DEVELOPMENT STATUS OF ELECTRODYNAMIC TETHERS FOR DEBRIS DE-ORBITING

Satomi KAWAMOTO(1), Yasushi OHKAWA(1), Shin-ichiro NISHIDA(1) and Shoji KITAMURA(1)

(1) Japan Aerospace Exploration Agency, 7-44-1 Jindaiji-Higashi-machi, Chofu-shi, Tokyo 182-8522, JAPAN, Email:kawamoto.satomi@jaxa.jp

ABSTRACT

The electrodynamic tether (EDT) is one of the most promising propulsion systems for de-orbiting debris in low earth orbit (LEO). End-of-mission de-orbit required by debris mitigation guidelines and orbital transfer for active debris removal require much propellant if a conventional propulsion system is used. An EDT, on the other hand, can provide deceleration without the need for propellant or high electrical power. The Japan Aerospace Exploration Agency (JAXA) is carrying out trial manufacture and testing of the key components of an EDT in parallel with a conceptual study on future debris removal systems. This paper introduces the current status of JAXA's EDT development, including plans for an EDT flight demonstration using a small satellite.

1. INTRODUCTION

Debris mitigation measures are needed so that space activities can be continued to the next generation. International space debris mitigation guidelines have recently been established and the 25-year rule (a spacecraft in LEO should have no more than a 25-year orbital lifetime) is one of the most important and effective mitigation measures for preserving the space environment. However, transfer from a higher orbit to a disposal orbit with a less than a 25-year lifetime requires much propellant if a conventional propulsion system is used. The requirement is particularly severe for spacecraft that would otherwise lack a propulsion system, because adding a propulsion system requires large design changes and greatly increases cost. As a result, the 25-year rule remains unsatisfied for many missions.

What is even worse, if the rate of increase in debris generated by on-orbit collisions overcomes the rate of debris reduction through re-entry due to atmospheric drag, the amount of debris will increase as the result of mutual collisions between debris objects even if no further objects are launched. Some evolutionary models including LEODEEM (Low Earth Orbital Debris Environment Evolutionary Model) developed at Kyushu Univ. in collaboration with JAXA, predict that this is already occurring in some crowded regions such as in the 900–1000km altitude band, and the effect of mutual collisions will be apparent within a few decades [1][2]. In such a case, active removal of existing debris is the only sure method to solve the debris problem. Here again, orbital transfer is the key technology for debris removal. To realize a practical debris removal system, it will be very important not only to overcome technological challenges but also to keep costs reasonable, and so a large propellant requirement for debris de-orbit is undesirable. The Japan Aerospace Exploration Agency (JAXA) has therefore been studying the electrodynamic tether (EDT) as a highly efficient propulsion system [3].

2. ELECTRODYNAMIC TETHER (EDT)

2.1. Principle of EDT

The principle of EDT thrust is as follows (Fig. 1). An electromotive force is set up within a conductive tether deployed from a space system as it moves through the geomagnetic field in its orbit round the Earth. If a pair of plasma contactors at either end of the tether emits and collects electrons, the circuit is closed via the ambient plasma and an electric current flows through the tether. The tether then generates a Lorentz force via interaction between the current and the geomagnetic field which acts opposite to the direction of flight. An EDT can thus provide deceleration without the need for propellant or high electrical power, and shows promise as a high efficiency propulsion system for debris de-orbit. An EDT is also suitable because its thrust is so small that it

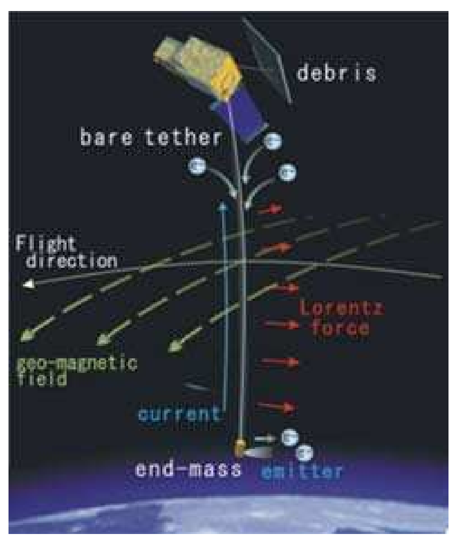

Figure 1 The principle of EDT

Proc. '5th European Conference on Space Debris', Darmstadt, Germany 30 March – 2 April 2009, (ESA SP-672, July 2009)

does not have to be as firmly affixed as a conventional propulsion system, so attaching an EDT to a debris object by a robot arm will be less challenging. The trade-off between different propulsion systems is shown in Tab. 1. The EDT is considered to be the most promising propulsion system for de-orbiting large debris objects from LEO, which is will be most effective for space environment preservation.

