Deployment of an Electrodynamic Tether from a Small Satellite

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As an effective countermeasure for suppressing space debris growth, the Aerospace Research and Development Directorate, Japan Aerospace Exploration Agency (JAXA) has been investigating an active space debris removal system that employs highly-efficient electrodynamic tether (EDT) technology as its orbital transfer system. A test flight experiment using a small satellite is planned for establishing and demonstrating the EDT technology. Precise tether dynamics during deployment phase is investigated in this study by numerical simulations in which the coiling of the tether is taken into consideration. The results of the simulation showed that the tether length becomes shorter than the full tether length when the coiling of the tether is severe. The in-plane libration angle of the tether grows larger when the spring constant of the coiling of the tether is specific value. The attitude motion of a mother satellite is less stable when the spring constant of the coiling of the tether is small because of the large tether tension.

Key Words: Electrodynamic Tether, Deployment, Numerical Simulation, Coiling

Nomenclature

\[ F \]: Braking force [N]
\[ V_{\text{deploy}} \]: Velocity of tether deployment [m/sec]

1. Introduction

The space environmental pollution by an increase of the space debris becomes a problem in recent years, and immediate measures are necessary. JAXA is now investigating a capture, repair and removal system for satellites that have ended their missions, or have malfunctioned1). A service satellite dedicated to debris removal would rendezvous with a debris object, and capture it for de-orbit into a disposal orbit. However, it is unfeasible to transfer large debris objects from a useful, crowded regions (800-1,500 km alt.) to a disposal orbit (e.g. below 650 km alt.) using a conventional chemical propulsion system, owing to the large propellant requirement. In this respect, electrodynamic tether systems are very promising, since they are able to generate a large enough thrust to conduct orbit transfer within a realistic time period without the need for much propellant – by utilizing interactions with the Earth’s magnetic field. A test flight experiment using a small satellite is planned for establishing and demonstrating the EDT technology.

In this study, the deployment of a conductive tether from a small satellite is studied by numerical simulations since the deployment is critical for the tether system. Not only large friction of the conductive tether, but also the small gravity gradient force provided by the small satellite make it difficult to deploy the tether stably. Moreover, it is considered that an influence of the coiling of the tether cannot be ignored when the tether tension is small such as tether deployment phase. Thus, the deployment dynamics of a conductive tether from a small satellite should be analyzed by numerical simulation. In this study, at first, the spring constant of the coiling of the tether is measured by the experiment. Then, the deployment dynamics of a conductive tether from a small satellite is analyzed by the numerical simulation using various range of the spring constant of the coiling of the tether.

2. Electrodynamic Tether Concept

2.1. Principle and System Configuration of EDT

The principle of EDT operation is as follows (Fig. 1.).

An electromotive force generated when a conductive tether deployed from a space system moves through the
geomagnetic field in its orbit around the Earth. If a pair of plasma contactors at either end of the tether emits and collects electrons via the ambient plasma, the electrons flow through the tether. The tether then generates a Lorentz force by the interaction between the current through the tether and the geomagnetic field. Therefore, EDT systems can provide the thrust without any propellant, and will become a high promising non-chemical thruster of next-generation

2.2. Debris Removal System

The expendable EDT is considered to be used for the debris removal system studied in JAXA. In this concept, the removal system carries several sets of small expendable EDT system and put each EDT system on each debris to dispose it into a lower orbit (Fig. 2). The debris and the expendable EDT will descend, until they reenter the atmosphere. On the other hand, the removal system will rendezvous with the next debris to do the same operation. They could also be installed on satellites for use in post-mission disposal.

The EDT system is composed of a conductive tether, a reel mechanism to deploy it, a collector and an emitter. A bare tether that is the conductive tether without non-conductive coating in order to collect electrons directly by the tether itself is considered to be as the collector in this study.

3. Elements of Small Satellite

A test flight experiment using a small satellite is planned for establishing and demonstrating the EDT technology. Hereafter, we will call the small satellite itself the “mother satellite” and an end-mass to be deployed from the mother satellite the “sub satellite”. The reel mechanism will be installed on the sub satellite and will be released from the mother satellite in orbit. The details of mother satellite, bare tether and the reel mechanism are described in this section.

