MECHANISMS AND LUBRICATION OF ELECTRODYNAMIC TETHER SYSTEM FOR DEBRIS REMOVAL

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ABSTRACT

A demonstration of electrodynamic tethers (EDT) has been planned as an active means of removing space debris. An EDT provides propulsion to de-orbit space debris using the Lorentz force generated from the current flow induced in a conductive tether and its movements through the Earth's magnetic field. A long tether is required to generate sufficient force, and since it requires high electric conductivity, a metallic tether is preferred. Moreover since the tether must be wound on a reel for launch and extended in orbit, smooth deployment and extension without adhesion or high friction between its parts in mutual contact and between the tether and reel core are necessary. To obtain smooth deployment and extension, the metal tether should be lubricated, and to collect electrons from the tether surface, the lubricant must have electrical conductivity. Conductive lubricant films for the tether, a deployment mechanism, a break mechanism to stop a tether extension and an installation part for a swinging tether after the extension were developed and evaluated.

1. INTRODUCTION

Space debris in earth orbit includes discarded man-made objects, such as defunct satellites that have been decommissioned or malfunctioned, and rockets that have finished their missions. The amount of space debris is further increasing due to these objects fragmenting following explosions and collisions, which will be a serious problem for future space activities. Prompt actions to avoid adding to space debris and to curtail the growth of debris by removing large objects are necessary.

The Japan Aerospace Exploration Agency (JAXA) has been planning to demonstrate electrodynamic tethers (EDT) as an active means of removing space debris [1 - 3]. An EDT provides propulsion to de-orbit space debris using the Lorentz force generated from the flow of a current induced in a conductive tether and its movement through the geo-magnetic field. Since the tether must be wound on a reel for launch and extended in orbit, smooth deployment and extension without adhesion or high friction between parts of the tether in mutual contact and between the tether and reel core are necessary. For this purpose, the metal tether should be lubricated, while to collect electrons from the tether surface, the lubricant must have electrical conductivity. Soft metals have been used as lubricants for space application due to good tribological properties in vacuum [4, 5] and they have excellent conductivity. However, soft metals create considerable increasing in mass by deposition, and it is difficult to deposit for long tethers. Therefore, there is a need to develop a new type of conductive solid lubricant, which can be deposited for long tethers. In addition, as related mechanisms, a deployment mechanism to release tethers, a break mechanism to gradually stop the tether extension and a tether installation part for a swinging tether after the extension are required. Details of research into the development of EDT systems, including tethers, their lubrication, and other related mechanisms for their demonstration are reported.

2. OVERVIEW OF AN EDT SYSTEM AND TETHER

A flight demonstration of an EDT debris removal system in earth orbit is being planned. The conceptual image of the demonstration flight is shown in Fig. 1. An EDT provides propulsion to de-orbit space debris using the Lorentz force generated from the flow of a current induced in an electrically conductive tether as it moves through the Earth's magnetic field. A tether a few thousand meters long is required to generate sufficient force, and since it requires high electric conductivity, a metallic tether is preferred.

The system will use a tether comprising three stranded wires woven in a net structure as shown in Fig. 2. Each stranded wire consists of several metallic wires composed of stainless steel for its tensile strength and aluminum alloy for its conductivity. Although the probability of a thin single-stranded wire tether being severed on impact with a small debris particle is relatively high, a net-type tether is expected to be capable of surviving for an extended period, since the spaces between the stranded wires greatly reduce the likelihood of all cords being severed on impact with a single piece of small debris.

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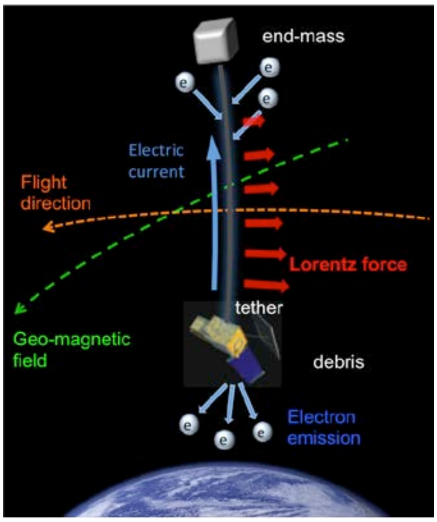

Figure 1. Conceptual image of demonstration of an EDT debris removal system.

