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On Appropriately Matching the Bottomhole Pendulum Assembly with the Anisotropic Drill Bit, to Control the Hole-Deviation

Deli Gao[1], **Zhen Dong**[1] **and Hui Zhang**[1]

Abstract: The bottom hole pendulum assembly is a type of bottom hole assembly (BHA) for controlling the hole deviation, and has been widely used in drilling engineering. Generally, the ability of the drill bit to penetrate laterally, is different from its ability to penetrate axially, so that the drill bit has an anisotropy which affects the hole-deviation-control characteristics of the BHA. The tilt angle and the side force of the drill bit are obtained by a BHA analysis based on the method of weighted residuals. Thus, the effective drilling force can be determined using the rock-bit interaction model. On this basis, the effects of the drill bit anisotropy on the hole-deviation-control characteristics of the bottom hole pendulum assembly are illustrated by a case study, which shows that the bottom hole pendulum assembly should be appropriately matched with the drill bit of the "side-aggressive" and "short gauge protection" type. The critical drill bit anisotropy index is defined and the factors which influence it are discussed. The bottom hole pendulum assembly would make the hole-deviation dropping or building when the drill bit anisotropy index may be greater or less than the critical drill bit anisotropy index, respectively. In summary, matching the drill bit anisotropy appropriately with the bottom hole pendulum assembly is critical to effectively control the hole deviation and improve the drilling efficiency.

Keywords: drilling engineering; hole deviation control; bottom hole pendulum assembly; the drill bit anisotropy; rock-bit interaction model

1 Introduction

Bottom hole pendulum assembly is a type of BHA for controlling the deviation of the hole, and it has been widely used on land and at sea. Most previous studies about the bottom hole pendulum assembly were concentrated on the optimization

[1] Key Laboratory Of Petroleum Engineering in the Ministry of Education, China University of Petroleum, Beijing 102249, China. E-Mail: gaodeli@cupedu.cn and dz19880317@126.com

of the BHA. Some researchers such as Yang (1982), Lei(1997) and Shi (2009) illustrated the optimal placement of the stabilizer. Song et al(2001) explained the reasons why the inclination angle will increase while the weight on bit (WOB) is increased, and brought out a new method to resolve this problem. Only a few studies were carried out, on the mechanism of matching the bottom hole pendulum assembly with the anisotropic drill bit [Nie et al(1991)]. Bottom hole pendulum assembly may increase the deviation angle even with the optimal parameters in some special cases. The reason for this phenomenon is due to ignoring the interaction of the drill bit and the formation, Studying the building mechanism of the bottom hole pendulum assembly, and establishing a criterion for matching, can effectively guide the process of the drill bit selection.

The development of the well trajectory is the result of the interaction between the drill bit and the formation, and anisotropy of the drill bit is an important factor which affects the deflection characteristics of the BHA. Gao et al (1989) considered the influences of the anisotropies of the formation as well as the drill bit, established a three-dimensional rock-bit interaction model (UPC model), and put forward the concept of an effective drilling force. The calculation of an effective drilling force [Gao et al(1989)] takes into account the mechanical properties of the bottom hole pendulum assembly and rock-bit interaction, and determines the ultimate deflection characteristics of the bottom hole pendulum assembly. The effective drilling force can be used as the physical standard for the control of the wellbore trajectory. Analyzing the effect of the drill bit anisotropy on the deflection properties of the bottom hole pendulum assembly has a profound significance to the process of the drill bit selection, and it also helps to control hole-deviation efficiently.

2 Effective drilling force

Drill bit anisotropy refers to the differences in the drilling ability of the bit in different directions, and it can be expressed by a drill-bit-anisotropy index[Gao et al(1989)].If an anisotropic drill bit penetrates in the isotropic formation, the drill bit anisotropy can be defined as follows:

$$\begin{cases} D_a = R_a / F_a \\ D_l = R_l / F_l \\ I_b = D_l / D_a \end{cases} \tag{1}$$

The range of the drill bit anisotropy index is (0, ∞), and taking into account the breaking of the rock, axial drilling efficiency is generally greater than the lateral drilling efficiency. If the drill bit anisotropy index is equal to 1, the drill bit is isotropic. If the drill bit anisotropy index is greater than 1, then the lateral drilling efficiency is greater than the axial drilling efficiency.

