P07

EDT を用いた PMD デバイスにおけるテザー伸展についての初期検討

Initial Study on Tether Deployment in PMD Device Using EDT

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著者らは EDT（Electrodynamic Tether）を用いた超小型衛星用 PMD（Post Mission Disposal）デバイスについて研究開発を行っている。このデバイスは衛星の運用終了後、折り畳んで収納したテープテザーを展開し、テザーに流れる電流と地球磁場との相互作用によって発生するローレンツ力と大気抵抗を推進力として利用することで、使用済み衛星の軌道離脱を支援することを目指している。 しかし EDT は地球磁場を利用するため、運用条件に応じてテザーの伸展方向に制約が生じる場合がある。そのためテザー展開時の初期条件がテザーの伸展挙動に与える影響について検討することは、テザー伸展の失敗リスクを低減するための設計や運用指針の策定に役立つと考えられる。 本研究では軌道平面内における二重振り子型の簡易モデルでシステムを記述し、モンテカルロ法による解析を行った。テザーで繋がれた子衛星の放出時の初期条件に対し、伸展の成否を判定する任意の指標を用いてテザー伸展の成否を検討した。 本稿ではその結果に関して報告する。

The authors are conducting research on post mission disposal (PMD) device for microsatellites using electrodynamic tether (EDT). In this PMD device, the atmospheric drag and the electromagnetic force are utilized for the propulsion of deorbit. In case of PMD device using EDT, the direction of tether deployment is constrained by the trajectory of satellites because of the electromagnetic force is generated by the interaction between the current flowing in the tether and Earth’s magnetic field. Therefore, the effect of initial conditions such as deployment velocity, deployment angle, and so on were evaluated by numerical simulations using Monte Carlo method. In this paper, the trend of tether deployment based on numerical simulations were shown.

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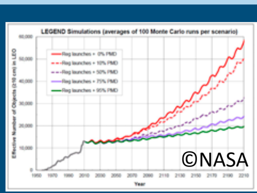
1. Background

The growth of micro-satellite business and concept of micro-satellite mega constellations plan.

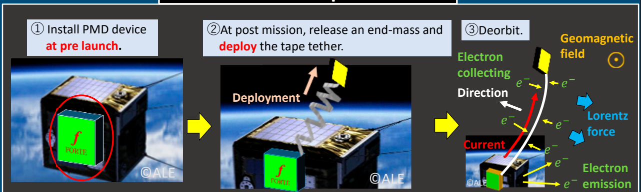
Concern about mass production of space debris from the post mission satellites.

The needs for mitigation of space debris on LEO.



Space debris increases on LEO.
→Environmental issues in space.

PMD device concept overview



- PMD technology is the method to de-orbit a satellite quickly after a mission.
- The authors are conducting research on post mission disposal (PMD) device for micro-satellites.
- This PMD device supports re-entry of a micro-satellite by **atmospheric drag** and **electrodynamic tether propulsion (electromagnetic force)**.
- The electromagnetic force is generated by the interaction between **the current** flowing in the tether and **earth's magnetic field**.
  →**The direction of tether deployment is constrained by the trajectory of satellites.**

2. Purpose and what was done

To evaluate the effect of initial conditions such as deployment velocity, deployment angle, and angular velocity of the satellite.

To provide the method to evaluate the trend of tether deployment for random initial conditions by numerical simulations using monte carlo method.

3. Evaluation method

Analysis procedure

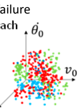
Input
- Input **random values** within the specified range for each initial condition.
  →**monte carlo method**

Initial condition
- **Initial velocity v_0**
- **Initial angle θ_0**
- **Angular velocity of the satellite $\dot{\theta}_0$**

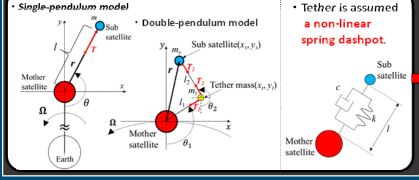
Random number range

Initial velocity v_0[m/s]	0.05~1.0
Initial angle θ_0[rad]	0~2π
Angular velocity of the satellite $\dot{\theta}_0$[rad/s]	0~2π

Evaluate the trend
- Determine the success or failure of tether deployment for each initial condition.
- Plot on the 3D graph.

