Rocket Separation Mechanism for Pico Mother and Daughter satellite “KUKAI”*  

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Abstract  
KUKAI is a pico-satellite developed by Kagawa University and was launched by the H-IIA rocket by the Japan Aerospace Exploration Agency (JAXA) on 23 January 2009. The primary objective of KUKAI is technical verification of a tethered space robot, which is a new type of space robot system proposed in previous work. KUKAI consists of mother and daughter satellites for tether deployment. This was the first time to launch mother-daughter satellite among pico-satellites less than 10kg in the world. Then, it is important to develop separation mechanism. The separation and the launch lock mechanisms for KUKAI have been developed, and confirmed and evaluated by launch environment and microgravity condition. As the launch result, KUKAI was separated from the rocket as planned, the system started normally, and deployment of the solar paddle and the antenna was succeeded.  

Key words: Space Engineering, Vibration of Mechanism, Modal Analysis, Mother-Daughter Satellite, Rocket Launch  

1. Introduction  
In recent years, the pico-satellites were been paid a bigger attention in the world [1]. They can be developed in short-term and by low cost. Kagawa University launched the Kagawa Satellite “KUKAI,” which is a kind of pico-satellites, in January 2009 by the H-IIA rocket from Tanegashima Space Center as a technology demonstration satellite of a tethered space robot. As a mother-daughter satellite with the purpose of tether deployment experiment, we developed the mother satellite to have a tether deployment and retrieval system and the daughter satellite to be the tethered space robot. As the development and on-orbit experiment of KUKAI was directed toward the practical application of a tethered space robot, this experiment, as the first trial of a mother-daughter pico-satellite in the world, a tethered satellite and a robotic satellite, can significantly contribute to technology acquisition in the field of developing small satellites, which has been paid much attention in recent years.  

Tethered space robot is a new type of space robot system proposed in the previous work [2], [3]. It can be a small robot without redundancy because emergency retrieval is possible. Also it has an advantage for energy consumption because translation and attitude controls by tether tension are possible. And then, collision damage of a target in robot task (its accident will happen with high possibility under the microgravity) will be slight. Tethered Satellite System (TSS) is expected for practical uses and has studied so long because of its lightness and compact storage [4]. Existing TSS is considered that tether is extended for several kilometers to hundreds kilometers [5], [6], [7]. Gemini-Agena program [8] and Tethered Satellite System Project by U.S.A. and Italy [9] were performed for space
verification experiments. On the other hand, recently, a formation flight mission [10] and a debris removal mission [11] are considered as tethered system applications.

KUKAI consists of mother and daughter satellites. Also it has motion parts, mainly as the tether deployment and robotic mechanisms. Those have to be locked under rocket launch. This is the first trial for a 10kg mass order satellite having such mission devices in the world. For simplify the launch lock mechanism, KUKAI employed a pod style for separation mechanism. Especially the launch lock mechanism for the mother and daughter satellites became very simple. Many 10cm cube size pico-satellites were launched in the world, and pod styles were employed for their separation mechanism. A pod style has merits as: firstly unexpected breakage of the satellite does not damage other satellites mounted on the same rocket; no switch is needed for solar power supply line under cold launch; and the satellite is not damaged during carriage. In this paper, measure against to launch vibration and impact is explained especially for the separation mechanism, and the vibration test result has been reported. Also, the microgravity experiment for rocket separation of the satellite has been reported. Finally, the launch result has been described.

2. Mission Outline

Main characteristics of KUKAI are: mother and daughter satellite; tether deployment satellite; robotic satellite having a camera. It launched by the H-IIA rocket from Tanegashima Space Center by JAXA on January 23, 2009, and succeeded in putting onto the planned orbit. Figure 1 shows the flight model of KUKAI, and table 1 shows the mass and the scale. The mother satellite and the daughter satellites are shown in the right and the left in figure 1, respectively.

<table>
<thead>
<tr>
<th>Table 1 Mass and scale of KUKAI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mother satellite</strong></td>
</tr>
<tr>
<td>Scale</td>
</tr>
<tr>
<td><strong>Daughter satellite</strong></td>
</tr>
<tr>
<td>Scale</td>
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</tbody>
</table>

Figure 2 shows the main mission sequence of KUKAI. In phase A, the mother and the daughter satellites perform orbital motion under the docking condition. They are separated away and tether is deployed by the command from the ground station (phase B). Here, the daughter satellite begins attitude control by arm link motion based on information of tether length obtained through inter satellite communication. The daughter satellite takes a picture of the mother satellite when the tether is extended enough (phase C). After that, tether is...
retrieved, and then the mother and the daughter satellites dock (Phase D). By the one command from the ground, the above sequence will be terminated.