In the actual drilling process, the effective drilling force determines the final drilling direction, and it can be expressed as follows:

$$\begin{pmatrix} F_\alpha \\ F_\phi \\ F_t \end{pmatrix} = [D][I_R][D]^{-1}[F][I_B][F]^{-1} \begin{pmatrix} F_{xd} \\ F_{yd} \\ F_{zd} \end{pmatrix} \tag{2}$$

3 Mechanical analysis of the bottom hole pendulum assembly

Without considering the change of the azimuth, the mechanical analysis of the bottom hole pendulum assembly can be simplified into a two-dimensional BHA problem. Fig.1 shows the reference coordinate system.

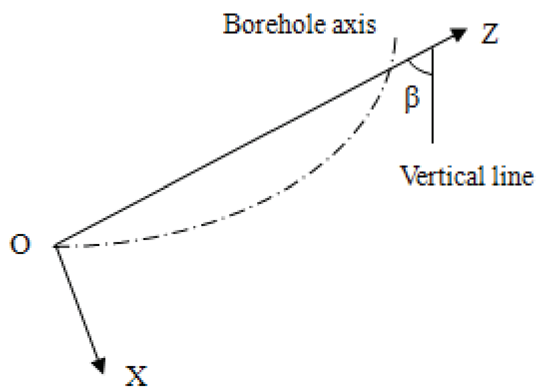

Figure 1: Reference coordinate system

The Origin-point is at the drill bit of the bottom hole: Plane xoz is the vertical plane, the z axis is through the drill bit and the upper stabilizer of the BHA, and pointing upward. The X axis is perpendicular to the Z axis and pointing to the low side of the bottom plane. The governing equation of the bending deformation [Gao et al(1994)] can be expressed as follows:

$$\frac{d^4u}{ds^4} + \frac{d}{ds}\left(F_z^* \frac{du}{ds}\right) = q_z \tag{3}$$

$$\begin{cases} F_z^* = P^* - q_z s = F_z/EI \\ q_x = q\sin\beta/EI \\ q_z = q\cos\beta/EI \\ P^* = P/EI \\ F_z = P - q\cos\beta\cdot s \end{cases} \tag{4}$$

The trial function for the deflection of the BHA [Gao et al(1994)] can be expressed as follows:

$$u_j(\mathrm{s}) = \sum_{1}^{5} C_{ij} s^{5-i} \qquad (j = 1, 2, \ldots, n+1) \tag{5}$$

The drill bit tilt angle and the side force are obtained by a BHA analysis based on the method of weighted residuals. The effective drilling force of the bottom hole pendulum assembly can be determined using the UPC model. The calculation formula of F_α can be expressed as follows:

$$F_\alpha = F_s(A_1B_1 + A_2B_3) + W_{ob}(A_1B_3 + A_2B_2) \tag{6}$$

Where

$$\begin{cases} A_1 = d_{11}^2 I_{r1} + d_{12}^2 I_{r2} + d_{13}^2 \\ A_2 = d_{11}d_{31}I_{r1} + d_{12}d_{32}I_{r2} + d_{13}d_{33} \end{cases} \tag{7}$$

$$\begin{cases} B_1 = I_b + A_t^2 \\ B_2 = A_t^2 I_b + 1 \\ B_3 = -A_t I_b + A_t \end{cases} \tag{8}$$

