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Rock Breaking Mechanism and Experimental Research on Axial Tilt PDC Bit Tool

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Abstract: *PDC bit has poor adaptability in soft and hard staggered, gravel-bearing and other heterogeneous layers and hard formations. The problem of easy pre-damage of the cutting teeth of the bit has not been solved yet. A shaft-tilted PDC bit tool is proposed. The most obvious feature of the tool is that the bit body is designed as an "axial-tilted" structure, which can realize the alternating trajectory movement of the cutting teeth under the cooperation of supporting tools. Researching and analyzing the corresponding theory of the shaft inclination PDC bit, conducting laboratory experiments to analyze the influence of transmission ratio and shaft inclination angle on drilling efficiency, revealing the rock breaking mechanism of the tool. This technology can effectively enhance the intrusion capability of PDC bits in complex and difficult-to-drill and deep formations, and improve rock breaking efficiency. This can provide beneficial support for the drilling industry, especially for deep and ultra-deep well drilling, to speed up, increase efficiency, and reduce costs. Contribute to the progress of our country's drill bit technology.*

Keywords: *shaft tilt; working mechanics; rock breaking work; transmission ratio*

1. Introduction

PDC drill bit is a drilling tool that mainly breaks rock by shearing. With the advantages of high rock breaking efficiency, long life, good reliability, and high design flexibility in soft to medium-hard formations, it has gradually occupied an increasingly important position in the field of oil and gas exploitation. However, with the technological advancement of the oil drilling industry, drilling operations are more in the direction of exploration and development of deep, deep water and unconventional oil and gas resources. With the increasing number of deep and ultra-deep wells, PDC bits are facing two main problems in the deep complex and difficult-to-drill formations: On the one hand, the rock located in the deep well section has a large compressive strength under the high confining pressure of the overlying strata. Increase, the rock drillability becomes worse, which makes it difficult for the cutting teeth to penetrate the rock, and the drilling stability of the drill bit is reduced. At the same time, the hydraulic capacity of the deep well section is drastically reduced, and the drilling fluid at the bottom of the well cannot effectively perform chip removal and auxiliary breaking. The role of rock; on the other hand, the wear of the drill bit cutting teeth in the deep difficult-to-drill stratum is increased, and the rock cannot be effectively penetrated, resulting in low drilling efficiency of the bit. In order to improve the drilling stability of the PDC bit in difficult-to-drill formations, improve the stratum adaptability of the PDC bit and broaden its application range, related scholars have carried out many research innovations. Many scholars at home and abroad have improved the drilling efficiency of PDC bits in the formation through the innovation of cutting teeth and the development of new supporting tools. However, the adaptability of PDC bits in uneven layers such as soft and hard interlaced, gravel and hard formations is poor, and the problem that the cutting teeth of the bit are easily damaged in advance has not yet been solved. The author proposes a shaft-tilted PDC bit tool. The most obvious feature of the tool is that the bit body is designed as a "axial-tilted" structure, which can realize the alternating trajectory movement of the cutting teeth under the cooperation of supporting tools. . Compared with the conventional concentric circular motion of cutting teeth, the alternating trajectory cutting motion mode can produce tiny ridges at the bottom of the well, so that the internal stress of the rock can be released, the shear strength is greatly reduced, and the cutting teeth can be formed more easily At the same time, the exposed rock ridges are easy to form through cracks when they are broken, resulting in volume fragmentation, which greatly reduces the crushing specific work of the rock; in addition, the uneven bottom morphology allows the cutting teeth to naturally intrude between the ridges, effectively The ground saves energy and improves the efficiency of rock breaking.

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2. Axial tilt type PDC drill bit structure and working principle

Figure 1 is the proposed axial tilt PDC bit tool, which is composed of two parts: the bit assembly and the outer shell group. The angle between the rotation axis of the bit body and the rotation axis of the outer casing is α. When the revolution speed and the rotation speed are not zero, the current cutting tooth's motion trajectory is a spatial curve, which must be in line with other cutting teeth (or itself) The movement trajectories of the previous circle (or the next circle) intersect to form an "alternating trajectory cutting movement".

