CMG Test Bed Development

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Abstract: JAXA has begun the study of a new type of earth observation satellite which can select an observation area actively using an attitude large angle maneuver. As an attitude control system, this kind of satellite requires a high-torque actuator, of which a control moment gyro (CMG) is one candidate. JAXA does not have sufficient experience related to CMG for use in satellites. Not only the hardware but also the CMG control logic is complicated. Evaluation of the CMG function using ground test equipment is necessary; therefore, we are developing a CMG Test Bed.

CMG 試験装置の開発

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概要：JAXA では宇宙からの地上の災害監視のためにボディ・ポインティングが可能な人工衛星の検討が始まっている。この衛星は高速で姿勢変更を行うことが必要なので、姿勢制御用アクチュエータとしてコントロール・モーメント・ジャイロ(CMG)に注目している。CMG は従来から広く使われてきた姿勢制御用アクチュエータであるリアクションホイールと比して数十倍のトルクを出力することができるが、トルクを発生できる方向が衛星機体座標系で固定されないため、姿勢制御アルゴリズムが複雑となる。わが国として軌道上で使用実績のない CMG を用いた人工衛星を着実に開発するために、私たちは地上試験にて CMG 単体及び CMG を組み込んだ姿勢制御系を動的に評価するための設備を開発している。

1. Introduction

Recently, JAXA has initiated the study of a new type of earth observation satellite which can select observation areas using an attitude large angle maneuver actively. Because this kind of satellite requires a high-torque attitude control system, a control moment gyro (CMG) is considered as an actuator candidate. The maximum torque produced by a CMG can be dozens of times the torque produced by a reaction wheel. Because the torque vector of CMG changes according to the gimbal angle, careful consideration must be given to singularity configurations. In the singularity configurations, the compound torque vector from CMGs is restricted to two dimensions. For that reason, a satellite loses tri-axial attitude control capability. Many researchers of CMG singularity avoidance problems have studied this problem and created various CMG steering logics. We must verify CMG control logic methods not only through numerical simulations, but also through experimentation using CMG hardware to develop satellite-mount CMGs.

Since 2005, we have studied CMG singularity avoidance logic in numerical simulations using Matlab/Simulink (The MathWorks Inc.). Then we developed CMG Software Evaluation Equipment from 2006. This equipment is now under construction; we present details of its features in this paper. Furthermore, we are developing a CMG Test Bed for use as ground test equipment to perform Dynamic Closed Loop Tests with CMG EM and Attitude and Orbit Control System (AOCS) Hardware. Details are described in Chapter 5.

2. Overview of CMG S/W Evaluation Equipment

An overview of the CMG Software Evaluation Equipment is presented in Figure 1. We developed an air bearing that comprises a ball and a saucer to demonstrate tri-axial free motion like that of a satellite in orbit. This ball floats in the saucer with air and rotates freely on three axes. An aluminum square pipe is attached over the air bearing as a balance. Four CMGs are mounted on one side of the balance (Fig. 1, right). The MPU, gyros and battery are mounted in the other side of the balance (Fig. 1, left). We call them collectively the floating subsystem.

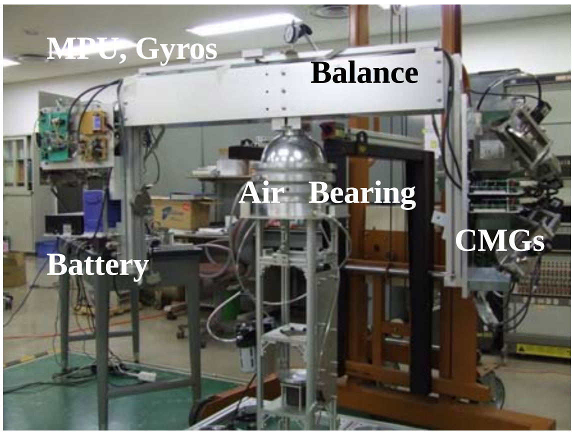

Figure 1 CMG S/W Evaluation Equipment

We designed the specification of CMG S/W Evaluation Equipment as shown in Table 1. We assembled this equipment using commercial off-the-shelf components.

Table 1 CMG Evaluation Equipment Specifications

Radius of Air Bearing	200 mm
CMG Rotor	3000 rpm
CMG Rotor Inertial	1.4×10^{-3} [kg·m^2]
Gimbal Axis Max Rate	5 [deg/s]
Floating Subsystem Mass	ca. 70 [kg]
Control Cycle	1 [Hz]
Air Bearing	No limit around vertical axis

Before evaluating the CMG S/W, we must evaluate basic characteristics of the air bearing using the following evaluation points.

