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Research on Modeling Technology of High-Spin Projectiles with Geomagnetic Information

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Abstract

In this study, geomagnetic information related to the attitude is introduced into the modeling process of high-spin ballistic projectiles. The measured values m_{x1}, m_{y1}, m_{z1} from geomagnetic sensors are utilized to calculate the geomagnetic azimuth σ_M and angular rate ω_ξ . Additionally, the relationship between the geomagnetic azimuth, pitch angle, and yaw angle is described. Combined with geomagnetic and GNSS data from sensors installed on the high-spin projectiles, the Chapman-Kirk (C-K) identification method is employed to obtain the aerodynamic force and moment coefficients based on the 6-degree-of-freedom (6DOF) projectile dynamic model. A convergence factor λ_k in the modified Gauss-Newton (G-N) method is proposed to accelerate the convergence of aerodynamic coefficient identification. The ballistic identification results demonstrate the effectiveness of the proposed method.

KEYWORDS

High-spin projectile, geomagnetic information, aerodynamic identification, 6-DOF trajectory model

1 | INTRODUCTION

As a key type of ammunition in modern precision strike weapon systems, the modeling accuracy of high-spin projectiles during flight directly affects guidance precision, control performance, and operational effectiveness; however, due to the high-speed rotation of the projectile body and the lack of effective attitude sensing means, traditional modeling methods mostly rely on position and velocity information to identify aerodynamic parameters (Combettes et al., 2018) combined with dynamic equations. It is difficult to directly obtain key attitude angle information such as roll angle and attitude angle during the projectile's flight process, which affects the inversion and identification of the projectile's aerodynamic moment coefficients, increases the difficulty of establishing a high-precision ballistic model, and the model identification results are also susceptible to the influence of test sample size and measurement errors.

Accurately obtaining the projectile's aerodynamic forces and moment coefficients is the foundation for establishing a high-precision ballistic model. Scholars at home and abroad have conducted long-term and in-depth research on this aspect: Combettes et al. proposed a method for estimating projectile attitude and velocity using low-cost three-axis magnetometers and two-axis accelerometers, verifying the feasibility of reconstructing motion states through a simplified 6-degree-of-freedom model and

filtering algorithms without gyroscopes (Combettes et al., 2018). This work shows that even in a strong dynamic environment, the information fusion strategy based on environmental field perception can provide effective support for state estimation. For high-spin projectiles, the phase shifting ratio method based on magnetometers has also been proven to achieve accurate attitude measurement, further expanding the application of geomagnetic sensors in attitude perception (Zhao et al., 2019). In addition, aiming at the non-orthogonality problem of magnetic sensors, a novel attitude estimation algorithm has been proposed to improve measurement accuracy, providing technical support for the reliability of geomagnetic data (Zhu et al., 2016).

The combined attitude measurement method based on inertial and geomagnetic information fusion provides a technical reference for multi-source information integration. Magnetometers can continuously measure the components of the Earth's magnetic field in the projectile body coordinate system, and their periodic changes are closely related to the rolling motion (Maley, 2016). For the nonlinear characteristics and noise interference of geomagnetic signals in high-spin projectiles, the moving horizon based wavelet de-noising method has been proposed to improve the quality of roll positioning data (Yin et al., 2020). The zero-crossing method can effectively extract the roll angular rate and geomagnetic azimuth (An et al., 2019; Li and Bu, 2010); further combined with the specific force information output by the accelerometer, partial observability of the pitch and yaw angles can be achieved without an external attitude reference (Combettes et al., 2018; Mi et al., 2015). Zhao et al. (Zhao et al., 2016) studied the attitude update algorithm based on MIMU and magnetometer, improving the attitude solution efficiency of low-power platforms; while Yang et al. (Yang et al., 2019) clearly proposed a roll angle measurement method suitable for rockets, confirming the usability of magnetic sensors under rotating conditions.

In terms of aerodynamic parameter identification for spin-stabilized projectiles, scholars have also made positive progress. For example, aiming at spin-stabilized trajectory correction projectiles with micro-spoilers, researchers have constructed an aerodynamic parameter identification scheme using a differential evolution algorithm with adaptive mutation operators, effectively identifying key parameters such as additional axial force coefficient and normal force coefficient (Yang et al., 2023). In addition, for the correction capability research of high-spin tail-controlled correction projectiles, the Hyperband-Bayesian optimization-LSTM network has been used to improve the prediction accuracy of correction effects, providing a new idea for the combination of data-driven methods and projectile modeling (Zhou et al., 2025).

