SOLAR PADDLE ACTUATOR FOR SMALL SATELLITES USING SHAPE MEMORY ALLOY

Toshiaki Iwata*, Yoshiki Fujiwara†, Akira Ogawa†, Hiroshi Murakami* and Yoshitsugu Toda*

* National Institute of Advanced Industrial Science and Technology (AIST)
1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
TEL: +81-298-61-5706
FAX: +81-298-61-5709
E-mail address: totty.iwata@aist.go.jp

†ACTMENT Co. Ltd.
7-15 Minami-Sakaecho, Kasukabe, Saitama 344-0057, Japan

Abstract

A new type of actuator that uses shape memory alloy (SMA) has been developed for the solar paddle of small satellites. This actuator can rotate 360 degrees continuously, can orient the solar paddle to face the sun by itself, and is equipped with a counterweight in order to compensate for the rotating motion of the small satellite in microgravity. The size of the actuator is 100 mm in diameter and 127 mm in height, and the mass is approximately 660 g including the counterweight. We use six SMA springs to rotate the paddle. Each spring has a cylindrical mirror behind it in order to concentrate the sun's energy onto the spring. Movement experiments in the microgravity field and in a vacuum were conducted, respectively. The microgravity experiment uses an air table and the actuator is set up vertically to avoid the effect of gravity. A vacuum chamber with a turntable and two windows is used. An infrared heater is used to heat the SMA from one direction to simulate the sun.

INTRODUCTION

Recently, small satellite systems have been actively investigated. They have been applied in many missions and operated in various forms such as a single satellite, formation flying and constellation. Some are used for observations of the Earth, such as observations of the atmosphere (PICASSO-CENA) [1], as well as for climate modeling (VCL) [2] or gravity and magnetic field modeling (GRACE) [3]; some are applied for space science interferometry missions such as Planet Finders [4], and yet others are used for communication purposes such as the Iridium project, the Globalstar system, Orbcomm and Teledesic [5-6].

In Japan, the National Space Development Agency of Japan (NASDA) has developed plans for such systems; their weight is typically less than 50 kg, and their size is smaller than 500 mm × 500 mm × 500 mm [7]. Since their mass and capacity are limited, the need for a motor actuator, which is massive, large, and requires a power and control system, should be avoided. By using shape memory alloy (SMA), however, we can design a light and small actuator that has no need for electric power or control systems. SMA application in space has been considered, such as for antenna deployment of a spacecraft [8], large-scale structure materials [9], deployment actuators [10] and actuators for robotic mechanisms [11]. In the former three examples, only one motion was needed, so that no control was required after deployment. In the last example, although SMA does not present tribological problems, the heating method for SMA using electrical power was not efficient and required a large power supply. Our proposed mechanism, however, uses SMA during the mission (not one motion). Moreover, since the heating energy comes from the sun, efficiency does not become a problem. Thus, a new type of actuator that uses shape memory alloy (SMA) has been developed for the solar paddle of small satellites.

MECHANISM

The developed mechanism is shown in Fig. 1. This actuator can rotate 360 degrees continuously, can orient the solar paddle to face the sun by itself, and is equipped with a counterweight in order to compensate for the rotating motion of the small satellite in microgravity.

The size of the developed actuator is 100 mm in diameter and 127 mm in height, and the mass is approximately 660 g including the counterweight. We use six SMA springs to rotate the paddle. Each spring is made of 0.8-mm-diameter wire and has 12 turns; the coil diameter is 5.8 mm, and the mass is 0.8 g. Each spring has a cylindrical mirror behind it in order to concentrate the sun's energy onto the spring. The type of SMA is TiNi (Ti 55.2 wt%) alloy, and the transformation temperature is about 330 K. The length of this spring at low temperature is 30 mm, while that at high temperature (above 330 K) is 8 mm, which causes the motion of the actuator. The force generated by the SMA spring is about 10 N, and thus the torque of the actuator is about 0.2 Nm. This torque is sufficient to rotate the solar paddle of a small satellite (the mass will be approximately 1 kg) in microgravity. The counterweight rotates in the opposite direction to the solar paddle rotation at two times the speed, which is achieved by a combination of four gears. This is because we assume that the weight of the solar paddle is two times that of the counterweight, and we can design a smaller actuator by increasing the counterweight's rotational speed. The mechanism was developed based on the concept of the heat engine devised by Ginell et al. [12].

