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# Attitude Algorithm Simulation and Experiment with Large Dynamic Geomagnetic Sensor

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**Abstract:** Aiming at the problem that projectile attitude information cannot be acquired timely and accurately, using geomagnetic sensor, coordinated with IMU testing devices to set up navigation system, a projectile attitude calculating algorism based on geomagnetic sensor is brought forward, and an inertial navigation prototype is constructed for numerical simulation and semi-physical experiment. The results show that in large dynamic of the system, projectile attitude calculation may inhibit error accumulation efficiently and that the system is feasible and effective. *Copyright © 2014 IFSA Publishing, S. L.*

**Keywords:** Large dynamic, Attitude, Geomagnetic sensor.

## 1. Introduction

Future battlefield shall be a battlefield with informationization, digitalization, intelligentization and technicalization [1]. The ammunition shall be an armament with wide variety, great demand, extensive application and the fastest consumption. However, the future development of ammunition shall be in the direction toward intelligentization, functionalization, cheap cost, high accuracy, informationization and modularization. One of the technical keys shall be acquisition of the flight attitude angle of projectile. The methods used to measure projectile attitude shall mainly include: to use a gyroscope to measure the flight attitude of projectile [2]; to use an accelerometer to measure the flight attitude of projectile [3]; to use solar azimuth to measure the flight attitude of projectile; to use gravity field to measure the flight attitude of projectile; to use a star sensor to measure the flight attitude of projectile; to use GPS to measure the flight attitude of projectile [4]. The datum of attitude selection in most of the above methods is varying, which therefore bring about inaccuracy of attitude calculation. The magnetic field of the earth is a natural magnetic field that is "hung" in the air [5], the natural reference datum is very stable, so the error shall not be accumulated with the increase of time [6]. Moreover, the magnetic sensor is characteristic of small volume, low power consumption, light weight, reliable performance, easy to use [7], wide range of operating temperature, free of moving parts, and additionally, a definite accuracy level [8]. Presented in this paper are calculating algorithm and experimental test based on geomagnetic sensor.

## 2. Mathematical Method for Attitude Calculation Based on Geometric Sensor

The three axles of triaxial magnetic sensor are mounted in three sensitive directions of the carrier respectively, which is used to measure the scores of the geomagnetic field in the coordinate system of the projectile carrier, namely Hxb, Hyb, Hzb. The output of magnetic resistance sensor shall be:

$$C_n^b = \begin{bmatrix} \cos\gamma\cos\psi+\sin\gamma\sin\theta\sin\psi & -\cos\gamma\sin\psi+\sin\gamma\sin\theta\cos\psi & -\sin\gamma\cos\theta \\ \cos\theta\sin\psi & \cos\theta\cos\psi & \sin\theta \\ \sin\gamma\cos\psi-\cos\gamma\sin\theta\sin\psi & -\sin\gamma\sin\psi-\cos\gamma\sin\theta\cos\psi & \cos\gamma\cos\theta \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} H_{xb} \\ H_{yb} \\ H_{zb} \end{bmatrix} = C_n^b \begin{bmatrix} H_{xn} \\ H_{yn} \\ H_{zn} \end{bmatrix}, \quad (2)$$

where $\begin{bmatrix} H_{xn} & H_{yn} & H_{zn} \end{bmatrix}^T$ is the three components of the local geomagnetic field, that is:

$$\begin{aligned} &(\cos\gamma\cos\psi+\sin\gamma\sin\theta\sin\psi)H_{xn}-\sin\gamma\cos\theta H_{zn} \\ &+(-\cos\gamma\sin\psi+\sin\gamma\sin\theta\cos\psi)H_{yn}=H_{xb} \\ &\cos\theta\sin\psi H_{xn}+\cos\theta\cos\psi H_{yn}+\sin\theta H_{zn}=H_{yb} \\ &(\sin\gamma\cos\psi-\cos\gamma\sin\theta\sin\psi)H_{xn}+\cos\gamma\cos\theta H_{zn} \\ &-(\sin\gamma\sin\psi+\cos\gamma\sin\theta\cos\psi)H_{yn}=H_{zb} \end{aligned} \quad (3)$$

Since the flight of the projectile is not long, it may be considered that the magnetic field intensity of the area passed through by the projectile is invariant, and the value that the magnetic sensor provided for the carrier is equivalent to the known $\begin{bmatrix} H_{xn} & H_{yn} & H_{zn} \end{bmatrix}^T$ and $\begin{bmatrix} H_{xb} & H_{yb} & H_{zb} \end{bmatrix}^T$. In general cases, three unknown numbers and three equations are solvable, however, the above formula is an equation set about trigonometric function, which cannot solve a trigonometric function. Since the projectile rotates at a high speed, the stability is fairly good, it is considered that the heading angle is given. In such a case, the pitch angle and the roll angle can be solved.

