RESEARCH OF CONTROL MOMENTUMGYROS FOR MICRO-SATELLITES
AND 3-DOF ATTITUDE DYNAMICS SIMULATOR EXPERIMENTS

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ABSTRACT

“Agility” is one of keywords for advanced missions of next generation satellites. In particular, agile attitude maneuver is one of advantages of micro-satellites. For the agile maneuver missions, Control Moment Gyros (CMGs) will meet the necessary requirements. CMG is a nice torque amplification device because a small gimbal torque input produces a large torque output. However, CMG has some difficulties in designing and control algorithm, because the amplitude of the output torque drastically changes with the gimbal angle configurations or output torque direction.

In the paper, a simplified method to calculate appropriate output torque is introduced. In the method, two parameters are used: manipulability and mean maximum angular. The proposed method is experimentally evaluated using a test model of CMG developed by the authors. A 3-DOF attitude dynamics simulator is also developed for the experiment. The authors explain the experimental models of the pyramid cluster CMG and the attitude simulator, and discuss the results of the functional evaluation experiments.

1. INTRODUCTION

Recently, many researchers are examining the possibility of the small satellites or micro satellites with the increase of the launch opportunity of these satellites. The university of Surrey and Surrey Satellite Technologies (SSTL) have had visions of small satellite from early time and have developed many small satellites. It was also activated in Japan. Micro-Lab-Sat, which is 60kg class satellite was launched by NASA, then JAXA in 2002. In addition, two 1kg class pico-satellites CubeSat were launched by The University of Tokyo and Tokyo Institute of Technology in June 2003.

About the possibility of a micro satellite, advantages such as short-term and low-cost development specially attract attention. In the CubeSat mission at Tokyo Institute of Technology, attitude and temperature data acquired by various sensors on the orbit have been accumulated [1]. The University of Tokyo have conducted the experiment to acquire the images of the Earth with a commercial off the shelf camera, and amateur radio users all over the world are acquiring them using the amateur radio.

The Authors are considering agile attitude maneuver is one of advantages of micro-satellites for remote sensing, astronomy observation as well as on-orbit robotic missions. Micro satellite will be able to do prompt attitude change because of its small inertia and less flexibility of structure. Therefore, Control Moment Gyros (CMGs) will meet the necessary requirements for the agile maneuver missions.

2. FUTURE MISSIONS OF MICRO-SATELLITE

The Authors are considering that small satellite or micro satellite will have important roles in on-orbit services and astronomy observation.

The on-orbit service mission that provides a variety of services for spacecraft will become important as increase the space infrastructure such as the International Space Station. On-orbit services include rescue of satellite, equipment exchange, provide with
propellant and disposal of satellite which finished all missions and so on. For on-orbit mission, high torque attitude control actuator is demanded because it usually needs to use the robotic arm, which has large inertial moment.

When the operation cost exceeds the launch cost of an alternative satellite which will be given services, these on-orbit satellites lose its value. Therefore, the on-orbit servicing satellite should be small or micro satellite.

Therefore, it is desired that on-orbit servicing satellite carries high torque but smaller attitude control device than reaction wheel, which is usually carried by small spacecraft [2].

The science satellite mission varies widely from a small-scale experiment conducted by few laboratories to a worldwide scale experiment. Especially, a small satellite is suitable for a small-scaled science mission [3].

Here, we explain an example of the observation mission, Gamma-Ray Burst using micro satellite carrying CMGs.

Gamma-Ray-Burst (GRB) is an explosion phenomenon happen in the cosmological distance, which corresponds to 98% of the age of the universe and we can seldom get knowledge of that scale of universe except GRBs. The generation mechanism is still unclarification, and the formation and the radiation mechanism of the jet that is the energy beam radiated strongly are covered with mystery even though it has been gradually understood in recent years. Especially, GRBs exists only in short time and returns to former dark about 60 seconds after generation. Therefore, it is important to change the direction of telescope and to start observation in 10–30 seconds immediately after first detection.

Using CMG for attitude control of a small satellite, prompt observation of GRBs can be realized [4]. In the paper, we assume that 90 degrees Rest to Rest maneuver should be done within 10 seconds.

The rotation angle and angular velocity can be shown as follows when it is calculated using time-optimal reorientation maneuver.

