CMG CONFIGURATION AND CONTROL FOR RAPID ATTITUDE MANEUVER OF SMALL SPACECRAFT

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Abstract

This paper describes 3-axis Control Moment Gyroscope control algorithm for small spacecraft which has 2 CMGs available. This configuration can be suitable for small in-orbit-servicing spacecraft when it needs to maneuver its attitude rapidly because the configuration, having 4 DOF, is the smallest CMG cluster for full 3-axis control (each rotor must have its speed controllable). The concept of this study is how small but efficient the attitude control device can become.

This CMG cluster can generate large output torque about 2 axes by strong gyro effect torque, while much smaller torque can be generated about the other axis by accelerating or decelerating the rotor speed, like Reaction Wheel. For this reason, rapid full 3-axis control is difficult although the cluster has 4-DOF. So it is needed mainly to use 2 axes even when 3-axis maneuver.

We introduce optimal control based method to the system in order to achieve 3-axis attitude control, not depending on the smallest output axis. Though this method sometimes requires a number of iteration to find a solution, the system, having actually 4 DOF controllable, at least one solution exists.

Tokyo Institute of Technology is planning to launch a small satellite which can control its attitude rapidly. The mission of the satellite is to observe Gamma Ray Burst or other burst phenomena requiring prompt maneuver of the attitude. This is the reason we use CMG for the satellite.

Tokyo Institute of Technology and Tamagawa Seiki Corporation are jointly developing tiny CMG for space use. The wheel size will be about 3cm (about 1.2 inch) and the wheel speed can be controlled. In this paper, descriptions of the satellite, CMG size and simulations are based on this model.

One of future directions of this study is how we introduce this algorithm to real CMG system. We have to reduce iteration further more although in this algorithm reduction of iteration is considered.

1. INTRODUCTION

Rapid attitude maneuver is one of keywords for advanced missions of next generation satellites. In particular, agile attitude maneuver is one of advantages of micro-satellites because of its small inertia and less flexibility in the structure. Recently, many researchers are examining the possibility of the small satellites or micro satellites with the increase of the launch opportunity. The University of Surrey has contributed to this with their pioneering work. In Japan, Micro Lab Sat, which is 60kg class satellite, was launched by JAXA and INDEX (Reimei) was also launched in 2005, which has magnetorquer based 3-axis control devices. The Canadian micro satellite "MOST" in 2003 can have inspired the following sophisticated attitude control missions of micro satellites. In addition, so called CubeSat is another style of small satellites. Two 1kg class pico-satellites "XI-IV" by The University of Tokyo and "CUTE-I" by Tokyo Institute of Technology were launched in 2003 and its successor "Cute-1.7 + APD" was launched in 2006.

In the CubeSat mission at Tokyo Institute of Technology, attitude determination and control using very small, COTS devices will be conducted on the orbit [1].

For the agile maneuver missions of micro satellites, Control Moment Gyros (CMGs) will meet the necessary requirements. CMG is a momentum exchange device that controls attitude of the satellite according to the preservation of angular momentum. It has some advantages that maximum angular momentum and the maximum output torque are larger than the reaction wheel. 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.

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 β is 54.73 degrees to make the cluster symmetric.

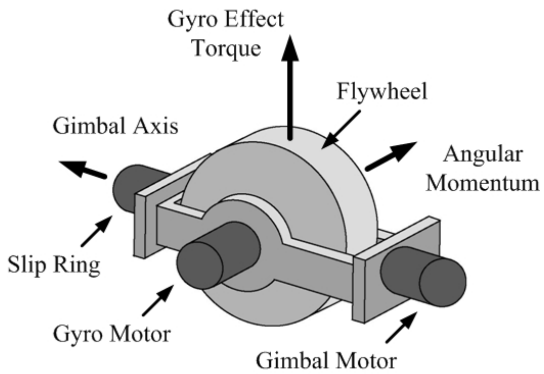

Figure 1: A CMG unit

CMG is a kind of 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.

Many researches have been made to overcome the problem about singularity. A solution called GSR [2] can work well to the problem in various kinds of configurations of CMG.

Another solution is Variable Speed CMG (VSCMG) control law. VSCMG control law is a way that is to control both gimbals and rotor speed. The controllability of the rotor is just like reaction wheels. Reaction Wheel consists of a spinning rotor and its speed is increased or decreased to generate reaction torque about the spin axis. A difference of the reaction wheel from CMG is to generate angular momentum and the output torque by the same motor. In many cases, a high-speed motor is used to increase the accumulation ability of angular momentum, the output torque becomes small. That is the largest problem about VSCMG. We consider the problem in the next chapter.