The main components of an EDT are the tether, an electron collector and an emitter, a reel and a deployment mechanism. For the electron emitter, an electron gun, a hollow cathode, and filed emitter cathodes (FEC) are proposed, while a spherical electron collector, a hollow cathode and a bare tether are proposed for the electron collector. A bare tether (a conductive wire without insulation) collects electrons directly from the ambient plasma when the tether has a positive electrical potential by induced electromotive force, and a combination of FEC and bare tether could realize the smallest and lightest EDT system.

A single line tether would be susceptible to being severed by collisions with even very small debris objects and micrometeoroids, and could be severed within a short period of time in crowded orbits [4], so a net tether is proposed. This is expected to have a longer lifetime because its multiple cords give it redundancy to survive debris impacts.

Table 1 Trade-off between propulsion systems for debris removal.

Methods	merits	demerits
Chemical thruster	- established technology	- low Isp - difficult to fix to debris object
Ion thruster	- high Isp	- high electrical power requirement
Solid rocket motor	- established technology - compact	- generates large amounts of slag/dust debris - difficult to fix to debris object
Air bag	- simple - no electrical power	- huge size required for heavy debris - debris impact risk
EDT	- high Isp - easy to attach to debris object	- debris impact risk (sustainable by net tether)

2.2. The roadmap

Our roadmap for developing debris mitigation technologies with an EDT is shown in Fig.2. Our final goal is to develop a cost-effective debris removal system with international cooperation to preserve the space environment. Although the debris removal system requires various advanced technologies such as autonomous rendezvous and capture of non-cooperative, uncontrolled objects, we understand that the development of a high efficiency propulsion system is the most fundamental and critical requirement. Therefore, the first step towards realization of the debris removal system is to establish EDT technology, and JAXA is planning an EDT flight experiment using a small satellite in the near future. We plan to use a tether length of about 1–2 km and a tether current of less than 0.1 A. If EDT thrust generation can be confirmed and thrust characteristics obtained by this experiment, we will be able to use these results to design and offer a de-orbit device for small satellites; that is, a small EDT that can be installed on new small satellites as an end-of-life de-orbit device.

The next step of our roadmap will be to develop technologies for de-orbiting large spacecraft such as launch vehicle upper stages and large satellites. De-orbiting a large space system conventionally requires much propellant (sometimes more than 100 kg), even if it has a propulsion system. It is also difficult for rocket upper stages to carry out multiple burns, since this requires a longer engine life, more battery power and contact with a ground control station. Our aim is therefore to develop a higher thrust EDT for de-orbiting large spacecraft. The EDT will require a tether length of 5-10 km and several Ampères of current, but we aim to develop it as a small, lightweight (about 30-50 kg) package.

For de-orbiting existing large debris objects, rendezvous with non-co-operative targets needs to be demonstrated. At JAXA, we are studying navigation using GPS and star tracker (where sunlight reflected from a target object is measured and the directional data obtained are used to estimate the target's position) to realize debris removal at low cost.

After EDT and non-cooperative rendezvous technologies are acquired, a complete debris removal system will be studied. First to be developed will be a "Micro Remover", a piggyback satellite launched alongside new satellites that will rendezvous with debris in crowded low altitude regions for disposal[5]. This small robotic satellite will be equipped with an

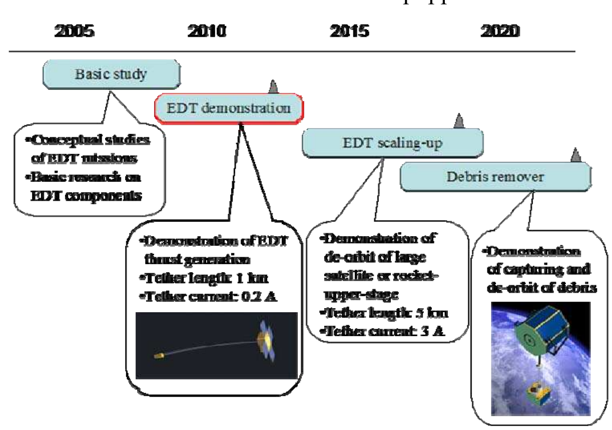

Figure 2 Roadmap of debris mitigation technology with EDT.