The pitch angle may be obtained from Formula (3):

$$\theta_1 = 2\arctan\frac{H_{zn}+\sqrt{H_{zn}^2+(\sin\psi H_{xn}+\cos\psi H_{yn})^2-H_{yb}^2}}{H_{yb}+(\sin\psi H_{xn}+\cos\psi H_{yn})},$$

$$\theta_2 = 2\arctan\frac{H_{zn}-\sqrt{H_{zn}^2+(\sin\psi H_{xn}+\cos\psi H_{yn})^2-H_{yb}^2}}{H_{yb}+(\sin\psi H_{xn}+\cos\psi H_{yn})},$$

$$\theta \in \left[-\frac{\pi}{2},\frac{\pi}{2}\right] \quad (4)$$

When the projectile is launched within the plane of departure, the missile axis is always in the plane of departure, that is, the value that the vector of Hzn and sinψHxn+cosψHzn projects on the missile axis is Hyb. When the missile axis and the resultant vector have any upward or downward angle deviation, the output values of the magnetic sensors on the missile axis are both $H_{yb}$, therefore the equation has two solutions θ1 and θ2. It is assumed that from the resultant vector $\sqrt{H_{zn}^2+(\sin\psi H_{xn}+\cos\psi H_{yn})^2}$ and axis OZn, an included angle $\varepsilon = a\tan\frac{\sin\psi H_{xn}+\cos\psi H_{yn}}{H_{zn}}$ is obtained, ε is used to judge which value, θ1 or θ2 is used as the pitch angle. Input the initial pitch angle θ after the projectile is installed into the missile-borne solver, when θ<ε, θ1 or θ2, whichever is smaller, shall be used for θ, then θ shall increases gradually. After it increases to the equal value of ε, θ1 or θ2, whichever is larger, shall be used for θ, and vice versa.

When the projectile is in flying motion, the roll angle has the largest range of variation and the highest frequency of variation. Common measuring devices shall go beyond their respective ranges. Nowadays, some devices may extend the ranges, but after variation, the accuracy of measurement shall drop [9]. This paper utilizes the characteristics of geomagnetic sensor, namely, wide measuring range and high accuracy, to present resolving method for roll angle. As shown in Fig. 1, roll angle is composed of two parts, reference angle σ and rotational angle Δ γ.

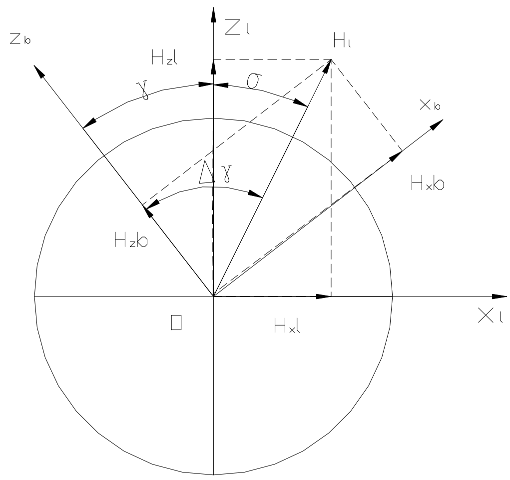


**Fig. 1.** Schematic diagram of roll angle.

Project the geomagnetism onto the missile body section to obtain cosine matrix $C_n^{b'}$ as follows:

$$C_n^{b'} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \cos\theta\sin\psi & \cos\theta\cos\psi & \sin\theta \\ -\sin\theta\sin\psi & -\sin\theta\cos\psi & \cos\theta \end{bmatrix}$$

