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Error Analysis of Rotray SINS Sensor

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Abstract: Using rotating modulation techniques for strap-down inertial navigation system (SINS) sensor is a self-compensation way to improve the accuracy. Inertial component errors can be effectively inhibited the inertial navigation system. The rotation principle and the error analysis of rotary SINS are presented in this paper, a two-axis rotary scheme is proposed. Simulation of rotary SINS calculation is made and rotation modulation is effective to the output of SINS sensor. *Copyright © 2013 IFSA.*

Keywords: Error analysis, Rotation, SINS, Rotary scheme.

1. Introduction

Last century, variety of strapdown inertial navigation sensors appeared. Laser, fiber optic gyroscope as the representative of the emergence of solid state gyro enlarges new energy to the SINS. Advanced manufacturing Technology and new material could improve the accuracy of SINS to some extent, which has its limitation [1]. Compared with the general series of SINS sensor, using a rotary SINS sensor with rotational modulation compensation technology, can effectively inhibit the inertia constant drift, which greatly improves the inertial navigation accuracy for a long time running. It is of great significance especially to ships, submarines requiring long-term support of autonomous navigation. Research on the rotary SINS sensor has a broad and important application value [2].

Automatic compensation by rotating gyro drift is one effective way to achieve high-precision inertial navigation. Rotary SINS technology is one of correction methods, it has a similar system with the platform rotating mechanism. SINS sensor is mounted on a rotating mechanism. In accordance with certain rules rotation, the inertial component errors on SINS can be eliminated [3].

Rotating SINS still uses SINS algorithm and the basic principle of rotation modulation is shown in Fig. 1.

2. Error Model

The error equation of SINS reflects the relationship between inertial components error and positioning error. On the basis of literature, SINS error model is:

$$\begin{aligned} \delta\dot{\boldsymbol{v}} &= [\boldsymbol{I}-(\boldsymbol{C}_t^{t'})^T]\boldsymbol{C}_b^{t'}\hat{\boldsymbol{f}}^b + \\ &\boldsymbol{C}_b^t\delta\boldsymbol{f}^b-(2\hat{\boldsymbol{\omega}}_{ie}^t+\hat{\boldsymbol{\omega}}_{et}^t)\times\delta\boldsymbol{v}, \\ &-(2\delta\boldsymbol{\omega}_{ie}^t+\delta\boldsymbol{\omega}_{et}^t)\times\boldsymbol{v}+\delta\boldsymbol{g} \end{aligned} \quad (1)$$

$$\dot{\boldsymbol{\phi}} = (\boldsymbol{I}-\boldsymbol{C}_t^{t'})\hat{\boldsymbol{\omega}}_{it}^t+\delta\boldsymbol{\omega}_{it}^t-\boldsymbol{C}_b^{t'}\delta\boldsymbol{\omega}_{ib}^b, \quad (2)$$

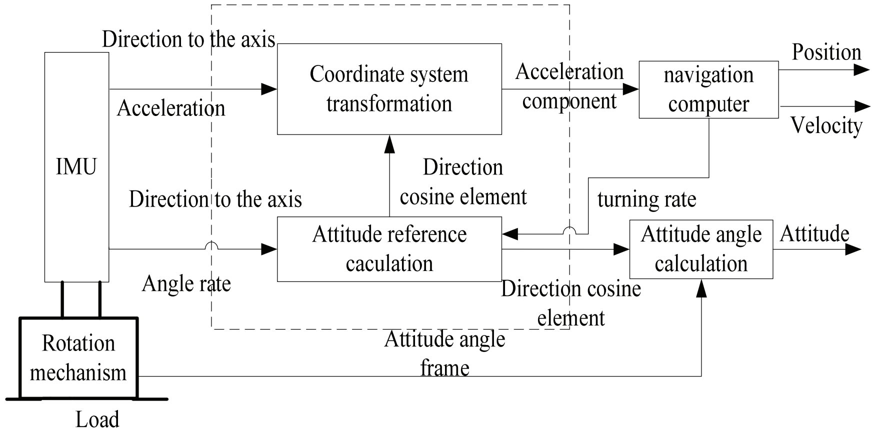

Fig. 1. Principle of rotation modulation.

