P03

デブリ除去用導電性テザー伸展における バーバーポールブレーキ機構導入の検討

Evaluation of a barber pole brake in deployment of conductive tether for debris removal

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宇宙航空研究開発機構(JAXA)ではデブリ除去用導電性テザー(EDT)の研究が進められている. 大型デブリ除去に必要な推力を確保するため, 数 km 級テザーの伸展が必要とされる. この際, 重力傾斜やコリオリ力の影響で伸展速度や面内振動が増大し, 最終的にテザー耐荷重を超える張力により破断する可能性がある. 本研究では, これに対し, 被覆無しの導電性テザーおよび比較的重量の重い 300kg 級の衛星による長距離伸展を想定し, 軌道上で実績のあるバーバーポールブレーキの導入検討を目的とした. まず, 地上伸展試験により, 自己潤滑性および低固着性をもつ PTFE をポール材とし, ブレーキ力のモデル化を行った. 次に, 地上試験によるモデルを反映させ, 数値シミュレーションによる軌道上テザー伸展予測を行った。これにより, 面内振動±10deg および最大張力 70N 以下に軽減することができ, 伸展中における本ブレーキ導入の有用性を示した.

The Japan Aerospace Exploration Agency (JAXA) has been investigating Electrodynamic Tether (EDT) systems for de-orbiting existing debris. EDT is a high-efficiency propulsion system to generate Lorentz force by the interaction with the Earth’s magnetic field. It is necessary to deploy a several kilometer tether in order to obtain sufficient thrust for large debris removal. In the deployment phase, excess of deployment velocity and in-plane libration by gravity gradient become issues, since the behavior of the tether becomes unstable or it is severed by the tension over in excess of the load limit. In some previous flight experiments, a barber pole brake was adapted as a simple brake to acquire effective braking force. However, the barber pole brake was applied for tether deployment with a non-conductive tether and a light satellite up to some tens of kilograms. The purpose of this study is to build a simple barber pole brake using a net-type bare conductive tether and a relatively heavy satellite of about several hundred kilograms. First, a braking force model is built based on on-ground tests with a high-sensitive sensor. Next, numerical simulations about tether deployment dynamics on orbit are performed in order to investigate its applicable limitation. In the numerical simulations using the brake model from the on-ground tests, a 10-km-long tether is deployed, and the changes in the form of the tether and the tether oscillations are also calculated. The simulation confirmed that the barber pole brake can decrease the in-plane libration angle to less than ±10deg, and the maximum tension up to the half value of the tether load limit 160N.

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- Evaluation of a barber pole brake in deployment of conductive tether for debris removal -

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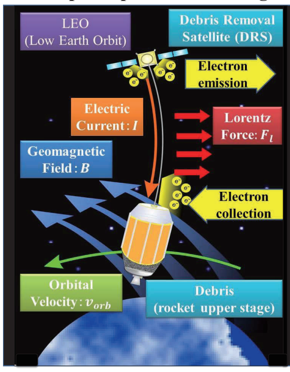
I. Introduction

I. The principle and advantage of EDT



- □**Propellant-free propulsion to generate Lorentz force by interfering with earth's magnetic field**
- □**High efficient propulsion**
  →**No high electrical power**
- □**Simple system**
  →**No fuel tank, valve, pipe**
- □**Easily attached to debris**
  →**Small thrust of EDT**
- ◆**EDT could deorbit many large debris from the crowded orbit within one year**

II. Tether deployment assuming Active Debris Removal

In order to generate sufficient thrust for deorbit large debris with mass of about 1-3 [ton],

□Need to deploy **a 5-10 [km] tether** on orbit

→ Excess of **deployment velocity, tether libration** and **tether tension** due to gravity gradient and Coriolis force

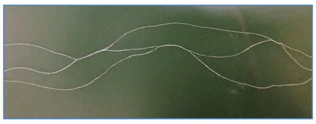
◆**Need a brake mechanism for decreasing them in tether deployment**

II. Assembly for tether deployment

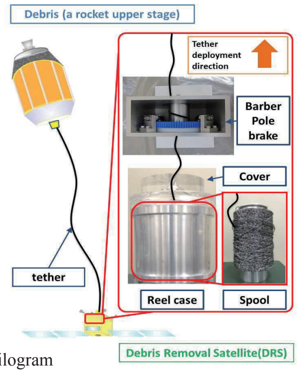
I. Tether

□Uncovered conductive wires

□Net-like structure for redundant



A portion of **net-type bare tether** spread out to show its structure



II. Barber pole brake

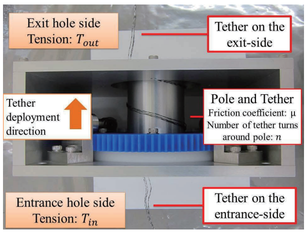
□Compact, light-weight, simple

□Used in previous tests with **non-conductive tether** and **lighter satellites** up to some tens of kilogram