$$\begin{cases} d_{11} = \cos\alpha\cos\gamma\cos\Delta\varphi - \sin\alpha\sin\gamma \\ d_{12} = -\cos\alpha\sin\Delta\varphi \\ d_{13} = -\cos\alpha\sin\gamma\cos\Delta\varphi - \sin\alpha\cos\gamma \\ d_{21} = \cos\gamma\sin\Delta\varphi \\ d_{22} = \cos\Delta\varphi \\ d_{23} = -\sin\gamma\sin\Delta\varphi \\ d_{31} = \sin\alpha\cos\gamma\cos\Delta\varphi + \cos\alpha\sin\gamma \\ d_{32} = -\sin\alpha\sin\Delta\varphi \\ d_{33} = -\sin\alpha\sin\gamma\cos\Delta\varphi + \cos\alpha\cos\gamma \end{cases} \tag{9}$$

Assuming that the formation is isotropic, and taking only the drill bit anisotropy into consideration, the formula for computing the effective drilling force can be simplified as follow:

$$F_\alpha = (F_s - A_t \cdot W_{ob})I_b + F_s \cdot A_t^2 + A_t \cdot W_{ob} \tag{10}$$

As can be seen from the above formula, the effective drilling force is related to the mechanical parameters and the drill bit anisotropy. There is a linear relationship

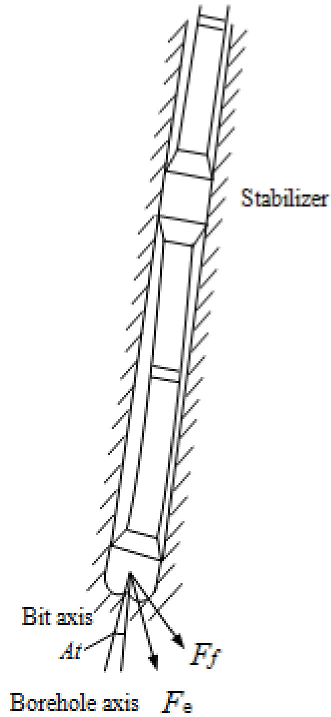

Figure 2: A schematic for the mechanical analysis of bottom hole pendulum assembly

between the drill bit anisotropy index and the effective drilling force [Gao et al (1991)].

The parameters of an example bottom hole pendulum assembly are expressed as follows: D_h is 216mm, D_s is 214mm, D_{cw} is 178mm, D_{cn} is 71.4mm, E is 210GPa, α is 3°, Wob is 100kN, ρ is 1.15 g/cm^3, q is 1.6kN/m, L is 21m.

As we can see from Table 1, the side force maintains as a compressive force as the hole angle increases from 3 ° to 15°, and the magnitude of the side force increases with the increase of the hole angle. For the same hole angle, the side force decreases with the increase of WOB.

As we can see from Table 2, the tilt angle of the bit increases with the increase of the hole angle. For the same hole angle, the drill bit tilt angle increases with the increase of WOB.

Table 1: The effect of the hole angle on the side force

Hole angle(°)	W_{ob}(kN)				
	90	100	110	120	130
3	-0.4609	-0.4510	-0.4409	-0.4307	-0.4202
5	-0.8052	-0.7890	-0.7724	-0.7554	-0.7380
7	-1.1504	-1.1278	-1.1047	-1.0809	-1.0564
9	-1.4950	-1.4662	-1.4364	-1.4058	-1.3742
11	-1.8384	-1.8032	-1.7668	-1.7294	-1.6907
13	-2.1798	-2.1383	-2.0954	-2.0512	-2.0054
15	-2.5188	-2.4710	-2.4217	-2.3707	-2.3179

Table 2: The effect of the hole angle on the drill bit tilt angle

Hole angle(°)	W_{ob}(kN)				
	90	100	110	120	130
3	0.0799	0.0808	0.0818	0.0829	0.0841
5	0.1522	0.1548	0.1576	0.1604	0.1635
7	0.2256	0.2298	0.2342	0.2389	0.2439
9	0.2991	0.3049	0.3111	0.3176	0.3244
11	0.3726	0.3800	0.3878	0.3961	0.4048
13	0.4458	0.4548	0.4643	0.4743	0.4850
15	0.5185	0.5291	0.5403	0.5520	0.5645

4 Effect of drill bit anisotropy on the effective drilling force

Not all the drill bits are isotropic, and the drill bit anisotropy index would change because of the drill bit wear and other factors. It is necessary to study the relationship between the effective drilling force and the drill bit anisotropy under the circumstances of different hole angles. Assuming that the formation is isotropic, and only taking the drill bit anisotropy into consideration, the effect of drill bit anisotropy on the effective drilling force could be expressed as in Figure 3.