For this reason, this paper obtains the geomagnetic field components induced by the projectile during flight based on a three-axis geomagnetic sensor, and uses them to calculate the geomagnetic azimuth and roll angular velocity strongly related to the attitude motion of high-spin projectiles (An et al., 2019; Li and Bu, 2010). The geomagnetic azimuth and roll angular velocity are fused with the position and velocity information provided by GNSS to construct a high-reliability measurement vector z_k containing position, velocity, attitude and angular velocity. On this basis, a 6-degree-of-freedom ballistic dynamic model is established, and the measurement vector z_k is used as an auxiliary input. Through the Chapman-Kirk (C-K) parameter identification algorithm and the modified Gauss-Newton method, a sensitivity matrix iterative model is established to realize the joint identification of key aerodynamic parameters such as drag coefficient, lift coefficient derivative, static moment coefficient derivative, polar damping moment coefficient derivative, and equatorial damping moment coefficient derivative.

2 | PREPARATION OF GEOMAGNETIC INFORMATION FOR HIGH-SPIN PROJECTILE

2.1 | Coordinate Systems

2.1.1 | Geographic Coordinate System $O-NED$

To describe the geomagnetic information of high-spin projectiles, the magnetic induction intensity M of the geomagnetic field is usually projected onto the $O-NED$ (North East Down) coordinate system. As shown in Figure 1, taking the Northern Hemisphere as an example, the vertical plane where the magnetic induction intensity M lies is called the magnetic meridian plane. The X-axis points north along the geographic meridian as the positive direction, the Y-axis points east along the parallel of latitude as the positive direction, and the Z-axis points vertically downward as the positive direction.

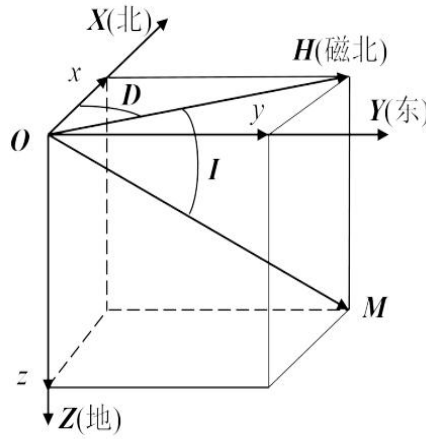


FIGURE 1 Geomagnetic field parameter diagram

The projections of the geomagnetic field intensity M onto the X, Y, and Z axes are referred to as the northward, eastward, and vertical magnetic intensities respectively. The projection of M onto the horizontal plane XOY is defined as the horizontal magnetic intensity. The angle D between the magnetic meridian plane and the geographic meridian plane is called the magnetic declination, with an eastward deviation specified as positive. The angle I between M and the horizontal plane is named the magnetic inclination. Since M points below the horizontal plane in the Northern Hemisphere, the magnetic inclination I takes a positive value.

2.1.2 | Velocity Coordinate System $O - x_2y_2z_2$

The Ox_2 axis of the velocity coordinate system $O - x_2y_2z_2$ points along the direction of the center-of-mass velocity vector $\vec{v}$. The Oy_2 axis is perpendicular to the velocity vector and points upward. The Oz_2 axis, determined by the right-hand rule, is perpendicular to the Ox_2y_2 plane with the rightward direction defined as positive. In the velocity coordinate system, the angle between the projection of the velocity vector $\vec{v}$ onto the vertical plane and the horizontal plane is called the velocity elevation angle, also known as the trajectory inclination angle θ . The angle between the projection of the velocity vector onto the horizontal plane and the geographic north direction is called the velocity azimuth angle, also known as the trajectory deflection angle ψ .

2.1.3 | Projectile Axis Coordinate System $O - \xi\eta\zeta$

The $O\xi$ axis is the projectile axis, with the forward direction defined as positive. The $O\eta$ axis is perpendicular to the $O\xi$ axis and points upward. The $O\zeta$ axis, determined by the right-hand rule, is perpendicular to the $O\xi\eta$ plane and points to the right. The angle between the projection of the $O\xi$ axis onto the vertical plane and the horizontal plane is called the pitch angle ϕ_1 . The angle between the projection of the $O\xi$ axis onto the horizontal plane and the geographic north direction is called the yaw angle ϕ_2 .

