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On-orbit verification of fuel-free attitude control system for spinning solar sail utilizing solar radiation pressure

Ryu Funase *, Yoji Shirasawa, Yuya Mimasu, Osamu Mori, Yuichi Tsuda, Takanao Saiki, Jun'ichiro Kawaguchi

Japan Aerospace Exploration Agency (JAXA), Yoshinodai 3-1-1, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan

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Abstract

This paper introduces a new attitude control system for a solar sail, which leverages solar radiation pressure. This novel system achieves completely fuel-free and oscillation-free attitude control of a flexible spinning solar sail. This system consists of thin-film-type devices that electrically control their optical parameters such as reflectivity to generate an imbalance in the solar radiation pressure applied to the edge of the sail. By using these devices, minute and continuous control torque can be applied to the sail to realize very stable and fuel-free attitude control of the large and flexible membrane. The control system was implemented as an optional attitude control system for small solar power sail demonstrator named IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun). In-orbit attitude control experiments were conducted, and the performance of the controller was successfully verified in comparison with the ground-based analytical performance estimation.

Keywords: Spinning solar sail; Flexible structure; Fuel-free attitude control; Solar radiation pressure; Liquid crystal thin film device; Reflectivity control device

1. Introduction

A solar sail, which consists of a huge and thin membrane deployed in space that acquires propulsive force by the reflection of sunlight, is considered to be one of the most essential propulsion systems for future solar system exploration. This is because solar photon propulsion does not require any consumable fuel. Thus, it can enable farther and longer space travel compared with a conventional propulsion system whose acceleration limit is determined by the amount of fuel. Although the acceleration obtained by sunlight reflection is very small, the total increase in velocity will become large if this acceleration is accumulated 24 h a day, every day.

One thing that should be noted is that not only inner solar system but outer solar system (e.g. Jupiter) where the density of sunlight becomes extremely small can be efficiently explored by solar sail. By following a trajectory with small perihelion distance and accumulating orbital energy near the Sun, the spacecraft can go far away from the Sun and reach Jupiter and beyond.

Numerous organizations such as those in Japan (JAXA), the United States of America (NASA and/or the Planetary Society), and Europe (ESA) have been studying various types of solar sails. There are two main types of solar sails: rigid-type solar sails and spin-type solar sails. The rigid type is a solar sail with a rigid structure such as booms or masts to deploy and support the flexible membrane (Fig. 1) (Johnson et al., 2010). The spin type is a solar sail without a rigid support structure, where the sail membrane is attached to the center spacecraft hub and is deployed and extended using the centrifugal force of the

* Corresponding author.
E-mail address: funase.ryu@jaxa.jp (R. Funase).

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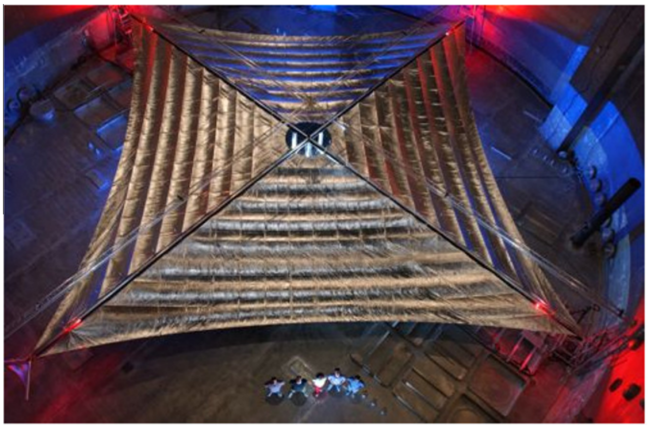

Fig. 1. Rigid-type solar sail.

spin motion (Fig. 2). JAXA originally proposed this type of solar sail (Kawaguchi, 2004).

