High-Speed Observation for Deployment of Super-Tether in Inverse-Origami Method *

By

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Abstract

Super tape is a bare electrodynamic tape tether which has superior properties than thin round cross-section tether in anti-debris feature and high electron collection characteristics. The super tether is thus expected to play important roles in space debris mitigation and space structures construction. Such mechanism as reel has difficulty for the deployment of the tape tether in comparison with thin tether, which is able to be wound in bobbins. New mechanism, inverse-origami method, is employed for the deployment and had successful 132.6m deployment on a sounding rocket experiment, T-Rex, in 2010 for the first in the world. A wide variety of examinations of one dozen are employed for preflight analysis in order to assure the reliability of the deployment. Based on the flight demonstration post flight analyses are also still in process including some reconfirmations of preflight analysis and such additional analysis as high-speed observation of deployment. Many plans are in progress in JAXA, ESA and NASA since the super tether can be an important element. This paper is to report a variety of experimental results of the folded tape deployment in the inverse-Origami method.

スーパー･テザーの逆オリガミ法による伸展特性の高速度解析について

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概要

スーパー・テザー（ベア導電テープテザー）は対デブリ特性でも集電特性においても多く用いられる細い円断面のひも状テザーに数倍勝り、宇宙デブリ減少や宇宙エレベーターへの応用など今後の宇宙開発において重要な役割を持つことが期待されている。このスーパー・テザーは、展開機構として逆オリガミ法を用い、2010年の観測ロケット実験、T-Rex, によって132.6mの世界初の伸展実験に成功した。この展開の信頼性を確認するために１ダースの飛行前解析を行った。宇宙飛行本実験を受けて高速度カメラ観察などを追加した展開信頼性解析の再検討が進行中である。スーパー・テザーが宇宙デブリ回避に有効で燃料を用いない推進の有用な要素であり、JAXA、ESAやNASAではいくつかの計画が進行中である。本論文ではこのスーパー・テザーの逆オリガミ法による折りたたみ展開特性に関して種々の実験解析について紹介する。

1. Introduction

Super tether, bare electrodynamic tape tether, is a tether system with excellent performance.

Tether technology is one of the advanced space technologies such as the inflatable technology. Tether is useful for construction of space structures since of its light weight in long structures, compactness in fold, high strength in tension, and in particular needs little effort of human work[1)-7)].

Tether can be divided into two types, one thin round cross-section tether and the other thin-tape (flat) tether. Tape tether is substantially enhanced tether survivability against hits by abundant small debris[8),9)]. The bare electrodynamic tape tether is called “super tether” because it is enhanced small debris survival against hits by abundant and it is also “a bare electric tether” several times superior in the electrodynamic performance[10)] in comparison with the round-cross-section of same section area.

The super tether is first in the world had success of space deployment in 2010 August 31 by an international team of Japan, Europe, USA and Australia launched from Uchinoura by JAXA sounding rocket S520-25 named T-Rex (Tether Rocket experiment). Object of the s520-25 is the demonstration of electrodynamic tether in space including both the science and engineering missions. The plans included are engineering mission to deploy bare electrodynamic tape tether with length 300m swiftly in 120 seconds, space ignition of Hollow cathodes, extension of inflatable electrodynamic boom, and electron collection employing these tether, Hollow cathodes, and the boom[11)].

Fig.1 Super tether deployed in space (Seen from subsatellite)

The first phase of the demonstration is the deployment of the electrodynamic tape tether and a lots of loads is devoted to assure the reliability of the super tether deployment in the preflight phase.

All of experimental methods in preflight analysis are dozen preflight experimental analyses and numerical simulation[11)-13)]. We had the space flight experiment in addition to these dozen preflight experimental analysis and one numerical analysis and the super tether has been deployed successfully in space first in the world in 2010. The demonstration is reported for the flight experiment at conferences including the AIAA conference in 2011[13)-17)].

The super tether is expected to be employed in such future space mission as debris mitigation plan, BETS project in ESA[18)-22)], and in NASA[1)] and also tape tethered space elevator[23)].