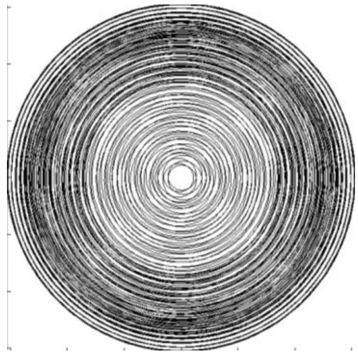
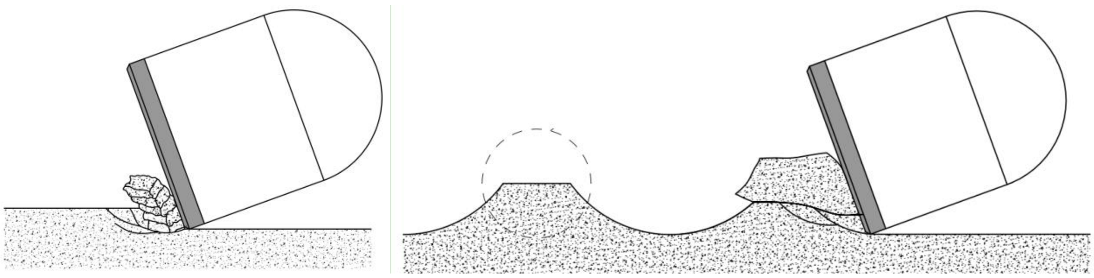


Figure 1 Ideal cross trajectory of PDC drill bit

The bit body is directly connected with the rotor of the screw motor assembly. The self-rotating force of the bit body is driven by the tool, and the "active rotation"motion law of the bit body can be determined by its own structural characteristics, and has little influence on the change of the rock properties of the formation, the vibration of the drill string and other factors, so its "alternating trajectory cutting motion" "It can be realized stably and reliably.



(a) (b)

Figure 2 Schematic diagram of the formation of cutting debris from conventional same trajectory (a) and alternating trajectory (b)

The working principle and beneficial effects of the axial tilt PDC bit are mainly reflected in the following aspects:

(1) It can realize the stable and reliable alternating trajectory cutting movement of the cutting teeth on the bit body, which can significantly improve the intrusion ability of the bit in hard rock formations, thereby improving the efficiency of rock breaking. The lower shell rotates with the drill string system around the axis of rotation (the revolution of the rock breaking tool), while the drill body is driven by the screw motor assembly to rotate around its own axis of rotation.

(2) The bit body is directly connected with the cardan shaft, which simplifies the structure of the "drill bit-screw drilling tool", improves the safety of drilling, and reduces the cost of drilling tools. The axial tilt PDC bit tool connects the cardan shaft assembly directly with the bit body, directly cancels the transmission shaft assembly in the conventional screw drilling tool, greatly reduces the failure probability of the lower drilling tool assembly, and improves the safety of drilling.

(3) The bit body is a solid structure with high strength and good safety. Outside the central flow channel on the bit body, from the bottom of the blade to the central flow channel, there is a solid structure, which has high strength and is not prone to damage to the bit body.

(4) The drill bit body with a solid structure has a flexible arrangement of water holes, and it is easy to realize the optimal design of the hydraulic structure of the drill bit body. The external water eye can be set in the non-central area, and the diameter, spray angle and quantity of the water eye can be

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flexibly designed according to the cutting structure of the bit body, so that it can obtain good cooling, rock carrying, auxiliary rock breaking and other high-efficiency hydraulic power Structural characteristics.

