Satellite Rotation Modulation Measurement System Based on Ultrasonic Motor

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Abstract: Rotation modulation technique is generally used to improve the performance of aviation and marine inertial navigation system. Considering of the performance requirements from current aerospace to MEMS micro-nano inertial device, this paper proposedrotary inertial device modulation technology application methods on the satellite. Firstly, taking the advantage ofultrasonic motor, like high resolution, fast response, electromagnetic compatibility, a lowmagnetic, high-precision and appropriate for use on satellite ultrasonic motor modulation turntable was developed. Then, through theoretical modeling and simulations, the rotation modulation technology was verified to improvethe precise of satellite attitude measurementeffectively, equivalent toimprove the accuracy of MEMS gyro over an order of magnitude. This work helpsachieve the application of rotation modulation technology in aerospace and acceleratethe promotion of the MEMS gyro in satellite attitude measurement.

Key words: rotation modulation; measurement system; MEMS; ultrasonic motor; nonlinear control

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0 Introduction

In the field of aviation and navigation, the inertial components with the bigger errors can be significantly improved by using rotation modulation technology. The wide spread use of various types of rotation modulation platforms also verifies the effectiveness of this technology[1-9].

The use of the inertial technology in aerospace is quite different from the strap-down and platform-based inertial technology in aviation and navigation. At present, there are little reports about rotation modulated inertial components in aerospace. Taking the low earth obit (LEO) satellite as an example, by using the attitude dynamics and kinematics, the satellite current attitude can be calculated theoretically without devices used to measure as the moment attitude and initial state are known [10-15]. However, seen from the orbital dynamics with no maneuver, the satellite location is a function of time. Therefore, different from the use on ground, the aerospace gyro is mainly used for the observation of angular velocity. Besides, in the weightless environment, the output of the accelerometer is zero. So it cannot be used for position calculation if there is no orbit maneuver. Due to different environment, it can thus be seen that the use of ground rotation modulation technology in aerospace will be a new problem.

In view of the ground, rotation modulation system based on the conventional motor is not suitable for use in aerospace because of its huge volume and severe residual magnetism. Firstly, this paper solved the problem by constructing a new kind of rotation mechanism based on the low magnetic and high-precision ultrasonic motor. Secondly, on that basis, by introducing the rotation modulation technology into satellite attitude

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kinematics equation, it achieved the successful application of the modulation-gyro in aerospace.

1 Principle of Rotation Modulation in Aviation and Navigation

Rotation modulation technology introduces a rotatory mechanism to modulate the inertial components. The navigation error can be modulated into triangle wave signal. During the calculation process of solving the navigation parametes, the navigation error generated by the random drift of the inertial components can be offset automatically in a rotating cycle through the integration of the mathematical operation. Consequently, the accuracy of navigation can be improved. To date, the rotation modulation technology has been mostly used in high-precision gyro strapdown inertial navigation system, and maturely developed in the field of aviation, navigation and modern weapon.

According to the number of the rotation axes, there exit uniaxial rotation modulation, biaxial rotation modulation and multiple spindle rotation modulation. As to the uniaxial rotation modulation, an indexing mechanism is joined into the strapdown inertial navigation system according to the requirements of the inversion. The inertial measurement unit (IMU) component is fixed on the turntable (Fig. 1).

Fig. 1 Uniaxial rotation inertial navigation system[2]

Let inertial gyrotriaxial direction coincide with the carrier coordinate. The drift errors are ε_x, ε_y and ε_z, respectively. If the carrier coordinate coincides with the navigation frame, under uniaxial rotation modulation, the inertial measurement unit rotates around the z-axis direction at a constant speed of ω. After t moment, the gyro drift error is

$$\boldsymbol{C}_s^n \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} = \boldsymbol{C}_s^b \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} = \begin{bmatrix} \cos\omega t & -\sin\omega t & 0 \\ \sin\omega t & \cos\omega t & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix} = \begin{bmatrix} \varepsilon_x \cos\omega t - \varepsilon_y \sin\omega t \\ \varepsilon_x \sin\omega t + \varepsilon_y \cos\omega t \\ \varepsilon_z \end{bmatrix} \quad (1)$$

where $\boldsymbol{C}_s^n$ and $\boldsymbol{C}_s^b$ are the conversion matrixes from the gyro coordinate and the carrier coordinate to the navigation frame, respectively; and t is the modulation time. As seen from Eq. (1), the x-axis and y-axis gyro drift errors are modulated into sine signals, but the z-axis gyro drift error is still as the original value. During a rotation cycle, the integrations of x-axis and y-axis errors are zeros, but the z-axis error still spreads as the original rule.