1) The difference between the center of gravity (CG) of the floating subsystem and the center of rotation (CR) of the air bearing
2) The value of the air bearing friction torque

The next chapter describes their evaluation and important results.

3. Air bearing performance validation

3.1. The CG floating subsystem adjustment

The difference between the CR of the air bearing and the CG of the floating subsystem affects the tri-axial free motion of the floating subsystem. Torque produced by gravity around the CR of the air bearing affects the motion of the floating subsystem, which is called pendulum motion if the difference is sufficiently large.

We propose a CG adjustment method that includes two steps. In the first step, we move CG on the vertical axis through CR by putting some weight on the floating subsystem. This process is depicted in Figure 2. We can estimate the CG position using that level. We put the level on the balance, as shown in Figure 3.

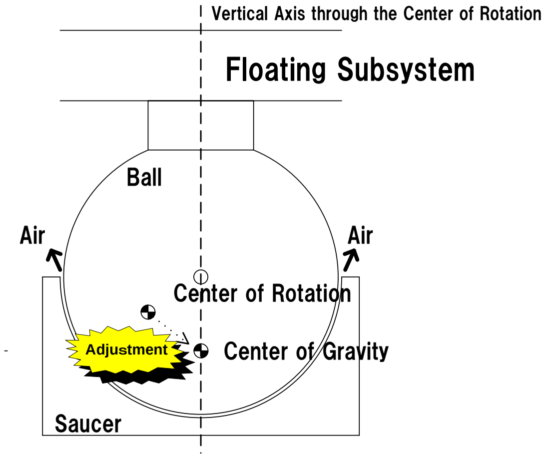

Figure 2 CG Adjustment (STEP 1)

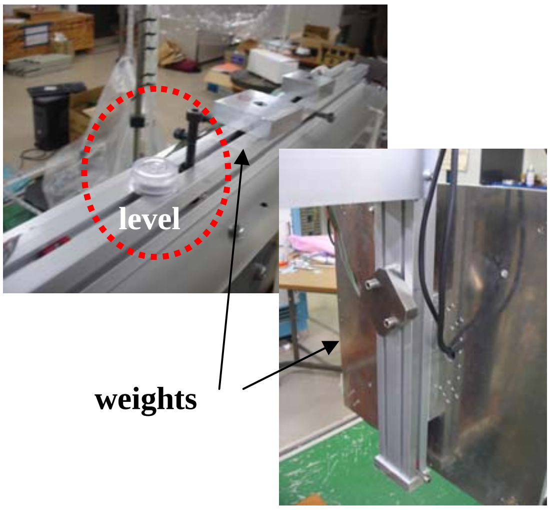

Figure 3 Level and weights at Step 2

In the second step, we move the CG close to CR by adjusting the two weights' positions as depicted in Figure 4. We can move CG along the vertical axis through CR under conditions of

$$L_l = L_r \, . \tag{1}$$

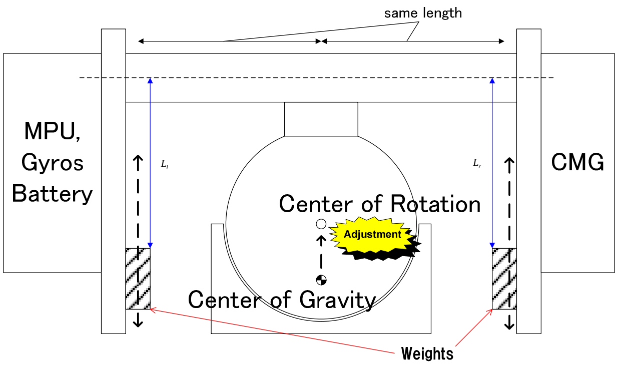

Figure 4 CG Adjustment (STEP 2)

The distance between CR and CG can be estimated using the period of the pendulum motion of the floating subsystem. We define the vertical axis and its origin as shown in Figure 5. Furthermore, we describe the CR as y_A, the CG of weights as y_m, the CG of the floating subsystem as y_{M+m} , and the CG of the floating subsystem without weights as y_M .

