Application of Ultrasonic Motor to Control of Moment Gyroscope Gimbal Servo System

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Abstract: Attitude control system is one of the most important subsystems in a spacecraft. As a key actuator, the control moment gyroscope (CMG) mainly determines the performance of attitude control system. Whereas, the control accuracy and output torque smoothness of the CMG depends more on its gimbal servo system. Considering the constraints of size, mass and power consumption for a small satellite, here, a mini-CMG is designed, in which the gimbal servo system is driven by an ultrasonic motor. The good performances of the CMG are obtained by both the ultrasonic motor and the rotary inductosyn. The direct drive of gimbal improves its dynamic performance, with the output bandwidth above 20 Hz. The angular and speed closed-loop control obtains the 0.02 °/s gimbal rate, and the output torque resolution better than 2×10^{-3} N·m. The ultrasonic motor provides 1.0 N·m self-lock torque during power-off, with 12 arc-second position accuracy.

Key words: control moment gyroscope; gimbal servo system; ultrasonic motor

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0 Introduction

Small satellites with quick maneuver on their attitude or orbit control are commonly called agile small satellites. They are typically applied to high precision earth observation space monitoring and environment monitoring[1-2]. Agility considerably increases the operational envelope and efficiency of spacecraft and can substantially increase the return of mission data. For an agile small satellite whose payload is a pointed-to-earth staring imaging system, its imaging system is fixed on the satellite body. When undertaking staring imaging, the optical axis of its on-board staring imaging system should always be pointed to a certain target on the ground, and the whole satellite need to keep a real-time rapid tracking to the target. According to the mission requirements, rapid roll maneuvers of the whole satellite may also be required to achieve observation on different terrains. All these actions above make great demands on small satellite's attitude maneuver ability and control precision.

Attitude control system (ACS) is one of the most important subsystems in a spacecraft. When used as a actuator for a satellite's attitude control system, compared with the flywheels, control moment gyroscope (CMG) makes a faster dynamic respond with higher efficiency, i.e., providing larger control torque at the same power cost. Consequently, to reach a higher angular velocity in shorter time, and to achieve rapid attitude maneuvers with high precision[3], agile small satellites commonly employ CMG as their actuator.

A CMG produces torque in a process known as torque amplification. Torque amplification created by changing the gimbal orientation of a constantly spinning flywheel (also referred to as a rotor). Since the flywheel spin rate is constant, it requires little power to maintain its angular mo-

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mentum. A motor which changes the flywheel's orientation can have relatively low torque capability, as it must overcome only the torque required to control the gimbal and the induced gyroscopic torque. The output torque of a CMG is a product of the flywheel's angular momentum h_{flywheel} and the gimbal rate $\dot{\sigma}_{\text{gimbal}}$. So the control accuracy and output torque smoothness of the CMG depends more on its gimbal servo system.

Most of the current CMG developments are focused on medium-size spacecraft, in the 1-ton class for Earth-observation platforms. The two CMGs available for these platforms are the Honeywell M50 CMG and the Astrium CMG 15-45S. The Honeywell CMG capitalizes on the wide range and experience of Honeywell for large CMGs that have flown on a number of military-related missions. Astrium's CMG 15-45S has been developed for the Pleiades constellation, a series of optical and radar agile spacecraft which was launched on December 17th 2011. These actuators, although powerful, would be too heavy to be used on small satellites (<500 kg) and expensive.

Considering the constrains on size, mass and power consumption for a small satellite (< 500 kg), a mini-CMG gimbal servo system is presented here.

