Influence of Axial Magnetic Interference on Wellbore Position Uncertainty

Degao Hu1, Xiaowen Liu1, Binbin Diao2, * and Chuang Jiang2

1 Jianghan Oilfield Company, SINOPEC, Hubei, 433124, China
2 China University of Petroleum, Beijing, 102249, China

*Corresponding author e-mail: diaobinbin@cup.edu.cn

Abstract. Accompanied with the widespread application of complex wells such as cluster wells in the exploitation of oil and gas resources, it is becoming more and more important to reduce or accurately describe the size of the wellbore position uncertainty as much as possible. It is well known that axial magnetic interference affects azimuth measurement. In this paper, the correction method of axial magnetic interference in azimuth measurement and uncertainty ellipsoid calculation method considering axial magnetic interference correction are introduced, and the influence of axial magnetic interference correction on the position uncertainty of a horizontal well is analyzed through an example. The research shows that the influence of axial magnetic interference on wellbore position measurement error varies with measurement depth, and axial magnetic interference plays an increasing role in the influence of wellbore position measurement error. Therefore, well trajectory should be measured in an environment free of axial magnetic interference.

1. Introduction
Accompanied with the popularization and application of complex wells such as cluster wells, dual horizontal wells, horizontal interconnected wells and relief wells, it is increasingly necessary to reduce wellbore position uncertainty as much as possible. Accurate description of wellbore position uncertainty is also becoming more and more important. Taking cluster well engineering as an example, cluster well engineering is becoming a commonly used engineering mode for efficient development of complex oil and gas fields. However, both the exploitation of oil and gas resources in new oilfields or the drilling of infill wells in old oilfield blocks are faced with the problem of how to prevent collision. At present, the anti-collision technology has become one of the key technologies to ensure the safe and efficient operation of cluster well drilling engineering. In cluster well drilling engineering, the results of distance scanning from adjacent wells and the results of separation factor calculation are generally used as the basis for wellbore anti-collision construction [1-3]. However, scientific evaluation of the wellbore position uncertainty is the basis for the accurate calculation of the separation factor.

The well trajectory is calculated from the measured values of the measurement depth, the inclination and the azimuth. Among them, the azimuth of the is generally measured by the three-axis fluxgate of the MWD (Measurement While Drilling), so it is susceptible to environmental magnetic interference, especially the axial interference produced by the drilling tool. Well-known foreign directional well service companies usually use professional magnetic interference correction software to correct the
aziimuth to improve its measurement accuracy. Obviously, the axial magnetic interference will inevitably affect the size of the wellbore position uncertainty [4].

The basis of wellbore position uncertainty calculation is the ISCWSA (Industry Steering Committee on Wellbore Survey Accuracy) model. This model was proposed by the Wellbore Measurement Accuracy Industry Steering Committee in 1995. The purpose of the model is to solve the problem of using and accuracy of inclinometer tools. The model includes error models suitable for MWD and GMWD (Gyroscopic MWD) [5-12]. Since the ISCWSA model was proposed, the model has undergone four revisions. The first revision introduced four new error sources to replace the original tool x-axis and y-axis misalignment error sources. The second correction modified the amplitude of the depth scalefactor and stretch error sources. The third revision introduced 20 new error sources to replace 16 old error sources related to the toolface. The fourth revision did not make any changes to the weight function of the error sources, but introduced a look-up table of uncertainty in the BGGM (British Global geomagnetic model) model.

At present, the wellbore position uncertainty is often calculated by using the ISCWSA MWD standard model. However, the standard model does not consider the influence of axial magnetic interference on the wellbore position uncertainty. Therefore, in order to meet the actual needs of the engineering site, it is necessary to discuss the influence of axial magnetic interference on the wellbore position uncertainty.

2. Calculation of axial magnetic interference correction

In order to eliminate the influence of axial magnetic interference on the azimuth and make the measured trajectory more in line with the actual field, there are generally three commonly used methods: vector sum method, drill tool section method and short drill collar measurement correction method.