Although these singularity avoidance can be installed and well working, in the past missions it had been avoided with redundant CMGs such as 4 CMGs in the pyramid array. So we need much margin to use CMG always in desirable condition. For such reason, CMGs have been installed in large-scale space platform such as Sky Lab, MIR and ISS.

In contrast, because small satellite usually has lack of electric power and space to carry redundant devices, examples of positively use of CMG are very few. BilSAT1 is an example of a small satellite carrying CMG, which was developed by Surrey. However, possibility of CMG is evaluated and it will be adopted for some satellites in the future.

This study is aimed to reduce size of CMG configuration, mainly reducing the number of CMGs in the configuration. The authors have developed very small CMG to be carried in the 40kg class micro satellite and have studied to control with small number of unit, for example, only 1 unit [3]. The least number with which the total configuration can output 3 axes torque may be 2. This paper describes 3-axis control algorithm for 2 CMGs available.

2. 2-CMG CLUSTER

2-1. INTRODUCTION OF 2-CMG SYSTEM

In order to reduce total weight of CMGs, we introduce a configuration of 2 CMGs whose gimbals are placed orthogonally. This cluster can output torque along 2 axes and if their rotor speed are controllable, it can output torque along 4 axes.

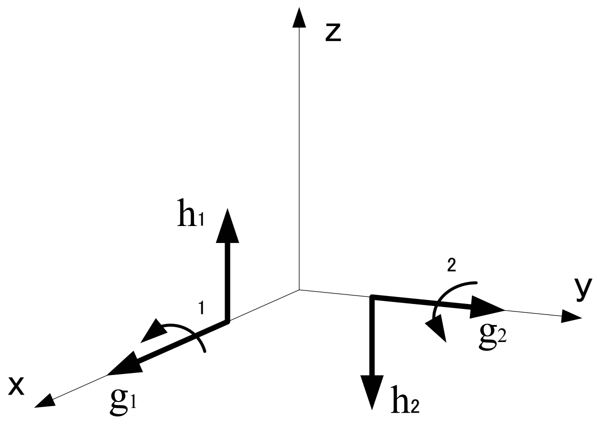

Figure 2: Orthogonal Configuration of 2-CMGs

The total angular momentum of the entire system becomes

$$\eta = \sum_{i=1}^{2} H_i = \begin{bmatrix} 0 \\ -h_1 \sin\delta_1 \\ h_1 \cos\delta_1 \end{bmatrix} + \begin{bmatrix} -h_2 \sin\delta_2 \\ 0 \\ -h_2 \cos\delta_2 \end{bmatrix} \quad (1)$$

Total angular momentum is a function of the length of angular momentum vector of each wheel, h and gimbal angle vector δ, then the Jacobean Matrix becomes

$$\dot{\eta} = \begin{bmatrix} \eta_h & \eta_\delta \end{bmatrix} \begin{bmatrix} \dot{h} \\ \dot{\delta} \end{bmatrix} = \eta_{h\delta} \begin{bmatrix} \dot{h} \\ \dot{\delta} \end{bmatrix} \quad (2)$$

$$\eta_{h\delta} = \begin{bmatrix} 0 & -\sin\delta_2 & 0 & -h_2\cos\delta_2 \\ -\sin\delta_1 & 0 & -h_1\cos\delta_1 & 0 \\ \cos\delta_1 & -\cos\delta_2 & -h_1\sin\delta_1 & h_2\sin\delta_2 \end{bmatrix} \quad (3)$$

Using control input torque u determined in the Attitude Control Subsystem (ACS) of satellite, required gimbal rate and wheel acceleration are calculated as in eq.(4).

$$\dot{\eta} = -\omega \times \eta - u \quad (4)$$

Substituting the result of (4) into (2), we calculate the inverse of equation (2) to determine the control parameters, gimbal rate and wheel acceleration.

A time optimal feedback control designed for spacecraft maneuver is described in the reference [4]

$$\begin{aligned} u &= \underset{U}{sat}(\tau) \\ \tau &= -J\left\{2k\ \underset{Li}{sat}(e) + c\omega\right\} \\ L_i &= (c/k)\sqrt{a_i|e_i|} \end{aligned} \quad (5)$$

In the following simulation, we chose

$$k = 3.0,\ c = 1.0,\ a_i = 0.4 \times U / J \quad (6)$$

To estimate the parameter U, which is the maximum output torque produced by total CMG configuration, we used a simplified method to calculate appropriate output torque using manipulability and mean maximum angular introduced in the reference [5].