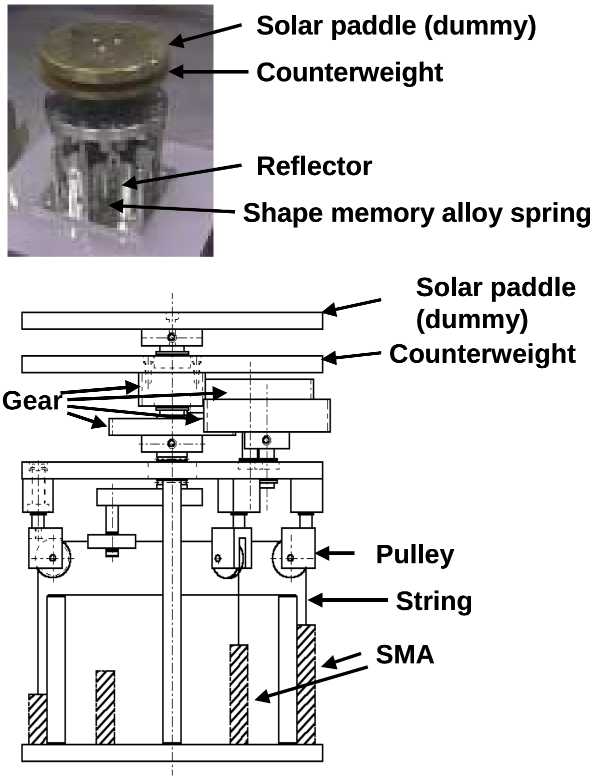

Fig.1 Solar paddle actuator

EXPERIMENTS

In order to confirm the movement in the space environment, motion experiments in a microgravity field and in a vacuum were conducted, respectively. Furthermore, the cooling process was observed under atmospheric conditions.

Microgravity Experiments

In order to confirm that the counterweight is appropriately designed to avoid attitude disturbance of the small satellite, we conducted experiments in a microgravity field. To realize the microgravity environment, an air table was utilized [13]. This method is often used to simulate the microgravity condition on the ground. The schematic diagram of the experimental apparatus is shown in Fig. 2. The small satellite model is levitated on the air table using compressed air, which is generated by a small air compressor (about 0.5 kgf/cm^2). The SMA actuator is set up vertically in order to avoid the effect of gravity. An infrared heater was used to heat the SMA from one direction to simulate the sun. The heater has a parabolic reflector to generate parallel radiation. The heating area is 150 mm × 40 mm. The input was 600 W (i.e., 10 W/cm^2), which is 100 times the sun's energy (0.1 W/cm^2). This heater was also used for other experiments.

