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Computer simulation of bottomhole trajectory of a spherical single cone bit

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ABSTRACT. *The single roller bit is an important tool for small bore drilling and high hard rock drilling. The bottomhole track of a single cone bit is the cutting mark left by a single cone bit in the bottomhole rock during the drilling process. In the past, the bit bottom hole trajectory was obtained mainly through bit bench test, which took a long time and cost was high. This paper simulates the bottom hole trajectory of single roller bit by computer simulation, and analyzes the influence of bit structure parameters on the formation of bottom hole trajectory. It provides guidance for structural design and mechanism optimization of single cone bit.*

KEYWORDS: *Spherical single roller bit, Bottom hole track, Computer simulation*

1. Introduction

The single roller bit is similar to the PDC bit in rock breaking by cutting, and the rock breaking is assisted by the impact mode of the common roller bit.However, because the main rock breaking method is rock scraping and the running distance is long, the early wear in the face of complex strata is serious, which has a greater impact on the average drilling speed and life of the bit [1]. In this study, there are two ways to improve the service life and rock breaking efficiency of the single roller bit.The first method is to use new materials with high strength and high wear resistance to extend the service life of cutting teeth.Method 2: Based on the study of geometry and kinematics, optimize the structure of the single cone bit, optimize the working mode and efficiency of the cutting teeth, improve the rock-breaking efficiency of the bit, and improve the rock-breaking efficiency.In this paper, by changing the geometric parameters of the single cone bit, the simulation of the cutting track of the cutting gear is carried out, which is of guiding significance for optimizing the tooth surface structure of the single cone bit.

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2. Bottom hole trajectory equation

Bottom hole trajectory is the graphical reflection of the drilling process of the bit, and the pattern of the bit alignment determines the trajectory of the cutting gear.Based on the geometry theory of single cone bit, the trajectory of bottom hole is plotted by computer simulation program.The characteristic point *M* is represented byρ, θ, Z, where ρ is the vector path, θ is the polar Angle, and Z is the height.

(1) Trajectory equation of the spherical single cone bit:

$$\rho_M = \sqrt{(r_M \sin\alpha_M)^2 + [(L-h_M)\sin\beta + r_M \cos\alpha_M \cos\beta]^2} \quad (1)$$

$$\theta_M = \theta_0 + \theta - \arctan[\frac{r_M \sin\alpha_M}{(L-h_M)\sin\beta + r_M \cos\alpha_M \cos\beta}] \quad (2)$$

$$Z_M = Z_{O'} - h_M \cos\beta - r_M \cos\alpha_M \sin\beta \quad (3)$$

In the formula: *L* and $Z_{O'}$ are the mechanism parameters of the single roller bit;β is the shaft inclination Angle of the bit;α_M is the pole Angle of the cone;r_M is the vector diameter from point *M* to the center line of the tooth shaft;h_M is the vertical height from point *M* to the base circle of the cone.

Convert cylindrical coordinate system to rectangular coordinate system:

$$\begin{cases} x = \rho_M \cdot \cos\theta_M \\ y = \rho_M \cdot \sin\theta_M \\ z = Z_{O'} - h_M \cos\beta - r_M \cos\alpha_M \cos\beta \end{cases} \quad (4)$$

Then according to the coordinate rotation formula:

$$\begin{cases} x' = \rho_M (\cos\theta_M \cos\theta_0 + \sin\theta_M \sin\theta_0) \\ y' = \rho_M (\cos\theta_M \sin\theta_0 - \cos\theta_M \sin\theta_0) \end{cases} \quad (5)$$

According to formula (5), the basic equation of plane trajectory of bottomhole projection can be obtained, which is the theoretical basis for the research and design of a new single-roller bit.