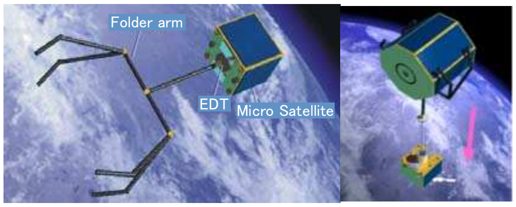

Figure 3 "Micro Remover", a piggyback satellite to dispose of a single debris object.

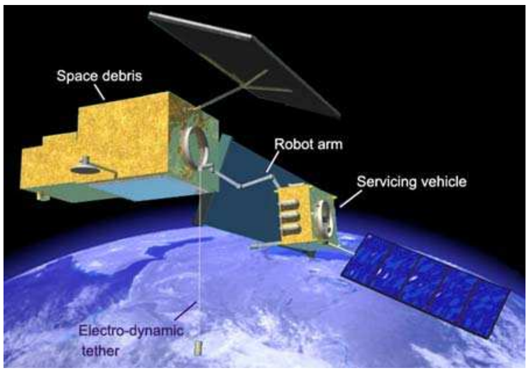

Figure 4 A dedicated debris removal satellite, which carries several EDT packages. and This can rendezvous with several debris objects in crowded regions to attach an EDT package for de-orbit.

extending robot arm for debris capture and a single EDT package for de-orbit. The micro remover itself will become an end-mass of the tether, and will re-enter along with the debris (Fig. 3). Finally, a dedicated debris removal satellite that can remove several debris objects from crowded regions will be developed with international cooperation. This satellite will carry several EDT packages and attach a package to each debris object (Fig. 4)

To achieve the greatest effect of debris removal, debris in crowded regions such as Sun-Synchronous Orbit (SSO), 900–1000 km altitude and 83 degree inclination, 1400–1500 km altitude and 74 degree, 83degree, and 52 degree inclinations, can be targets [6]. It is considered that removal from these crowded regions will be effective in preventing collisional cascading. In these regions, several debris objects can be found within an inclination difference of less than one degree and a RAAN (Right Ascension of Ascending Node) difference of less than a few degrees. For rendezvous with an object in such regions, RAAN can be coincided using a smaller ΔV by utilizing the nodal regression of the J2 effect by changing altitude and waiting for a while. Rendezvous with a debris object will therefore require about 150 m/s of ΔV, that is, about 8% of the satellite's mass in fuel if a cost-effective mono-propellant thruster is used. This makes it feasible for a small satellite to rendezvous with debris, or a dedicated debris removal satellite to rendezvous with several debris objects in crowded regions. Other technologies required for debris removal such as motion estimation of the non-cooperative object and capturing by a robot arm are also being studied [7][8].

3. NUMERICAL SIMULATION OF EDT

To study the de-orbit capability of an EDT, a numerical simulation model that takes into account changes in environmental factors such as plasma density and geo-magnetic field is being developed. Precise simulations are being conducted for some aspects of mission analysis, such as determining available electric current and Lorentz force, and verifying tether deployment dynamics [9].

3.1. Model

A tether is modeled as a lumped mass to take into account its flexibility by dividing it into point masses connected by segments consisting of a spring and viscous damper (Fig. 5). To model electron collection by a bare tether, the two-dimensional Orbital Motion Limit (OML) theory is used. The following models are used: IGRF 2000 (International Geomagnetic Reference Field) (10 *10) for the geomagnetic field, IRI2001 (International Reference Ionosphere) for the plasma density, NRLMSISE-00 (NRL Mass Spectrometer, Incoherent Scatter Radar Extended Model) for atmospheric density, and EGM96 (Earth Gravitational Model) (10 *10) for the Earth's geo-potential field. Orbital perturbations caused by the Lorentz force, atmospheric drag and geo-potential are taken into account using Gauss's variational equations of motion. Thermal calculations are carried out by considering the direct solar flux, albedo, the Earth's infrared emission, Joule heat, electron collection heat, and aerodynamic heat. The measured parameters of a fabricated prototype tether are used in the numerical simulations.