2.1.4 | Projectile Body Coordinate System $O - x_1y_1z_1$

The Ox_1 axis remains the projectile axis, while the Oy_1 axis and Oz_1 axis are fixed to the projectile body and rotate around the Ox_1 axis along with the body. Let γ be the rotation angle (roll angle) of the projectile body relative to the projectile axis coordinate system.

2.1.5 | World Geodetic System-1984 (WGS-84) Coordinate System

The measured trajectory data of the projectile from the GNSS sensor are defined in the WGS-84 coordinate system, which consists of longitude, latitude, and altitude during the flight process. At the same time, the GNSS sensor also provides the velocity

of the projectile in the North-East-Up coordinate system. Using the coordinate system transformation matrices in (Han et al., 2022), these measured values can be transformed into the flight states x, y, z, v, θ, ψ required in this paper.

2.2 | Geomagnetic Information and Establishment of High-Spin Projectile Models

2.2.1 | Geomagnetic Azimuth

The geomagnetic azimuth is defined as the angle between the geomagnetic vector and the projectile axis vector, which can be described as follows (An et al., 2019):

$$\cos(\sigma_M) = \cos(I) \cos(D - \alpha_N) \cos(\phi_1) \cos(\phi_2) - \sin(I) \sin(\phi_1) \cos(\phi_2) + \cos(I) \sin(D - \alpha_N) \sin(\phi_2) \quad (1)$$

where α_N is the angle between the X-axis of the Inertial Coordinate System $O-XYZ$ and the North-axis of the Geographic Coordinate System $O-NED$.

2.2.2 | Measurement of Geomagnetic Azimuth Angle and Roll Rate

The geomagnetic sensors are installed along the projectile body coordinate system $O-x_1y_1z_1$, with measured values denoted as m_{x1}, m_{y1}, m_{z1} . The relationship between these measured values, the geomagnetic azimuth angle σ_M , and the roll angle γ is given as follows (An et al., 2019):

$$\begin{cases} m_{x1} = M \cdot \cos(\sigma_M) \\ m_{y1} = M \cdot \sin(\sigma_M) \cos(\gamma) \\ m_{z1} = M \cdot \sin(\sigma_M) \sin(\gamma) \end{cases} \quad (2)$$

Then, the expressions for measuring the geomagnetic field intensity M , roll angle γ , and roll rate ω_ξ are derived as follows:

$$\begin{cases} M = \sqrt{m_{x1}^2 + m_{y1}^2 + m_{z1}^2} \\ \gamma = \arctan\left(\frac{m_{z1}}{m_{y1}}\right) \\ \omega_\xi = \frac{d\gamma}{dt} \end{cases} \quad (3)$$

where ω_ξ is the time derivative of the roll angle γ (i.e., the roll angular rate).

2.2.3 | Flight Dynamics Model of Projectiles

The 6-DOF (degree-of-freedom) flight dynamics model of projectiles is defined as (Han et al., 2022):

$$\begin{cases} \dot{x} = v \cdot \cos(\psi) \cos(\theta) \\ \dot{y} = v \cdot \cos(\psi) \sin(\theta) \\ \dot{z} = v \cdot \sin(\psi) \\ \dot{v} = \frac{1}{m} F_{x2} \\ \dot{\theta} = \frac{1}{mv \cos(\psi)} F_{y2} \\ \dot{\psi} = \frac{1}{mv} F_{z2} \\ \dot{\phi}_1 = \frac{\omega_\xi}{\cos(\psi)} \\ \dot{\phi}_2 = -\omega_\eta \\ \dot{\gamma} = \omega_\xi - \omega_\zeta \tan(\phi_2) \\ \dot{\omega}_\xi = \frac{1}{C} M_\xi \\ \dot{\omega}_\eta = \frac{1}{A} M_\eta - \frac{C}{A} \omega_\xi \omega_\zeta + \omega_\xi^2 \tan(\phi_2) \\ \dot{\omega}_\zeta = \frac{1}{A} M_\zeta + \frac{C}{A} \omega_\xi \omega_\eta - \omega_\eta \omega_\zeta \tan(\phi_2) \end{cases} \quad (4)$$

