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Research on the characteristics of earthworm-like vibration drilling

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ABSTRACT

The load transfer difficulty caused by borehole wall friction limits the rate of penetration (ROP) and extended-reach limit of complex structural well enormously. A new friction reduction technology called "earthworm-like drilling", which can improve the load transfer and extended-reach limit, is proposed in this paper. A mathematical model based on "soft-string" model is developed to analysis the characteristics of this technology. Simulation results indicate that more stick-slip and load transfer issue are caused by higher friction. The earthworm-like drilling is more effective in reducing friction than single-point vibration drilling and less effective than multi-point vibration drilling because of the pulse pressure attenuation. However, this disadvantage can be offset by adding the number of axial oscillators. Amplitude and frequency of pulse pressure and the installation position of axial oscillators have great impact on the friction reduction and load transfer. An optimizing model based on projection gradient method is developed and used to optimize the position of three axial oscillators in a three-dimensional horizontal well. The weight on bit (WOB) increases significantly after the optimized position and the new position of axial oscillators move towards bottom of well and close to each other. Results verify the feasibility and advantages of earthworm-like drilling, and lay a solid theoretical foundation for its application in oil field drilling.

1. Introduction

Complex structural well is a series of well types with the characteristic of horizontal well and can be classified as directional well, horizontal well, extended reach well and so on (see Fig. 1). Drilling a complex structural well can ensure hitting the pay zone successfully and achieve good formation protection. Besides, it's compatible with the future stimulation to help boost the well production efficiently and economically and improve the final recovery rate. There is great difficulty in controlling the well trace of complex structural well, which make directional drilling be a key technology to build the complex structural well. At present, two well track controlling modes have formed, i.e. slide steering controlling mode and rotatory steering controlling mode. The slide steering controlling mode has wider application than rotatory steering controlling mode because of its better cost-performance. However, the drill-string do not rotate under slide steering mode, which results in huge friction between drill-string and borehole wall and decreases the axial load transfer efficiency. The weight component of upper drill-string can't be transmitted to the drill bit, and the rate of penetration (ROP) and extended-reach limit are decreased. Therefore, decreasing the friction between drill-string and borehole wall during directional drilling of complex structural well has great significance, and is an important issue of petroleum drilling engineering for many years (Gao et al., 2009).

Many scholars have carried out research on friction reduction, which in general can be divided into decreasing normal contact force or frictional coefficient. The methods of decreasing normal contact force include optimizing well track, using light drill pipe. The methods of decreasing frictional coefficient include developing high performance lubricant, using cylindrical roller sub and non-rotating protective joint (Wang et al., 2017a). However, all these methods belong to passive friction reduction methods, which achieve limited application effect. As early as 1983, Roper proposed the idea of decreasing the friction between drill-string and borehole wall by adding vibrators in drill-string (Roper and Dellinger, 1983). Until recent years, several petroleum technology service companies began to carry out application research of this idea, and focused on development of vibrator (Maidla et al., 2005; Steve et al., 2016). In addition to the development of vibrators, several scholars research the friction reduction mechanism and load transfer rule of drill-string under vibration conditions through simulation and modelling

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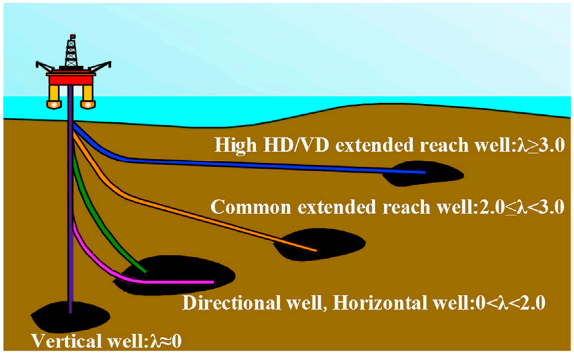

Fig. 1. Classification of complex structural well (λ = horizontal depth/vertical depth).

(Parbon et al., 2010; Wicks et al., 2012; Ritto et al., 2013; Shor et al., 2015; Gee et al., 2015; Wilson and Noynaert, 2017; Wang et al., 2017b). The mechanism of friction reduction by vibrating drill-string can be summarized as follows: (a) the axial and torsional vibrations change the static friction to dynamic friction (Skyles et al., 2012); (b) the axial and torsional vibrations change the direction of dynamic friction, which decreases the average friction force during a vibrating cycle (Gutowski and Leus, 2012, 2015); (c) the lateral vibration decreases the normal contact force periodically (Tolstoi et al., 1973). In these models, the exciting force of vibrator is usually treated as sinusoidal or cosinoidal acting on disperse nodes. In fact, the exciting force generated by disc valve structure of vibrators is bidirectional (such as axial oscillation tool (Alali et al., 2012): upward 25% and downward 75%), and the stiffness of the vibrators equals to the stiffness of disc spring used in axial oscillator sub. Inattention to the bidirectional vibrating and disc spring stiffness is an important reason for the deviation between simulation results of models and practical application effect. Meanwhile, the deficiency of limited action distance by adding only one vibrator in drill-string is increasingly apparent as designed horizontal displacement of complex structural wells increasing. The "multi-point vibration technology" realized by adding several vibrators in drill-string has become the development tendency of friction reduction technology by vibrating drill-string, also is a reserved technique meeting the increasingly urgent friction reduction demand in the future (Gee et al., 2015).

