# Mechanism of Attitude Control Device for Floating Object

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*Abstract*—**This paper describes the new mechanism on attitude control device for unfixed objects. Flywheel is a common attitude control device on spacecraft that provides precise control at an easy rate. However, rapid response is hardly achieved since low reaction torque is available applying flywheel. The purpose in this paper is to improve the response of attitude control device with flywheel. Brake equipment is mounted on the flywheel in order to raise the maximum torque. Maximum torque is raised dramatically utilizing the braking torque to the attitude control. Twin drive system is applied to this attitude control device so that the braking torque works in both rotation directions. It also made possible to charge the momentum without any interference to attitude control. The prototype of the attitude control device is constructed in order to examine the performance of the proposed mechanism. Experimental results show that its response improved applying the suggested mechanism. The two actuators, an electric DC motor and a powder brake, were compared in detail. It was shown that powder brake can apply high torque without large power supply in any frequency.**

## I. Introduction

Floating objects such as spacecrafts and suspended loads need appropriate attitude control device since they have no fixed points. A great deal of studies have been conducted especially on the attitude control of satellites.

Spin stabilization is a very simple way to keep the satellites pointed in a certain direction. Although it is a very reliable method, large amounts of electric power are not available since large solar collectors cannot be used.

Reaction wheels are devices used on many satellites to hold the satellite steady or move the satellite to the desired attitude. It is composed of a spinning flywheel and the rate of rotation can be adjusted by an electric motor to apply force and rotate the satellite. Reaction wheel is commonly used as the attitude control device for satellites because it can control the attitude precisely at an easy rate compare to thruster. Oda discussed the method to restrain the attitude alteration by controlling reaction wheel and the manipulator cooperatively[3]. Flywheel is also commonly applied as an energy storage device. Some studies show that power tracking and attitude control could be achieved simultaneously applying flywheel[4], [5]. Patel utilized regenerative torque on flywheel for attitude control.

Flywheel is so useful that it is applied to many other control systems. Yoshida studied about the rotational control and swing suppression of a crane suspended load model using inertia rotors[6].

Rapid response was hardly achieved in these researches since low reaction torque is available applying flywheel. High inertia wheel, high torque motor and high power battery are needed in order to achieve rapid response. However, compact device is badly needed for satellites to increase payload capacity or reduce launch cost. Although it is able to speed up the attitude control by applying control moment gyro (CMG)[7], [8], CMG has some disadvantages that the control scheme becomes complex and the structure becomes large.

Consequently, this paper aims at improving the response of the attitude control device with flywheel. The mechanism of the flywheel is described in Section II. The main suggestion on this paper is to mount the brake equipment on flywheel in order to improve the response of attitude control. Maximum torque is raised utilizing the braking torque to the attitude control. Powder brake is selected as the brake equipment since it gives accurate and rapid control of braking torque. Twin drive system[9] is applied to this mechanism so that the braking torque works in both rotation directions. Section III shows the prototype constructed to validate the performance of proposed mechanism. Experimental results in Section IV show the improvement on response and robustness of the attitude control. In Section V, electric DC motor and powder brake are compared in detail to see the exact ability limits of both drive units.

## II. Mechanism of Attitude Control Device

In this paper, attitude control device is considered as an independent device that can be equipped to various objects such as suspended loads, satellites, and so on as shown in Fig.1. It has ability to provide torque to the controlled objects with no fixed points. Its performance is evaluated with two indices, maximum angular momentum and maximum reaction torque. In this section, the conventional mechanism of flywheel is described at first. After that, the new mechanism of flywheel type attitude control device is suggested.

### A. Conventional Mechanism

Flywheel is a heavy wheel, usually composed of metal. It is a common attitude control device on spacecraft that provides precise control. Additionally, weight saving is available applying flywheel since it has the energy storage function too.

Base link rotates due to action-reaction effect when driving torque is applied from the motor to the wheel. The torque that occurs on the device is named reaction torque and it could be utilized for attitude control.

The mechanism of simple flywheel is shown in Fig.2.