where F_{x2}, F_{y2}, F_{z2} are the projections of the resultant force $\vec{F}$ acting on the projectile onto the velocity coordinate system $O-x_2y_2z_2$; M_ξ, M_η, M_ζ are the projections of the resultant moment $\vec{M}$ acting on the center of mass of the projectile onto the projectile axis coordinate system $O-\xi\eta\zeta$; the resultant force $\vec{F}$ is composed of gravity, aerodynamic drag, lift, Magnus force, and Coriolis force; the resultant moment $\vec{M}$ is composed of static moment, equatorial damping moment, polar damping moment, and Magnus moment; x, y, z are the trajectory positions of the high-spin projectile during flight; v, θ, ψ are the velocity magnitude, trajectory inclination angle, and trajectory deflection angle; ϕ_1, ϕ_2, γ are the pitch angle, yaw angle, and roll angle; $\omega_\xi, \omega_\eta, \omega_\zeta$ are the projections of the total rotational angular rate $\vec{\omega}$ of the projectile onto the projectile axis coordinate system; m is the mass of the projectile; A and C are the moments of inertia of the projectile around the transverse axis and longitudinal axis respectively.

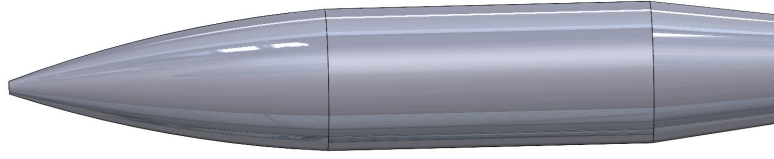


FIGURE 2 High-Spin Projectile

3 | AERODYNAMIC PARAMETER IDENTIFICATION

3.1 | Measurement Data

The measurement data vector Z can be expressed as:

$$Z = [z_1, z_2, \dots, z_n]^T \quad (5)$$

where n represents the number of data points in the identification interval, and the sub-vector z_k is defined as:

$$z_k = (x_k, y_k, z_k, v_x, v_y, v_z, \cos(\sigma_{Mk}), \omega_\xi)^T, \quad k = 1, \dots, n$$

In the above formula, $(x_k, y_k, z_k, v_x, v_y, v_z)$ are the trajectory and velocity data at time t_k , $\cos(\sigma_{Mk})$ denotes the cosine value of the geomagnetic azimuth angle at t_k , and ω_ξ is the roll angular rate of the projectile at t_k .

3.2 | Parameters to be Identified

The vector of aerodynamic parameters to be identified, denoted as C , is given by:

$$C = [c_x, c'_y, m'_z, m'_{xz}, m'_{zz}]^T \quad (6)$$

where: c_x is drag coefficient, c'_y is lift coefficient derivative, m'_z is static moment coefficient derivative, m'_{xz} is polar damping moment coefficient derivative, m'_{zz} is equatorial damping moment coefficient derivative.

3.3 | Estimated Values of Measurement Data

The estimated value $\hat{Z}$ of the measurement data vector Z can be derived from the ballistic equation. Let $\hat{Z}_0$ represent the estimated measurement data calculated by substituting the initial identification parameter C_0 into the ballistic equation, which is

expressed as:

$$\hat{Z}_0 = [\hat{z}_1(t_1, C_0), \hat{z}_2(t_2, C_0), \dots, \hat{z}_n(t_n, C_0)]^T \quad (7)$$

The relationship between the actual measurement data Z and the unknown parameters C is given by:

$$Z - \hat{Z}_0 = \tilde{B}_0 \Delta C + \eta \quad (8)$$

where $\eta \in \mathbb{R}^{8n \times 1}$ is the random error of the measurement data, and the matrix $\tilde{B}_0$ is defined as:

$$\tilde{B}_0 = [B_1, B_2, \dots, B_n]^T \quad (9)$$

In the matrix above, $B_k = \frac{\partial z_k}{\partial C} \in \mathbb{R}^{8 \times 5}$ ($k = 1, 2, \dots, n$).

