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Drilling Trajectory Prediction Model for Push-the-bit Rotary Steerable Bottom Hole Assembly

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ABSTRACT

The study of rotary steering drilling technology is currently one of the hot topics in the drilling engineering field. It requires accurate well trajectory control instructions when rotary steerable tools are applied to achieve the well trajectory control goal. A drilling trajectory prediction model will benefit this progress. According to the continuous beam theory, a mechanical model of push-the-bit rotary steerable bottom hole assembly (RSBHA) was established to characterize the bit steering property. The relation of bit lateral force and bit tilt angle with the influencing parameters such as borehole parameters and drilling operation parameters was obtained. Then further considering the bit cutting anisotropy, the drilling trajectory prediction model was built which quantitatively estimated the variation of inclination and azimuth angle. The model calculation result showed a consistency with the field experimental data proving the prediction model is reasonable in theory and feasible in engineering. This study could provide guidance for selecting the steering parameters to meet the control goal.

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NOMENCLATURE

F	Resultant steering force (kN)	A_P, A_Q	Tendency angle in the P and Q plane (rad)
F_P, F_Q	Component force in the P and Q plane at steering pads (kN)	V_x, V_y, V_z	Drilling speed component in x, y and z axis separately (m/h)
N_{bP}, N_{bQ}	Bit lateral force in the P and Q plane (kN)	ΔL	Well depth micro increment (m)
P_b	Weight on bit (kN)	**Greek Symbols**	
q_1	Weight per meter of first string span (kN)	ω	Tool face angle (rad)
M_{1P}	Bending moment at stabilizer in the P plane (kN·m)	$\theta_i^R, \theta_{i+1}^L$	Tilt angle at the right and left end of the number i and i+1string span (rad)
y_1	Y-axis coordinate value of stabilizer's center (m)	Δ	Gap between stabilizer and borehole (m)
L_1	Length of the first string span (m)	α_P, α_Q	Tilt angle on bit in the P and Q plane (rad)
L_{11}	Distance between steering pads and bit (m)	α_b	Inclination angle (rad)
K_P, K_Q	Borehole curvature in the P and Q plane (° /30m)	φ_b	Azimuth angle (rad)
EI_1	Flexural rigidity of first string span (kN·m^2)	**Subscripts**	
$X(u_1), Z(u_1)$	Amplification factors	P, Q	Inclination plane and azimuth plane
k	Stability factor	i	The number of string span
I_b	Bit cutting anisotropy	b	Bit
V_l, V_a	Drilling speed component in lateral direction and axial direction (m/h)	l, a	Bit lateral and axial direction
F_l, F_a	Bit lateral force and axis force (kN)	R, L	Right and left

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1. INTRODUCTION

With the development of oil and gas resources, more horizontal wells, extended reach wells and other complex structure wells are drilled today [1]. Rotary steerable drilling technology has the advantages such as high drilling speed, good borehole quality and strong ability to extend the horizontal section, so the application of rotary steerable drilling has become more extensive in drilling these wells. There are two commonly used rotary steerable tools (RST): push-the-bit and point-the-bit RST. For whichever RST, proper drilling operation parameters need to be set up to make sure the RST drilling along with designed well track. Understanding the RST's drilling tendency is the basis of operation parameters selection.

So far, much research work has been done on the structure optimization design to get a better performance [2-4], however, theoretical analysis of RST's drilling trajectory under certain steering parameters is not enough. In the drilling process of using RST, steering parameters selection is mainly based on the field state.The empirical operation will limit the better use of rotary steerable tools. A good understanding on how well inclination and azimuth angle quantitatively change with the influencing factors such as drilling operation parameters, borehole parameters and bit cutting property can help engineers to make the correct steering parameters decision to improve the accuracy of well trajectory control [5].