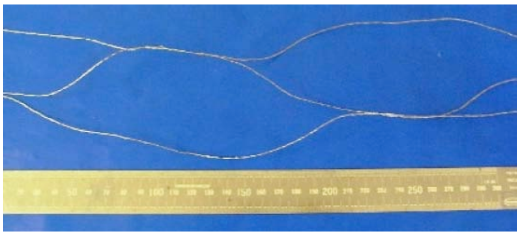

Figure 2. Photograph of a net-type tether.

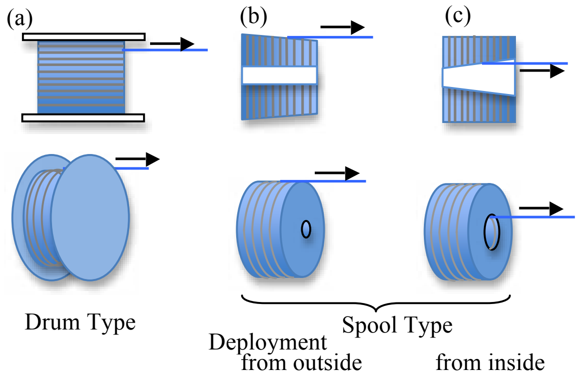

Figure 3. Types of tether deployment systems.

In the flight demonstration, a spool-type reel will be used, with the tether unwinding from the inside (see Fig. 3 (c)). This system has the advantages of no moving parts and lower deployment friction than alternatives such as a drum-type reel or spool-type reel deployed from the outside, shown in Figs. 3(a) and 3(b) respectively. The reel core is made of aluminum alloy. Friction arises between the reel core and tether and between the tether surface in mutual contact during the rubbing or sliding when the tether is deployed or due to launch vibrations.

3. MECHANISMS AND LUBRICATIONS

JAXA's EDT debris removal system consists of certain mechanical parts. Details of the parts and their tribological issues are described in the following section.

3.1. Lubrication for Tether

To obtain smooth extension in orbit without adhesion or high friction between parts of the tether in mutual contact and to avoid hindering electron collection, a conductive solid lubricant is applied to the tether. Considering the increase in mass caused by the deposition of lubricant films, their friction coefficients in a vacuum and the potential deposition for long tethers, a few types of conductive bonded lubricant films were developed for the tether and evaluated. These films consist of lubricants, a binder, and carbon and/or metal particle additives for conductivity. Four types were selected from the results of preliminary friction tests in the air and under low vacuum conditions. The constituents of the selected films are listed in Tab. 1. All films used the same polymer material as the binder. Graphite as a lubricant and additive is distinguished from other carbon materials, as shown in the table.

To evaluate tribological properties of the lubricant films, friction tests were carried out in a linear motion pin-on-disk type configuration using a vacuum reciprocating tribometer. Disk specimens with a deposit of the lubricant films were moved linearly against a counterpart pin specimen. Because of materials of the tether proposed for JAXA's EDT, a 6000 series aluminum alloy and a stainless steel were used as both substrate and counterpart. Tab. 2 shows conditions of the friction tests. The sliding speed and distance were 10 mm/s and 10 mm, respectively. Typically, the applied load was 1 N and the friction test was stopped after 10,000 strokes (5,000 cycles) if the wear life was not reached prematurely. All friction tests were conducted under environmental pressure of less than 1×10^{-5} Pa.

Table 1. Constituents of tested specimens

	Lubricant	Binder	Additives
Film A	Graphite	Polymer	Carbon
Film B	MoS_2	Polymer	Graphite
Film C	MoS_2	Polymer	Graphite, Carbon
Film D	MoS_2	Polymer	Graphite, Carbon, metal

Table 2. Conditions of friction test

Applied load	1 N
Sliding speed	10 mm/s
Sliding distance	10 mm
Number of sliding	10,000 strokes (5,000 cycles)
Atmosphere pressure	less than 1×10^{-5} Pa
Substrate materials	aluminum alloy, stainless steel
Counterpart materials	aluminum alloy, stainless steel

