

ELECTRODYNAMIC TETHER SYSTEMS FOR DEBRIS REMOVAL

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Abstract

As a countermeasure for suppressing space debris growth, the Institute of Space Technology and Aeronautics, Japan Aerospace Exploration Agency (JAXA), is investigating an active space debris removal system that employs highly-efficient electrodynamic tether (EDT) technology as its orbital transfer system. Firstly, a small, expendable EDT package is under development that consists of a bare conductive tether and field emission cathodes (FECs) that utilize carbon nanotubes. This package presents a possible technique for lowering the orbit of a debris removal system without the need for propellant. A test flight experiment using a rocket upper stage or a small satellite is planned for establishing and demonstrating the EDT technology. First, precise numerical simulations are performed for some aspects of mission analysis, such as available electric currents, orbital changes, tether stability, and deployment dynamics. The status of the trial fabrications and some evaluation test of the tether such as electric discharge are also described.

1. Introduction

As space debris is steadily on the increase, effective and reasonable mitigation measures are indispensable to ensure safe space development activities in future. Space debris left in orbit is dangerous, since it can pose a serious collision risk to operating space systems, and moreover a huge number of smaller bits of debris could be generated by mutual collisions between large objects. In some crowded regions such as around 1000 km and 1500 km in altitude, the debris density is quite high and a "cascade" effect could cause the amount of debris to grow drastically, thereby further degrading the near-Earth space environment. To prevent this unpleasant scenario, the active removal of large space debris, that is, defunct or malfunctioning satellites and rockets, is one of the most proactive strategies. JAXA is now investigating a capture, repair and removal system for satellites that have ended their missions, or have malfunctioned [1]. 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., 650 km alt.) using a conventional 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 transfers within a realistic time period without the need for much propellant – by utilizing interactions with the Earth's magnetic field.

2. EDT

The principle of EDT thrust is as follows. 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, electric current flows through the tether by closing the circuit via the ambient plasma. The tether then generates a Lorentz force via interaction between the current and the geomagnetic field. Therefore, EDT systems can provide deceleration without the need for propellant, and show promise as a next-generation non-chemical thruster. It is also possible to raise the orbit by applying a voltage that overcomes the electromotive force and reverses the direction of the current.

There exist two concepts of EDT systems as applied to debris removal: expendable and reusable EDT systems (Fig. 1 and 2 respectively). In the former, the removal system carries up to ten sets of small EDT system and installs one on each debris object to be moved to a lower orbit. In the latter concept, the debris removal system has a single EDT system and attaches one end of the tether to the captured debris. The debris removal system completes a round trip for each space debris object: down to the disposal orbit with the debris, then back up to a higher orbit to continue operations. Although this concept is much more sophisticated and more efficient than the first one [2], there exist technical difficulties, such generating the required electrical power to overcome the electromotive voltage and reverse of electrical current. Therefore, it is considered that an expendable EDT system should be developed first. It is simple and provides a greater reliability safety margin; however it is important to make the EDT package as light and small as possible. Once developed, they could also be installed in satellites for use in post-mission disposal.

As to the plasma contactors, a combination of bare tether [3] and FECs [4,5] is considered the best candidate for the expendable EDT, since this offers a simple, light system with no consumable gas requirements. For the reusable EDT, two hollow cathodes for both the emitter and collector would be suitable, since a reverse current capability is essential.