There is a linear relationship between the drill bit anisotropy index and the effective drilling force. The slopes of the lines are approximately equal under the different WOB. When the drill bit anisotropy index is greater than a certain value, the effective drilling force is the dropping force, and the larger the drill bit anisotropy index, the greater the effective drilling force. For the same drill bit anisotropy index, the effective drilling force decreases with the increase of WOB.

Fig.4 shows that the deflection characteristics of bottom hole pendulum assembly

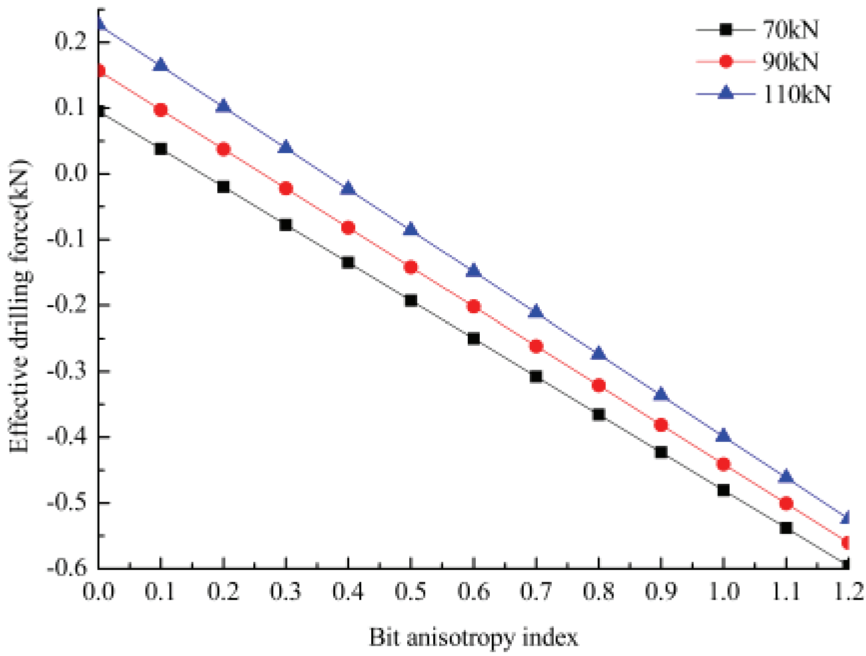

Figure 3: The effect of drill bit anisotropy index on the effective drilling force

are also related to the deviation angle. There is a linear relationship between the hole angle and the effective drilling force, and the slope of the line characterizing this linear relationship is dependent on the drill bit anisotropy. With the drill bit anisotropy index increasing from 0 to 1.2, the absolute value of the slope decreases first and then increases.

We definine I_{bt} as the critical drill bit anisotropy index, which is the value for the drill bit anisotropy index when the deflection characteristics of the bottom hole pendulum assembly begins to change from dropping to building in hole angle. For certain BHA and drilling parameters, the bottom hole pendulum assembly would be a dropping BHA if the drill bit anisotropy index is greater than a critical drill bit anisotropy index, and the bottom hole pendulum assembly would be a building BHA if the drill bit anisotropy index is less than a critical drill bit anisotropy index. I_{bt} can be expressed as:

$$I_{bt} = \frac{F_s \cdot A_t^2 + W_{ob} \cdot A_t}{A_t \cdot W_{ob} - F_s} \tag{11}$$

