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Study on the Methods for Determining Tooth Orientation of Cone Bit

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Abstract: There is an important effect for improving bit drilling performance to adjust tooth orientation of cone bit pertinently. In this paper, to determine tooth orientation reasonably, Tooth coordinate system was established. And a computational method for projecting and decomposing tooth velocity to the axes of tooth coordinate system was presented. Considering the layer condition, the tooth orientation was adjusted and determined. Although the instantaneous cone/bit speed ratio is ambiguity, there is some significance of practical application to use average cone/bit speed ratio when we compute. The methods for determining tooth orientation is easy to apply. It provides a theoretical basis for computing and determining tooth orientation, which has great guiding significance for optimal design of cone bit.

Keywords: Cone bit; Tooth orientation; Tooth tip line; Computational methods.

1. Introduction

The cone bit is one of the most widely used rock breaking tools in oil and gas drilling, and its rock breaking efficiency directly affects the drilling efficiency. The cone bits can adapt to various formations from soft to hard. The fracturing effect of the cone bit on rock includes impact fracture and lateral scraping. The depth of the bottom contact teeth pressed into the bottom hole and the area swept by the lateral scraping directly affect the rate of penetration (ROP) of the bit. The cone bits are divided into steel teeth and insert teeth. The steel teeth are wedge-shaped, while the insert teeth are either wedge-shaped (such as wedge, spoon) or point-symmetrical (such as spherical, conical, etc.). Point symmetrical teeth have a point at the top, and wedge-shaped teeth have a line at the top of the tooth. Most of the existing cone bits, no matter steel teeth or insert teeth, their tooth tip lines are mostly in the same direction with the cone generatrix of the cone. We call the teeth non-deflection. However, the scraping direction of the bottom contact teeth at the bottom of the well is generally not perpendicular to the direction of the cone generatrix of the cone. The design of the tooth tip line in the same direction as the cone generatrix of the cone is obviously unreasonable.

In order to develop a bit with a more reasonable direction of the tip line, the Drilling Bit Research Laboratory of Southwest Petroleum Institute first obtained a patent of three-cone bit with deflected insert tooth (ZL9121413512) in 1991. The laboratory has designed more than 10 kinds of cone bits suitable for medium and soft formations for many drill plants in China, and the tip line of these drill teeth is perpendicular to the tooth scraping direction. The aim is to increase the area and volume of tooth scraping rock, so as to increase the ROP. Fig.1 is one of the deflections insert bits designed by the laboratory.



Fig.1 Three-cone bit with deflected insert tooth

Subsequently, the U.S. RBI Company obtained an American patent (US51975551) of the wedge deflection insert bit in 1993. In hard formations, the tooth tip line can be parallel to the tooth scraping direction to reduce the fracture of teeth. In soft formations, the tooth tip line is perpendicular to the scraping direction of the tooth to increase the volume of scraped rocks. Halliburton Company of the United States obtained the patent US60952622 for deflection steel tooth bit in 2000, which developed into the American patent US6412577 in 2002. Make the tooth tip line perpendicular to the tooth scraping direction to increase the scraping rock volume, thereby increasing the ROP. In 2003, American Smith Company obtained the American patent US6527068 for steel tooth deflection drill.

In the past 20 years, many bit technologies with tooth deflection have been developed in the word. However, according to the author's survey, there are few teeth deflection of wedge-shaped cone bits used in drilling projects, especially among the bits provided by domestic manufacturers, there are almost no bits with deflected teeth. Is it because the targeted deflection of the teeth has little significance to improve the drilling performance of the bit? The author believes that there are several reasons for the lack of application of tooth deflection bits over the years: (1) Patent protection, most manufacturers do not use them to avoid others' patents; (2) Design tradition, the traditional design habits for many years

have made many designers accustomed to applying the established design methods; (3) The scraping direction of the bottom contact teeth at the bottom of the well varies a lot, how the instantaneous relative motion between tooth and rock is still inconclusive, and the design lacks theoretical basis.

Targeted deflection of the teeth is very helpful to improve the drilling performance of the bit. This can be explained by the introduction of relevant patent technologies at home and abroad, and can also be verified by the use effect of deflection bits previously developed by the Drilling Bit Research Laboratory of Southwest Petroleum Institute. In order to reasonably determine the tooth deflection of cone bits, this paper intends to discuss the calculation method for determining the deflection direction of wedge-shaped teeth.

