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Advances in Space Research 55 (2015) 639–646

Advances in Space Research (a COSPAR publication)

www.elsevier.com/locate/asr

Deployable dynamic analysis and on-orbit experiment for inflatable gravity-gradient boom

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Received 28 June 2014; received in revised form 18 October 2014; accepted 20 October 2014
Available online 28 October 2014

Abstract

Inflatable structures have numerous advantages, such as small folding size, high deployable reliability, and low cost. This paper accomplishes several tasks with a focus on the gravity-gradient boom of microsatellite. An inflatable boom model balanced by inflatable deployment and delaminating resistance is presented. A system is established to simulate agravic deployment. The inflatable deployment of a tip mass has been tested with the aid of a 3.0 m rolled deployable boom. The perturbation moment during the inflatable deployment is analyzed. Three inflatable booms are tested in a thermal vacuum chamber further. Based on the tests and analyses, the microsatellite which carried an inflatable gravity-gradient boom was launched into orbit successfully in November 2012. After being stored on-orbit for 6 months, the inflatable method was applied to the inflatable boom to unfold the 2.0 kg tip mass steadily at a distance 3.0 m away from the microsatellite in May 2013. This work completes the test of inflatable on-orbit deployment on the base of microsatellite for the first time internationally.

Keywords: Gravity-gradient boom; Inflatable; Deployable dynamics; Perturbation analysis; Thermal vacuum test; On-orbit

1. Introduction

Inflatable structures have numerous advantages, such as small folding volume, high reliability, and low cost. An inflatable deployable boom is one of the simplest structures. An inflatable gravity-gradient boom for microsatellite consists mostly of an inflatable boom, a tip mass on the free end, and an inflation system. As a passive microsatellite control method, gravity-gradient stabilization generates torque caused by different gravities of different microsatellite locations on the Earth for attitude control. To use this control method, a dumbbell-shaped tip mass should be placed on the top of the inflatable boom. A key component of gravity-gradient stabilization is the inflatable boom. The quality and size of traditional gravity-gradient booms are limited because of the rigid telescope-feed structure. Thus, this paper focuses on a inflatable boom that uses deployable dynamic and asymptotic damping as support of an ultra-light structure. This type of stiffness can form a self-supporting structure with thin-shell enhanced bars in the inside wall for steady unfolding. Moreover, this deployable boom offers the advantages of light quality and small folding size. USA, Europe, and Japan are currently conducting relevant research for the wide use of such design in solar sails (Block et al., 2011), solar arrays, and other inflatable structures (Lachenmeier and Murai, 2004).

The deployment dynamic characteristic of the inflatable structures is the key focus of the researches. The folding

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http://dx.doi.org/10.1016/j.asr.2014.10.024
0273-1177/

inflatable booms are mainly zigzag and rolled patterns. The boom relies on the deployment of internal pressure. A mathematical model was constructed by using methods of analytical mechanics (Zakrzhevskii et al., 2004). The behavior of a microsatellite with a deployable gravity-gradient boom was analyzed. Salama et al. (2002) studied the dynamic characteristic of Velcro-controlled deployable boom and simulated the inflatable process with a finite-volume model. Wei et al. (2009) analyzed the dynamic characteristic of a rolled inflatable boom with the use of the rigid-body planar motion method. Bouzidi et al. (2013) assumed a formulation of self-contact to solve quasi-static deployment. Gajbhiye et al. (2014) studied eigen-frequencies of the inflatable structures on the basis of three-dimensional small-strain elasticity theory. For zigzag folding booms, Wei et al. (2012a) simulated inflatable deployment of this folding boom by the gas-structure interaction method. Katsumata et al. (2014) used the finite point-set method to compare the deployment behavior of inflatable boom models and modified zigzag folding patterns. Steele and Fay (1998) analyzed the relationship between the internal pressure of rolled boom and unfolding torque. As regards the improvement in inflatable boom stiffness, Fang et al. (2006) studied the deployment dynamic characteristic of inflatable self-support boom. This characteristic depended on enhanced bars of elastic steel tape to improve the bending stiffness of inflatable booms. The steel tape has excellent mechanical property but is easily magnetized, which may change the magnetic environment of the microsatellite body.