This paper is devoted to report the post flight analysis of the deployment performance in reference to the space flight data obtained in the space demonstration in 2010.

These post flight analyses includes; 1) Re-examination of the side friction force of the box, and 2) High-speed experimental observation.

We are still analyzing the deployment behavior of the super tether since the precise deployment is required for useful future space missions.

1.1 Super tether.

The T-Rex demonstration has employed bare electrodynamic tape tether of reinforced aluminum tape in dimension 25mm*0.05mm with length 300m and weight 7kg.

The tape tether has shown to have difficulty in the process of deployment in the project ATEX in 1998[24),25)]. The tape tether employed was deployed only 22m and was jettisoned to ensure the safety of the host spacecraft. It is suggested that the condition was caused by a slack in the tether due to its rapid heating after coming into the sun.The object of the T-Rex project is to demonstrate the reliable deployment of the tape tether and also the performance of electron collection of the tape tether. The tether was deployed successfully in 120 seconds. The length in the tape tether deployment was 132.6m and could not reach to the objective length of 300m. The high fidelity is however confirmed for the deployment scheme employing the tape tether folding and that the length of 132.6m is the world record of the longest deployment in the space tape tether.

1.2 Space demonstration (T-Rex project)

The super tether is deployed successfully on the sounding rocket experiment, T-Rex.

The super tether was a bare electrodynamic tether, which is a reinforced aluminum with width 25mm and thickness 0.05mm, and the science experiments employs the Langmuir tube as a main measurement device.

The present mission requires reliable and robust deployment because the bare tape tether is shown to have many unknown dynamic characteristics and a complex dynamic behavior. The deployment system employs a foldaway storage method. The present foldaway tape tether deployment system is based on a new concept "Inverse ORIGAMI" method and is totally different from the usual reel type tether deployers which was unsuccessful in the project ATEx. This innovative storage method can afford reliable fast deployment and is a key idea of the proposal to satisfy the requirements of the science mission. Figure 2 shows the folded tape tether in a box.

The tether was deployed successfully in 120 seconds in order to afford sufficient time periods for science experiments of about 300 seconds in space. The length in the tape tether deployment was 132.6m and could not reach to the objective length of 300m as shown in Fig.3. The flight record shows sudden decrease of the tether deployment speed in about one minute after the start in acceleration -0.042m/s^2 as estimated by the parabolic approximation (red dotted line).

The drag in the decrease of deployment is estimated to be much greater than the estimation in the on-ground experiments. Some reasons are supposed to cause the incomplete deployment including the deformation of tether, the centrifugal force due to the spin of the rocket and an excessive drag in the vacuum environment. Six cameras were on board in the rocket payload and three among them were used to observe the deployment process. One camera to observe the behavior of folded tether inside the box was unfortunately inactivated.

To clarify the reason of the short deployment post flight analysis is employed experimental analysis in addition to the preflight analysis in a variety of experiments as will be shown later.

2. Design/examination of deployment system

Deployment of the tether starts the T-Rex space experimental process and should be the first success of the demonstration. The tape deployment is required high reliability. The inverse ORIGAMI method is employed in the T-Rex project to assure the high reliability of the deployment without rotation mechanism which is possible to induce slackness in the course of the deployment. Fast deployment of tether was also necessary in order to afford sufficient time for science mission in 300sec. Total flight time of the rocket is 440sec and thus it was necessary to deploy the tether in 140sec, i.e., 440sec -300sec.