1 CMG Gimbal Servo System Design

1.1 Composition of CMG gimbal servo system

Control moment gyroscope consists of a flywheel and a gimbal system. The control performance of gimbal system mainly depends on gimbal motor's performance. The framework of the gimbal system is shown in Fig. 1. The feedback angle position and velocity are output by encoder and it is a demodulation circuit. According to the given

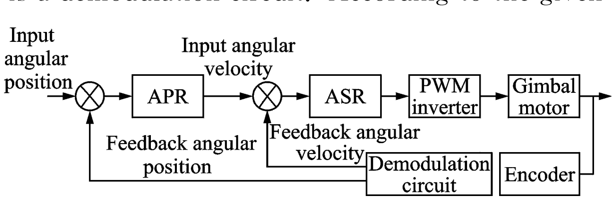

Fig. 1 Framework of the gimbal system

angle position and velocity, the corresponding control variable is obtained by the angle position controller calculation and angle velocity controller calculation. The gimbal motor drives the flywheel to rotate around the gimbal shaft.

1.2 Gimbal motor selection

Usually, stepper motor driver[4] and indirect brushless motor driver[5] are used. In the first case, it is difficult to maintain a smooth gimbal angular rate and is unfavorable for satellites demanding high attitude accuracy. In the second case, the dynamic response is largely restricted by the transmission gears. Charles Koeck presents the employment of CMG 15-45S used by Permanent Magnet Synchronous Motor in satellite Pleiades[6]. However, when the CMG does not output torque, the gimbal system needs to add electric locking at a certain angle position, and digestive energy.

Rotary USMs have many advantages over electrostatic or electromagnetic motors because they have excellent high torque and low speed performance, zero power off state with high holding torque, high efficiency, and small size[7].

The gimbal system adopts Nanjing University of Aeronautics & Astronautics USM-60 series rotary ultrasonic motor driven by a traveling wave. The motor parameters are listed in Table 1.

Table 1 USM parameters

Model	USM-60
Drive frequency/kHz	40—45
Nominal torque/(N • m)	0.6
Self-locking torque/(N • m)	1.0
Rated revolution/(r • min^{-1})	120
Startup response time/ms	<3
Shutoff response time/ms	<1
Mass/g	<250

1.3 Gimbal encoder selection

Usually, optical encoder, resolver and inductosyn are used for gimbal angular position detection and feedback. The results of these calculations are summarized in Table 2.

Table 2 Angular position detection components

Detection component	Resolver	Optical encoder	Inductosyn
Resolution and accuracy	21 bit, 25″	21 bit, 10″	24 bit, 10″
Mass/g	500	870	400
Size/(mm×mm×mm)	∅90×∅8×32.3	∅137.8×27	∅109×∅14×12.5
Installation requirement	Easy to installation	Installation of high precision	Easy to installation

Inductosyn features a simple structure, easy installation, high reliability, light weight, small axial size, and so on. So inductosyn is suitable for mini-CMG gimbal angular position detection, and be good for CMG design of smaller and lighter.

2 CMG Gimbal Controls and Drive Circuit Design

CMG gimbal control and drive circuit is an important part of the CMG gimbal control system, its main functions are as follows:

(1) Receiving control commands which send by the host computer, and upload the CMG state data to the host computer, when it was required.

(2) Receiving gimbal angular position sensor′s output signal, and solving the gimbal angular position and the gimbal speed, etc.

(3) In accordance with the instructions to control the ultrasonic motor to rotate or lock.

(4) To guarantee the gimbal work security and stability, the safe mode was designed to prevent the gimbal loss control.

2.1 Gimbal angular position detection and demodulation circuit design

CMG gimbal control system uses 180 pairs of poles absolute inductosyn as gimbal angular position detection device. Inductosyn works in the electromagnetic coupling principle. Excitation signal is applied to the rotor, and then active conductors have varying current flows through the rotor, generating a mutative magnetic field. At the same time, the inducing voltage comes from active conductors on the stator witch among the mutative field, with the same frequency as the excitation signal. Its amplitude is related to the relative position between the stator and the rotor. Gimbal angular position is determined by

$$\theta_e = \arctan\left(\frac{E_A}{E_B}\right)$$

where E_A the EMF amplitude of sinusoidal winding, E_B the EMF amplitude of cosine winding, and θ_e the gimbal electrical angle.