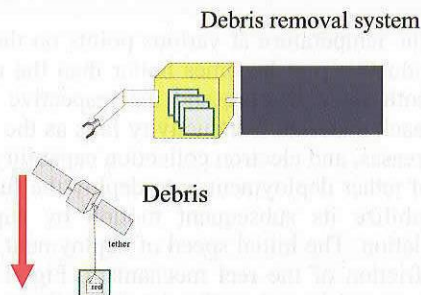


Fig. 1 Expendable EDT system

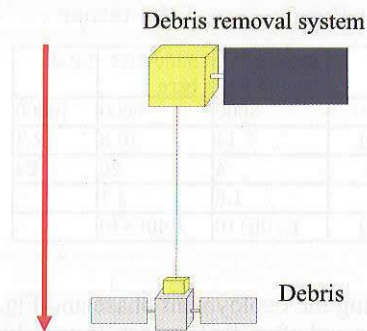


Fig. 2 Reusable EDT system

For establishing and demonstrating EDT technology, a test flight experiment is planned using a rocket upper stage or a small satellite that can offer an opportunity for a low-cost experiment with a short development time. Fig. 3 shows the case where a rocket upper stage is used. After the main satellite is deployed from the upper stage, an end-mass with an on-board emitter is released using a spring-loaded mechanism. The tether is simultaneously deployed, since it is connected to the end-mass. The upper stage quickly lowers its orbit by means of EDT thrust, until it enters the atmosphere.

3. Numerical Simulation

First, precise numerical simulations are performed for some aspects of mission analysis, such as to calculate available electric currents, orbital changes, tether stability, and deployment dynamics.

3.1. Model

A tether is modeled as a lumped mass to take into account tether flexibility, done by dividing the tether into point masses; each segment in between consisting of a spring and viscous damper. The equation of motion of each point mass is formulated in the coordinate system whose origin is at the center of mass of the system rotating around the Earth. Orbital perturbations caused by the Lorentz force, air drag and geo-potential are taken into account using Gauss's variational equations of motion. The following models are used respectively, IGRF 2000 (International Geomagnetic Reference Field) (10 * 10) for the geomagnetic field, IRI2001 (International Reference Ionosphere) for plasma density, NRLMSISE-00 (NRL Mass Spectrometer, Incoherent Scatter Radar Extended Model) for atmospheric density, EGM96 (Earth Gravitational Model) (10 * 10) for the Earth's geo-potential field, and two-dimensional OML (Orbital Motion Limit) theory for electron collection model by the bare tether.

As the details of the experiment, including orbit and schedule, are not yet fixed, some examples are shown here assuming the following values: the mass of the mother satellite 3400 kg; end-mass 50 kg. The length of the bare tether is 5 km, in order to generate a large thrust compared to that of atmospheric drag. Its mass is about 10 kg. Three types of the tether shown in Fig. 4 are studied. The other parameters of the tether are shown in Table 1. The orbit is assumed to be a 300-km circular orbit with an inclination of 52 deg. The date of the experiment is assumed to be 2010 and the last solar cycle (that of the previous 11 years) was used.

3.2. Results

Figures 5 - 16 show the results of some numerical simulations. The available current changes depending on the plasma density, geomagnetic field, the state of the tether and so on. It was found that the rocket upper stage re-enters the atmosphere within ten days. Since the mass of the rocket upper stage and that of the end-mass are quite different, the center of mass is not located in the middle of the tether. Thus, EDT thrust generated a torque that causes the tether to turn away from the local vertical, and start to librate. As the out-of-plane period of libration is almost equal to the orbital period, resonance effects occur that increase the amplitude until uncontrolled tumbling occurs. To prevent this, a non-conductive tether is required to stabilize the conductive tether by enlarging the gravity gradient torque; alternatively electric current control

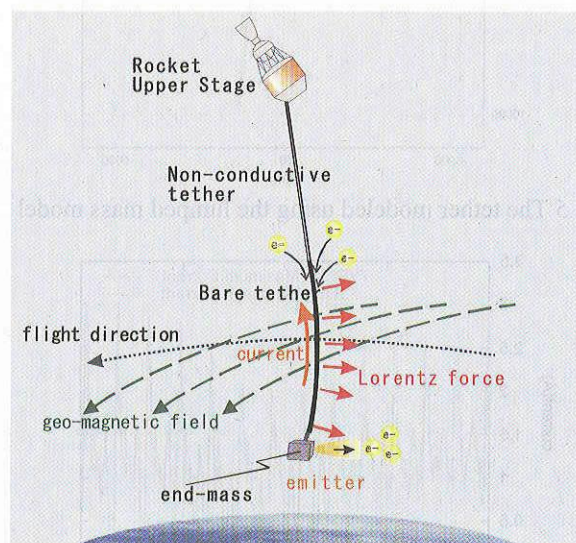


Fig. 3 A test flight of an EDT system using a rocket upper-stage

Table 1 Parameters of the tether

	non-conductive	conductive -bare	total
length(m)	5000	5000	10000
mass(kg)	2.14	10.3	12.4
segment	4	20	24
α / ϵ	1.6	3.1	-
E(N/m2)	1.70E+10	1.40E+10	-