Currently, three point geometry method [6, 7] and balanced curvature method [8, 9] are the two commonly used methods to estimate the build-up rate of ordinary bottom hole assemblies (BHAs) and then build-up rate is used to reflect the change of well drilling trajectory. The three point geometry method assumes BHA as rigid body. No elastic deformation will generate under the action of weight on bit and gravity. The balanced curvature method further takes effects of drilling parameters and borehole parameters into consideration. Then bit lateral force is calculated to determine the build-up rate. The latter method is considered as a more accurate prediction model. However, the balanced curvature method also neglects the bit cutting anisotropy when bit acts with rocks. Researches have shown that bit cutting property played an important role in the forming of well trajectory [10, 11]. So, it is necessary to take this factor into consideration and build an improved prediction model.

In this paper, the study is mainly focused on push-the-bit RST. Neglecting the dynamic characteristics [12], we established a three-dimensional mechanical analysis model of push-the-bit bottom hole assembly (RSBHA) to obtain the steering parameters on bit. Then an index reflecting the bit cutting anisotropy was used to derive the well trajectory prediction model. Finally, the calculation result of inclination and azimuth angle was compared to the field data to verify the validity of the built well trajectory prediction model.

2. RSBHA MECHANICAL MODEL

The steering principle of push-the-bit rotary steerable drilling tool can be summarized as: when a well control instruction is given, the three steering pads will extend to the borehole wall, pushing the drill string to the other side of wellbore and generating lateral forces on the bit and stabilizer. Then bit will generate side cutting and drill towards orientation of resultant steering force [13]. The directional drilling of push-the-bit RSBHA is shown in Figure 1.

Bit lateral force and tilt angle play an important role in directional drilling. For push-the-bit rotary steerable tool, the two mechanical parameters are greatly affected by the steering force generated by three extendable pads. Figure 2 shows the decomposition of resultant steering force on the cross section of bias unit at steering pads.

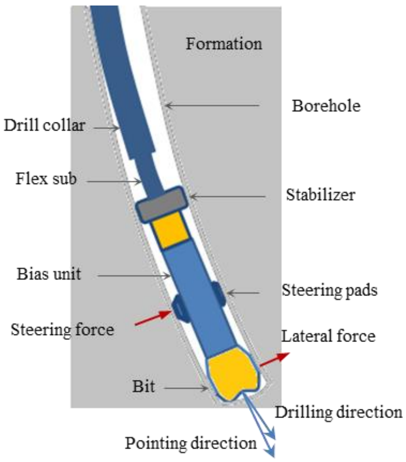

Figure 1. Directional drilling of push-the-bit RSBHA

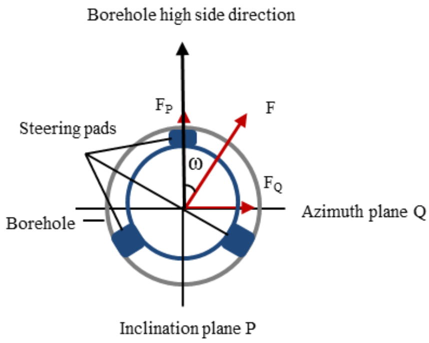

Figure 2. Decomposition of resultant steering force

Inclination plane and azimuth plane are usually used in directional drilling as shown in Figure 2. Component forces in inclination plane P and azimuth plane Q decomposed by resultant steering force can be expressed as:

$$\begin{cases} F_P = F\cos\omega \\ F_Q = F\sin\omega \end{cases} \tag{1}$$

where F_P is the component steering force in the P plane; F_Q is the component steering force in the Q plane; F is the resultant steering force generated by three steering pads and ω is the tool's face angle.

Continuous beam theory is an effective method to calculate the bit mechanical property [14, 15]. The theory considers a multi-stabilized bottom hole assembly in borehole as a continuous beam-column with many supports. Then the beam-column can be divided into several simply-supported beam-columns by separating the sections at each stabilizer. Figure 3 shows the continuous beam model of push-the-bit RSBHA in the P plane.

The whole RSBHA can be divided into three string spans. The first one is the string between bit and stabilizer. Flex sub has a smaller cross section size and lower flexural rigidity than its upper section. So the section between stabilizer and tangent point can be divided into two parts from the connection of flex sub and upper drill collar. The continuity condition is the equal tilt angle at both sides of the support:

$$\theta_i^R = \theta_{i+1}^L \tag{2}$$

where θ_i^R is the tilt angle at the right end of the number *i* string span and θ_{i+1}^L is the tilt angle at the left end of the number *i+1* string span. According to the continuity condition, three moment equation can be obtained with unknown quantity bending moment at stabilizer to be solved.