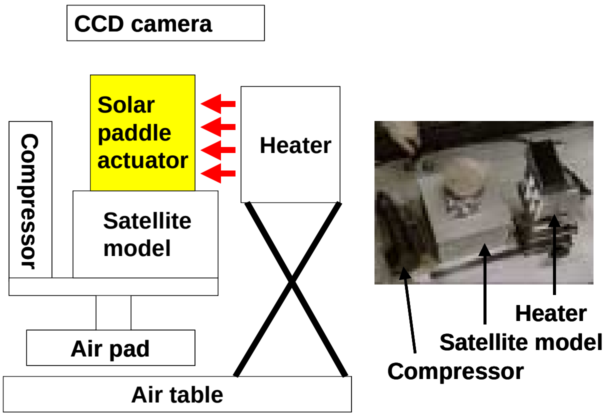

Fig. 2 Microgravity experiment

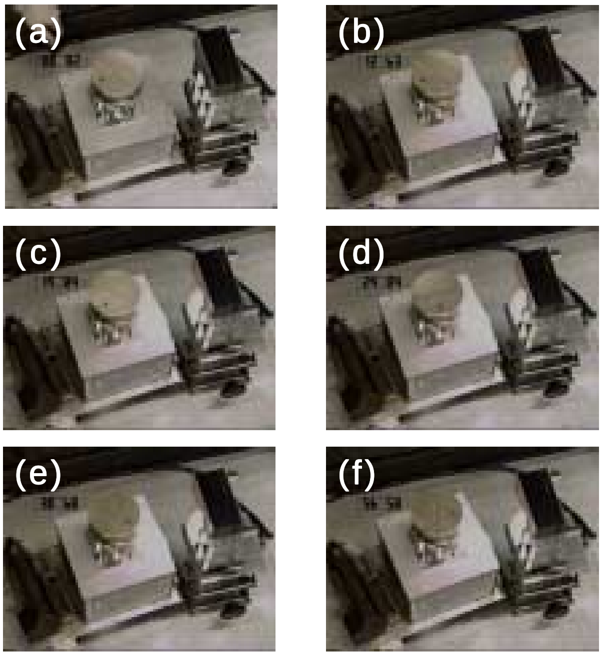

Fig. 3 Paddle motion with counterweight in microgravity.
(a) Observation starts (0 s), (b) motion begins (12 s), (c) approximately 45 deg. motion (19 s), (d) 90 deg. (24 s), (e) 135 deg. (30 s), and (f) motion ends (56 s, approximately 170 deg).

The motions of the paddle with the counterweight and without the counterweight are shown in Fig. 3 and Fig. 4, respectively. The effect of the counterweight is not clear in these results. In the case of no counterweight, the actuator motion is slightly faster than that with the counterweight.

Since the experiments took about one minute, drift motion above the air table makes the evaluation difficult. However, avoiding drift motion for one minute requires extremely difficult adjustment. Thus, we positioned a plate on the air table to disturb drift motion. This may also disturb the rotation of the satellite model. We need other experimental methods to confirm the effect of counterweight.

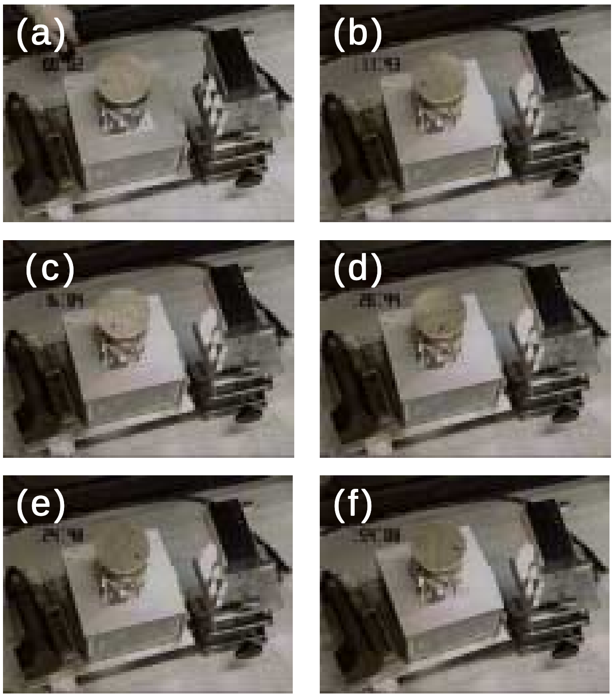

Fig. 4 Paddle motion without counterweight in microgravity.
(a) Observation starts (0 s), (b) motion begins (11 s), (c) approximately 45 deg. motion (16 s), (d) 90 deg. (20 s), (e) 135 deg. (24 s), and (f) motion ends (54 s, approximately 170 deg).