Thus, according to the inductosyn working principle, gimbal angular position detection and demodulation circuit should functions as module:

(1) To output the excitation signals to the rotor of inductosyn.

(2) To receive the signal that inductosyn stator output, and make the signal amplification, shaping and filtering

(3) To demodulate the analog signals into digital ones, and do coupling operation on the demodulated data. Therefore, the mechanical gimbal angle data can be obtained.

The gimbal angular position detection and demodulation circuit design is shown in Fig. 2.

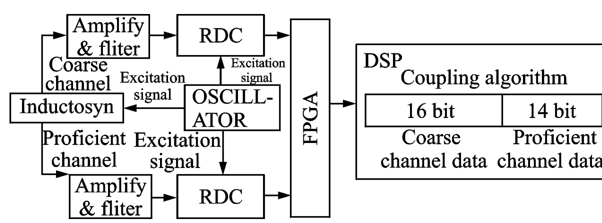

Fig. 2 Gimbal angular position detection and demod ulation circuit design

In the excitation signal generation circuit OSCILLATOR made by DDC is used. Excitation signal frequency was set to 10 kHz and RMS was set to 1 V, as output to inductosyn rotor, and demodulation chip.

The amplitude of the signal witch output by inductosyn stator is infinitesimal, even only several millivolts. What′s the worse, many interfering signal superimposed on the signal. Therefore, gimbal angular position detection and demodulation circuit should amplify the signal first. Using high-gain differential operational amplifier, the signal is amplified to ±1—2 V. And then, using active threshold filter, filter out the interference signals with a different frequency of the excitation signals. Hence, we can get inductosyn processed signal.

Using RD chip RDC, made by AD Company, demodulation the inductosyn analog signals into digital datas, RDC′s conversion timing signal generated by FPGA, which is also responsible for put the data into DSP, by the data bus. Finally, the gimbal angular position data can be obtained, after the coupling of two channel data of Inductosyn by DSP.

The maximum speed of CMG gimbal control system is set as 60°, inductosyn fine channel′s maximum speed as 10 800 °/s, because we choose a 180 pairs of poles absolute inductosyn (60 °/s× 180=10 800 °/s). According to the datasheet of RDC, let the sampling resolution to be 14 bit, angle detection resolution 0.22 arcsec.

2.2 Coarse channel and fine channel data coupling algorithm

Absolute inductosyn is composed of a coarse channel and a fine channel. Data from these two sets converted by chip OSCILLATOR, needs to be solute by the coupling algorithm. Solution result is CMG gimbal angular position. In this paper, fine channel′s pair of poles is 180, which means an electrical angle cycle of the fine channel with the correspond mechanical angle as 2°. The coupling algorithm process is shown in Fig. 3.