tension during the deployment phase and Fig. 14 shows the dynamics of the tether. Fig. 15 shows the in-plane libration angle during and after deployment. It was shown that both libration and oscillation of the tether can be suppressed with this brake. The attitude dynamics of the objects at the end of the tether are also considered. During the deployment phase, the tension of the tether is assumed to be small, since the reel possesses low friction to enable smooth deployment. Therefore, the attitude of the rocket upper stage cannot be stopped, since it has a large inertia. Thus, deployment should be completed while the rocket upper stage is still alive. After battery power runs out, it may start rotating with a residual angular velocity of up to 0.3 deg/sec. Neither the rocket upper stage after that nor the end-mass possesses any attitude control capability: their attitude motion may couple with the oscillation and libration of the tether. It was found that there exists a maximum current limit to avoid unexpected conflict between tether and satellites (Fig. 16).

will be necessary.

Fig. 12 shows the temperature at various points on the tether. It was found that the conductive part becomes hotter than the non-conductive part because of both Joule heating and the respective thermo-optical characteristics of each material. Conductivity falls as the temperature of the bare tether increases, and electron collection capability falls.

The objective of tether deployment is to deploy the full length of the tether, and to stabilize its subsequent motion by suppressing both libration and oscillation. The initial speed of deployment needs to be set according to the friction of the reel mechanism. Fig. 13 shows tether

