

Error analysis and compensation methods of geomagnetic attitude detection accuracy affected by projectile swing

Li Long*

Nanjing Institute of Technology, 211167 Jiangsu Nanjing, China

Abstract. This paper addresses the issue of significant measurement errors in geomagnetic/GPS combined attitude detection systems due to projectile swing. By analyzing the errors caused by projectile swing, a new attitude detection method based on the combination of geomagnetic and gyroscope is proposed. The method involves establishing a geomagnetic-gyroscope combined attitude detection model, using the angular rates measured by a two-axis MEMS gyroscope to calculate the projectile's yaw angle in real-time, and combining it with the three-dimensional geomagnetic components output by the geomagnetic module to solve for the projectile's attitude information. The results show that compared with the geomagnetic/GPS combined solution, adding a gyroscope module can eliminate the error fluctuations in roll and pitch angles caused by projectile swing, enabling stable attitude measurement under various motion conditions.

1 Introduction

1.1 Research background

Equipping conventional ammunition with simple guidance capabilities is a research hotspot in the field of navigation, with broad prospects for military applications. The measurement of flight attitude angles of conventional ammunition is a key technology directly related to the guidance of conventional ammunition [1-4]. The Earth's magnetic field, being an inherent and stable resource, can be measured by geomagnetic sensors, and relevant algorithms can be used to achieve real-time detection of the projectile's flight attitude angles. With the development of microelectronics and the emergence of new geomagnetic sensors, geomagnetic attitude detection technology has made significant progress and has attracted attention in the military field, becoming a new research hotspot in the navigation domain.

* Corresponding author: longliv5mail@163.com

1.2 Research significance

The research on geomagnetic attitude detection technology is of great significance for improving the guidance and control capabilities of conventional ammunition. By analyzing the errors caused by projectile swing and proposing a new attitude detection method, this paper aims to provide a more accurate and reliable solution for the attitude measurement of projectiles, which can effectively enhance the performance of simple guided ammunition.

2 Geomagnetic/GPS attitude detection model

2.1 Basic principle

The projectile's attitude angles are determined based on the relative rotation angles of the projectile axis coordinate system and the projectile body coordinate system with respect to the launch coordinate system. The geomagnetic vector transformation equation for the projectile's attitude angles can be established as follows [6-8]:

$$\begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \varphi & 0 & -\sin \varphi \\ 0 & 1 & 0 \\ \sin \varphi & 0 & \cos \varphi \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma & \sin \gamma \\ 0 & -\sin \gamma & \cos \gamma \end{bmatrix} \begin{bmatrix} X_n \\ Y_n \\ Z_n \end{bmatrix} \quad (1)$$

where ϕ is the pitch angle, θ is the yaw angle, and ψ is the roll angle. X_b , Y_b , and Z_b are the components of the geomagnetic vector T in the projectile body coordinate system (measured by the geomagnetic sensor), and X_n , Y_n , and Z_n are the components of the geomagnetic vector T in the launch coordinate system (obtained through the geomagnetic vector at the launch point). The equation set decomposed from equation (1) contains only three unknowns but is not mutually independent, so it cannot independently solve all three attitude angles.

2.2 Limitations

The combination of geomagnetic and GPS for attitude measurement assumes that the projectile's flight trajectory is an ideal or standard trajectory, thereby using the trajectory angle provided by GPS to replace the yaw angle [5]. However, during the projectile's launch and correction process, the swing of the projectile body cannot be ignored, and using the trajectory angle to replace the yaw angle will inevitably affect the measurement accuracy.

3 Impact of projectile swing on geomagnetic attitude detection

3.1 Analysis of projectile swing

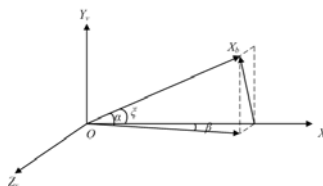


Fig. 1. Schematic diagram of the attack.

In the process of establishing the geomagnetic attitude detection model, it is usually assumed that the projectile's flight trajectory is an ideal or standard trajectory, thereby using the trajectory angle provided by GPS to replace the yaw angle. A very important premise of this assumption is that the angle of attack is zero. The angle of attack is the angle between the projectile axis and the velocity vector v , but in reality, it is not zero. During the projectile's flight, the angle of attack not only exists but also continuously changes. Due to the existence of the angle of attack and accompanied by aerodynamic torque, the projectile's motion trajectory forms an aerial spiral line[9]. Introducing the velocity coordinate system $O_v X_v Y_v Z_v$, as shown in Figure 1, the angle of attack ξ is the angle between the projectile axis OX_b and the direction of the velocity vector OX_v . The projection of the projectile axis in the $OX_v Y_v$ plane and its angle with OX_v is the angle of attack α , with positive values for upward angles. The projection of the projectile axis in the $OX_v Z_v$ plane and its angle with OX_v is the sideslip angle β , with positive values for angles to the right of the symmetry plane. Since the yaw angle calculated by GPS ignores the angle of attack, its existence will affect the results of the attitude angle detection and cause calculation errors.