Thought and method of bionics have permeated into many subjects and industries. For example, many drilling and pipe protection problems have been resolved by using bionics theory in petroleum industry, and bionics increasingly influences the technical innovation concept and thought of petroleum exploration and development. Based on the thought of "multi-point vibration technology", the authors find that the assembly of multi-point vibration is exactly similar to the segmented body of earthworm. Every vibrator and adjacent drill-string is equivalent to one somite of earthworm. Earthworm can generate backward wave passing along its body by controlling the shrink and relaxation of muscle of somite, and can adjust the friction force between its somite and wall of hole by controlling the bristle stretching out and retracting into the somite. The earthworm moves forward, combined with squeezing and devouring soil, a cave is formed (Mezoff et al., 2004; Ren, 2009). In this process, earthworm decomposes the required huge friction of whole body moving towards into smaller friction of every somite. Meanwhile, there is always bristle of a somite penetrating into soil as fulcrum to drive neighbouring somite moving towards in the process of movement, which achieves making full use of friction.

Refer to the decomposition and using of friction, the authors propose a new friction reduction idea called earthworm-like drilling scheme (see Fig. 2). A hydraulic pulse generator and more than one axial oscillators are mounted in the drill-string from bottom to top. The hydraulic pulse generator can generate successive pulse pressure through a mechanical column valve. The axial oscillators can elongate axially with a maximum of 10 mm-15 mm (equals to the moving clearance 7) after receiving the positive pulse pressure generated by hydraulic pulse generator, while shorten to original condition after the pulse pressure disappearing. The upper sub 1 and sleeve 2 are connected to a whole by thread, and the center shaft 4 and lower sub 3 are connected to another whole by thread. All the parts of axial oscillator are revolution solid except the match position of bottom of center shaft 4 and sleeve 2 (see section view A-A in Fig. 2) which is hexagon. This specific hexagon structure makes the center shaft can only slide axially relative to sleeve 2 to transmit axial load and torsion torque of drill-string. The upper sub 1, center shaft 4 and sleeve 2 constitute a high-pressure chamber 9. The center shaft 4 and sleeve 2 constitute a low-pressure chamber 10. In the process of drilling, the high-pressure chamber fills with high-pressure drilling fluid and the low-pressure chamber fills with low-pressure drilling fluid of annulus. There are four forces acting on the center shaft 4 in axial direction, including: ①pressure difference of high-pressure chamber and low-pressure chamber; ②spring force difference of disc springs in high-pressure chamber and low-pressure chamber; ③force from lower sub 3; ④weight component of center shaft 4. The displacement and density of drilling fluid, bit nozzle pressure-drop and circulating pressure loss when drilling a well are in a specific range and can be calculated. Then the force balance of ①, ② and ④ can be realized through choose suitable disc spring stiffness of axial oscillator. Therefore, small force from lower sub 3 can make the moving clearance 7 equal to zero. As the drill-string segment where axial oscillators installed are compressed, all the axial oscillators can keep "closed" during the process of drilling if there is no positive pulse pressure. When drilling, the positive pulse pressure excited

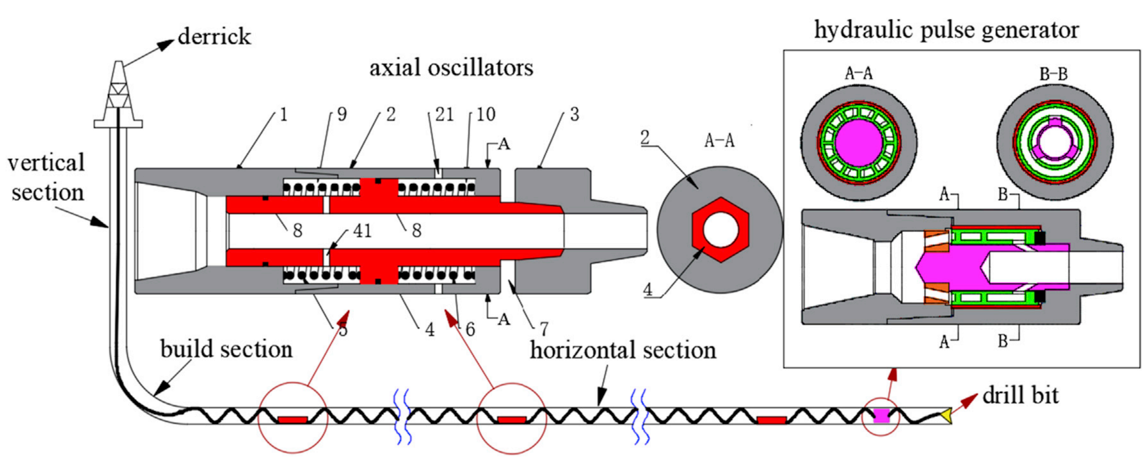

Fig. 2. Schematic diagram of earthworm-like drilling. Parts of axial oscillator: 1-upper sub; 2-sleeve; 21- low-pressure hole; 3-lower sub; 4- center shaft; 41-high-pressure hole; 5,6-disc spring; 7- moving clearance; 8-seal; 9-high-pressure chamber; 10-low-pressure chamber.