where $\delta \boldsymbol{v}$ is velocity error vector, $\boldsymbol{\phi}$ is misalignment angle vector, $\boldsymbol{C}_b^t$ is direction cosine matrix from carrier coordinate to geography coordinate, $\boldsymbol{C}_b^{t'}$ is direction cosine matrix from carrier coordinate to calculated geography coordinate. $\hat{\boldsymbol{f}}^b$ is real proportional output, $\delta \boldsymbol{f}^b$ and $\delta \boldsymbol{\omega}_{ib}^b$ are measurement errors, $\hat{\boldsymbol{\omega}}_{ie}^t$ is earth rotation angle rate in calculated geography coordinate, $\hat{\boldsymbol{\omega}}_{et}^t$ is rotation angle rate relative to geography coordinate, $\hat{\boldsymbol{\omega}}_{it}^t$ is rotation angle rate relative to inertial coordinate, $\delta \boldsymbol{g}$ is error of gravity acceleration.

Where $C_t^{t'} = [a_{ij}]_{3\times 3}, i, j = 1,2,3$, each element is below:

$$\begin{cases} a_{11} = \cos\phi_y \cos\phi_z - \sin\phi_y \sin\phi_x \sin\phi_z, \\ a_{13} = -\sin\phi_y \cos\phi_x, \\ a_{23} = \sin\phi_x \\ a_{22} = \cos\phi_z \cos\phi_x, \\ a_{21} = -\sin\phi_z \cos\phi_x \\ a_{31} = \cos\phi_z \sin\phi_x + \cos\phi_y \sin\phi_x \sin\phi_z, \\ a_{32} = \sin\phi_y \sin\phi_z - \cos\phi_y \sin\phi_x \cos\phi_z, \\ a_{33} = \cos\phi_y \cos\phi_x \end{cases}, \quad (3)$$

And other parameters are as follows:

$$\begin{cases} \hat{\omega}_{it}^t = \omega_{it}^t + \delta\omega_{it}^t \\ \omega_{it}^t = \omega_{ie}^t + \omega_{et}^t \\ \delta\omega_{it}^t = \delta\omega_{ie}^t + \delta\omega_{et}^t \\ \omega_{ie}^t = \begin{bmatrix} 0 & \omega_{ie}\cos\varphi & \omega_{ie}\sin\varphi \end{bmatrix}^T \end{cases}, \quad (4)$$

$$\begin{cases} \delta\omega_{ie}^t = \begin{bmatrix} 0 - \delta\varphi\omega_{ie}\sin\varphi \\ \delta\varphi\omega_{ie}\cos\varphi \end{bmatrix}^T \\ \omega_{et}^t = \begin{bmatrix} -\dfrac{v_y}{R_m + h} & \dfrac{v_x}{R_n + h}, \\ \dfrac{v_x \tan\varphi}{R_n + h} \end{bmatrix}^T \end{cases} \quad (5)$$

$$\begin{cases} \hat{\omega}_{it}^t = \omega_{it}^t + \delta\omega_{it}^t \\ \omega_{it}^t = \omega_{ie}^t + \omega_{et}^t \\ \delta\omega_{it}^t = \delta\omega_{ie}^t + \delta\omega_{et}^t \\ \omega_{ie}^t = \begin{bmatrix} 0 & \omega_{ie}\cos\varphi & \omega_{ie}\sin\varphi \end{bmatrix}^T \end{cases}, \quad (6)$$

