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Mechanical Characteristics of Bottom Hole Assembly in Two-Dimensional Borehole with Air Drilling

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Abstract

Bottom hole assembly (BHA) with regards to a significant component of drill string, the drilling efficiency and wellbore quality are directly determined by mechanical characteristic. Aiming at the serious problem of well deviation in the air drilling, the mechanical property of BHA in two-dimensional borehole is studied in the present work. Firstly, the three-moment equation of BHA is obtained according to mechanical model and beam-column method, and bit side force is solved by using dichotomy method. Then, considering the result of numerical computation, the influences of enlargement ratio of borehole diameter, weight on bit, well deviation angle, diameter of drill collar and bending moment of formation on bit side force are discussed. Finally, compared with finite element method, the theoretical analysis and numerical calculation of beam-column method are further demonstrated. Research shows that the side force of bit in two-dimensional borehole is the drop force, and the larger enlargement ratio of borehole diameter, well deviation angle and diameter of drill collar, the greater the drop force is; and the weight on bit affecting on bit side force is slight; however, the direction of formation bending moment has a significant effect on the drop force. This study can provide theoretical guidance to control well deviation.

Keywords

Well Deviation Control; Air Drilling; Bottom Hole Assembly; Static Analysis.

1. Introduction

As a new drilling technology, air drilling technology with advantage of drilling speed increasing is widely used in petroleum exploration and development. However, due to a series of problems such as the mechanical behavior characteristics of drill string, wellbore purification, and water production of the drilled formation, air drilling is more likely to occur well deviation than conventional liquid drilling [1]. Therefore, studying the mechanical properties of bottom hole assembly (BHA) is an indispensable part of controlling well deviation. For decades, scholars have been studying on drill string mechanics, which has achieved fruitful results and laid a solid foundation for the development of drilling industry. Walker, Bradley and Williamson et al. [2-4] studied the stress and deformation law of BHA by using elastic mechanics theory, and revealed the mechanism of well deviation. Bai et al. [5-6] studied the stress and deformation of BHA under one-dimensional, two-dimensional and three-dimensional wellbore by using the beam-column continuous beam method, respectively, which is also widely used in the analysis of mechanical properties of BHA. Gao et al. [7-9] completed the small deflection mechanical analysis of BHA by using the weighted residual method. Later, on the basis of determining the tangential position of the BHA, a method for judging the radial position of stabilizer in the wellbore is proposed. In this paper, the beam-column method is used to establish the three-bending moment equation of the BHA, and then the effects of borehole expansion rate, weight on bit (WOB), inclination angle, drill collar diameter and formation bending moment on the lateral force of the bit are discussed. Through the above research, the static characteristics of two-dimensional downhole BHA in air drilling are obtained, which provides a certain theoretical basis for controlling the well deviation.

2. Mechanical Model of BHA with Double-stabilizer

2.1. Basic Assumptions

In this paper, the following assumptions are used to establish the BHA mechanical model:

(1) The bottom hole assembly, consisting of drill bit, stabilizer and drill collar, is a small elastic deformation system;

(2) The weight on bit is constant, and center line is along the wellbore axis;

(3) The shaft wall is a rigid body;

(4) The drill string above the upper tangent point is close to the lower shaft wall;

(5) The cross section of the drill collar in each span remains unchanged and circular;

(6) The effects of drill string on rotation and vibration are ignored.

2.2. Mechanical Model

In the two-dimensional plane, the azimuth angle of wellbore is considered a constant, and the inclination angle is changed with the depth of wellbore trajectory. In order to analyze the mechanical properties of the BHA, the centerline of the wellbore is an arc located in the vertical plane, and the curvature of upper tangent point of the BHA is the same as the curvature of the wellbore axis.