The first string span is mainly affected by weight on bit (WOB), weight per meter of string, steering force, bit lateral force and bending moment at stabilizer. The bit lateral force in the P plane can be expressed as Equation (3) based on the balance principle:

$$N_{bP} = -\left(\frac{P_b y_1}{L_1} + \frac{q_1 L_1}{2} + \frac{M_{1P}}{L_1} + \frac{F_P(L_1 - L_{11})}{L_1}\right) \tag{3}$$

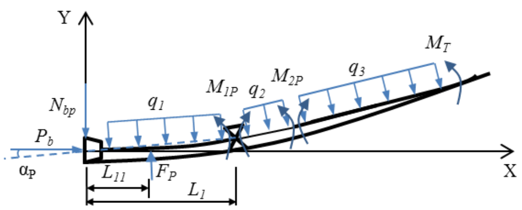

Figure 3. Continuous beam model of RSBHA

where N_{bP} is the component force in the P plane of bit lateral force, called deviation force; P_b is the WOB; q_1 is the weight per meter of the string span between bit and stabilizer; M_{1P} is the bending moment in the P plane at stabilizer; L_1 is the length of string span between bit and stabilizer; L_{11} is the distance between steering pads to bit; y_1 is the Y-axis coordinate value of stabilizer's center in an arc borehole expressed as:

$$y_1 = \frac{K_P \cdot L_1^2}{2 \times 1719} \pm \frac{\Delta}{2} \tag{4}$$

where, Δ is the gap value between stabilizer and borehole wall.

Tilt angle can be expressed as:

$$\alpha_P = \frac{q_1 L_1^3}{24 EI_1} X(u_1) + \frac{M_{1P} L_1}{6 EI_1} Z(u_1) + \frac{F_P \sin(k(L_1 - L_{11}))}{P_b \sin(kL_1)} - \frac{F_P(L_1 - L_{11})}{P_b L_1} - \frac{y_1}{L_1} \tag{5}$$

where, α_p is the tilt angle in the P plane; EI_1 is the flexural rigidity of the first string span; $X(u_1)$ and $Z(u_1)$ are the amplification factors. k is a stability factor resulting from the effect of axis forces applied at both ends of simply-supported beam-column and can be expressed as:

$$k = \sqrt{P_b / EI_1} \tag{6}$$

Azimuth force N_{bQ} and tilt angle α_Q in azimuth plane Q can also be gotten with the similar analysis.

3. DRILLING TRAJECTORY PREDICTION MODEL

3. 1. Model Establishment Generally, bit cutting capacity is different in lateral direction and axial direction. It is called bit cutting anisotropy and can be expressed by an index as seen in Equation (7):

$$I_b = \frac{V_l / F_l}{V_a / F_a} \tag{7}$$

where, I_b is the bit cutting anisotropy index; V_l and V_a are the drilling speed component in lateral direction and axial direction of bit coordinate system separately; F_l and F_a are the bit lateral force and axis force in bit coordinate system.

Establish the geodetic coordinate system O-NED taking wellhead O as the origin. Taking bottom hole center o as the origin, establish bottom hole coordinate system o-xyz and bit coordinate system o-x'y'z' separately. The coordinates are shown in Figure 4. In the bottom hole coordinate system, axis x points to the tangent direction of the borehole axis and axis z points towards high side direction of borehole. The direction of axis y is determined by the right-hand rule. Bit coordinate system is formed through bottom hole coordinate by turning an angle value of α_P around y axis, and then turning α_Q around z axis [16]. The axis x' points towards bit axis and y' and z' point towards bit lateral direction.