3. Rocket Interface

3.1 Separation Box

Separation mechanism of KUKAI is a pod style. As shown in figure 3, the mother and the daughter satellites under the locked configuration are inserted in the separation box having the top cover. Under the locked configuration, the mother and the daughter satellites contact at the top four points, and the four guide parts restrict the satellites in the horizontal
direction. The top cover restricts the satellites in vertical direction. Also, KUKAI has the solar paddles having the antennas for communication with the ground station, named Solar Paddle Antenna (SPA). The SPA are locked as shown in figure 5, therefore the SPA are unlocked automatically by separation of the mother and the daughter satellites. As shown in figure 6, KUKAI is separated from the rocket by opening the top cover, the SPA are deployed after separating away enough from the rocket, and then Morse signals begins to be transmitted. The sequence was confirmed by the microgravity experiment for separating condition and by the electrical test for starting time of transmission.

MS: Mother satellite, DS: Daughter satellite

Fig. 4 Frame guide contact.

Fig. 5 Solar paddle launch lock.

Fig. 6 Separation from the rocket and solar paddle deployment.
3.2 Separation Mechanism

Figure 7 shows the scale of the separation box. Its mass is 12kg, and then the total mass with the satellites is 20kg. It consists of the main box, the bottom plate, and the top cover. The main body is fixed to the rocket at the bottom. The top cover can be closed and opened by the rotational hinge joint. As shown in figure 8, the bottom plate is suspended by the springs in the main body, and the springs are extended by the satellites. The satellites are locked by closing the top cover. Through the solid lubrication parts, the satellites contacts with the top cover and the bottom plate, and the bottom plate contacts with the main body. By opening the top cover, the bottom plate pushes the satellites by the force of spring extension. Figure 9 shows opening and closing mechanism of the top cover. The top cover is fixed by the lock bolt. The lock bolt is fixed by the nylon line, which can be cut by the heater cutter to open the top cover.

Fig. 7 Design parameters of the separation box.

Fig. 8 Stowed condition of the separation box.
4. Rocket Launch Vibration

4.1 Vibration Test Condition

The requirements for the rocket launch are that the structural characteristics is kept, and that there are no extremely resonance frequency less than 100Hz in horizontal, and that less than 50Hz in vertical. In the ground environmental test, the following vibrations were given to the satellites in the separation box, and frequency responses were measured before and after each vibration:

(a) random vibration;
(b) sinusoidal vibration and quasi-static acceleration.

Tables 2, 3, and 4 show the maximum quasi-static acceleration, the sinusoidal vibration, and the random vibration level, respectively.

Table 2 Maximum quasi-static acceleration

<table>
<thead>
<tr>
<th>Axis</th>
<th>Longitudinal</th>
<th>Lateral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compresson</td>
<td>-58.84m/s²/2</td>
<td>±49.04m/s²/2</td>
</tr>
<tr>
<td></td>
<td>{−6.0[G]}</td>
<td>{5.0[G]}</td>
</tr>
<tr>
<td>Tension</td>
<td>49.04m/s²/2</td>
<td>±49.04m/s²/2</td>
</tr>
<tr>
<td></td>
<td>{5.0[G]}</td>
<td>{5.0[G]}</td>
</tr>
</tbody>
</table>

Table 3 Sinusoidal vibration

<table>
<thead>
<tr>
<th>Axis</th>
<th>Frequency [Hz]</th>
<th>Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>5～100</td>
<td>24.52m/s²/2_{O.P}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{2.5G_{O.P}}</td>
</tr>
<tr>
<td>Lateral</td>
<td>5～100</td>
<td>19.62m/s²/2_{O.P}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>{2.0G_{O.P}}</td>
</tr>
</tbody>
</table>

(Duration: 1 cycle by 4 octave/minute)
Table 4 Random vibration level

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power spectral density(G²/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20~200</td>
<td>+3dB/oct</td>
</tr>
<tr>
<td>200~2000</td>
<td>0.032</td>
</tr>
<tr>
<td>Effective value</td>
<td>7.8 [Grms]</td>
</tr>
</tbody>
</table>

1G = 9.80665m/s²/2 (Duration: more than 60 seconds)

4.2 Vibration Test Result

Frequency responses were measured by the acceleration sensors attached to the two points ① and ② as shown in figure 10. The structural characteristic of point ② is important for separation. Each response ratio was shown in figure 11.