Fig. 4 shows the friction behaviors of the four bonded lubricant films in a vacuum with substrates of stainless steel and aluminum alloy against counterparts of the same metals. Although all films showed good tribological characteristics in air and low steady-state friction coefficients in a vacuum in the preliminary selection tests, differences in friction and wear life were observed between the tested specimens. For all combinations of substrate and counterpart, film A reached its wear life before 10,000 sliding strokes. Film B had lower friction coefficient and longer wear life than film A except where a stainless steel substrate and aluminum alloy counterpart were combined, but it also reached its wear life before the end of the test duration, despite containing molybdenum disulfide, which has good tribological properties in a vacuum. Films C and D had the lowest friction coefficients and did not reach their wear lives. No differences in either the values or friction behaviors between films C and D were observed, except that in the early stage of the tests film C had a higher friction coefficient than film D.

No differences were found in friction behaviors between the two metal substrates and two counterpart materials. Although films A and B had slightly different behaviors in the case of a stainless steel substrate and aluminum alloy counterpart compared to other combinations, no clear tendencies due to the different substrate and counterpart materials were found.

The electrical resistances of bonded films C and D were measured as volume resistivity by the 4-terminal method using a 4-pin probe a few times. The same types of films were deposited on non-conducting aluminum oxide disk. The averages of the measured volume resistivity of the films are listed in Tab. 3. Both films had orders of volume resistivity of 10^0, meaning the tested films are near semiconductors. However, it was recognised that the conductivities were enough to collect electrons via electron collection test [6, 7] under space plasma.

Table 3. Volume resistivity of tested bonded films

	Volume resistivity [Ω•cm]
Film C	1.21×10^0
Film D	1.04×10^0

3.2. Release and Deployment Mechanism

An end-mass including a tether, its case and a brake to stop a tether extension and so on will be released using a mechanical spring after a kind of launch-lock open, as shown in Fig. 5. A reel core remains on the board on which the tether case is set. The tether collides with and slides against the reel core due to vibration during launch, while sliding also occurs between the tether and reel core following the release of end-mass. The resulting damage to the reel core and the effects of