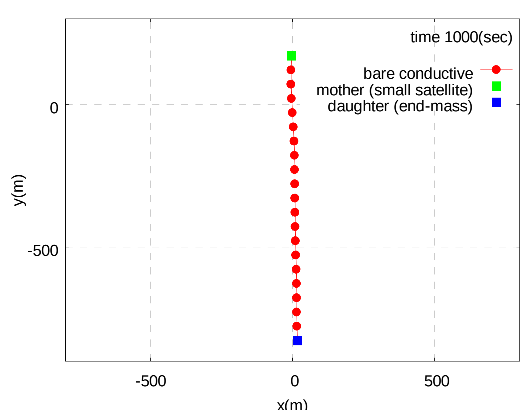

Figure 5 The tether as a lumped mass model

3.2. Results

Results of the numerical simulations for some debris de-orbit cases are shown below. The available current varies depending on the plasma density, geomagnetic field and so on. Fig. 6 shows the average Lorentz force on a 10 km EDT in various orbits with different altitudes and inclinations. The Lorentz force becomes smaller at high altitudes and high inclinations, but is still great enough to transfer debris from SSO.

Figs. 7 and 8 show the altitude change of an object with a 10 km EDT attached. To reduce calculation time in the simulations, the average thrusts are computed for

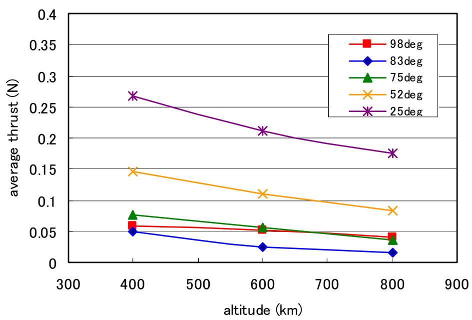

Figure 6 Average thrust of a 10 km EDT

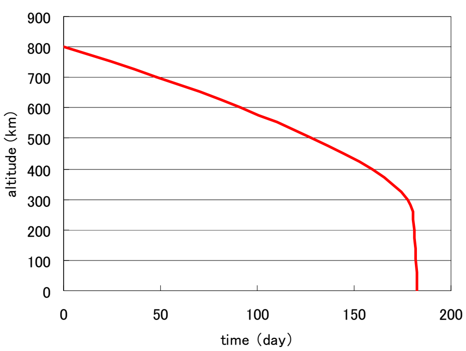

Figure 7 Change in altitude of a 3400kg object in SSO with a 10km EDT.

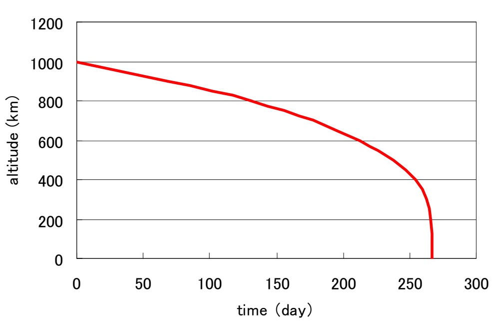

Figure 8 Change in altitude of a 1400kg object in a 1000 km, 83 deg inclination orbit with a 10 km EDT.

each altitude as shown in Fig. 7 and times required to re-enter the atmosphere are calculated. In Fig. 7 the target is a large Earth observation satellite in SSO with a mass of 3400 kg, and in Fig. 8 the target is a 1400 kg rocket remnant, of which there are many in 900–1000 km altitude, 83 degree inclination orbits. These figures show that using a 10 km EDT the debris will reenter within one year. Many other debris objects at crowded altitudes will re-enter within one year unless they are very heavy.

As mentioned above, the tether could be severed by small debris and meteoroids [4] but lifetime evaluation using NASA's ORDEM 2000 (Orbital Debris Environment. Model) debris flux model estimates that the de-orbit time will be short enough for its survival if the tether has debris-tolerant structure such as a net composition. In fact, TiPS (Tether Physics and Survivability Satellite), a 4 km-long tether launched in 1996, orbited for about 10 years at 1000 km without being severed, although there were frequent close approaches by debris objects to within a few kilometers. This demonstrated that a tether several kilometers in length can have a good chance of surviving for several years. It is also noted that the numerical simulations in this study used OML theory, which can simulate electrons collection by a single tether in a static plasma. However, Particle in Cell (PIC) simulations to calculate the motion of electrons and ions show that more current can be obtained by a multi-line tether in a flowing plasma [11]. On-orbit experiments will be necessary to estimate the real EDT thrust.

