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著者	KATSUMATA Nobuhisa, KAIMORI Masaaki, YAMASAKI Masanobu, HIGUCHI Ken, NATORI Michihiro, YAMAKAWA Hiroshi
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Deployment Characteristics of Braid Coated Bi-Convex Tape and Bi-SMA Convex Tape Booms for Deployable Membrane Structures

Nobuhisa Katsumata[1], Kaimori Masaaki[1], Masanobu Yamasaki[2], Ken Higuchi[1], Michihiro Natori[3] and Hiroshi Yamakawa[3]

1. Department of Mechanical, Aerospace and Materials Engineering, Muroran Institute of Technology, Muroran 050-8585, Japan

2. Department of Modern Mechanical Engineering, Waseda University, Tokyo 169-8555, Japan

3. Faculty of Science and Engineering, Waseda University, Tokyo 169-8555, Japan

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Abstract: The purpose of this paper is to demonstrate and investigate the concepts of new deployable boom systems, which consist of the BCON (braid coated bi-convex tape) boom and the SMA-BCON (braid coated bi-shape memory alloy convex tape) boom. Both booms are developed for the deployable membrane structures such as solar sails, thin membrane solar array panels, deorbit mechanisms for small satellites and reflectors of space solar power satellite, etc. BCON booms can store around polygonal or cylindrical center hub, and the booms can deploy by the stepwise manner by releasing a constraint mechanism which pins the boons into two or three points for the total length. SMA-BCON booms are mainly developed for a square center body systems, and SMA is adapted on the bent points of the booms where stored around each edge of the center hub. Through the deployment experiments of both booms, the stepwise deployment behavior and its tendency are obtained. The design concept of BCON boom and SMA-BCON boom is demonstrated through this study.

Key words: Braid coated bi-convex tape boom, braid coated bi-SMA convex tape boom, membrane structures.

1. Introduction

The combined structures of a deployable membrane and extendible boom have become a key technology for recent and near future gossamer space structures. They can adapt many kinds of space structures, such as light weight high precision space antennas, solar sails and sun shields. Membrane is a tension elements and centrifugal force. Due to spinning of spacecraft, it is also effective to deploy and stabilize it. A spinning solar sail spacecraft "IKAROS" [1] is one of the example and demonstrates such basic structural concept. However, a combined structure of membranes and booms is more useful to support compression force during and after deployment, and it depends on deployment manner and various mission requirements. From these view points, there are many kinds of researches about how to store and deploy/extend membranes and booms [1-21], and/or how to connect membranes to booms. In the previous studies, various types of extendible booms [8-18] are developed such as the coilable lattice booms, inflatable rigidized booms, shape memory composite booms and convex tape booms. The extendible forces of these booms are the stored elastic energy during packing, except for inflatable boom. The extension rate is controlled by a many kinds of release mechanisms, although it seems that there are some trade-off design relationship between the mechanical simplex and the extension controllability. In most of the recent studies, some

Corresponding author: Nobuhisa Katsumata, D.Eng., assistant professor, research fields: space structures, structural and vibrational dynamics. E-mail: nobuhisa-k@mmm.muroran-it.ac.jp.

square membrane structures for solar sail spacecraft [1-6] supported by four extendible booms have been well investigated. It is though that a membrane shape may be flexible, its mean pentagonal or hexagonal membranes are also possible, but the square membrane can minimize the number of booms and have more controllability for total spacecraft system operations.

In this paper, from the viewpoints of the simpler extension mechanism and the controllability of boom extension, the newly developed two types of extendible booms are investigated through deployment demonstrations aiming to applying a square membrane structures, one of which is the BCON boom (bi-convex tape boom covered by braid) [18-21] and the other of which is the SMA-BCON boom (BCON boom partly applied shape memory alloy). As for the BCON boom, the booms are elastically bended at the corners of the square center body, and they deploy a stepwise manner to control the extension rate just releasing the holding pin mechanism without any rotational actuator. As for the SMA-BCON boom, only the convex tape shape like SMA is bended at the corners of the square center body, and they deploy by using shape recovery force of SMA due to heating. Through these deployment experiments, the deployment characteristics of both booms are investigated, and the design concepts for membrane space structures are considered.

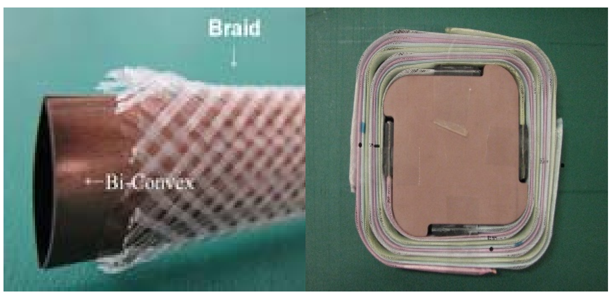
This paper is organized as follows: Section 2 explains the detail about the BCON boom, the SMA-BCON boom and the concepts of stepwise deployment; Section 3 shows the deployment experimental results of BCON boom structures with and without membrane condition, setting the boom length in each deployment steps as parameter; Section 4 explains the deployment demonstration results of SMA-BCON boom; Finally in Section 5, we conclude this research by comparing the results of BCOM boom and SMA-BCON boom deployment experiments and from the viewpoint of future deployable membrane structure systems.