$$\begin{cases} \delta\omega_{ie}^t = \begin{bmatrix} 0 - \delta\varphi\omega_{ie}\sin\varphi \\ \delta\varphi\omega_{ie}\cos\varphi \end{bmatrix}^T \\ \omega_{et}^t = \begin{bmatrix} -\dfrac{v_y}{R_m + h} & \dfrac{v_x}{R_n + h}, \\ \dfrac{v_x \tan\varphi}{R_n + h} \end{bmatrix}^T \end{cases} \quad (7)$$

$$\begin{cases} \delta\omega_{et}^t = \begin{bmatrix} \omega_1 & \omega_2 & \omega_3 \end{bmatrix}^T \\ \omega_1 = -\dfrac{\delta v_y}{R_m + h} + \delta h \dfrac{v_y}{(R_m + h)^2} \\ \omega_2 = \dfrac{\delta v_x}{R_n + h} - \delta h \dfrac{v_x}{(R_n + h)^2} \\ \omega_3 = \dfrac{\delta v_x \tan\varphi}{R_n + h} + \dfrac{\delta\varphi v_x \sec\varphi^2}{R_n + h} - \dfrac{\delta h v_x \tan\varphi}{(R_n + h)^2} \end{cases}, \quad (8)$$

IMU (Inertial measurement unit) belongs to SINS sensor. Gyro and accelerometer are major component of IMU, which directly affect the accuracy of the inertial system accuracy. In practice, due to the inevitable interference factors which led to the gyro and accelerometer produce errors, beginning from the initial alignment, the navigational error will grow with time, especially in the position error, which is the principal inertial navigation system shortcoming. IMU has three accelerometers and three angular rate sensor (gyroscope) composed of accelerometers to sense the vertical plane relative to ground acceleration component, the speed sensor to sense the angle of the aircraft information [4, 5].

3. Error Analysis

MU is mounted on the rotating frame. Suppose r coordinate is a new coordinate rotating with IMU [6]. Analyze the effect of rotation. IMU revolves round z-axis: $x_b y_b z_b \xrightarrow{\beta} x_r y_r z_r$.

$$C_b^r = \begin{bmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} = (C_r^b)^T , \quad (9)$$

The output of angular velocity and proportion is:

$$\left.\begin{aligned} \omega_{ib}^b &= C_r^b \omega_{ir}^r + \omega_{rb}^b \\ f_{ib}^b &= C_r^b f_{ir}^r \end{aligned}\right\}, \quad (10)$$

where $\omega_{br}^r = \begin{bmatrix} 0 & 0 & \omega \end{bmatrix}^T$, $f_{br}^r = 0$. The output of gyroscope and accelerometer is:

$$\left.\begin{aligned} \omega_{ir}^r &= C_b^r \omega_{ibd}^b + \begin{bmatrix} \varepsilon_x & \varepsilon_y & \varepsilon_z \end{bmatrix}^T + \omega_{br}^r \\ f_{ir}^r &= C_b^r f_{ibd}^b + \begin{bmatrix} \nabla_x & \nabla_y & \nabla_z \end{bmatrix}^T \end{aligned}\right\}, \quad (11)$$

That changes into:

$$\begin{bmatrix} \omega_{ibx}^b \\ \omega_{iby}^b \\ \omega_{ibz}^b \end{bmatrix} = \omega_{ibd}^b + \begin{bmatrix} \varepsilon_x \cos\omega t - \varepsilon_y \sin\omega t \\ \varepsilon_x \sin\omega t + \varepsilon_y \cos\omega t \\ \varepsilon_z \end{bmatrix}, \quad (12)$$

$$\begin{bmatrix} f_{ibx}^b \\ f_{iby}^b \\ f_{ibz}^b \end{bmatrix} = f_{ibd}^b + \begin{bmatrix} \nabla_x \cos\omega t - \nabla_y \sin\omega t \\ \nabla_x \sin\omega t + \nabla_y \cos\omega t \\ \nabla_z \end{bmatrix}, \quad (13)$$

