PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 41, Issue 3, June 2014
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: PETROL. EXPLOR. DEVELOP., 2014, 41(3): 393–398.

RESEARCH PAPER

Evolution pattern and control mode of well deviation for spatial-arc trajectories

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Abstract: The well deviation equation of spatial-arc trajectory was established, the solution methods to determine the posture of the inclined plane that the spatial-arc trajectory lies on and the extreme value of inclination angle of the spatial-arc trajectory were presented, and the evolution pattern and control mode of well deviation for spatial-arc trajectories was revealed. Some parameters can be calculated by the forward model and inverse model respectively, including the inclination angle and azimuth angle at any point along a spatial-arc trajectory, the inclined angle and inclined azimuth angle of the inclined plane that the spatial-arc trajectory lies on and the various parameters at the point with extreme inclination angle, and the calculated results from the forward model are the same as those from the inverse model. There are two points with extreme inclination angles along a spatial-arc trajectory or its trendline, and the tangent lines of wellbore trajectory at the points with minimum and maximum inclination angles point to downdip and updip directions of the inclined plane respectively, the bending angle and azimuth angle differences between the two points are both 180°. The posture of inclined plane and parameters at extreme inclination points relate to the inclination angle and tool face angle at the beginning point of well interval, but have nothing to do with the interval length. The inclined angle mode for controlling a spatial-arc trajectory is ambiguous, so the tool-face angle or directional azimuth angle modes should be used.

Key words: drilling theory; directional drilling; wellbore trajectory; spatial-arc model; well deviation evolution

Introduction

At present, the spatial-arc model is widely used in planning, monitoring and controlling borehole trajectory, and incorporated into the oil and gas industry standards [1–2]. Early research focused on survey calculation to calculate drilled wellbore trajectories, especially for the coordinate parameters at the survey stations [3–5]. Along with the increasingly complex geological condition and progress in drilling technology, various types of three-dimensional directional wells have been completed, thus a series of methods for planning three dimensional wellbore trajectories based on the spatial-arc model have been developed [6–13]. At the same time, the modeling research on spatial-arc trajectory has also made significant progress [14–17].

A spatial-arc trajectory is an arc located in an inclined plane in space, with a constant borehole curvature and zero borehole torsion, so it can be regarded as a two-dimensional curve, the simplest model of borehole trajectory. However, neither the spatial-arc trajectory on the vertical expansion plot nor that on the horizontal plot are circular arcs, and the tool-face angle also changes with the measured depth, which brings about some difficulties to the theoretical calculation and design of construction technology. In 2006, the author found that the formula used for azimuth correction could produce abnormal results [18], then Han Zhiyong explained the phenomenon by studying the change rule and characteristics of inclination angle [19], and proposed the inclined angle mode used to control the spatial-arc trajectory [20]. In this paper, we study the extreme value of inclination angle on a spatial-arc trajectory, the posture of the inclined plane and the corresponding relationship between them, aiming at figuring out the evolution pattern and control mode of well deviation for spatial-arc trajectories, and providing references for wellbore trajectory planning, monitoring and controlling.

1 Well deviation equations of spatial-arc trajectory

Assuming a well interval as a specific curve with clear physical meaning and geometric meaning, the wellbore trajectory model can be applied in wellbore trajectory design and

Received date: 20 Feb. 2014; **Revised date:** 10 Apr. 2014.
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Foundation item: Supported by the National Key Basic Research and Development Program (973 Program), China (2010CB226700); National Science and Technology Major Project (2011ZX05005-006).

actual wellbore trajectory. In wellbore trajectory models, trajectory parameters at the starting point of the well interval are usually known, and the basic trajectory parameters (measured depth, inclination angle and azimuth angle) at the ending point can be calculated if the trajectory characteristic parameters over the well interval are given. Conversely, the trajectory characteristic parameters can be calculated if the basic trajectory parameters at the ending point are given. The wellbore trajectory models for the two cases are called the forward model and inverse model respectively. Obviously, the known conditions are different for the forward and inverse models, and they can convert and verify each other and calculate the coordinate increments of well interval.

The characteristic parameters of spatial-arc trajectory (Fig. 1) are borehole curvature κ (or radius of curvature R) and tool-face angle at the starting point of well interval ω_A (called initial tool-face angle in this paper), the former determines the shape of the wellbore trajectory, and the latter determines the posture of the wellbore trajectory [17].