In the process of rock breaking, the single roller bit is different from the three-roller bit and the PDC bit. Some of them are always in contact with the bottom hole rock strata, some are alternately in contact with the bottom hole and some are never in contact with the bottom hole [2]. Therefore, the cone of a single cone bit is divided into permanent contact zone *III*, discontinuous contact zone *II* and never contact zone *I*, as shown in FIG.1

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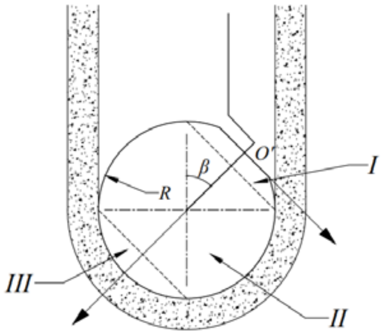

Figure. 1 Working area of cutting teeth for a single cone bit

Based on the geometry of a single cone bit, the point M on the spherical cone moves along the direction of the center line of the bit, and the origin of the z-axis is taken at the intersection point between the bottom section of the cone and the axis of the bit, and then:

$$Z_{O'} = R + L\cos\beta \tag{6}$$

Substituting formula (6) into formula (3), we can get:

$$Z_M = R + L\cos\beta - h_M\cos\beta - r_M\cos\alpha_M\sin\beta \tag{7}$$

(1) Permanent contact area:

$$L + R\sin\beta \le h_M \le L + R \tag{8}$$

(2) Rotating contact area:

$$L - R\sin\beta \le h_M \le L + R\sin\beta \tag{9}$$

(3) Never contact area:

$$0 \le h_M \le L - R\sin\beta \tag{10}$$

3. Bottom hole trajectory simulation

3.1 Rotate the contact area track

The structural parameters on the cone of a single cone bit determine the trajectory of the cutting teeth.After obtaining the bottom hole shape and the trajectory of the cutting teeth of the single cone bit, the structure and position parameters of the cutting teeth can be optimized.

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Given the structural parameters of the single cutting gear as shown in Table 1, the bottomhole projection trajectory of the cutting gear at the characteristic point M can be obtained, as shown in Figure 2.

Table 1 Structural parameters of feature point M of cutting teeth

The bit diameter Φ/mm	Roller diameter $2R/mm$	Distance from the center of the cone to the base surface L/mm	Bearing Angle $\beta/°$	Cutting gear position height h_M/mm	Speed ratio i	Initial position of the cone pole Angle $\alpha_0/°$	Bit initial position pole Angle $\theta_0/°$
118	104	27	45	60	0.866	0	0

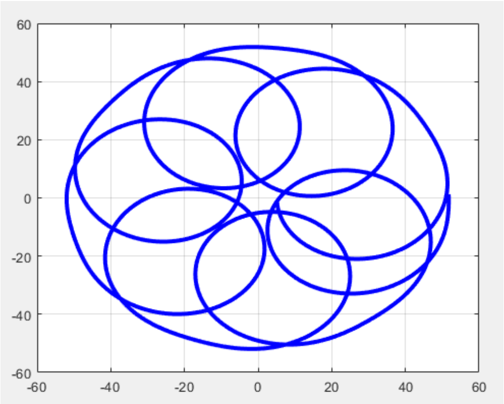

Figure. 2 Bottomhole projection trajectory of single cutting gear

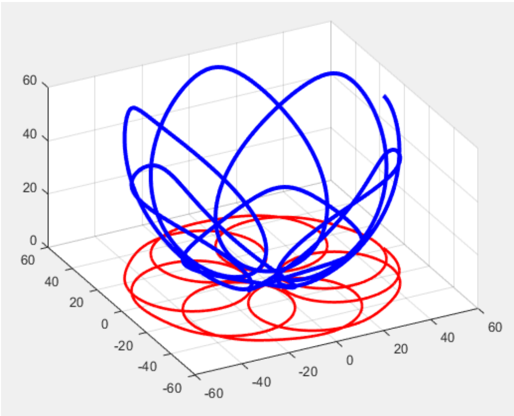

Figure. 3 Stereo - projected bottomhole trajectory

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According to Table 1 and Formula (9), the feature point M is located in the rotation contact area. It can be seen that when the z-axis height coordinate of any feature point M is less than the radius R of the cone, the point contacts the bottom of the well, and vice versa when Z_M is greater than R.Namely to meet:

$$Z_M \le R \text{ (Working condition)} \tag{11}$$

$$Z_M > R \text{ (Non-Working state)} \tag{12}$$

As shown in Figure 3-4.