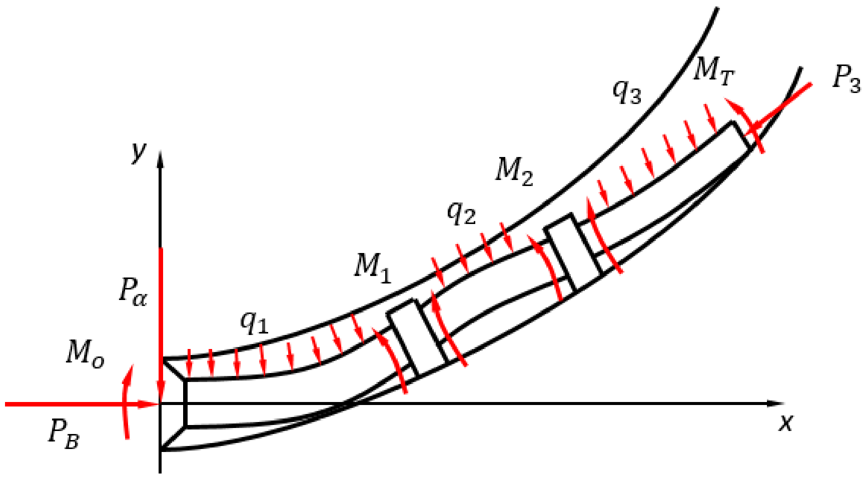

Fig 1. Bottom hole assembly mechanical model

Figure 1 shows the force analysis of the BHA under the two-dimensional well. where, M_1 and M_2 represent internal bending moment attached to the stabilizer, respectively; M_0 represents the bending moment at the bit, and M_T represents the bending moment of the BHA at the upper tangent point, expressed as

$$M_T = EI_3K \tag{1}$$

where, K represents the borehole curvature, and EI_3 represents the bending stiffness of the third cross drill collar.

The horizontal uniform load $q_i\left(i=1,2,3\right)$ is the weight of drill collar in each span, which is expressed as

$$q_i=\omega_i\sin\left(\alpha_i\right)_m \tag{2}$$

with

$$\omega_i=\left(\rho_1\frac{R_i^2-r_i^2}{4}+\rho_2\frac{r_i^2}{4}\right)\pi g \tag{3}$$

$$\left(\alpha_i\right)_m=\alpha_0-K\sum_{i=1}^{i}L_i+\frac{KL_i}{2} \tag{4}$$

where, $\omega_i(i=1,2,3)$ represents the line weight of the *i*-th span drill collar; $\left(\alpha_i\right)_m(i=1,2,3)$ represents the well inclination Angle at the midpoint of the *i*-th span drill collar; ρ_1 and ρ_2 represent the drill collar density and compressed air density, respectively; $R_i(i=1,2,3)$ and $r_i(i=1,2,3)$ represent the outer and inner diameters of the *i*-th span drill collar, and $L_i(i=1,2,3)$ represents the length of the *i*-th span drill collar, respectively.

P_B is the weight on bit, and the relation between the axial force $P_i\left(i=1,2,3\right)$ and weight on bit P_B can be expressed by

$$P_i=P_B-\sum_{j=1}^{i}\omega_jL_j\cos\left(\alpha_j\right)_m+\frac{\omega_iL_i\cos\left(\alpha_i\right)_m}{2} \tag{5}$$

The lateral force P_α in the bit can be obtained by analyzing the first cross drill collar by torque balance

$$P_\alpha=-\left(\frac{P_By_1}{L_1}+\frac{q_1L_1}{2}+\frac{M_1-M_0}{L_1}\right) \tag{6}$$

According to the superposition principle of simply supported beams, the corner of drill collar at both ends can be expressed as

$$\begin{cases}\theta_1^R=\dfrac{q_1L_1^3}{24EI_1}X\left(u_1\right)+\dfrac{M_1L_1}{3EI_1}Y\left(u_1\right)+\dfrac{M_0L_1}{6EI_1}Z\left(u_1\right)+\dfrac{y_1-y_0}{L_1}\\ \theta_2^L=\dfrac{q_2L_2^3}{24EI_2}X\left(u_2\right)+\dfrac{M_1L_2}{3EI_2}Y\left(u_2\right)+\dfrac{M_2L_2}{6EI_2}Z\left(u_2\right)-\dfrac{y_2-y_1}{L_2}\\ \theta_2^R=\dfrac{q_2L_2^3}{24EI_2}X\left(u_2\right)+\dfrac{M_2L_2}{3EI_2}Y\left(u_2\right)+\dfrac{M_1L_2}{6EI_2}Z\left(u_2\right)+\dfrac{y_2-y_1}{L_2}\\ \theta_3^L=\dfrac{q_3L_3^3}{24EI_3}X\left(u_3\right)+\dfrac{M_2L_3}{3EI_3}Y\left(u_3\right)+\dfrac{M_3L_3}{6EI_3}Z\left(u_3\right)-\dfrac{y_3-y_2}{L_3}\\ \theta_3^R=\dfrac{q_3L_3^3}{24EI_3}X\left(u_3\right)+\dfrac{M_3L_3}{3EI_3}Y\left(u_3\right)+\dfrac{M_2L_3}{6EI_3}Z\left(u_3\right)+\dfrac{y_3-y_2}{L_3}\end{cases} \tag{7}$$