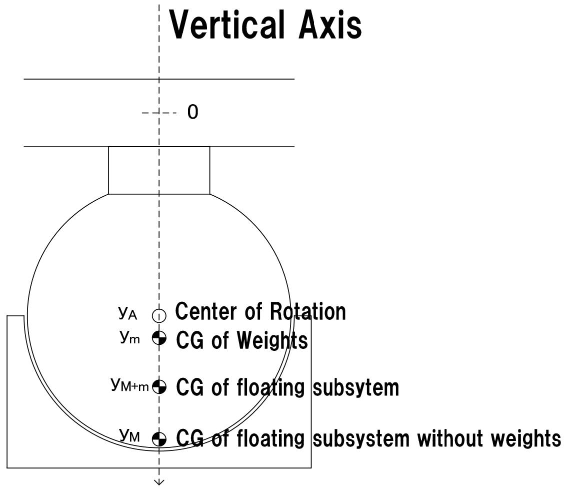

Figure 5 Definitions of CR and CG

The pendulum motion can be described as shown below.

$$I_A \ddot{\theta} = -(M+m)g(y_{M+m} - y_A)\theta \tag{2}$$

In Eq. 2, I_A is the inertial moment of the floating subsystem around CR, θ is the rotating angle of the floating subsystem, M is the mass of the floating subsystem without weights, m denotes the mass of weights, and g indicates the gravitational acceleration.

Using Eq. 2, we can solve the angular frequency of this pendulum motion ω

$$\omega^2 = \frac{(M+m)g(y_A - y_{M+m})}{I_{M+m} + (M+m)(y_A - y_{M+m})^2} \, . \tag{3}$$

In Eq. 3, I_{M+m} signifies the inertial moment of the floating subsystem around the CG of the subsystem.

In Eq. (3) I_{M+m} and y_{M+m}, (CG of the floating subsystem) are unknown values. We set the positions of weights arbitrarily as y_{m1} and y_{m2} then measure the pendulum angular frequency corresponding to each case as ω_1 and ω_2 to estimate these values.

Using y_{m1}, y_{m2}, ω_1, ω_2 and known physical parameters, we can solve y_{M0} (inertial moment of the floating subsystem without weights around origin) and y_M from Eq. 4.

$$\begin{bmatrix} I_{M0} \\ y_M \end{bmatrix} = \frac{1}{\left|\left(\omega_2^2 - \omega_1^2\right)Mg\right|} \begin{bmatrix} -Mg & Mg \\ -\omega_2^2 & \omega_1^2 \end{bmatrix} \times \begin{bmatrix} -\left(I_m + my_{m1}^2 - (M+m)y_{ac}^2\right)\omega_1^2 + mgy_{m1} - (M+m)gy_{ac} \\ -\left(I_m + my_{m2}^2 - (M+m)y_{ac}^2\right)\omega_2^2 + mgy_{m2} - (M+m)gy_{ac} \end{bmatrix} \quad (4)$$

We can obtain the CG of the floating subsystem without weights y_M. The position of the weights must be selected under the constraint of

$$y_A - y_{M+m} = 0 \quad . \qquad (5)$$

Therefore, we can place the weights as shown below

$$y_m = \frac{(M + m_y)y_A - M \cdot y_M}{m_y} \qquad (6)$$

We next present the experimental results. The first case we set y_{m1} on 0.55 [m]. The motion of the floating subsystem is shown in Figure 6

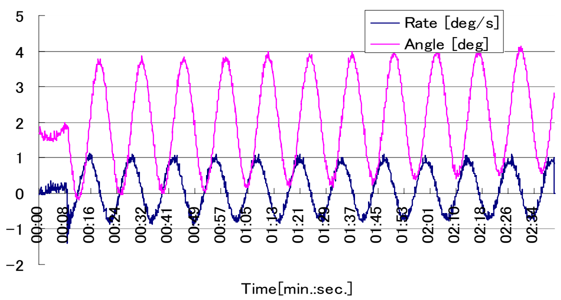

Figure 6 Pendulum motion of the floating subsystem ($y_{m1} = 0.55$ [m])

Using Figure 6, we can calculate the angular frequency ω_1 as 0.48 [rad/s]. Then, as in the second time, we set the position of weights y_{m2} on 0.31 [m]. The motion of the floating subsystem is depicted in Figure 7. It is readily apparent that the angular frequency ω_2 is about 0.1 [rad/s].

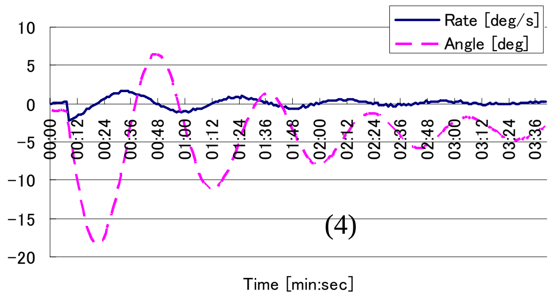

Figure 7 Pendulum motion of the floating subsystem ($y_{m1} = 0.31$ [m])

Consequently, we set the weights at 0.3 [m].