In the following simulation, we assumed that the angular momentum of each wheel is 0.05 Nms, which is actual value of our mini-CMG jointly developed by Tamagawa Seiki Corporation, and the moment of inertia of the satellite is 1.0 kgm^2, which is from 40kg class micro satellite.

Then we calculate the inverse of equation (2) as following.

$$\begin{bmatrix} \dot{h} \\ \dot{\delta} \end{bmatrix} = W\eta_{h\delta}^{\ T}\left(\eta_{h\delta}W\eta_{h\delta}^{\ T}\right)^{-1}\dot{\eta} \quad (7)$$

We assume the maximum gimbal and wheel rate as

$$|\dot{h}_i| < 0.001,\ |\dot{\delta}_i| < 0.1$$

So the matrix W is determined as

$$W = \begin{bmatrix} 0.01 & 0 & 0 & 0 \\ & 0.01 & 0 & 0 \\ & & 1 & 0 \\ symm. & & & 1 \end{bmatrix} \quad (8)$$

2-2. SIMULATION RESULT

A simulation to rotate 90 degrees about Y axis of a spacecraft which has orthogonal cluster of 2 CMGs shown in the figure 2 was performed. Results are shown in figure 3.

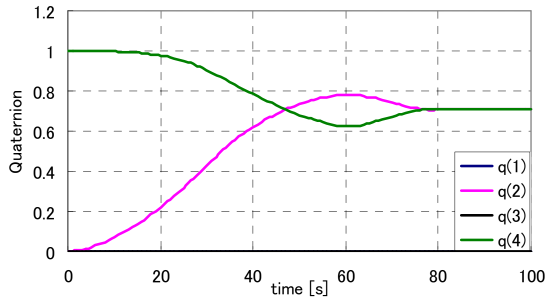

Figure 3(a): Quaternion

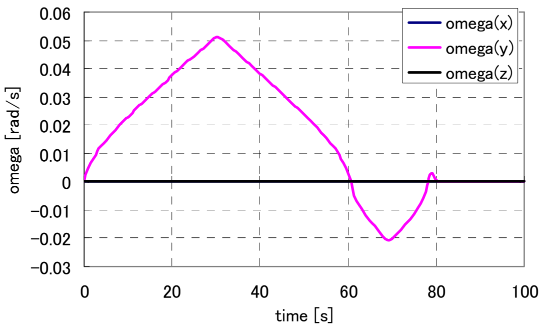

Figure 3(b): Angular velocity

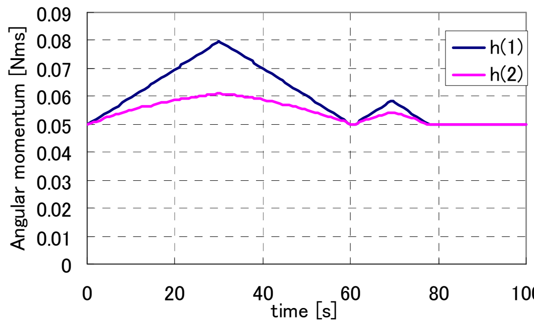

Figure 3(c): Angular momentum of each rotor

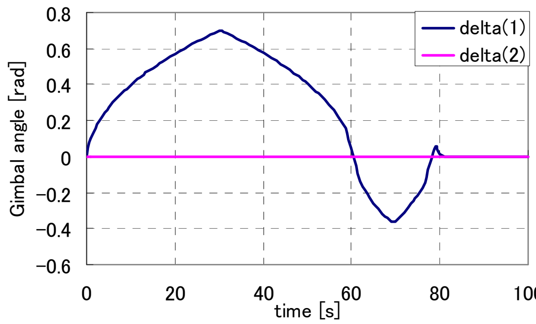

Figure 3(d): Gimbal angle of each CMG

Total maneuver time was about 80 seconds. The results show that we have a little overshoot. Even if we conducted a perfect bang-bang control which has no overshoot, we would not finish the maneuver faster than 60 seconds. Although gimbal rate limit is set to 0.1 rad/s, actually the gimbal did not move faster than that because wheel rate is limited to 0.001 Nm. The VSCMG actuating logic is provided with demanded torque input that should be obeyed perfectly so the gimbal rate is restricted by the speed of wheel rate.