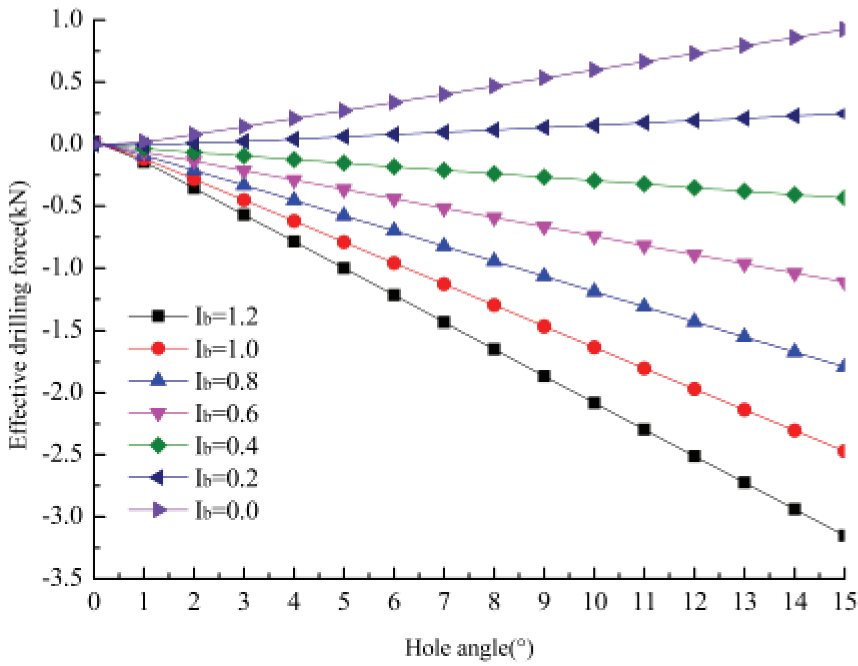

Figure 4: The effect of hole angle on the effective drilling force

As we can see from Fig.5, the critical anisotropy index increases with the increase of the hole angle, and it increases fast in the beginning and tends to flatten out quickly. For the same hole angle, the greater the WOB, the greater will be the critical drill bit anisotropy index. The bottom hole pendulum assembly may be a building BHA if the drill bit anisotropy index is smaller than the critical value.

Through the above analysis, the bottom hole pendulum assembly should be appropriately matched with the drill bits, depending on the different hole angles and WOB. If the drill bit anisotropy index is much smaller than the critical value, the bottom hole pendulum assembly may cause an increase in the hole angle, and the increase in the hole angle will increase the effective drilling force, causing a serious hole deviation eventually.

5 Conclusions

1. The critical value of the drill bit anisotropy index is defined, so as to appropriately match the drill bit anisotropy with the bottom hole pendulum assembly. In order to control the deviation of the hole effectively, the drill bit should be