3. Single-tooth cutting simulation research

3.1 Analysis of simulation parameters and simulation results

For the single-tooth cutting rock breaking process, the influencing factors mainly include: rock strength, intrusion depth, tooth profile diameter, forward inclination angle and high wear. Therefore, this paper selects these five main factors, chooses the specific crushing power and the total cutting force as the evaluation indicators of the cutting effect, uses the orthogonal experiment method to carry out the simulation experiment analysis, and obtains the two evaluation indicators of the main cutting force and the crushing specific power. As a result, the orthogonal table $L_{16}(4^5)$ is used to obtain the interaction scheme and results as shown in Table 1. Figure 3 shows the simulation results of analyzing the rock breaking process.

Table 1 Single-tooth cutting simulation orthogonal experiment table

Experiment number	Rock strength/(MPa)	Penetration depth/(mm)	Tooth diameter/(mm)	Forward angle/(°)	Wear height/(*R)
1	50.57	0.5	10	10	1/32
2	50.57	0.8	13.44	15	1/16
3	50.57	1.3	15.88	20	1/8
4	50.57	2	19.05	30	1/4
5	67.55	0.5	13.44	20	1/4
6	67.55	0.8	10	30	1/8
7	67.55	1.3	19.05	10	1/16
8	67.55	2	15.88	15	1/32
9	105.95	0.5	15.88	30	1/16
10	105.95	0.8	19.05	20	1/32
11	105.95	1.3	10	15	1/4
12	105.95	2	13.44	10	1/8
13	126.52	0.5	19.05	15	1/8
14	126.52	0.8	15.88	10	1/4
15	126.52	1.3	13.44	30	1/32
16	126.52	2	10	20	1/16

After performing range analysis on the simulation results, the following simulation

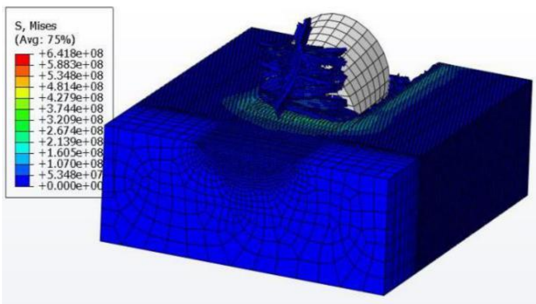

Figure 3 Single-tooth cutting analysis under different simulation scenarios

After performing range analysis on the simulation results, the following simulation data tables can

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be obtained respectively:

Table 2 Single-tooth cutting simulation analysis table of extreme difference of crushing specific work

	Rock strength/(MPa)	Penetration depth/(mm)	Tooth diameter/(mm)	Forward angle/(°)	Wear height/(*R)
k1	24.21	33.64	43.99	36.63	50.29
k2	29.88	41.33	43.70	36.33	43.56
k3	45.74	45.78	39.16	47.62	34.92
k4	69.19	49.12	41.66	46.17	37.55
R	44.98	15.49	4.83	11.29	15.37

Table 3 The analysis table of the total cutting force range of the single-tooth cutting simulation

	Rock strength/(MPa)	Penetration depth/(mm)	Tooth diameter/(mm)	Forward angle/(°)	Wear height/(*R)
k1’	526.31	494.43	757.41	825.26	778.11
k2’	560.47	615.10	919.79	698.61	782.68
k3’	945.49	853.40	754.22	856.84	843.20
k4’	1289.32	1358.65	890.16	940.87	917.59
R’	763.01	864.22	165.56	242.26	139.48

In the table, R represents the extreme value of a certain factor, which reflects the maximum range of the factor's change. The larger the extreme value, the more sensitive the simulation result is to the change of the factor. From this, the priority order of the sensitivity of the crushing specific work to various factors can be listed, and the order of sensitivity is as follows:

- Rock strength> intrusion depth> tooth profile diameter> wear height> forward inclination angle.

For the sensitivities of the main cutting force factors, the order of sensitivity is as follows:

- Invasion depth>rock strength>forward inclination angle>tooth diameter>wear height.

From the above analysis, it can be seen that the rock strength and forward inclination angle have the most significant influence on the simulation results of crushing specific work. Therefore, these two parameters are selected as the research object for further analysis.