Therefore, in order to rotate faster, we should use more powerful wheel motor that can be accelerated faster than 0.001, or we should modify the whole attitude control system, for example, to accomplish attitude maneuver by only gimbaling.

3. OPTIMAL CONTROL FOR 2-CMGS

3.1 OPTIMAL CONTROL

To overcome the difficulty of using VSCMG or its reaction wheel, we introduce optimal control theory. In general, according to the results of optimal control theory, spacecraft can rotate about any axis using 2 input torque. Before we introduce the theory into the 2 CMGs system, a calculation of attitude maneuver using 2 reaction wheels is described here. We applied the method from Prof. Yamaura's reference [6].

After that, the authors introduce the parameter adjustment in order to reduce calculation. In general, we do not need strictly time optimal solution. In this case we would like a solution which can satisfy the terminal condition and can be at lease faster than the normal feedback control.

A state vector is 3 components of MRP and those of omega described bellow. Here, angular momentum of wheels is neglected.

$$x = \begin{bmatrix} \sigma \\ \omega \end{bmatrix} \tag{9}$$

A state equation is

$$\begin{aligned} \dot{x} &= \begin{bmatrix} [\sigma]\omega \\ -J^{-1}[\omega\times]J\omega + J^{-1}Bu \end{bmatrix} \\ &= \begin{bmatrix} [\sigma]\omega \\ -J^{-1}[\omega\times]J\omega \end{bmatrix} + \begin{bmatrix} 0 \\ J^{-1}B \end{bmatrix} u \end{aligned} \tag{10}$$

And the terminal condition is

$$\Psi(T) = x(T) - \begin{bmatrix} \sigma_f \\ 0 \end{bmatrix} = 0 \tag{11}$$

A cost function which should be minimized is

$$L = \int_0^T \left(1 + \lambda\left(f(x,u) - \dot{x}\right)\right) dt + \nu\Psi(T) \tag{12}$$

The final time T is not fixed. So we introduce a new variable p that indicates final time T as shown bellow.

$$t = p\tau \quad (0 \le \tau \le 1) \tag{13}$$

Then problems is rewritten as

$$\begin{aligned} x'(\tau) &= \begin{bmatrix} [\sigma]\omega p \\ -J^{-1}[\omega\times]J\omega p \end{bmatrix} + \begin{bmatrix} 0 \\ J^{-1}Bp \end{bmatrix} u \\ p' &= 0 \\ \Psi(1) &= x(1) - \begin{bmatrix} \sigma_f \\ 0 \end{bmatrix} = 0 \end{aligned} \tag{14}$$

$$L = \int_0^1 \left(p + \lambda_x\left(f(x,p,u) - x'\right) + \lambda_p p'\right) d\tau + \nu\Psi(1) \tag{15}$$

Introducing Hamiltonian, variations of the cost function is calculated as

$$\delta L = \int_0^1 H_u \delta u d\tau + \lambda_p(0)\delta p(0) \tag{16}$$

Update of the input and time scale are shown.

$$\begin{aligned} u_{k+1} &= u_k + \delta u = u_k + \alpha H_u \\ p_{k+1} &= p_k + \delta p = p_k + \beta\lambda_p(0) \end{aligned} \tag{17}$$

This problem is "final state fixed". But it has problem that Lagrange multipliers λ_p, λ_x and even ν can not be determined.

Then using a way of the reference [6], one can consider this problem as "final state free", but update of input vector and final time is made so that the terminal condition is satisfied.

$$\begin{aligned} u_{k+1} &= u_k + \alpha\left(H_u + \nu W_u\right) \\ p_{k+1} &= p_k + \beta\left(\lambda_p(0) + \nu W_p(0)\right) \end{aligned} \tag{18}$$

In this way λ are determined easily and parameter ν, and W is properly calculated

3.2 PARAMETER ADJUSTMENT

The authors defined α and β so that the iteration can be reduced.

Our goal is to find a solution which satisfy the terminal condition and if possible a solution that can be at lease faster than the normal feedback control.