$$\begin{bmatrix} H_{xl} \\ H_{yl} \\ H_{zl} \end{bmatrix} = C_n^{b'} \begin{bmatrix} H_{xn} \\ H_{yn} \\ H_{zn} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \cos\theta\sin\psi & \cos\theta\cos\psi & \sin\theta \\ -\sin\theta\sin\psi & -\sin\theta\cos\psi & \cos\theta \end{bmatrix} \begin{bmatrix} H_{xn} \\ H_{yn} \\ H_{zn} \end{bmatrix}$$

$$\sigma = \begin{cases} \arctan(\frac{H_{xl}}{H_{zl}}), where H_{zl} > 0 \\ \arctan(\frac{H_{xl}}{H_{zl}}) + \pi, where H_{xl} > 0 and H_{zl} < 0 \\ \arctan(\frac{H_{xl}}{H_{zl}}) - \pi, where H_{xl} < 0 and H_{zl} < 0 \end{cases}$$

It is known from the definition of roll angle that the angle is the included angle between $oz_b$ and $oz_l$, therefore the roll angle shall be:

$$\gamma' = \sigma - \Delta\gamma$$

## 3. Simulation Analysis

### 3.1. Numerical Analysis

Numerical experiment has been conducted for the exactitude and accuracy of the verification system and the algorithm [10]. A certain missile is taken as the example in the simulation. Given parameters are substituted into six-degree-freedom equation [11] to calculate ideal variations of projectile attitude. White noise output is added on the basis of ideal mathematical model of geomagnetic sensor [12], the calculated attitude is the resolving attitude. It is compared with the ideal attitude as follows.

Shown in Fig. 2 and Fig. 3 are the system simulation results of calculating attitude based on magnetic sensor. In the case that the yaw angle is known, the projectile attitude is calculated in the case of large dynamic high rotation. The errors of roll angle and pitch angle are within ±10°, which complies with the accuracy requirement for projectile attitude calculation. Delay in calculation is reduced because real time parameters are used when the attitude is calculated by using the magnetic sensor.

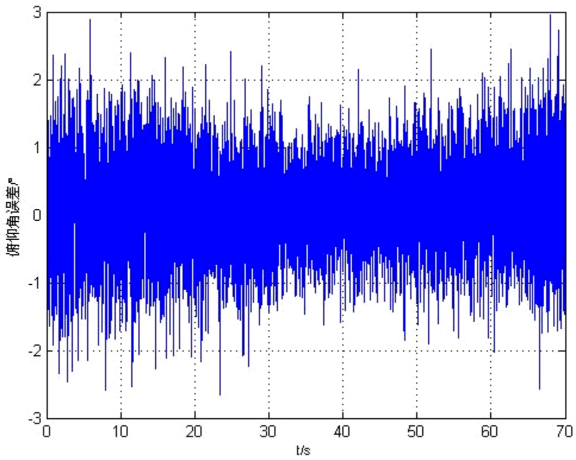


**Fig. 2.** Roll angle error curve.

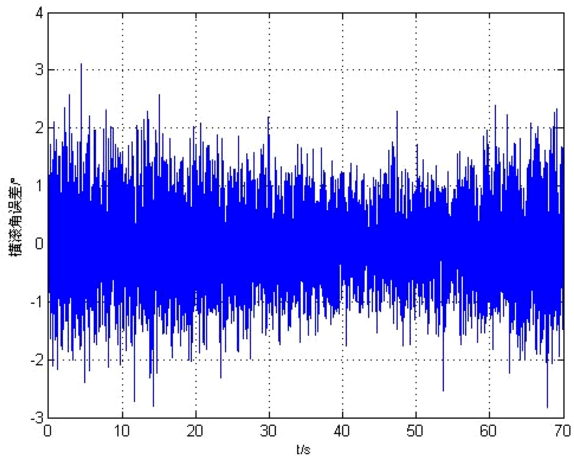


**Fig. 3.** Pitch angle error curve.

### 3.2. Semi-Physical Testing Experiment

Devices used for the experiment include MTi, GPS receiver, inertia navigated prototype, two computers, trolley and 200 meters of power cord. Since it is a trolley experiment, there is not a good reference. This experiment uses MTi developed by Holland XSENS as a reference prototype. MTi consists of three-axis gyroscope, three axis accelerator and three-axis magnetometer. MTi has zero deviation and excursion, so the error of the device is very small, moreover, the power consumption of internal processor is low, and the attitude angle output of the internal system calculation has already been recognized by specialists. It has been comparison with the processed and calculated attitude of the inertia navigated prototype. Two computers record the data during operation of the trolley synchronously.

