Untwisting Spin Low-Cost Platform Design Used for Strap-Down Inertial Navigation System in High-Speed Spin Flight Vehicle

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(Received September 4th, 2013)

Flight vehicle high-speed spin movement has caused difficulties in the application of the strap-down inertial navigation system due to gyroscope performance limits. One method for designing a low-cost untwisting spin platform used for high-speed spin flight vehicle is proposed. A permanent magnet synchronous motor (PMSM) is selected as the drive motor. The platform and PMSM rotor are directly connected to reduce the influence of the gear clearance on inertial measurement unit measurement accuracy. Signal transmission between the spin flight vehicle and micro-electro-mechanical system (MEMS) gyroscope is carried out by a slip ring. The PMSM is controlled by a speed loop and current loop without angle loop, which is able to achieve fast tracking of flight vehicle spin movement and reduce the MEMS gyroscope output noise influence on platform performance. The demand on gyroscope performance is also decreased. The design method is verified experimentally and results show that the method can not only effectively isolate the inertial measurement unit from the spin movement of the flight vehicle, but also decrease the attitude angle error.

Key Words: Strap-Down Inertial Navigation System, PMSM, MEMS Gyroscope, Untwisting Spin, Platform

1. Introduction

Flight vehicle rotational motion around the longitudinal axis during in-flight processes has a unique advantage to break through the defense system due to reduction in the dwell time of interception system emissions.\(^1,2\) As guidance technology is introduced into the spin flight vehicle, a guidance device is used to search, identify and track attack targets. It has great significance in penetration weapon interception and high-precision attacks. It could play an important role in future high-tech local wars.\(^3\)

This kind of spin motion always has high speed. Some flight vehicle spin speed can reach up to 10,800 \(\text{rad/s}\). How to accurately measure the spin inertial navigation system attitude information under high speed feature environment has become a difficult problem in inertial navigation development, since it greatly affects control precision and attack effect.

According to the installation method of the inertial measurement unit, the inertial navigation system can be divided into strap-down inertial navigation systems and platform inertial navigation systems.\(^4\) In the strap-down inertial navigation system, the accelerometer and gyroscope are fixed on the flight vehicle shell. It has a high demand for the gyroscope in the aspects of shock, vibration resistance and a large measurement scope because of poor working environment. Although high-range inertial devices have been developed, it is difficult to achieve precise measurement of the large-scope angular velocity due to current gyroscope level of technology and process. Thus, it will produce great attitude angle error after decoupling. The mainly used strap-down inertial navigation system spin angular velocity is always not over 500 \(\text{rad/s}\). In the platform inertial navigation system, the accelerometer and gyroscope are fixed on platform. Therefore the working environment of the inertial measurement unit is optimized. The spin angular velocity cannot limit its application range, because the platform isolates the spin angular velocity from inertial measurement unit. However it also has some disadvantages, such as increased weight and size, complicated structure and difficult maintenance. Combining the advantages of the above two kinds of navigation systems, the single axis stable strap-down inertial navigation system uses a platform to isolate spin angular velocity and reduce demand of the inertial measurement unit, providing high-precision inertial navigation system attitude information.\(^5,9\) It also has the following advantages such as light weight, small size and low cost.

A good platform driving method has great significance in aspects such as control precision improvement, reliability enhancement, size reduction and application range expansion. The hydraulic driving method which was adopted by the early platform needed an oil source cabinet with large size and high cost, and the oil leakage phenomenon increased maintenance workload.\(^10\) With the merits of wide speed range and high controllability, the DC motor driving method has become the first choice of platform driving way instead of the hydraulic driving way.\(^11\) However, this driving method also has many problems, such as inaccessible high speed, big torque fluctuation, serious brush spark and high brush friction torque. These problems result in restriction on flight vehicle parameters on spin angular velocity and accelera-
tion. The commutator is prone to oxidation corrosion in the ground save process, which degrades reliability of the platform. The PMSM uses a permanent magnet to produce the air gap magnetic flux without external excitation. Thus, it has great efficiency and high power density. The ratio between torque and inertia is high. Our research group uses the PMSM driving platform, gaining a highly dynamic performance platform.