We assume that small β is important not to diverge. However, small β makes it slow to reach the final time optimal solution. So we define β so that it becomes small when terminal condition is not satisfied and becomes large when terminal condition is almost satisfied. Also, we assume that α is relatively torrent for divergence. So we define them as in equation (19).

$$\alpha = -0.1$$
$$\beta = \begin{cases} -\dfrac{10^{-5}}{\|\Psi(1)_{k-1}\|} & for\ k > 1 \\ 0 & for\ k = 1 \end{cases} \qquad (19)$$

To reach near the time optimal solution faster, initial value of p is needed to near the final value of p. However, the authors confirmed that the initial p must have margin from the final value, otherwise calculation is not converged. So we determined the initial value as 2 times larger than the time in which the spacecraft rotates when time optimal feedback control of the reference [4] is used.

One result of a 90 degrees maneuver about Z axis of spacecraft which has 2 reaction wheels in X and Y axes is shown. The maneuver of time that the spacecraft rotates when the most desirable 3 axis output torque can be used was 4 seconds. So we determined the initial value of p to 8.

The initial input vector was set to

$$u_1(\tau) = [0.001 \quad 0.001]^T \quad for\ any\ \tau \qquad (20)$$

Then residual error $\|\Psi(1)\|$ and maneuver time along 100 iterations are shown here

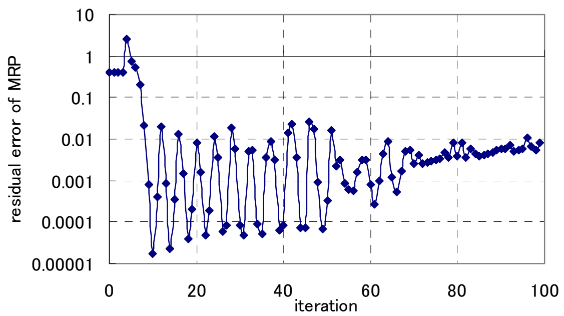

Figure 4(a): residual error versus iteration

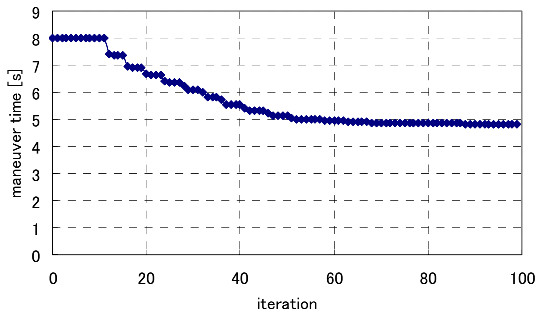

Figure 4(b): total maneuver time

In this method, after 10th iteration, residual error of MRP becomes small and then maneuver time is gradually decreasing.

Shown following are the MRP, angular velocity, and control input after 50^{th} iteration.

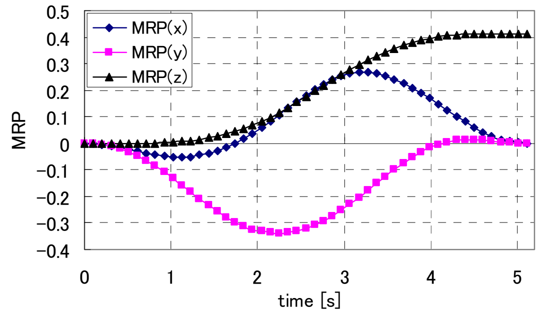

Figure 5(a): MRP

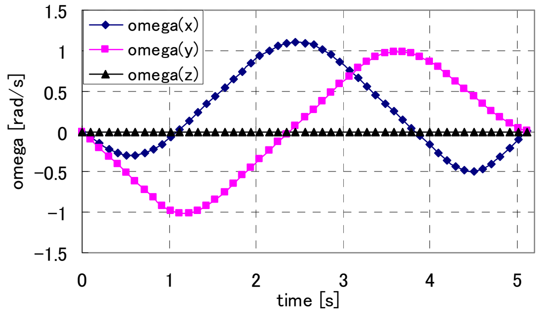

Figure 5(b): Angular momentum

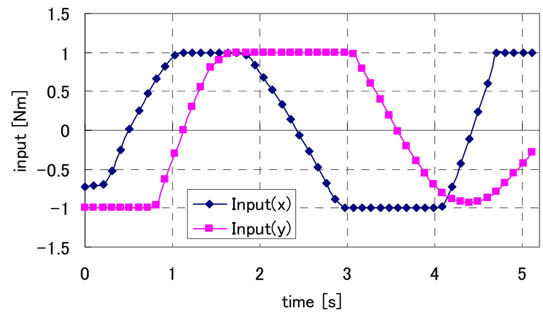

Figure 5(c): Input torque

In actual usage, we can start maneuver after 10^{th} iteration because at least terminal condition is satisfied. After that, input is updated, for example, every 10 calculation. Therefore we can finish the maneuver 5 or more, for example, 6 seconds from the first calculation.