The error changes into:

$$\left.\begin{matrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{matrix}\right\} \to \left.\begin{matrix} \varepsilon_x \cos\omega t - \varepsilon_y \sin\omega t \\ \varepsilon_x \sin\omega t + \varepsilon_y \cos\omega t \\ \varepsilon_z \end{matrix}\right\}$$

and

$$\left.\begin{matrix} \nabla_x \\ \nabla_y \\ \nabla_z \end{matrix}\right\} \to \left.\begin{matrix} \nabla_x \cos\omega t - \nabla_y \sin\omega t \\ \nabla_x \sin\omega t + \nabla_y \cos\omega t \\ \nabla_z \end{matrix}\right\}$$

In a complete rotary alternation, the error except z-axis could be inhibited.

4. Rotation Method and Simulation

Here proposed a two-axis rotary scheme. IMU revolves round the z-axis negative 180 degree, y-axis negative 180 degree, z-axis 180 degree, y-axis 180 degree, z-axis 180 degree, y-axis 180 degree, z-axis 180 degree, y-axis 180 degree. The error of three axes can be inhibited.

The rotation scheme is shown in Fig. 2.

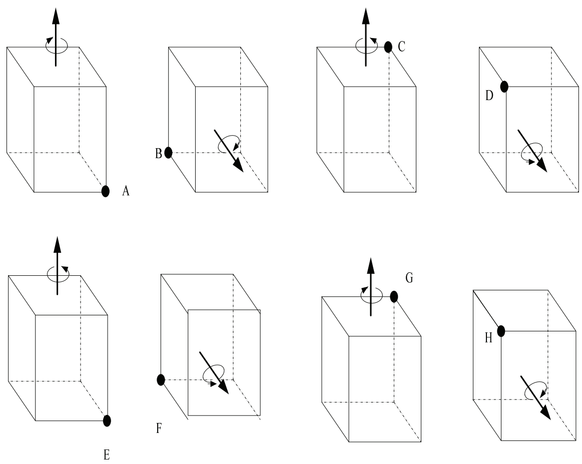

Fig. 2. Rotation scheme.

The attitude angle and the velocity error are shown in Fig. 3 and Fig. 4.

IMU revolves round the y/z axes to make an arbitrary axis rotation axis. The sensitive axis perpendicular to the shaft axis of inertia element can be modulated in a complete cycle, the accumulated error tends to be zero.

And position error for SINS sensor without rotation is shown in Fig. 5 and Fig. 6.

The position error of Rotary SINS sensor is shown in Fig. 7 and Fig. 8.

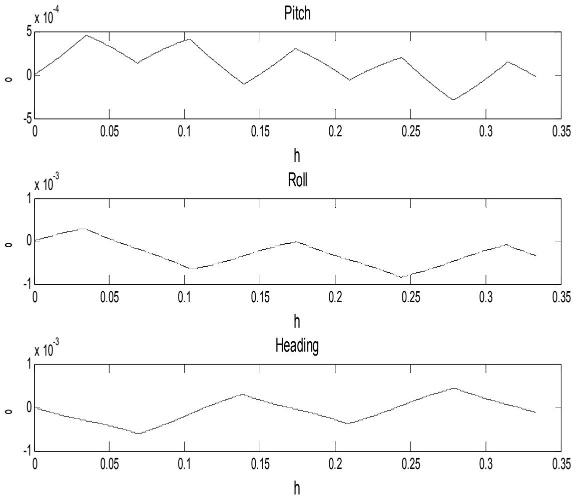

Fig. 3. Attitude angle.