2. BCON Boom and SMA-BCON Boom

2.1 BCON Boom and the Stepwise Deployment Device

Fig. 1 shows the detail view of the BCON boom and the packed configuration around quadrangular center body. Two independent uni-convex tape booms are covered by braid. The convex tapes can slide toward the longer direction in the inside of braid. The braid restrain the deformation toward cross direction by adjusting the tightness of braid. This flexible restraint condition toward longer direction help compact packing because the perimeter difference between inner and outer convex tape during rolled-up is well managed. As the result, for this boom, it is easy to be rolled around any polygonal body.

Fig. 2 shows the stepwise deployment device and the deployment configuration with membrane. The size of center body is 94 mm square. The yellow encircled part in Fig. 2a shows the pin to hold the BCON boom into each length. There are three pins in the figure, and it means this stepwise deployment has three steps. Fig. 3 shows the schematic illustration of stepwise deployment. For example, from (a) to (d) configuration shows a 1st step deployment, from (d) to (g) configuration shows a 2nd step, and from (g) to (k) shows a 3rd step. The compartmental location of stepwise deployment depends on the length of the boom held by pins. The springs shown inside the white circle in Fig. 2a get up the pin in each steps. There has a ball bearing on the bottom side of the device and a dark brown column in Fig. 2a, and it can deploy under free-spin condition and non-spin condition.



(a) Detail view of BCON boom (b) Packed configuration

Fig. 1 The detail view of the BCON boom and the packed configuration around center body.

(a) The detail view of deployment device (b) Deployment configuration

Fig. 2 The detail view of deployment device and deployment configuration.

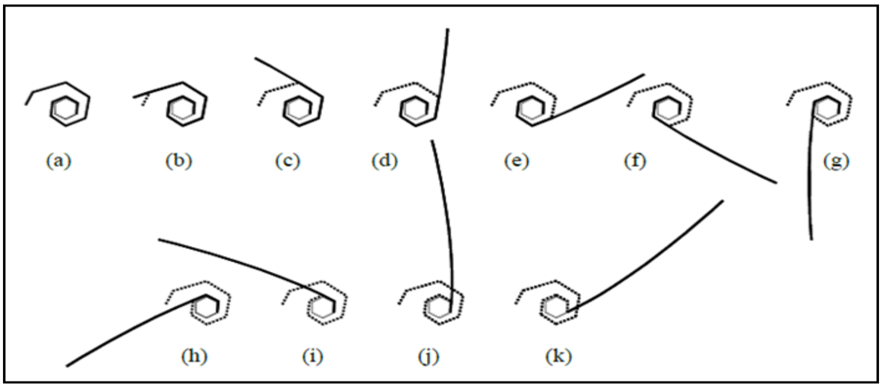


Fig. 3 Schematic illustration of the stepwise deployment.

In this case, the boom length is 500 mm and the PET film membrane thickness is 15 μm.

2.2 SMA-BCON Boom and the Stepwise Deployment Device

The BCON booms are bent only every corner around the quadrangular center body shown in Fig. 1b. In case of the quadrangular center body, about 50% of the booms are straight (unbent) condition around the each side of tetragon. From the viewpoint of stowed elastic energy and deployment efficiency, the separate design between bent parts and unbent parts through the total booms should be effective. In addition, if we apply the convex tape shape like SMA on the bent parts, it is possible to control deployment behavior through SMA temperature control. Based on the previously described concept, we design the laboratory level SMA-BCON boom for conceptual study. Fig. 4 shows the cross-section view of SMA memorized the convex tapes shape.

The SMA is made of Ni-Ti alloy and the temperature at the transformation point is about 70-80 °C. The memorized shape is the straight toward longer direction and the convex shape toward cross-section direction shown in Fig. 4. The length of the SMA along the longer direction is 150 mm. The unbent parts, set along each side of quadrangular center body, are made of acrylic plate shown in Fig. 5. The thickness of the plate is 3 mm, which thickness is just fit the gap between bi-convex tapes. The joint parts shape and dimensions are designed based on the basic bending and torsion test using gravity force. Fig. 6 shows the covering braid configurations. The material of the braid is PFA (fluoroplastic) fiver, and 64 fivers are weaved. The braid is easy to expand just pushing longer direction because of a much stretch properties. The SMAs are inserted inside of braid during expanded condition shown in Fig. 6b, and after inserting, the SMAs are tightly covering by stretching the braid toward longer direction.

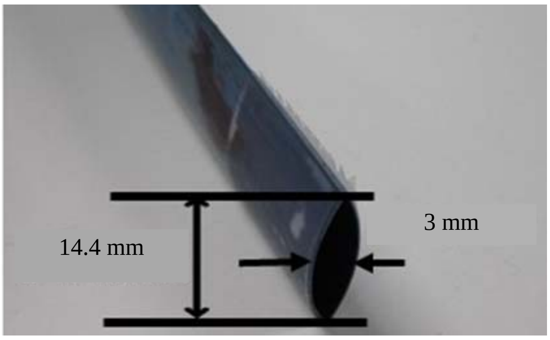


Fig. 4 Cross-section view of SMA.