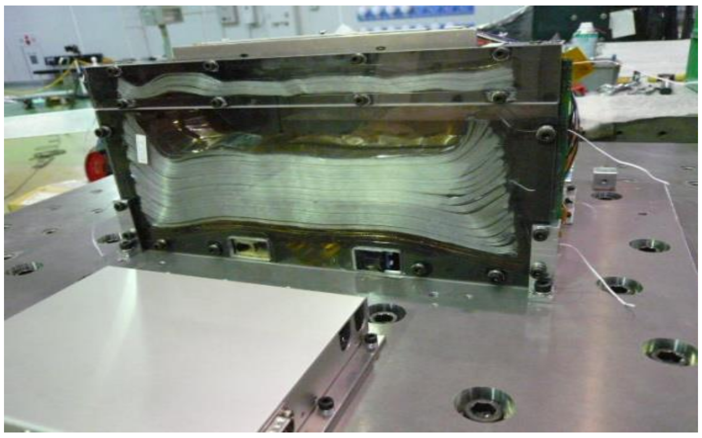


Fig. 2 Tape tether folded in the Inverse Origami method

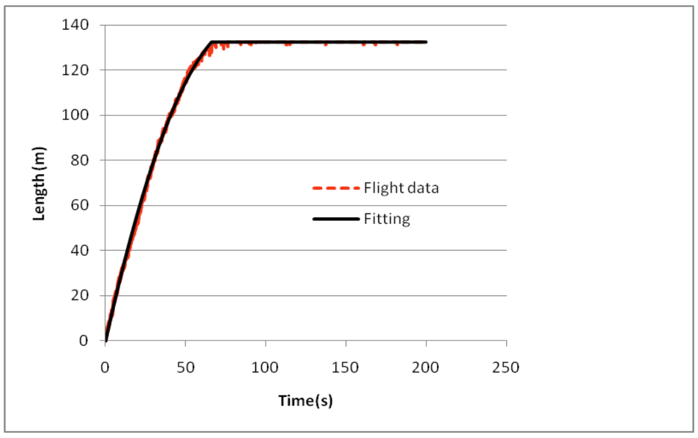


Fig.3 Time response of tether deployment in T-Rex space demonstration

It is necessary to reserve space environment without such pollution as gas jets for the science missions of charged particle correction. The tether is deployed passively by spring ejection without any active control using the gas jet[26)].

2.1 Reel system and Z-folding method

The spinning reel type deployment is most employed for tether deployment of round-cross section thin tether but is not appropriate for the present tape tether[27)-32)].

The dram reel type deployment requires precise control of tether tension with respect to the angular momentum of the reel dram.

The present inverse ORIGAMI method has no rotating element and so no significant phenomena as slackness of tether invoked by the difference in the speed of reel dram rotation and tether deployment. The present method has high reliability characteristics for deployment. Precise estimation of the tether deployment phenomena is however necessary in order to deploy tether for a prescribed length in deployment. This precise estimation of phenomena includes estimation of the drag in the total procedure of deployment and the energy to be stored in the ejection spring.

2.2 Preflight analysis (Simulation of space environment)

A variety of methods are searched and analyzed experimentally and numerically in the preflight analysis in order to assure the high reliable deployment of the super tether. The conducted methods include almost possible methodologies to simulate the space environment.

All of experimental methods in preflight analysis are revisited and summarized shortly as follows:

1. Air table
2. Vertical extraction
3. Vacuum chamber
4. Water rocket
5. Linear motor
6. Horizontal ejection by carts
7. Low friction table
8. Spin table
9. Vertical ejection using wire cutter
10. Ballistic flight
11. Freezer test
12. Space environment simulation experiment.
13. Numerical simulations including two-dimensional numerical analysis from folding to deployment and Large deformation analysis

3. Dynamics of Deployment (On-Ground experiment and numerical simulation)

It is necessary for the deployment to afford precisely enough mechanical energy to overcome the drag applied in the course of the deployment.

Necessary energy for deployment is expressed as

$$E_d = E_f + D_d \bullet L_t + \alpha \qquad (1)$$

where E_d is energy stored in the springs, E_f deployment energy of the folds, D_d deployment drag, L_t length of deployed tether, and α is other necessary energy including that of braking.

4. Re-examination of the exit and side friction of the box

Friction generated around the exit and side of the tether box has been considered to have much influence on the high speed deployment test of tape tether in the ground experiment.

Three kinds of experiments have been conducted for re-examination of friction including ejection tests with the box horizontal, vertical, and inclined, the horizontal extraction development test and free fall test[33)-40)].

Examination of side wall drag includes

1. Vertical extraction test
2. Horizontal extraction test
3. Inclined extraction test
4. Sophisticated side wall examination
5. Freezing test
6. Free-fall test.