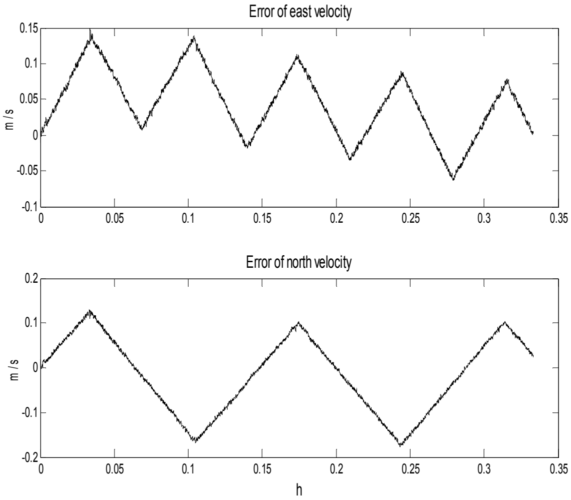

Fig. 4. Error of velocity.

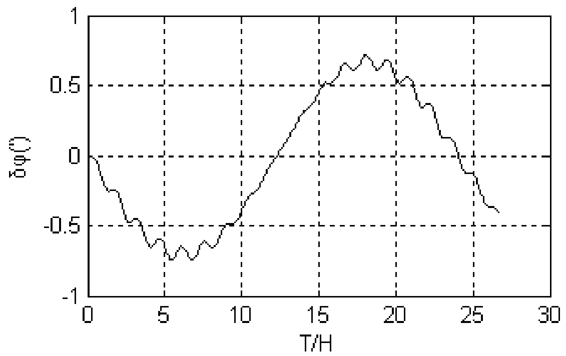

Fig. 5. Longitude error without rotation.

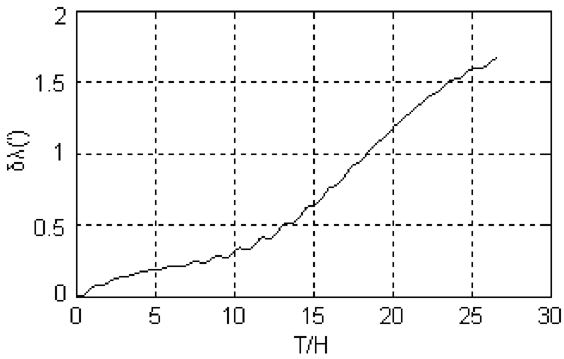

Fig. 6. Latitude error without rotation.

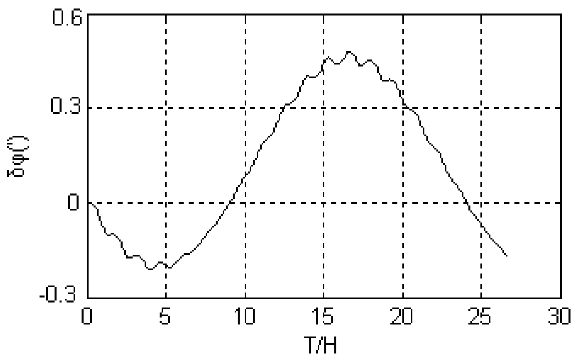

Fig. 7. Longitude error of rotary SINS sensor.

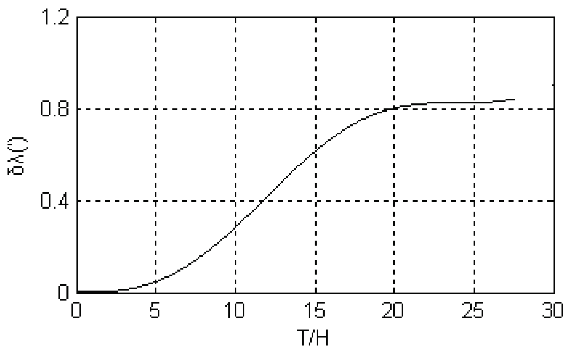

Fig. 8. Latitude error of rotary SINS sensor.

The positioning accuracy is superior to the traditional SINS.

5. Conclusion

Rotary technology improves the accuracy of SINS sensor. The system cost is relatively small, the Rotary SINS sensor can fully tap the potential to obtain higher precision navigation.

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