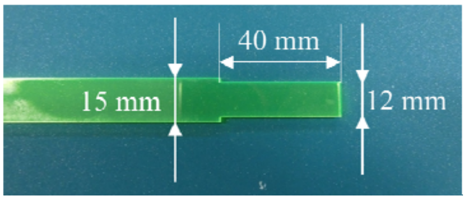
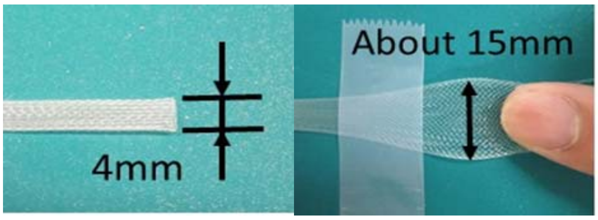


Fig. 5 Joint parts shape and dimensions.

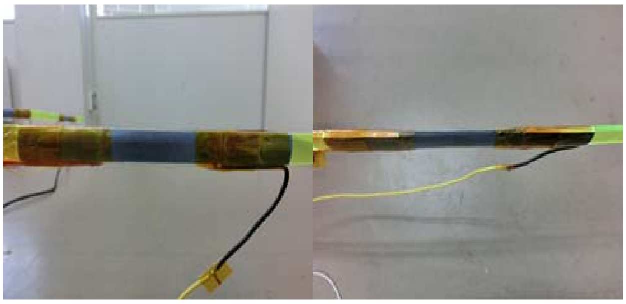


(a) Initial condition (b) Expanded condition

Fig. 6 The covering braid configuration.

The assembled configurations of SMA-BCON boom are shown in Fig. 7, and the deployment devise is shown in Fig. 8. Based on this SMA-BCON boom concept, the quadrangular center body is designed. Like BCON boom deployment device, there also has thrust bearing on the bottom of the devices to reproduce a rotational free condition. The direct power distribution for SMA is used for heat, and the electronic power is supplied by DC power supply located below the devise. The measurement devise is set on the center of the deployment devise.

The size of the square deployment devise is 300 mm on a side. As shown in Figs. 8a and 8b, each boom is compactly stored around the center body. The deployment step of this device is two steps, and the deployed configuration after 1st step and 2nd step (fully deployed configuration) are shown in Figs. 8d, 8e and 8f. The total length of the SMA-BCON boom is about 850 mm.



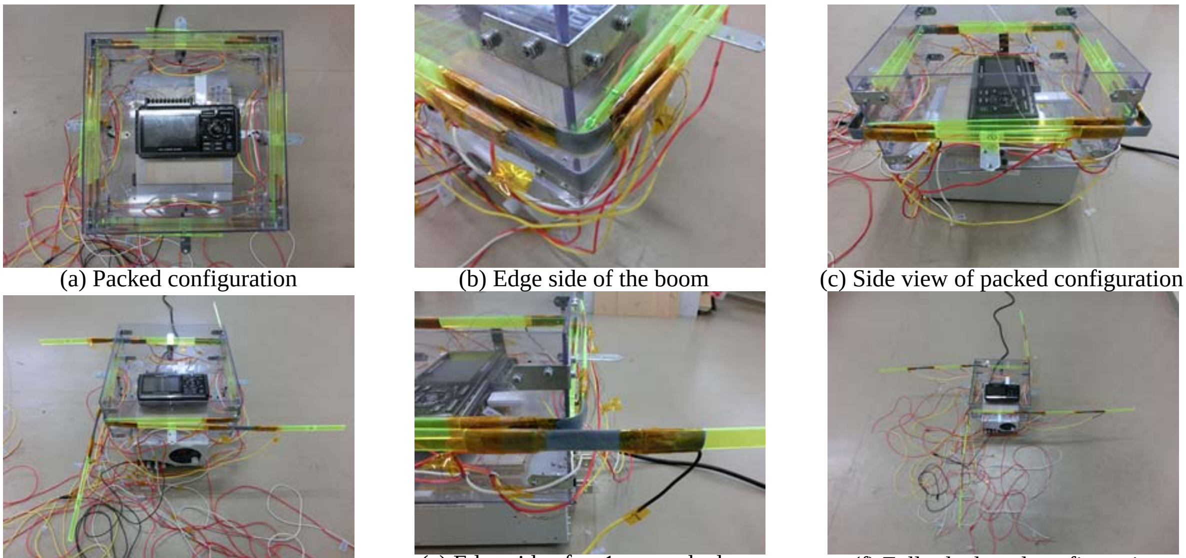
(a) Side view (b) Top view

Fig. 7 Assembly drawing of SMA-BCON boom.