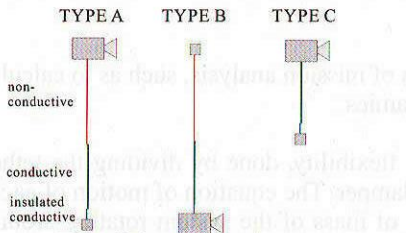


Fig. 4 Types of tether

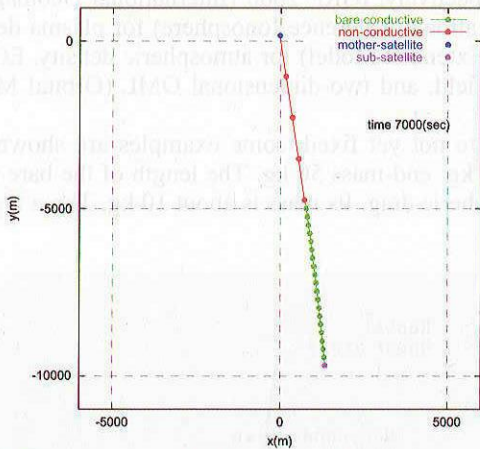


Fig. 5 The tether modeled using the lumped mass model

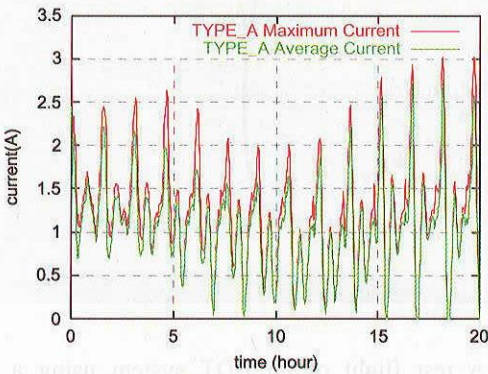


Fig. 6 Change in the current

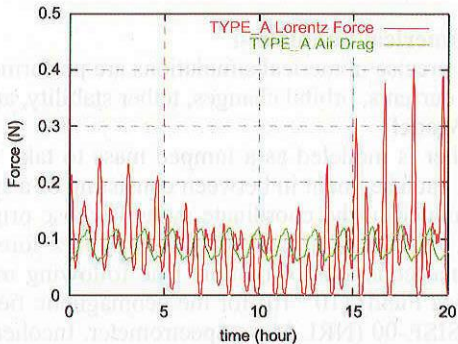


Fig. 7 Change in Lorentz force and atmospheric drag

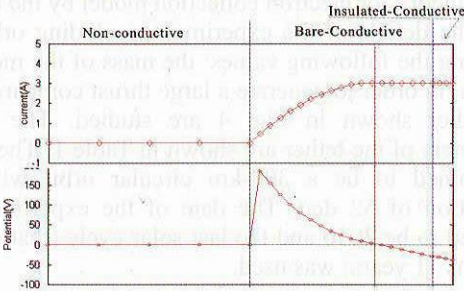


Fig. 8 Potential and current distribution along the tether by OML2D theory.