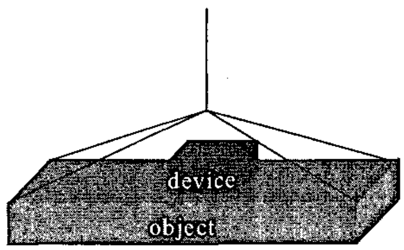
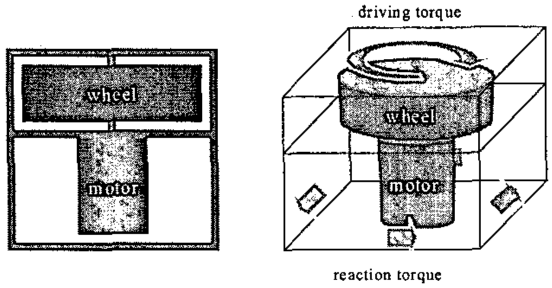



Fig.1. Attitude control device




a) mechanism of flywheel b) reaction torque generation

Fig.2. Conventional flywheel

In this research, flywheel is examined on single axis based on CoG of whole system to simplify the performance assessment. The dynamic equation of such a system is shown as follows. It is assumed that no gravity or external force affect the system.

$$\ddot{\phi} = -\frac{\tau_m}{J_o + J_d} \tag{1}$$

$$\ddot{\theta} = \frac{\tau_m}{J_w} - \ddot{\phi} \tag{2}$$

where $\phi$ is rotation angle of the object, $\theta$ is rotation angle of the flywheel based on the object, $\tau_m$ is the motor torque, $J_o$ is the object inertia, $J_d$ is the inertia of device body and $J_w$ is the flywheel inertia.

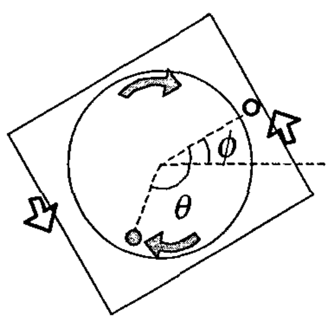



Fig.3. Rotation angle of the object and wheel

The role of the attitude control device is to control $\phi$, the rotation angle of the object. Hence, the control performance of this system is measured with maximum angular velocity and maximum angular acceleration. They are figured out as follows, assume if no disturbance occurs to the device and the object.

$$\ddot{\phi}^{max} = \frac{\tau_m^{max}}{J_o + J_d} \tag{3}$$

$$\dot{\phi}^{max} = \frac{J_w}{J_o + J_d + J_w}\dot{\theta}^{max} + \dot{\phi}_0 \tag{4}$$

where, superscript max denotes maximum value and subscript 0 denotes the initial value.

Both $\ddot{\phi}^{max}$ and $\dot{\phi}^{max}$ depend on inertia parameters and actuator performance. Actuator performance should be improved so as to obtain rapid response of attitude control since inertia parameters are strongly restricted with the demand on downsizing.

### B. Braking equipment

Although flywheel provides precise control, its attitude control response is slow since the whole control device rotate as a reaction to the wheel movement. The control response is due to $\ddot{\phi}^{max}$ and $\dot{\phi}^{max}$. As shown in Fig.4, braking equipment is mounted on the device in order to improve $\ddot{\phi}^{max}$.

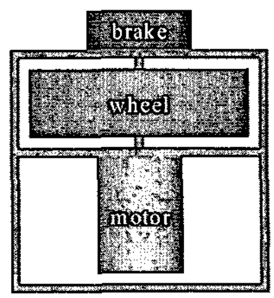



Fig.4. Flywheel with brake equipment

Compare to electric motor, braking equipment has ability to provide much larger torque. $\ddot{\phi}^{max}$ becomes much larger as shown in Eq.(4) due to the braking torque.

$$\ddot{\phi}^{max} = \frac{\tau_b^{max} + \tau_m^{max}}{J_o + J_d} \tag{5}$$

where $\tau_b$ is braking torque.

Although the maximum angular acceleration improves, there are still some problems in this system. At first, the braking torque works on only one rotational direction. Secondly, angular momentum is needed to be charged after the braking torque works. Furthermore, the attitude fluctuates when angular momentum is charged to the flywheel due to the action-reaction effect.