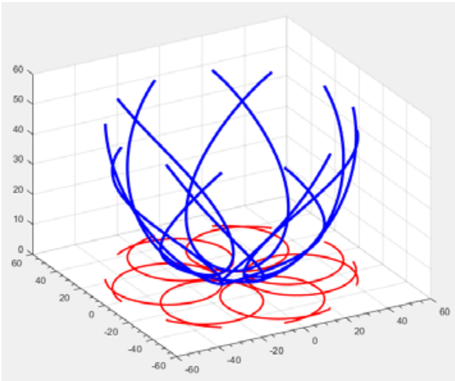

Figure. 4 Stereoscopic - Projection effective trajectory

FIG. 4 shows the stereo-projection track of the cutting teeth located in the rotating contact area at the bottom of the well after the bit rotates several times. The cutting teeth in the rotating contact area scrape and break rocks at the bottom of the well alternately.The blue line in the figure is the effective cutting track of bottom hole with cutting gear.The red line is the projected trajectory of the effective bottomhole cutting trajectory.From the stereo-projection effective track, it can be seen that after the cutting gear moves for a long distance along the rotation direction, the cutting gear rotates backward and cuts upward. After the motion height meets the equation (12), the cutting gear and the bottom hole are separated, forming a single fishtail cutting track [3].

In order to fully reflect the motion characteristics of cutting teeth in the rotational contact area, another 3 points were selected, and h_M is 30mm, 40mm and 50mm respectively.

As shown in FIG. 5, at the position height hM of the cutting gear at different positions, the cutting track of the cutting gear decreases with the decrease of hM, and the lowest point of the cutting track gradually moves away from the front of the bottom hole.At the same time, the fishtail cutting path formed by the drilling bit is gradually sharp, the cutting area is reduced to some extent, and the clearance between adjacent cutting paths increases gradually.

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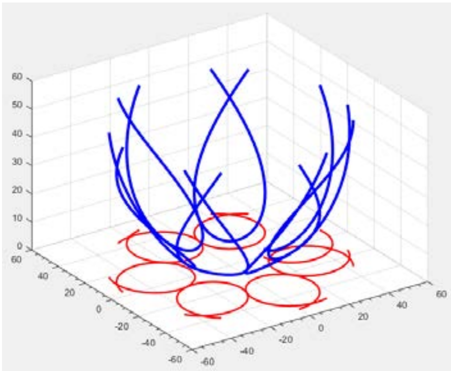
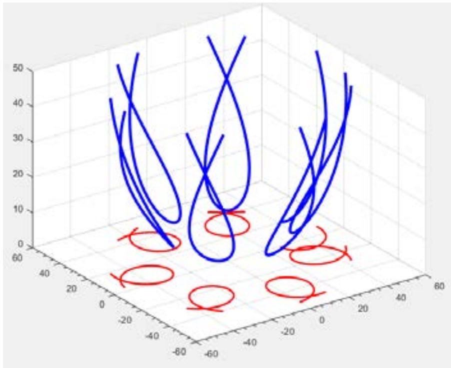
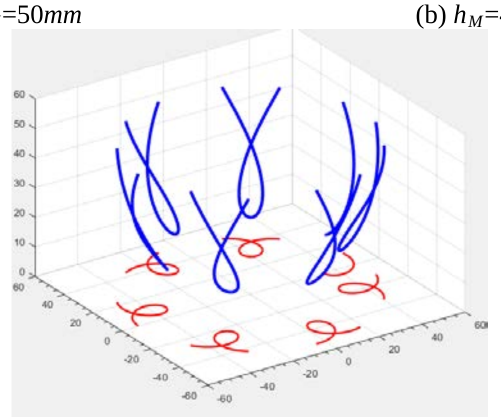