Table 1 shows a comparison of the two types of solar sails. The spin-type solar sail can approximate an ideal solar photon sail because of its potential to realize almost the same weight/area ratio (or acceleration) as the thin-film membrane material. However, it has some disadvantages in terms of attitude control. First, the attitude motion is complicated because of the flexibility of the membrane, which does not have any support structure but relies on the centrifugal force for its shape maintenance. Impulsive torque input by conventional chemical thrusters will induce oscillatory motion in the membrane. Second, in terms of the fuel consumption for attitude control (or steering the sail), the spin type has to change the orientation of the large angular moment of the large spinning membrane. In some cases, the amount of fuel may limit the lifetime of the spinning solar sail. On the other hand, it also has some advantages, as follows. It is resistant to external disturbance torque induced by the solar radiation pressure applied to deformed sail, because the torque is averaged during the spin motion, which makes the attitude behavior fairly safe.

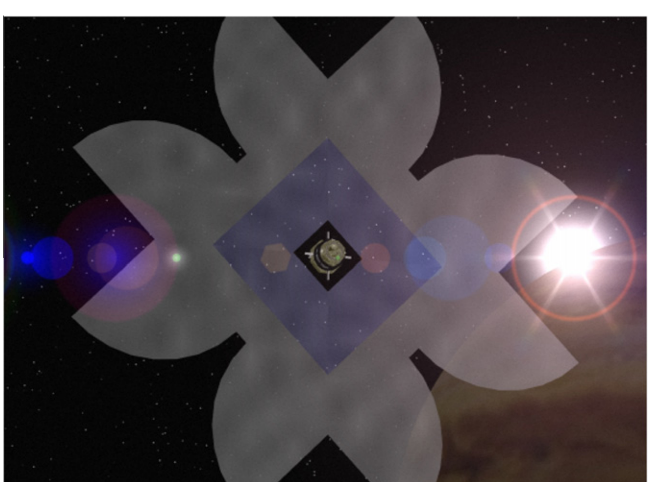

Fig. 2. Spin-type solar sail.

Table 1
Comparison between rigid- and spin-type sails.

	Rigid type	Spin type
Weight/area ratio	△ (larger than spin type)	○ (can achieve almost same weight/area ratio as sail membrane)
Attitude dynamics	○ (almost as simple as rigid body)	△ (flexibility of the membrane should be considered)
Fuel consumption for attitude control	○ (small angular momentum to be controlled)	△ (large angular momentum to be controlled)
Disturbance torque	△ (large SRP torque to be managed)	○ (SRP torque can be averaged by the spin motion)
Attitude control scheme	△ (active feedback control) (feedforward control is difficult)	○ (very safe; infrequent control is possible) (even follows the sun direction without control for several days)
Difficulty in deployment	? (many countries/ organizations have conducted deployment tests on ground)	○ (IKAROS has demonstrated)

○: advantageous, △: disadvantageous, ?: impossible to evaluate.

It can even track the direction of the sun automatically (Kawaguchi and Shirakawa, 2007).

With these trade-offs, an attitude control system that does not induce oscillation in the flexible membrane and does not consume much fuel for attitude control will extend the potential/applicability of the spin-type sail. This will lead to an ideal solar photon sail with the theoretical maximum acceleration, which is the intrinsic advantage of the spin-type solar sail.

In this paper, we propose an active attitude control system for spinning solar sails that utilize only the solar radiation pressure and solar energy. The concept of the attitude control system is introduced in Section 2. In Section 3, a reflectivity control device (RCD) is introduced, which was specially developed for this control system. In Section 4, the attitude control logic and its control performance is analyzed. The control system was implemented as an optional attitude control system for JAXA's small solar power sail demonstrator named IKAROS (Mori et al., 2010). The in-orbit attitude control experiment results are shown in Section 5. Finally, Section 6 provides a summary of the paper.

2. Attitude control of spinning solar sail using solar radiation pressure

Fig. 3 shows the concept of the attitude control system, which utilizes the solar radiation pressure. In this system, a number of devices that can control their optical parameters