The block diagram of the rotation strap down inertial navigation system[1] is shown in Fig. 2. The navigation algorithm still adopts the strap down algorithm.

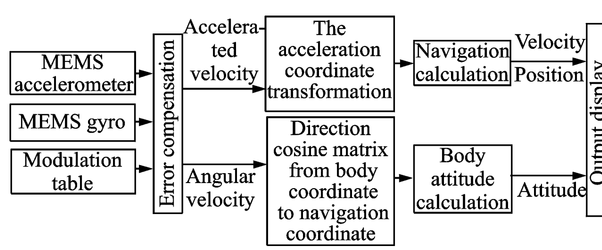

Fig. 2 Block of rotation strapdown inertial navigation system

The mathematic platform established in the navigation computer is considered as the reference navigation frame, and a new IMU coordinate is introduced, which varies with the change of the IMU position. Using the angular position and angular velocity of the indexing mechanism, the measured IMU axial angular velocity and specific are transformed into the carrier coordinate. In the strap down loop, the navigation information after rotation modulation can be calculated according to the attitude, velocity and the position error propagation equations.

2 Rotation Modulation Structure Based on Ultrasonic Motor

Current research resultsindicate that the performance of rotation modulation turntable is one of the keys to the rotation modulation system[17]. The traditional electromagnetic motor turntable with huge volume, high power consumption and serious remanence interference is not suitable for the aerospace requirements of low power consumption and small volume. So in this paper, we take the new type of ultrasonic motor into consideration to develop the rotation mechanism. Compared with the traditional electromagnetic motor, the ultrasonic motor has the following significant characteristics: (1) Power self-locking; (2) Low speed and high torque; (3) Simple construction, large torque/weight ratio, small volume; (4) Small inertia of rotating parts, quick response, high positioning accuracy, starting and stopping time of millisecond level; (5) Shape structure design tends to diversification, adapted to the use of different occasions; (6) Good electromagnetic compatibility; (7) Not easily influenced by vacuum environment. The design drawing of the self-developed turntable is shown in Fig. 3 and the physical map is shown as Fig. 4. The maximum size of the ultrasonic motor turntable is 100 mm×100 mm. The motor encoder and the circuit board are all inside the turntable. There are four mounting holes arranged on the turntable top for fixing the IMU.

Through the incremental proportion-integral-derivative (PID) algorithm, the nonlinear control problem of the ultrasonic motor turntable has been solved by adjusting the PID parameters. By tests, the start and shut off response curves of the ultrasonic motor are shown in Fig. 5. It can be seen from Fig. 5 that the rotation angular rate reversing time is less than 5 ms, the start time and the corresponding stop time from static to a certain rate are better than that of 2 s.