(a) h_M=50*mm*



(b) h_M=40*mm*



(c) h_M=30*mm*

Figure. 5 Trajectory changes of h_M cutting teeth at different positions

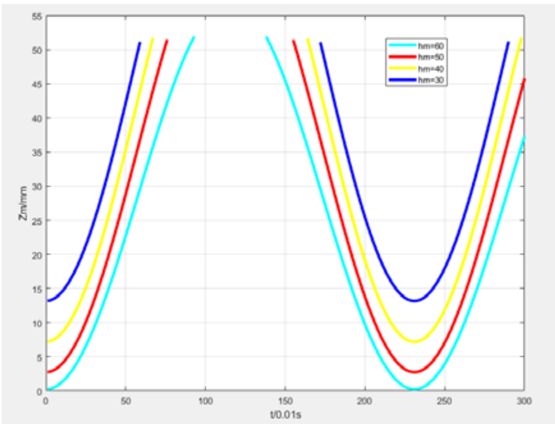


Figure. 6 h_M-Z_M changes

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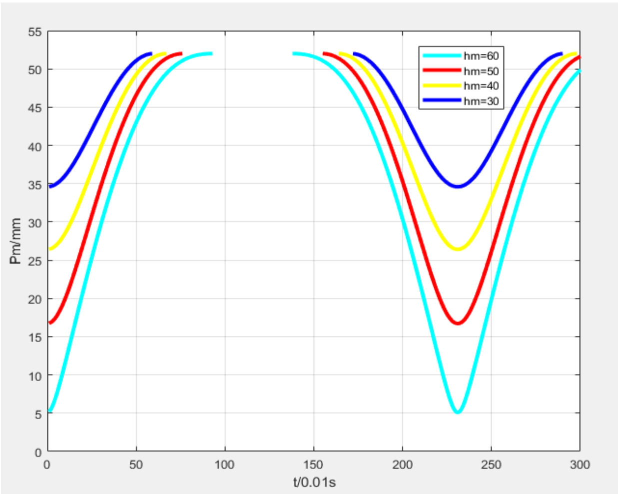

Figure. 7 h_M—ρ_M changes

Formula in reference (1) and (7) can be effective, highly h_M change position, other things being equal, have significant differences in the Z_M and ρ_M, as shown in figure 6 and 7, then place the decrease of the highly hM, Z_M and ρ_M have a narrow, said cutting trajectory distance of the cutter and cutting and broken rock area is smaller, the single cone bit rotation cutter abrasion modulus of different contact area, highly h_M to position the cutter tooth shape choice is different.

3.2 Permanent contact area trajectory

Referring to formula (8), the feature point M is selected, as shown in Table 2, to study the bottomhole cutting track in the permanent contact area, as shown in Figure 8.

Table 2 Structural parameters of feature point M of cutting gear in permanent contact area

The bit diameter Φ/mm	Roller diameter $2R/mm$	Distance from the center of the cone to the base surface L/mm	Bearing Angle $\beta/°$	Cutting gear position height h_M/mm	Speed ratio i	Initial position of the cone pole Angle $\alpha_0/°$	Bit initial position pole Angle $\theta_0/°$
118	104	27	45	70	0.866	0	0

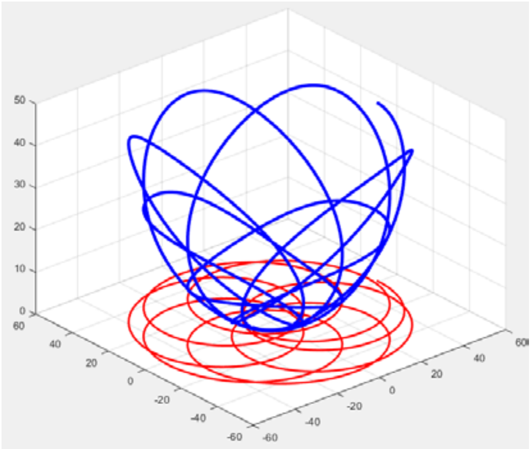

Figure. 8 Rotation of contact area stereo - projection trajectory

FIG. 8 shows the bottomhole track of the single gear cutting in the permanent contact area, which is in contact with the bottomhole all the time. From the track circle, it can be seen that after the cutting gear is scraped and cut downward along the rotation direction of the bit body for a long distance at the bottom hole, a "spiral fishtail shape" is formed at the bottom hole, and the cycle begins.The scratch track of the same cutting gear will cross, and the cross area is generally concentrated in the bottom hole area.

