Characterization of Environment-driven Thermal Buckling Actuator for an Asteroid Exploration Rover

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Abstract

Asteroid probe HAYABUSA 2 and asteroid exploration rover MINERVA 2 with a hopping mechanism on the asteroid are planned by JAXA. For locomotion mechanism of the rover, we propose a thermal buckling-type bimetal actuator which is driven by environmental temperature change at sunrise and sunset. This paper describes the design and fabrication of a practice model of the bimetal buckling actuator with a movable mass. A hopping examination model was also fabricated and examined under 1G gravity on the earth. The actuator successfully hopped to a height of 25 mm at 71°C in heating and 20 mm at 49°C in cooling by the buckling and reverse-buckling motion. These results suggest that the rover can hop to 1.4 m and 1.1 m height in heating and cooling cycles at the asteroid surface with micro gravity. Moreover, deformation properties of the bimetal actuator were evaluated in detail. No plastic deformation occurred below 150°C under operative condition. The bimetal actuator was able to keep elastic property at 80°C for 700h even when it was under clamped condition for launch and flight in space.

1 Introduction

Several asteroid probe missions have been executed in last two decades. The “NEAR Shoemaker“ developed by NASA reached near the earth asteroid Eros in 2000 [1]. Asteroid probe “Hayabusa” (MUSES-C) developed by JAXA reached the asteroid Itokawa in 2005, and the mission of sample-return to Earth was successfully accomplised in 2010 [2]. In 2011, DAWN developed by NASA has gone to the asteroid Vesta [3]. JAXA is planning a mission of “Hayabusa 2” to visit the asteroid named 1999 JU3 in 2018 [4].

In the Hayabusa mission, an exploration rover ”MINERVA” was developed and carried to the asteroid Itokawa. Although it could not land on the asteroid, main system of it was able to work in space. The rover MINERVA has a torquer for hopping motion on the asteroid surface for in-situ observation at multiple points [5]. In the next Hayabusa 2 mission, JAXA is planning to release small exploration rovers (MINERVA 2) and small lander (MASCOT) to the asteroid surface when Hayabusa 2 approaches near the asteroid [6].

In our previous work, we proposed a novel mobility concept named environment-driven-rover [7]. Several rover prototypes using shape memory alloy (SMA) and bimetal actuators, which could be actuated by environmental temperature change, have been designed.

Rovers with hopping mechanisms based on novel concepts are planned by Japanese university consortium for the MINERVA 2 project. In our research project, we have proposed a basic model of environment-driven thermal buckling actuator for the hopping [8], and thermal actuator with a magnetic latch mechanism for torque [9]. The actuators can instantaneously provide large kinetic momentum and angular momentum, resulting in the hopping and rotating motion of the rover on the asteroid under micro gravity. Our environment-driven actuators have advantage that they need no battery and no CPU for the driving. In addition, the actuators also have an advantage to protect regolith inversion into the rover because the actuators are built-in the rover inside.

In this paper, we focus on the buckling type actuator. we present a novel practical model that the loading capability to the rover is considered. Hopping ability on the earth is also described. Moreover, we describe evaluation results of reliability of the bimetal actuator at high temperature.

2 Concept and structure

Principle of the rover hopping mechanism with a thermal buckling actuator is shown in Fig.1. When the bimetal actuator is heated by sunshine at sunrise, it is deflected by the effect of thermal expansion difference. When the bimetal deflection exceeds a threshold, it is rapidly deflected in the opposite direction due to the buckling phenomenon [2]. In contrast, when the bimetal actuator is cooled at sunset, reverse buckling occurs toward the initial position. A movable mass can be lifted up of the bimetal by the buckling deflections,. The exploration rover can be hopped and rotated by the kinetic momentum of the movable mass.

