Development of a Non-explosive Segmented Nut-type Holding and Release Mechanism for Cube Satellite Applications*

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A nylon cable cutting mechanism triggered by a nichrome burn wire is generally used for cube satellite applications for the purpose of holding and releasing onboard appendages owing to its simplicity and low cost. However, the disadvantages of this mechanism are a lower constraint force and also unavoidable system complexity when it is applied to cube satellites with multiple deployable structures. In this study, as the result of an internal development program for cube satellites, we propose a segmented nut-type holding and release mechanism that affords advantages such as high load capability and negligible induced shock. A demonstration model of the mechanism has been fabricated, assembled and functionally tested under qualification temperatures.

Key Words: Holding and Releasing Mechanism, Nichrome Burn Wire, Cube Satellite

1. Introduction

Cube satellites are a type of cube-shaped, nano-class miniaturized satellite that are much smaller than commercial satellites, used for space research. One satellite usually has a volume of 1,000 cm$^3$ for a standard size of 1U, and a mass of less than 1.33 kg, and it typically uses commercial off-the-shelf components. This type of satellite allows scientists to perform space science and exploration missions with relatively low development costs. It is also a great way to attract and train students who will serve as the future generation of engineers because they are engaged before and after the launch, including during stages such as the generation of mission ideas, hands-on development, operations and on-orbit data analysis.

Cube satellites are being used for increasingly complex missions, and their functionality in an extremely small package brings rise to numerous mechanisms and deployable structures that are necessary for achieving mission-related challenging functions. Cube satellite architectures also require that deployable structures such as solar arrays, antennas and other appendages stowed for launch are released and deployed in orbit for operation. The appendages require holding and releasing mechanisms that can provide adequate strength and stiffness to survive the launch mechanical environment and release functions that enable the deployment of these appendages in orbit.

Pyrotechnic devices are widely used in the aerospace engineering field, especially for satellite separation and the holding and releasing of appendages owing to their high strength, stiffness and space heritages. However, these devices often induce a high-level of dynamic response owing to the sudden transient release of the restraining energy. This high-frequency pyroshock sometimes induces malfunctions of electrical components or critical damage to the brittle components of a launch vehicle or a satellite, resulting in mission failure. The issue of the high shock generated from the pyrotechnic device becomes even more critical, especially for pico-class satellites. The application of pyrotechnic devices to a separation mechanism for pico-satellites may easily cause problems because the external and internal parts are physically closer to the source of shock than those on larger satellites owing to the small size and limited volume.

To reduce the shock level of pyrotechnic devices, several types of non-explosive separation devices using shape memory alloy have been developed and applied in actual space missions. The advantages of the non-explosive actuators are the relatively lower shock, high load capability and reusability for many cycles after simple resetting. However, even though the shock level is low, these devices may still have some applicability limitations for the cube satellite owing to their high cost and the lack of suitable specifications, such as low weight, suitable dimensions and a relatively high shock on that scale. The high cost of these devices makes them impractical to use on cube satellites that have development cost limitations.

A nylon cable cutting mechanism triggered by a nichrome burn wire has been widely used for cube satellite applications owing to its simplicity and low cost. Nakaya et al. developed a separation mechanism dedicated for cube satellite separation from a launcher. The four jaws of the mechanism that holds the cube satellite under the launch environment are tightened by a nylon cable, which is cut by heating a nichrome wire. The turnstile antenna developed by Gomspace consists of four monopole antennas with near omni-directional coverage. All four antenna elements are individually fixed by nylon cables and released by the activation of burn resistors. Thurn et al. developed a burn wire release mechanism to release two carpenter tape deployments and a stacer and tether deployment system. It utilizes

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a compression spring system in order to apply a force and stroke to the nichrome burn wire for safer release. They performed functional performance tests under vacuum conditions with the qualification temperature range of -50°C and 70°C. The test results under vacuum conditions show a shorter cut time for the burn release mechanism than under ambient conditions.