2.1. Vector sum method

Using the known geomagnetic field strength \( B_t \) and the measured accurate radial magnetic induction intensity components \( B_x \) and \( B_y \), the axial magnetic induction intensity component \( B_{ZC} \) is calculated. And then the azimuth can be calculated from the calculated value of \( B_{ZC} \) [4]. It should be noted that to find out the \( B_{ZC} \) needs to determine the positive or negative of its value. Substituting it into the azimuth calculation equation, two azimuths will appear, just select the solution that is close to the previous azimuth value.

\[
B_{ZC} = \pm \sqrt{B_t^2 - B_x^2 - B_y^2}
\]

\[
\sin \phi = \frac{-(B_x \sin \phi + B_y \cos \phi)}{\cos \phi} \quad \text{cos } \alpha (B_x \cos \omega + B_y \sin \omega) + B_{ZC} \sin \alpha
\]

Where, \( B_t \) is the magnetic induction intensity of the geomagnetic field; \( B_{ZC} \) is the axial magnetic induction intensity component; \( \phi \) is the azimuth; \( \alpha \) is the inclination; \( \omega \) is the high-side tool face angle; \( B_x, B_y, B_z \) are the magnetic induction intensity components of the geomagnetic field.

2.2. Drilling tool section method

The drilling tool section method uses the local magnetic field parameters and the measured accurate radial magnetic induction intensity component, establishes the geometric relationship among them through the azimuth, and then reverses the azimuth [4]. As shown in Fig. 1, there are the geodetic coordinate system \( NEV \) and the instrument coordinate system \( XYZ \).

\[
B_t = B_x + B_y
\]

\[
B_x = B_{X} + B_y + B_Z
\]
Figure 1. Geodetic coordinate system and instrument coordinate system

The $P$-plane is the borehole cross section, and the $H$-axis is the high-side direction. Then there are:

$$B_N \cos \varphi \cos \alpha - B_V \sin \alpha = B_X \cos \phi - B_Y \sin \phi$$  \hspace{1cm} (5)

$$B_N \sin \varphi = -B_X \sin \phi - B_Y \cos \phi$$  \hspace{1cm} (6)

From the two equations above,

$$\frac{\sin \varphi}{\cos \varphi} = \frac{-(B_X \sin \phi + B_Y \cos \phi) \cos \alpha}{(B_X \cos \phi - B_Y \sin \phi) + B_Y \sin \alpha}$$  \hspace{1cm} (7)

Where, $B_V$ is the $V$-axis component of the geomagnetic field; $B_N$ is the $N$-axis component of the geomagnetic field;

The azimuth can be obtained by using the toolface angle and the well inclination calculated from the known $B_X$ and $B_Y$. It should be noted that when the inclination $\alpha$ is equal to 90°, $\cos \alpha$ is equal to 0 and the azimuth cannot be calculated.

2.3. Short drill collar measurement correction method

Sperry-sun's MWD software provides a short collar measurement correction method, which uses a loop iteration method to indirectly correct the azimuth [13]. In the absence of magnetic interference, the following equations can be obtained:

$$\sin \alpha = \frac{g_X^2 + g_Y^2}{g}$$ \hspace{1cm} (8)

$$\cos \alpha = \frac{g_Z}{g}$$ \hspace{1cm} (9)

$$\sin \phi = \frac{g_Y}{g \sin \alpha}$$ \hspace{1cm} (10)

$$\cos \phi = -\frac{g_X}{g \sin \alpha}$$ \hspace{1cm} (11)

$$B_N = B_V \cos \theta$$ \hspace{1cm} (12)
\[ B_y = B_x \sin \theta \]  
\[ B_{ZC} = B_N \cos \phi \sin \theta + B_x \cos \alpha \]  
\[ \frac{\sin \phi}{\cos \phi} = \frac{- (B_x \sin \phi + B_y \cos \phi)}{\cos \alpha (B_x \cos \phi + B_y \sin \phi) + B_{ZC} \sin \alpha} \]

Where, \( \theta \) is the magnetic inclination; \( B_{ZC} \) is the axial magnetic induction intensity component; \( g_x \), \( g_y \), \( g_z \) are the triaxial components of gravitational acceleration in \( XYZ \) system. When there is axial magnetic interference, the value of \( B_{ZC} \) in Eqs. (14) and (15) is not accurate, and iterative solution is required as shown in Fig. 2.

