High accuracy evaluation method of deployment characteristics for large deployable structures

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Abstract

An index that well shows the difficulty of ground deployment test is the ratio of gravity torque to deployment torque. The object of this study is to quantitatively clarify the relationship between this index and the accuracy of deployment test. We perform deployment tests using a simple planar truss under micro gravity and gravity environments. Ground tests in which the index value of the truss is increased are also performed. Comparing these test results, we find that the estimation error of the development drive force is 10%, even for the simplest structure whose difficult index value = 1. The accuracy of the deployment drive force predicted from the mean value of gravity direction and the opposite direction results cannot be said to be sufficient even for simple models such as the planar truss. We introduce an empirical equation that sets a linear relationship between the difficulty index value and the evaluation accuracy. We can conclude that that it is infeasible to test the ground deployment of structures whose difficulty index value exceeds 1000.

1. Introduction

Deployable space structures such as solar cell paddles, deployable antennas, and deployable masts must be evaluated by ground deployment tests before launches. However, the deployment behavior of such structures under gravity is strongly influenced by the ground test equipment in many cases. In these cases, it is very difficult to evaluate the actual characteristic of the deployable structure. Instead of evaluating the characteristics of the deployable structure, we are actually evaluating the characteristics of the ground test equipment.

The accuracy of estimating the deployment characteristics of a deployable structure worsens as the structure's size increases. Mitsugi defined the index of difficulty of deployment test as a function of the size of the deployable structure [1]. The index showed that we could not measure the deployment drive force of deployable structures that were more than 10 m in diameter. In response, we proposed the deployable mesh antenna, which consists of multiple modular structures [2]~[4]. However, the quantitative relation between module size and evaluation accuracy remained unclear.

The object of this study is to clarify the relationship between the difficulty index value and the accuracy of estimating the deployment characteristics quantitatively, and to introduce an index that indicates the size limit of deployable structures permitting accurate ground test evaluations. We performed a deployment test of a simple planar truss under a micro gravity environment created within a jet airplane. The results were taken as "true" deployment characteristics. We then performed ground deployment tests under two test conditions. We compared the results of the deployment tests and evaluated deployment characteristics quantitatively. This paper describes the relationship between the difficulty index value and the evaluation accuracy.

2. Planar truss

The index that shows the difficulty of the ground deployment test is the ratio of gravity torque to deployment torque. Figure 1 indicates the difficulty index value calculated by Mitsugi's formulation for launched and planned space deployable structures [5]~[9]. Here, d represents the stowed diameter. In figure 1, the difficulty index value of a structure with deployed diameter of 5 m is 100, it is more than 1000 for structures whose deployed diameters exceed 10 m. In this study, a simple planar truss, whose difficult index value was changed from from 1 to 100, was used to estimate the relationship between the index and the accuracy of ground test.

The model was based on the deployable truss support structure of the modular mesh antenna developed by NTT [3]. Module mesh antenna, whose size is 18 m X 17 m, consists of 14 basic modules. Each basic module is 4.8 m in diameter and is 0.6m in thickness shown in Figure 2. The planar truss was selected to simplify factor analysis. Its size was decided after considering the free space within the airplane. The planar truss, shown in Figure 3, consists of six beams (there are 2 synchronous beams) on both sides of the center beam; each beam is joined by a rotation hinge. The right and left diagonal beams and the lower beam are linked by a plate. Planar truss deployment and stowing involves moving the plate along the center beam. A constant force spring and a motor are mounted on the plate (A). The planar truss stows when the motor winds in the drive cable, and deploys when the drive cable is released. When the plate (A) slides by 0.135m, the planar truss is fully stowed. The stands are used to add weight to the center of the side beams. The difficulty index value can be altered by changing the weights. The beams and plates are made of aluminum. The length of the planar truss is 1.2 m (deployed) and 0.1 m (stowed). Its weight is 4.7 kg. The spring force is 8.2 N when the difficulty index value =1. Spring force is 6.3 N when the difficulty index value > 1 to minimize the weight needed to increase the difficulty index value.

