Fundamental Experiments for Attitude Control of a Low Earth Orbit Satellite Using Ion Drag

Miho Ohue, Hiroyuki Koizumi, Hitoshi Kuninaka
ISAS/JAXA
3-3-1 Yoshinodai, Sagamihara 229-8510, Japan
Michio Nishida
Sojo University
4-22-1 Ikeda, Kumamoto 860-0082, Japan
ohue@ep.isas.jaxa.jp

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Abstract

Generally, reaction wheels or thrusters are used for attitude control of a satellite. There is a potential method for the attitude control utilizing the plasma flow on the Low Earth Orbit. In the present study, experiments which simulate attitude control of a Low Earth Orbit Satellite using the ionosphere were conducted. In this experiment, a plasma flow was generated by a steady-state Hall type accelerator. However it is known that the Hall type accelerator, which is used as plasma source, produces a torque around its axis called "swirl torque". This torque would affect the attitude control in the above-mentioned experiments. First of all, we conducted the measurement of the swirl torque. Secondly, experiments using a satellite model with negative electrodes were conducted. The negative electrodes generated torque around the axis, and controlled the attitude of the satellite model by changing the applied voltage.

Generation of Swirl Torque

Swirl torque is the torque around the axis of a Hall type accelerator. Such torque was observed in the Hall type accelerator onboard the satellite1). The accelerator ionizes working gas and then accelerates the plasma by the Lorentz force due to a Hall current and an external magnetic field. At the acceleration division of the accelerator, ions are slightly reflected by the radial magnetic field even if the following conditions are satisfied:

Ion Larmor radius > Acceleration length
Electron Larmor radius << Acceleration length

This deflection generates swirl torque. The swirl torque T_s is roughly estimated by the equation:

$$T_s = R\int IBdl \qquad RIBl$$

where R is the radius of acceleration division, I the ion beam current, B the mean magnetic flux density and l the acceleration length.

Swirl Torque Measurement

Vacuum System

Swirl torque measurements were carried out in a space chamber, which is 2.8 m in length and 1.5 m in diameter. The space chamber, made of stainless steel and electrically grounded, was evacuated by two oil diffusion pumps with a pumping speed of 3,700 l/sec. The diffusion pumps were backed by an oil rotary pump with a pumping speed of 4,500 l/min and a mechanical booster pump. The pressure in the space chamber was around 4×10^{-6} torr before the working gas was supplied.

Hall Type Accelerator

The diameter of the Hall type accelerator is 30 mm, the operational conditions were typically 1.5 A in discharge current, 125 V in discharge voltage, 20 sccm in mass flow rate of the working gas, argon, and 9×10^{-5} torr in back pressure. Under these conditions, ion beam current was 225 mA2).

