right) \tag{3}$$

When velocity changes, $\theta(\infty) = \frac{D_c}{v}$.

The law of friction has proved to be universally applicable, not only to rocks, but also to materials of various properties. In the Dieterich-Ruina friction law, friction coefficient is calculated respectively for a steady-state sliding and at a relatively low velocity:

For a steady-state sliding, the friction coefficient is:

$$\mu = \mu_0 - (a-b)\ln\left(\frac{v^*}{|v|}+1\right) \tag{4}$$

At a relatively low velocity ($|v| << v^*$), the friction coefficient is:

$$\mu \approx \mu_0 - a\ln\left(\frac{v^*}{|v|}\right) + b\ln\left(\frac{v^*\theta}{D_c}\right) \tag{5}$$

Where μ is sliding friction coefficient (dimensionless), μ_0 is friction coefficient without taking account of instantaneous velocity and state variables (dimensionless), generally depending on material properties, v is instantaneous sliding velocity (m/s), v^* is decision velocity (m/s), generally taken as 0.2 m/s, D_c is sliding length (m), θ is state variables (s). a, b is constant (dimensionless), for drill string-well wall system, $a > b$.

For the unsteady state transition process, a friction process with a sliding velocity of v_1 is considered. If the sliding velocity changes rapidly from v_1 to v_2, the behavior is illustrated in Fig. 1, and the experimental data are from Marone (1998).

As the drill string with a hydro-oscillator is sliding axially, the relative velocity of the drill string to the well wall is:

$$v = v(t) = v_0 + v_a\sin(\omega t) \tag{6}$$

Where v_0 is slide drilling velocity of drill string without hydro-oscillator (m/h), generally being 1 m/h~10 m/h, i.e. 0.2 mm/s~2.78 mm/s, v_a is the maximum vibration velocity of hydro-oscillator relative to drill string (m/h), $\frac{\omega}{2\pi}$ is operating frequency of hydro-oscillator (Hz).

The hydro-oscillator will generate axial vibration, with an operating frequency being 9 Hz–26 Hz, the maximum instantaneous acceleration being about 1–3 times of the gravitational acceleration and an amplitude being 3 mm–10 mm. Friction coefficient between drill string and well wall is calculated with formula (2)–(6) and under decision conditions. Fig. 2 shows the variations of steel-rock friction coefficient subject to axial vibration during the slide drilling in one or more cycles.

It can be seen from Fig. 2 that the friction coefficient in one vibration cycle will, under the axial vibration of hydro-oscillator, drop first and then rise as vibration goes on. However, the friction coefficient is always less than the constant friction coefficient in the classical friction theory throughout this cycle. Where: Assuming constant friction coefficient is 0.37, vibration frequency is 15 Hz and vibration amplitude is 5 mm, the calculated results show that the minimum value of friction coefficient between drill string and wellbore is 0.3675 and the average friction coefficient is 0.368. This shows that hydro-oscillator can generate axial vibration which will reduce the friction coefficient and further reduce the friction on the drill string; however, the friction coefficient keeps changing during the axial vibration and is always lower than the constant friction coefficient.

3. Finite element dynamic model for drill string with hydro-oscillator

3.1. The 3D borehole coordinate system

In order to precisely describe the real boreholes and full-well drill strings, three coordinate systems are introduced: geodetic coordinate system $O-XYZ$, natural coordinate system o_1-tnb and body-fixed coordinate system $o-xyz$, as shown in Fig. 3.

Basic survey data are necessary for determining coordinates of survey