□**Exponential performance** in wide range of tension levels

Euler's belt formula;

$$T_{out} = T_{in}e^{2\pi\mu n}$$

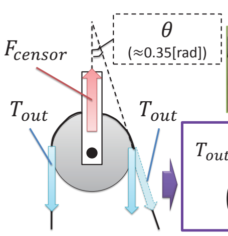


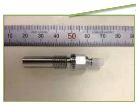
◆ **The subject of this study is a barber pole brake to be used for ADR mission with DRS**

III. Ground deployment experiment

□Tether : Composed of aluminum and stainless steel wires

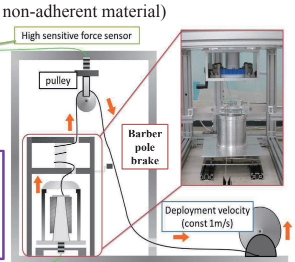
□Pole : Adopted PTFE pole (self-lubricating and non-adherent material)





$$T_{out} = \frac{F_{censor}}{(1+\cos\theta)} \left(\approx \frac{F_{censor}}{1.94}\right)$$

How to measure exit tension (braking force)



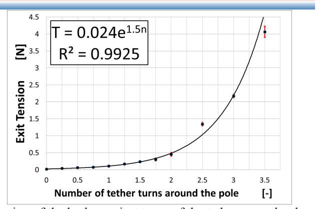
Tether deployment set-up

□**Nominal brake model**

$$F_{brake}(=T_{out}) \approx 0.024ve^{1.50n}$$

□Modeled as an exponential function of number of tether turns around the pole

□Two-sigma noise from average measured tension amounted to about 5〜30[%]



The exit tension of the brake against turns of the tether around pole

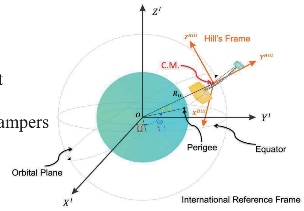
IV. Numerical Simulation

I. Models

□Tether deployment is modelled by adding point masses to lumped mass model

□Each point mass is connected by springs and dampers

□Tether tension acting on the DRS = brake model including the relative error from on-ground experiment

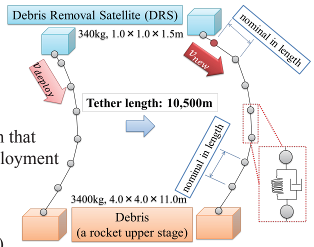


II.Conditions

□Initial conditions

- ・Ejection velocity: 1.0[m/s]
- ・In-plain ejection angle: -45[deg]
- ・Deploy tether as long as possible before brake

□Brake system starts operation at **1,200[m]** with consideration of the minimum tether length that gravity gradient prevail on Coriolis force in deployment



$$l = \frac{2\mu_e v_{deploy}}{3{r_0}^3 \sin\theta_{xy}} (\geq 1{,}333[m])$$

l:tether length, r_0:radius of orbit(= 6,998[km])

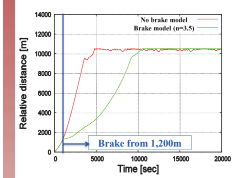
μ_e:gravitational constant of the Earth(=3.986 × 10^5[km^3/sec^2])

θ_{xy}:in-plane libration angle, v_{deploy}:deployment velocity

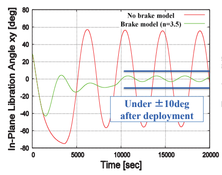
□Number of turns around pole was set at 3.5 turn (i.e. brake force is set at about 8.0[N] at start-up) since max gravity gradient is about 10[N] in a 10-km-long tether deployment

III. Results

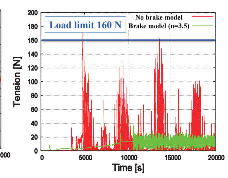
i. Compared brake and non-brake



Distance between DRS and debris vs time



In-plane libration angle vs time



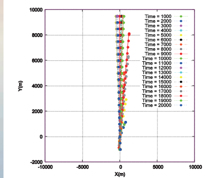
Tension vs time

◆In-plane libration angle after deployment is reduced under ±10[deg] by brake

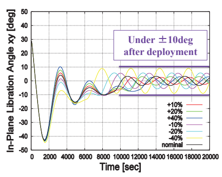
◆Maximum tether tension during deployment is less than a quarter of the tether load limit 160[N] by brake

ii. Robustness assessment for the brake

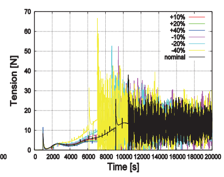
□Include the error of brake force set at ±10, 20, 40 % from on-ground experiment



Time history of changes in the form of tether during deployment **(nominal)**



In-plane libration angle vs time



Tension vs time

◆In-plane libration angle after deployment is reduced under ±10[deg] in any cases

◆Maximum tether tension 70 [N] during tether deployment is less than the half value of the tether withstand load 160[N]

V. Conclusions

◆Investigated the tether deployment utilizing a barber pole brake with a net-type bare tether and a DRS for ADR mission with EDT

◆Numerical simulation indicated the 10-km-long tether can be deployed smoothly and without unstable behaviour by utilizing a barber pole brake from on-ground experiment