With

$$\begin{cases} e_0 = \dfrac{D_w - D_b}{2} \\ e_1 = \dfrac{D_w - D_{s1}}{2} \\ e_2 = \dfrac{D_w - D_{s2}}{2} \\ e_3 = \dfrac{D_w - D_{c3}}{2} \end{cases}, \begin{cases} y_0 = e_0 \\ y_1 = \dfrac{KL_1^2}{2} - e_1 \\ y_2 = \dfrac{K\left(L_1 + L_2\right)^2}{2} - e_2 \\ y_3 = \dfrac{K\left(L_1 + L_2 + L_3\right)^2}{2} - e_3 \end{cases}, \begin{cases} X\left(u_i\right) = \dfrac{3}{u_i^3}\left(\tan u_i - u_i\right) \\ Y\left(u_i\right) = \dfrac{3}{2u_i}\left(\dfrac{1}{2u_i} - \dfrac{1}{\tan 2u_i}\right) \\ Z\left(u_i\right) = \dfrac{3}{u_i}\left(\dfrac{1}{\sin 2u_i} - \dfrac{1}{2u_i}\right) \end{cases}$$

where, u_i represents the stability coefficient of the beam, i.e., $u_i = \dfrac{L_i}{2}\sqrt{\dfrac{P_i}{EI_i}}$; $X\left(u_i\right)$, $Y\left(u_i\right)$ and $Z\left(u_i\right)$ represent the amplification factor; y_0, y_1, y_2 and y_3 represent the ordinates of the drill bit, the first stabilizer, the second stabilizer and the upper tangent point respectively; e_0, e_1, e_2 and e_3 represent the clearance value among the drill bit, the first stabilizer, the second stabilizer, the third span drill collar and the shaft wall, respectively; D_w, D_b, D_{s1}, D_{s2} and D_{c3} represent the diameters of the wellbore, bit, first stabilizer, second stabilizer and third span drill collar, respectively.

According to common tangent at the ends of the stabilizer, the continuity condition is further given

$$\begin{cases} \theta_1^R = -\theta_2^L \\ \theta_2^R = -\theta_3^L \end{cases} \tag{8}$$

Since the upper cut point of drill collar is closed to shaft wall, the curvature of the drill collar at the upper cut point is equal to the borehole curvature, and the boundary conditions can be expressed as

$$\theta_3^R = \theta_T = K\left(L_1 + L_2 + L_3\right) \tag{9}$$

Considering continuity condition and boundary condition, the beam-column method can be used to derive the three-bending moment equation of the BHA with double-stabilizers, which can be expressed as

$$\begin{aligned} & M_0 Z\left(u_1\right) + 2M_1\left[Y\left(u_1\right) + \frac{L_2 I_1}{L_1 I_2} Y\left(u_2\right)\right] + M_2 \frac{L_2 I_1}{L_1 I_2} Z\left(u_2\right) \\ & = -\frac{q_1 L_1^2}{4} X\left(u_1\right) - \frac{q_2 L_2^3 I_1}{4 L_1 I_2} X\left(u_2\right) - \frac{6EI_1}{L_1}\left[\frac{y_1 - y_0}{L_1} - \frac{y_2 - y_1}{L_2}\right] \end{aligned} \tag{10}$$

$$\begin{aligned} & M_1 Z\left(u_2\right) + 2M_2\left[Y\left(u_2\right) + \frac{L_3 I_2}{L_2 I_3} Y\left(u_3\right)\right] + M_3 \frac{L_3 I_2}{L_2 I_3} Z\left(u_3\right) \\ & = -\frac{q_2 L_2^2}{4} X\left(u_2\right) - \frac{q_3 L_3^3 I_2}{4 L_2 I_3} X\left(u_3\right) - \frac{6EI_2}{L_2}\left[\frac{y_2 - y_1}{L_2} - \frac{y_3 - y_2}{L_3}\right] \end{aligned} \tag{11}$$

$$\begin{aligned} & q_3 X(u_3) L_3^4 + 4\left[2M_3 Y(u_3) + M_2 Z(u_3)\right] L_3^2 \\ & = 24EI_3\left[L_3(L_1+L_2+L_3)K + y_2 - y_3\right] \end{aligned} \tag{12}$$

3. Numerical Calculation

In this section, the effects of borehole expansion rate, WOB, inclination angle, drill collar diameter, and formation bending moment on bit lateral force are discussed by using a conventional double-stabilizer BHA. The BHA is composed of Φ311.2mm tricone bit + Φ279.4mm drill collar + Φ305mm stabilizer + Φ228.6mm drill collar + Φ203.2mm drill collar + Φ149.2mm weighted drill pipe. In addition, some basic parameters of the BHA are shown in Table 1.