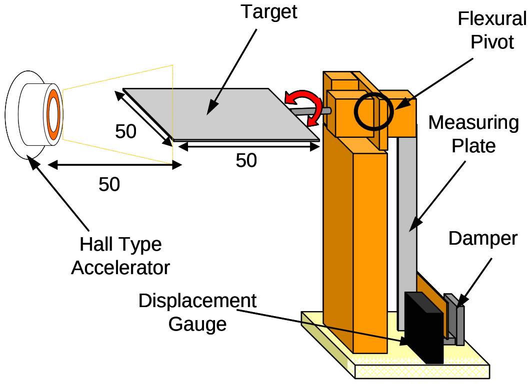

Fig.1 Torque measurement system

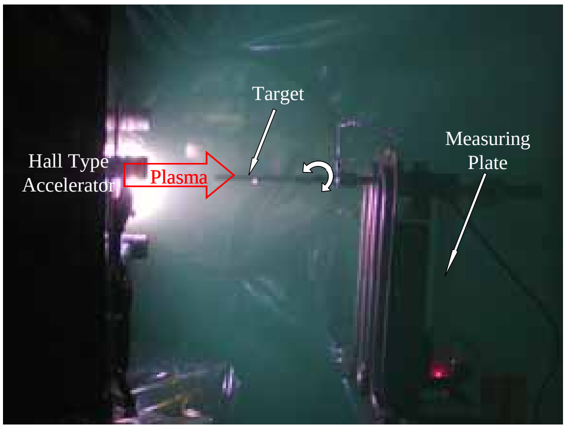

Fig.2 Operation Hall type accelerator

Torque Measurement

Figures 1 and 2 show a torque measurement system. The swirl torque was measured by a displacement of a target that was rotated by the swirl torque. The target, 0.2×50×50 mm molybdenum plate, was placed in the plasma generated by the accelerator. This target caught 2.6% of the whole swirl torque. The flexural pivot is a rotation bearing that has a crossed spring with a spring constant of 1.29×10^{-3} Nm/rad. The displacement of the target was measured on 100 mm lower side from the axis of the pivot by a displacement gauge.

In the measurements, the direction of the magnetic field was reversed from the usual one. It is useful to know the cause of rotation of the target. The reverse magnetic field changes the ion deflection. If the rotational direction of the target is changed in this condition, it means that the rotation is caused by the swirl torque. If the rotational direction is unchanged, the rotation means the fixing error of the measurement system. The fixing error is considered to be due to the inclination of the target, center gap, etc.

Experimental Results and Discussion of Swirl Torque

Figure 3 shows the typical history of displacement of the plate while the accelerator was ignited in a usual magnetic field direction, and Fig.4 shows the results in the reverse magnetic field one. The rapid changes of discharge voltage show ignition. Both of these were rotated in the same direction, so that the rotation of the target is considered to be caused by fixing error.

Figures 5 and 6 show the amount of displacement of the measuring plate. The circle and cross symbols represent the results for the usual and reverse magnetic fields, respectively. In the experiments of Figs.5 and 6, the target was rotated in the different direction, which means that the target was placed on a tilt different direction. It is seen from Fig.6 that the measuring plate placed in the usual magnetic field

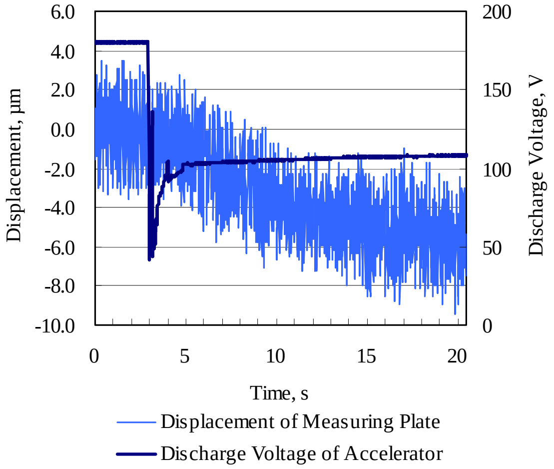

Fig.3 Typical history of displacement of the measuring plate in usual magnetic field direction

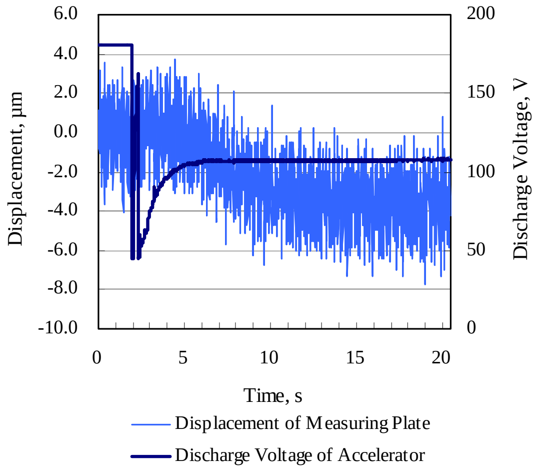

Fig.4 Typical history of displacement of the measuring plate in reverse magnetic field direction

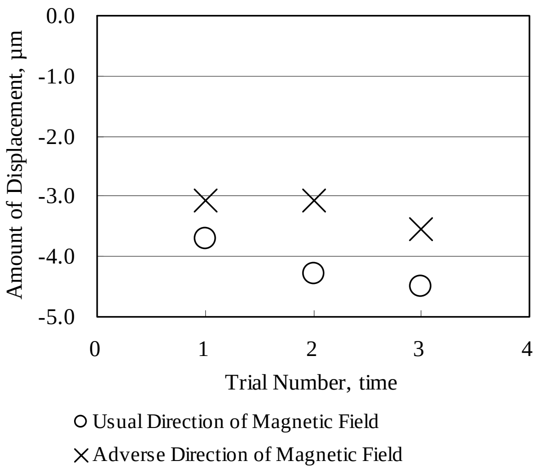

Fig.5 Difference of the displacement of the measuring plate between usual and reverse magnetic field direction