3. Deployment Behavior of BCON Boom

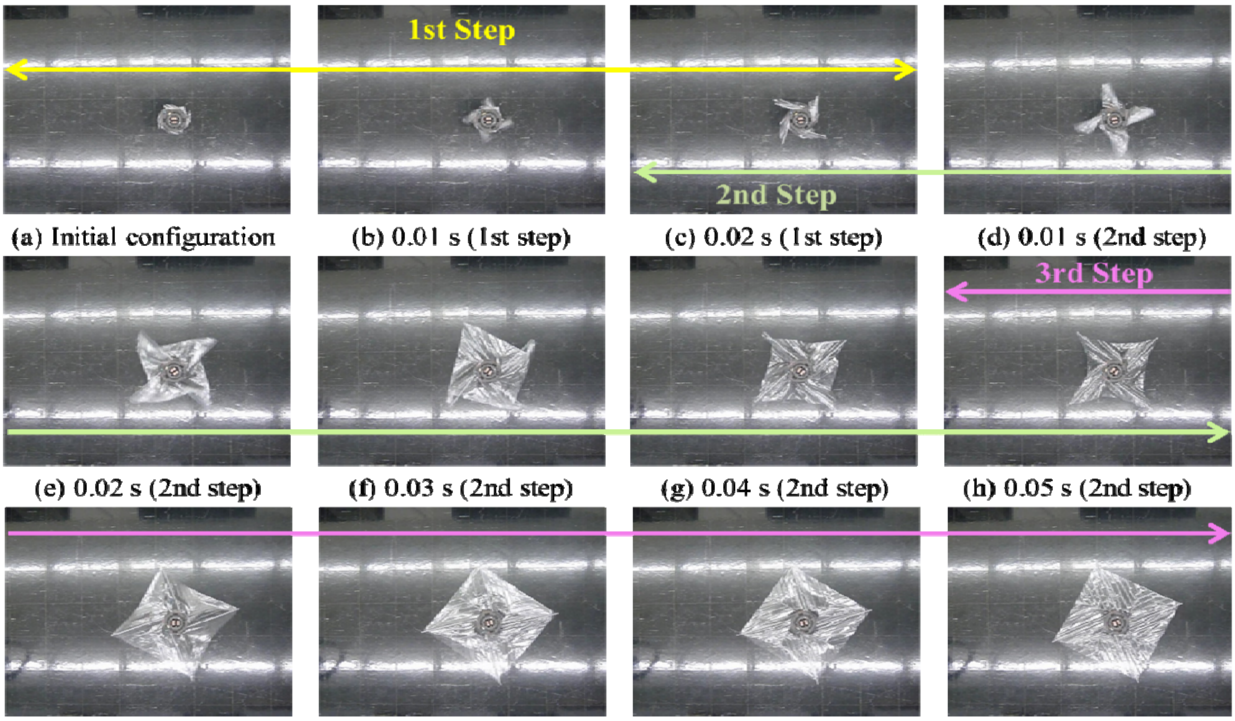
The deployment behavior of BCON boom with membrane condition is shown in Fig. 9. Three-step deployment is achieved under gravity conditions. After the second and third step deployment, the tensional force act to the membrane and the membrane fully deployed after third step. In this case, deployment length of the boom in the second step is longer than other steps. To investigate the relationship between the deployment length and the deployment steps, three deployment cases are examined. The effect of membrane for deployment behavior is important for this deployable membrane system, and the deployment experiments with and without membranes condition are also investigated. The released length of booms in each steps is shown in Table 1. In the case of No. 1, the deployment length in the 1st step is the longest. The longest deployment in case No. 2 is 2nd step and in case No. 3 is 3rd step. Fig. 10 shows the average distance of four booms between boom tip and rotational axis in the only boom conditions, and the Fig. 11 shows them in the booms with membrane condition. The angular velocity during deployment is also measured by using gyroscopic sensor, and these results in each cased are shown in Fig. 12.

Shown as Figs. 10 and 11, there are overshoot in each step. In Figs. 9f, 9g and 9k, the overshoot behavior is clearly tracked. From the angular velocity variations in each steps shown in Fig. 12, the rotational direction change drastically around the overshoot phenomenon.



(a) Packed configuration (b) Edge side of the boom (c) Side view of packed configuration
(d) After 1st step deploy (e) Edge side after 1st step deploy (f) Fully deployed configuration

Fig. 8 Packed and deployment configuration of SMA-BCON boom devise.



(a) Initial configuration (b) 0.01 s (1st step) (c) 0.02 s (1st step) (d) 0.01 s (2nd step)
(e) 0.02 s (2nd step) (f) 0.03 s (2nd step) (g) 0.04 s (2nd step) (h) 0.05 s (2nd step)
(i) 0.01 s (3rd step) (j) 0.02 s (3rd step) (k) 0.03 s (3rd step) (l) 0.04 s (3rd step)

Fig. 9 Deployment behavior of BCOM boom with membrane (Case 2).

Table 1 Released length of booms in each steps into three cases.

Case No.		1	2	3
Initial distance from rotational axis (mm)		125 (0)	127 (0)	134 (0)
Distance after each steps (mm)	1st step	357 (232)	238 (111)	262 (128)
	2nd step	426 (69)	426 (188)	328 (66)
	3rd step	520 (94)	520 (94)	520 (192)

The numbers in parentheses mean released length between the steps.