Table 1. Basic parameters

Parameter	Unit	Value
First stabilizer diameter	mm	305
Second stabilizer diameter	mm	308
Wellbore diameter	mm	311.2
Bit diameter	mm	311.2
Young modulus	GPa	206
WOB	kN	10-40
Drill collar density	kg/m^3	6256
Compressed air density	kg/m^3	50
First span length	m	19
Second span length	m	9

3.1. Borehole Expansion Rate

In the air drilling engineering, the borehole diameter is larger than the bit diameter due to the continuous erosion of the shaft wall by air. Therefore, by analyzing the measured data, the borehole expansion rate is 0%, 10%, 20% and 30% respectively, which effects on the bit lateral force are discussed. When the WOB is up to 20kN, the variation law of the lateral force of the bit is declination force, as shown in Figure 2. It can be seen from the figure that the borehole expansion rate has a significant impact on the deviation reduction force of the BHA; the greater the expansion rate of borehole, the greater the deviation reduction force is. Therefore, a larger borehole expansion rate is conducive to controlling well deviation.

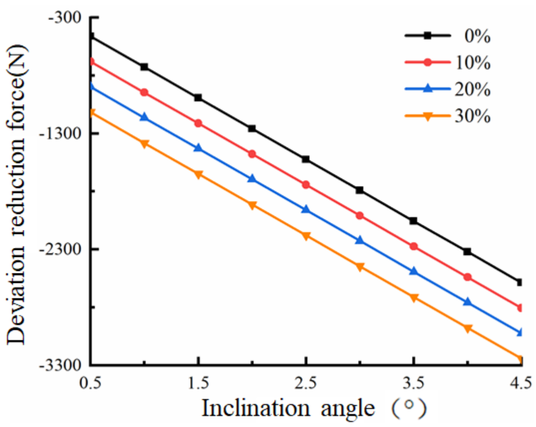

Fig. 2 Influence of borehole expansion rate on lateral force of drill bit

3.2. Weight on Bit

As shown in Fig. 3, this section discusses the influence of WOB on bit lateral force when the borehole expansion rate is 10% in the air drilling, in which the range of WOB is 10kN ~ 40kN. It can be seen from the figure that under the condition of the same well deviation angle and well diameter, the WOB has no obvious effect on the bit lateral force; in the same condition of WOB and well diameter, the bit deviation reduction force increases significantly with the increase of well deviation angle. Therefore, the deviation reduction force is not sensitive to WOB, but it is sensitive to well deviation angle.

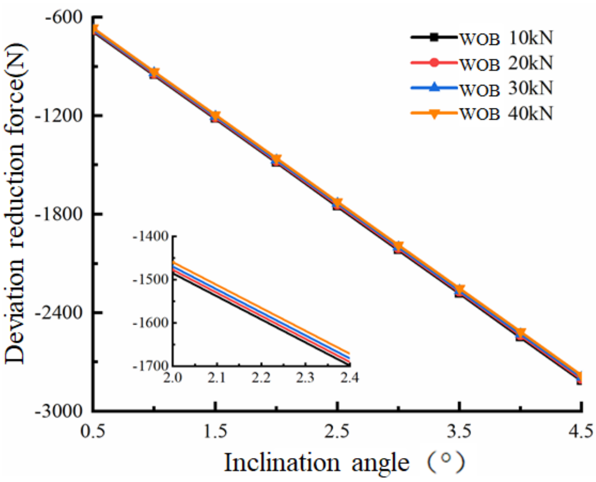

Fig 3. Influence of WOB on bit lateral force

3.3. Drill Collar Diameter

The quality and stiffness of drill collars with different diameters under the same length are different; and the larger the outer diameter of the drill collar, the stronger the bending rigidity is. By analyzing the mechanical model of BHA, it can be seen that the quality and stiffness of the drill collar are important factors affecting the lateral force of the drill bit. Considering that the diameter of the drill collar is 9 inches and 11 inches respectively, the variation law of the deviation reduction force is shown in Fig. 4; It can be seen from the figure that under the same borehole expansion rate and well deviation angle, the deviation reduction force of BHA increases with the rise of the diameter of the drill collar, and the deviation reduction force of the large diameter drill collar increases with the increase of the well deviation angle, which has a wider range of increase. Therefore, in order to reduce the wellbore deviation, a drill collar with a larger diameter is selected.