In the course of these post flight examination we could obtain at the present the following three qualitative results as the important characteristic parameters of the super tether deployment.

4.1 Effect of the deployment speed

Linear dependence of the friction drag of the side wall is obtained with respect to the deployment speed. The friction drag of the deployment has a linear function dependent on the deployment speed of the tether as clearly shown for the case of inclined ejection in Fig.4[37)]. This can be understood easily taking into account the length of tether deployed in same time period. It may be noted that this effect was already investigated widely in the process of design of tether box as shown in Fig.5[38)].

4.2 Effect of side-wall friction

The static friction coefficient is able to have effect on drag of tether deployment. This effect is studied in a variety of ways including the vertical ejection, horizontal ejection and extraction, and also inclined ejection to change the weight of tether on side wall. In addition to these results, the static friction of the side wall of the box is changed in material and

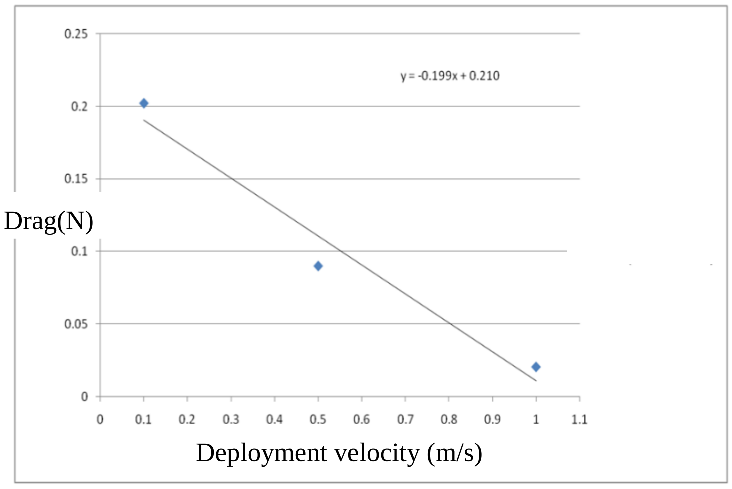


Fig.4 Drag with respect to deployment speed (Inclined box)

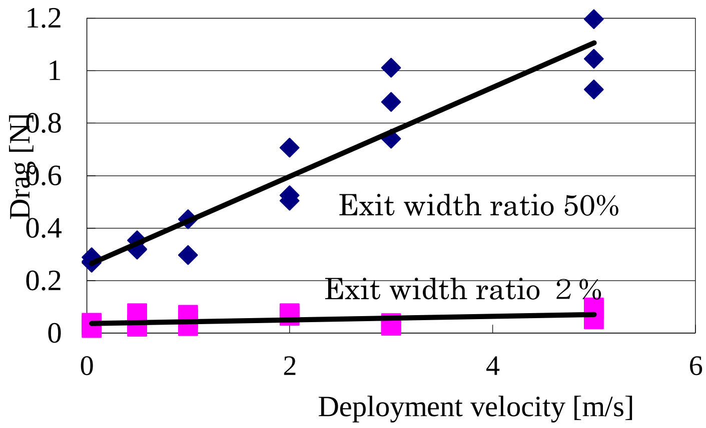
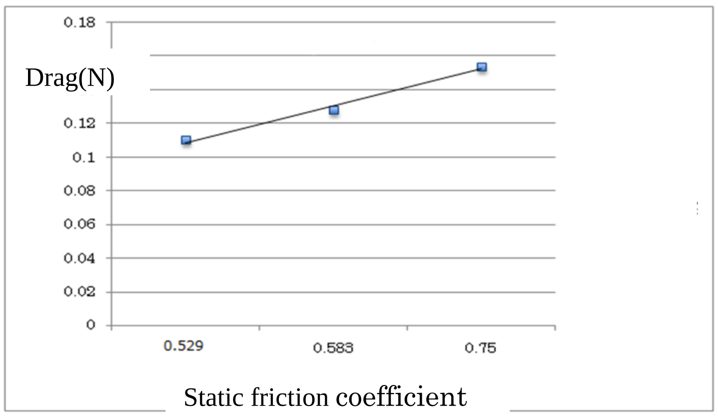