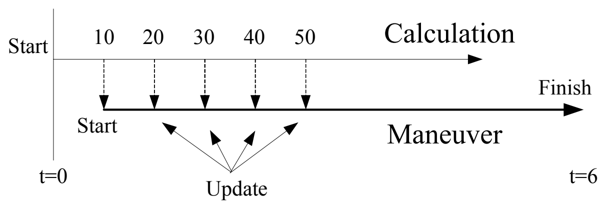

Figure 6

4. OPTIMAL CONTROL FOR 2-CMGS

4-1. CMG USE

Using the result of the former chapter, we introduce the optimal control for 2CMG orthogonal array. At first, only gimbals are controlled.

A state vector is 3 components of MRP, those of omega, and gimbal angle vector, described bellow

$$x = \begin{bmatrix} \sigma \\ \omega \\ \delta \end{bmatrix} \quad (21)$$

Euler's equation of motion is

$$J\dot{\omega} = -\omega \times J\omega - \omega \times \eta - \eta_\delta \dot{\delta} \quad (22)$$

Then a state equation becomes

$$\dot{x} = \begin{bmatrix} [\sigma]\omega \\ -J^{-1}[\omega\times](J\omega+\eta) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ -J^{-1} m \eta_\delta \\ mI^{(2)} \end{bmatrix} u \quad (23)$$

Here, *m* indicates gimbal rate limit,

$$u = \frac{1}{m}\dot{\delta} \quad , \quad |u_i| \le 1 \quad (24)$$

The result was shown as in the followings. Total time required to maneuver 90 degrees was 43.51 seconds.

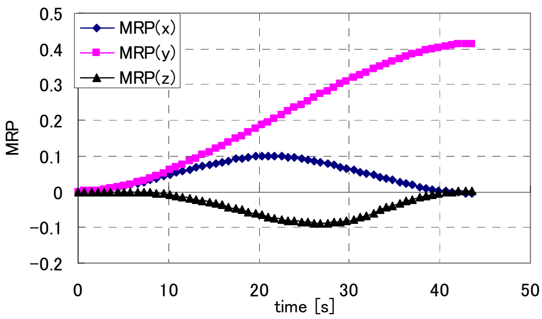

Figure 7(a): MRP

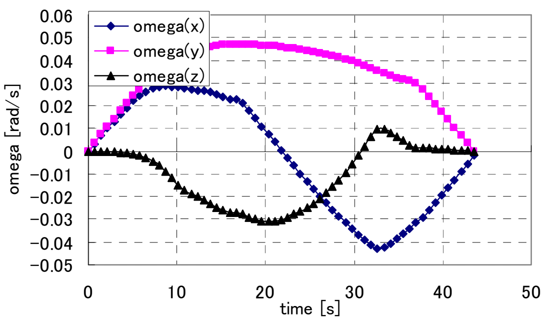

Figure 7(b): Angular velocity

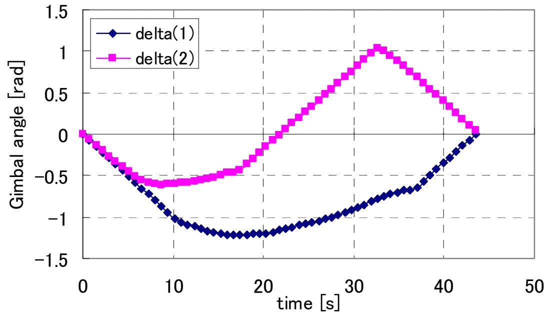

Figure 7(c): Gimbal angle

4-2. VSCMG USE

Next, we consider the case in which rotor speed of each wheel is controllable, which is called VSCMG. Angular momentum of each wheel is added to state vector as follows.

$$x = \begin{bmatrix} \sigma \\ \omega \\ h \\ \delta \end{bmatrix} \quad (25)$$

Equation of motion is

$$J\dot{\omega} = -\omega \times J\omega - \omega \times \eta - \eta_h \dot{h} - \eta_\delta \dot{\delta} \quad (26)$$

Then a state equation is

$$\dot{x} = \begin{bmatrix} [\sigma]\omega \\ -J^{-1}[\omega\times](J\omega+\eta) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ -J^{-1}\eta_{h\delta} m \\ mI^{(4)} \end{bmatrix} u \quad (27)$$