2. Basic theory of the cone bit

2.1. Coordinate system

The fixed cylindrical coordinate system of the cone bit and the cylindrical coordinate system of the tooth wheel are established with reference to Reference, and the right-hand Cartesian coordinate system OXYZ of the cone bit and OiXiYiZi of the tooth wheel are established simultaneously. The origin of the Cartesian coordinate system coinciding with the origin of the corresponding cylindrical coordinate system. The Z and X axes are respectively congruent with the vertical axis and polar axis of the corresponding cylindrical coordinate system.

For the convenience of research, we have established a right-hand Cartesian coordinate system for each tooth, as shown in Fig.2. The origin of the coordinate system Oijk (the origin of the tooth coordinate system of the k-th tooth on the j-th ring of the i-th cone) is at the center of the tooth root, the OijkXijk axis points to the tip of the cone along the direction of the tooth crest line, and the OijkZijk axis points out of the cone along the direction of the tooth height. The OijkXijk axis in the figure and the angle δ between the OijkXijk axis, the bus line over the point Oijk on the wheel cone is the deflection angle of the tooth, i.e. the angle between the tooth apex line and the bus line over the tooth root center. It is specified that the anticlockwise deflection of the top line from the top direction is positive.

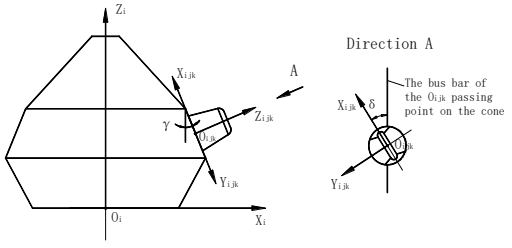


Fig.2 Cartesian coordinate of the tooth

2.2. Basic equations of geometry and kinematics of the cone bit

In the coordinates of the cylindrical coordinate system, the basic equations of geometry and kinematics of any point T(r,α,h) on the dental wheel drill of the cone bit are as follows.

Basic equations of geometry:

$$\begin{aligned}\rho &= \sqrt{(C - h\cos\beta + r\sin\beta\cos\alpha)^2 + (r\sin\alpha - S)^2} \\ \theta &= \theta_0 - \frac{2\pi(n-1)}{3} - \arctan\left(\frac{r\sin\alpha - S}{C - h\cos\beta + r\sin\beta\cos\alpha}\right) \\ Z &= Z_0 - h\sin\beta - r\cos\beta\cos\alpha\end{aligned} \tag{1}$$

Basic equations of kinematics:

$$\begin{aligned}V_\rho &= \lambda_\rho r\omega_i \\ V_\tau &= \rho\omega_b - \lambda_\tau r\omega_i \\ V_Z &= V_{bz} + \lambda_Z r\omega_i\end{aligned} \tag{2}$$

$$\begin{aligned}\lambda_\rho &= [\frac{r}{2}\cos^2\beta\sin 2\alpha - (C - h\cos\beta)\sin\beta\sin\alpha - S\cos\alpha]/\rho \\ \lambda_\tau &= [(C - h\cos\beta)\cos\alpha + r\sin\beta - S\sin\beta\sin\alpha]/\rho \\ \lambda_Z &= \cos\beta\sin\alpha\end{aligned} \tag{3}$$

The meaning of the parameters in the above equations is the same as in the Reference.

2.3. Coordinate transformation matrix under the Cartesian coordinate

While establishing the cylindrical coordinate system of the bit, we also established the rectangular coordinate system of the bit. After the structural parameters of the bit are determined, the relative geometric positions of the bit body, cone and tooth are determined. When the bit is rotating, the motion relationship of the points on the bit body, the runner and the teeth can also be established through the rotation parameters of the bit. In the rectangular coordinate system, the coordinate value of a vector in the fixed coordinate system of the bit, the coordinate value in the roller coordinate system and the coordinate value in the tooth coordinate system can be calculated through the coordinate transformation matrix.

To give a uniform form to the coordinate transformation matrix, we adopt the method of homogeneous coordinates, i. e., “n+1” components represent “n” components. This means that the(x,y,z)coordinates are expressed as a four-dimensional position vector(x,y,z,1).

The rotation transformation matrix of coordinates (x,y,z) in Cartesian coordinate is as follows.

Rotate around the ox-axis

$$T_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha & 0 \\ 0 & -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

The α is the angle at which the point rotates around the ox-axis.

Rotate around the oy-axis

$$T_y(\beta) = \begin{bmatrix} \cos\beta & 0 & -\sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ \sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

The β is the angle at which the point rotates around the oy-axis.

Rotate around the oz-axis

$$T_z(\lambda) = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 & 0 \\ -\sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

The γ is the angle at which the point rotates around the oz-axis.