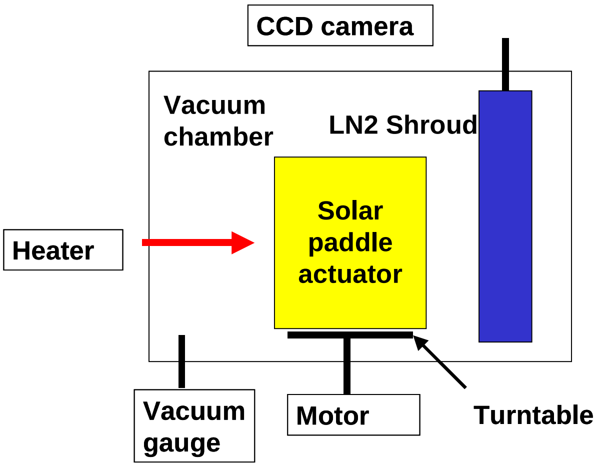

Fig. 5 Block diagram of vacuum chamber.

Vacuum Experiments

Figure 5 and Fig. 6 show the block diagram and photograph of the vacuum chamber, respectively. The vacuum chamber is equipped with a turntable and two windows. The pressure in the vacuum chamber was approximately 2 Pa because we only used the rotary pump. This chamber is also equipped with features that were not used in this study, such as a turntable and a liquid nitrogen shroud. They are used in future experiments.

Fig. 6 Photograph of vacuum chamber

Figure 7 and Fig. 8 show the motion in the counterclockwise direction and clockwise direction, respectively. Compared with Figs. 3 and 4, the difference in the response times in the air and in vacuum was not clear. The heating property of the SMA spring is not affected by the existence of air. In heating the SMA in air, energy is consumed to heat both air and the SMA, however, the amount of energy required for the former seems to be estimated very small.

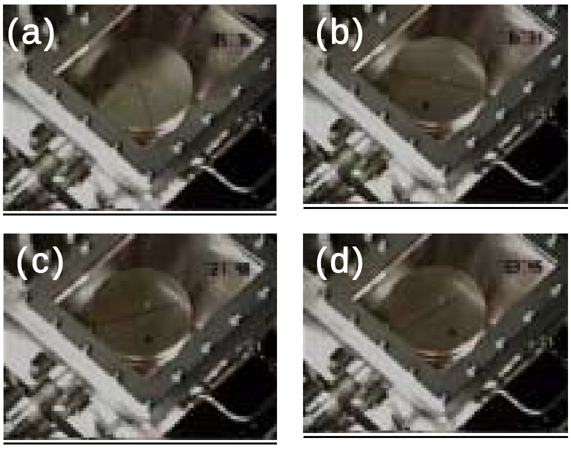

Fig. 7 Paddle motion in counterclockwise direction in a vacuum.
(a) Motion begins (5 s), (b) approximately 45 deg. motion (16 s), (c) 90 deg. (21 s), (d) motion ends (53 s, approximately 120 deg).

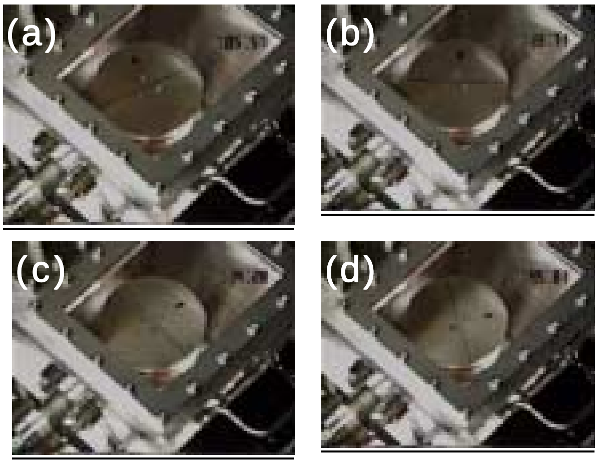

Fig. 8 Paddle motion in clockwise direction in a vacuum.
(a) Motion begins (5 s), (b) approximately 45 deg. motion (13 s), (c) 90 deg. (14 s), (d) motion ends (45 s, approximately 120 deg).

Observation by IR Camera

In order to investigate the cooling property of the SMA spring, observation using an infrared camera in atmosphere was conducted. The brighter the image is, the higher the temperature is, however, the quantitative temperature is unknown. The observation should be conducted in a vacuum, however, the position of the vacuum chamber window was not suitable for such an observation, and we did not conduct it at this time.