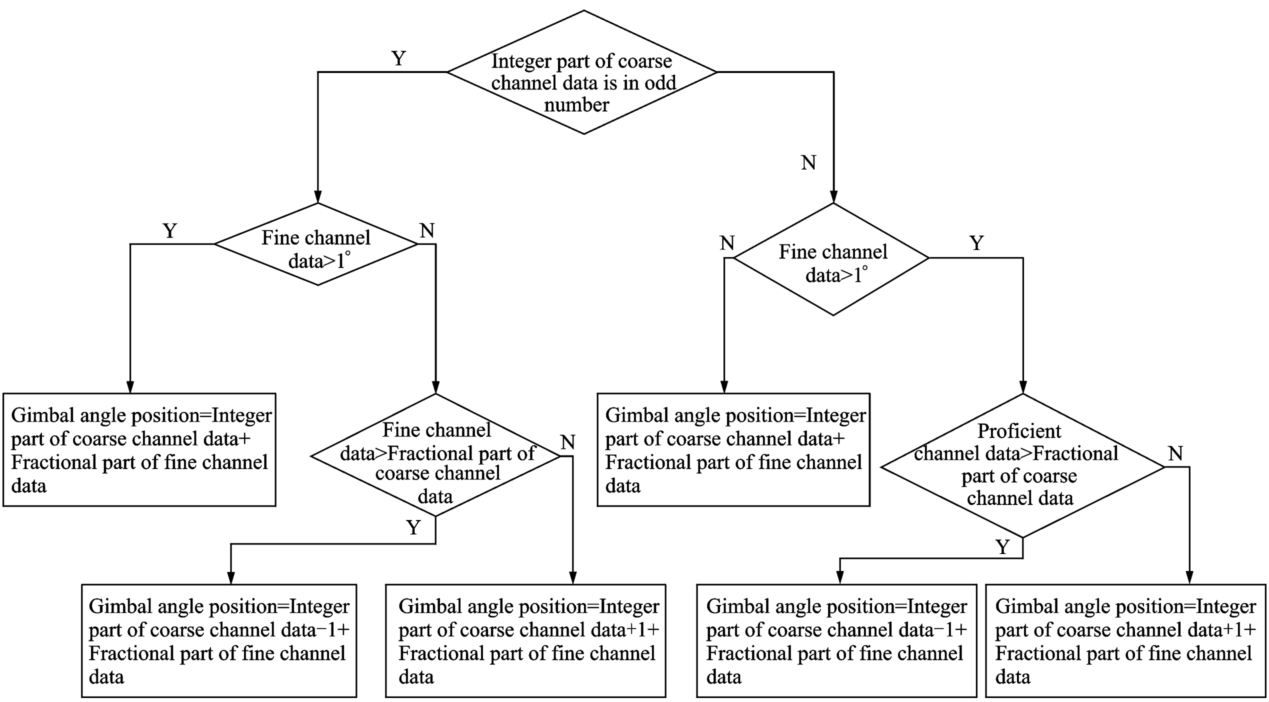

Fig. 3 Coupling algorithm

2.3 Ultrasonic motor drive circuit

USM is used as CMG gimbal driving motor. It utilizes the inverse piezoelectric effect of piezoelectric ceramics to generate vibrations in the stator. Then the rotor rotates driven by friction between the stator and the rotor. The inverse piezoelectric effect of piezoelectric ceramics produced by a high frequency and high voltage sinusoidal excitation signal. Thus, ultrasonic motor drive circuit needs to convert the PWM control signal to the high voltage sinusoidal excitation signal, whose frequency is the same as that of PWM control signal. The driving circuit is mainly composed by two full-bridge inverter circuit, step-up transformer, and matching network.

To improve circuit reliability and to meet the space requirements of anti-space radiation, power driver circuit is composed of discrete components. The MOSFET was used as the two full-bridge circuit′s main switch, and Darlington circuit was used as driving the MOSFET with freewheeling circuit. Step-up transformer design parameters are as follows: primary voltage is 28 V, PSA 1:20, frequency 35—50 kHz, and power 50 W.

The main function of the matching network converts the high voltage square wave to a sine wave signal. Low-pass filter circuit with double inductor will be used to match the capacity of USM, for achieving the goal that the signal inputed into the ultrasonic motor approximates a sine wave.

3 Test of CMG Gimbal Control System Based on Ultrasonic Motor

3.1 Inductosyn accuracy test

Inductosyn accuracy testing system is shown in Fig. 4. Precision angle encoder, with angle measurement accuracy of 0.4 arcsec is used to calibrate the inductosyn. Test results show that inductosyn angle measurement accuracy is better than 13 arcsec. The testing system is shown in Fig. 4, and the test results are shown in Fig. 5.