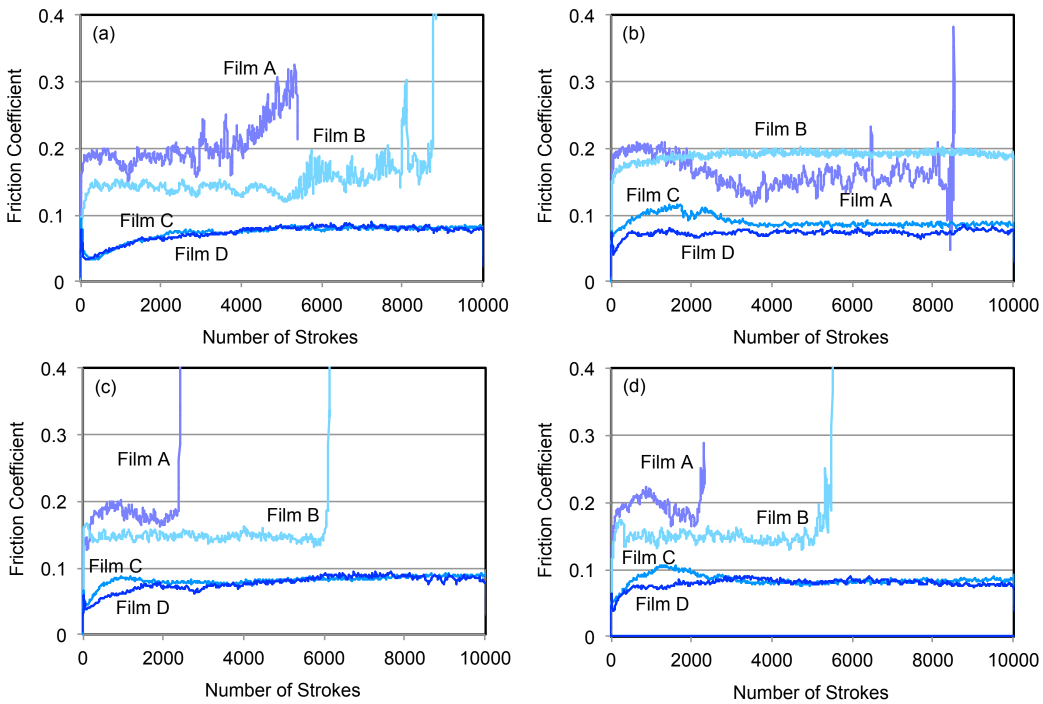

Figure 4. Friction behaviors of tested bonded lubricant films with different substrates and counterparts. Substrate/Counterpart: (a) stainless steel/ stainless steel, (b) stainless steel/aluminum alloy (c) aluminum alloy / stainless steel, (d) aluminum alloy /aluminum alloy

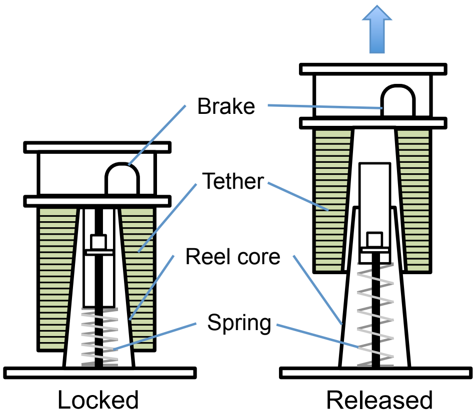

Figure 5. Schematic drawing of tether release systems.

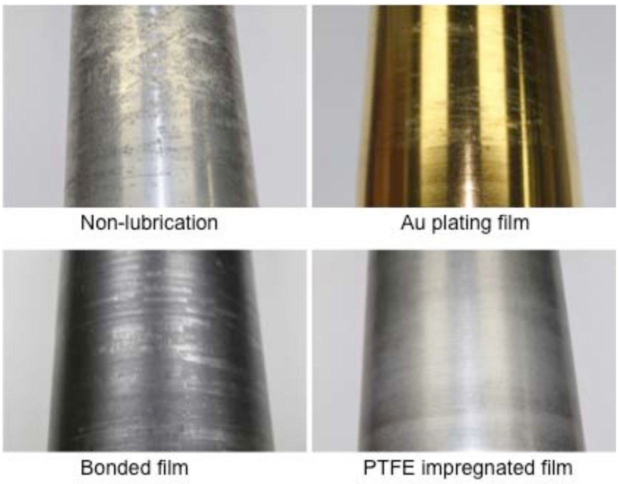

Figure 6. Surfaces of reel cores after a vibration test and pulling out from a rolled tether.

lubrication on the reel core were evaluated using an optical microscope after vibration and release tests.
Vibration tests were carried out in two or three directions, parallel and vertical to the reel core, in air and a vacuum. Subsequently, the reel core was pulled out from the rolled tether via a release test. Fig. 6 shows the faces of reel cores without lubricant and with lubricant films after the vibration tests and the release test. The lubricant films were gold plated and MoS_2 bonded films, which had electric conductivity, and PTFE impregnated film. Many scars were found on the non-lubricated reel core, almost none of which were long. It means many scars formed during the vibration test. The reel core lubricated by MoS_2 bonded film also showed many scars, and that by gold plated film showed several scars. These were not observed on the reel core lubricated by PTFE impregnated film, although it did not have conductivity. The transferred film from the PTFE film was not observed on tether. Since electron collection is not hindered due to film transfer, the PTFE film is a potential lubricant for the reel core.

3.3. Brake Mechanism

A brake system is needed to stop the tether extension gradually, because breaking the tether by impact force must be avoided. Fig. 7 shows a schematic diagram of the brake system. At the end of the tether extension, last a few tens of meters of the tether rotate brake rotor with a brake disk. Friction between the rotated brake disk and fixed brake pad slow down the tether extension. The imposed load can be controlled by changing the springs that push the brake pad. The materials selected for the brake disk and pad were stainless steel and polymer material, respectively. To obtain data to select the optimum load, a friction test was carried out using brake disk and pad materials in the air and a vacuum at room and low temperatures.
The friction behaviors of the polymer material in the form of a brake pad against stainless steel as a brake disk are described in Fig. 8. No difference in friction coefficient was observed between air and vacuum, but the fluctuation of the friction value in a vacuum was larger than that in air. At a low temperature in a vacuum, the friction behavior resembled that at room temperature, and the friction coefficient gradually decreased. A few tens of cycles were required for the friction coefficient to reach a steady-state level under all conditions.