Currently, the untwisting spin platform generally adopts a three-axis stabilized platform by controlling single degree freedom mechanism, with three-loop control structure of angle, speed and current. Because platform size affects flight vehicle lethality, the single-axis stabilized platform should be used in order to enhance lethality. A high performance platform is established on the basis of high-performance gyroscopes which makes the platform price relatively expensive. Compared with traditional gyroscopes, the MEMS gyroscope has advantages such as low cost, small size, low power consumption and high reliability. Thus, it has become the first choice for a platform movement transducer. In improving the MEMS gyroscope output precision aspect, some scholars have put forward some ideas and methods. To our knowledge, studies on the angle output filter have not previously been reported. The performance of the angle closed-loop control based on the MEMS gyroscope is poor due to MEMS angular velocity output noise. In this paper, one method for designing a platform used for high speed flight vehicle strap-down inertial navigation untwisting spin is proposed based on double-loop control with a MEMS gyroscope. Experimental results verify the feasibility and effectiveness of the proposed method.

2. Single Axis Stable Strap-Down Inertial Navigation System Attitude Angle Analysis

The single axis stable strap-down inertial navigation system is mainly composed by the strap-down inertial navigation system and the untwisting spin single axis stabilized platform. The former part is used to navigation calculation through inertial measurement unit measurement data. The latter part is used to fix inertial measurement unit in order to avoid the effect of spin motion.

The angle $[\phi_x, \phi_y, \phi_z]^T$ between the platform coordinate system and the ideal platform coordinate system can be obtained by inertial measurement unit measurement data. The corresponding direction cosine matrix elements can be described as following

$$
C_{11} = \cos \phi_x \cos \phi_z + \sin \phi_x \sin \phi_z
$$
$$
C_{12} = -\cos \phi_y \sin \phi_z + \sin \phi_y \sin \phi_x \cos \phi_z
$$
$$
C_{13} = -\sin \phi_x \cos \phi_z
$$
$$
C_{21} = \cos \phi_x \sin \phi_z
$$
$$
C_{22} = \cos \phi_y \cos \phi_z
$$
$$
C_{23} = \sin \phi_y
$$
$$
C_{31} = \sin \phi_y \cos \phi_z - \sin \phi_x \cos \phi_y \sin \phi_z
$$
$$
C_{32} = -\sin \phi_x \sin \phi_z - \sin \phi_x \cos \phi_y \cos \phi_z
$$
$$
C_{33} = \cos \phi_x \cos \phi_y
$$

The direction cosine matrix updating equation can be described as follows

$$
\mathbf{C}_p^T = \mathbf{C}_p^T \begin{bmatrix}
0 & -w_{TPz}^p & w_{TPy}^p \\
-w_{TPz}^p & 0 & -w_{TPx}^p \\
-w_{TPy}^p & w_{TPx}^p & 0
\end{bmatrix}
$$

(2)

$w_{TPx}^p$, $w_{TPy}^p$, $w_{TPz}^p$ respectively represent the spin angular velocity component of the platform coordinate system relative the ideal platform coordinate system. It can be described as

$$
w_{TP} = \begin{bmatrix} w_{IPx}^p & w_{IPy}^p & w_{IPz}^p \end{bmatrix}^T - \mathbf{C}_p^T \begin{bmatrix} w_{ITx} & w_{ITy} & w_{ITz} \end{bmatrix}^T
$$

(3)

$w_{IPx}^p$, $w_{IPy}^p$, $w_{IPz}^p$ respectively represent the angular velocity of the gyroscope fixed on platform. $w_{ITx}$, $w_{ITy}$, $w_{ITz}$ respectively represent the angular velocity of the ideal platform coordinate system relative the inertial coordinate system. Although the platform can insulate the spin angular velocity, the platform has slow movement in the space as a result of the gyroscope drift phenomenon. The roll angle can be described as following

$$
\theta_x = \theta_x + \varphi_x
$$

(4)

$\theta_x$ represents the angle of the platform on roll direction.