3.4 | Identification Method

The objective function for parameter identification is defined as:

$$J = \|Z - \hat{Z}_0 - \tilde{B}_0 \Delta C\|^2 \quad (10)$$

Using the least squares method, the estimated value $\hat{\Delta C}$ of the parameter correction term ΔC is obtained as:

$$\hat{\Delta C} = (\tilde{B}_0^T \tilde{B}_0)^{-1} \tilde{B}_0^T (Z - \hat{Z}_0) \quad (11)$$

Thus, the estimated value of the unknown parameters C is:

$$\hat{C} = C_0 + (\tilde{B}_0^T \tilde{B}_0)^{-1} \tilde{B}_0^T (Z - \hat{Z}_0) \quad (12)$$

To improve the accuracy of the parameter estimation, an improved Gauss-Newton (G-N) iterative method is adopted. After obtaining the k -th estimated parameter $\hat{C}_k$, an appropriate step size λ_k is selected to update the parameters as:

$$\hat{C}_{k+1} = \hat{C}_k + \lambda_k \hat{\Delta C}_k \quad (13)$$

where the correction term $\hat{\Delta C}_k$ is calculated as:

$$\hat{\Delta C}_k = (\tilde{B}_k^T \tilde{B}_k)^{-1} \tilde{B}_k^T (Z - \hat{Z}_k)$$

$\hat{Z}_k$ is the estimated measurement data calculated from the k -th parameter $\hat{C}_k$. The iteration converges if the updated parameter $\hat{C}_{k+1}$ satisfies the following inequality:

$$(Z - \hat{Z}_{k+1})^T (Z - \hat{Z}_{k+1}) \leq (Z - \hat{Z}_k)^T (Z - \hat{Z}_k) \quad (14)$$

If the inequality (14) is not satisfied, the step size is adjusted as $\lambda_{k+1} = 0.5\lambda_k$ and the iteration is repeated until convergence is achieved.

Define the key dimensions: $n_z = 8$ (number of measurement variables), $n_c = 5$ (number of parameters to be identified), $n_x = 12$ (number of system states). The Jacobian matrix $B_k = \frac{\partial z_k}{\partial C} \in \mathbb{R}^{n_z \times n_c}$ and the sensitivity matrix $P_k = \frac{\partial x}{\partial C} \in \mathbb{R}^{n_x \times n_c}$, where the system state vector is:

$$x = [x, y, z, v, \theta, \psi, \phi_1, \phi_2, \gamma, \omega_\xi, \omega_\eta, \omega_\zeta]^T$$

Based on the chain rule of partial derivatives, B_k can be rewritten as:

$$B_k = \frac{\partial z_k}{\partial C} = \frac{\partial z_k}{\partial x} \cdot \frac{\partial x}{\partial C} = B_{1k} \cdot P_k \in \mathbb{R}^{n_z \times n_c} \quad (15)$$

where $B_{1k} = \frac{\partial z_k}{\partial x} \in \mathbb{R}^{n_z \times n_x}$ is the partial derivative of the measurement vector with respect to the system state vector. The time

derivative of the sensitivity matrix P_k is:

$$\dot{P}_k = \frac{\partial \dot{x}(x, C)}{\partial C} = \frac{\partial \dot{x}}{\partial x} \cdot P_k + \frac{\partial \dot{x}}{\partial C} \quad (16)$$

Let $F(x, C) = \dot{x}(x, C)$ (the state equation of the projectile), then:

$$\frac{\partial \dot{x}}{\partial x} = \frac{\partial F(x, C)}{\partial x}, \quad \frac{\partial \dot{x}}{\partial C} = \frac{\partial F(x, C)}{\partial C} \quad (17)$$

Equation (17) can be solved using the 6-degree-of-freedom (6DOF) ballistic equation system of the projectile.

4 | RESULTS

To verify the effectiveness of the proposed modeling and identification method, a simulation case is carried out based on a type of 155-mm projectile. The key parameters of the projectile and launch conditions are set as follows: actual launch angle 52° , launch direction angle 90° relative to north, initial velocity 930 m/s, position latitude 31.233° , position longitude 118.36° , and position altitude 100 m. The GNSS and geomagnetic data measured by the ballistic measurement device are obtained through 6-degree-of-freedom (6DOF) simulation, and aerodynamic parameter identification is performed based on these telemetry data.

4.1 | Telemetry Simulation Data

The GNSS position coordinate data, velocity component data, longitude-latitude-altitude data, as well as the geomagnetic measured roll angular velocity and azimuth angle data during the projectile flight are shown in Figures 3–5. These data provide a reliable foundation for subsequent aerodynamic parameter identification.