**Figure 2.** The calculation process of azimuth correction

3. **Calculation of wellbore position uncertainty without considering axial magnetic interference**

The model after the third revision of ISCWSA MWD considers the influence of 41 error sources. The ISCWSA MWD standard model that does not consider the axial magnetic interference correction considers the influence of 27 error sources, and the ISCWSA MWD model that considers the axial magnetic interference correction considers the influence of 25 error sources.

The basic purpose of the standard model after the third revision of ISCWSA MWD is to combine the influence of 27 error sources that cause wellbore position uncertainty to determine the three-dimensional error ellipsoid of any specific measuring point. The uncertainty of the position of the measuring point caused by a single error source can be expressed as [12]:

\[ (\varphi - \varphi^*) < \varepsilon \]

\[ \varphi = \varphi^* \]
\[ e_{ij} = \sigma_j \frac{dr_j}{dp} \frac{\partial p}{\partial e_j} \]  

**Where,** \( e_{ij} \) **represents the position error matrix of the \( i \)-th well section caused by the \( j \)-th error source;** \( \sigma_j \) **represents the standard deviation of the \( j \)-th error source.**

In Eq. (16), \( \frac{dr_j}{dp} \) **represents the influence of the measurement error of along hole depth, inclination and azimuth on the position of the \( i \)-th well section in the coordinate system NEV;** \( \frac{\partial p}{\partial e_j} \) **represents the weight function of the \( j \)-th error source.** The wellbore position uncertainty covariance matrix of the \( i \)-th measuring point can be expressed as:

\[ M_i = \sum_{i=1}^{N} \sum_{j=1}^{N} e_{ij} \]  

**Where,** \( N \) **represents the number of error sources considered by the model of wellbore position uncertainty.** The position error of the \( i \)-th measuring point can be described by an ellipsoid. The three semi-axes lengths of uncertainty ellipsoid are [14-15]:

\[ \begin{align*}
    r_{i1} &= \delta \sqrt{\lambda_{i1}} \\
    r_{i2} &= \delta \sqrt{\lambda_{i2}} \\
    r_{i3} &= \delta \sqrt{\lambda_{i3}} 
\end{align*} \]  

**Where,** \( \delta \) **is the confidence factor;** \( \lambda_{i1}, \lambda_{i2} \) **and** \( \lambda_{i3} \) **are the three eigenvalues of the wellbore position uncertainty covariance matrix** \( M_i \) **of the \( i \)-th measuring point respectively.** The directions of the three semi-axes \( (r_{i1}, r_{i2} \text{ and } r_{i3}) \) **of the error ellipsoid are the directions of eigenvectors** \( P_{i1}, P_{i2} \text{ and } P_{i3} \) **corresponding to the eigenvalues** \( \lambda_{i1}, \lambda_{i2} \text{ and } \lambda_{i3} \) **of the covariance matrix** \( M_i \).

4. **Evaluation of the influence of axial magnetic interference on wellbore position uncertainty**

In order to evaluate the influence of axial magnetic interference on the wellbore position uncertainty, it is necessary to import the well depth, inclination and azimuth measured by MWD of the same well into the ISCWSA MWD standard model and the ISCWSA MWD model considering axial magnetic interference correction. Thus, the three semi-axes lengths \( (\lambda_{i1}, \lambda_{i2}, \lambda_{i3}) \) **of the error ellipsoid are calculated by the ISCWSA MWD model considering axial magnetic interference correction at the \( i \)-th measuring point:**

\[ \begin{align*}
    r_{i1}^* &= \delta \sqrt{\lambda_{i1}^*} \\
    r_{i2}^* &= \delta \sqrt{\lambda_{i2}^*} \\
    r_{i3}^* &= \delta \sqrt{\lambda_{i3}^*} 
\end{align*} \]  

Then, the influence rate of the axial magnetic interference correction on the \( k \)-th semi-axis length of the uncertainty ellipsoid at the \( i \)-th measuring point can be expressed as:

\[ R_k = \frac{r_{ik} - r_{ik}^*}{r_{ik}^*} \times 100\% \]  