Fig.5 Drag with respect to deployment speed (Box design study)

Fig.6 Drag with respect to static friction coefficient of the



side-wall

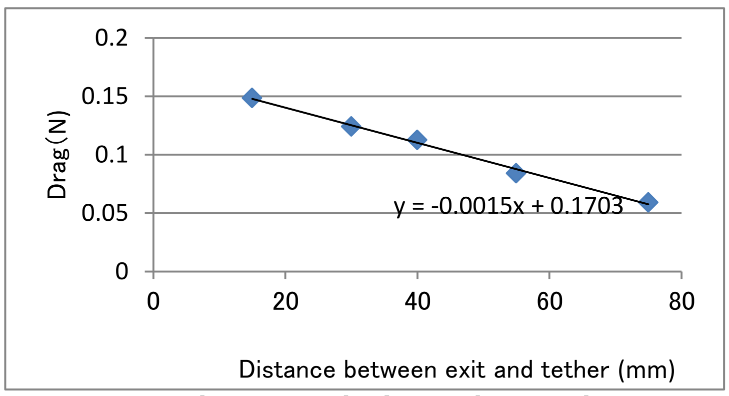


Fig.7 Drag with respect to the distance between the ejection exits of the box from the folded tape tether

this experimental result has shown a typical relation, i.e., linear dependence of the friction drag is obtained with respect to the static friction coefficient of the side-wall as shown in Fig.6[39].

This fact indicate us that we can adjust the tether deployment drag by selecting the material of the tether box.

4.3 Effect of vacancy of box

Important parameter is cleared in the post flight analysis as the distance between the ejection exits of the box from the folded tape tether. Uncertainty of ambient in space flight has come to study the deployment performance when the gravity is almost upside-down. Accident in deployment is easily imagined for the case much tether is jamming at the exit. Tether is set changing the distance from the exit of the box and the deployment drag is measured in the experiment as shown if Fig.7. Linear dependence is observed of the deployment drag with respect to the distance from the exit.

4.4 Characteristics of drag force in deployment

The drag force varies in frequencies since the tape tether is folded in Z shape for the inverse-Origami method and is deployed every fragment in accordance with the length of the fragment, 60cm. The time response of the drag is shown in Fig.8. It is seen in Fig.8 that the frequency of increase of deployment drag is 0.4s which is simultaneous with the ejection frequency of the deployment velocity 1.0m/s. It is then concluded the timing of the top drag in deployment is mutual dependence on the folded segment of tape tether.

It is also observed a sudden increase of deployment drag in the tape tether deployment procedure as shown in Fig.9. This is considered that the folded segment comes in pile resulting in the change of thickness of tether at the instance and thus increase of the drag.

5. High-speed camera observation

Deployment behavior of tape tether is observed for its micro feature employing a high speed camera. Markers are attached to the tape tether for the observation and the deployment behavior is observed by the high speed camera including the effects of the vacancy in box and the exit ratio. The deployment is seen to be 90% with respect to full flat deployment in the high-speed camera observation.

5.1 Movie analysis for deployment behavior

Effect of the deployment speed is shown in Fig.10 where the exit ratio is changed from left to right as 17%, 67%, 33% and 100%, and the deployment velocity is changed from top to down as 0.5m/s, 1.0m/s and 1.5m/s.

The drag at open of the folded parts is observed to have dominant effect on the deployment process. Tether is deployed much longer in space in comparison with the on-ground experiment leading to much increased numbers of folded parts in space demonstration than in the on-ground experiment. It is then considered the continuous increase of drag to open the folded parts until full deployment could cause increase of drag in space demonstration.

Effect of the vacancy in box is shown in Fig.11 where the exit ratio is changed from left to right as 17%, 33%, and 67%, and the distance of tether from exit is changed from top to down as 12.3cm, 7.4cm, and 2.5cm.

5.2 Deployment drag measured by electric balance

The effect of vacancy in the box is also observed by measuring the deployment drag employing an electric balance. Results are shown in Fig.12 where time responses of deployment drag is shown for the distance to exit 12.3cm and 2.5cm from left to right.