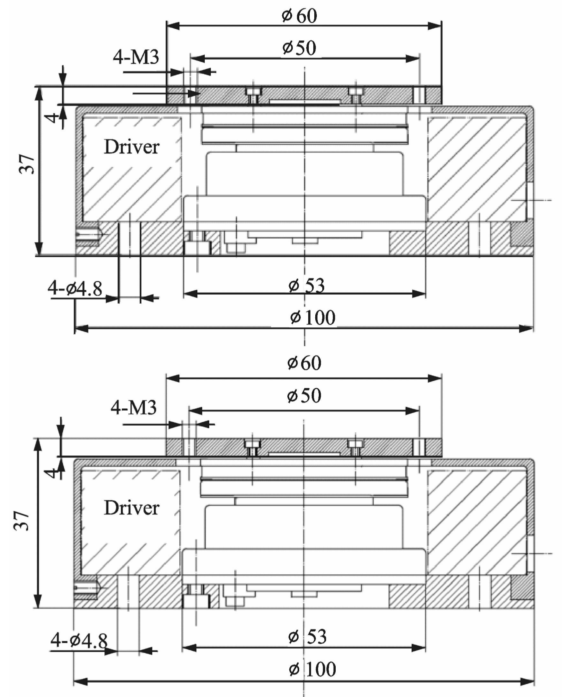

Fig. 3 Design of ultrasonic motor turntable

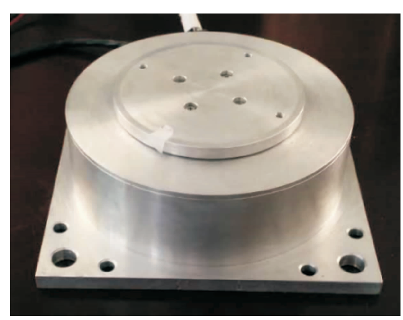

Fig. 4 Rotation motor turntable

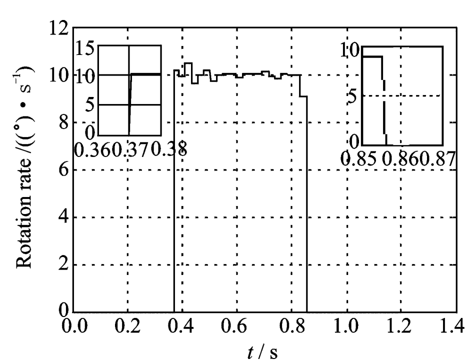

Fig. 5 Start and shut-off response of ultrasonic motor

The performance indicators of the rotation mechanism system are described as follows:

(1) Reciprocating rotation function: it can

move back and forth at a constant angular rate between 0° and 360° with controllable speed and run-down time. The angular rate range is not less than ±100 °/s;

(2) The accuracy of angular position measuring: superior to 40″ (3σ);

(3) Locking: locking accuracy is better than 2.5′ (3σ), the accuracy after locking is better than 40″ (3σ);

(4) Payload: 0.3—0.6 kg;

(5) Size: 100 mm×100 mm×37 mm.

The development of the ultrasonic motor turntable solved the basis application problem of rotation modulation technology in aerospace, which laid a foundation for the rotation modulation of the inertial devices.

3 Rotation Modulations in Aerospace

After a long time integration of the satellite gyro measuring attitude, the attitude error caused by the gyro drifts spreads quickly, thereby leading to the unavailability of the attitude. In practice, the inertial measurement attitude determination is usually connected with external reference vector attitude determination. By the mean of correcting the inertial measurement attitude and estimate the gyro drifts through external reference vector measurement, the precision of inertial measurement is expected to be improved. However, this way of measurement is high cost and its calculation is relatively complex. In this paper, by introducing rotation modulation technology, it improves the gyro measurement accuracy and then simplifies the complexity of the satellite attitude determination system.

When the gyro measures the satellite attitude relative to the inertial system, the next time attitude quaternion can be calculated from the attitude quaternion kinematics equation and the current moment three-axis angular rate measured by gyro, and then the attitude angle can also be easily obtained. But the actual angular rate measured by MEMS gyro usually contains large drift error, which includes constant drift and random drift. In case of no error compensation, the gyro drift error will result attitude quaternion error when calculating the attitude by the use of those measured values, namely generating attitude angle error. Moreover, the error gradually increases with the accumulation of time, which reduces the accuracy of the inertial attitude measuring determination.

As shown in Fig. 6, by introducing the rotation modulation technology, the gyro random drift error is modulated into sine signal. The quaternion motion equation after integral can eliminate the attitude error periodically caused by the gyro drift error, which can improve the accuracy of attitude determination and extend the time of inertial measurement.

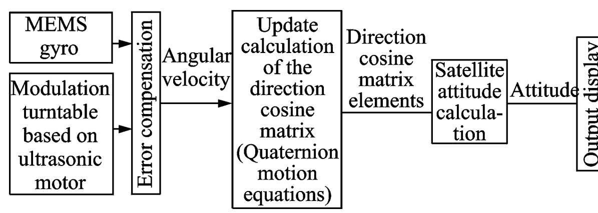

Fig. 6 Satellite attitude algorithm structure diagram

The attitude quaternion motion equation is

$$\dot{\boldsymbol{q}}=\frac{1}{2}\boldsymbol{\Omega}(\boldsymbol{\omega})\boldsymbol{q}=$$