3. Deployment tests

Figure 4 shows the appearance of the micro gravity deployment test. The test time was set up 20 seconds, and measurements during deployment and stowing were performed three times under the same condition. The planar truss can stow until the configuration shown in Figure 4 within the given test time. Figure 5 shows the appearance of the ground suspension deployment test. The test time of the ground test equaled that of the micro gravity test. Two suspension methods were used as shown in Figure 5. One fixed the lower side of the center beam to the floor and supported the upper part of the side beams with cables to offset gravity torque. The other method supported the lower side of the center beam with a cable of fixed length, and the center part of the side beams with cables exerting constant force. As you can see in Figure 5, the planar truss deployed in the gravity direction in ground test (1), and deployed against gravity in ground test (2). The height of the suspension position is also shown in figure 5. The suspension cables were tensioned by counter weights through pulleys. The weights were 0.220 kg (W1) and 0.130 kg (W2). Next, we attached weights to the stands on the side beams to increase the difficulty index value of the planar truss. We performed the ground test using large difficulty index values. The relation between the weight and the difficulty index value of the planar truss is shown as Table 1. The difficulty index value changes with the deployment position. Table 1 presents the maximum values.

4. Experimental results

The tension of the drive cable, which was wound or released by the motor, was taken as the deployment drive force. The mean value of the deployment drive force can be obtained as an average value by adding the tension of the drive cables in deployment and stowing motion and dividing by 2 at each position. Friction force can also be obtained by subtracting the tension in deployment stowing motion from the tension in deployment stowing motion and dividing by 2 at each position.

There are two approaches to compensating the gravity effect and so determine the true deployment drive force. One is to cancel the gravity force by averaging the test results obtained in both the gravity direction and the opposite direction. The other is to estimate gravity effects by analysis models and extract the deployment drive force from the test results. The accuracy of the former method is influenced by the non-linearity of the test article and test equipments, and that of the latter is influenced by the accuracy of the analysis models used. Figure 6 shows the deployment drive force in the microgravity, two ground tests, and the mean value of ground test (1) and ground (2) respectively. As mentioned above, the mean value represents the predicted deployment drive force in micro-gravity. In Figure 6, the result of the micro gravity test and the mean value of the ground tests differ by more than 10 %. The accuracy of the deployment drive force predicted by averaging the test results obtained in both the gravity direction and the opposite direction is insufficient even for this simple model. Moreover, the mean value of the ground test is higher than the results of the micro gravity test. This means that the predicted deployment drive force does not indicate the worst case.

Next, an analysis model of the planar truss was established including ground test equipment. Figure 7 shows the analysis result as compared to the result of ground test (1). There is approximately 10 % difference between the analysis result and the test result. The factors are thought to be errors in the mass property of the planar truss and the suspension arrangement (the suspension position and the counter weight) in the test equipment. In this test, the measurement accuracy of the suspension position is 1 % and the measurement accuracy of the counter weight is 0.1 %. Therefore the accuracy of the analysis model for the test equipment is small compared to the error of estimating the mass property of the planar truss.

Figure 8 shows the change in deployment drive force when the mass added to the planar truss was changed. 5 % and 10 % of the planar truss weight was added to the upper part of one side beam to assess the influence of a change in the mass property on the deployment drive force. In Figure 8, when weight equivalent to 5 % of the planar truss was added, the deployment drive force corresponded to experiment result. In this analysis, the given deployment drive force is true, therefore, the accuracy of the test results is mainly determined by the estimation error of the mass property of the planar truss. In actual deployment tests, it is very difficult to estimate the true mass properties of large deployable structures during deployment.

Figure 9 shows the experiment results and the analysis results as functions of the difficult index value. Here, E and A indicate the experiment result and the analysis result, respectively, and the difficulty index value is denoted in parentheses. The deployment drive force increase rapidly when the slide length exceeds 0.08 m. Here, we define the accuracy of the deployment drive force. In figure 8, the analysis result is assumed to be exact except for the spring force. Therefore, the difference between the experiment results and the analysis result is caused by the estimation error of the deployment drive force. The estimation error is directly added to or subtracted from the deployment drive force as follows.

$$DDF_{exeriment}(x) = DDF_{analysis}(x) + Error_{average} \quad (1)$$

Here x denotes slide length, DDF denotes the deployment drive force.