**Fig. 4.** Material object of experiment equipment.

The trolley runs two rounds clockwise and four rounds counterclockwise along an 8m-diameter circular trajectory, four rounds clockwise and six rounds counterclockwise along a 12 m-long-sided square trajectory respectively. During the operation, the trolley passes a preset slope. After the operation is finished, MATLAB software is used to analyze the data collected respectively by the two computers. Hereinafter only one group of experiment data are analyzed rather than analyze and explain the experiment data one by one. The case that the trolley runs two rounds clockwise along the circular trajectory is taken as the example to analyze the semi-physical experiment results.

As shown in Fig. 5 and Fig. 6, the experiment has basically achieved the expected effect.

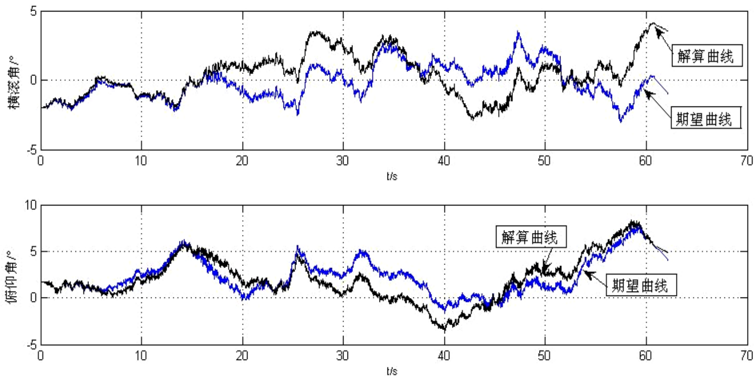


**Fig. 5.** Comparison curve of semi-physical attitude.

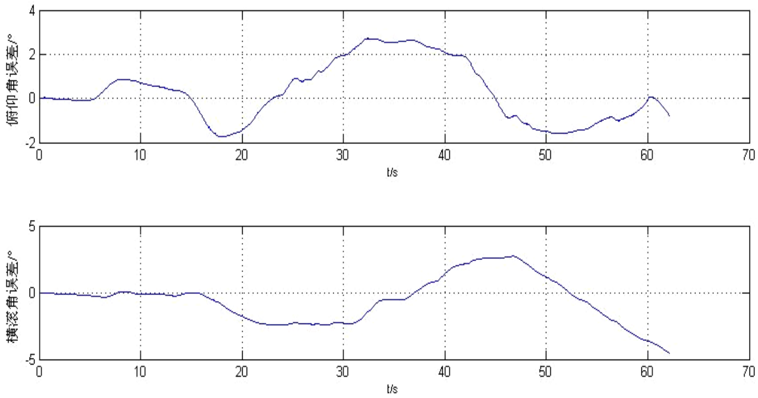


**Fig. 6.** Error curve of semi-physical attitude.

During the experiment, the system is able to collect data and transmit them to the processing chip, which indicates that the connections between all the hardware are correct, that the data information modes can be transformed mutually, that the circuit design is correct and that the data channel is smooth; the data collected and transformed by the sensor can be displayed and saved by the computer, which proves that the software part of the inertia navigated prototype is correct, which is able to process the data and calculate the attitude. The measuring results of the semi-physical experiment show that the error of roll angle is within ±5°, the error of pitch angle is within ±3°, so the calculating accuracy of the system is not high, which cannot meet the accuracy requirement for the guidance system. However, the variation trends of the roll angle and pitch angle calculating curves are the same as the variation trends with MTi as the expected curves, indicating that the design of the inertia navigated prototype is feasible and effective.

## 4. Conclusions

This paper presents measuring method for high-rotating projectile based on magnetic sensor, which overcomes the weakness that gyroscope cannot work in high rotating speed. The measuring error of calculated attitude angle is within a reasonable range without any accumulation with the time, as a result, the calculating accuracy of high-rotating speed navigation is increased. However, due to all types of external factors such as modern manufacturing technological level and variable measuring environment, the system has to be compensated during operation. This scheme has a certain boundedness, which is applicable to the circumstances in which the flight time of the projectile is not long, otherwise other integrated navigation algorithm shall be required.

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