3.3 The influence of shaft inclination Angle on bottom hole trajectory

For a single cone bit, in addition to position height h_M affecting the cutting track of a single cutting tooth, the bearing inclination of the tooth palm on a single cone bit will also affect the bottom hole coverage formed by the superposition of the single cutting track formed by each cutting tooth on a single cone bit, and the bottom hole coverage.

According to the working principle of the single cone bit, design a set of single cone bit model Φ118 mm, the other geometrical parameters of the drill bit is changeless, beta bearing Angle of 30 °, 35 °, 40 ° respectively, 50 °, 55 °, 45 °, 60 ° and 65 °.

When axial Angle take different values, the spherical single cone bit after 7s of downhole operation to get the bottom of the simulation trajectory projection as shown in figure 9, in cyan for position height for h_M = 25 mm cutter track projection, the same red for position height for h_M = 40 mm, yellow for position height for h_M = 55 mm, cyan for position height for h_M = 70 mm cutter track projection, including cutter distribution in rotating contact area and permanent contact area, have certain representativeness.

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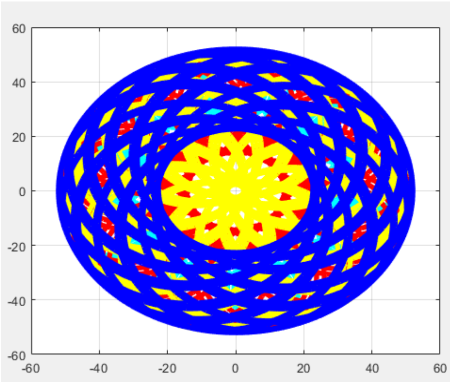
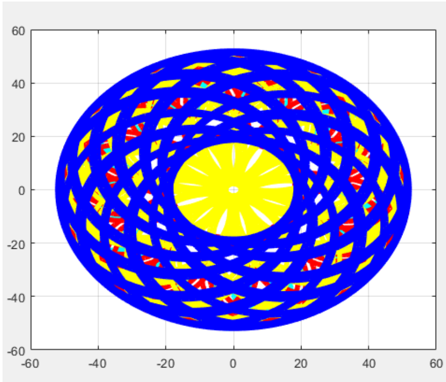
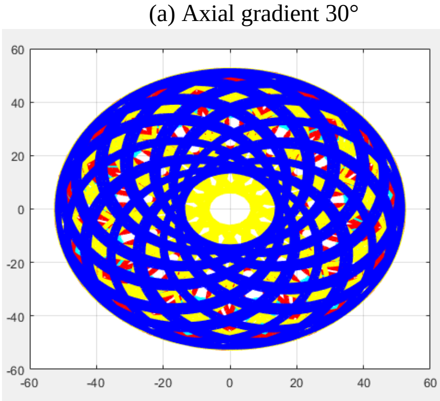