2.4. Transformation matrix for the vector transformed from the bit coordinates to the tooth coordinates

Define the vector A(a,b,c) to be a vector in the OXYZ rectangular coordinate system of the bit, where the vector A is projected onto the OXYZ triaxial coordinate system OX, OY and OZ. The basic geometric parameters of the drill bit are known: offset wheelbase S, center arm length C, beta axis

β. In the cylindrical coordinate system of the tooth wheel, the coordinates of the Oik are (rk,αk,hk), γk is the cone angle of the tooth ring, and δk is the deflection angle of the tooth tip line.

According to the spatial position relationship between the cone bit coordinate system and the tooth wheel coordinate system, the calculation formula of A along the components of OiXi, OiYi and OiZi axis is ai, bi and ci. The calculation formula of the components ai, bi and ci along the OiXi, OiYi and OiZi axes can be obtained as follows

$$[a_i, b_i, c_i, 1] = [a, b, c, 1] \bullet T_z(\tfrac{-360^\circ \cdot i}{n})^{-1} \bullet T_y(-90^\circ - \beta)^{-1} \bullet T_z(-180^\circ)^{-1} \quad (7)$$

In Eq.(7), "n" is the number of drill teeth, Tz(-360°/n) -1, Ty(-90°-β)-1 and Tz(-180°)-1 are the inverse matrices of matrices Tz(-360°/n), Ty(-90°-β) and Tz(-180°), Ty(-90°-β) meaning homogeneous Eq.(5), Tz(-360°/n) and Tz(-180°) meaning homogeneous Eq.(6).

Then the vector Ai (actually vector A) represented by(ai,bi,ci)is decomposed into the three axes directions of the right-angle coordinate system OikXikYikZik of the tooth K. According to the spatial position relationship between the tooth wheel coordinate system and the tooth coordinate system. Similarly, we can be obtained for the three components aik, bik and cik of Ai along the axis directions OikXik, OikYik and OikZik, the calculation equation is

$$[a_{ik}, b_{ik}, c_{ik}, 1] = [a_i, b_i, c_i, 1] \bullet T_z(-\alpha_k)^{-1} \bullet T_y(90^\circ - \gamma_k)^{-1} \bullet T_z(\delta_k + 180^\circ)^{-1} \quad (8)$$

In Eq. (8), Tz(-αk)-1, Ty(90°-γk) -1 and Tz(δk+180°)-1 are the inverse matrices of matrices Tz(-αk), Ty(90°-γk) and Tz(δk+180°), Ty(90°-γk) meaning homogeneous Eq. (5), Tz(-αk) and Tz(δk+180°) meaning homogeneous Eq. (6).

Substituting Eq. (7) into Eq. (8), the components of the projection of vector A(a,b,c) along the triaxial direction of the right-angle coordinate system of teeth K can be calculated as

$$[a_{ik}, b_{ik}, c_{ik}, 1] = [a, b, c, 1] \bullet T_z(\tfrac{-360^\circ \cdot i}{n})^{-1} \bullet T_y(-90^\circ - \beta)^{-1} \bullet T_z(-180^\circ)^{-1} \bullet T_z(-\alpha_k)^{-1} \bullet T_y(90^\circ - \gamma_k)^{-1} \bullet T_z(\delta_k + 180^\circ)^{-1} \quad (9)$$

3. Methods for Calculating and determining the tooth orientation

3.1. Basic assumptions

Because the instantaneous angular velocity of the tooth wheel varies randomly, the motion of the cone bit in the bottom of the well is very complex. Despite the instantaneous angular velocity of the tooth wheel varies complexly, its average angular velocity is quite smooth. Experiments have shown that the time required for each revolution of the tooth wheel is nearly equal . Therefore, when calculating the tooth speed, we assume that when the cone bit rotates at a certain speed, the tooth wheel rotates at an average speed. Then the angular velocity ratio between the tooth wheel and the cone bit is constant, so the wheel-head speed ratio "t" is fixed.

3.2. Calculation and decomposition of velocity vector of the tooth

The angle formed between the tooth tip line and the lateral scraping direction of the tooth at the bottom of the well, which has a direct effect on the tooth force and rock-breaking volume. According to the basic equation of cone bit kinematics (2), when the structural parameters and motion parameters of the cone bit are determined, although the movement speed of the tooth can be accurately calculated, the calculation result cannot reflect the relationship between the velocity vector of the tooth and the tooth tip line. That is, we cannot see by equation (2) whether the directional angle of the tooth tip line is appropriate and whether the tooth is working at the optimal deflection angle. In order to clearly see the quantitative relationship between the direction of the tooth tip line and the direction of tooth movement relative to the rock, we decompose the tooth movement velocity to the triaxial direction of the tooth Cartesian coordinate system, and then determine the tooth deflection angle.