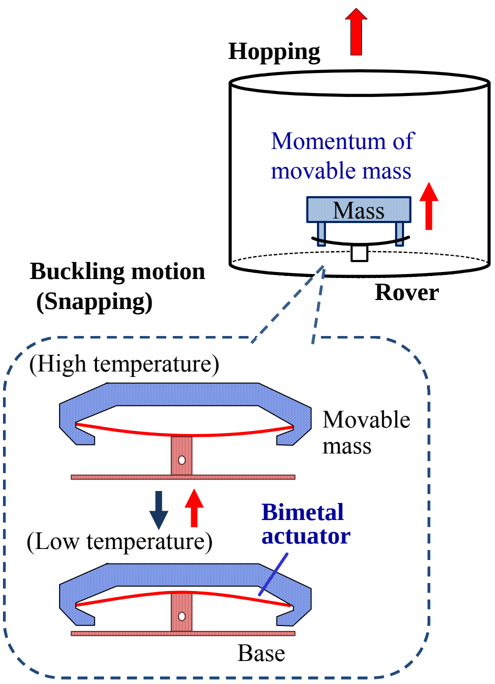


Fig.1 Concept of the environmental -temperature-driven buckling actuator for hopping motion of asteroid exploration rover

2.1 Structure

The structural design of the practical model of buckling actuator is shown in Fig.2. The buckling actuator consists of a Fe-based bi-layered bimetal thin plate (Fuji bimetal Corp., M4 type, length: 59 mm, width: 10 mm, thickness: 0.5 mm), movable mass (7.24 g) made of hard-coated aluminum, and base structure for attaching the rover. The length, width, and height of the practical model are 68 mm, 15 mm, and 27.3~30.0 mm, respectively. Total weight of the practical model was 16.7 g.

Figure 3 shows the fabricated practical model of the bimetal buckling actuator. In our practical model, another bimetal actuator with a magnetic-latch mechanism will also be attached along perpendicular axis of the buckling actuator [9].

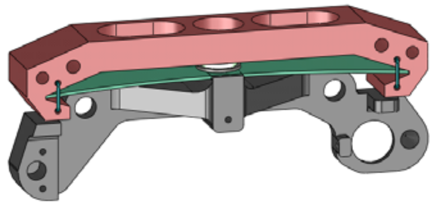


Fig.2 Design of the buckling bimetal actuator (Practical model)

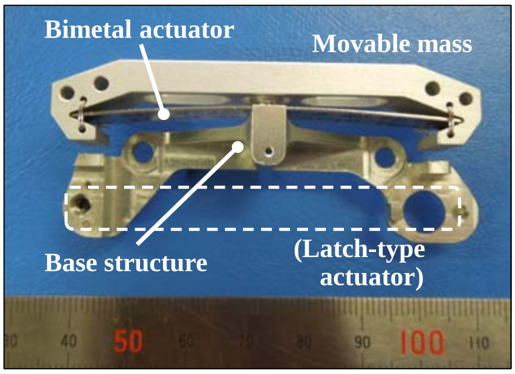


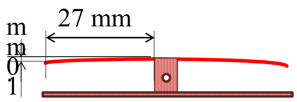
Fig.3 Fabricated buckling bimetal actuator (Practical model)

2.2 Assembly

Figure 4 shows the assembly sequence of the bimetal buckling actuator. As shown in Fig.4(a), the bimetal plate was plastically deflected (initial deflection, 1.0 mm) so that the low-thermal-expansion side of the bimetal was expanded. The initial deflection was necessary to avoid bi-stable deformation behavior. After the initial deflection, the bimetal plate was attached to the movable mass at both hinged ends with further elastically deflection of 0.3 mm (total deflection: 1.3mm) (Fig.4(b)). Thin wires were attached to the both end to avoid the bimetal releasing from the mass. Center of the bimetal plate was fixed to a pillar of the base structure with a screw. The fixed length of the bimetal was 5mm, resulting in the deformable length of the bimetal plate was 27 mm for one side.