The attitude angle computed by the direction cosine matrix can be described as follows,

$$
\begin{align*}
\theta_p &= \arcsin (C_{32}) \\
\theta_R &= \theta_x + \arctan (-C_{31}/C_{33}) \\
\theta_h &= \arctan (C_{12}/C_{22})
\end{align*}
$$

(5)

The attitude angle error can be described as

$$
\delta \mathbf{G} = \delta \mathbf{G} + M \cdot \delta \mathbf{P} - C_p^T \begin{bmatrix} \delta w_{IPx}^p \\
\delta w_{IPy}^p \\
\delta w_{IPz}^p \end{bmatrix}
$$

(6)

$\delta K_G$ represents the gyroscope scale factor error. $\delta G$ represents the gyroscope fix angle error. $w_P$ represents the platform movement speed.

It can be seen from Eq. (6) that the flight vehicle spin angular velocity has no influence on attitude accuracy, because it is isolated by the platform. Platform influence on attitude performance is mainly related to two aspects. One is the platform angular velocity measurement precision on the roll direction. The other one is itself movement speed.

3. Direct Driving Low-Cost Small Size Untwisting Platform Design

3.1. Structure design

The driving method of the untwisting spin platform has a great influence on the platform performance indicators such as wide speed range, high frequency response and high precision. Because the PMSM has a high ratio between power
and size, PMSM is selected as the driving motor to achieve a smaller platform size. The past decade has seen a rapid development of the MEMS gyroscope, gradually toward miniaturization, intelligence, multi-functions and high integration. Compared with other kinds of gyroscopes, it has a unique advantage of low cost. Thus, the MEMS gyroscope is selected for platform movement measurement.

Considering the influence of gear gap on the gyroscope and accelerometer measurement precision, direct driving method is adopted. Platform is directly connected to the PMSM rotor through the rigidity shaft coupling. The MEMS gyroscope is fixed on the platform, providing feedback signals for control. The encoder is installed on the other side of the PMSM rotor, and measure the relative information between the rotor and stator for PMSM vector control. In practical application, there exists a great angular velocity between the PMSM controller and the platform. A thought-transference slip ring is applied to solve the signal communication problem between the PMSM controller and the MEMS gyroscope. The detailed structure design is shown in Fig. 1.

3.2. Control strategy design

The control strategy determines how the platform driving system produces amendment torque effectively to ensure platform stability. In the platform control field, modern control methods such as neural network control and variable structure control are used to solve nonlinear problems. However these methods are still in the stage of theory analysis and simulation. The classical three-ring PID method and its improved algorithm are the most widespread methods in the practical equipment application.

The MEMS gyroscope used for attitude information detection, provides feedback to servo control. The output signal effectiveness has great importance on platform performance. Many reasons can produce error of the MEMS gyroscope applied to a high flight vehicle untwisting spin platform, such as temperature change, pressure change, sound field change and electromagnetic environment change.

PMSM torque ripple also affects the MEMS gyroscope output accuracy. Thus, the MEMS gyroscope output signal has great noise. Because the angle loop control feedback signal is always obtained by integration gyroscope angular velocity output, the effectiveness of angle loop control is reduced.

In order to reduce the influence of the MEMS gyroscope measurement noise on angle loop control, a double loop high-speed flight vehicle untwisting spin platform control method is put forward. The structure diagram is shown in Fig. 2. The reference given signal of the speed loop controller is equal to zero. The feedback signal of the speed loop controller is the MEMS gyroscope angular velocity output. Vector control based on space vector pulse width modulation with smaller torque ripple is adopted as the PMSM control method. Thus, the current loop control has two parts. One part is the cross axis current controller. And the input is the speed loop output. The other part is the direct axis current controller. And the input depends on which vector control method is used.

