C-5
Design and Development of the Tether Deployment Mechanism
For Nano-Satellite

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Abstract
An electro dynamic tether is the effective way to deorbit nano-satellite not to become debris. In this way, tether deployment is one of the fundamental technologies. The authors focused on tether deployment and developed a small tether deployment mechanism as demonstration in orbit. It was design for nano-satellite and installed in Cute-1.7 + APD which was developed by Laboratory for Space Systems (LSS) at Tokyo Tech and was launched into orbit by a Japanese rocket M-V-8 in Feb. 2006. Before launch, it was conducted many evaluation tests such as micro gravity test, environmental tests and so on. In this paper, the tether deployment mechanism is introduced and the results of the function checkout and environmental tests are described.

1. Introduction
In recent years, the development of the nano-satellite gets active mainly among the universities around the world. Because it has remarkable possibilities of space technology education, and realizes advanced scientific and technological demonstrations in orbit quickly. A lot of nano-satellites will be launched into orbit near future. However, these satellites have risk to become harmful space debris after stopping working.

One of the effective ways not to become debris is to deorbit with an electro dynamic tether. Fig.1 shows the principle of getting force for decelerating with an electro dynamic tether. Cross-interaction between electric current and earth magnetism makes lorentz force. It makes a satellite deaccelerate and reentry into the earth.
One of the key technologies of this method is tether deployment. The authors focused on it and developed prototypes of a tether deployment mechanism and conducted many evaluation tests. Furthermore, we developed a flight model installed in Cute-1.7 + APD, the nano-satellite. In this paper, the characteristics of the tether deployment mechanism and the results of the evaluation tests are described.

2. Cute-1.7 + APD

Cute-1.7 + APD, as shown in Fig.2, is a nano-satellite developed by LSS (Laboratory for Space Systems), Matunaga Lab., at Tokyo Institute of Technology. Its size is about 10*10*20 cm³ and mass is about 3.6kg. It was launched with a Japanese rocket M-V-8 on 22 February, 2006[1-3]. One of Cute-1.7 + APD missions is demonstration of the tether deployment in orbit for future disposal method using electrodynamic tether [4]. Fig.3 shows an image of tether deployment operation.

3. Tether Deployment Mechanism

The following requirements should be reflected to design of the tether deployment mechanism.

- a) Maximum volume is 85*80*8 mm³
- b) Easy to attach to and detach from the satellite main body
- c) No pyrotechnic is used
- d) Ability to deploy tether over 10m length in space environment
- e) Durability against launch condition

A polyethylene type line named Dyneema™ made by TOYOBO is used to tie the separation plate and inner plate. It is melted to cut by heating through a nichrome line heater. Then three springs push the separation plate and tether attached on it is pulled out from the inner plate. This method is called a string hold method as shown in Fig.5.

The tether deployment mechanism consists of three pushing springs, coiled stored tether, tether cover, separation detector, tether deployment sensor and separation control electronics. Fig.6 shows these components of the inner plate.

There are two sensors on the inner plate. One is a separation detector and the other is a tether deployment sensor, as shown in Fig.7. A phototransistor is used as the separation detector. When the separation plate is released, it detects sun light as shown in Fig.8. The tether deployment sensor is
designed to measure a deployed tether length using a photo-diode array and a LED as shown in Fig.9. The sensor output value is more increased as the tether deploys longer. Fig.10 shows an example of the output with respect to every 10m. According to the sensor output, the length of the deployed tether can be measured roughly.

Tether is copper line whose diameter is 0.1mm and total length is about 30m. It is stored by crossed winding as coil. Fig.11 shows a tether storage part. A flange is adopted to prevent the tether from being tangled as shown in Fig.12.
Current electricity generated by solar cells on the separation plate is transmitted to the power subsystem of the Cute-1.7 + APD main body through the two pushing spring, as shown in Fig.13.

The current characteristic of this method is shown in Table 1. According to the table, current output is almost the same as theoretical figures. It indicates that current transmission in this way has no problem in practical use.

<table>
<thead>
<tr>
<th>Load [Ω]</th>
<th>V [V]</th>
<th>I [A]</th>
<th>Theoretical Figure [A]</th>
</tr>
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<tbody>
<tr>
<td>15.06</td>
<td>4.35</td>
<td>0.25</td>
<td>0.29</td>
</tr>
<tr>
<td>12.07</td>
<td>4.16</td>
<td>0.34</td>
<td>0.34</td>
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<td>10.01</td>
<td>4.13</td>
<td>0.41</td>
<td>0.41</td>
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<tr>
<td>8.21</td>
<td>4.01</td>
<td>0.495</td>
<td>0.49</td>
</tr>
<tr>
<td>7.44</td>
<td>3.99</td>
<td>0.53</td>
<td>0.54</td>
</tr>
<tr>
<td>6.82</td>
<td>3.73</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>5.57</td>
<td>3.6</td>
<td>0.655</td>
<td>0.65</td>
</tr>
<tr>
<td>3.9</td>
<td>3.04</td>
<td>0.82</td>
<td>0.78</td>
</tr>
<tr>
<td>3.03</td>
<td>2.76</td>
<td>0.92</td>
<td>0.91</td>
</tr>
<tr>
<td>2.02</td>
<td>1.06</td>
<td>0.54</td>
<td>0.52</td>
</tr>
</tbody>
</table>

4. Evaluation tests

Horizontal deployment test was conducted using a laser displacement sensor to estimate the initial velocity. Fig.14 shows the set-up for the test. The estimated ideal initial deployment speed neglecting friction loss is 0.75 m/s. On the other hand, the actual initial deployment speed is 0.48 m/s in average. The velocity loss due to friction is about 35%.