3.2 Establishment of cutting mechanics model

Because the rock strength and intrusion depth have a significant impact on the simulation results, the sensitivity is much greater than other factors. Therefore, in order to facilitate the establishment of the mechanical model, we ignore other secondary factors and only consider these two factors as model parameters.

Assuming that the total cutting force is $\mathrm{F_c}$, the rock strength is σ, and the invasion depth is h, the total cutting force can be expressed as a binary function of rock strength σ and invasion depth h, namely:

$$F_c = f_1(\sigma, h)$$

The graph can be expressed as:

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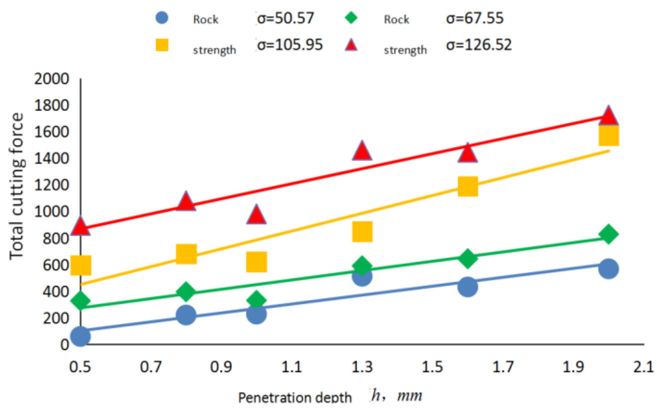

Figure 4 The relationship between intrusion depth and total cutting force under different rock strengths

In the same way, the functional expressions of crushing specific work W, rock strength σ, and intrusion depth h can be obtained as:

$$W = f_2(\sigma, h)$$

The graph can be expressed as:

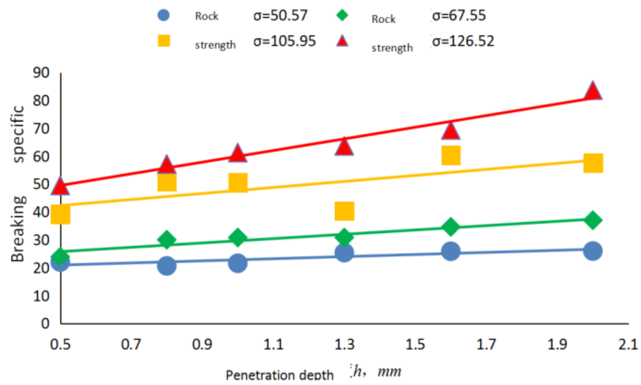

Figure 5 The relationship between intrusion depth and crushing specific work under different rock strengths

4. Research on Cutting Simulation of Alternating Path

4.1 Simulation parameters and simulation results analysis

In this simulation, the rock strength is 67.55MPa, the intrusion depth is 2mm, the forward inclination angle is 15 °, the wear height is 0, the tooth profile diameter is 13.44mm for simulation, and the crossing angles are 15 °, 30 °, 45 °, 60 °, respectively. , 90 °.