When the torque generated by EDT thrust is large compared with the gravity gradient torque, the tether may start tumbling and tether current control (by switching it on and off) is needed to prevent this. The method to estimation tether inclination angle using Kalman filter and the current control is also studied[12].

4. DEMONSTRATION USING A SMALL SATELLITE

Up to the present, many on-orbit experiments of tether systems including electrodynamic tethers have been conducted, but thrust generation by an EDT has yet to be demonstrated. A flight experiment using a small satellite is therefore planned as low cost means to prove the technology (Fig. 9). We plan to use a satellite with a total mass of around 50 kg. The objective of this demonstration is to confirm the generation of EDT thrust and to obtain measurements of EDT characteristics such as electron emission and collection in the space plasma. The orbit for the experiment has not yet been decided; however, it is most likely to be a sun-synchronous orbit with an altitude of approximately 700 km.

After the small satellite is deployed from its launcher's upper stage, it will release a daughter satellite (an end-mass with an on-board reeled tether) using a springloaded mechanism while simultaneously deploying the tether, since the other end of the tether is connected to the mother satellite. Tab. 2 shows target specifications of the on-orbit experiment and Fig. 10 shows the arrangement of the principal system elements. Tab. 3 shows the mass and power requirements of components. At present the electron emission capability of the FEC is not large and limits the maximum tether current. Fig. 11 shows time histories of the Lorentz force when the available tether current is not limited, and when it is limited to 40 mA. Fig. 12 shows the time histories of the orbit semi-major axis for these cases. In the case of a limited current, the average Lorentz force will only be about two to three times greater than atmospheric drag and it is not clear whether the effect of Lorentz force will be distinguishable from that of atmospheric drag. However, the orbital inclination time history can provide evidence of thrust generation; as Fig. 13 shows, the orbital inclination angle will be almost constant without EDT thrust, but will change if an EDT thrust is generated.

5. DEVELOPMENT STATUS OF EDT COMPONENTS

The EDT system for the flight demonstration is being designed and tested. The key components—tether, FEC and reel mechanism—are introduced below.

5.1. Bare tether

A net bare tether has been developed and tested. This is constructed using aluminum to give conductivity with a low mass and impedance, and carbon fibers to reinforce the tethers. A net tether is expected to have a longer lifetime because the gaps between the cords that results when one cord of the net is longer than the others plays an important role in surviving debris impacts (Fig. 14). A net tether also has a greater electron collection capability than a single cord tether.
Tests to measure the tether's properties such as tensile strength, tensile modulus under temperature extremes, damping ratio, thermal expansion, thermo-optical characteristics, electric discharge [10] and electron collection have been conducted.

5.2. FEC

An FEC is an efficient electron source that uses the phenomenon of field emission of electrons from the surface of a solid material. Electric fields concentrate at the sharp tips of emitters on the surface and when a voltage is applied between a gate and the emitters, electrons are emitted by the tunnel effect. In our study, a carbon nanotube (CNT) FEC is adopted because it is simple and durable in a low vacuum environment.

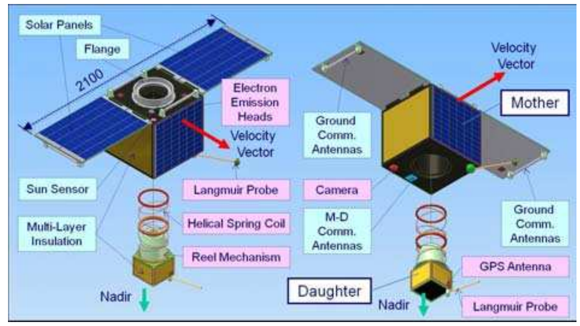

Figure 9 Conceptual image of EDT flight demonstration.

Table 2 Target specifications of EDT demonstration flight.

EDT system mass	14 kg
Required electric power	14 W
Maximum thrust	0.4 mN
Maximum tether current	0.04 A
Tether length	1 km
Electron collector	Bare tether
Electron emitter	Field emission cathode
Orbit (TBD)	700-km SSO

Table 3 Mass and power requirement breakdowns of EDT components (Estimate based on current development status).