We can get the bit force value $F(x,y,z)=\begin{bmatrix}P_b & N_{bP} & N_{bQ}\end{bmatrix}^T$ in the bottom hole coordinate system and tilt angle α_P, α_Q by the push-the-bit RSBHA mechanical analysis model above. Then by converting the bit force into bit coordinate system, we can get an equation as follows:

$$F(x',y',z')=[k_1]^{-1}F(x,y,z) \tag{8}$$

where, $F(x',y',z')$ is the bit force in bit coordinate system; $[k_1]$ is the transformation matrix of bottom hole coordinate and bit coordinate system shown as:

$$[k_1]=\begin{bmatrix}\cos\alpha_P\cos\alpha_Q & \sin\alpha_Q & \sin\alpha_P\cos\alpha_Q \\ -\cos\alpha_P\sin\alpha_Q & \cos\alpha_Q & -\sin\alpha_P\sin\alpha_Q \\ -\sin\alpha_P & 0 & \cos\alpha_P\end{bmatrix} \tag{9}$$

According to the definition of bit cutting anisotropy index, drilling speed components of bit in bit coordinate system can be described as follows:

$$V(x',y',z')=\begin{bmatrix}1 & & \\ & I_b & \\ & & I_b\end{bmatrix}F(x',y',z') \tag{10}$$

where, $V(x',y',z')$ is the drilling speed of bit in bit coordinate system.

Then convert the drilling speed components back to bottom hole coordinate system:

$$V(x,y,z)=[k_1]V(x',y',z') \tag{11}$$

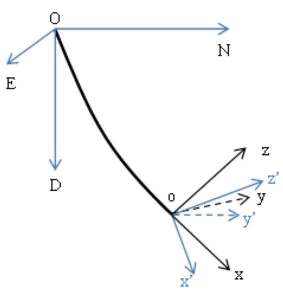

Figure 4. Geodetic, bottom hole and bit coordinates system

Tendency angle can be expressed as:

$$\begin{cases} A_P=\arctan(V_Z/V_X) \\ A_Q=\arctan(V_y/V_X/\sin\alpha_b)\end{cases} \tag{12}$$

where, A_P and A_Q are the inclination tendency angle in plane P and azimuth tendency angle in plane Q, collectively called tendency angle [14, 17]; V_x, V_y and V_z are the drilling speed component in x, y and z axis separately and α_b is the inclination angle at bit. The tendency angle represents the included angle value of bit resultant velocity direction and borehole axis direction in the P and the Q plane separately.

It was assumed that the section between bit and stabilizer AB (the first string span) was located in the borehole which took $\widehat{AB}$ as the borehole axis as shown Figure 5. When inclination tendency angle A_P is zero, the well trajectory will extend in a certain curvature. So the string span will be in the position A'B' when it goes forward micro segment length ΔL. The inclination angle at bit can be expressed as:

$$\alpha'_b=\alpha_b+\frac{\Delta L}{30}\cdot K_P\cdot\frac{\pi}{180} \tag{13}$$

where, ΔL is the well depth micro increment and α'_b is the inclination angle at bit after the well depth increment.

When inclination tendency angle A_P is not equal to zero, there will be an extra angle β added to the inclination angle.

It is assumed that the string span will be in the position A'B'' when it goes forward micro segment length ΔL. Then the angle β can be expressed as Equation (14) considering the geometric relation:

$$\beta=A_P\cdot\frac{\Delta L}{L_1}\cdot\frac{\pi-\beta}{\pi-2\times(\alpha_P+A_P-\alpha)+\beta} \tag{14}$$

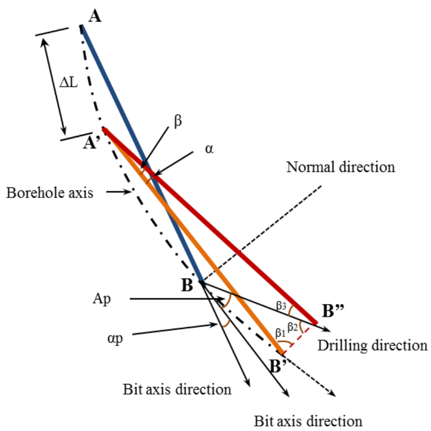

Figure 5. Inclination angle change in inclination plane

where β is the included angle when the string span is in position A'B' and A'B'', respectively; α is the included angle when the string span is at position A'B' and position AB, respectively. Because angle β, α and A_P are much smaller than π, so the following expression can be obtained:

$$\beta \approx A_P \cdot \frac{\Delta L}{L_1} \tag{15}$$

Then Equation (12) and Equation (14) can be summarized as a united form shown as:

$$\alpha'_b = \alpha_b + A_P \cdot \frac{\Delta L}{L_1} + \frac{\Delta L}{30} \cdot K_P \cdot \frac{\pi}{180} \tag{16}$$