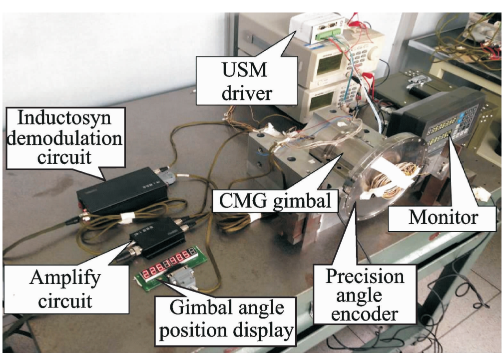

Fig. 4 Inductosyn accuracy testing system

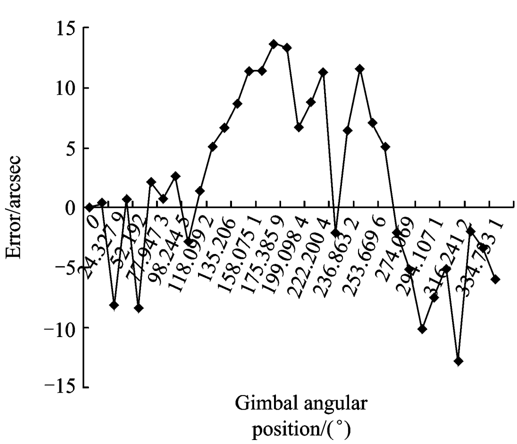

Fig. 5 Test results of inductosyn accuracy

3.2 CMG gimbal control performance test

Control moment gyroscope prototype is used to test the control performance of CMG gimbal. The CMG gimbal speed control accuracy, locking accuracy, and bandwidth were tested with the CMG wheel speed of 8 000 r/min. Test data are uploaded to PC through an RS422 interface. Sampling frequency is set to 30 Hz. Fig. 6 shows the low speed control results at three typical required speed of 0.01, 0.05 and 0.1 °/s. Fig. 7 shows the high speed control results at three typical required speed of 0.5, 10 and 60 °/s. Fig. 8 shows the required step speed control.