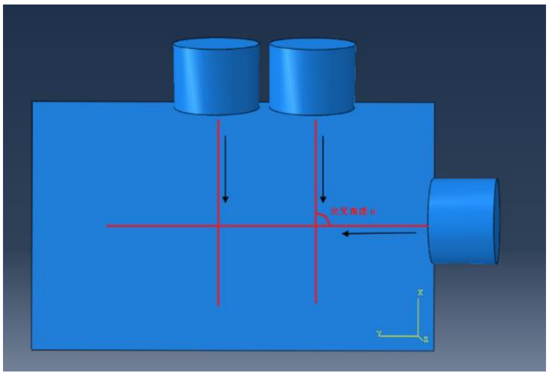

Figure 6 Cross cutting model

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In terms of simulation model settings, compared with single-tooth cutting, cross-cutting simulation needs to add an analysis step to generate pre-broken cutting grooves, and then let the cutting teeth cut through the cutting grooves at a certain angle, as shown in Figure 6. It should be noted that in the first analysis step, after the cutting teeth produced a cutting groove with an intrusion depth of 2mm, in the second analysis step, the cutting teeth need to be set to an intrusion depth of 4mm compared to the original rock plane for cutting. . This is because in the actual drilling process, the drill bit has the drilling speed, that is, the axial footage. When the cutting teeth cut through the rock ridge, the contact position between the cutting teeth and the rock should be below the root of the rock ridge. In the case of keeping other parameters unchanged, Figures 7 and 8 are graphs showing the change of cross angle with crushing specific work and total cutting force. In the figure, in order to compare the rock breaking effects of cross cutting and single-tooth cutting, an additional set of single-tooth cutting simulation studies are carried out. The simulation parameters are the same as the cross cutting simulation, namely, the rock strength is 67.55MPa, the intrusion depth is 2mm, and the forward tilt The angle is 15°, the wear height is 0, and the tooth profile diameter is 13.44mm.

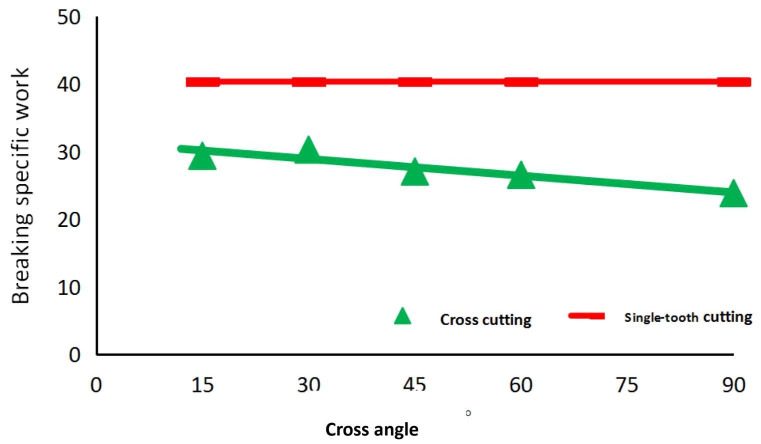

Figure 7 The relationship between cross angle and crushing specific work

Comparing the specific crushing work, it can be found that regardless of the crossing angle, the crushing specific work in the cross-cutting simulation is smaller than that of the single-tooth cutting simulation, which shows that the alternating path cutting method has the effect of saving work.

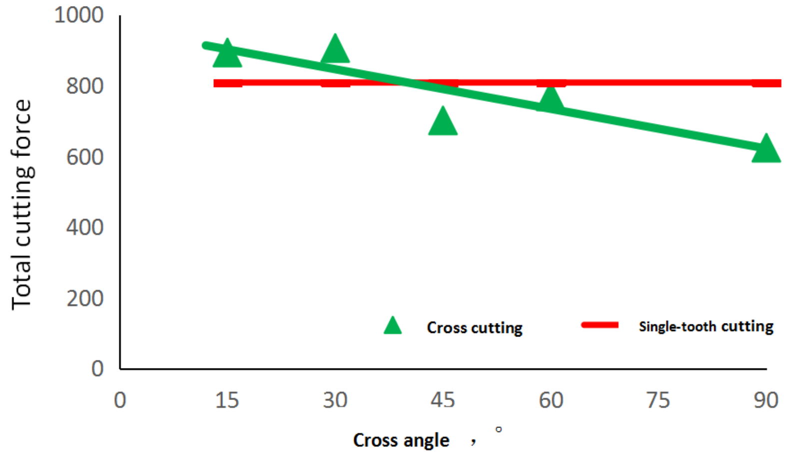

Figure 8 The relationship between crossing angle and total cutting force

Comparing the simulation results, it can be found that comparing the total cutting force, when the cross angle is less than or equal to 30°, the total cutting force in the single-tooth cutting simulation is less than the total cutting force in the cross cutting simulation. This is mainly due to the cutting angle in the cross cutting simulation. The smaller the size, the closer the cutting state is to single-tooth cutting. In addition, since the actual penetration depth of the cutting teeth is 4mm when the model is set up, when the cutting angle is small, the cutting teeth need to cut more rocks, which will generate a greater total cutting force; when the crossing angle is greater than 30°, The total cutting force in the cross-cutting simulation was initially lower than that of single-tooth cutting, which verified the view that cross-cutting can save effort, that is, the alternating path cutting method can save effort.