### C. Twin drive system

Twin drive system[10] is applied so as to solve the problems in the attitude control device with braking equipment. Conventional twin drive system is composed of two motors connected by a differential mechanism such as differential gear. Its generated output is the difference of torque between two motors. The twin drive system in this research is composed of two motors with braking equipments as shown in Fig.5.

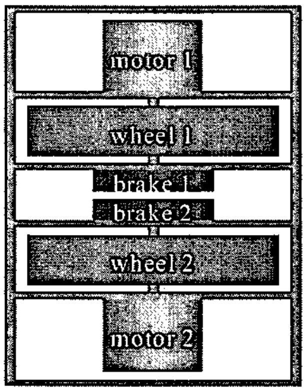



Fig.5. Twin drive system

It doesn't have a differential gear. Since the attitude control device in this paper is supposed to control unfixed objects, the device itself works as a differential mechanism. Difference of the reaction torque between two motors works as the generated output. The angular acceleration of the object is figured out as follows.

$$\ddot{\phi} = \frac{\tau_{m1} - \tau_{m2} + \tau_{b1} - \tau_{b2}}{J_o + J_d} \tag{6}$$

where subscript $m1$, $m2$, $b1$ and $b2$ denotes first motor, second motor, first brake and second brake respectively.

First flywheel and second flywheel are revolved reversely at a high velocity so that the braking torque can act on both rotative direction. Additionally, it is able for the device to charge angular momentum on flywheels without any interference on the object attitude if equivalent torque are given to both flywheels.

Uniaxial simulation is done to confirm the validity of the suggested mechanism in satellite system. The satellite is modeled as a rigid body cuboid. Table I shows the parameters of the satellite. Fig.6 shows the response values on satellite angle in simulation. At first, only motors were actuated to control the attitude as the conventional method. Secondly, brakes were activated in the phase of falling edge to contract the falling time. Finally, twin drive system was applied to contract both rising time and falling time. Bang-Bang control was applied in every simulation.

In order to have a fair comparison between conventional methods and suggested twin drive system, both motors were driven in the first simulation and both motors and brakes were driven in the second simulation.

Since frequency limits of the wheels exist, there are limits of object velocity. It should be noted that this is a common constraint on every rotating wheel mechanism. Eq.(7) denotes the velocity range that motor torque is operative. Braking torque is operative while the wheels have momentum. For this reason, wheels should be driven as fast as possible in order to extend the velocity range. Eq.(8) denotes the velocity range that braking torque is operative. Here, superscript 0 shows the initial value and superscript max shows the maximum value. $\theta_1$ and $\theta_2$ denote the angles of first flywheel and second

TABLE I
PARAMETERS ON SUGGESTED SYSTEM

| | |
|---|---|
| Total MOI(roll axis)[$kgm^2$] | 959.9 |
| Wheel MOI(roll axis)[$kgm^2$] | 0.2 |
| Total Weight[$kg$] | 740.0 |
| Maximum motor torque[$Nm$] | 1.0 |
| Maximum braking torque[$Nm$] | 8.0 |
| Maximum revolution[$RPM$] | 4000.0 |

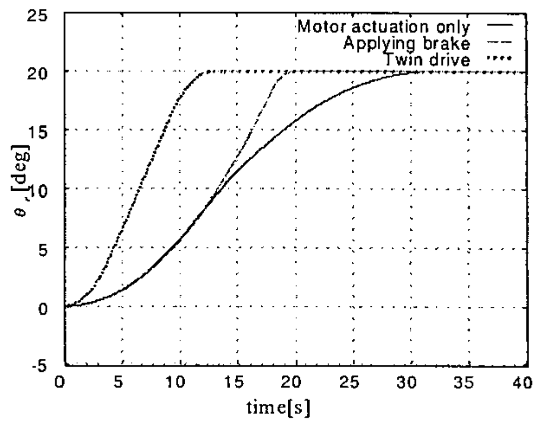



Fig.6. Response value on satellite angle(Simulation)

one respectively.