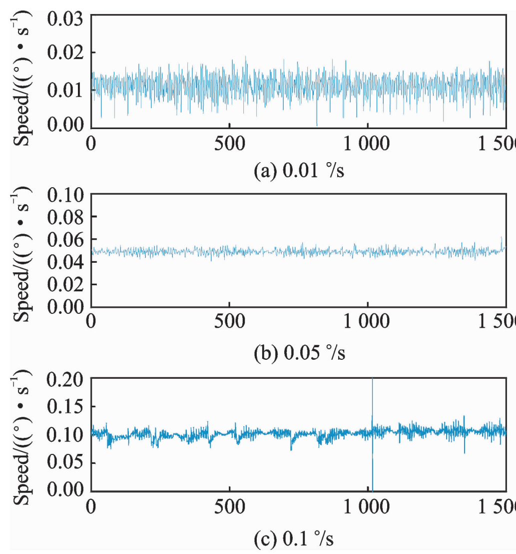

Fig. 6 CMG gimbal low-speed control performance test

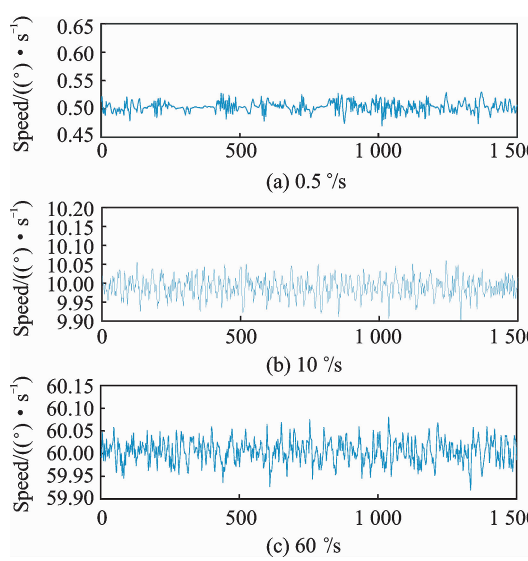

Fig. 7 CMG gimbal high speed control performance test

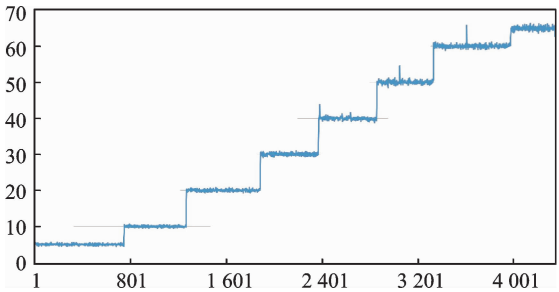

Fig. 8 CMG gimbal bandwidth control performance test

All of the test results at the required speed are summarized in Table 3.

Table 3 CMG gimbal control performance test results

Target speed/ ((°)·s⁻¹)	Test result/ /((°)·s⁻¹)	Index requirement/ ((°)·s⁻¹)	Meet requirements or not
0.01	0.004	0.02	Y
0.02	0.008	0.02	Y
0.03	0.01	0.02	Y
0.04	0.006	0.02	Y
0.05	0.007	0.02	Y
0.06	0.012	0.02	Y
0.07	0.013	0.02	Y
0.08	0.014	0.02	Y
0.09	0.015	0.02	Y
0.1	0.013	0.02	Y
0.5	0.05	0.10	Y
1	0.025	0.10	Y
5	0.02	0.10	Y
10	0.005	0.10	Y
20	0.0025	0.10	Y
30	0.00166	0.10	Y
40	0.00125	0.10	Y
50	0.001	0.10	Y
60	0.0006	0.10	Y
70	0.00057	0.10	Y

The CMG gimbal control system had been tested, and a good performance was obtained, as shown in Table 4.

Table 4 CMG gimbal control system test results

Model	Requirement	Test result
Speed control accuracy (0.01—0.1)/(d·s⁻¹)	0.02	0.015
Speed control accuracy (0.5—70)/%	10	5
Bandwidth/Hz	15	20
Lock torque/(N·m)	1	1.0
Lock accuracy/arcsec	20	12

4 Conclusions

Considering the constraints on size, mass and power consumption for a small satellite, here, a mini-CMG is designed with an ultrasonic motor in the gimbal servo system. The good performances of the CMG are obtained by both the ultrasonic motor and the rotary inductosyn.

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References:

[1] ROSER X, SGHEDONI M. Control moment gyroscopes (CMG's) and their application in future scientific missions[C]//Proc 3rd International Conference on Spacecraft Guidance, Navigation and Control Systems. Noordwijk, the Netherlands: [s. n.], 1996: 523-528.

[2] WARD J, JASON S, SWEETING M. Microsatellite constellation for disaster monitoring[C]//Proceedings of the 13th Annual AIAA/USU Conference on Small Satellites. Logan, Utah:[s. n.],1999.

[3] TU S C. Satellite attitude dynamics and control[M]. Beijing: China Astronautics Publishing House,2006: 266-267.

[4] LAPPAS V J. Design, analysis and in-orbit performance of the BILSAT-1 microsatellite twin control moment gyroscope experimental cluster[C]// AIAA Guidance, Navigation, and Control Conference and Exhibit. [S. l.]:AIAA, 2004:1-34.

[5] SARIKAN A, AYDEMIR M T, YAVUZOGLU E, et al. Real time digital simulation of a satellite attitude control system[J]. Power Electronics Electrical Drives Automation and Motion, 2010(14/15/16): 827-832.

[6] KOECK C. First in-orbit results of Pleiades CMG-based attitude control system[C]// 63nd International Astronautical Congress. [S. l.]:[s. n.],2012.

[7] Zhao Chunsheng. Ultrasonic motors: technologies and applications[M]. Berlin, Germany: Springer, 2011.

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