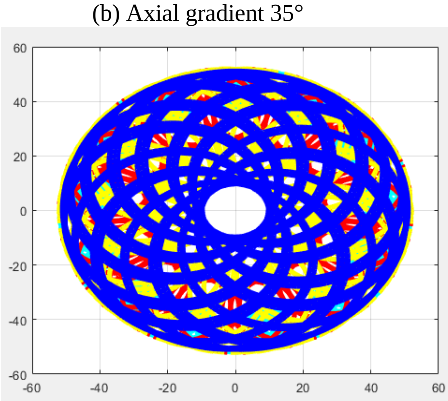
(a) Axial gradient 30°



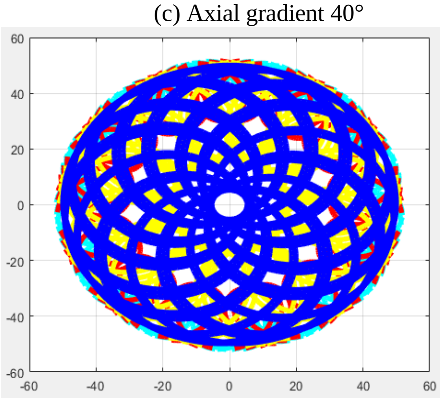
(b) Axial gradient 35°



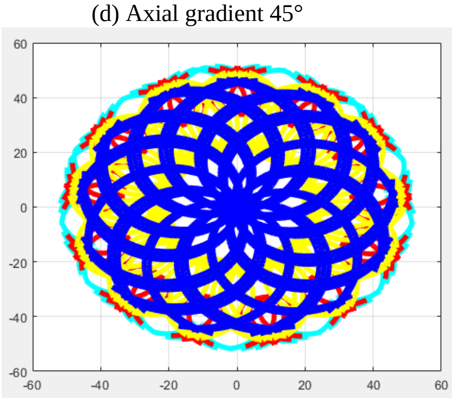
(c) Axial gradient 40°



(d) Axial gradient 45°



(e) Axial gradient 50°



(f) Axial gradient 55°

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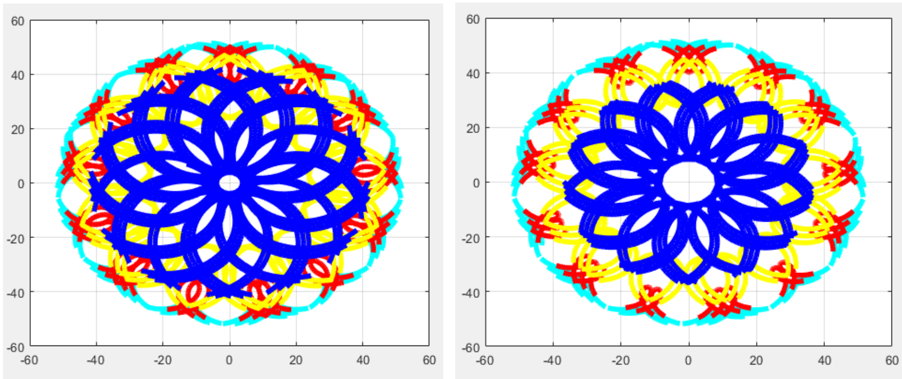

(g) Axial gradient 60°　　(h) Axial gradient 65°

Figure. 9 Bottom hole projection trajectory with different coaxial dip angles

In the figure, the coverage rate of the single roller bit bearing dip Angle of 55°~ 65° decreases gradually, and the bottom hole shows a network structure. The coverage of the cutting track of the cutting gear in the permanent contact area represented by the blue line is gradually reduced, which makes it difficult to cover the whole bottom hole.Other colors represent the rotation of the contact area of the cutting gear cutting ability decreased, unable to effectively rock on the bottom hole.The rock crushing work in the central area of the bottom hole is mainly completed by the cutting teeth in the permanent contact area, and the central area begins to appear, with a large uncovered area and a large undamaged area around it.

The axial dip is between 30° and 50°, which means the cutting range of the permanent contact area is expanding continuously. In the center of the projection track at the bottom of the well, within the axial dip range of 30°~40°, the projection track of the cutting gear in the rotation contact area is covered. However, with the increase of the axial dip Angle, the projection track of the cutting gear in the rotation contact area is gradually separated from the central area, and the required ability to the central area at the bottom of the well decreases.