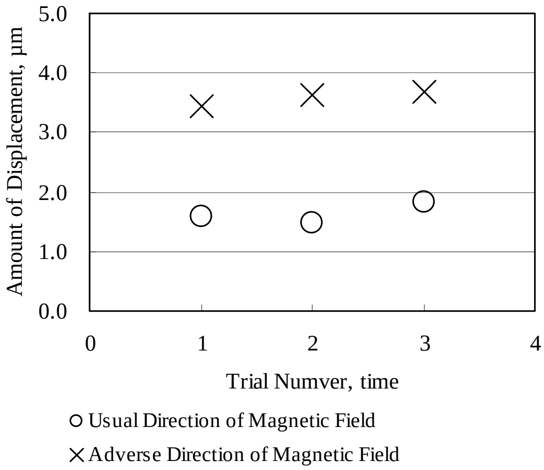

Fig.6 Difference of the displacement of the measuring plate between usual and reverse magnetic field direction

direction displaced wider about 2.0 µm than that in the reverse one, so the difference of the amount of displacement in Figs.5 and 6 is 1.0 µm. The target experienced a swirl torque of 92.0 nNm at a maximum. Thus, the Hall type accelerator generated only a swirl torque of 3.6 µNm. Hence, the swirl torque is so small that it does not affect the simulations of attitude control.

Experiments for Simulations of Attitude Control

In our past study[3)], it was demonstrated that ion force was generated by backscattering and sputtering on the negative electrode attached on the satellite surface flying in the ionosphere. The backscattering is such that primary particles are reflected from a satellite surface, whereas the sputtering means the ejection of the secondary ones. In the present study, experiments which simulate attitude control of a Low Earth Orbit Satellite using this force were conducted.

Vacuum system and Plasma Source

Satellite model experiments were conducted in the same space chamber as in the swirl torque measurement. The Hall type accelerator which measured swirl torque was also used for a plasma source. The operational conditions were typically 2 A in discharge current, 110 V in discharge voltage, 28 sccm in mass flow rate of the working gas, argon, and 1×10^{-4} torr in back pressure.

Fig.7 Satellite model experiments
Upper: near side electrode was applied the voltage
Under: far side electrode was applied the voltage

Satellite Models and Torque Measurement

The torque generated by ion force on negative electrode was measured by the same system as the swirl torque measurement system. The target was changed to a satellite model. Figure.7 shows satellite model experiments. The satellite models was a simple insulated boron-nitride plate of 1×50×50 mm with a pair or two pair of electrodes of 0.2×50×22 mm. One electrode of the pair was attached on the half of boron-nitride surface, and another electrode was attached on the diametrically opposite surface. The electrodes were made of molybdenum, tungsten, or aluminum. Differences of torque generated by ion force due to material of electrodes were measured using these electrodes.

Electrical Circuit

In the experiments using the satellite model with a pair of molybdenum or tungsten electrodes, the electrodes were applied by -250, -500, or -1000 V with reference to the ground. In the experiments with

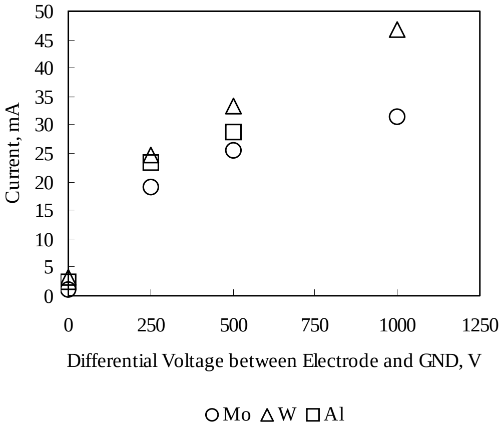

Fig.8 The inflowing ion current dependence on the material of electrodes; molybdenum, tungsten, and aluminum