When this satellite is 40kg and the maximum moment of inertia of the satellite is 1kgm², a necessary torque will be 0.035mNm.

Moreover, the satellite must have 0.2mNms of angular momentum at this time. To control without CMG saturated, 0.2mNms or more angular momentum should be able to be accumulated by momentum exchange devices.

3. CONTROL MOMENT GYROS

3.1 Momentum Exchange Device

CMG is a Momentum Exchange Device (MED) that controls attitude of the satellite according to the preservation law of angular momentum. It has some advantages that maximum angular momentum and the maximum output torque are larger than the reaction wheel. However, there are still problems when controlling, and they had been avoided with redundant CMGs in the past missions. Another problem is the difficulties in designing. Because the output torque of CMG drastically changes with the gimbal angle configurations or output torque direction, designers have to take much margin to use CMG always in desired condition. For such reason, CMGs have been installed to large-scale space platform such as Sky Lab, MIR and ISS. Therefore, high reliability has been demanded.

In contrast, because small satellite usually has lack of electric power and spatial room to carry redundant devices, examples of positively use of CMG are very few. BiSAT1 is an example of a small satellite carrying CMG [5]. However, possibility of CMG is evaluated and it will be adopted for some European satellites in the future.

3.2 CMG Dynamics

Control Moment Gyro (CMG) contains a spinning rotor with large, constant angular momentum. But its angular momentum vector can be changed with respect to the gimbal, and torquing the gimbal results in a
precessional reaction torque orthogonal to both the rotor spin and gimbal axes.

Figure 2 CMG

Because CMG is used only for one axis by SG-CMG in one unit, some CMG are combined to control full 3-axes. The pyramid array that uses four SG-CMGs is a typical cluster of CMG. This array has fixed gimbals vertically to the slope, whose skew angle $\beta$ is 54.73 degrees to make the cluster symmetric. So angular momentum of each wheel moves in the slope.

An easy mathematics model of the pyramid array is described as follow. When momentum of i-th CMG is described as $H_i$, angular momentum of the entire system is as follows [6].

$$\textbf{h} = \sum_{i=1}^{4} H_i$$  \hspace{1cm} (1)

The motion equation is given as follows.

$$\textbf{J}\dot{\textbf{\omega}} + \textbf{\omega} \times \textbf{J}\textbf{\omega} = \textbf{u} + \textbf{T}_{\text{ext}}$$  \hspace{1cm} (2)

$$\textbf{h} + \textbf{\omega} \times \textbf{h} = -\textbf{u}$$  \hspace{1cm} (3)

Using control torque $\textbf{u}$ decided in the ADCS,

$$\textbf{h} = -\textbf{\omega} \times \textbf{h} - \textbf{u}$$  \hspace{1cm} (4)

is decided to actuate gimbals.

So that CMG may keep angular momentum of the wheel constant, only gimbals work.

$$\textbf{h} = h\textbf{A} \delta \dot{\delta}$$  \hspace{1cm} (5)

If matrix $\textbf{A}$ has inverse, gimbals angle necessary for the control can be requested about each CMG. Here, $h$ is a size of angular momentum of each CMG and $\textbf{A}$ is Jacobian matrix.

4. MANIPURABILITY AND MEAN MAXIMUM ANGULAR MOMENTUM

To design CMG for Gamma-Ray Burst observation satellite, necessary output torque and maximum angular momentum to be accumulated should be properly determined. In the paper, they are evaluated using two parameters, which are Manipurability and Mean maximum angular.

Though the output torque generated by entire CMG array cannot be simply expressed because the output torque of CMG drastically changes with the gimbal angle configurations or output torque direction, the average output torque in a certain configuration of the gimbals angle can be estimated as follows.

$$\textbf{\bar{T}} = h\sqrt{\text{det}(\textbf{A}^T \textbf{A})} \|\delta\| = hm\|\delta\|$$  \hspace{1cm} (6)

where,

$$m = \sqrt{\text{det}(\textbf{A}^T \textbf{A})}$$

is called Manipurability, which means the average gain [7]. Because this value becomes almost 1 in many configurations, this value is used in the following designing. The larger each angular momentum $h$ is, the more the torque magnification rises.

Enough torque cannot be output when the average gain becomes small, and there is a possibility to which the control becomes impossible or difficult. It is said that singular point and the torque cannot be output about a certain axis. A variety of arrays and the control methods have been researched for such a singular problem of the CMG system.