Generally, these devices meet many of the basic requirements for appendage separation of cube satellites. However, system complexity is unavoidable when applied to cube satellites with multiple deployable structures. In some cases, where more than one heated nichrome burn wire is used, synchronous release is an important factor in mission success. A lower constraint force is also one of the disadvantages of the mechanism. The drawbacks mentioned above are compelling motives for the investigation of new approaches for holding and releasing mechanisms for cube satellite applications. In this study, a segmented nut-type holding and release mechanism is proposed and investigated. The nut segment built up by nylon cable winding is released by cutting the nylon cable, which is triggered by a nichrome burn wire. To demonstrate the effectiveness of the mechanism, we performed a function test, a static test and a shock measurement test. The test results indicate that the proposed mechanism functions well, as intended by the design.

2. Design Description of Segmented Nut-type Holding and Release Mechanism

2.1. Configuration and operating principle

A segmented nut-type holding and release mechanism is proposed and investigated as a type of non-explosive mechanism. It has the advantage of negligible induced shock and higher load capability than conventional nylon cable cutting mechanisms generally used for cube satellite applications. In addition, this mechanism also enables the synchronous release of multiple deployable structures according to the implementation method.

Figure 1 shows the configuration of the segmented nut-type holding and release mechanism before and after separation. Figure 2 shows the demonstration model of the separation nut assembly integrated with the nichrome burn wire and the housing with a Velcro fastener. The mechanism is made out of Al6061 and is composed of the segmented nut, an M6 constraint bolt, a nylon cable, a nichrome burn wire, a separation spring and the housing with Velcro fasteners. The mechanical constraint of the segmented nut is implemented by the nylon cable winding and a Velcro strip is attached to the surface of the integrated nut. For easier application of the nylon cable, V-shaped grooves are added to the surface of the nut. The constraint bolt is integrated into the nut through the housing to apply the constraint force to the appendage located between the housing and the constraint bolt, as shown in Fig. 1(a). For releasing the mechanical constraint between the segmented nut and the constraint bolt, the nichrome burn wire is used as an actuator. When the nichrome burn wire is heated, the nylon cable wound around the integrated nut is cut and the segmented nut is consequently separated by the restoration force of the two separation springs compressed inside the segmented nut. The separation springs allow the separated nuts to move radially away from the released constraint bolt and to become attached to the Velcro fastener inside the housing to avoid interference between the released nut and the constraint bolt immediately after separation, as shown in Fig. 1(b).

2.2. Nichrome burn wire implementation

To determine an effective nichrome burn wire implementation method for ensuring a successful cut, two types of segmented nut mechanisms were investigated. Figure 3 shows the integrated nut with the two types of nichrome burn wire interfaces. In Type-I, the nichrome wire is located on the insulation tape and directly fixed by the nylon cable to avoid heat sinking from the nichrome wire to the rest of the mech-
anism. Type-II has a different wire interface. In this model, the nichrome wire is positioned on the V-shaped interface and it is far away from the mechanism’s heat sinks to avoid heat loss and ensure a successful cut. In addition, the nichrome wire is implemented reciprocally in a zigzag line along the fastened nylon cable, as shown in Fig. 3(b).

Figure 4 shows the test configuration to check the release functionality of the mechanism. To confirm the release status of the mechanism, a constraint bolt is connected to a tensioned bar to retract the bolt immediately after activation of the mechanism. A total of five release function tests were performed for each type of mechanism.

Figure 5 shows a successful release sequence of the mechanism, from holding to the releasing state of the mechanism triggered by the nichrome burn wire. The released nut is successfully attached to the Velcro fastener without any interference with the constraint bolt during the release sequence.

Tables 1 and 2 summarize the release test results of the mechanism with Type-I and Type-II nichrome burn wire interfaces, respectively. The Type-I mechanism was released successfully only when the input power was 11 W. The other cases with an input power of 6 W failed. This was caused by inferior contact between the nichrome burn wire and the

Table 1. Summary of release function test results for the Type-I nichrome burn wire interface.

<table>
<thead>
<tr>
<th>No. of tests</th>
<th>Input power (W)</th>
<th>Release time (s)</th>
<th>Bolt release (Pass/Fail)</th>
<th>Nut release (Pass/Fail)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1.5</td>
<td>P</td>
<td>P</td>
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<tr>
<td>2</td>
<td>11</td>
<td>1.4</td>
<td>P</td>
<td>P</td>
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<tr>
<td>3</td>
<td>6</td>
<td>—</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>—</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>—</td>
<td>F</td>
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Table 2. Summary of release function test results for the Type-II nichrome burn wire interface.