$$-J_w(\dot{\theta}_1^{max} + \dot{\theta}_2^{max}) \leq (J_o + J_d)(\dot{\phi} - \dot{\phi}^0) \leq J_w(\dot{\theta}_1^{max} + \dot{\theta}_2^{max}) \tag{7}$$

$$-J_w\dot{\theta}_1^0 \leq (J_o + J_d)(\dot{\phi} - \dot{\phi}^0) \leq J_w\dot{\theta}_2^0 \tag{8}$$

This could be extended to show the range of the disturbance impulse that the device can compensate.

$$-J_w\dot{\theta}_2^0 \leq \tau^{dis}\Delta t \leq J_w\dot{\theta}_1^0 \tag{9}$$

where $\tau^{dis}$ denotes the disturbance torque.

The wheel momentum is released when the disturbance occurs. And if the disturbance impulse becomes larger than the wheel momentum, braking torque becomes nonusable. In other words, Braking torque is available while the integral of disturbance torque is in the range of initial wheel momentum.

## III. Structure of the prototype

A prototype is constructed in order to verify the performance of the proposed mechanism. Fig.7 shows the prototype of attitude control device. It is composed of two parallel flywheels. A DC-motor and a powder brake mounted on opposite drive a flywheel together. Powder brake is selected as the brake equipment since it is able to control the braking torque accurately. Table.II shows the brief feature of each drive units.

Parameters of the prototype are shown in Table.III To realize the floating state in rotating direction, the whole device is fixed to the bearing carrier. This realizes the free rotation of whole device on the axis of flywheels rotation. This attitude control device is not

TABLE II
FEATURE OF DRIVE UNITS

| | Electric motor | Powder brake | Friction brake |
|---|---|---|---|
| Control accuracy | very high | high | low |
| Maximum torque | low | high | very high |
| Regeneration efficiency | good | — | — |
| Current/torque ratio | low | very high | high |
| Maintainability | good | good | bad |

affected by any gravity or external force except the slight friction on rotation axis. The encoder mounted on the free joint measures the attitude. In the experiment, weights are mounted symmetrically on the frame as an ideal control object.

TABLE III
PARAMETERS OF CONSTRUCTED PROTOTYPE

| | |
|---|---|
| Total weight | 8.314($kg$) |
| Wheel weight | 1.130($kg$) |
| Body MOI | 0.0206($kgm^2$) |
| Wheel MOI | 0.0030($kgm^2$) |
| Object MOI | 0.0420($kgm^2$) |
| Material | Aluminum |

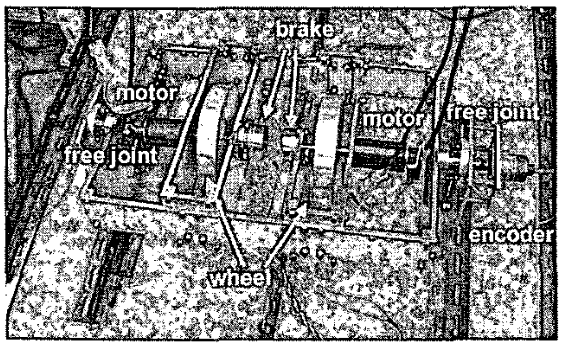



Fig.7. Overview of the prototype

## IV. Experiment

Experiments are done to see the performance of the constructed prototype. Each nominal maximum current is given as the current limit on motor and brake. Motor and brake torque limits due to the current limit were 0.232 Nm and 0.5 Nm respectively.

### A. Step response

Fig.8 shows the result of the experiment when attitude command value is given as a step function. The step command value was 0.8 rad. Bang-Bang control is applied in order to compare the response. It only took 0.60 second to converge to the desired position by the brake drive control, while it took 0.96 second by motor drive control. The convergence time applying both motor and brake drive was 0.54 second. These results show that response became faster with brake drive control compare to motor drive control. By applying both device at the same time, the response became much faster.