![Acceleration measurement point](image)

It is noted from the results that the structural characteristics was kept, and that there were no extremely resonance frequency in horizontal, and that less than 80Hz in vertical. Table 5 shows the lowest frequency of extremely large response in each axis. In the X axis (the vertical), the resonance frequency could not be observed, therefore here shows the lowest frequency in the experimental data calculated by the analysis software, and the peak frequency is shown by ( ).

Table 5  Measured primary frequency

<table>
<thead>
<tr>
<th></th>
<th>X axis</th>
<th>Y Axis</th>
<th>Z Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-measure</td>
<td>359</td>
<td>84</td>
<td>91</td>
</tr>
<tr>
<td>(666)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Random</td>
<td>350</td>
<td>94</td>
<td>97</td>
</tr>
<tr>
<td>(643)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>350</td>
<td>91</td>
<td>94</td>
</tr>
<tr>
<td>(644)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 11 Response ratio of amplitude by spectral analysis
5. Separation Test Under Microgravity

Microgravity experiment by parabolic flight of an airplane was performed in order to verify and evaluate the separation sequence. The separation is restricted by the rocket requirement as:

(a) separation speed: 0.8 m/sec ± 0.2 m/sec;
(b) attitude error at separation: less than 10 degree.

Figure 12 shows the layout in the cabin and strategy of the experiment. The satellites are deployed from the back to the front in the cabin. Under the microgravity, the satellites are separated by opening the top cover of the separation box. The video camera 1 captures the top position (a) at 30fps, and also the camera 3 captures the bottom position (b) at 30fps, respectively. In this experiment, the dummy weight satellites, those total mass (and theoretical separation speed) can be adjusted as 5.64 (0.97), 7.14 (0.86), 8.6kg (0.79m/s), were used.

Figure 13 shows time histories in horizontal axis of (a) the top position and (b) the bottom position of the satellite, respectively. It is noted that the satellites were accelerated until the satellite went out of the separation box (see figure (a)), and after separation, it kept constant velocity (see figure (b)). Also, the large mass accelerated slowly and separated speed was slow. Figure 14 shows separated velocity with respect to the three kinds of mass. Also, it was confirmed from the video camera pictures that attitude error was less than 10 degree. It is noted that the developed separation mechanism satisfies the restriction by the rocket requirement.

6. Launch Result

Figure 15 shows pictures of the satellites under the locked configuration and the separation box. Figure 16 shows the picture taken by the main satellite “GOSAT” when it was separated from the rocket. It is noted from the picture that KUKAI had no troubles under the launch condition.
The H-IIA rocket No. 15 was launched at 12:54 JST (Japanese Standard Time) on January 23, 2009. According to the planned sequence, KUKAI comes into communication area of the ground station in Kagawa University at 14:34 JST for the first time. At that time KUKAI goes from the north to the south. We could receive the Morse signals from the mother satellite at 14:34 JST, and from the daughter satellite at 14:36 JST. It could be said that KUKAI was separated from the rocket as planned, the system started normally, and
deployment of the solar paddle antenna was succeeded. In the main mission, although tether was extended for several centimeters, separation of the mother and the daughter satellites, and inter satellite communication in phase B shown in figure 2 were succeeded. Also, the daughter satellite succeeded to take a picture of the mother satellite. And also, functions of arm motion and docking by retrieving tether were verified. It can be said from the orbital experiment results that technology for 10kg-pico mother and daughter satellite was acquired.

7. Conclusion

This paper describes vibration test and separation experiment of KUKAI, focusing on the separation mechanism. KUKAI was developed for the purpose of technology demonstration for a tethered space robot. This was the first trial in the world for a 10kg mass order satellite having such characteristics as mother and daughter system, tether deployment system, and robotic system. The pod style separation mechanism, which is simplified and suitable for the above characteristics, was developed. Its performance was
verified and evaluated by vibration test and microgravity experiment. Those results confirmed the requirement of the H-IIA rocket launch. As the launch result, KUKAI was separated from the rocket as planned, the system started normally, and deployment of the solar paddle and the antenna was succeeded. It can be said that rocket separation technology for 10kg mass order and mother-daughter satellite was acquired.

Acknowledgement

This work is partially supported by the Japan Space Forum, Grant-in-Aid for Scientific Research, and New Energy and Industrial Technology Development Organization.

References