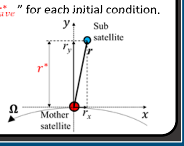


Dynamics model



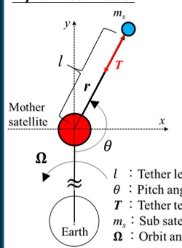
- Tether is assumed **a non-linear spring dashpot.**

Output
- The index "r^*" output.
- Calculate the mean value "r^*_{ave}" for each initial condition.



4. Dynamics model

Single-pendulum model



- l : Tether length [m]
- θ : Pitch angle [rad]
- T : Tether tension [N]
- m_s : Sub satellite's mass [kg]
- Ω : Orbit angular velocity [rad/s]

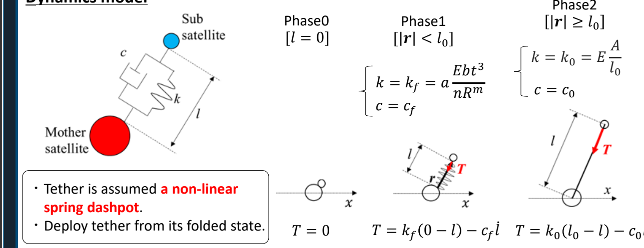
The equation of motion

Lengthwise direction : $\ddot{l} - l\dot{\theta}^2 - 2\Omega l\dot{\theta} - 3\Omega^2 l\cos^2\theta = -\frac{T}{m_s}$

Pitch direction : $l\ddot{\theta} + 2\dot{l}\dot{\theta} + 2\Omega\dot{l}\dot{\theta} + 3\Omega^2 l\sin\theta\cos\theta = 0$

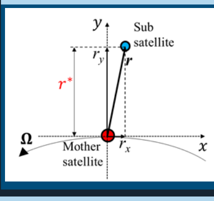
- Consider only the motion in the orbital plane.
- Mother satellite : On a circular orbit. Much heavier than the sub satellite.
- Earth : A perfect circle.

Tether model



- Tether is assumed **a non-linear spring dashpot.**
- Deploy tether from its folded state.

5. The index "r^*"



- The index "r^*" is the y-component of the sub satellite position vector $\boldsymbol{r}$.
- Determine the success or failure of tether deployment for each initial condition using the mean value "r^*_{ave}".

$r^*_{ave}/l_0 > 0.6$: Success in the zenith direction.
$-0.6 < r^*_{ave}/l_0 < 0.6$: Failure to deploy.
$r^*_{ave}/l_0 < -0.6$: Success in the earth center direction.

6. Example of analysis result

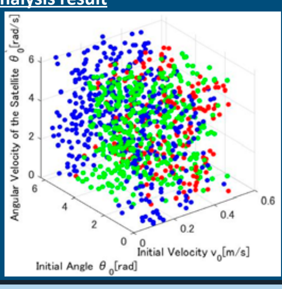
Analysis conditions

Initial tether length l_i[m]	0.01
Tether length l_0[m]	10.0
Weight of the sub satellite m_s[kg]	0.10
Orbital altitude [km]	500
Orbit angular velocity Ω[rad/s]	1.103×10⁻³

Tether specification

Tether material	ALPET
Thickness t[m]	45.0×10^{-6}
Width b[m]	0.01
The interval of folded R[m]	0.10
Young's modulus E[GPa]	5.0
Phase1 spring constant k_f[N/m]	0
Phase1 attenuation coefficient c_f	0
Phase2 spring constant k_0[N/m]	0.001
Phase2 attenuation coefficient c_0	0.045

Analysis result



Green	Success in the zenith direction
Red	Failure to deploy
Blue	Success in the earth center direction

- Confirmed that the initial velocity and the initial angle had significant effects on the success or failure of tether deployment.

7. Conclusions

- The method to evaluate the trend of tether deployment was shown.
- This method will be useful in designs that reduce the risk of deployment failure.

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