Next, angular momentum is described. Maximum angular momentum means the maximum value of angular momentum to which the CMG array can be absorbed. Maximum angular momentum envelop can be calculated and is found that it can not become sphere because the rotation of gimbals has one dimension. Therefore, maximum angular momentum to be accumulated differs with its direction.
Here, Mean maximum angular is assumed to be simply the average of any directions. It is calculated to be as follows.

\[ \bar{\psi} \approx 2(1 + \cos \beta)h \]  

(7)

Figure 4 Angular momentum envelop

5. COMPARISON OF RW WITH CMG

Here, CMG parameter design is described comparing with the reaction wheel in order to clarify the advantage to use CMG in the GRB observation satellite.

Reaction Wheel (RW) consists of a spinning rotor whose spin axis is fixed to the spacecraft and its speed is increased or decreased to generate reaction torque about the spin axis. A difference from CMG is to generate angular momentum and the output torque by one motor. In many cases, a high-speed motor is used to increase the accumulation ability of angular momentum, the output torque becomes small.

The performance of MED can be evaluated by two points, which are an output torque and maximum angular momentum. That is, to request the performance of a necessary device for a certain mission, it only has to specify a necessary torque and angular momentum that can be absorbed not to be saturated while the mission period.

In the comparison, the structural size of both attitude devices is compared when designing the reaction wheel and CMG that achieve each of them.

- Maximum output torque
  - 35mNm should be able to be generated.
- Maximum angular momentum
  - 200mNms of angular momentum should be able to be accumulated.

5.1 In the case of Reaction Wheel

First of all, the motor that can achieve demanded angular momentum and output torque is selected. Here, demand torque 35mNm is achieved by using 20:1 gears for the motor of maximum speed 4,000 rpm when no load, maximum torque of 3mNm.

Table 1 reaction wheel

<table>
<thead>
<tr>
<th>diameter</th>
<th>180 mm</th>
</tr>
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<tbody>
<tr>
<td>thickness</td>
<td>15 mm</td>
</tr>
<tr>
<td>mass</td>
<td>3000 g</td>
</tr>
</tbody>
</table>

The size of one unit is about 180mm x 180mm x 50mm. To control full 3-axis using this RW, this should be orthogonalized and be arranged in three axes. The volume of entire device is requested to be 10,000cm³. Weight becomes 3,000g a unit and more for motors, bearings and the control circuits.

5.2 In the case of CMG

The motor is used for CMG wheel which has maximum speed of 4,000 rpm when no load and maximum torque of 3mNm.

Using manipurability, required torque per one CMG becomes,

\[ \frac{\bar{\psi}}{\beta h} \geq 0.035 \]  

(8)

where, gimbal rate is assumed to have limitation of 0.25rad/s because of gimbal motor output torque. If gimbal rate is limited within this level, gimbal motor can achieve any desired control.

Mean maximum Angular momentum of the pyramid array is described in (7).

Then, the demand angular momentum per one CMG becomes,

\[ 2h(1 + \cos \beta) > 0.2 \]  

(9)

To achieve both output torque and angular momentum requirements, the following specification was estimated.

Table 2 CMG wheel

<table>
<thead>
<tr>
<th>diameter</th>
<th>60 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness</td>
<td>15 mm</td>
</tr>
<tr>
<td>mass</td>
<td>330 g</td>
</tr>
</tbody>
</table>

For gimbal motors, 159:1 gears are combined. The size of whole system becomes 200mm x 200mm x 150mm.

To control full 3-axis using this CMG, volume of entire system is requested to be 5,000cm³, which is a half of the case using RW. Weight becomes 330g a unit and more for motors, bearings and the control circuit.

Though it is said that CMG need more electric power than RW and has internal disturbance, CMG use can greatly reduce the size and weight of whole system.

Therefore, we can conclude that if we don’t care about electric power and internal disturbance, we should use CMG for agile small satellite such as GRB observation satellite.
6. CMG DESIGNING

Here, development of test model of CMG pyramid cluster is described. Performances of this test model is the same as one described in the former chapter.

-Components of CMG

The CMG is composed of motor for the wheel, motor for gimbals, collector ring, motor driver, and the processing computer. The optical encoder is installed in the motor, and the rotational speed can be measured. 159:1 gears are installed on the motor for gimbals.