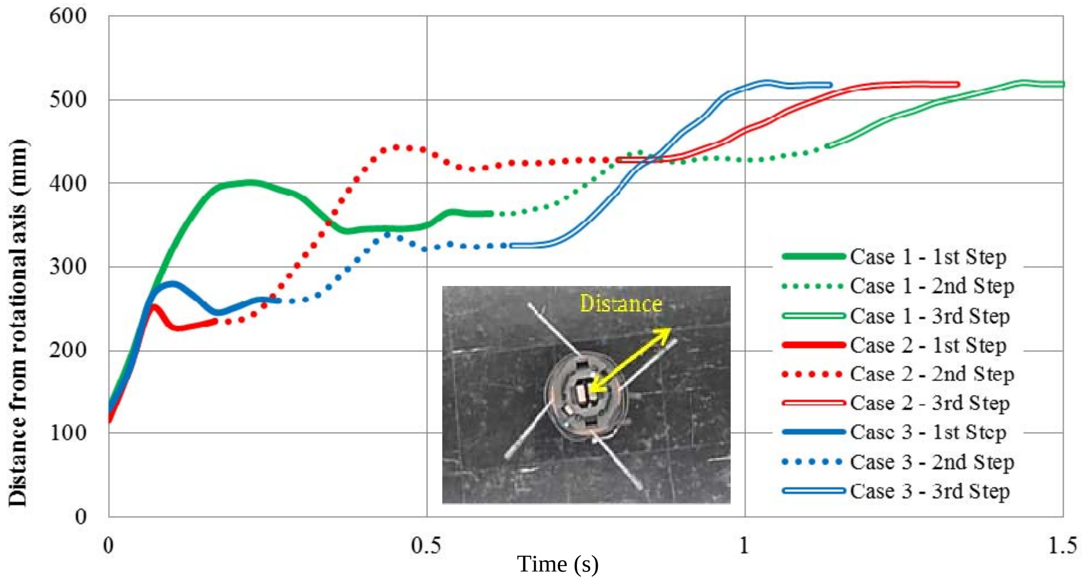


Fig. 10 Average distance between boom tips and rotational axis (boom only).

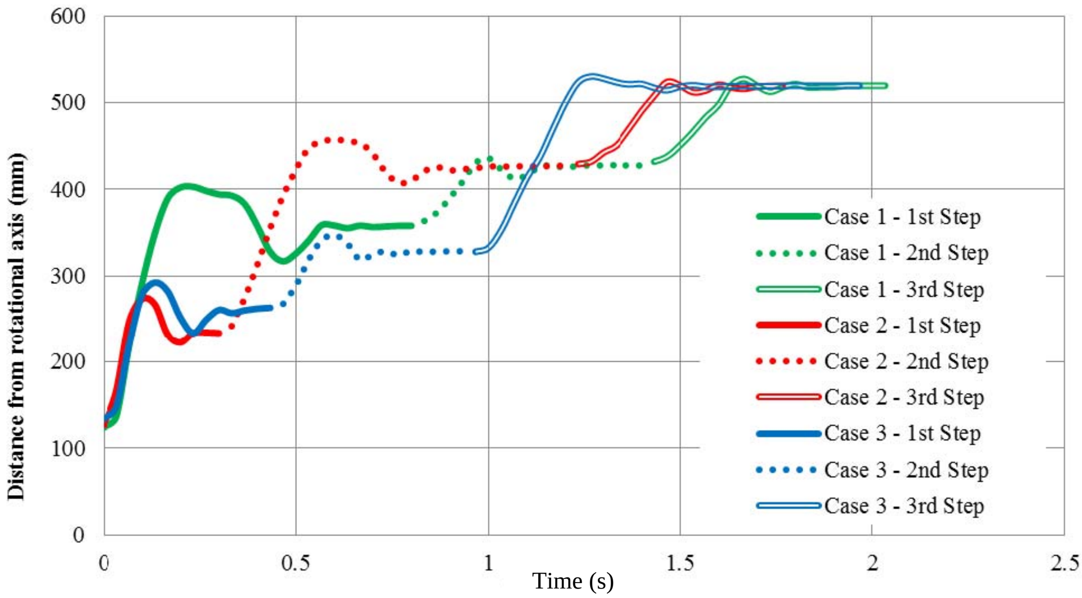
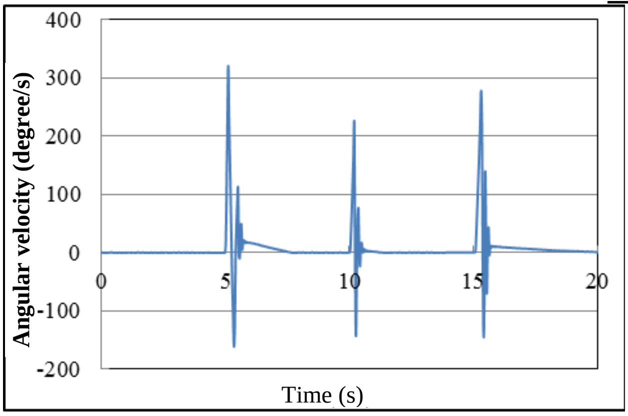


Fig. 11 Average distance between boom tips and rotational axis (boom with membrane).