3.2. Air bearing friction torque

The air flow rate is an important parameter; it affects the friction torque between the ball and saucer. Because the rate is too small, the ball contacts with the saucer and the torque increases. On the other hand, if the air flow rate is too high, the air flow between the ball and the saucer will affect the free motion of the floating subsystem because the disturbance and the air flow excites a pneumatic hammer. In this chapter, we describe a method of setting the air flow and its results.

Figure 8 depicts the air flow system of the CMG S/W Evaluation Equipment. The air compressor maintains the air tank pressure automatically as 0.8–1 [MPa]. We set regulator **1** as 0.7 [MPa] and regulator **2** as 0.65 [MPa]. Then we attempted to evaluate the torque loss by adjusting regulator **3**.

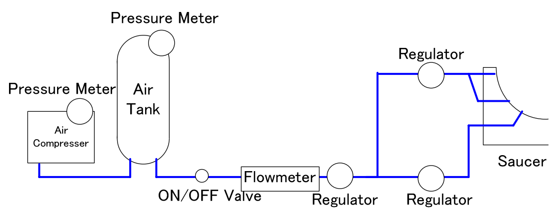

Figure 8 Air Flow System

The ball rotates on the saucer on three axes, but we evaluate the loss torque around the vertical axis as depicted in Figure 9.

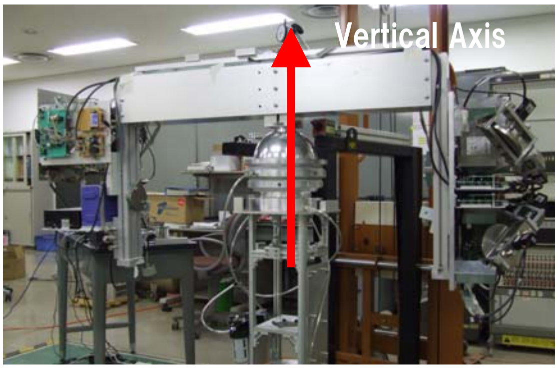

Figure 9 Torque Loss Evaluation

Figure 10 and Figure 11 show the free rotate motion of the floating subsystem in the case for which the value of Regulator **3** is 0.027 [MPa]. We applied a shock to the floating subsystem to create rotation around its vertical axis.

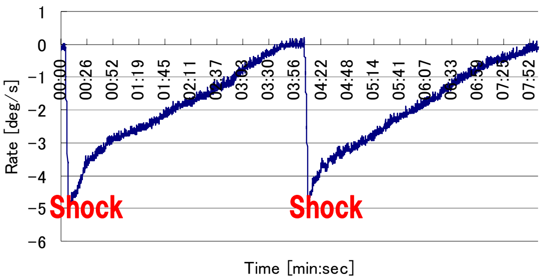

Figure 10 Rate of the floating subsystem (Regulator 3 = 0.027 [MPa]

Figure 11 Angle of the floating subsystem (Regulator 3 = 0.027 [MPa])

Figure 12 and Figure 13 show the other case in which the value of Regulator **3** is 0.027 [MPa].

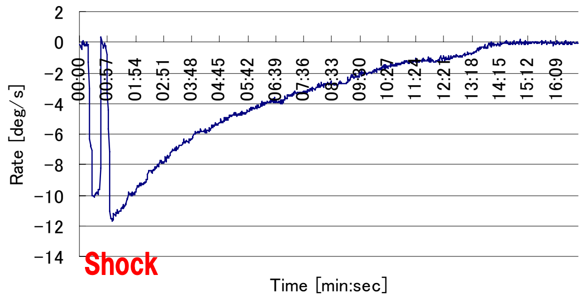

Figure 12 Rate of the floating subsystem (Regulator 3 is 0.042 MPa)

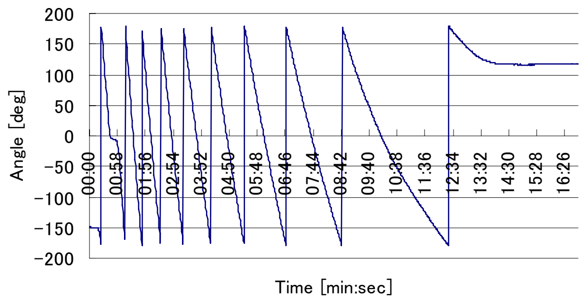

Figure 13 Angle of the floating subsystem (Regulator 3 is 0.042 MPa)

From Figure 12, we can infer that the loss torque is a quadratic curve depending on the rate. Consequently, we can estimate the loss torque as shown below.