The estimation error can be obtained by fitting the analysis profile to the experimental profile as shown in Figure 10. The accuracy of the deployment drive force is defined as the ratio of the estimation error to the reference deployment drive force (obtained by spring assembly tests) Figure 11 shows the relationship between the difficulty index value and the evaluation accuracy. By assuming a linear relationship between the difficulty index value and the estimation accuracy, we obtained the empirical equation (2).

$$R = 0.1i + 2.4 \quad (2)$$

Here, i represents the difficulty index value and R indicates the ratio of the error in deployment drive force to the spring force.

The estimation error of the deployment drive force is approximately 12% when the difficulty index value =100. When the difficulty index value =1000, the estimation error of the deployment drive force exceeds the spring force. Therefore, we can conclude that that it is infeasible to ground deploy structures whose difficulty index value exceeds 1000.

5. Conclusion

An index that predicts the difficulty of ground deployment test is defined as the ratio of gravity torque to deployment torque. The index can be used to assess the maximum size of deployment structures for which ground deployment test is feasible. A simple planar truss, whose difficult index value was changed from from 1 to 100, was used to estimate the relationship between the index and the accuracy of ground test. Our results can be summarized as follows.

(1) The estimation error of the development drive force is 10%, even for the simplest structure whose difficult index value = 1.
(2) The accuracy of predicting the deployment drive force by averaging the test results obtained in both the gravity direction and the opposite direction is insufficient even for this simple model.
(3) The accuracy of the test results is strongly influenced by the error in estimating the mass property of the structure.
(4) We obtained an empirical equation that sets a linear relationship between the difficulty index value and evaluation accuracy.
(5) We can conclude that that it is infeasible to test the ground deployment of structures whose difficulty index value exceeds 1000.

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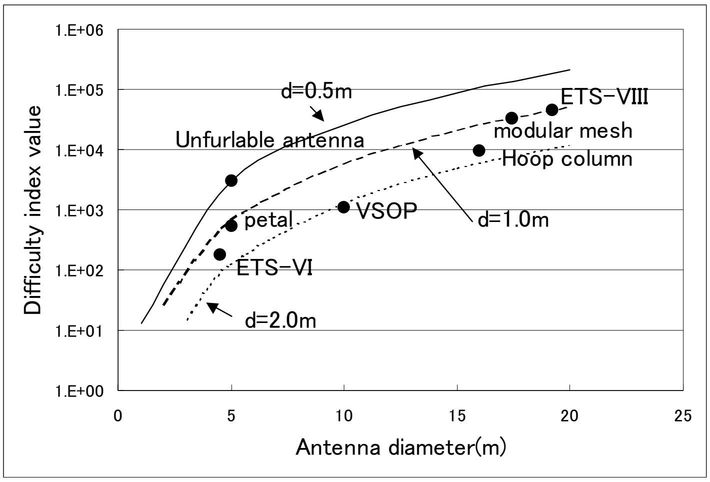