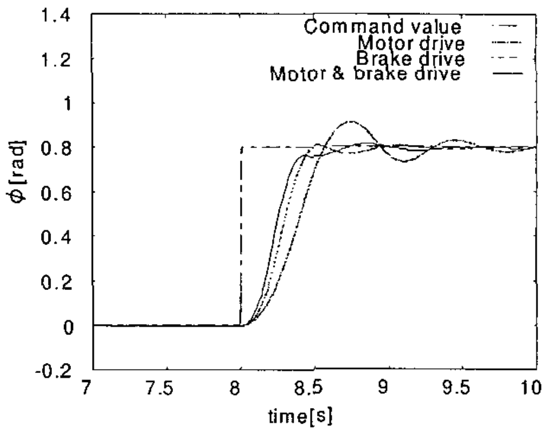



Fig.8. Step response

### B. External force application

Fig.11 and Fig.12 show the experimental result when external force was applied to the prototype. The device was controlled by PD controller so that the body of device is kept horizontal. PD controller gains were set up as same value in every experiment. $k_p$ was 50.0 and $k_v$ was 4.0. The external force was given by laying down the weight on the edge of the device as shown in Fig.9. The weight was laid down on both side of the device alternately for two times. The weight was laid down for about 1 second. At first, only motors drove the flywheels. In the latter half, braking torque was applied to the PD control in both results. Fig.11 shows the result when the weight was 172 g. The average disturbance torque should be 0.25 Nm. Since the PD controller gains were equivalent in both control, no difference was detected. In contrast, Fig.12 shows the result when the weight was 520 g. The average disturbance torque should be 0.76Nm. The device couldn't keep the command attitude since torque saturated when the brake was not activated. On the contrary, the device could keep its command attitude by applying braking torque.

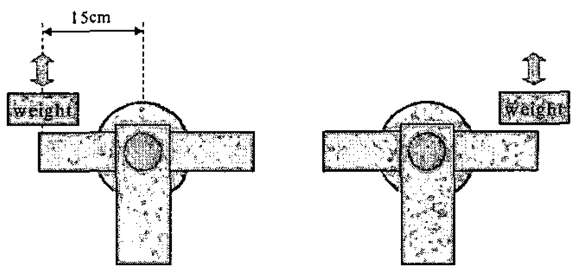



Fig.9. The way to apply external force

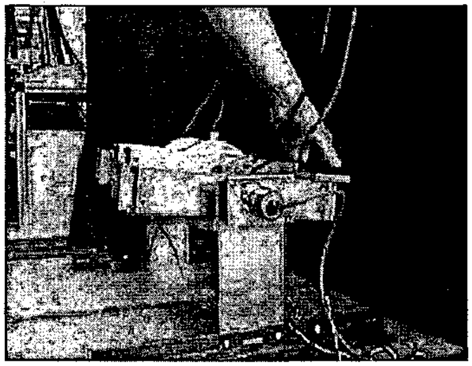


Fig.10. Picture of experiment

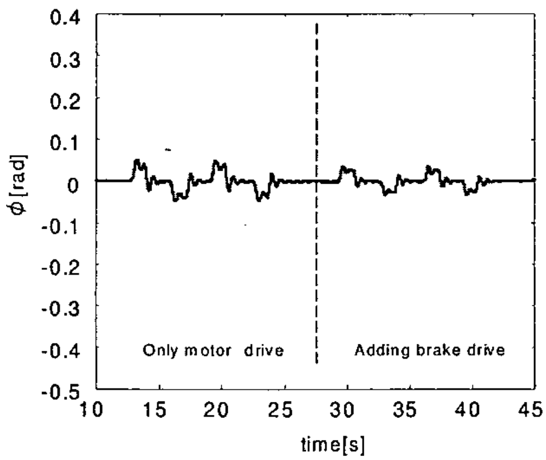



Fig.11. When 172g weight was layed down(PD control)

