Current Collection Experiment of Bare Electrodynamic Tether Using Sounding Rocket

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Three innovative tether technologies, tape tether deployment, attitude control by tether robot, and current collection by bare tether, will be verified in the Tether Experiment (T-REx) by using JAXA's sounding rocket S-520 in 2010. In the experiments, the current collection experiment by bare tether is the first experiment in space in the world, and it is expected that this experiment not only will give the new knowledge in plasma physics but also will be very important for the understanding of the charging phenomenon of spaceship and the design of the electrodynamic tether system in the future. The detail and the state of preparation of the experiment are shown in this paper.

Key Words: Current Collection, Plasma, Rocket Experiment, Tether

1. Introduction

The electrodynamic tether (EDT) system can be propelled without propellant by means of the Lorentz force generated by the interaction between the current flows through the tether and the geomagnetic field (Fig. 1). So EDT is a very useful technology in future space developments because a wide variety of applications such as orbit transfer, deorbit of space debris, station keeping, power generation for space systems, etc., is possible^{1,2)}. To establish current flow through the tether, an electrical circuit must be formed between the tether wire and ambient plasma by using contactors at the end of tether and emitting and collecting electrons. Generally, an electron gun or a hollow cathode is used as electron emitter, and a spherical metal ball or a hollow cathode is used as electron collector. But, an idea called bare tether is recently proposed³⁾ and is expected as high efficient electron collector.

A bare tether is a concept that electrons are collected by the bare conducting surface of tether itself. A bare tether can collect electrons efficiently more than its surface area according to the OML (Orbital Motion Limit) theory as described later, but, its collection theory of electrons is not verified in space at present.

In 2010, a tether rocket experiment (T-REx) including an experiment of bare tether verification in space is performed by Japanese universities and JAXA team with advisers from NASA and ESA using a S-520 type sounding rocket of JAXA. There are some experiments of EDT verification in space until now⁴⁻⁶⁾, but they are all for the combination of electron gun, hollow cathode, and metal spherical collector as contactors, and T-REx is a first experiment of bare tether verification in the world. This paper shows the outline of current collection

experiment of bare electrodynamic tether in T-REx.

Fig. 1. Conceptual figure of the operation of electrodynamic tether.

2. Outline of Tether Rocket Experiment (T-REx)

The Tether Rocket Experiment (T-REx)⁷⁾ is a rocket experiment combined a bare tape tether deployment and EDT operation experiment proposed by Tokyo Metropolitan University and Shizuoka University with a tether robot (TSR) experiment proposed by Kagawa University. The purpose of T-REx is the verification and data collection of tether basic technology and theory and three experiments;

- 1) verification of deployment of folded bare tape tether,
 - 2) verification of bare EDT operation and current collection theory of bare tether,
 - 3) verification of tether robot operation,
- are performed in T-REx.

Figure 2 shows a composition of T-REx experiment. The basic components are a mother satellite (MOT), a daughter satellite (DAU), and a tape tether between them. MOT is attached at the second stage of S-520, and its mass is 580 kg, its length is 8 m, and its diameter is 0.52 m. MOT includes a quick start hollow cathode (FAST-HC) as electron emitter, a boom as electron collector, battery and various measurement apparatus including a Langmuir probe. A tether robot (TSR) and a bare tape tether are loaded on DAU at first. A tape tether has a dimension of 300 m length and 25 μm width and is composed by 25 μm thickness PET film sandwiched between two 10 μm thickness aluminum foils, and is folded and put in a container (Fig.3). MOT and DAU are connected by this tape tether. A quick start hollow cathode (Fig.4) is distributed by Hakuto Co. and is operated by supplying xenon gas, and its electron emission ability is 5A maximum. A boom is made by PET film coated by copper and is inflated by supplying the argon gas. After inflation, the boom dimension is to be a cylindrical shape of 4 m long and 36 mm in diameter (Fig.5).

The experiments, tape tether deployment, EDT operation test, tether robot (TSR) test and OML theory verification test, are performed sequentially during about 8 minutes experimental time in a ballistic flight of S-520 of 300 km maximum altitude (Fig. 6).

Fig. 2. Composition of T-REx.

Fig. 3. Folding tape tether housing in container (demo model).

Fig. 4. Hollow cathode module.

Fig. 5. Boom module and the dimension when it is inflated.

Fig. 6. Time sequence of T-REx.

3. Detail of Current Collection Experiment

A detail of current collection experiment is shown here. There are two phases in the current collection experiment

(Fig.7);

- (1) Phase B; verification of bare EDT operation by using a hollow cathode as electron emitter and a bare tape tether as electron collector,
- (2) Phase A; verification of OML theory by using a boom as electron collector and a bare tape tether as ion collector.