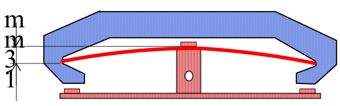
After the assembly was completed, the movable mass should be mechanically clamped to avoid error motion during launch and flight in space. The bimetal plate was further elastically deflected to 0.6mm (total elastically deflection: 1.6 mm), and then the movable mass was clamped to a pillar and the base structure with a tight wire (Fig.4(c)). The wire will be cut by external signal for releasing the movable mass when the rover arrives at the asteroid surface.

When environmental temperature rises by sunshine on the asteroid, the bimetal plate will provide rapid motion of buckling, resulting in rapid lifting motion of the movable mass. The asteroid exploration rover is hopped by the momentum of the movable mass. Reverse buckling motion in the opposite direction also occurs when the bimetal plate is cooled after sunset. The hopping motion is expected every 4 hours on the target asteroid of HAYABUSA 2 mission.



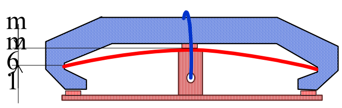
(Plastic deformation)

(a) Initial deformation



(Elastic deflection: +0.3 mm)

(b) Assembly with movable mass



(Elastic deformation: +0.6 mm)

(c) Clamp with wire for launch and flight in space

Fig.4 Assembly and clamping sequence of the buckling bimetal actuator.

3 Buckling and hopping examination

In order to evaluate the hopping property of the buckling bimetal actuator on the earth, hopping examination model was fabricated, as shown in Fig.5. The bimetal actuator and movable mass were attached to a simple base structure. A long bolt was fixed to the base structure. The head of the bolt which threw out the movable mass was used as a base on the ground surface in reverse hopping examination. Total weight of the hopping examination model was 15.0 g. In addition, a small dummy mass (5.3 g) was attached to the base structure.

The buckling motion of the actuator was evaluated in accurately temperature-controlled oven in air under 0 G condition (set in horizontal direction). The buckling motion of the bimetal actuator occurred at about 65°C and 49°C in heating and cooling cycles, respectively.

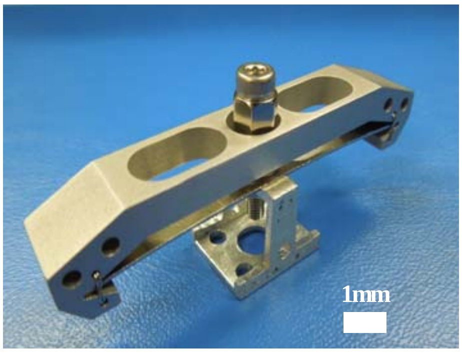


Fig.5 Hopping examination model of the buckling bimetal actuator (with additive 5.0g mass)

The hopping examination model was placed on a ceramic plate heater in the oven, and then it was slowly heated up. Figure 6 shows the hopping motion of the examination model. It successfully hopped to a height of 25 mm by the buckling motion of the bimetal. The buckling temperature slightly rose up to 71°C due to the effect of 1G gravity.

Hopping property in cooling cycle was also evaluated. After buckling occurred at high temperature, the examination model was placed upside down on the ceramic plate, and then it was cooled down. It also successfully hopped by the reverse buckling motion in cooling cycle. The hopping height was 22 mm in the cooling cycle.

According to an estimation based on simple translation motion without rotational, hopping ability of an actual rover on the asteroid was estimated. The hopping examination results on the earth suggests that hopping heights of 1.4 m and 1.2 m are expected in heating and cooling cycles on the asteroid surface where gravity is assumed as 5μG.. Initial velocity of hopping of the rover can be estimated as 11 mm/s which is much less than escape velocity on the asteroid surface. In hopping motion of the actual rover, we should consider