Here,

$$u = m^{-1}\begin{bmatrix} \dot{h} \\ \dot{\delta} \end{bmatrix} \quad (28)$$

$$m = \begin{bmatrix} \dot{h}_{MAX} & 0 \\ 0 & \dot{\delta}_{MAX} \end{bmatrix} \quad (29)$$

One importance is that the angular momentum of each wheel is limited by the motor characteristics. Apparently, the motor can not work much faster than its normal operation speed, here we assumed to be 0.05Nms. We can set a limit by replacing the cost function as follows.

$$L = \int_0^1 (p + pF_H(h)) d\tau$$

TYPE A:

$$F_H(h) = \begin{cases} k(h-0.05)^2; & h > 0.05 \\ 0; & h \le 0.05 \end{cases} \quad (30)$$

$$L = \int_0^1 \left(p + pu^T Ru\right) d\tau$$

TYPE B:

$$R = \begin{bmatrix} r & 0 & 0 & 0 \\ & r & 0 & 0 \\ & & 0 & 0 \\ symm. & & & 0 \end{bmatrix} \qquad (31)$$

TYPE A could be more suitable because in this way the cost function becomes large only when wheels are rotating faster than normal operation while the cost function does not become large when slower. In the way of TYPA B, the cost function becomes large when the rotor is accelerated or decelerated, which is not strictly undesirable because deceleration of the wheel is good for energy consumption. However, TYPE B is much simpler to calculate and widely used in many control theory. So in the following simulation, we used TYPE B. The parameter r is decided to 4.0.

The result was shown as in the followings. Total time required to maneuver 90 degrees was 39.30 seconds, about 10% earlier than in the case of CMG use.
Apparently, total maneuver time is smaller here than in the case in which angular momentum of each wheel is fixed and only their gimbal is controlled. Some of the reason is from the point that the angular momentum of each wheel is a little increased. However gimbal control is near the bang-bang control.