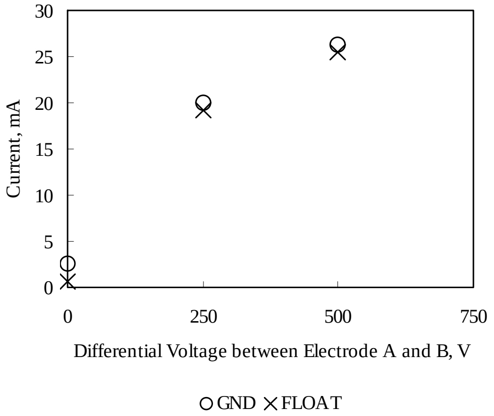

Fig.9 The inflowing ion current dependence on the electrode condition, electrically grounded or floating, for the molybdenum electrodes

a pair of aluminum electrodes, the electrodes were applied by -250 and -500 V with reference to the ground. In the experiments with two pairs of molybdenum electrodes, one pair of electrodes was applied by -250 and -500 V with reference to the ground or another pair of electrode. When the voltage is applied to one pair of electrode with reference to the ground, another pair of electrodes was electrically grounded. When the voltage reference to another pair of electrode is applied, the satellite model was electrically at a floating potential. In every case, inflowing ion currents were also measured.

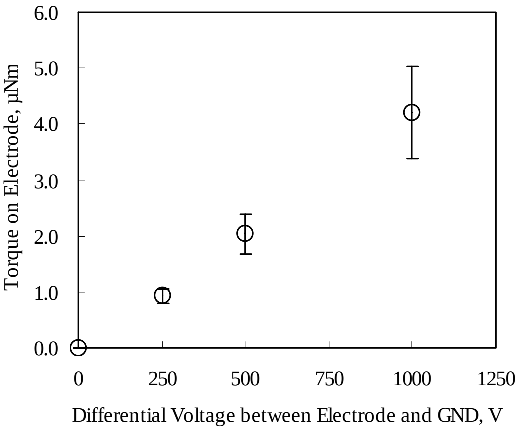

Fig.10 Torque by the ion force on the molybdenum electrodes

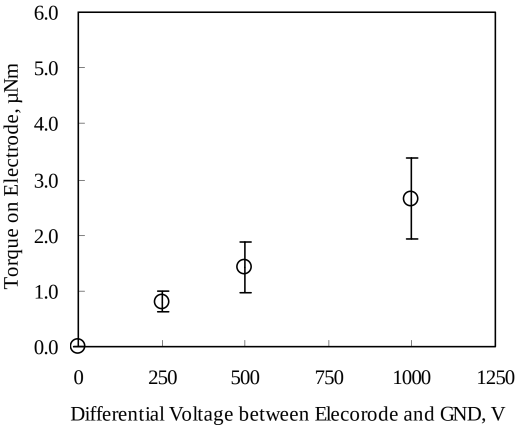

Fig.11 Torque by the ion force on the tungsten electrodes

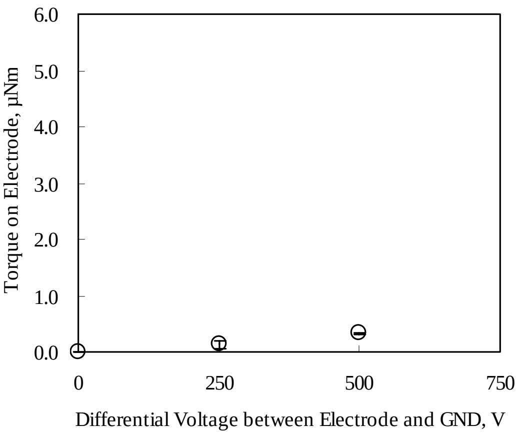

Fig.12 Torque by the ion force on the aluminum electrodes

Experimental Results and Discussion of Satellite Models

Characteristics of Ion Current

The dependence of the inflowing ion current on the material of electrodes is shown in Fig.8. The circle, triangle, and square symbols represent the results for the molybdenum, tungsten, and aluminum electrodes, respectively. The dependencies of the inflowing ion current on the electrode condition for molybdenum electrodes are shown in Fig.9. The circle and cross symbols represent the results for electrically grounded and at a floating potential, respectively. It is seen that they show almost the same values.