Azimuth angle at bit after the well depth increment can be obtained similarly:

$$\varphi'_b = \varphi_b + A_Q \cdot \frac{\Delta L}{L_1} + \frac{\Delta L}{30} \cdot K_Q \cdot \frac{\pi}{180} \tag{17}$$

where, φ_b is the azimuth angle at bit in original position; φ'_b is the azimuth angle at bit after well depth increment ΔL and K_Q is the borehole curvature in the Q plane.

3. 2. Calculation Flow Chart The whole drilling trajectory prediction model can be expressed in a flow chart as shown in Figure 6.

A computer program was developed to realize the calculation progress based on the analysis shown in the flow chart. Taking RSBHA configuration parameter, borehole parameter, drilling operation parameter and bit cutting anisotropy index into the program, inclination and azimuth angle at different well depths can be automatically calculated.

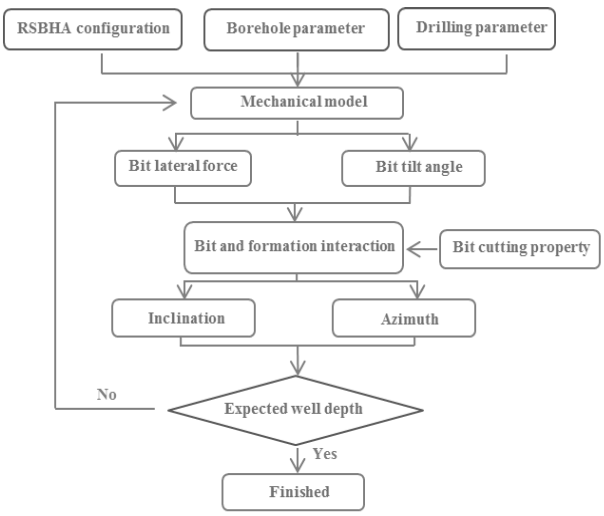

Figure 6. Flow chart of drilling trajectory prediction

As for the determination of bit cutting anisotropy index, it should change the index value until the program trial result has a good consistence with the field data.

4. MODEL VERIFICATION

In order to verify the reliability of the build-up rate prediction model of push-the-bit RSBHA, we take the experimental well gas storage-1-C2 drilling data of Chuanqing Drilling & Production Technology Research Institute to compare with the result of the prediction model.

Push-the-bit RSBHA: Φ215.9mmPDC bit×0.34m +Φ192mm adapter×0.39m+Φ178mm rotary steerable system×13.17m +Φ165.1mm non-magnetic drill collar×18.9m +Φ165.1mm drill collar +Φ127mm drill string×66.15m.

Tool's concrete configuration value such as the distance between bit and steering pads L_{11} and the first string span L_1 was not given out for confidential reasons.

Drilling fluid density is 1.27 g/cm^3. The steering parameters in drilling experimental well section are summarized in Table 1.

The predicted inclination and azimuth angle and actual field data are shown in Figure 7. Further dealing with the angle data, dogleg severity (DLS) was calculated to give out an error analysis as shown in Figure 8. Bit cutting anisotropy index: bit type 1 is 0.043 and bit type 2 is 0.05.

As we can see from Figure 7, the inclination and azimuth angle prediction result has a good consistency with the actual field data in the experimental well depth section. DLS error shown in Figure 8 is within a small range (-0.52~0.47°/30 m). This error can meet the engineering requirement. The comparison proves the prediction model is reasonable and feasible.

The formation property [18] also affects the accuracy of the drilling trajectory prediction result. When drilling in the soft formation, the steering pads may get stuck into the formation causing a lower actual weight on bit due to the increase of axial drag.