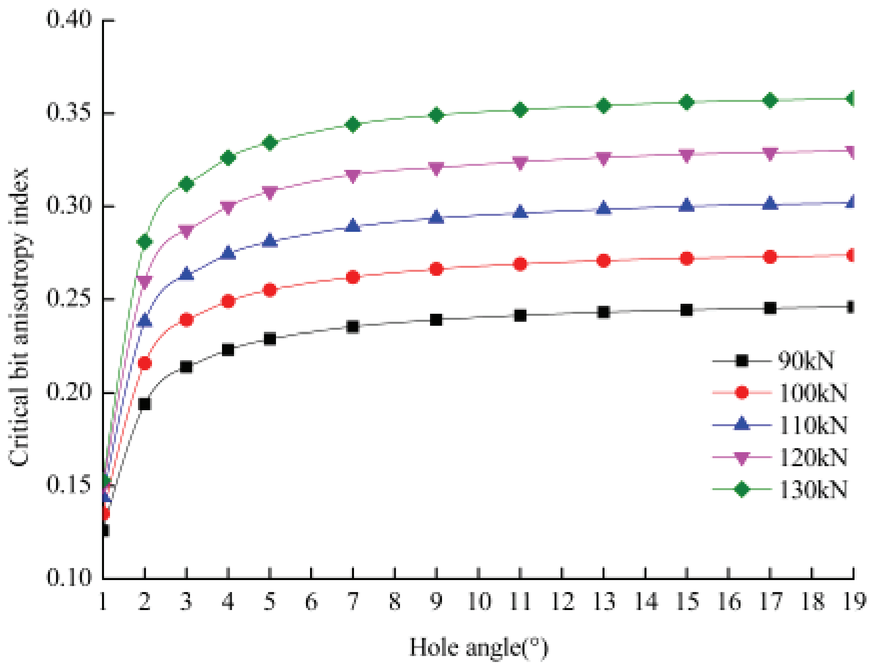

Figure 5: The effect of the hole angle on the critical drill bit anisotropy index

designed to be of the "side-aggressive" and "short gauge protection" type, to make the drill bit anisotropy index greater than its critical value.

2. The drill bit anisotropy index not only has a significant impact on the effective drilling force, but also it could change the deflecting characteristic of BHA. There is an approximately linear relationship between the drill bit anisotropy index and the effective drilling force.

3. For the bottom hole pendulum assembly, the effective drilling force would cause a serious hole deviation, with the increase of the hole angle, if the drill bit anisotropy index is equal to zero.

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Nomenclature

F_a	axial force of the drill bit, kN;
R_a	ate of penetration in axial direction of the drill bit, m/s;
F_l	lateral force of the drill bit, kN;
R_l	rate of penetration in lateral direction of the drill bit, m/s;
D_a	axial cutting ability of the drill bit, m/(h·kN);
D_l	lateral cutting ability of the drill bit, m/(h·kN);
$[D]$	transformation matrix from the strata coordinate system to the bottom hole coordinate system;
$[F]$	transformation matrix from the drill bit coordinate system to the bottom hole coordinate system;
$[D]^{-1}$	inverse matrices of matrix $[D]$;
$[F]^{-1}$	inverse matrices of matrix $[F]$;
$[I_R]$	matrices of formation anisotropy index;
$[I_b]$	matrices of drill bit anisotropy index;
$[D_n]$	drillability of the formation in normal direction;
F_α	effective inclination force, kN;
F_ϕ	effective azimuth force, kN;
F_e	effective resultant force, kN;
u	lateral deflection displacement of BHA elastic deforming line relative to the Z axis, m;
s	arc length coordinate variable of any point on the elastic deformation, m;
q	effective weight of the unit length of the drill collar, kN/m;
EI	bending stiffness, kN/m^2;
P	pressure at the origin in the direction of the Z axis ,kN;
C_{ij}	undetermined coefficients;
n	the number of the stabilizers;
α	hole angle at the drill bit, $^\circ$;
Φ	azimuth at the drill bit, $^\circ$;
γ	dip angle of the formation, $^\circ$;
β	the angle between the Z axis and the vertical line, $^\circ$;
$\Delta\Phi_f$	the difference between the drilling azimuth and formation down dip azimuth, $^\circ$;
I_b	drill bit anisotropy index;
I_{bt}	critical drill bit anisotropy index;
I_{r1}	formation anisotropy index in the dip direction;
I_{r2}	formation anisotropy index in the direction of strata;
F_f	mechanical resultant force on drill bit ,kN;
F_s	inclination force, kN;

A_t drill bit tilt angle, rad;
Wob weight on the drill bit, kN;
D_h outer diameter of the drill bit, mm;
D_s outer diameter of the stabilizer, mm;
D_{cw} outer diameter of drill collar, mm;
D_{cn} inner diameter of the drill collar, mm;
E elastic modulus, GPa;
ρ density of the drilling fluid, g/cm^3;
q weight of the unit length of the drill collar, kN/m;
L the length from the drill bit to stabilizer, m;

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