For a well section of spatial-arc trajectory $\overset{\frown}{AB}$, the inclination equation and azimuth equation at any point P can be obtained from the forward model and inverse model respectively:

$$\begin{cases} \cos\alpha = \cos\alpha_A \cos\varepsilon - \sin\alpha_A \cos\omega_A \sin\varepsilon \\ \tan(\phi - \phi_A) = \dfrac{\sin\omega_A \sin\varepsilon}{\sin\alpha_A \cos\varepsilon + \cos\alpha_A \cos\omega_A \sin\varepsilon} \end{cases} \tag{1}$$

$$\begin{cases} \cos\alpha = a\cos\alpha_A + b\cos\alpha_B \\ \tan(\phi - \phi_A) = \dfrac{b\sin\alpha_B \sin(\phi_B - \phi_A)}{a\sin\alpha_A + b\sin\alpha_B \cos(\phi_B - \phi_A)} \end{cases} \tag{2}$$

Where

$$\varepsilon = \kappa\Delta L = \frac{180}{\pi}\frac{L - L_A}{R} \qquad a = \frac{\sin(\varepsilon_{A,B} - \varepsilon)}{\sin\varepsilon_{A,B}}$$

$$b = \frac{\sin\varepsilon}{\sin\varepsilon_{A,B}}$$

This shows that both the forward model and inverse model express the inclination angle α and azimuth angle ϕ at any measured depth as a function of the bending angle ε. In consideration of the relationship between bending angle and interval length, inclination angle and azimuth angle are also functions of interval length. Therefore, Equation (1) and (2) can be used to calculate the inclination angle and azimuth angle at any measured depth, and they apply to both interpolation calculation and extrapolation calculation [17].

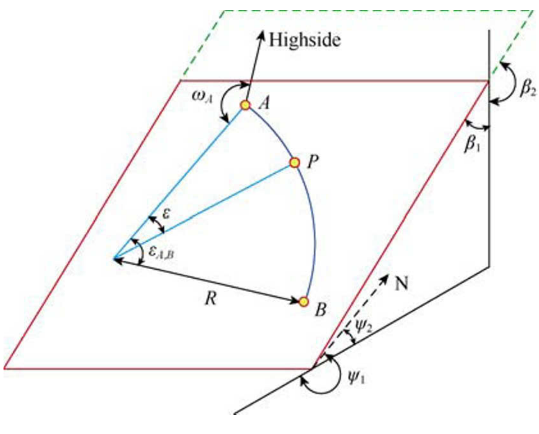

Fig. 1 Spatial-arc trajectory and the inclined plane it lies on

2 Posture of spatially-inclined plane

A spatial-arc trajectory is an arc located in an inclined plane in space, so the posture of the spatial-arc trajectory determines that of the inclined plane. The inclined angle β and inclined azimuth angle ψ of the inclined plane are used to characterize the posture of inclined plane [20], the inclined angle refers to the included angle of inclined plane and vertical direction, and the inclined azimuth angle refers to the included angle of projected inclined direction of the inclined plane onto the horizontal plane and north direction (Fig. 1).

According to the constraint relationship between the spatial-arc trajectory and inclined plane, using spatial analytic geometry and vector analysis theory, the posture parameters of inclined plane are obtained based on forward and inverse models respectively:

$$\begin{cases} \sin\beta = \sin\alpha_A \sin\omega_A \\ \tan(\psi - \phi_A) = -\dfrac{1}{\cos\alpha_A \tan\omega_A} \end{cases} \tag{3}$$

$$\begin{cases} \sin\beta = \sin\alpha_A \sin\alpha_B \dfrac{\sin(\phi_B - \phi_A)}{\sin\varepsilon_{A,B}} \\ \tan(\psi - \phi_A) = \dfrac{\sin\alpha_A \cos\alpha_B - \cos\alpha_A \sin\alpha_B \cos(\phi_B - \phi_A)}{\cos\alpha_A \sin\alpha_B \sin(\phi_B - \phi_A)} \end{cases} \tag{4}$$

Both inclined angle β and inclined azimuth angle ψ have two values in downdip direction and updip direction, respectively (Fig. 1). The smaller inclined angle is the inclined angle in downdip direction, and the corresponding inclined azimuth angle is also the downdip direction. The bigger inclined angle is the inclined angle in updip direction, and the corresponding inclined azimuth angle is also the updip direction. In addition, the range of inclined angle and inclined azimuth angle are [0, 180°] and [0, 360°] respectively, and the principal range of arcsine function and arctangent function is all [–90°, 90°], thus the calculated results from inverse trigonometric function need to be converted to the corresponding range of inclined angle and inclined azimuth angle.

3 Extremum of inclination angle

The research results above show that when the shape and posture of spatial-arc trajectory are determined, the change of inclination angle vs. measured depth is not monotonic increasing or decreasing, but trigonometric function relationship, which suggests that an extremum of inclination angle may exist. For example, in holdup turn mode the inclination angle at the ending point equals to that at the starting point, but in between the whole well section, there are one buildup part and one dropoff part and the increment equals to the decrement in inclination angle, thus they counteract each other and then