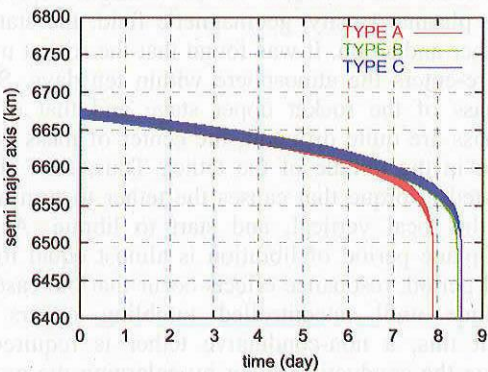


Fig. 9 Change in semi-major-axis

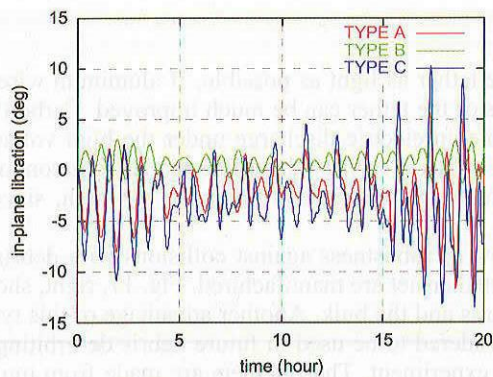


Fig. 10 Change in in-plane libration

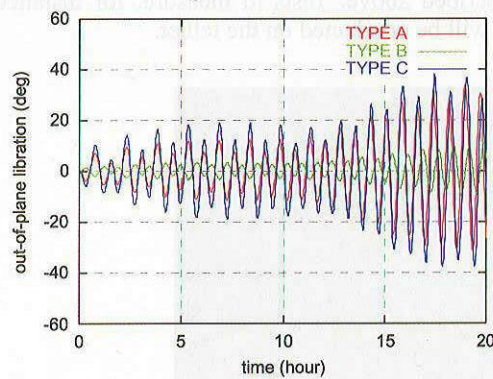


Fig. 11 Change in out-of-plane libration

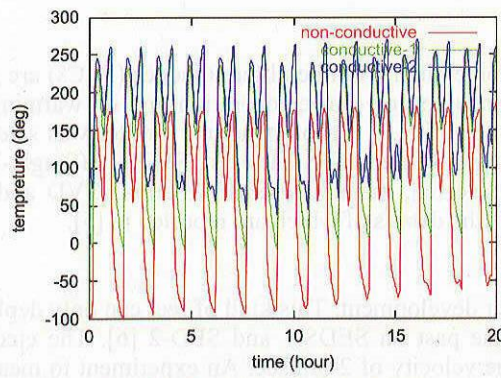


Fig. 12 Change in temperature

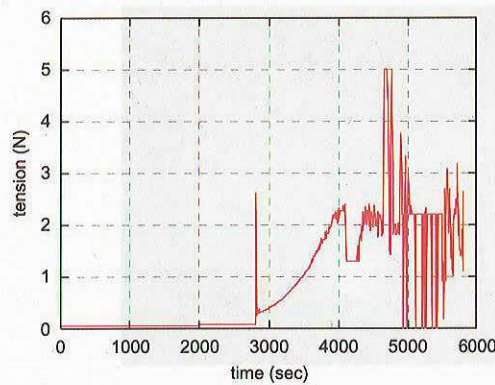


Fig. 13 Change in the tension during deployment phase

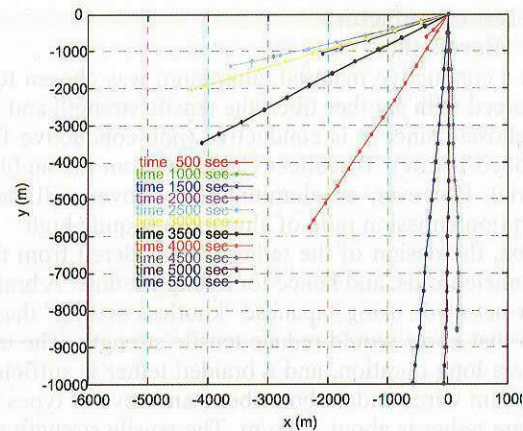


Fig. 14 Change in the form of the tether during deployment phase.

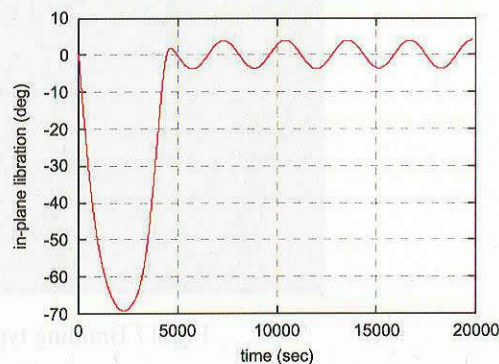


Fig. 15 Change in the libration angle during and after the deployment phase. The libration angle after the deployment is less than 5 deg.

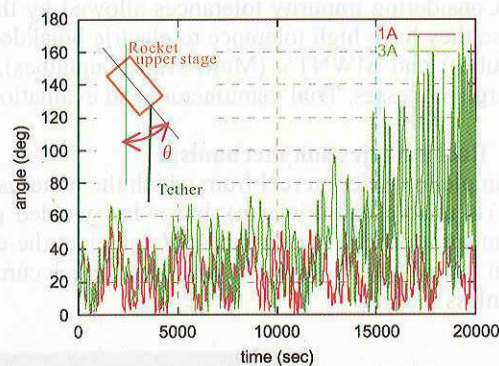


Fig. 16 Attitude motion of the rocket upper stage. (Change in angle between the tether end and local vertical. If this angle is more than around 90 deg, the tether may be come into contact with the rocket upper stage. The initial libration angle is assumed to be 10 deg.)

4. Test manufacture

4.1. Bare tether

As a conductive material, aluminum was chosen to make the bare tether as light as possible. If aluminum wires are reinforced with another fiber, the tensile strength and tensile modulus of the tether can be much improved. Carbon fiber was chosen, since it is conductive (non-conductive fiber can generate an electric discharge under the high voltage as described below). To collect electrons from the ambient plasma, the tether's surface should be made from conductive material. However, an aluminum-only cover will cause the temperature of the tether to become too high, since the absorption/emission ratio of aluminum is quite high.

Next, the design of the tether is considered from the point of view of robustness against collisions with debris and micrometeoroids, and hence for a long lifetime. A braided tether and tether-net are manufactured. Fig. 17, right, shows a tether-net made using Japanese "knotless netting" that reduces the mass and the bulk. Another advantage of this type of net is that knots would reduce tensile strength. The tether-net is considered to be used in future debris de-orbiting that requires long duration, and a braided tether is sufficient for the test experiment. These tethers are made from multiple aluminum wires and carbon fibers, and several types can be manufactured by altering the braid and pitch. The mass of the bare tether is about 2.0 g/m. The tensile strength of these tethers is about 250-300 N while the maximum tension is estimated to be several tens of N by the numerical simulation described above. Tests to measure, for instance, the growth in normal length and tensile strength at temperature extremes will be conducted on the tether.