Component	Mass, kg	Power, W
Bare tether	2	0
Reel mechanism	1	0
Release mechanism	1	0
Field emission cathode	1.5	8
Plasma probe	2	1
Magnetic probe	0.5	0.2
GPS receiver	0.6	1.5
CCD camera	0.2	1.4
Mother-daughter com. device	0.2	0.5
Battery for daughter satellite	0.5	0
Others(structure, harness, etc)	3	1
Total	13.4	13.1

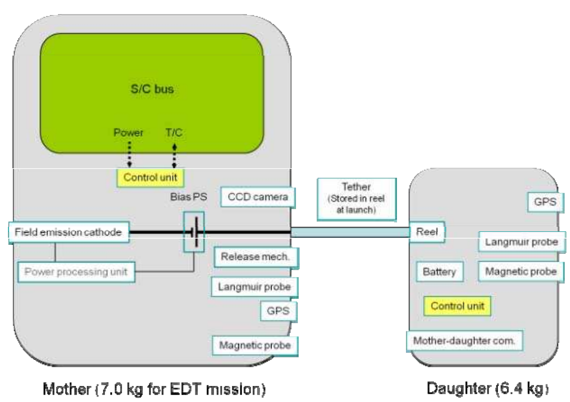

Figure 10 System configuration of EDT system for demonstration flight.

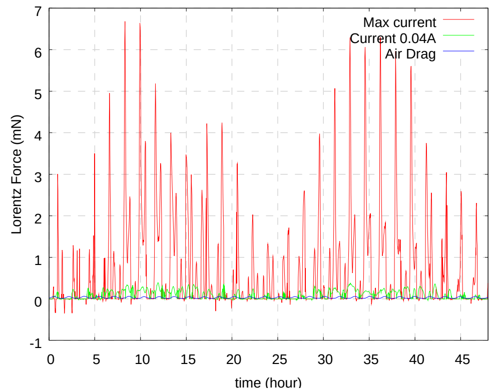

Figure 11 Time history of Lorentz force

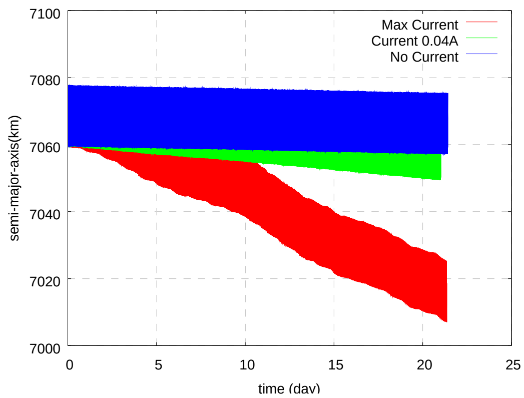

Figure 12 Time history of semi-major axis with and without EDT thrust

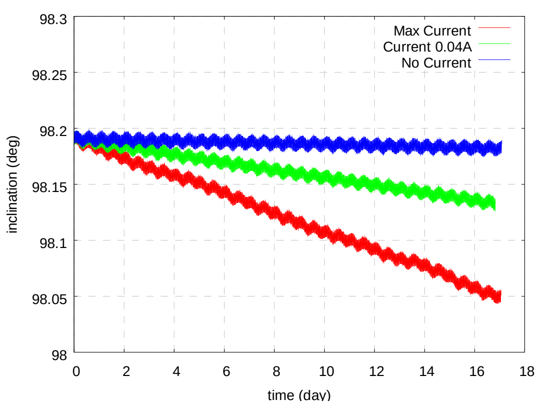

Figure 13 Time history of orbital inclination with EDT thrust

Fig. 15 shows a laboratory test model. In this device, a 2.2 mm-diameter CNT sheet is used as a cathode, and a mask-and-gate structure is adopted to obtain high electron-extraction efficiency. Typical current-voltage characteristics of the CNT-FEC are shown in Fig. 16 The figure shows an extraction current up to 0.3 mA (7 mA/cm^2) is obtained at an extraction voltage of approximately 660 V with negligible drain current to the gate. The FEC's endurance is also being studied

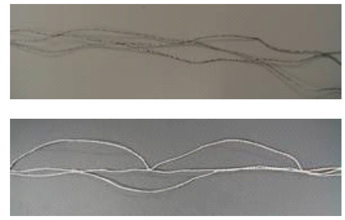

Figure 14 Net tethers. A net tether with different lengths of cord (bottom) has spaces between the cords.

because the interaction between CNTs and atomic oxygen is not sufficiently well understood (Fig. 17). In the flight experiment, an FEC array with an emission current of 40 mA will be used by clustering FECs that each emit 0.5 mA.