It is seen that results for exit ratios 17% and 33% are piled up at the distances 2.5cm. This fact shows as natural that the

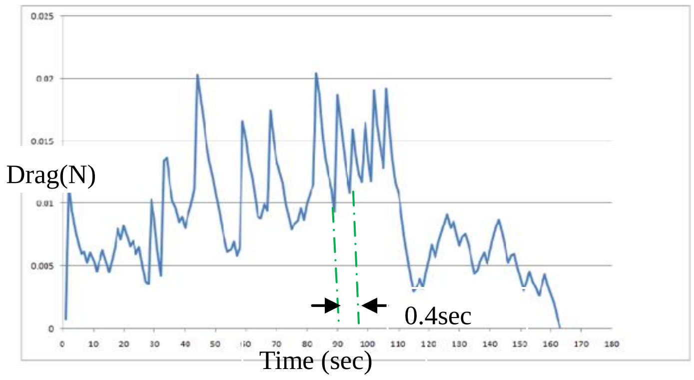


Fig.8 Time response of the drag (Deployment velocity 1.0m/s)

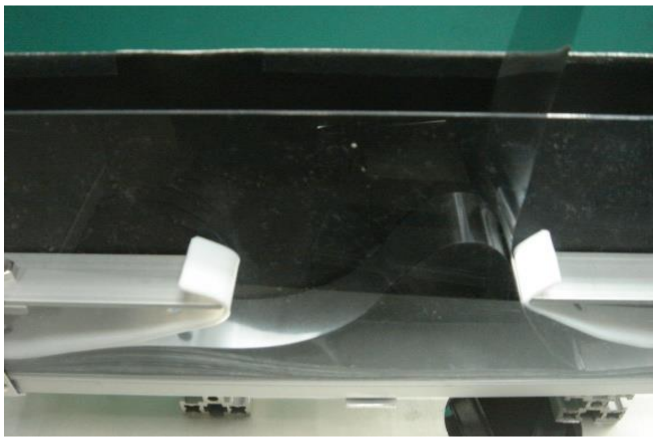


Fig.9 tape tether in pile at exit

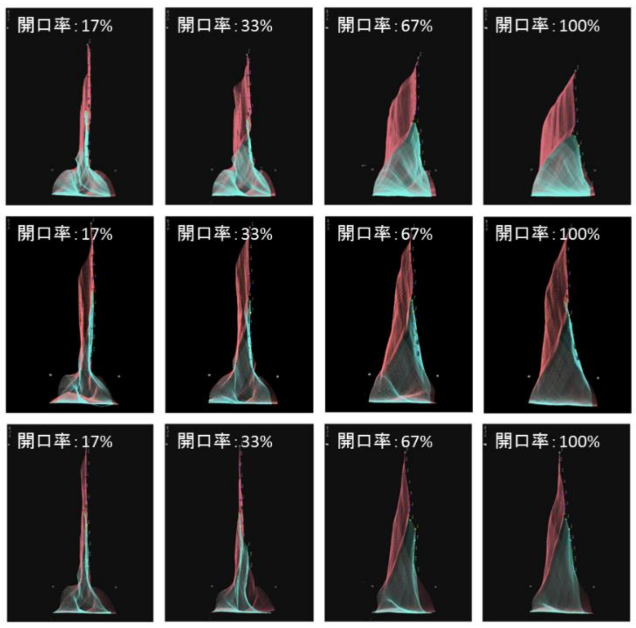


Fig.10 Deployment behavior for different deployment speeds

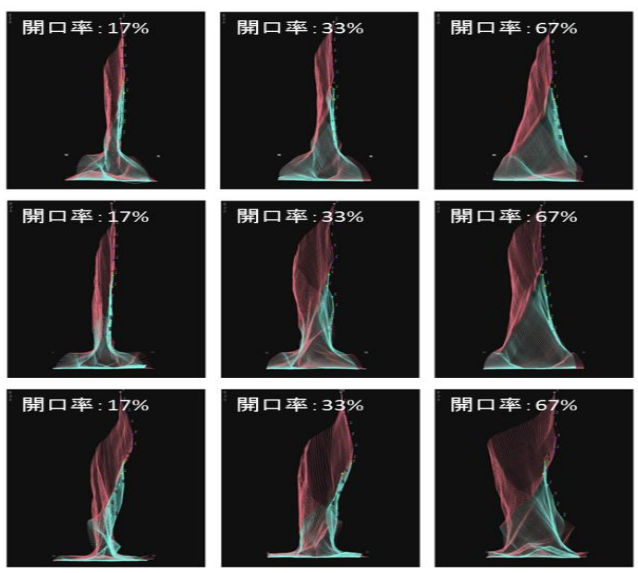


Fig.11 Deployment behavior for different vacancies in box

effect of the exit ratio becomes obscure as the distance to exit decreases. It may also be noted in the result of distance to exit 2.5cm that the first peak of the drag for the case of exit ratio 33% is greater than that of exit ratio 17%.

It is thus concluded that the vacancy has much effect on the behavior of tape tether in deployment resulting in much complexity for estimation of the tape tether deployment drag.

6. Total deployment performance

Tape tether deployment speed has suddenly reduced in T-Rex demonstration. This fact may show the technical difficulty inherent in deploying tape tether fast from tumbling spacecraft by spring ejection system.

Future plans employing orbiting spacecraft may not require fast deployment as in T-Rex and it is necessary to understand whole general deployment characteristics of tape tether.

It was realized that the folding segments open 90% for full flat tape tether of 100% open on the ground experiment by the present study. This fact indicates the importance of space tether employment since very long tether includs a large numbers of folds with living spring-like force at the folds.

7. Conclusion and Recommendation