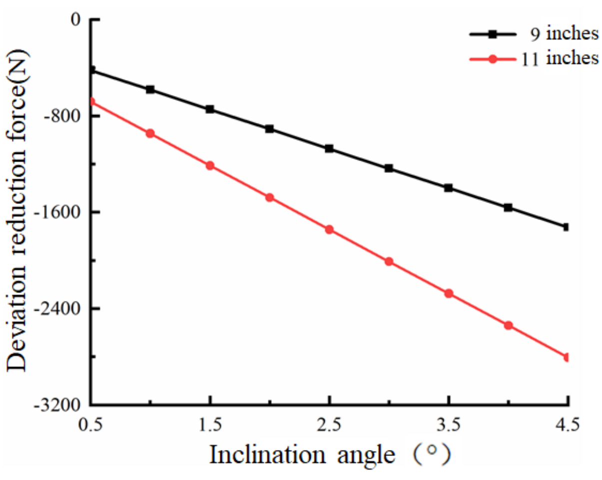

Fig 4. Influence of drill collar diameter on bit lateral force

3.4. Formation Bending Moment

The formation encountered during drilling is complex. When the heterogeneity of the drilled formation is strong, the reaction force of the formation on the bit is unevenly distributed, resulting in bending moment at the bit. Therefore, it is necessary to discuss the influence of formation bending moment on bit lateral force in this section. Fig. 5 shows the effect of formation bending moment on the deviation reduction force of the drilling tool. It can be found that the direction of the formation bending moment has a significant effect on the deviation reduction force of the drilling tool. When the formation bending moment is positive, the slope-reducing force decreases as the bending moment increases; however, when the formation bending moment is negative, the slope-reducing force also increases with the increase of the bending moment.

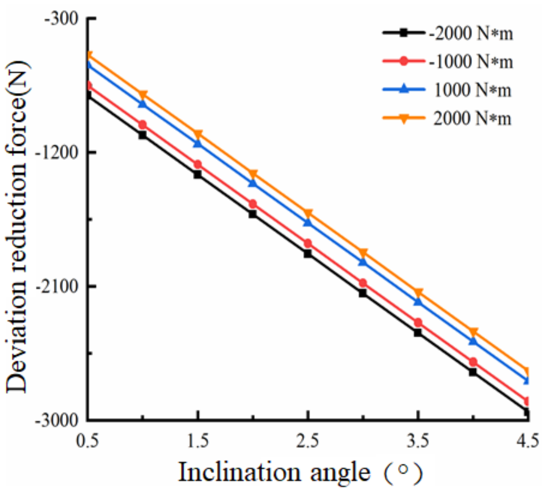

Fig 5. Influence of formation bending moment on bit lateral force

4. Model Validation

In order to verify the accuracy of model establishment and numerical calculation in this paper, taking a BHA composed of Φ 311.2mm tricone bit + Φ 228.6mm drill collar + Φ 308.5mm stabilizer + Φ 228.6mm drill collar + Φ 308.5mm stabilizer + Φ 228.6mm drill collar + Φ 203.2mm drill collar + Φ 139.7mm reinforced drill pipe as an example. The finite element method is used to verify the correctness of the mechanical model. As shown in Fig.6, the calculation results of the two methods are listed. It can be found that the results obtained by the finite element method and the longitudinal-transverse method are in good agreement. Therefore, the models and numerical results established by using the beam and column method are reliable.

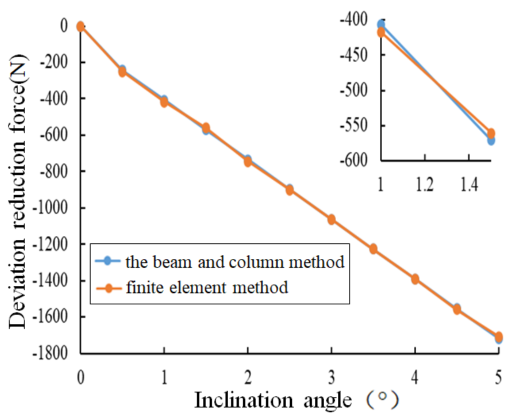

Fig 6. Comparison of finite element method and the beam and column method

5. Conclusion

In this paper, the mechanical properties of BHA are revealed through theoretical derivation, numerical calculation and method comparison. Its important conclusions are summarized as follows:

(1) The model established by the beam-column method can accurately calculate the lateral force of the drill bit, and the lateral force is related to the position of the upper tangent point;

(2) The lateral force of the drill bit is the deviation reduction force, which is mainly affected by the expansion rate of the wellbore, the inclination angle, the diameter of the drill collar and the bending moment of the formation;

(3) The numerical calculation results of the longitudinal and transverse method and the finite element method are in good agreement, which verifies the correctness of the model.

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