Fig.1 Difficulty index value

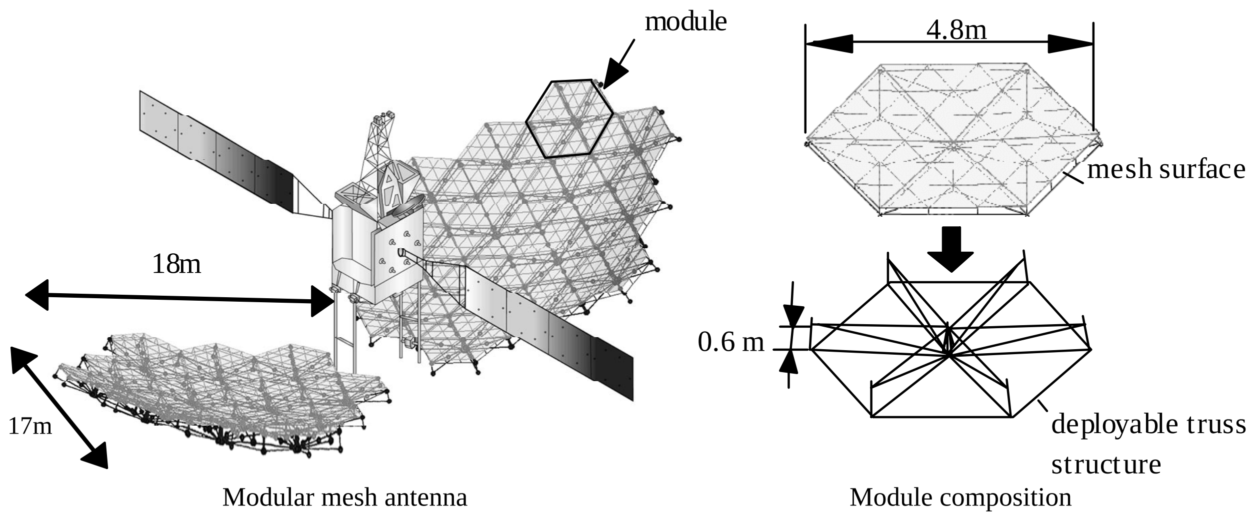


Fig.2 Modular mesh antenna

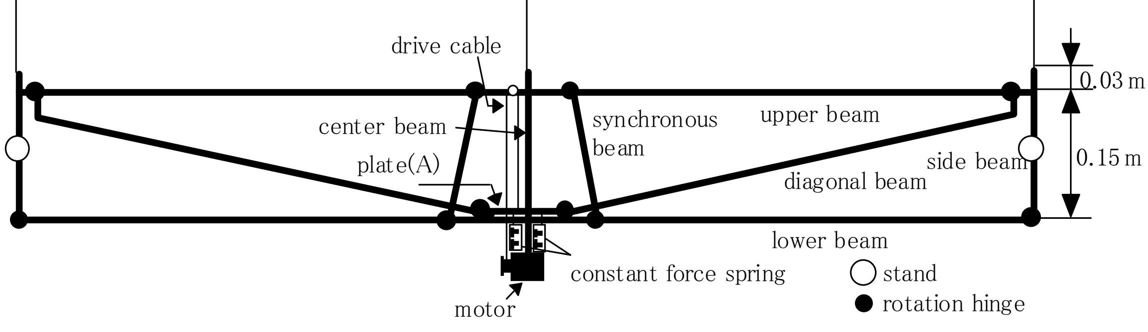
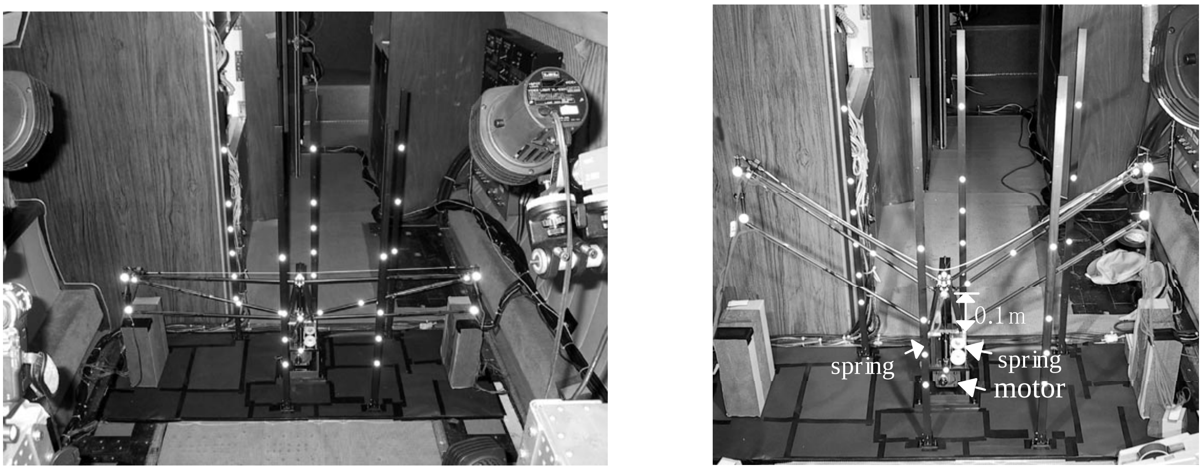