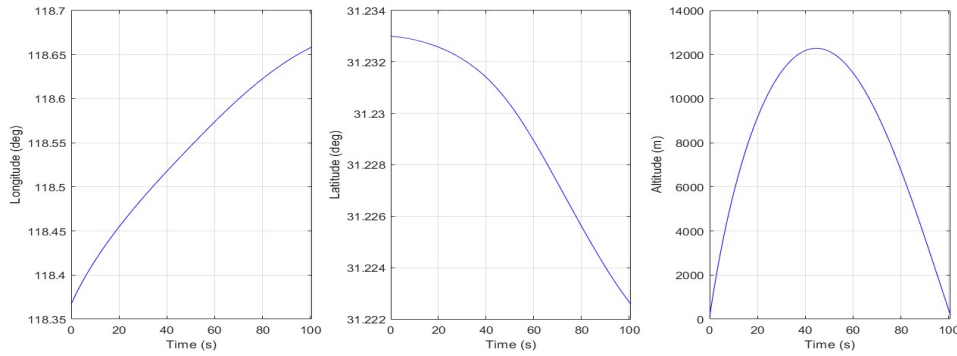


FIGURE 3 GNSS-measured longitude-latitude-altitude data

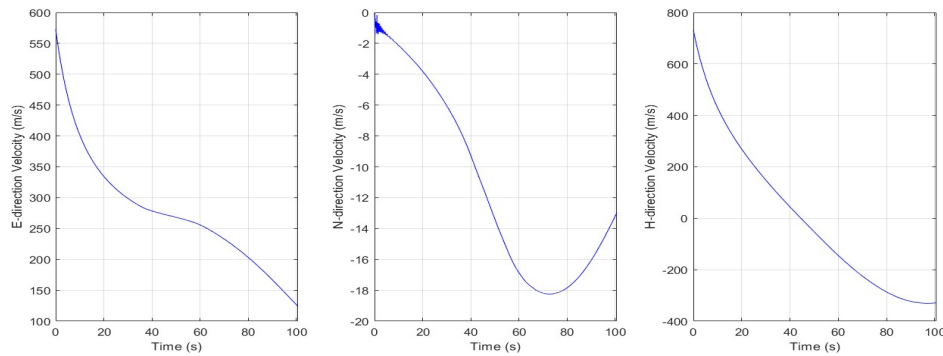


FIGURE 4 GNSS-measured velocity component data

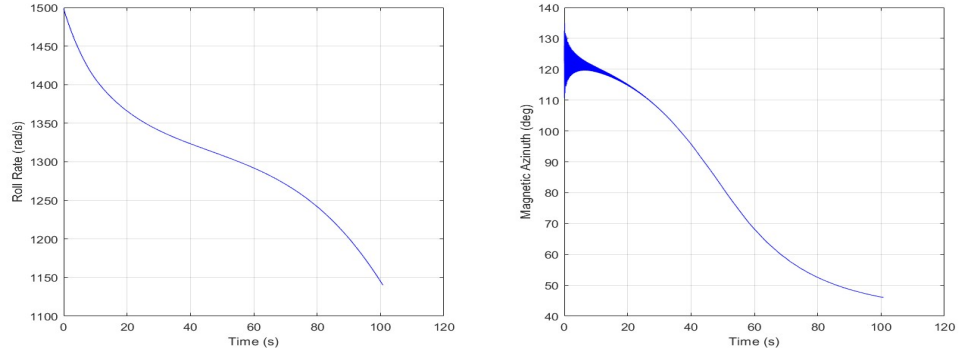


FIGURE 5 Rolling angular velocity and geomagnetic azimuth angle

4.2 | Aerodynamic Parameter Identification Results

The aerodynamic parameter identification results obtained by the proposed telemetry data-based method are shown in Figures 6–7 and Table 1. The results indicate that the proposed method can achieve accurate aerodynamic parameter identification with high reliability.