3.1. Mother Satellite and Sub Satellite

The mother satellite is equipped with an emitter, and satellite bus such as communication and attitude control systems. The size and the mass of the mother satellite are assumed to be 0.5m*0.5m*0.5m and 42.5kg.

The sub satellite is equipped with the reel on which the tether is wound. The size and the mass of the sub satellite are assumed to be 0.2m*0.2m*0.2m, the mass is 7.5kg.

3.2. Bare Tether

The prototype of the bare tether was made and some evaluation tests such as tensile strength, thermo-optical characteristics, discharging characteristic and electron collection are performed. The measurement values of physical properties of the prototype bare are used as much as possible in the numerical simulations in this study.

3.3. Reel and Release Mechanism

The reel and release mechanism are composed of a fixed spool type reel, a braking reel, and a release mechanism (Fig. 3). The spool type reel is adopted because this type of reel has a simple structure and has yielded good results in the past. The braking reel is rotary, and the eddy current braking effect is used. The braking force can be written as:

\[ F = 2.0 \times V_{\text{deploy}} \quad \text{[N]} \]  \quad (1)

The last 100m of the tether is wound on the braking reel and the remainder of the tether is wound on the spool type reel. The tether wound on the spool type reel will be paid out first, and the brake is applied to the terminal part of the tether by the braking reel. These reels will be released from the mother satellite by using the helical spring with the releasing velocity of about 0.8 m/s (Fig. 4). The performance evaluation of the reel and the release mechanism is now undergoing. The measurement values of physical properties of the prototype reel and release mechanism are used as much as possible in the numerical simulation in this study. The assumed value of the reel friction between the reel and the tether during deployment phase is used because the measurement has not performed in vacuum environment at present.

4. The Coiling of the Tether

A tether becomes coiled when it is deployed from a reel especially if the tether is stiff as a conductive wire. It is
considered that an influence of this coiling of the tether (Fig. 5.) cannot be ignored when the tether tension is small such as tether deployment phase. The thrust of the EDT cannot be obtained efficiently since the tether length becomes shorter than the full tether length when the spring constant of the coiling is large. Furthermore, there is the possibility that the tether motion is unstable when the tether oscillation is occurred by the coiling of the tether. In this study, at first, the spring constant of the coiling of the tether is measured by the experiment. Then, the deployment dynamics of a conductive tether from a small satellite is analyzed by the numerical simulation using various range of the spring constant of the coiling of the tether.

5. Modeling of EDT System

A tether is modeled as a lumped mass to take into account tether flexibility. The lumped mass modeling of the tether is done by dividing the tether into point masses and the each point mass is connected by a spring and a viscous damper in between. The equation of motion of each point mass is formulated in the coordinate system in which the origin is at the center of mass of the system rotating around the Earth (Fig. 6.). The following models are used: IGRF 2000 (10*10) for the geomagnetic field, EGM 96 (10*10) for the Earth’s geo-potential field.

The attitude motion of the mother satellite and the sub satellite is also considered (Fig. 7.). The attitude motion is induced by the torques owing to the tension of the tether. The in-plane libration angle and the bending angle are defined as shown in Fig. 8.

The deployment of the tether is modeled by adding point masses to above-mentioned lumped mass model (Fig. 9.). When the distance of a satellite and a lumped mass reaches to the certain fixed value a new lumped mass is added to the model.

The coiling of the tether model is shown in Fig. 10. The coiling of the tether is modeled by a weak spring other than the above mentioned spring for modeling the tension of tether itself. The equilibrium length of the coiling of the tether is shorter than the original tether length. It is considered that the force by the original tether works when the coiling of the tether is stretched tight(1)), and force by the coiling works until the length of the coiling reaches to the nominal length(2)).
6. Requirement and Objectives of Deployment

To utilize the EDT system, it is necessary to deploy the tether at first. The following conditions are required for the tether deployment.
- Full length of the tether wound on the reel is to be deployed.
- The in-plane libration after deployment should be suppressed to some extent.
- The tether tension during deployment must be below the tensile strength of the tether.