3.2 Simulation and analysis

3.2.1 Ballistic model establishment

The ballistic model of the projectile in the passive segment is relatively simple, which is convenient for analyzing the swing characteristics of the projectile. This paper mainly studies the swing of the projectile through the ballistic characteristics in the passive segment. Setting the elements at the end of the active segment v, θ, x, y, z , the rocket projectile is not subjected to thrust in the passive segment and is only affected by air resistance and gravity. First, the center of mass motion equation of the projectile in the launch coordinate system is studied [10]:

$$\left\{ \begin{array}{l} m \frac{dv}{dt} = -mg \sin \theta_1 \cos \varphi_1 - mcH(y)F(v, c_s) \\ mv \cos \varphi_1 \frac{d\theta_1}{dt} = -mg \cos \theta_1 + \frac{1}{2} \rho v^2 SC'_y \alpha \\ mv \frac{d\varphi_1}{dt} = mg \sin \theta_1 \sin \varphi_1 + \frac{1}{2} \rho v^2 SC'_y \beta \\ \frac{dx}{dt} = v \cos \varphi_1 \cos \theta_1 \\ \frac{dy}{dt} = v \cos \varphi_1 \sin \theta_1 \\ \frac{dz}{dt} = v \sin(-\varphi_1) \end{array} \right. \quad (2)$$

where v is the projectile velocity, $x, y,$ and z are the coordinates of the projectile in the launch coordinate system. θ_1 is the trajectory angle, and $F(v, c_s)$ is the drag force, which is obtained by looking up tables based on altitude y and velocity v . C_y is the gravitational acceleration.

3.2.2 Simulation results

The simulation results show that the angle of attack converges after initial disturbance, with a maximum initial disturbance amplitude of about 3° and a stable convergence disturbance amplitude of only 0.08° . The disturbance curves of the angle of attack during the initial stage and during the rudder correction are basically consistent. To study the error impact of projectile swing on the geomagnetic attitude detection system, the angle of attack can be assumed to be a sine wave sequence with an amplitude of 3° .

4. Improvement of geomagnetic attitude detection system

4.1 Methodology

To eliminate the impact of projectile swing on the geomagnetic attitude detection system, a new method based on the combination of geomagnetic and gyroscope is proposed. The method utilizes the angular rates measured by a two-axis MEMS gyroscope to calculate the yaw angle in real-time, and then combines it with the three-dimensional geomagnetic components output by the geomagnetic module to solve for the projectile's attitude information.

4.2 Experimental verification

To verify the performance improvement of the improved attitude detection system, the system was installed on a three-axis non-magnetic turntable, as shown in Figure 2. Two sets of experiments were conducted.



Fig. 2. The axis turntable to install extension bar and missile body.

4.2.1 Experiment 1

In the first experiment, the turntable's yaw angle was set to 0° (magnetic north direction), and the turntable was controlled to roll while oscillating in the yaw direction with a period of 5 seconds and an amplitude of about 5° . The yaw angle motion curve is shown in Figure 11. The roll and pitch angle error curves of the geomagnetic attitude detection system are shown in Figure 3. It can be found that the roll angle error was reduced from 5° to 0.3° , a reduction of 94%, while the pitch angle error remained basically unchanged. This is because when the turntable's yaw angle is near 0° , the Y-axis and Z-axis magnetic field

components used for roll angle calculation are small, and are more affected by projectile swing.

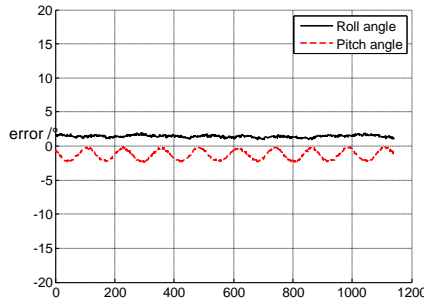


Fig. 3. Geomagnetic attitude module error when the yaw angle is 0° .

4.2.2 Experiment 2

In the second experiment, the turntable's yaw angle was set to 90° (due east direction), and the turntable was controlled to rotate while oscillating in the yaw direction with a period of 5 seconds and an amplitude of about 5° . The roll and pitch angle error curves of the geomagnetic attitude detection system are shown in Figure 4. It can be found that the results are opposite to those of the first experiment. The roll angle error is a fluctuation with an amplitude of 3° , and the pitch angle error was reduced from 10° to 4.9° , a reduction of 51%. This is because when the turntable's yaw angle is near 90° , the X-axis magnetic field component used for pitch angle calculation is small and is more affected by projectile swing.

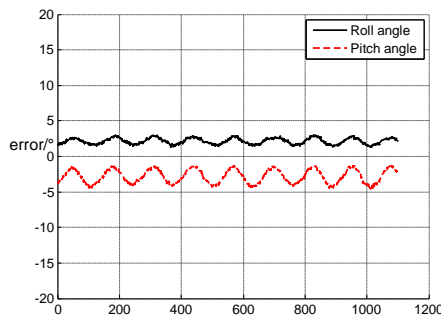


Fig. 4. Geomagnetic attitude module error when the yaw angle is 90° .

5. Conclusion

The measurement accuracy of attitude angles directly affects the trajectory correction capability of simple guided ammunition. This paper simulates the actual trajectory, studies the impact of projectile swing on the measurement accuracy of geomagnetic attitude detection systems, proposes a geomagnetic-gyroscope combined attitude detection method based on the analysis of the impact of projectile swing errors, and conducts corresponding experimental verification. The experimental results show that the geomagnetic-gyroscope combined attitude detection system can effectively eliminate the error fluctuations in roll

and pitch angles caused by projectile swing, enabling stable attitude measurement under various motion conditions.

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