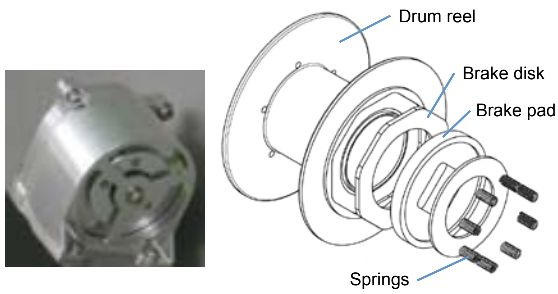

Figure 7. Schematic diagram of brake systems.

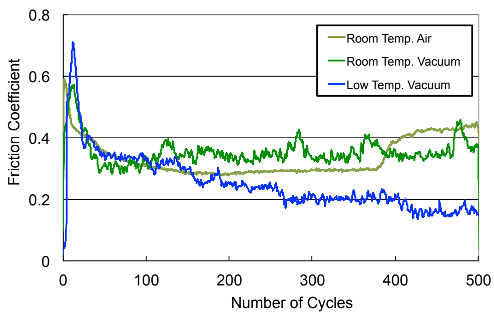

Figure 8. Friction behaviors of brake materials under different conditions.

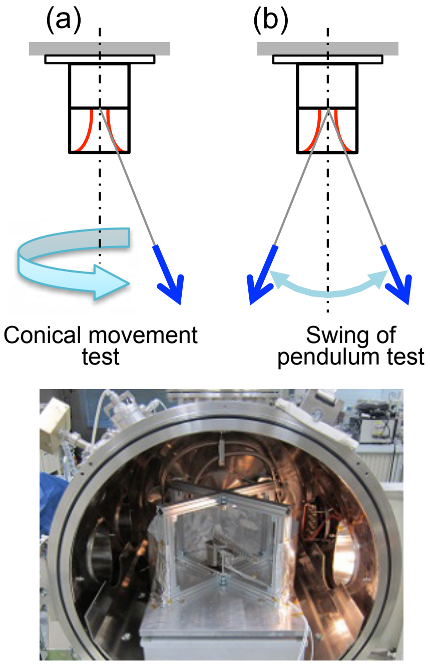

Figure 9. Durability tests for the tether installation part. (a) Conical movement test, (b) Swing of pendulum test.

Adaptability, running-in is required, for which an optimal condition should be determined.

3.4. Tether Installation Part

After tether extension, a long tether may move like a pendulum swing. Therefore, provisions are needed to avoid the tether breaking at the root and/or coming into contact with any parts on the satellite as debris during operation. A tether installation part is mounted on the root of the tether. The inside of this part spreads out like a trumpet shape, and solid lubricants were also coated on the surface for smooth movement. The tether is placed through a PTFE tube, to prevent it bending and breaking.

The durability of the tether installation part was evaluated in a vacuum. The method used for the tests and the test situation are shown in Fig. 9. Two types of tests, which demonstrate conical movement or swing of pendulum, were carried out with constant tension for the tether. Consequently, no breakage of the tether was observed whereas torsion of the tether occurred by the estimated motion for a month in orbit.

4. CONCLUSIONS

A demonstration of electrodynamic tethers (EDT) has been planned as a means of active space debris removal. A tether and some mechanical parts for the system were also developed and evaluated.

1. Conductive bonded films were developed for the tether to obtain smooth extension in orbit without adhesion between its parts in mutual contact and to keep electron collection. Some film obtained good tribological properties and volume resistivity.
2. In vibration tests demonstrated launch condition, the tether caused many scars on the reel core. To prevent such scars and to obtain smooth deployment, a PTFE coating was a potential lubricant for the reel core.
3. To stop the tether extension gradually, a brake mechanism was developed and the friction properties of the brake material were evaluated. Stable properties were obtained under some conditions
4. A tether installation part was developed and evaluated to prevent the tether breaking after extension and during operation. It was confirmed that the tether was remained unbroken by motion after a month in orbit.

5. REFERENCES

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