Characteristics of Torque by Ion Force

The torque by ion force on the different electrodes

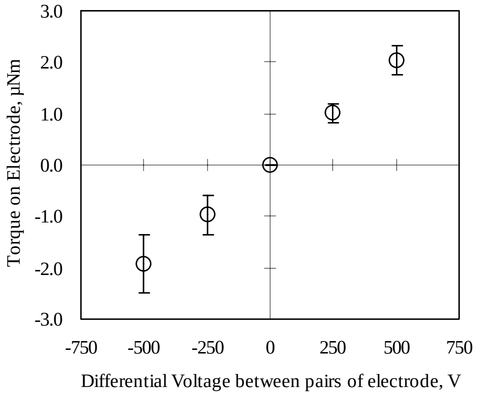

Fig.13 Torque by the ion force on the molybdenum electrodes, electrodes were electrically grounded

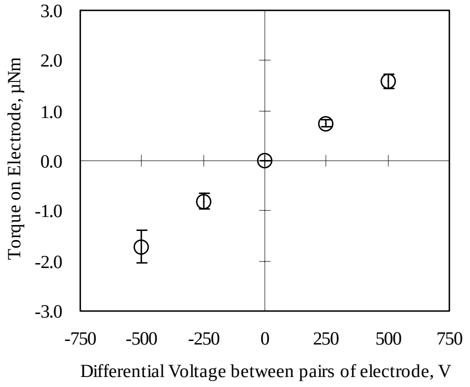

Fig. 14 Torque by the ion force on the molybdenum electrodes, electrodes were electrically floating

versus the differential voltage between electrode and ground are shown in Fig.10 to 12. Plots are mean values over several measurements and error bars are the standard deviation of the mean value. It is seen that the torque increase in a linear manner.

The dependences of the torque by ion force on the electrodes on the differential voltage between pairs of electrodes are illustrated in Fig. 13 and 14. The satellite model has two pairs of electrodes. One pair of electrode: electrode A generated torque that rotates satellite model to positive direction, another one: electrode B generated torque that rotates satellite model to negative direction. Differential voltage between pairs of electrodes means the voltage between the electrodes B A.

There is no difference of the torque due to the direction of the satellite model rotation. In the condition that the satellite model was electrically floating, the torque was generated in the same manner. Hence, it may be mentioned that the present method of attitude control by ion force can use in the ionosphere.

Fig.15 shows the torque by the ion force for different material of the electrode and the condition of the electrode. Mo;1 is the satellite model with a pair of molybdenum electrodes, Mo;2 is the satellite model with two pairs of molybdenum electrodes. There are well-defined difference of the torque among the different material of the electrode.

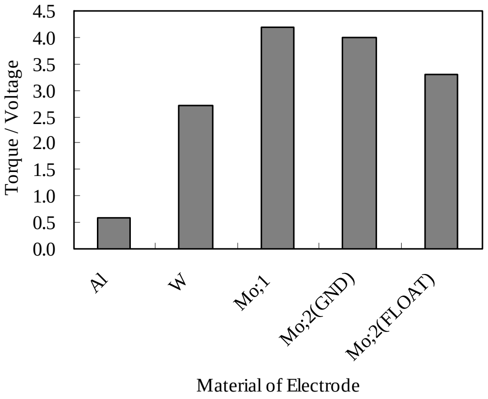

Fig.15 Degree of the torque by the ion force due to material of the electrode and condition of the electrode

Concluding Remarks

The swirl torque and the torque by the ion force were measured for the simulation of attitude control of a Low Earth Orbit Satellite. In this study, the following results were obtained.

1. The measurement of the swirl torque shows 3.6 μNm at a maximum.
2. The torque by the ion force was measured on the electrodes of molybdenum, tungsten and aluminum. Of these, molybdenum electrode generated the maximum torque.
3. A large torque by the ion force can be generated even when the electrodes are electrically floating.

References

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