5.3. Reel and Release mechanism

A simple reel to store the tether and a deployment mechanism which utilizes a double helical spring for stable deployment are being developed. The reel mechanism is composed of a fixed spool-type reel and a braking reel (Fig. 18). A spool-type reel is adopted because it has a simple structure and has yielded good results in the past. The first 900 m of the tether is wound

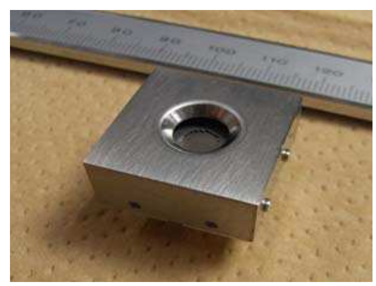

Figure 15 A laboratory model of carbon nanotube cathode.

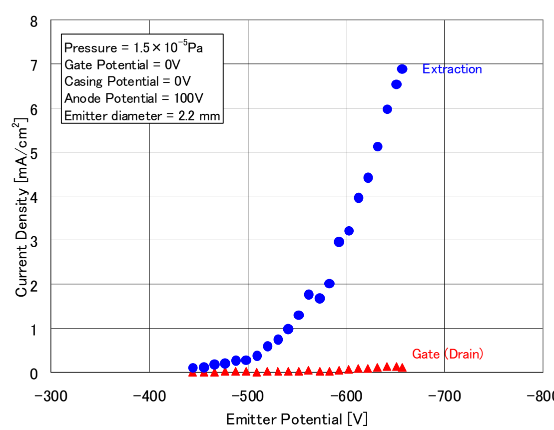

Figure 16 Typical current-voltage characteristics of carbon nanotube cathode, which possesses mask-and-gate structure.

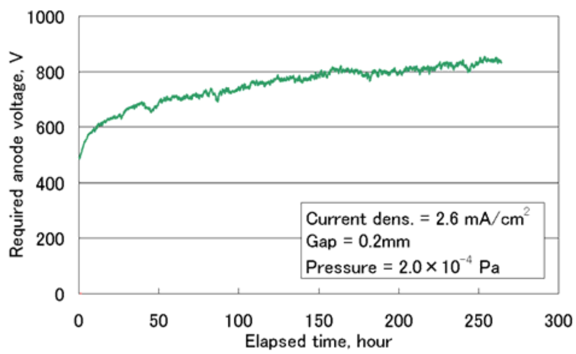

Figure 17 Typical endurance performance of carbon nanotube cathode in oxygen environment. Voltage required for constant-current-emission is plotted against elapsed time.

on the spool-type reel and the last 100 m is wound on the braking reel. The tether wound on the spool-type reel will be payed out first. Braking is applied to the terminal part of the tether by the rotary braking reel using the eddy current braking effect. At present, the vibration tests in vacuum environment in order to investigate the effect of adhesion in vacuum are being conducted.

As deployment is critical for the tether system, the deployment dynamics are investigated by numerical simulation [13]. Stable tether deployment is made difficult not only by the large friction of the conductive tether but also by the small gravity gradient force provided by the small micro-remover satellite. Moreover, the effect of tether coiling cannot be neglected when the tether tension is small, such as during deployment. In the numerical simulations, the deployment of the tether is modeled by adding point masses to above-mentioned lumped mass model. The coiling of the tether is modeled by a weak spring other than the springs between the mass elements which model the tension of tether itself. The attitude motions of the mother satellite and the daughter satellite are also considered. Fig. 20 shows the time history of the form of the tether for the EDT flight experiment.

6. CONCLUSION

JAXA is investigating EDT as a highly efficient propulsion system for space debris removal. A flight experiment being planned to demonstrate EDT technology using a small satellite was introduced. In preparation for this, precise numerical simulations have been performed for certain aspects of mission analysis, such as available electric currents, orbital changes, tether stability, and tether deployment dynamics. The current status of development of EDT components for the demonstration, such as a bare tether, FEC and reel mechanism, was also described.