The paper mainly studies the deployment dynamic of an inflatable boom; that stiffness is enhanced by carbon and Vectran composite thin-shell. The gravity-gradient boom consists of an inflatable boom with the length of 3.0 m and a diameter of 60 mm, as well as a 2.0 kg tip mass, to realize the function of gravity-gradient stabilization. After the rolled folding process, the boom is formed as a cylinder of $\Phi 180$ mm $\times$ h90 mm. The analysis of the microsatellite body perturbation caused by deployment of the inflatable boom is important in determining whether the tip mass on the top of the boom can be unfolded steadily. To simulate the agravic deployment test, we reduce the friction in the system and the centripetal force caused by the suspension system. The agravic experiences are tested both vertically and horizontally, and the perturbation of different motion directions is analyzed. Moreover, the on-orbit inflatable process is simulated in a thermal vacuum chamber. According to the results, the deployment and self-support testing of the 3.0 m inflatable boom in space was completed in May 2013.

2. Perturbation analysis during inflatable deployment

The inflatable boom stays in a rolled state when launched and will then inflate from the fixed end with a gas cylinder when it is on-orbit. Internal expanded pressure delaminates the suede and hook sides of Velcro strips, as well as realizes sequential deployment. To make the deployment test of rolled boom on orbit come true, it is important to master the perturbation torture characteristic on the ground for the inflatable boom is a kind of thin-wall deployable structure, and its quality, volume, and pressure changes all the time during the movement. In accordance with the abovementioned requirement, this paper works out a 3.0 m long inflatable boom with a diameter of 60 mm. This boom has six carbon/Vectran/carbon thin-shell enhanced bars of 0.36 mm thickness as support. These bars are located at two, four, six, eight, ten, and twelve o'clock (see Fig. 1). For the stiffeners of the boom, when no inner pressure, the boom as a state level of cantilever beam and no tip mass, the bending stiffness is 228.27 Nm^2 through the experiment testing. The bending stiffness of the boom which as a cantilever beam is 562.35 Nm^2 at the inner pressure of 40 Kpa. The first natural frequency of the inflatable boom is 0.778 Hz when 40 Kpa has been filled into the deployed boom with a 2 kg tip mass fixing to the free end, on the contrary, the first natural frequency is 0.732 Hz when there is no inner pressure inside the boom (Wei et al., 2012b). A 2.0 kg dumbbell-shape tip mass on the end of the boom is used to achieve the gravity-gradient stabilization (see Fig. 2). To solve the perturbation problem of the boom during unfolding, the paper sets up an agravic deployment test system to simulate the inflatable process in the vertical and horizontal directions.

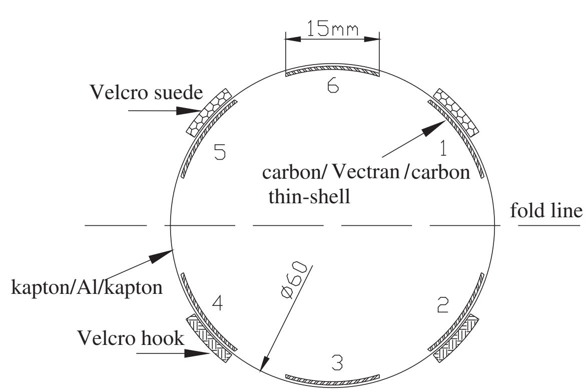

Fig. 1. The section of the inflatable boom.

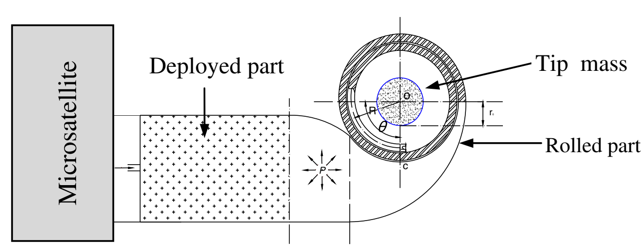

Fig. 2. Deployable movement of inflatable gravity-gradient boom.