In phase B, the negative terminal of the power supply is connected to a cathode device (a hollow cathode), and the positive terminal is connected to the tape tether. Electrons collected by the tape tether cross the power supply and are ejected from the hollow cathode. The current loop between EDT and the ambient plasma is formed by this procedure. It will verify the EDT operation and the effective current collection by bare tape tether in this phase. An electron collection ability of bare tape tether for applied tether voltage is also evaluated.

Fig. 7. Phase of current collection experiment.

In phase A, the negative terminal of the power supply is connected to a bare tape tether, and the positive terminal is connected to the boom. Electrons are collected by the boom and ions are collected by bare tape tether. Secondary electrons are also ejected from the bare tape tether by the impact of ions. The positive potential of boom and the negative potential of bare tether to surrounding plasma are determined by the balance of collected electron current by the boom and collected ions + ejected electrons on the bare tape tether. A current collection theory (OML theory), that is considered to govern the current collection by an electrodynamic tether, is verified in this phase over a wide range from the out of OML regime to in OML regime to collect the data of electron and ion collections under the different the ratio of the representative length of the collector to the Debye length of surrounding plasma with changing the altitude from 300 km to 100 km (change of altitude means the change of the plasma density around tether, so the Debye length changes) by using the tape tether and the boom of different dimension.

4. OML (Orbital Motion Limit) Theory

As described above, the purpose of current collection experiment in T-REx is to verify OML theory in space that is considered to govern the electron collection by tether.

In the case of spherical collector, the representative length of the collector (radius for cylinder or width for tape) is enough larger than the Debye length (or sheath thickness) of the surrounding plasma, and the current collection by collector is explained by Langmuir theory, and the (maximum) collected current only depends on electron temperature and density of the surrounding plasma. However, in the case of bare tether, the representative length of the collector is almost equivalent to or is smaller than the Debye length (or sheath thickness), and OML theory is applied for the current collection by collector, and the collected current also depends on the potential difference between the collector and the surrounding plasma in addition to plasma density. In this case, collected current value obtained will be larger than that obtained by Langmuir theory because charged particles near the collector “feel” the collector’s potential and their trajectories are bended to the direction to collector (Fig. 8).

Fig. 8. Difference of current collection between spherical collector and bare tether.

The maximum collected current by OML theory is determined by the orbital motion theory of charged particle near the collector, and is shown as follows;

$$I_{OML} = eN_p L \frac{p}{\pi} \sqrt{\frac{2e\Phi_p}{m_e}} \quad (1)$$

where, e : electrical charge, N_p : plasma density, L : probe length, p : perimeter of collector, Φ_p : voltage drop between plasma and probe, m_e : electron mass.

For a boom and a tape tether, the maximum collected electron currents^{8), 9)} are;

$$I_{OML,boom} = eN_p L_b 2R_b \sqrt{\frac{2e\Phi_p}{m_e}} \quad (2)$$

$$I_{OML,tape} = eN_p L_t 2 \frac{w_t}{\pi} \sqrt{\frac{2e\Phi_p}{m_e}} \quad (3)$$

where, L_b : boom length, R_b : boom radius, L_t : tape tether length, w_t : tape tether width

(in phase A of the experiment, m_e will be m_i (ion (oxygen) mass) for tape tether because ions will be collected at tape tether.)

The current can be collected with this maximum value I_{OML} if the condition that an equivalent radius R_{eq} ($R_{eq}=R_b$ for boom or $R_{eq}=wt/4$ for tape) is smaller than Debye length λ_D (the condition in OML regime) is satisfied. Such a case is in OML regime. For the condition that an equivalent radius R_{eq} is larger than Debye length λ_D (the condition of out of OML regime), the collected current, $I_{collect}$, will be smaller than I_{OML} , and decreases with increasing the ratio of the representative length of the collector to the Debye length (Fig. 9)^{8,9)}.

The OML theory basically can be applied for the cases without magnetic field and plasma flow, but it is not verified yet in orbit where the geomagnetic field and a plasma flow are existed. This tether rocket experiment will be the first case of the verification of OML current collection theory in orbit. The experiment of current collection in plasma in orbit with the existence of the fast relative velocity between the collector and the surrounding plasma under the geomagnetic field will not only give the new knowledge in plasma physics but also be very important for the understanding of the charging phenomenon of spaceship and the design of the tether system which is expected for the useful system of the propulsion and power generator in space in near future.

Fig. 9. Change of collected current when the ratio of equivalent radius of probe to Debye length is changed.