$$\frac{1}{2}\begin{bmatrix}0 & \omega_z & -\omega_y & \omega_x\\ -\omega_z & 0 & \omega_x & \omega_y\\ \omega_y & -\omega_x & 0 & \omega_z\\ -\omega_x & -\omega_y & -\omega_z & 0\end{bmatrix}\begin{bmatrix}q_1\\ q_2\\ q_3\\ q_4\end{bmatrix} \tag{2}$$

where ω_x, ω_y and ω_z are three axis angular rate components measured by gyro, $\boldsymbol{q}$ the attitude quaternion vector, q_1, q_2, q_3 and q_4 the quaternion vector components. The actual inertial gyro rate measurement model is $\boldsymbol{\omega}_g=\boldsymbol{\omega}+\boldsymbol{v}_g$, here $\boldsymbol{\omega}_g$ is the actual gyro measuring angular rate, $\boldsymbol{\omega}$ the real attitude angular rate, and $\boldsymbol{v}_g$ the drift error, commenly including the constant drift and random drift error. Then the real quaternion motion equation can be expressed as

$$\tilde{\dot{\boldsymbol{q}}}=\frac{1}{2}\boldsymbol{\Omega}(\boldsymbol{\omega}_g)\boldsymbol{q}=\frac{1}{2}\boldsymbol{\Omega}(\boldsymbol{\omega}+\boldsymbol{v}_g)\boldsymbol{q}=$$

$$\frac{1}{2}\boldsymbol{\Omega}(\boldsymbol{\omega})\boldsymbol{q}+\frac{1}{2}\boldsymbol{\Omega}(\boldsymbol{v}_g)\boldsymbol{q}=\dot{\boldsymbol{q}}+\delta\dot{\boldsymbol{q}} \tag{3}$$

From Eq. (3), the gyro drift error results attitude quaternion error and then generates attitude angle error, which increases over time accumulation and consequently reduces the accuracy of the inertial attitude measuring determination. By introducing the rotation modulation technology, the gyro random drift error is modulated into sine signal.

In the case of the uniaxial rotation modulation, in the T rotation cycle, the integral quaternionerror is

$$\delta \boldsymbol{q} = \frac{1}{2}\int_0^T \begin{bmatrix} q_4 \\ q_3 \\ -q_2 \\ -q_1 \end{bmatrix} (\varepsilon_x \cos\omega t - \varepsilon_y \sin\omega t)\mathrm{d}t + \frac{1}{2}\int_0^T \begin{bmatrix} -q_3 \\ q_4 \\ q_1 \\ -q_2 \end{bmatrix} (\varepsilon_x \sin\omega t + \varepsilon_y \cos\omega t)\mathrm{d}t + \frac{1}{2}\int_0^T \begin{bmatrix} q_2 \\ -q_1 \\ q_4 \\ -q_3 \end{bmatrix} \varepsilon_z \mathrm{d}t = \frac{1}{2}\int_0^T \begin{bmatrix} q_2 \\ -q_1 \\ q_4 \\ -q_3 \end{bmatrix} \varepsilon_z \mathrm{d}t \tag{4}$$

where ω is the rotation modulation angular rate, and $T=\frac{2\pi}{\omega}$ the rotation cycle. It can be deduced that the influence from x-axis and y-axis gyro drifts errors to quaternions is eliminated by uniaxial rotation modulation, but z-axis drifts error still causes quaternions error.

From the analysis above, it can be proved that when introducing a rotatory mechanism into gyro measuring attitude system, the effect from gyro drifts error to attitude determination can be eliminated by rotation modulation. Thus, the accuracy of attitude determination will be improved and the time of inertial measurement will be extended.

4 Attitude Measurement System Using Rotation Modulation-Gyro

4.1 Attitude measurement system

The attitude measurement system of the rotation modulation-gyro, as shown in Fig. 7, mainly includes four parts: (1) Ultrasonic motor rotation modulation turntable; (2) IMU component (includes the sensitive element ADI(Analog Device Inc), data acquisition board and power supply module); (3) The core board for navigation calculation; (4) Display computer. The IMU module is installed on the turntable. During the rotation modulation, the real-time data through the wireless serial will be transferred to the navigation calculating core board. Finally, the calculated navigation information will be shown by the display computer.