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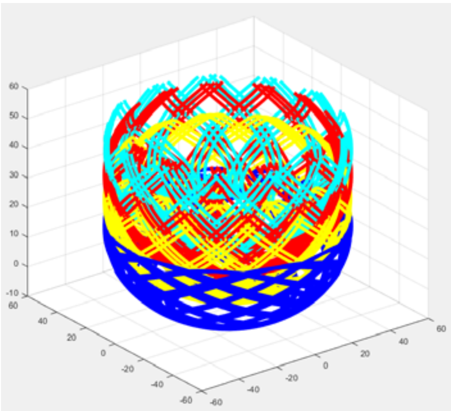
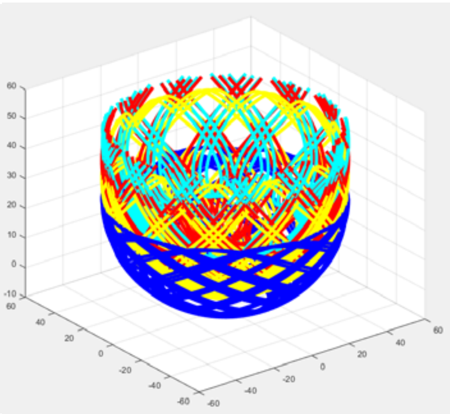
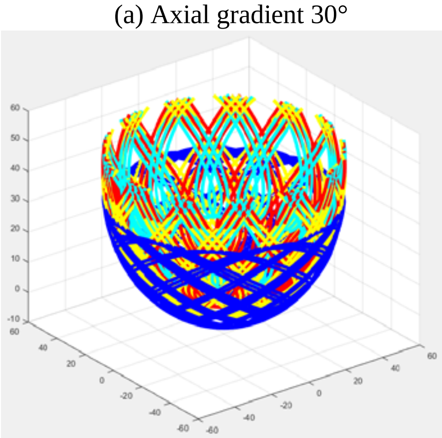