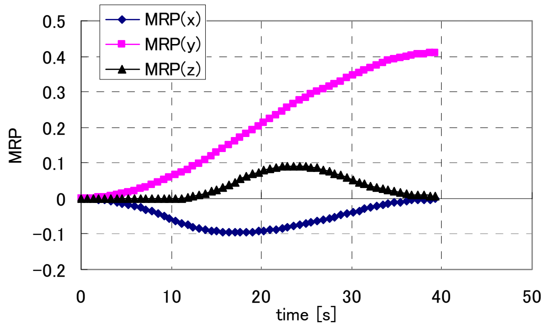

Figure 8(a): MRP

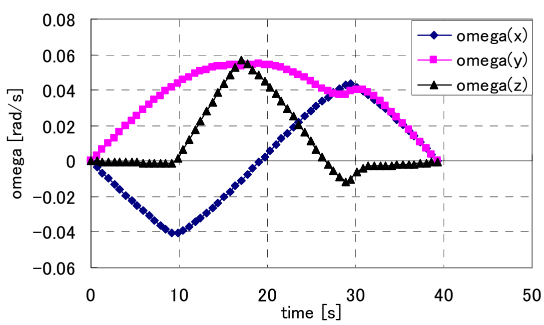

Figure 8(b): Angular velocity

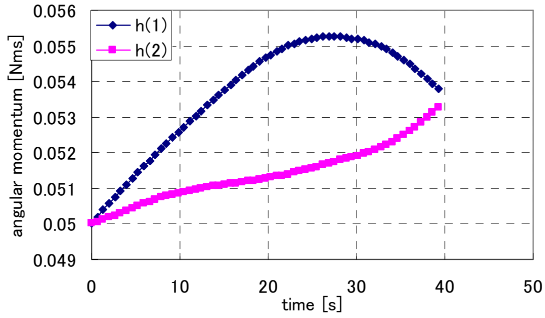

Figure 8(c): Angular momentum of each wheel

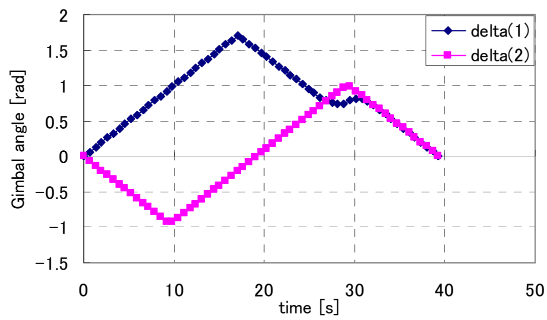

Figure 8(d): Gimbal angle

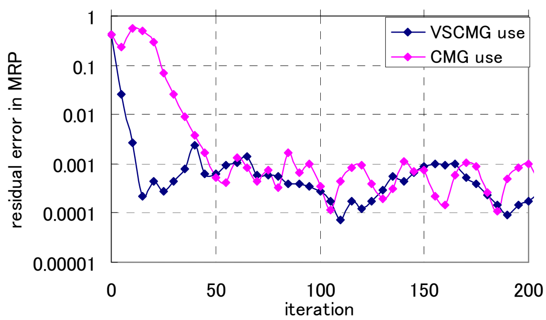

Figure 9(a): residual error versus iteration

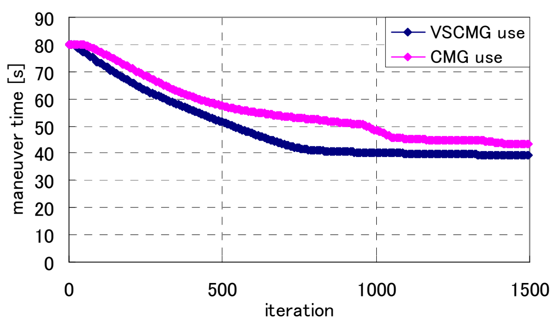

Figure 9(b): total maneuver time

Now we will compare the iteration number and time to convergence. As a result, in the VSCMG use, only 15 iterations are needed to get a first result which means a solution only satisfying the terminal condition, while in the CMG use, we need 50 iterations to get. This means that we can start maneuver after 15th calculation in the VSCMG use, 30% of time needed to calculate in the CMG use.

More than that, the final result which means a time optimal solution satisfying the terminal condition, is got in 900 iterations in the VSCMG use while 1400 are needed to get in the CMG mode. Therefore, though gimbal control is mainly used to maneuver, wheel control is also important to calculate the optimal theory.

5. MINI CMG FOR MICROSATELLITE

Finally we introduce our CMG now being developed in cooperation with Tamagawa Seiki Corporation. This CMG is designed to be installed in out future satellite TSUBAME [7] which will weigh 40kg.

The wheel is about 3cm (about 1.2 inch), rotating in 4,000 revolutions per minutes. The angular momentum of the wheel will be about 0.05 Nms, which was used in the simulations in the paper. Because the motor is synchronous motor, we can get high acceleration capability in high speed area, which can accelerate 10% upper from nominal speed in about 5 seconds. Therefore maximum acceleration of angular momentum becomes 0.001 Nm. The high acceleration torque of wheel motor is important as we saw before.

A small DC motor is used for the gimbal motor. But we are planning to replace it to the stepping motor in thought of space use in the future.

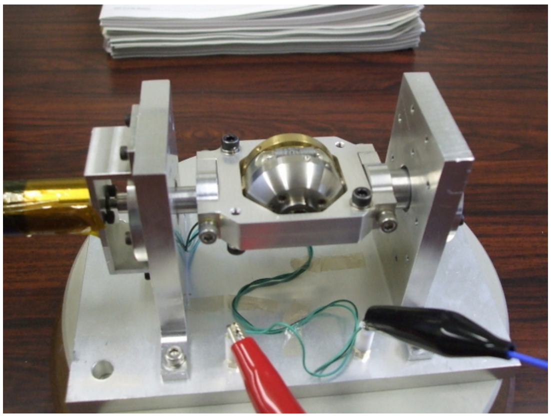

Figure 10: Mini CMG developed in Tokyo Tech

6. CONCLUSION

In this paper, we introduced a light weight cluster using 2 CMGs orthogonally. Although this configuration has 4 degrees of freedom when its rotor speed is controllable, small output torque produced by wheel acceleration or deceleration made a total performance worse.

Then we proposed an optimal control based method to use 2 CMGs array effectively. 2 of 4 output torque are used mainly in this way because it is more effective to depend more on gimbal effect torque, not depending on the small reaction wheel like torque.

Actually, only 2 torque are needed to control a spacecraft as seen in the chapter 3, we confirmed that the controllability of its wheel has great advantage since allowing its rotor speed controllable can reduce iteration to find a solution.

Parameters of CMG devices in the simulations are based on actual devices that are now being developed in Tokyo Tech and Tamagawa Seiki. This study will be applied to our next satellite project namely TSUBAME.

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