<table>
<thead>
<tr>
<th>No. of tests</th>
<th>Input power (W)</th>
<th>Release time (s)</th>
<th>Bolt release (Pass/Fail)</th>
<th>Nut release (Pass/Fail)</th>
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</thead>
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<td>P</td>
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<td>P</td>
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<td>6</td>
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<td>P</td>
</tr>
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</table>

Fig. 3. Nichrome burn wire interface. (a) Type-I, (b) Type-II.

Fig. 4. Function test configuration.

Fig. 5. Sequence of successful releases of the mechanism.
cables induced by the loosening of the cable tension due to partial cutting of the cables. The Type-II mechanism, on the other hand, exhibited successful releases in all test cases. The release time was within 3.5 s under ambient room temperature conditions, and it could be reduced by increasing the input power and under vacuum conditions. The test results indicate that the Type-II design can guarantee a reliable cutting through the cable without failure when the minimum required power is 6 W. This can be provided by a Li-ion battery with a maximum capability of 10 W, which can be adjusted by using an electrical circuit design to supply a constant current to the nichrome wire independent of the resistance of the wire and the voltage available from the spacecraft.

2.3. Cube satellite applications

Figure 6 indicates an application example of the mechanism for the synchronous release of a deployable turnstile antenna. Some parts are intentionally blanked for an easier understanding of mechanism implementation. For effective accommodation in the limited small volume of a 1U Cube Satellite (CubeSat), some appendages are positioned near the mechanism. A single mechanism is proposed for the synchronous release of the four turnstile antennas contrary to the conventional multiple burn wires cutting method, which requires four burn wires to be activated for deployment. The out-of-plane direction of constraint for the upper cube module of the cube satellite is achieved by the holding and release mechanism to ensure the structural safety of the satellite during lift-off. The in-plane directional constraint is achieved by a guide rail interface, as shown in Fig. 6(a). When the current is sent through the nichrome burn wire, the upper cube module with the antenna-holding brackets is deployed by the restoration force of the springs compressed inside the beam. Subsequently, the released antenna is automatically deployed, as shown in Fig. 6(b).

The holding and releasing mechanism proposed in this study is one of the main payloads to be verified in the Cube Laboratory for Space Technology Experimental Project (STEP Cube Lab) mission, which is the first pico-class satellite developed at the Space Technology Synthesis Laboratory (SSTL) of Chosun University, and is scheduled to be launched in 2015. The main objective of the STEP mission is to verify the effectiveness of the fundamental space technologies researched at domestic universities by investigating mission data obtained from on-orbit thermal analysis. Figure 7 indicates the release time measurement test results obtained from the ambient, minimum and maximum qualification temperature conditions, respectively, judged by the stabilized target temperature is located on the head of the constraint bolt. The low and high target temperatures were achieved by using dry ice and a heater, respectively. The function tests were performed successfully. The measured release times were less than 3.4 s and 5.1 s under high and low qualification temperature conditions, respectively, although there were variations. The test results indicate that the mechanism functions under the qualification temperature limits, as intended in the design.

3. Test Results

3.1. Function test

To verify the functional performance of the proposed mechanism, we performed functional tests with the same test configuration shown in Fig. 4 under qualification temperatures of −20°C and 50°C, obtained from on-orbit thermal analysis. Figure 7 indicates the release time measurement test results obtained from the ambient, minimum and maximum qualification temperature limits. For the experiment, a total of five release function tests were performed for each temperature condition. The temperature reference point to judge the stabilized target temperature is located on the head of the constraint bolt. The low and high target temperatures were achieved by using dry ice and a heater, respectively. The function tests were performed successfully. The measured release times were less than 3.4 s and 5.1 s under high and low qualification temperature conditions, respectively, although there were variations. The test results indicate that the mechanism functions under the qualification temperature limits, as intended in the design.