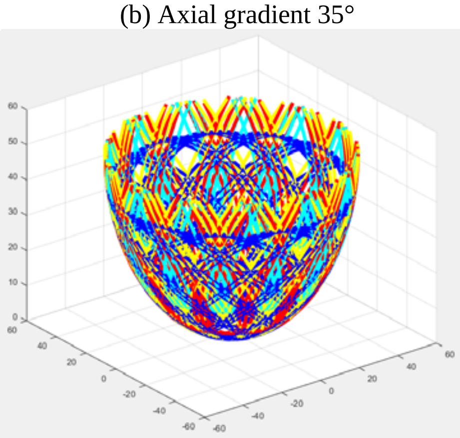
(a) Axial gradient 30°



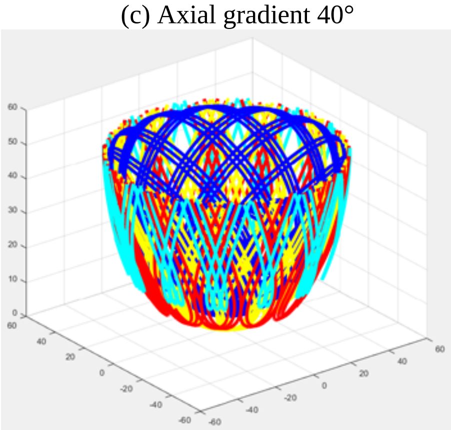
(b) Axial gradient 35°



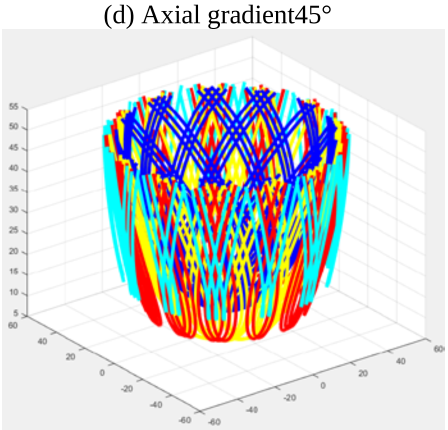
(c) Axial gradient 40°



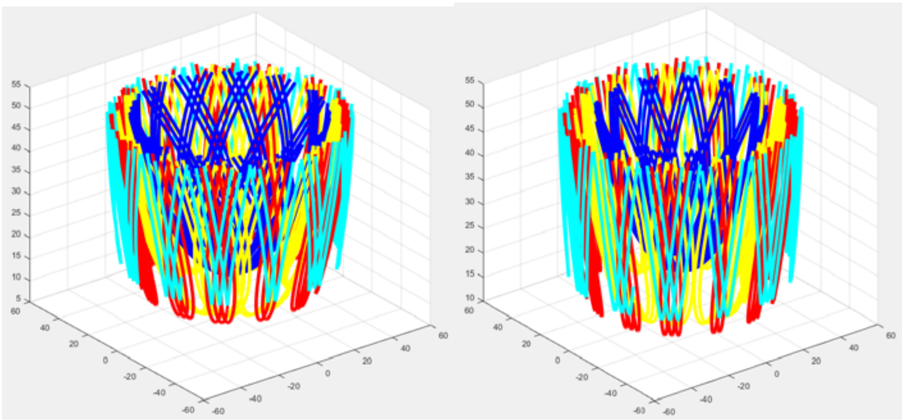
(d) Axial gradient45°



(e) Axial gradient 50°



(f) Axial gradient 55°



(g) Axial gradient 60° (h) Axial gradient 65°

Figure. 10 Three-dimensional trajectory of bottom hole with different coaxial dip angles

Taking the z-axis height coordinate Z_M into consideration, as shown in Figure 10, a three-dimensional hemispheric shape bottomhole pattern is formed.From (a) to (d) when the axis tilts 30°, the blue cutting track represents the permanent contact area, forming a hemispherical bottomhole pattern at the bottom.However, the cutting track of the cutting gear representing the rotation contact zone of different positions and heights has formed hemispherical bottom hole coverage, but the intersection between them is less and the well-organized shaft wall has been improved somewhat.

When the axial dip Angle increases to 30°~45°, the hemispherical motion trajectory formed by each cutting trajectory is mercifully close.The intersection of the cutting track in the permanent contact area and the cutting track in each rotation contact area gradually increases until the axial dip reaches 45° and the cutting track of each cutting gear is superimposed on a surface. At this time, all cutting gears act on the same bottom surface.At this point, the hemispherical bottom hole is in good cutting condition, and the "fish tail" along the cutting track of the stage along part of the rotational contact area plays the role of partially regularizing the shaft wall.

When the total Angle of the single cone bit in 45° ~ 55°, as shown in figure 10 (d)~ (f), the increase of bottom hole pattern of concrete shaft Angle change is small, rotating contact region of borehole wall neat effect is abate, single cone bit bottom hole pattern to the trend of the development of the frustum of a cone, began to have started to rotate at the same time contact region cutter cutting cutting trajectory track gradually divest the permanent contact area, but on the bottom cover and cutting action is still there.

Finally arrived at 55°~ 65°, the bearing Angle as shown in figure 10 (h) ~(f), blue for permanent contact with the cutting path coverage began to decrease, the bottom hole which is formed by the model gradually into a sharp cone, and start from the bottom hole, can lead to permanent contact region cutter cutting path

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cannot reach bottom hole, appeared from the extremes of the bottom hole.In addition, the cutting trajectories in the rotational contact area also change, and the cutting trajectories gradually become sharp, and the intersection between the cutting trajectories decreases here and starts to be perpendicular to the projection plane.

4. Conclusion

(1) The shape and length of the cutting track are affected by the cutting teeth at different positions and heights.

(2) The shaft inclination affects the bottomhole pattern of the single roller bit.

The design of the single cone drill diagram can adjust the cutting and rolling of the bit by adjusting the structural parameters of the single cone bit, so as to adapt to different bottomhole strata and achieve the ideal bottomhole pattern.Compared with the single-roller bit, the three-roller bit mainly cuts through rock by punching and scraping, and has fewer adjustable structural parameters and a smaller range.There are still many adjustable structural parameters, such as speed ratio and gear arrangement mode, except the position of gear arrangement and shaft inclination of single roller bit.And the cutting gear material is also one of the main factors affecting the bottom hole cutting effect.Therefore, structural optimization and cutting gear material are both important ways to optimize the bottomhole effect of the single cone bit. For the spherical single cone bit, more extensive research and development prospects are still needed.

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