7. Measurement of the Coiling of the Tether

Experiment to measure the spring constant of the coiling of the tether is shown in this section. The experimental set up is shown in Fig. 11. In this experiment, the oscillation frequency of the coiling of the tether with a mass attached to the end of the tether was measured using a video camera. Two types of net tether were used: one is made by aluminum, and the other is made by aluminum and carbon fiber (Fig. 12.). A result of the measurement using Al net type tether whose length is 120 cm is shown in Fig. 13. as an example. The spring constant of the coiling of the tether is so small and the attached mass should be light enough to observe the oscillation. Thus, the mass of the tether itself cannot be ignored, so the spring constants were estimated by changing the length of the tether.

Result of the measurement of the coiling of the tether is shown in Table 1. The spring constant per 50 m of the Al net type tether has an order of 1.0e-4 and that of the Al and Carbon net type tether is about 1.0e-3.

8. Result of the Numerical Simulation

Results of the numerical simulations are shown in this section. In all simulations, the following conditions are assumed; the tether length is 1,000m, the number of lumped mass is 21, time step is 0.0002sec, the orbit is 300km altitude circular, and the inclination is 98.0deg. The conditions of the spring constant of the coiling of the tether are 1.0e-4, 1.0e-3, 1.0e-2, and 1.0e-1 N/m. The ratio of the length of the coiling to the straight tether length is assumed to be 0.8, and the damping ratio of the coiling of the tether is 0.01. In reality, the ratio varies according to the spring constant and the diameter of the coiling. The ratio will be larger than 0.8 when the spring constant is small, and the ratio will be smaller than 0.8 when it is large.

Fig.14 and Fig.15 show the change in the form of the tether during deployment when the spring constants of the coiling are 1.0e-4 and 1.0e-1 N/m, respectively. The tethers are deployed stably in both cases. However, when the spring
constant of the coiling of the tether is 1.0e-1 N/m, the tether length becomes shorter than the full tether length of 1,000m.

Fig.16 shows the distance between the mother satellite and the sub satellite. In the conditions of the spring constant of 1.0e-2 and 1.0e-1 N/m, the tether length contracts because of the coiling of the tether.

Fig.17 shows the in-plane libration angle. The in-plane libration angles are small enough in all condition. However, when the spring constant of 1.0e-3, the in-plane libration angle becomes larger than the other conditions. It is found that the in-plane libration angle of the tether grows larger when the spring constant of the coiling of the tether has a specific value.

Fig.18 and Fig.19 show the tension of the coiling of the tether and the gravity gradient force. The maximum gravity gradient force is -2.5e-2 N. When the spring constants are 1.0e-2 and 1.0e-1 N/m, the tension of the coiling of the tether have an order of 1.0e-2 N. It is found that the coiling of the tether remains since the tension of the coiling is larger than the gravity gradient force.

The amplitude of the longitudinal vibration after the tether is deployed becomes large when the tension of the coiling of the tether is nearly equal to the maximum gravity gradient force 0.025N. In this analysis, the distance between two masses is 50m, and the natural length of the coiling is 40m. In such condition, the tension of the coiling of the tether is balanced with the gravity gradient force when the spring constant of 1.0e-3 ~ 1.0e-2 N/m. As a result, the longitudinal vibration of the tether becomes large.

Fig.20 shows the in-plane attitude angle of the mother satellite attitude motion without attitude control, and Fig.21 shows the moment of the attitude control when the mother satellite attitude is controlled. For the case of the small spring constant of 1.0e-4 N/m, the mother satellite attitude motion is less stable. It is found that the in-plane attitude angle is larger by the primary tension of the tether when the tension of the coiling of the tether is very small (Fig.22).
9. Conclusion

In this study, dynamics of the tether deployment from a small satellite was studied considering the coiling of the tether. As results of the analysis, the followings were found:

- In the experiments to measure the spring constant of the coiling of the tether, Al net type tether is an order of 1.0e-5 ~ 1.0e-4 N/m, and Al and Carbon net type is about 1.0e-4 N/m.
- In this analysis, the tension of the coiling of the tether is balanced with the gravity gradient force when the spring constant of 1.0e-3 ~ 1.0e-2 N/m. As a result, the longitudinal vibration of the tether becomes large.
- The tether length becomes shorter than the full tether length when the spring constant of the coiling is large.
- The in-plane libration angle of the tether can become large when the spring constant of the coiling of the tether has a specific value.
- The attitude motion of a mother satellite is less stable when the spring constant of the coiling of the tether is small because of the large tether tension.

References