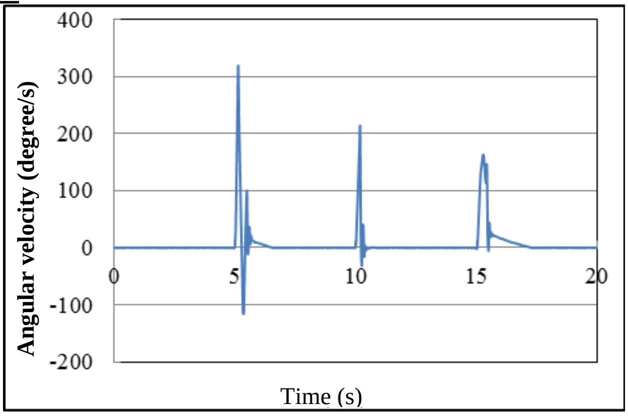
However, the amount of overshoot decrease according to the higher steps, and at the third steps with membrane condition, there are almost no overshoot shown in Figs. 10 and 11. This result is notably shown in the angular velocity variations of membrane condition. Due to the overshoot, the only boom condition shows the large opposite angular velocity shown in Figs. 12a, 12c and 12e. But in the boom with membrane condition, the amount of opposite angular velocity decrease, and there are not opposite angular velocity value in the every third step deployment shown in Figs. 12b, 12d and 12f.

As for deployment with membrane configuration, the total mass, the moment of inertia accretion and air drag may decrease the overshoot deployment. As for only boom condition, the longer deployment in the higher steps also shows less overshoot deployment. It is thought that the friction between the sliding convex tape and the covering braid due to the perimeter difference between outer and inner convex tapes during

Case 1

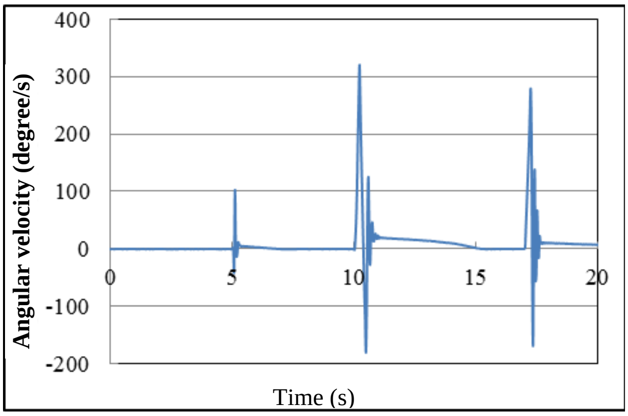


(a) Boom only configuration

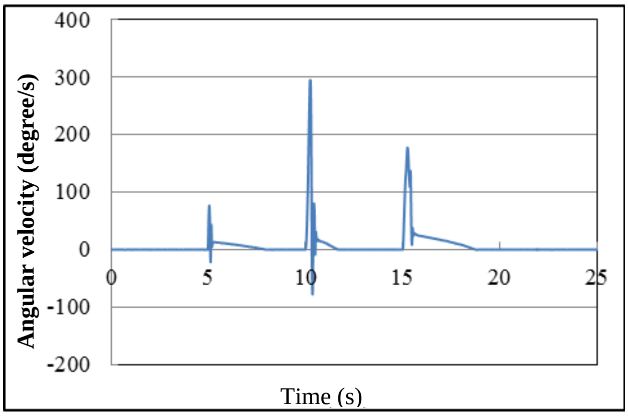


(b) Boom with membrane configuration

Case 2

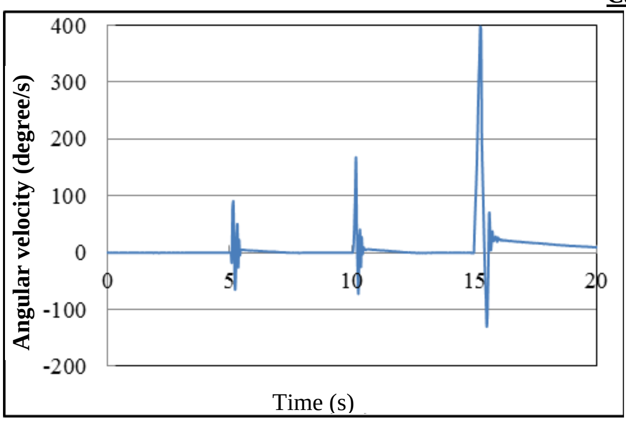


(c) Boom only configuration

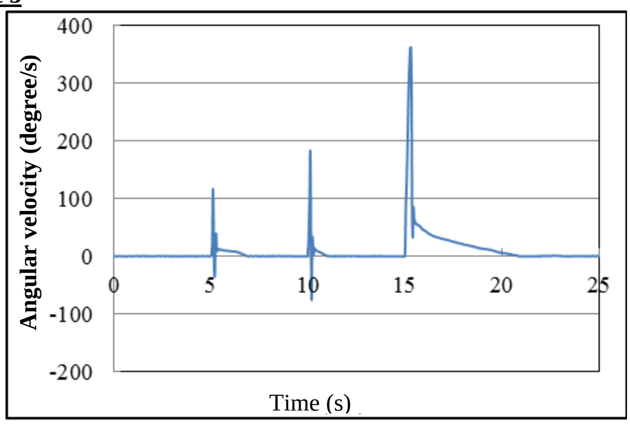


(d) Boom with membrane configuration

Case 3



(e) Boom only configuration



(f) Boom with membrane configuration

Fig. 12 Angular velocity during deployment in the three cases.

deployment is one of the cause to decrease overshoot of higher step deployment. But from the view point of the angular velocity, the longer boom deployment leads the large angular velocity shown in Figs. 12a and 12b around 5 s, Figs. 9c and 9d around 10 s, and Figs. 9e and 9f around 15 s.