Let the midpoint of the top line of a tooth P of the i-th tooth wheel be Q. Its coordinates in the cylindrical coordinate system of the tooth wheel are Q(rQ, αQ, hQ), and the cone angle of the complex cone where the tooth ring is located is γp. For research convenience, we use the velocity VQ of the midpoint Q of the tooth apex line to represent the velocity of the tooth P. The three components of VQ in the cylindrical coordinate system of the drill are VQρ, VQτ and VQz, then we decompose VQ into the Cartesian coordinate system of the drill OXYZ of the triaxial decomposition, we get the velocity components VQX, VQY and VQZ of VQ along OX, OY and OZ axes calculated as

$$\begin{gathered} V_{QX} = V_{Q\rho}\cos\theta_Q - V_{Q\tau}\, sin\theta_Q = \lambda_{Q\rho} r_Q \omega_i\, cos\theta_Q - (\rho_Q \omega_b - \lambda_{Q\tau} r_Q \omega_i)\, sin\theta_Q \\ V_{QY} = -V_{Q\rho}\sin\theta_Q - V_{Q\tau}\, cos\theta_Q = -\lambda_{Q\rho} r_Q \omega_i\, sin\theta_Q - (\rho_Q \omega_b - \lambda_{Q\tau} r_Q \omega_i)\, cos\theta_Q \\ V_{QZ} = V_{QZ} = V_{bZ} + \lambda_{QZ} r_Q \omega_i \end{gathered} \quad (10)$$

In Eq. (10), ρQ and θQ are the polar diameter and polar angle of point Q in the cylindrical coordinate system of the drill, respectively, which can be calculated from Eq. (1); VQρ, VQτ and VQZ are calculated from Eq. (2), and λQρ, λQτ and λQZ are calculated from Eq. (3).

In the Cartesian coordinate system OipXipYipZip of tooth P, VQX, VQY and VQZ are projected in the direction of OipXip, OipYip and OipZip of the three axes of the Cartesian coordinate system. According to equation (9), VQ is calculated along the three components ViQXx, ViQYy and ViQZz of OipXip, OipYip and OipZip as

$$[V_{iQXx}, V_{iQYy}, V_{iQZz}, 1] = [V_{QX}, V_{QY}, V_{QZ}, 1] \bullet T_z(\tfrac{-360^\circ \cdot i}{n})^{-1} \bullet T_y(-90^\circ - \beta)^{-1} \bullet T_z(-180^\circ)^{-1} \bullet T_z(-\alpha_k)^{-1} \bullet T_y(90^\circ - \gamma_k)^{-1} \bullet T_z(\delta_k + 180^\circ)^{-1} \quad (11)$$

In the equation, "n" is the number of drill teeth.

From the relationship between the position of the tooth coordinate system on the tooth, it is known that ViQXx is along the tip line of the tooth, ViQYy is perpendicular to the tip line of the tooth and ViQZz is along the height of the tooth.

3.3. Methods for determining the tooth orientation

When the wheel-head speed ratio "t" is constant, the speed of the cone bit does not affect the distance, trace and shape of the teeth acting with the rock at the bottom of the well, but only determines the time of the teeth contacting the rock [7-9], which has also been confirmed by the author's simulation calculations.

The calculation Eq. (11) includes: the basic structural parameters of the cone bit, the profile parameters of the tooth wheel, the position parameters of the teeth on the tooth wheel and the drill movement parameters. In order to analyze intuitively, the following calculation is combined with a

specific example to introduce the method of determining the tooth tip line direction of the tooth wheel cone bit.

We first select the 2nd row of teeth of the 2nd tooth ring of a certain 8-1/2″(215.90mm) triple tooth wheel cone bit for calculation. The basic structural parameters of the cone bit are known as S=4.76mm, C=83.8mm, β=33°; the top center of the 2nd tooth ring of the 2nd tooth wheel in the cylindrical coordinate system of the wheel has the pole diameter r22=64.37mm, the vertical height h22=34.53mm, and the cone angle γ22=12° of the complex cone where the tooth ring is located; assuming the wheel-head speed ratio t=1.42, the cone bit speed ωb=7.33rad/s(70r/min), the axial drilling speed of the cone bit VbZ=-1.67mm/s (-6m/h, the negative sign means opposite to the positive direction of Z axis). It is calculated that the position angle (the polar angle in the cylindrical coordinate system of the tooth wheel) of the tooth contact with the rock of the 2nd ring of the 2nd tooth wheel of the cone bit ranges from -17° to 15°. For the convenience of analysis, we take the middle value of the above angle range and substitute it into the calculation, i.e., take α22=-1°.