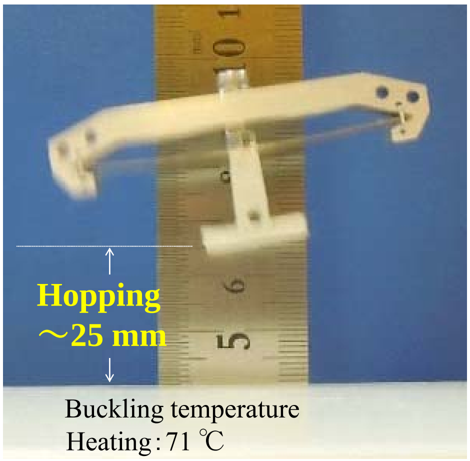


Fig.6 Result of hopping examination on the earth

not only translational hopping motion just above, but also rotational motion caused by angular momentum which depends on the setting position in the rover.

4 Deformation properties of bimetal

Deformation properties of the bimetal actuator were evaluated in detail. A bimetal plate with 27mm length, corresponding to half of the buckling actuator, was used as a cantilever. An end of the bimetal cantilever was fixed to a force sensor at 20°C with additional elastic deformations of +0.3 mm (operative condition in Fig.(b)), +0.6 mm (clamped condition in Fig.(c)), and 2.0 mm (extremely large deflected condition). The bimetal and force sensor were set in an accurately temperature-controlled oven so that the force generation of the bimetal was measured during environmental temperature change. Figure 7 shows the dependence of environment temperature on force generation of the bimetal actuator. In the case of +0.3 mm elastic deformation, the bimetal showed completely elastic behavior in the temperature range of 20 to 150°C. No plastic deformation was observed. When the bimetal was clamped with +0.6 mm elastic deformation, small hysteresis was observed above 140°C (above 6N force), suggesting that the bimetal plastically deformed in such a high temperature range. However, it also showed completely elastic deflection below 140°C. In the case of extreme deflection of +2.0mm, small hysteresis was also observed above 120°C.

Moreover, long term stability of the bimetal under various temperatures was evaluated. No plastic deformation occurred even when the bimetal actuator was left under the clamped condition (+0.6mm deformation) at 80°C for 720 hours. The period when the inner temperature of the rover exceeds 80°C will be much shorter than 720 hours in space flight. Consequently, the bimetal actuator is expected to maintain its elastic property until the rover arrives at the asteroid.

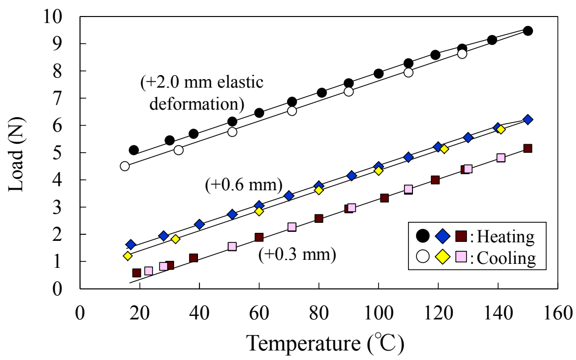


Fig.7 Dependence of environmental temperature on force generation of the bimetal actuator.

5 Conclusions

Environment-driven thermal buckling actuator was proposed and developed for asteroid exploration rover MINELVA 2 in asteroid probe Hayabusa 2 mission planed by JAXA. Novel practical model (16.7 g) and a hopping examination model of the buckling actuator were fabricated using a small aluminum movable mass, a bimetal thin plate, and base structure. The bimetal actuator was successfully driven at about 71°C and 49°C in heating and cooling cycles, respectively. The examination model with a dummy mass hopped to a height of 25 mm and 22 mm by the buckling and reverse-buckling motion under 1G gravity condition. The results suggest that a rover with 900 g mass can hop to 1.4 m and 1.2 m at sunrise and sunset on the asteroid.

Deformation properties of the bimetal actuator were evaluated in detail. The bimetal actuator showed completely elastic behavior in the range to 150°C under the operative condition. No plastic deformation occurred even when the bimetal actuator was left at 80°C for 720 h under the clamping condition. The bimetal actuator is expected to maintain its elastic property until the rover arrives at the asteroid.

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