The friction force control during the deployment may become one of the keys for stable deployment, however the tighter covering by braid inhibit the slide of convex tape, and lead deployment error. We think that the deployment experiments acting centrifugal force during deployment and/or experiments in a large vacuum chamber is a next works to clearly discern the effect of membrane, air drag and some frictions. Furthermore, the trade-off or optimal system design is more important for this stepwise deployment system, which means how to manage the overshoot, the spinning of center body, the centrifugal force, frictions and membrane to adapt the mission requirements.

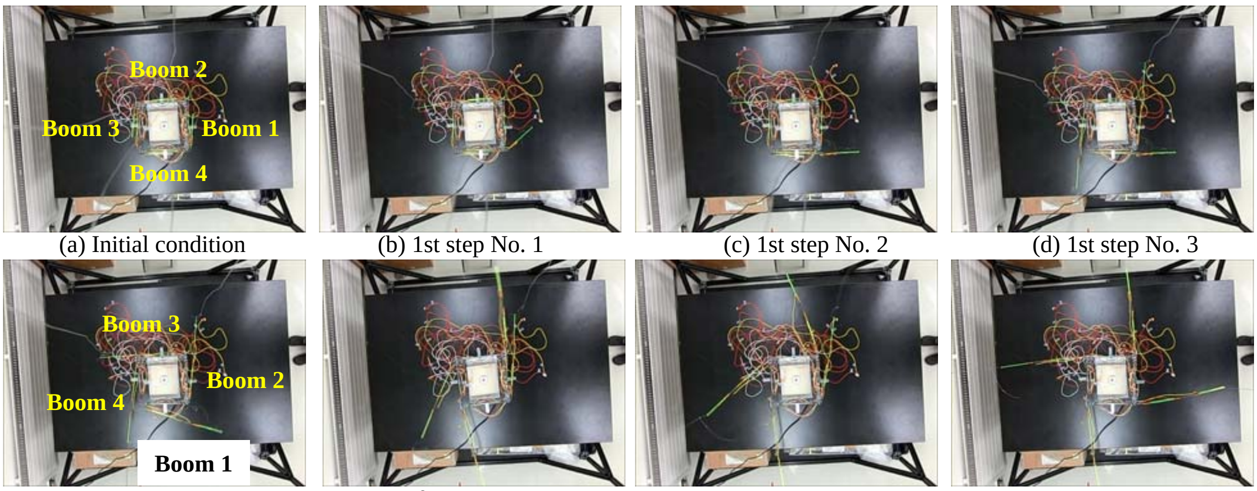
4. Deployment Behavior of SMA-BCON Boom

The deployment behavior of SMA BCON booms for the conceptual examination is shown in Fig. 13. The supplied electrical power in the 1st and 2nd steps is 150 W fixed. The each SMA in the same steps is connected series circuit. The fixed power is supplied without any value controlling according to the deployment behavior at the present stage.

The booms are hanged by fishing line from about 3 m high position due to cancelling the gravity force. After the complete deployment and heating condition, this SMA BCON boom can keep the straight shape and resister gravity force. But during the deployment, the parallel folded part of SMA where located in each corner of center body has less bending and torsion stiffness than the convex tape shape, and it is difficult to resister the gravity force and the SMA-BCON booms are bent down. It is possible to realize unbent down SMA-BCON boom during deployment by increasing the thickness of SMA, but we think those kinds of design may be over stiffness structures in space.

In Fig. 14, the distance between rotational axis and boom tips is shown in the left vertical axis value and the corresponding angular velocity is shown in right vertical axis value. The deployment order and the angular velocity change due to asynchronous deployment in each step are well shown in Fig. 14. Table 2 shows the angular difference between center body side and each boom after 1st step deployment.

Through this conceptual study, the synchronous deployment like BCON boom is not achieved. In Fig. 13, each boom deploys independently. The deployment order on the 1st step is Boom 3, Boom 1, Boom 2 and Boom 4, and on the 2nd step, the deployment order is Boom 1, Boom 3, Boom 4 and Boom 2. We examined deployment test many times,



(a) Initial condition (b) 1st step No. 1 (c) 1st step No. 2 (d) 1st step No. 3
(e) 2nd step No. 1 (f) 2nd step No. 2 (g) 2nd step No. 3 (h) 2nd step No. 4

Fig. 13 Deployment behavior of SMA-BCON boom.

Table 2 Angular difference between center body side and each booms after 1st step deployment.