4. Experimental Analysis

In order to verify the proposed method effectiveness, experimental analysis is performed on the device shown in Fig. 3. The right part located between two bracket bearings is designed according to Fig. 1. The platform is installed on the carrier. PMSM controller takes TMS320F2812 as the
CPU. The MEMS gyroscope model is L3G4200D. In order to simulate vehicle spin flight motion, an asynchronous motor is adopted. In Fig. 3, the left part is an asynchronous motor. And it drives the carrier spin. The left part connecting the middle bracket bearing is the slip ring. It is used to establish a communication path between the MEMS gyroscope and industrial personal computer so as to watch MEMS gyroscope output. The far right support frame is used to fix the absolute value encoder. This encoder is used for measuring the platform motion.

The MEMS gyroscope angular velocity output is shown in Fig. 4 under static condition. The angle information by corresponding angular velocity integration is shown in Fig. 5. The MEMS gyroscope contains much noise, including zero drift part and random signal part. As using integration gained angle information, the angle has great error. Thus, the controller effectiveness is reduced.

In the experimental process, the speed regulator and current regulator use PID methods. The carrier remains static for the first several seconds. And then the frequency converter control signal suddenly changes to $1,800^\circ/s$. And the rising time is set to 0.01 s. Thus carrier spin speed changes quickly. Then, the spin speed remains at $1,800^\circ/s$. Two control methods are used to control the platform. One is the proposed method without angle control. The other one has angle control loop. The MEMS gyroscope output signal is simple processed with zero drift noise. The angle loop control period is 5 ms. Platform angular velocity properties measured by the MEMS gyroscope are shown in Fig. 6 and Fig. 7 with sample period equal to 200 ms. This sample period is just for watching MEMS gyroscope motion. It cannot influence platform control performance. Platform angle properties measured by MEMS gyroscope output integration are shown in Fig. 8 with sample period equal to 200 ms. Platform angle properties measured by the absolute value encoder are shown in Fig. 9.

It can be seen from Figs. 6 and 7 that both methods can isolate carrier spin speed using the MEMS gyroscope angular velocity as the feedback signal.

In Fig. 8, the angle control method shows good angle control performance. The average angle value remained near zero. Because this angle is integrated by the MEMS gyroscope angular velocity, it cannot reflect platform actual movement. Although this method has good angle performance in its feedback signal aspects, the platform angle changes over $12^\circ$.

In Fig. 9, the angle of angle control method has a clearly rising tendency before the carrier begins to spin. This phenomenon causes a deviation of the platform in the horizontal plane before flight vehicle emission. At the beginning of carrier spin, the angle of angle control method has little change. The reason lies in the fact that the integration angle is bigger than zero at the beginning. Angle control plays a dominant role. But integration angle gradually drifts away from the actual value. The control performance becomes
worse. The angle of the proposed method changes more smoothly. In the whole experiment process, the angle change with the proposed method is $7.4^\circ$. But the angle of angle control method change over $12^\circ$. Thus, the proposed method reduces attitude angle error because of slow platform movement.

5. Conclusion

Aiming to solve the untwisting spin problem of high-speed spin flight vehicle roll direction, a double-loop low-cost MEMS gyroscope platform control method was put forward. By eliminating the angle loop, the influence of MEMS gyroscope output noise on control performance was reduced. The controller structure was also simplified. Experiment results showed that the proposed method could effectively isolate the platform from the roll direction movement. It could reduce attitude angle error. The proposed method could provide a reference basis in the design of a guidance system for high-speed spin flight vehicles.

Acknowledgments

We would like to acknowledge support from Foundation of Shaanxi Key Laboratory of Small & Special Electrical Machine and Drive Technology under Grant No. 2013SSJ1004. We would also like to acknowledge support from Natural Science Basic Research Plan in Shaanxi Province of China under Grant No. 2014JQY7261.

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