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4.2 Establishment of cutting mechanics model

Assuming that the total cutting force is $F_c{}'$ and the intersection angle is α, based on the cross cutting simulation results, through curve fitting, the relationship expression of the total cutting force with respect to the intersection angle can be obtained:

$$F_c{}' = -3.77\alpha + 957.36$$

In this expression, the intercept is b=957.36, which means that the total cutting force is 957.36N when the cross angle is α=0°. This value can only be applied to the above cross cutting conditions; the front part of the expression is F_t=-3.7701α, which reflects Under the condition of the rock strength of 67.55Mpa, the total cutting force is a function of the intersection angle, so this function can be applied to the single-tooth cutting simulation mentioned above. If the intersection angle parameter is added to the above single-tooth cutting mechanics model, the new expression should be:

$$F_c{}' = F(X_1, X_2, \alpha) = -3.77\alpha + f_1(67.55, h)$$

5. Establishment of cutting mechanics model of axial tilt PDC bit

For the force analysis of the bit body of the shaft tilting rock breaking tool, it is necessary to synthesize the force of each cutting tooth. The single-tooth cutting mechanics model established above is decomposed into the axial force, tangential force, and radial force of the tooth, and then synthesized separately. Assuming that the main cutting force received by the cutting teeth on the drill bit is, and the roll angle is 0°, then after decomposing the main cutting force, there are:

(1) PDC tooth axial force F_{nJ}:

$$F_{nJ} = F_J(\sin\alpha^i \cos\gamma^i \cos\beta + \cos\alpha^i \sin\beta) \quad (1)$$

Where:

α^i——is the forward inclination angle of the cutting tooth, °;

γ^i——is the normal angle of the cutting tooth, °;

β——is the axis inclination angle of the drill bit, °.

(2) PDC tooth radial force F_{rJ}:

$$F_{rJ} = F_J \sin\alpha^i \sin\gamma^i \quad (2)$$

(3) PDC tooth tangential force F_{tJ}:

$$F_{tJ} = F_J(-\sin\alpha^i \cos\gamma^i \sin\beta + \cos\alpha^i \cos\beta) \quad (3)$$

Regardless of the cutting method, the force of the rock on the drill bit can always be represented by three force components, which are: axial force along the axis of the drill bit F_N, transverse force perpendicular to the axis of the drill bit F_R, vector direction Torque M_T parallel to the axis of the drill bit, side bending moment M_B where the vector direction is perpendicular to the axis of the drill bit. Assuming that the point is the coordinate of the equivalent contact point $P(x_i,y_i,z_i)$ of the first cutting tooth in the Cartesian coordinate system, the calculation model of each force component will be introduced below.

(1) Axial load of bit body F_N:

The axial force on the drill bit should be the sum of the axial forces on all cutting teeth, namely:

$$F_N = \sum_{i=1}^{N} F_{nJ}{}^i \quad (4)$$

Where:

N——Total number of cutting teeth on the bit body;

$F_{nJ}{}^i$——The axial force of the first cutting tooth on the PDC bit, N.