3.2. Static test

Figure 8 shows the static load test configuration used to measure the characteristics of the mechanism in constant-rate extension/contraction tests in which the high and low qualification temperatures of the mechanism were obtained by using heaters and dry ice, respectively. The temperature
reference point to judge the target temperature stabilization is on the bolt head. In the test, five cycles of extension/contraction force were applied repeatedly to the mechanism in the axial direction by moving the crosshead of the load tester up and down under various temperatures. The stiffness was measured to judge the structural safety of the mechanism before and after exposure to the qualification temperatures.

Figure 9 indicates the measured stiffness values under ambient and qualification temperatures. The measured stiffness values after testing under the low and high qualification temperatures are also plotted in the figure for comparison with the value before exposure to the qualification temperatures. The average stiffness of the mechanism in the axial direction was 6710 N/mm, and the stiffness variation before and after exposing the mechanism to the low and high qualification temperatures was within 4%, which had a negligible effect on mechanism performance. A release function test was performed to check the functional performance of the mechanism after the static load test. Release of the mechanism, triggered by the nichrome burn wire, was performed successfully without any failure, as shown in Fig. 8.

Figure 10 shows the fracture test results for measuring the allowable axial load of the mechanism. The mechanism is capable of holding an approximate axial load of 3600 N. This is a sufficient margin for the required allowable axial load of 40 N for the current application, as shown in Fig. 6. However, this also indicates that the mechanism can be applied to various deployment systems for small satellites, where a high allowable axial load capability is required.

3.3 Shock level measurement test

Figure 11 indicates the shock level measurement test configuration. The accelerometer is installed 16 mm from the center of the mechanism. Figure 12 indicates the Shock Response Spectrum (SRS) obtained from the acceleration release shock measurement test. The maximum SRS is approximately 3 G when a $Q$ factor of 10 is applied. The shock is mainly induced when the separated nut hits the housing due to the restoration force of the separation springs after triggering the burn wire. However, the shock level is negligibly lower than the conventional frangibolt-type SMA actuator (i.e., FC2 Model) with the maximum SRS value of...
2000 G, although the allowable axial load of the mechanism is almost the same as that of the conventional SMA actuator. Table 3 summarizes the specification of the non-explosive segmented nut-type holding and release mechanism obtained from the experimental investigations performed in this study. The table indicates that the mechanism is effective for achieving the main development objectives of low cost, high load capability and negligible low shock.

4. Conclusion

A non-explosive segmented nut-type holding and release mechanism developed for the purpose of cube satellite implementation guarantees a high load capability and negligibly low shock. This mechanism’s high load capability in the axial direction is achieved by clamping the constraint bolt to the segmented nut built up by nylon cable winding. A nickel-chrome burn wire is used to release the segmented nut, and the implementation method proposed in this study is effective for reliably cutting through the cable without failure under the qualification temperature limits. The high load capability and negligibly low shock of the mechanism were also demonstrated by static and shock measurement tests. In addition, combined with the ball-and-socket interface proposed in this study, also opens up the possibility of applying the mechanism to other cube satellite applications such as the synchronous release of multiple deployable structures and the mechanism for separating the cube satellite from its launcher.

Acknowledgments

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References

4) TiNi Aerospace, Inc.: http://www.tiniaerospace.com

Table 3. Specifications of the demonstration model for the non-explosive segmented nut-type holding and release mechanism.

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
</tr>
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<tbody>
<tr>
<td>Volume</td>
<td>φ 28 mm × 26 mm</td>
</tr>
<tr>
<td>Mass</td>
<td>19 g</td>
</tr>
<tr>
<td>Allowable axial force</td>
<td>3600 N</td>
</tr>
<tr>
<td>Release time</td>
<td>&lt;3.5 s (ambient), &lt;6 s (at –20°C)</td>
</tr>
<tr>
<td>SRS max.</td>
<td>3 G</td>
</tr>
<tr>
<td>Required power</td>
<td>6 W</td>
</tr>
<tr>
<td>Qualified temperature</td>
<td>–20°C / 50°C</td>
</tr>
<tr>
<td>Release principle</td>
<td>Nichrome burn wire cutting</td>
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