TABLE 1. Experimental steering parameters

Well section (m)	Bit	WOB (kN)	F (kN)	ω (°)
737.3-757.5	Type 1	70	22.5	30
757.5-805.5		90	22.5	15
805.4-844.9		90	22.5	0
844.9-862.4		90	15	-15
862.4-891.2	Type 2	90	22.5	-15

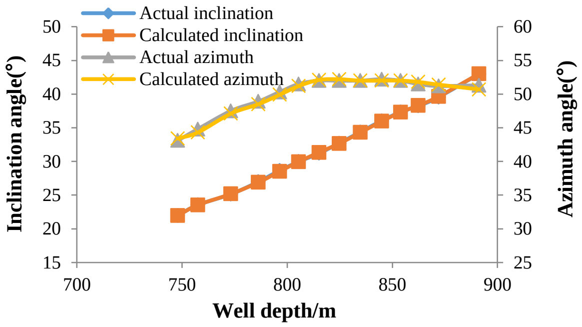

Figure 7. Inclination and azimuth analysis

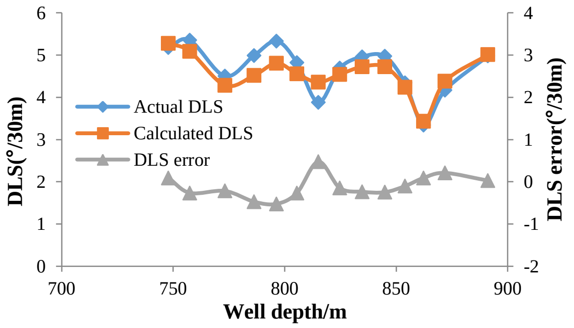

Figure 8. Comparison of DLS

Then the bit axial cutting will decrease with a relatively bigger bit side cutting speed. So the predicted inclination and azimuth angle will generate error. What's more, the prediction accuracy of azimuth angle is lower than inclination angle as shown in Figure 7. Researchers pointed out a bit climbing tendency around the borehole wall in their studies of BHA dynamics [19, 20]. This climb phenomenon caused by the friction between BHA and wellbore will have an effect on azimuth angle prediction. Therefore, it is necessary to further study the effects of rotation state on the drilling tendency.

5. CONCLUTION

(1) Considering the drilling characteristic of push-the-bit rotary steerable tool, drilling trajectory prediction model took RSBHA configuration, borehole parameter, drilling operation parameter and bit cutting anisotropy into consideration. The model was more comprehensive in theory and can realize the calculation of well inclination and azimuth angle.

(2) The prediction model has a good consistency with the actual field data proving the model is reasonable and feasible. It can meet the requirements of engineering. This model can prove theory basis for the next determination of steering parameters to meet the control goal.

(3) The variation of formation property and rotation state of RSBHA may have an effect on the accuracy of the prediction model. Further studies should continue to reveal the actual influence on the drilling tendency. A corrected model considering the two factors will be more advanced.

6. ACKNOWLEDGEMENT

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Drilling Tendency

چکیده

مطالعه تکنولوژی حفاری چرخشی در حال حاضر یکی از موضوعات داغ در زمینه مهندسی حفاری است. زمانی که هدف دستیابی به مسیر صحیح است ابزار چرخشی نیاز به دستورالعمل های مسیریابی دقیق دارد. یک مدل پیش بینی مسیر حفاری به این پیشرفت کمک خواهد کرد. با توجه به تئوری اشعه پیوسته، یک مدل مکانیکی (RSBHA) برای مشخص کردن ویژگی فرمان مته ایجاد شد. رابطه نیروی جانبی مته و زاویه شیب مته با پارامترهای تأثیرگذار مانند پارامترهای دیواره چاه و پارامترهای عملیات حفاری بدست آمد. سپس با توجه به ناهمسانگردی برش مته، مدل پیش بینی مسیر حفاری ساخته شد که تغییرات زاویه و جهت را به صورت کمی محاسبه می کرد. نتایج محاسبات مدل سازگاری خوبی با داده های تجربی میدانی داشت که نشان می دهد مدل پیش بینی کننده منطقی است و استفاده از آن در محاسبات مهندسی امکان پذیر است. این مطالعه می تواند راهنمای خوبی جهت تعیین پارامترهای فرماندهی برای دستیابی به هدف کنترل باشد.

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