Table 2 Loss Torque at the air bearing

Rate [deg/s]	Torque Loss [Nm]
5	0.007
4	0.005
3	0.005
2	0.002–0.003

4. Maneuver Experiment using CMG

In Chapter 3, we described the setup of CMG S/W Evaluation Equipment. Next, we present the experimental results. We select the maneuver situation that the floating subsystem rotates 60 [deg] along the vertical axis. The CMG logic that we have proposed includes Feed Forward and Feed Back. As depicted in Figure 14, we roughly rotate the floating subsystem using Feed Forward logic. Then we control the floating subsystem using Feed Back logic. For the Feed Forward, we use a Bang-Bang Control theory and steering pair with a CMG gimbal with the same angle.

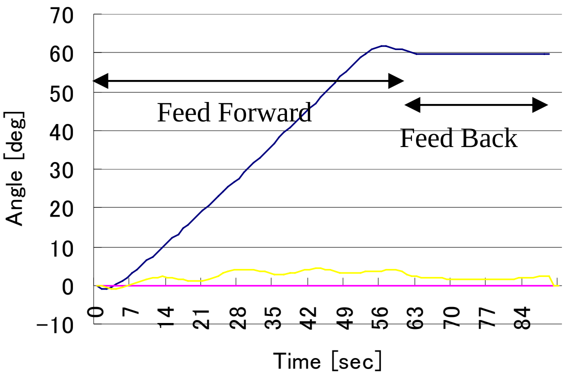

Figure 14　Experiment result (Angle)

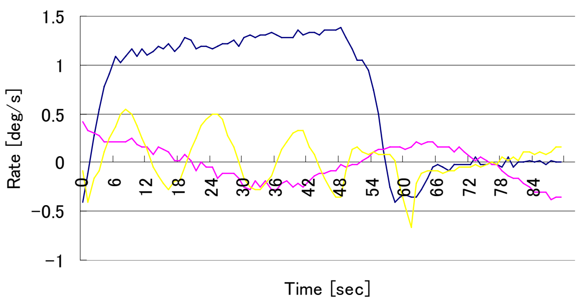

Figure 15 Experiment result (Rate)

Figure 14 and Figure 15 show that the floating subsystem was controlled as designed. We can conclude that the equipment is useful to evaluate CMG control logic.

5. The CMG Test Bed

The CMG S/W Evaluation Equipment is used to evaluate only the CMG Control logic. We have just begun to develop the CMG Test Bed to evaluate not only S/W but also the H/W. The concept is presented in Figure 16. An especially ambitious undertaking is to mount an experimental electronics device in the ball to eliminate moving limit (roll, pitch, yaw). The ball must be large. As shown in Figure 17, we produced an aluminum hemisphere with radius of 2000 [mm].

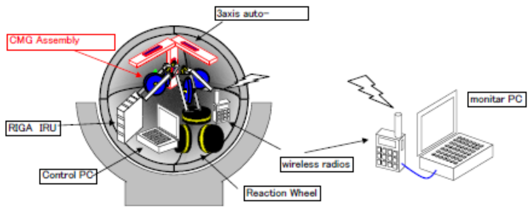

Figure 16 The CMG Test Bed Concept

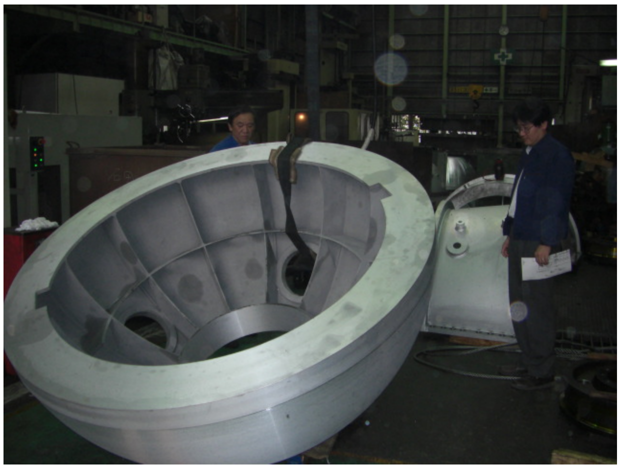

Figure 17 Aluminum hemisphere (ϕ2000)