Boom No.	Boom 1	Boom 2	Boom 3	Boom 4
Angle (degree)	2.79	8.13	1.51	7.41

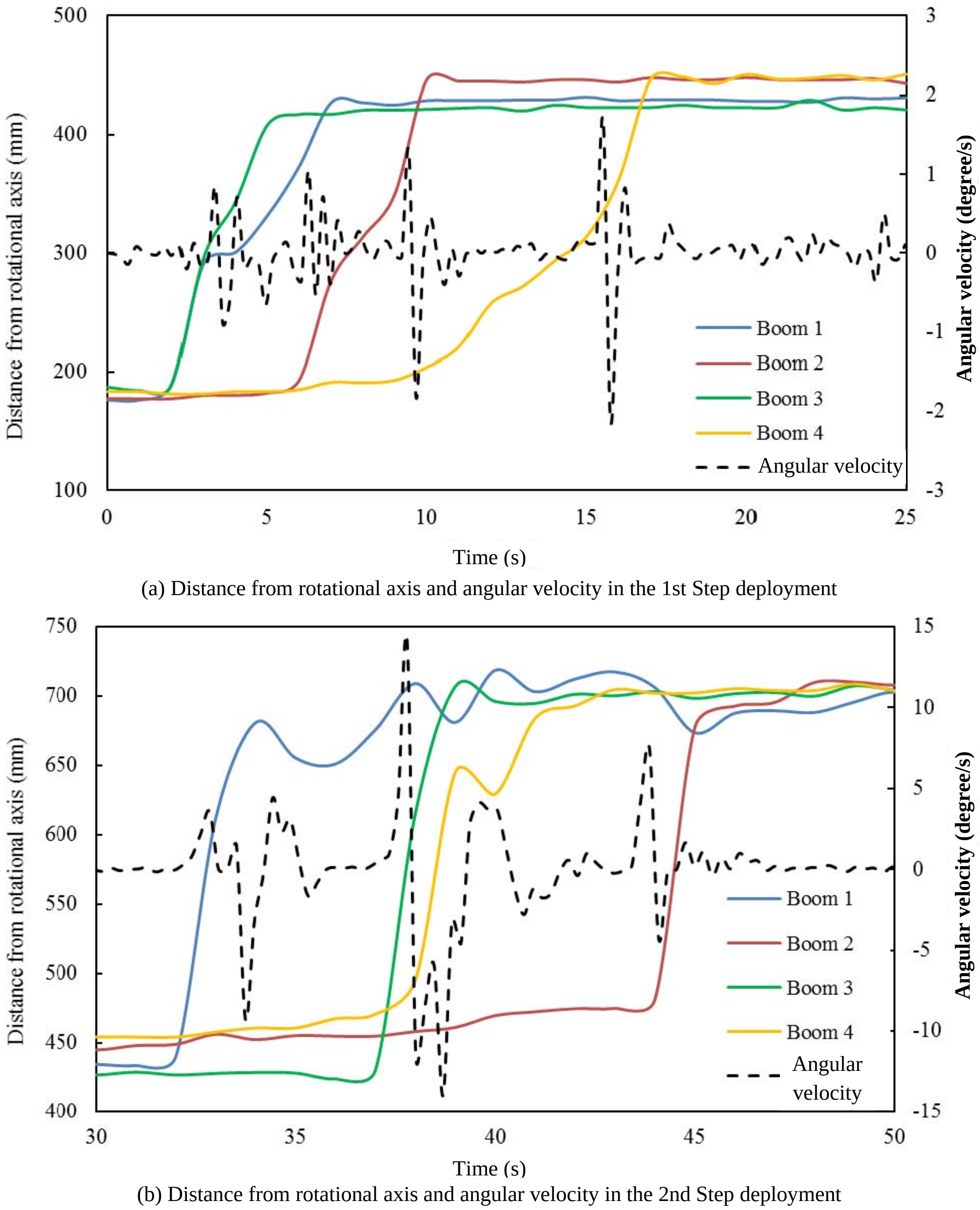


Fig. 14 Distance and angular velocity during deployment.

but it is difficult to find some relations of deployment order. It is thought that the connections between energy supply to SMA, and the hanging tension among each booms may affect asynchronous deployment. However, it is not clear at this moment.

Through this experiments, the conceptual parts of this deployable boom is investigated, but there remains are a lot of agendas, such as heating methods and controlling of SMA temperature. The stable heating and heating controlling to realize synchronous deployment are next work.

5. Conclusions

Deployment characteristics of two kinds of deployable boom system for space membrane structures are investigated through deployment experiments. One is the BCON boom and the other is SMA-BCON boom. Both booms are newly developed and they can deploy stepwise manner to control the deployment behavior.

As for BCON boom experiments, the effects of the deployable length in each steps are examined and the difference between only boom condition and booms with membrane condition are compared. Through the results, the longer deployment length in the higher deployment steps will decrease the overshoot deployment of the booms due to the total mass and the moment of inertia accretion, air drag and friction force between braid and sliding convex tape. But from the viewpoint of angular velocity variations, the shorter deployment length in the lower deployment steps will be effective. The trade-off deployment system design, such as the centrifugal force by spinning, deployment length control will be the next important points on this BCON boom system.

As for SMA-BCON boom, the laboratory scale conceptual study model is developed, and the stepwise deployment is demonstrated. There have future subjects, such as heating methods and heating controls, but the conceptual advantages of the SMA-BCON boom is presented through the experiments, which are the controllability of the deployment speed, angular velocity of center body. The controlling and the sensing methods are next works of SMA-BCON boom systems.

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