Some important design parameters are studied experimentally including those examined in the preflight analysis and the vacancy of tether in the box. Effct of the distance between the tether and the exit is studied in the postflight analysis in addition to study the effect of gravity to change the inclination of tether boax on ground as the vertical, horizontal and inclined ejection analysis. The exit open ratio and the distance between tether and exit show the effect of the vacancy in the box and the effect is shown to have much effect on the deployment performance of tape tether especially related to the increase of deployment drag. This effect is concerned with the physical phenomenon reduced from mechanism that tape tether deploys by contacting tape surface to the exit wall of the box. This mechanizm has been well observed by analysing the movie results in high speed camera.

The bundle of folded tether may not stay in the tether box in space flight condition and it is not easy to estimate the drag precisely in the on-ground examination if the tether bundle is not fixed in the box.

Even a small amount, the effect is integrated over long tether in the deployment time period due to such disturbances as spin, acceleration, physical properties of tape, and microgravity environment. It is thus observation inside the box in the deployment process is necessary in order to analyse the depoloyment behavior and any design may be necessary to fix the residual tethers in the box for the deployment process.

Such small force as the residual spring force spreads along the long tether in deployment process to open many folding segments in 100% rather than about 90% in the high speed observation. Such fact suggests us to realize the difficulty in the design of long space tether not only in the present tape tehter deployment.

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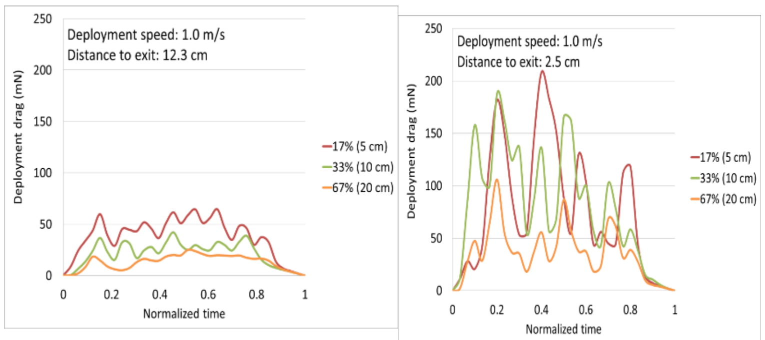

Fig.11 Time response of drag in the deployment

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