**Where,** \( k = 1, 2, 3 \).

5. **Example calculation and analysis**

The partial survey data of a horizontal well (JYAHF) is shown in the Table 2. The geomagnetic field intensity at this well location is 49.69 \( \mu T \), the geomagnetic dip is 45.57°, and the geomagnetic declination is -3.67°. According to the anti-collision convention of cluster wells, the value of the
confidence factor $\lambda$ is 2.976. In order to study the influence of axial magnetic interference on the wellbore position uncertainty, MATLAB was used to program the standard model and the model considering axial magnetic interference correction respectively and import MWD survey data. The three semi-axes lengths of the wellbore position uncertainty ellipsoid of JYAHF calculated by the two models varies with measured depth are shown in Figures 3-5.

| MD/m  | INC/(°) | AZI/(°) | TVD/m | NS/m  | EW/m  |
|-------|---------|---------|-------|-------|-------|
| 0.00  | 0.00    | 0.00    | 0.00  | 0.00  | 0.00  |
| 878.41| 7.7     | 293.64  | 876.46| 10.13 | -21.90|
| 887.90| 7.4     | 298.74  | 885.87| 10.68 | -23.02|
| 897.50| 8.3     | 302.94  | 895.38| 11.35 | -24.15|
| 906.84| 8.7     | 311.04  | 904.62| 12.18 | -25.25|
| 2875.38| 90.2   | -2.06   | 2366.74| 1130.77| -249.89|
| 2885.00| 90.3   | -1.96   | 2366.70| 1140.38| -250.23|
| 2894.44| 90.5   | -1.86   | 2366.63| 1149.82| -250.54|
| 2904.00| 91.6   | -1.96   | 2366.46| 1159.37| -250.86|
| 2913.50| 91.7   | -1.96   | 2366.18| 1168.86| -251.18|
| 2923.15| 91.9   | -1.86   | 2365.88| 1178.5 | -251.51|
| 2930.00| 91.9   | -1.86   | 2365.65| 1185.34| -251.73|
| 4129.34| 95.3   | 0.84    | 2338.96| 2382.98| -251.53|
| 4133.00| 95.3   | 0.84    | 2338.63| 2386.62| -251.48|
| 4163.00| 95.3   | 0.84    | 2335.86| 2416.49| -251.04|

**Figure 3.** The error ellipsoidal semi-axis lengths in the direction of the along hole axis varies with the measured depth
As shown in Figures 3-5, the magnetic interference has different effects on the three semi-axes of the uncertainty ellipsoid. In general, it will reduce the error ellipsoidal semi-axis lengths in the direction of the along hole axis, has no effect on the error ellipsoidal semi-axis lengths in the direction of the upward axis, and will increase the error ellipsoidal semi-axis lengths in the direction of the lateral axis. The three semi-axes length differences of the uncertainty ellipsoids calculated by the two models are shown in Fig. 6, and the relationship between the influence rate of axial magnetic interference on the wellbore position uncertainty is shown in Fig. 7.
Figure 6. The difference of the semiaxis of the ellipsoid calculated by the two models varies with the measured depth.

Figure 7. The influence of axial magnetic interference on the semi-main axes of the ellipsoid varies with the measured depth.

As shown in Fig. 6, the maximum influence of axial magnetic interference correction on the semiaxis $r_3$ in the direction of the lateral axis can reach 16.9m, and the maximum influence on the semiaxis $r_1$ in the direction of the along hole axis can reach -3.1m. This shows the importance of axial magnetic interference correction for the calculation of the wellbore position uncertainty and the formulation of anti-collision decisions. It can also be seen from Figures 3-6 that as the along-hole depth increases, the influence of the axial magnetic interference on the length of the semiaxis is constantly changing. Taking the semiaxis $r_3$ as an example, when the measured depth is small, the axial magnetic interference will reduce the length of $r_3$; When the measured depth is large, the axial magnetic interference will increase the length of the semiaxis $r_3$. As shown in Figures 6 and 7, in the vertical section, the lateral position error caused by axial magnetic interference is the largest, and the influence rate on $r_3$ of the uncertainty...
ellipsoid is the largest; in the inclined section, the along hole position error caused by axial magnetic interference is the largest, and the influence rate on $r_1$ of the uncertainty ellipsoid is the largest; in the horizontal section, the lateral position error caused by axial magnetic interference is the largest, and the influence rate on $r_3$ of the uncertainty ellipsoid is the largest.