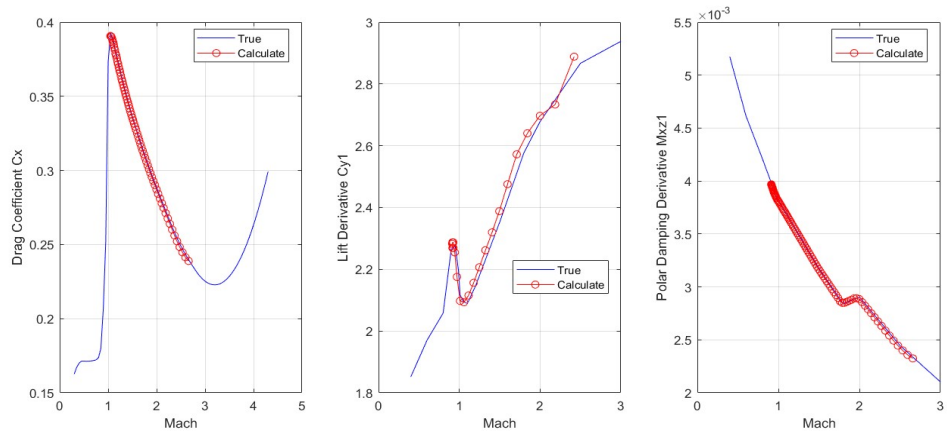


FIGURE 6 Aerodynamic force identification result 1

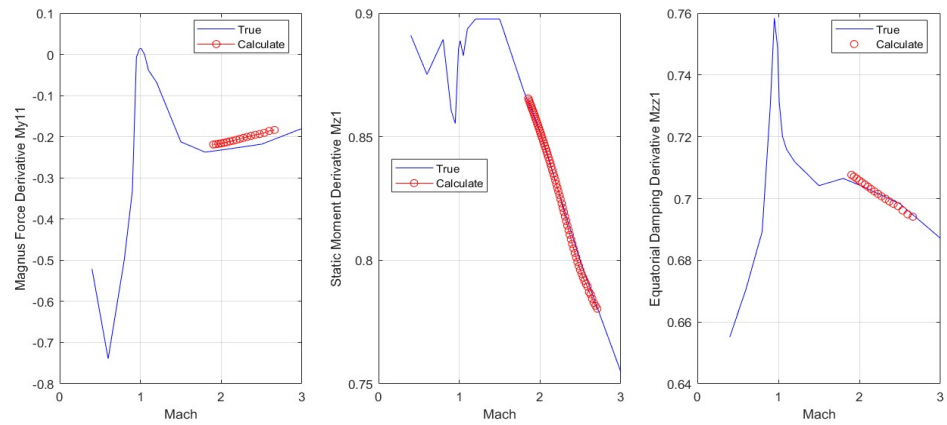


FIGURE 7 Aerodynamic force identification result 2

TABLE 1 Calculation accuracy summary

Parameter name	Mean square error percentage (%)
Drag coefficient	0.506
Lift coefficient derivative	1.383
Static moment coefficient derivative	0.248
Polar damping moment coefficient derivative	0.547
Equatorial damping moment coefficient derivative	0.163
Magnus moment coefficient derivative	9.612

CONCLUSION

To address the challenges of low modeling accuracy and limited attitude sensing means in traditional high-spin projectile research, this study proposes a novel method integrating geomagnetic information and GNSS data. By calculating the geomagnetic azimuth σ_M and roll angular velocity ω_ξ via a three-axis geomagnetic sensor, the method solves the attitude acquisition problem in gyro-free scenarios and constructs a comprehensive measurement vector for the joint identification of six key aerodynamic parameters using the C-K method and modified Gauss-Newton algorithm. The identification results show high precision: the minimum error is 0.163% (equatorial damping moment coefficient derivative), four parameters have errors within 2%, and the overall accuracy meets engineering requirements despite the relatively larger error (9.612%) of the Magnus moment coefficient derivative due to airflow disturbance. The method reduces the cost of the measurement system without compromising precision, providing reliable technical support for the guidance and control of high-spin projectiles. Future research will focus on optimizing robustness under complex disturbances and expanding the application to other rotating projectiles.

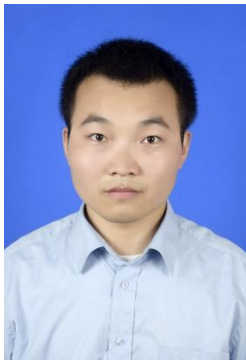
CONFLICT OF INTEREST

The authors declare no potential conflicts of interest.

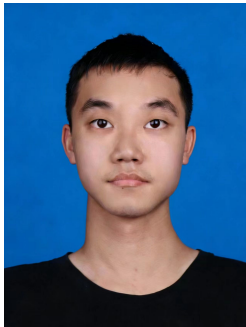
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