After obtaining the magnitude of the axial force, the point of action of the axial force (X_N,Y_N) needs to be requested. The specific method is as follows: the torque generated by the axial force on the

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X_N and Y_N axes of the coordinate system should be equal to the sum of the axial force on each cutting tooth of the PDC drill bit against the X_N and Y_N axes of the coordinate system. From this, two equations can be established to get the value of and:

$$\begin{cases} X_N = \dfrac{\sum_{i=1}^{N} F_{nJ}{}^{i} x_i}{F_N} \\ Y_N = \dfrac{\sum_{i=1}^{N} F_{nJ}{}^{i} y_i}{F_N} \end{cases} \tag{5}$$

(2) Lateral load of bit body F_R:

The lateral force on the bit is synthesized by the radial force on the cutting teeth. The synthesis method is: firstly, the radial force of each cutting tooth is orthogonally decomposed into x axis and y axis. Here, it is defined that the x axis coincides with the OR axis in the drill bit polar coordinate system, and the y axis is perpendicular to the OR axis, and then each The component forces on the cutting teeth are synthesized separately, and the component forces of the lateral force on the drill bit in the 1-axis and y-axis directions are obtained. Finally, the component forces are synthesized into lateral force F_R, namely:

$$\begin{aligned} F_{Rx} &= \sum_{i=1}^{N} F_{rJ}{}^{i} \cos\theta_i \\ F_{Ry} &= \sum_{i=1}^{N} F_{rJ}{}^{i} \sin\theta_i \\ F_R &= \sqrt{F_{Rx}{}^2 + F_{Ry}{}^2} \end{aligned} \tag{6}$$

Direction of lateral force:

$$\begin{aligned} \theta_R &= \mathrm{acos}\left(\frac{F_{Ry}}{F_R}\right), F_{Ry} \geq 0 \\ \theta_R &= 360 - \mathrm{acos}\left(\frac{F_{Ry}}{F_R}\right), F_{Ry} < 0 \end{aligned} \tag{7}$$

In the above formula, the clockwise direction of the x axis is positive.

(3) Torque load of bit body M_T:

The torque on the drill bit is generated by the tangential force on the cutting teeth, and its value is the sum of the torque on the axis of the drill bit by the tangential force on the cutting teeth. The direction of rotation is opposite to the direction of rotation of the bit, namely:

$$M_T = \sum_{i=1}^{N} F_{tJ}{}^{i} \cdot r_i \tag{8}$$

among them:

r_i——Current tooth positioning radius, mm.

(4) Side bending moment of bit body M_B:

If the point of action of the axial load on the bit body is not located at the origin of the coordinate system, then additional lateral bending moments will inevitably occur, the magnitude of which is:

$$\begin{cases} M_{Bx} = \sum_{i=1}^{N} F_{rJ}{}^{i} \cos\theta_i \, r_i \times 10^{-3} \\ M_{By} = \sum_{i=1}^{N} F_{rJ}{}^{i} \sin\theta_i \, r_i \times 10^{-3} \end{cases} \tag{9}$$

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$$M_B = \sqrt{{M_{Bx}}^2 + {M_{By}}^2}$$

Vector direction of side bending moment:

$$R_N = \sqrt{{X_N}^2 + {Y_N}^2}$$

$$\theta_B = \text{acos}\left(\frac{Y_N}{R_N}\right), Y_N \geq 0 \quad (10)$$

$$\theta_B = 360 - \text{acos}\left(\frac{Y_N}{R_N}\right), Y_N < 0$$

Among them:

θ_B——The azimuth angle of the side bending moment received by the PDC bit, with x axis clockwise as positive. °

6. Conclusion

The article mainly focuses on the research on the unique structure of the axial tilt PDC bit tool, so the unique structural parameters of the tool are selected as the experimental variables. The other experimental parameters are all fixed values. The drilling speed obtained by the experiment, The torque results are analyzed and compared, and the following conclusions are obtained:

(1) Axial tilt PDC bit can achieve the effect of alternating trajectory cutting and breaking rock. In the research results of rock breaking mechanism, it is also believed that this rock breaking mode can effectively improve drilling efficiency.

(2) The interactive effect of drilling performance under the dual influence of the real-axis inclination angle and transmission ratio of the shaft-tilted PDC bit rock breaking tool, which greatly improves the drilling efficiency compared with the conventional PDC bit.

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