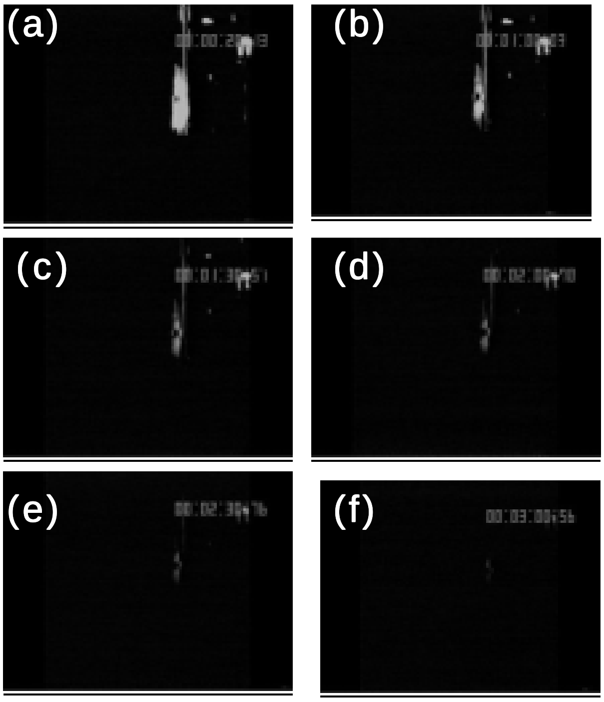

Fig. 9 IR observation in atmosphere.
(a) Heater off (switch on after 20 s), (b) switched on after 60 s, (c) 90 s, (d) 120 s, (e) 150 s, and (f) 180 s.

The heating time was 20 seconds, which corresponds to 24 seconds in Fig. 3 or Fig. 4 because, in those experiments, the heater was turned on a few seconds after the observation began. It takes more than 130 seconds to cool the SMA spring in atmosphere. This suggests that more than ten minutes would be required to cool the spring in a vacuum. In the actual use in space, if the satellite is in the low earth orbit (LEO) such as at the altitude of 200 km, the period of orbit is approximately 90 minutes, so that the satellite receives the sun's radiation for 45 minutes and is in shadow for 45 minutes. We consider that 45 minutes is sufficient for cooling the SMA springs.

The least-cooled part is the connector to the thin string, where the thermal transmission condition is the worst, and depends on the materials of the string.

DISCUSSION

Microgravity experiment

As we described, we placed a plate on the air table to disturb the drift motion. That was caused by the vibration of the air compressor and/or tilt of the air pad due to center-of-mass offset.

There is another method of verifying the microgravity effect: drop shaft experiments. We have previous experience with drop shaft experiments so far [13], thus we are planning an experiment using the drop shaft.

Energy density

In our experiments, we use input energy, that is 100 times as much as the actual energy from the sun. The main purpose of our work is the proposition of the mechanism and investigation of its feasibility. We needed quick response to check these objectives. However, we must verify the energy level of the sun. To consider this issue and design the mechanism, we should take the transformation temperature and thickness of the SMA spring into account. We used the value of 330 K and 0.8 mm, respectively, for our spring, but these values might be overestimated.

Future plan

We will conduct the following studies.

(1) To measure the direction controllability, an rotary encoder will be attached to the solar paddle.
(2) To estimate the lifetime, repeated motion experiments will be conducted.
(3) To investigate the SMA characteristics, the temperature and motion relationship will be investigated. At the same time, the cooling property in a vacuum will be measured.
(4) To investigate the counterweight performance, drop shaft experiments will be carried out.
(5) To obtain the optimal design, mechanism and materials will be reconsidered.

CONCLUSIONS

The study can be summarized as follows.

(1) A solar paddle actuator using SMA springs was designed and tested in microgravity and in a vacuum.

(2) The mechanism worked well both in atmosphere and in a vacuum.

(3) The effect of the counterweight was not clear due to poor microgravity field quality.

(4) The cooling property indicates that only a few minutes is required for sufficient cooling in atmosphere.

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