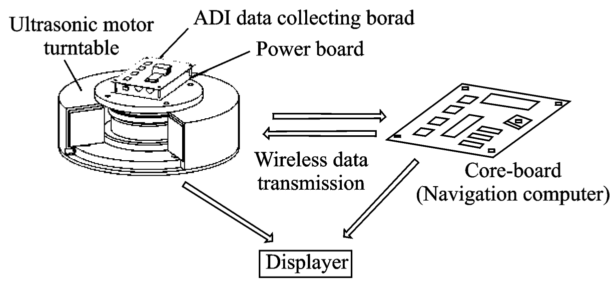

Fig. 7 Attitude measurement system of rotation modulation-gyro

4.2 Simulation results

According to the application principle mentioned in the third segment, the effect of the rotation modulation technology was simulated in this section. The initial simulation conditions: the three-axis gyro constant drift error was 5°/ h; the random drift error was 100°/ h; the simulation step size was 1 s; the simulation time was 1 h; the initial values of the yaw angle, the pitch angle and the roll angle were 10°, 5° and 15°, respectively; the three-axis attitude angle rates were all 0°/ s. According to the results of the third section, the navigation error caused by the rotation speed error can be ignored because of the high precision ultrasonic motor turntable. Thus, in the process of simulation, the rotation speed does not include the error and can be regarded as constant.

Simulated in the conditions of no rotation modulation and uniaxial rotation modulation, curves of the three-axis attitude angle error were obtained, as shown in Figs. 8, 9.

According to the analysis from Figs. 8, 9 for the uniaxial rotation modulation, the yaw angle and the roll angle error reduced by one-order of magnitude, which verifies the conclusion that the rotation modulation technology can obviously improve the accuracy of the attitude measurement, especially by a high precision turntable.

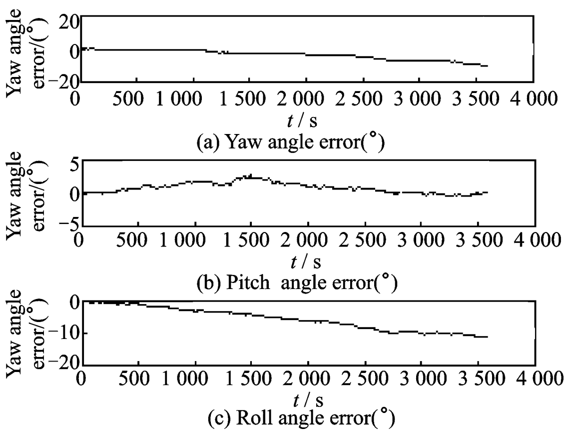

Fig. 8 Three-axis attitude angle error without rotation modulation

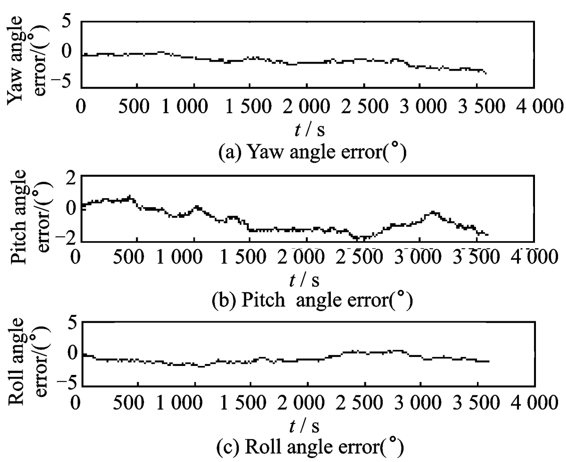

Fig. 9 Three-axis attitude angle error with uniaxial rotation modulation

5 Conclusions

Introducing the rotating modulation technology into the satellite attitude determination system can improve the precision of satellite attitude measurement and satisfy the high precision, low cost requirements of the satellite to the inertial devices. Moreover, it simplifies the system complexity and reduces the system development difficulty compared with the commonly way of combining the inertial measurement with external measurement.

The developed ultrasonic motor rotation modulation system in this paper can be used in the occasions like modulation-gyro, and can also be popularized in aerospace where demands high precision in rotation, such as the pointing platform of the remote sensing camera, which can be a key device for satellite performance improvement.

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