Substituting the above parameters into equations (2), (3), (10) and (11), respectively. Comprehensive calculation shows that when the 2nd tooth ring of the 2nd tooth wheel acts with the rock at the bottom of the well, the three-components V220Xx, V220Yy and V220Zz of the decomposed tooth velocity are projected along the triaxial direction of the Cartesian coordinate system of the tooth as follows

$$V_{220Xx} = -38.47\cos\delta_{22} + 10.80\sin\delta_{22}(\mathrm{mm/s})$$

$$V_{220Yy} = 38.47\sin\delta_{22} + 10.80\cos\delta_{22}(\mathrm{mm/s})$$

$$V_{220Zz} = 2.65(\mathrm{mm/s})$$

The constant value of V220Zz in Eq. (12) indicates that the component of tooth velocity along the Z-axis direction of the tooth coordinate system is independent of the tooth deflection angle δ22. This is not difficult to understand because V220Zz is perpendicular to the tooth tip line along the tooth height direction. V220Zz characterizes the press-in (eat-in) velocity of the tooth when it acts with the rock, while V220Xx and V220Yy indicate the lateral scraping action of the tooth on the rock. No matter how the tooth deflection angle is taken, it has no effect on the tooth ingestion velocity.

Since V220Xx is along the tooth tip line and V220Yy is perpendicular to the tooth tip line, if the drill is used in soft strata, the tooth tip line should be perpendicular to the tooth scraping direction in order to increase the tooth scraping area, i.e., V220Xx should be as small as possible, let V220Xx=0mm/s and get δ22=74.3°, then V220Yy=39.96mm/s. If the drill is used in hard strata, the tooth tip line should be parallel to the tooth scraping direction, which can reduce and avoid tooth breakage, then determining δ22=-15.7°.

The same method can be used to calculate the direction of the tip line of the teeth of the other rings of the No. 2 tooth wheel of the drill. If the drill is used in soft substrates, the tip line of each tooth ring should be perpendicular to the direction of tooth scraping. It is calculated that when the drill is used in soft bottom layer, the tooth deflection angles of other rings on the No.2 tooth wheel of the drill are δ21=-30.9°, δ23=20.9° and δ24=35.9°. As shown in Fig. 3, it is a diagram of the deflection angle of the teeth of each tooth ring of No. 2 tooth wheel when this cone bit is used in soft stratum.

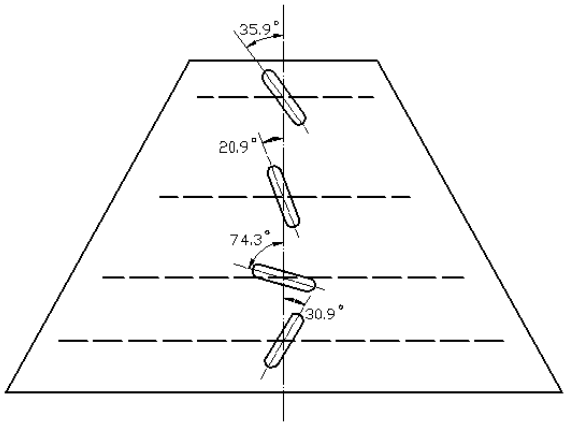


Fig.3 Schematic diagram of the tooth orientation

The above calculation example introduces the method of determining the tip line of the tooth. The deflection angle of other teeth of the drill can also be determined by the above calculation method. When the cone bit is applied to soft formation, the tip line of the tooth can be made perpendicular to the scraping direction to increase the scraping area. When the cone bit is applied to hard formations, the tooth tip line should be parallel to the scraping direction. This increases the indentation stress, makes it easier for the tooth to press into the rock, and reduces tooth breakage.

4. Conclusions

(1) When designing a cone bit, a targeted deflection of the tooth tip line of the tooth will improve the drilling performance. When the instantaneous wheel head speed ratio of the wheel cone bit is not clear, the average wheel head speed ratio can be used instead of the tooth deflection angle. This method has certain practical application value.

(2) The calculation method of projection decomposition of tooth velocity to the axis in the tooth coordinate system introduced in this paper is easy to understand, which provides a theoretical basis for determining the deflection angle of the tooth tip line. The application of this method is of great significance to guide the optimal design of dental wheel cone bits.

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