TTTech DriverII is used for the motor driver. That was developed in Tokyo Institute of Technology. The processing computer is H8S/2626 manufactured by Renesas Technology. To control the motor for the wheels and for gimbals, 4 microcomputers are needed. These 4 computers are connected with Controller Area Network (CAN).

The motor driver installs various sensors. The A/D converter and the pulse counter are necessary to read the sensors. H8S/2626 can also be used as converter and counter.

-Collector ring

Collector ring manufactured by JAPAN SERVO is used. These collector rings are four poles, and continuous current is limited by 100mA. Therefore, the wheel motor should be used within the current limit.

-Microcomputer H8S/2626F for control

Timer Pulse Unit (TPU), which is installed in H8S/2626, measures the pulse the optical encoder generated. TPU is also a standard timer of the H8S Series.

To deal with signal at the level of voltage +/-10V in TITech DriverII, the amplification circuit is also equipped. In the circuit, operational amplifier \( \mu \text{PC4064} \) by NEC is used for the voltage conversion.

Because four H8 are necessary for this system, Controller Area Network (CAN) is used for these communications. CAN is used to communicate with a number of microcomputers usually installed in industrial equipments.

The specification of CMG of the pyramid array is shown below. Total weight became 6.4kg. The size is 450mm x 450mm x 150mm. This size is much larger than that estimated before because it was not able to miniaturize the control circuits. The output torque is nominally 35mNm when limiting gimbal rate within 0.25rad/s. If lose of controlling correctness can be permitted, output torque can be larger up to 210mNm depending on gimbal rate. This system totally uses
about 1A for control circuits and another 1A for the motors. So it consumes electric power of 48W in total while working. The wheel speed is 4,000 rpm nominally.

<table>
<thead>
<tr>
<th>Table 3 CMG spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight</td>
</tr>
<tr>
<td>Size</td>
</tr>
<tr>
<td>Torque</td>
</tr>
<tr>
<td>Maximum Angular</td>
</tr>
<tr>
<td>Power</td>
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</tbody>
</table>

Because nominal output torque produced by the entire system of this CMG is only 35mNm, the gimbals rate limitation is unlimited up to be 1.0rad/s to make the effect of CMG emphasised more clearly. The torque five times larger than nominal is generated. However, CMG is saturated in this case within one second.

7. 2-DIMENTIONAL GROUND EXPERIMENT

To evaluate the basic performance of this CMG, it was tested on the ground experiment simulator, which is called “Dynamics and Intelligent control Simulator for satellite Cluster (DISC)” [8]. DISC is a system that simulates dynamics of the spacecraft under 2-dimensional microgravity environments on the ground. DISC achieves a flat microgravity environment except for only air resistance and some friction by using the air floating pad. The range of the movement is restrained to the size of a flat floor of 3m x 5m. Inside that, it can move using jet thrusters of compressed air without dynamic interference because of remote control by wireless LAN and battery to supply the power to equipments. The experiment time depends on the capacity of two tanks that are the compressed air supply source.

Because air floating pad is not symmetry, the rotation occurs naturally even if DISC is on the flat floor. In the experiment, it is necessary to subtract this effect. Then, this torque is first calculated from the rotation profile of DISC on the flat floor.

This profile showed that it rotated 90 degrees in 15 seconds. At this time, the torque of about 35mNm generated by air pad. In the following experiments, the effect of this torque is subtracted.

Average 150mNm is expected as for the output torque. In the figure, lines are the expected output torque and calculated attitude angle. And circle is experiment data. It is considered that CMG can almost demonstrate the performance because reaching time to 90 degrees was almost the same as the expectation.
8. 3-DIMENTIONAL ATTITUDE DYNAMICS EXPERIMENT

To evaluate the basic performance of this CMG, it was also tested on the 3-DOF attitude dynamics simulator developed for CMG experiment. The simulator consists of a low friction ball bearing, balance adjusters and sensors for attitude determination. The ball bearing was selected because of the system simplification. Although it is commonly said that the ball bearing makes larger friction than an air bearing, the effect of friction is assumed not to be so large as the CMG output torque. Spherical ball bearing is shown below.