Integration test was conducted as shown in Fig.15. PDA used as OBC also controls the tether deployment mechanism. Sensor data are acquired and saved in PDA memory through a DAQ board. A camera equipped on the same side plate of the satellite takes pictures of tether deploying. System block diagram is shown in Fig.16.
Environmental tests such as vibration test, vacuum test and thermal test were also successfully conducted to check the performance. Random, low and high frequency shock tests were conducted. In the vacuum test, vacuum level was $10^{-5}$ torr order. The performance under thermal range from -20 deg. to 20 deg. was checked in the thermal test.

![Vibration Test](image1)

![Vacuum Test](image2)

![Thermal Test](image3)

(a) Vibration Test  
(b) Vacuum Test  
(c) Thermal Test  
Fig.17 Environmental Tests

5. Micro-Gravity Test

Micro-gravity test was conducted to measure deployment speed and attitude disturbance of the separation plate at MGLAB (Micro-Gravity Laboratory) in Japan. MGLAB has a vertical 150m underground vacuum tube. It realizes good quality microgravity environment, $10^{-4}$ order G level, for about 4.5 seconds.

Tether deployment mechanism used in the micro-gravity test was the equivalent of FM installed in Cute-1.7 + APD, as shown in Fig.18. And Fig.19 shows the experimental set-up. Experimental volume was about $200*300*600$ mm$^3$. There were two video cameras and a light on the bottom of this area. And a video camera was located at the top-side of the tether deployment mechanism. Locations of these equipments are shown in Fig.19 and the image from the bottom camera is shown in Fig.20.

![Model for Micro-Gravity Test](image4)

![Set-up for Micro-Gravity Test](image5)

![Image from the bottom camera](image6)

Fig.18 Model for Micro-Gravity Test  
Fig.19 Set-up for Micro-Gravity Test  
Fig.20 Image from the bottom camera
The motion of the separation plate could be measured using images taken by the bottom cameras. 30mm interval grid lines were drawn on all inside walls to calibrate the camera-based measurement. The motion of the tether immediately after separation could be taken by the top-side camera.

The initial release seed of the separation plate and the amount of the winding tether were experimental parameters in the micro-gravity test. The initial release speed was changed by exchanging the pushing spring. These parameters and measured results are shown in Table 2.

<table>
<thead>
<tr>
<th>Exp.No.</th>
<th>Spring</th>
<th>Ideal Initial Speed ***</th>
<th>Measured Initial Speed</th>
<th>Winding Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>same *</td>
<td>0.75 m/s</td>
<td>0.43 m/s</td>
<td>half</td>
</tr>
<tr>
<td>2</td>
<td>same *</td>
<td>0.75 m/s</td>
<td>0.47 m/s</td>
<td>full</td>
</tr>
<tr>
<td>3</td>
<td>stronger **</td>
<td>1.4 m/s</td>
<td>1.1 m/s</td>
<td>half</td>
</tr>
</tbody>
</table>

*: Spring constant is the same as used in Cute-1.7 + APD.
**: Spring constant is stronger than used in Cute-1.7 + APD.
***: Neglecting friction loss

The experimental results show that the measured initial release speed (0.43-0.47 m/s) was almost the same as that of ground experiment results (0.48 m/s). A part of coiled tether was taken away from the tether storage in case of the full winding amount (Exp. No.2), though the tether was not tangled. The tether was also not tangled at Exp. No.1. According to these results, amount of winding tether did not disturb normal tether deployment. The attitude disturbance was relatively smaller at low speed (Exp. No.1) than that of high speed (Exp. No.3). Fig.21 shows the camera images in Exp. No.1.

Cute-1.7+APD installing the tether deployment mechanism was successfully launched into orbit and initial operations were also conducted. But the communication receiver control unit had a trouble. Radiation hazard was supposed to cause it. Now we are continuing a recovery operation, so experiment of tether deployment in orbit is not yet conducted.

6. Conclusions

In this paper, a tether deployment mechanism was developed for Cute-1.7 + APD. And the characteristic of the tether deployment mechanism and results of evaluation and environmental tests were described. As for the characteristic, originally developed elements such as string hold method, tether storage method, tether deployment sensor and electricity transmission method through pushing springs were explained. The feasibility of the tether deployment mechanism was verified in several evaluation and environment tests. Cute-1.7 + APD installing the mechanism was successfully launched into orbit, but tether deployment test on orbit was not yet conducted due to satellite failure.

References

[1] Cute-1.7 + APD website: lss.mes.titech.ac.jp/ssp/cute1.7/index_e.html