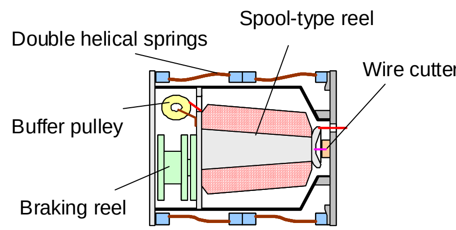

Figure 18 Schematic drawing of reel and release mechanisms in one body.

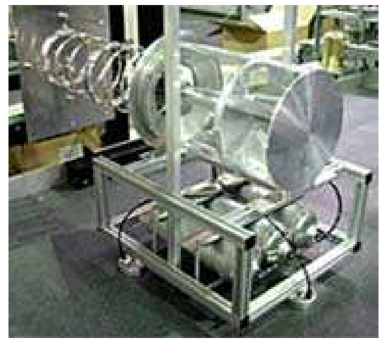

Figure 19 Reel and deployment mechanism

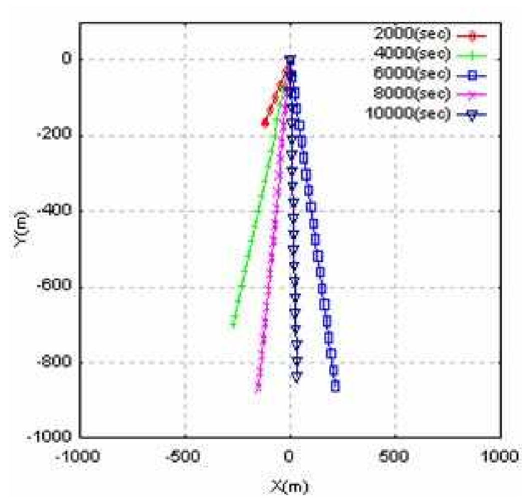

Figure 20 Time history of the form of the tether during deployment

7. REFERENCES

[1] Liou, J.-C and Johnson, N.: Risks in Space from Orbiting Debris *Science,* **311**(2006), pp.340-341.

[2] Lewis, H.G., Newland, G.G. and Saunders, A. (2008) A New ANALYSIS OF DEBRIS MITIGATION AND REMOVAL USING NETWORKS, IAC-08-A6.4.9

[3] Ohkawa, Y., Kawamoto, S., *et al.*: Research and Development of Electrodynamic Tethers for Space Debris Mitigation, ISTS, 2008

[4] Pardini, C., Hanada, T. and Krisko, P.: Benefits

and risks of using electrodynamic tethers to de-orbit spacecraft, *IAC-06-B6.2.10*, 2006.

[5] Nishida, S., Kawamoto, S., *et al*.: Space debris removal system using a small satellite, *IAC-06-B6.4.02*, 2006.

[6] Kawamoto, S. Ohkawa, Y., *et al*.: Strategy for Active Debris Removal Using an Electrodynamic Tether, ISTS, 2008

[7] Terui, F., and Nishida, S.,: Relative Motion Estimation and Control to a Failed Satellite by Machine Vision, Space Technol. Vol.27, Numbers 2-3, 2007, ISSN 0892-9270, pp. 90, 2007

[8] Nishida, S. and Yoshikawa, T.: Capture and Motion Braking of Space Debris by a Space Robot, ICCAS2007, Seoul, 2007

[9] Kawamoto, S., Makida, T., *et al*.: Precise Numerical Simulations of Electrodynamic Tethers for an Active Debris Removal System, *Acta Astronautica Volume* 59 pp.139-148, 2006.

[10] Kashihara, K., Qu, D., *et al*.: Simulation of Plasma Environment around a Bare Tether, *Proc. of ISTS,* 2006.

[11] Ikeda, T., Nakamura, Y., *et al*.: Multiple Bare Tethers for Electrodynamic Tether Propulsion, *IEPC-2007-280*, 2007.

[12] Kikkawa, C.: Current control of Electrodynamic Tethers using GPS measurements, ISTS 2008.

[13] Kobayashi, Y.: Deployment an Electrodynamic Tether from a Small Satellite, ISTS 2008.