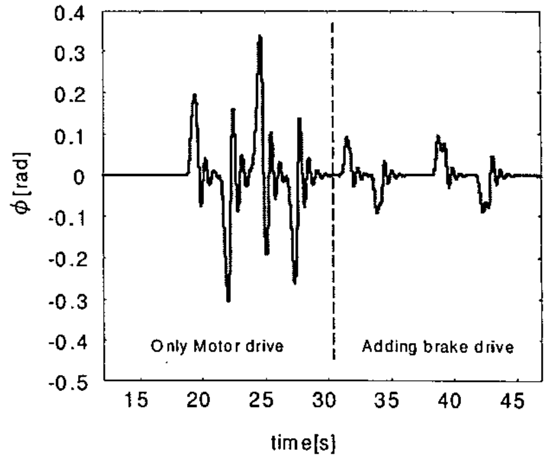



Fig.12. When 520g weight was layed down(PD control)

TABLE IV
PARAMETERS OF MOUNTED DRIVE UNITS

| | Motor | Brake |
|---|---|---|
| Model | maxon DC motor RE$\phi$40 | Ogura OPB5N |
| Weight[g] | 480 | 400 |
| Maximum continuous torque[Nm] | 0.232 | 0.50 |
| Maximum continuous current[A] | 3.64 | 0.27 |
| Maximum heat radiation[W] | 4.84 | 25 |
| Heat capacity[kJ/K] | 57.9* | 115.5* |
| Mechanical time constant[ms] | 3.8 | 17.0 |

*found value

## V. Comparison between DC motor and powder brake

In this section, electric DC motor and powder brake are compared in detail to see the exact ability limits of both drive units. We do not discuss about the mechanical strength of actuators here since it is not an essential problem to compare the power of actuators.

Table.IV shows the parameters of drive units mounted on the prototype.

The motor and the brake mounted on the prototype are about the same weight and the same cubic content. Although powder brake can work on only one rotational direction, the direction to stop the rotation, it has the advantage of high torque. It should be noted that powder brake can apply high torque with small current input. Accordingly, small power supply or small battery is needed for this control system. This brings a big advantage as a control device for a system that is required to be compact. An electric motor also applies high torque without large power supply when it acts as a regenerative brake equipment. Since regenerative torque is related to the frequency, a DC motor can apply high torque in high frequency area. From the nominal value of maxon DC motor RE$\phi$40, it is figured out that this motor can apply maximum continuous torque, 0.232 Nm, without any power supply when the frequency is higher than 638 rpm.

Maximum continuous torque of motors and brakes depends on their heat radiation. It is the value that the actuators will not be heated over than their permissible maximum temperature. However, it is able to drive the motors or brakes over the maximum continuous torque for a short while since it takes time for actuators to be heated up. The latitude of the temporal high torque drive depends on heat capacity of the actuator. If heat capacity is large, the actuator can apply higher torque for a long time since the temperature of the actuator would not rise so fast. Although the heat capacity of the powder brake is larger than that of the DC motor, DC motor would be less heated up since majority of kinetic energy will be regenerated as electric power. To investigate and compare the temporal maximum torque on motors and brakes will be our future works.

Although mechanical time constant of the brake is 17 ms, larger than that of the motor, it rarely affects slow control system like satellite maneuver.

Consequently, powder brake is useful to apply high torque in any frequency without large power supply. Compare to motors, it can apply higher torque in a long run. When the actuator is rotating in high frequency, electric DC motor also can apply high torque.

In this section, the feature of the electric DC motor and the powder brake was compared. There are many other types of brake equipment that may be useful. For example, it is able to provide much larger braking torque by friction brake although its mechanical response is slow and its control becomes inaccurate. Some other brake equipments should be examined and the adoption of actuator should depend on the intended purpose of the device.

## VI. Conclusion

A novel mechanism on attitude control device for flying object was considered in this paper. The aim in this paper was to improve the response of the attitude control device with flywheel. In order to improve the response, a mechanism that mounts braking equipment on flywheel was suggested. Twin drive system was constructed to solve the problems in the brake system. Rapid response was achieved by contracting the rise time and fall time. A prototype was constructed to validate the performance of the suggested mechanism. It was confirmed by uniaxial experiment that response of the floating object attitude control was improved. The two actuators, an electric DC motor and a powder brake, were compared in detail. It was shown that powder brake can apply high torque without large power supply in any frequency.

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