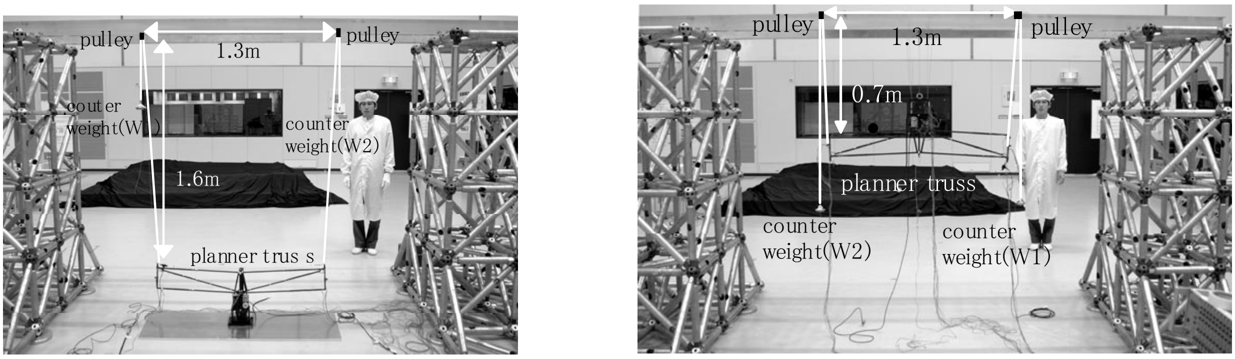
Fig.3 Planar truss



deployed configuration

stowed configuration

Fig.4 Micro gravity test



ground test(1)

ground test (2)