As shown in Fig. 8, the blue area is the schematic diagram of the error ellipsoid calculated by the ISCWSA MWD standard model for the two wells. The brown area is the ellipsoid of the wellbore position uncertainty of the two wells calculated by the ISCWSA MWD model considering the axial magnetic interference correction. When the measured depth is small, if the wellbore position uncertainty is calculated by using a model that does not consider the axial magnetic interference correction, the risk of wellbore collision will be underestimated. When the measured depth is large, if the wellbore position uncertainty is calculated by using the model that does not consider the axial magnetic interference correction to make the anti-collision decision, the risk of wellbore collision will be overestimated, and the collision avoidance decision will become conservative. This shows the existence of axial magnetic interference will make anti-collision decisions conservative or wrong.

![Figure 8](image-url)

**Figure 8.** Schematic diagram of the wellbore position uncertainty ellipsoid calculated by using the standard model and the model considering the axial magnetic interference correction

6. Conclusions

(1) Axial magnetic interference not only affects the survey data of borehole trajectory, but also affects the measurement error of wellbore position.

(2) The influence of axial magnetic interference on wellbore position measurement error varies with measurement depth. As shown in the example, in the vertical section and the horizontal section, the lateral position error caused by axial magnetic interference is the largest, and the influence rate on the lateral axis of the uncertainty ellipsoid is the largest; in the inclined section, the along hole position error caused by axial magnetic interference is the largest, and the influence rate on the along hole axis of the uncertainty ellipsoid is the largest.

(3) Axial magnetic interference plays an increasing role in the influence of wellbore position measurement error. Therefore, well trajectory should be measured in an environment free of axial magnetic interference.

Acknowledgements

The authors gratefully acknowledge the financial support of the Natural Science Foundation of China (NSFC, 51974336, 51821092, U1762214).

References

[1] XU Junfu XU Wenhao GENG Yingchun. Anti-collision optimization design technology for large-scale infill drilling for cluster well groups in the artificial island of the Bohai Sea [J]. Petroleum Drilling Techniques, 2018, 46(02): 24-29.

[2] LI Hongxing. Anti-collision and obstacle bypassing techniques in cluster wells drilling in shallow layers of the PY30-1 gas field [J]. Petroleum Drilling Techniques, 2015, 43(06): 125-129.

[3] DIAO Binbin, GAO Deli. Calculation method of adjacent well oriented separation factors [J]. Petroleum Drilling Techniques, 2012, 40(01): 22-27.
[4] FAN Guanfdi, PU Wenxue, ZHAO Guoshan, et al. Correction Methods for Magnetic Inclinometer while Drilling [J]. Petroleum Drilling Techniques, 2012, 40(01): 22-27.
[5] WILLIAMSON H S. Accuracy prediction for directional MWD [R]. SPE 56702-MS, 1999.
[6] WILLIAMSON H S. Accuracy prediction for directional measurement while drilling [J]. SPE 67616-PA, 1999.
[7] TORGEIR T, HAVARDSTEIN T S, WESTON L J, et al. Prediction of wellbore position accuracy when surveyed with gyroscopic tools [J]. SPE 90408-PA, 2004.
[8] BROOKS A G, WILSON H, JAMIESON A L, et al. Quantification of depth accuracy [R]. SPE 95611-MS, 2005.
[9] EKSETH R, TORKILDSEN T, BROOKS A G, et al. The reliability problem related to directional survey data [R]. SPE 103734, 2006.
[10] EKSETH R, TORKILDSEN T, BROOKS A G, et al. High integrity wellbore surveys: Methods for eliminating gross errors [R]. SPE 105558, 2007.
[11] MACMILLAN S & GRINDROD S. Confidence limits associated with values of the Earth’s magnetic field used for directional drilling [J]. SPE 119851-PA, 2010.
[12] JAMIESON A. Introduction to wellbore positioning [M]. Scotland: University of the Highlands & Islands, 2017.
[13] Sperry-Sun Drilling Services Company. Basic concepts of directional surveying [R]. 1995.
[14] DONG Benjing, GAO Deli, LIU Gonghui. Discussion on the analytical method of well track uncertainty [J]. Natural Gas Industry, 1999, 19(4): 59-63.
[15] LIU Gonghui, DONG Benjing, GAO Deli. Probability analysis of error ellipsoid (ellipse) and hole intersection [J]. Drilling & Production Technology, 2000, 23(3): 5-11.