5. Design of Current Collection Experiment

In order to verify the OML theory in OML regime, a low plasma density is appropriate because the Debye length is large at low plasma density. On the other hand, a sufficient level of plasma density is necessary for the test of the effective operation of EDT system. To satisfy the both conditions, the sounding rocket S-520 will be launched at the dawn. This flight condition also satisfies that the tape tether dynamics are well visible. At this condition, the plasma density at the altitude of 300 km will be about 10^{11} m^{-3} , and the Debye length is about 6mm if the electron temperature T_e of 0.1 eV is assumed. The tape tether and the boom was designed that the tape is almost in OML regime and the boom is out of OML regime at this condition to verify the current collection by the probe with different dimension and regime. Of course, the data in more wide range of OML regime will be obtained

in the phase A because the experiment is performed at the altitudes from 300 km to 100 km.

The design values of the tape tether and the boom are;

Tape tether: L_t ; 300 m, w_t ; 25 mm

Boom: L_b ; 4 m (conductive part; 3m), R_b ; 18 mm

The tape tether and the boom must be insulated at the part near the mother ship because the measurement data will be affected if the sheath spreads over the mother ship. Figure 10 shows the variation of sheath thickness around the boom, r_{sh} , when the voltage, V_{total} , is applied at different altitudes. About 1 m insulation is necessary for this purpose. We insulated 1 m of the surface of boom at the mother ship side and 15 m of the surface of tape tether at the mother ship side for this purpose.

Fig. 10. Variation of sheath thickness around the boom when the voltage applied.

The applied potential between the hollow cathode and the tape tether (in phase B) or between the tape tether and the boom (in phase A) is maximum 500 V.

Figure 11 and 12 shows the expected collection current values in phase B and in phase A, respectively, if the current collection depends on OML theory.

Based on these results, the specifications of the current collection experiment are as follows;

- Power for experiment; max. 1.5 kW (500 V, 3 A) in phase B, and max. 10 W (500 V, 20 mA) in phase A
- Experimental altitudes; 300 km ~ 100 km
- Flight direction; east (the direction across the geomagnetic field lines)
- Direction of tether deployment; vertical to flight direction
- Measurement apparatus; a Langmuir probe for the measurement of plasma density and electron temperature, a plasma potential probe for the measurement of plasma potential to tape tether, a magnetometer for the geomagnetic field strength and direction, a attitude sensor for the measurement of probe direction
- current data; obtain with changing the (total) voltage, 0, 100, 200, 300, 400, 500 V in 2 seconds each in succession (in phase A and B)
- Langmuir probe data; 2~4 data set per second

Fig. 11. Estimation of collected current in phase B.

Fig. 12. Estimation of collected current in phase A.

Fig. 13. Assembly of tether module including deployer and ejector.

6. Present State of Preparation of Experiment and Schedule until Launch (as of July, 2009)

A production of tape tether module including the deployer and the ejector (Fig.13) is accomplished. The deployment and ejection tests were successfully done on the ground test and the test under a micro-gravity condition using airplane ballistic flights. The operation tests of quick start hollow cathode module and a boom module are also successfully finished.

Figures 14 and 15 show the setup of current collection

ground experiment and its results of current collection compared with the estimated collection current by OML theory. Basically, the collected currents almost correspond to the estimated values by OML theory in a high vacuum pressure. However, an abnormal increase of corrected current is shown for the high applied voltages. This is caused by the discharge, but such a discharge will not occur in the rocket experiment, because the environmental pressure is much lower than that in the ground test. The coupling test of bare tether and the hollow cathode in a plasma environment and the coupling test of total system will be done during this autumn before the rocket launch in 2010.

Fig. 14. Setup of current collection ground experiment.

Fig. 15. Result of current collection in ground experiment.

7. Summary

This paper shows an overview of the current collection experiment of bare electrodynamic tether in the Tether Rocket Experiment (T-REx) which will be performed by using JAXA's sounding rocket S-520 in 2010. The main objectives of the current collection experiment are to verify the bare electrodynamic tether operation in space and to verify the current collection theory (OML theory), that is considered to govern the current collection by a bare electrodynamic tether, over a wide range of operating condition. The fabrication of

engineering and flight models of main parts of the experiment and verification tests on the ground are progressed at present for the rocket launch in the summer of 2010. This is a first experiment of bare tether in space in the world and is expected to obtain valuable data for a bare electrodynamic tether, which has a variety of applications in space infrastructures including a propulsion system to increase/decrease orbit, an accelerator and ejector for payload, and an electric power generator. In addition, this experiment also offers the useful data for the evaluation of current collection theory concerns about the electrical charge of spacecrafts and structures in space.

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