Fig.5 Ground test

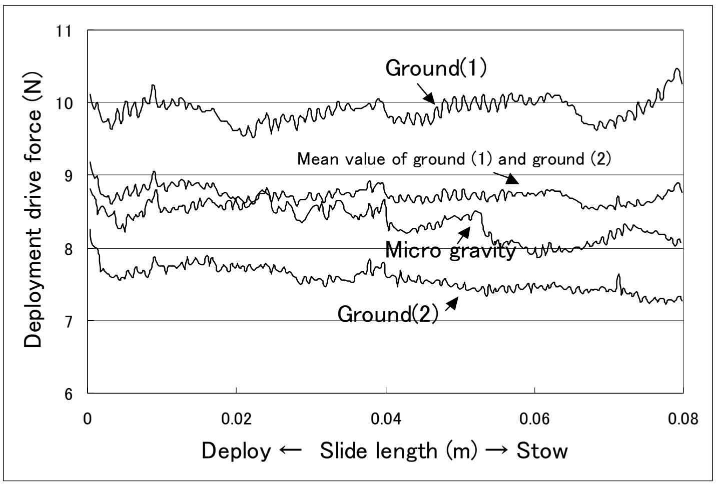


Fig.6 Estimation error due to gravity cancellation residual

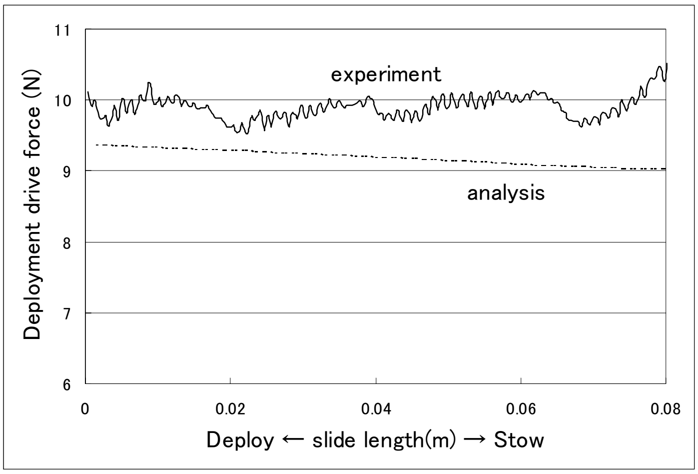


Fig.7 Estimation error due to analysis model

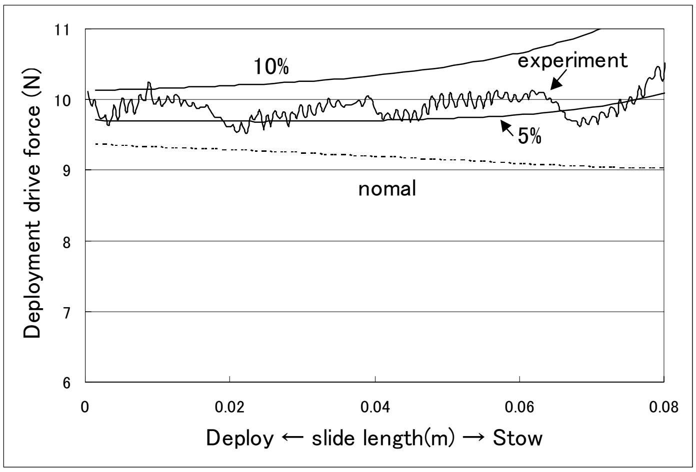


Fig.8 Influence of the error in the mass property of the planar truss

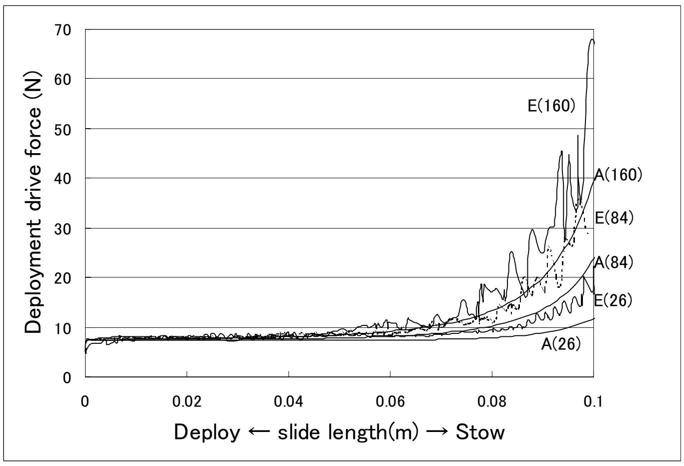


Fig.9 Estimation error due to the difficulty index value

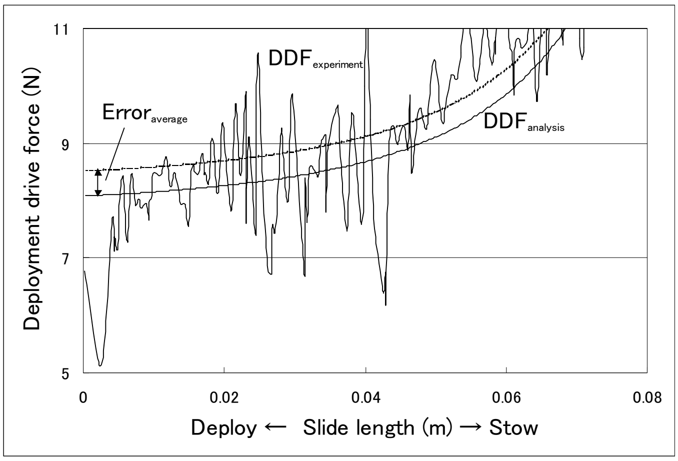


Fig. 10 Accuracy of the deployment drive force

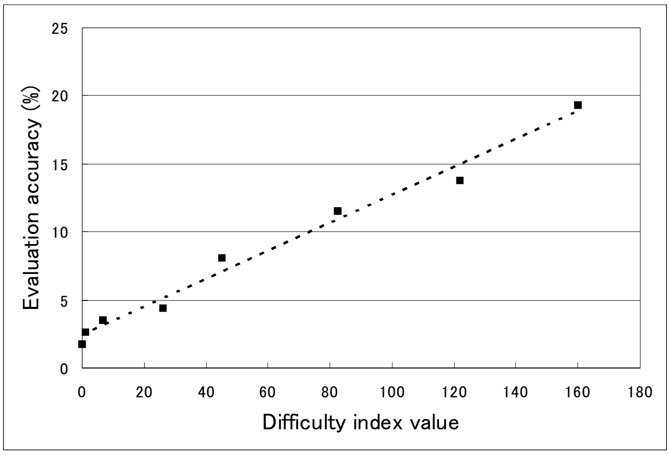


Fig.11 Relationship between the difficulty index value and the evaluation accuracy

Table1 Relationship between the weight and the difficulty index value

Weight(kg)	Difficulty index value
0.5	26
1.0	45
2.0	84
3.0	122
4.0	160