Figure 12

-Balancer
The whole of the simulator is supported with the spherical bearing, and centre of gravity can be matched to the ball centre by moving adjusting weight. Then, the torque by the gravity causes no rotation regardless of the attitude of the simulator and thus movement on orbit can be simulated.

These adjusters can be installed almost anywhere on the simulator. They can be roughly installed before CMG is attached on the simulator, and the centre of gravity position shall be adjusted precisely to the position of the body and CMG.

-Ball Bearing
The bearing whose friction has been decreased without floating itself by air developed in recent years. We chose such kind of spherical bearing, SRJ. It is a product that brought friction close to the air bearing while having the merit of the ball bearing of easiness to treat.

The bearing is pressurized and even when it doesn't have the axis torque, a constant friction torque is loaded. However, it is thought that when the generation torque of the CMG is very large compared with the friction torque, it is possible to neglect it. And it’s able to evaluate the control performance of CMG considering the effect of the friction torque.

-Sensors
The acquisition of attitude information of the simulator is necessary and indispensable so that a purpose of the simulator is an evaluation of the performance of CMG. Here, to acquire the angle information Fibre Optic Gyro (FOG), which was manufactured by Japan Aviation Electronics Industry is installed. And the acceleration sensor was installed to detect the direction of gravity directly. The roll angle and the pitch angle are derived from the direction of gravity, and the yaw angle is derived by using gyro with high accuracy.

The sampling period of the gyro is 20ms, and data is sent and received by COM port, RS-232C. It is possible to instruct angle reset and the bias automatic correction from an onboard computer.

-Processing and Communications
Processing and the communication of the sensor data are done by microcomputer H8/3069 by Renesas Technology. It communicates with gyro and the bus controller receives the signal data converted from output of other sensors with an A/D converter. The acquired data are sent to external PC using wireless LAN. The sensor sampling frequency is 50Hz. Moreover, the command data from external PC to the CMG can be forwarded to it through this computer.

Wireless LAN is used in order to free the effect of harness disturbances. The wireless modem is Connect WI-ME by Digi International. Both CMG data and sensor data are brought together to the external PC using this wireless network.

Figure 13

-Rotation around Z axis
The attitude change operation around yaw (Z) axis was done by installed CMG, and a movement expected under a microgravity environment using CMG data and an actual attitude acquired by FOG are compared. CMG is controlled in open loop using time optimal control.

The bold line in figure 14 is acquired data by FOG on the simulator and the thin line in this figure is expected attitude change calculated using CMG data. They are almost the same but actual attitude change is smaller than desired change based on CMG data. It was easily considered that it was an effect of friction at the ball bearing. It is necessary to examine how much the
attitude movement in completely microgravity environment can be estimated using obtained data with little friction.

Figure 14

9. CONCLUSION

In this paper, the design process and experimentally evaluation of agile attitude control devices were described. In the design process, CMG and Reaction Wheel were compared and it was confirmed that CMG is superior to Reaction Wheel in its small size and weight when used for agile attitude reorientation.

There is a problem in the design of CMG output torque because of drastically changing of its output torque depending on an internal gimbal configuration and its output direction. In this paper, a simplified method using two standard parameters, which are manipulability and mean maximum angular was proposed and it was confirmed that was suitable to use while designing CMG size based on two experiments. However, to design CMG, singular problem should be considered as well. This paper assumed that gimbal driving law could overcome it, but it actually should be dealt with care.

As the method of simulating the microgravity environment, two systems were introduced. One is the air floating 2-dimentional flat floor. It has very low friction between simulator and other environment. Therefore, the acquired data from CMG reorientation experiment and expected data calculated based on design parameters of CMG were fairly close. But it can rotate only in one direction. If effect of other axis is needed, flat floor use is not suitable.

The other is 3-DOF attitude dynamics simulator developed for this experiment.

This paper described the development and CMG experiment using this simulator. Although using the air bearing was majority, spherical ball bearing was installed because it aimed at the miniaturization and the simplification of experiment system.

In the experiment, it was evaluated how much the effect of friction exists comparing the acquired data with expected data calculated based on CMG design parameters.

3-DOF attitude dynamics simulator should be used when a nonlinear attitude maneuver in three dimensions is to be examined and 2-simentional flat floor should be used when an accurate attitude maneuver about one axis is to be examined.

10. REFERENCES