Fig. 17 Braiding type tether (left) and net type tether (right)

4.2. FECs

Although there are a number of devices available for use as electron emitters, field emitter cathodes (FECs) are very promising by virtue of their simplicity and the features of no-consumable, low-power operation and no warming-up time. Considering impurity tolerances allowed by the conditions of operation, a carbon nanotube emitter was selected because they have high tolerance to electric breakdown. Of the two types of nanotube that exist, SWNT's (Single-Wall Nanotubes) and MWNT's (Multi-Wall Nanotubes), the latter was selected, manufactured by thermal CVD and arc discharge processes. Trial manufacture and evaluation was conducted, the details of which are reported in [5].

4.3. Reel and ejection mechanism

A simple low-friction reel from which the tether is paid out is under development. This kind of reel can only deploy a tether (is unable to retrieve it), but it has yielded good results in the past on SEDS-1 and SED-2 [6]. The ejection mechanism utilizes a spring-load and can eject the end-mass with the velocity of 2-3m/sec. An experiment to measure tension during the deployment phase and the accuracy of ejection will be conducted on an air table that can simulate frictionless motion.



Fig. 18 SEM image of the carbon nanotube (left) and the FECs emitting the electron (right).

5. Evaluations

First, a negative voltage was set up in the tether in a plasma-filled space chamber. The samples were a) an insulated tether, b) conductive wire and a non-conductive fiber (Kevlar®), and c) conductive wire and a conductive fiber (carbon fiber). It was found that in case a, that is, if the tether is perfectly insulated, electric discharge does not occur until -500V . In case b, electric discharge occurs at -200V . In case c, electric discharge occurs at -300V , however this may have been caused by dust unexpectedly attaching itself to the tether. It was shown that a bare tether without non-conductive exposure would be safe. The connection point between bare conductive and non-conductive tethers requires special treatment to prevent electric discharge.

Next, a preliminary experiment to test electron collection was conducted by loading the tether with a positive voltage. A current much more than that predicted by the theory was observed. Fig. 19 shows the results of the electron collection with K1 (one Al wire + one Kevlar®), K5 (K1*5), C1 (one Al wire + one carbon fiber), C5 (C1*5). The length of the samples was 20 cm in each case. The plasma density in the space chamber was about $3 \times 10^{12}/\text{m}^3$ and the pressure was about 1.2×10^{-4} torr.

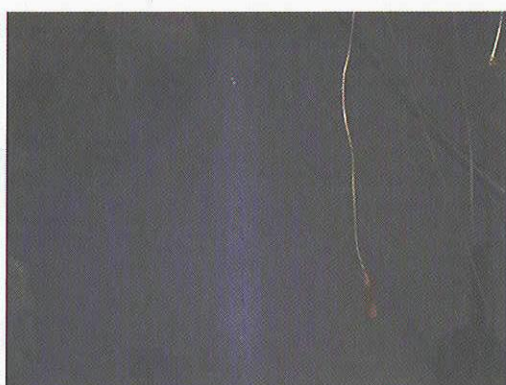


Fig. 20 Electron collection by the bare tether

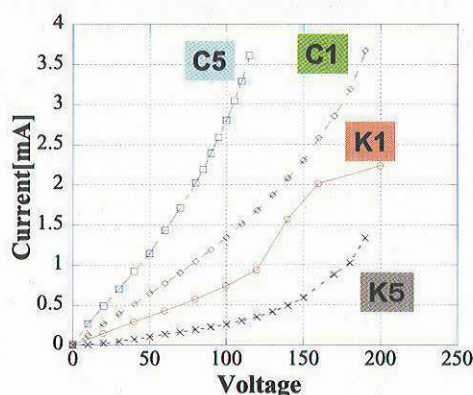


Fig. 19 Change in current-voltage during electron collection by the bare tether

6. Conclusion

We are conducting studies on EDT's as a very promising highly-efficient system for space debris removal. An experiment using a rocket upper stage or a small satellite is planned for establishing and demonstrating the technologies needed for a small, expendable EDT package that consists of a bare tether as a collector and FECs as emitters. Precise numerical simulations are performed for mission analysis. Test manufacture of the bare tether, FECs, and a reel mechanism have been described. Further tests will be conducted to evaluate these components, and the results of the test will be applied to future numerical simulations.

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