Nanorover Solar Sail Dynamic Simulation

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SUMMARY: The Nanorover Solar Sail is a concept being evaluated for the deployment of small rovers that may be used for extra-terrestrial exploration. This paper describes an ADAMS simulation of a demonstration model of the sail. The simulation showed that the sail deploys as envisioned, and helped define the deployment time of the sail demonstration model as a function of air damping. Additionally, the simulation gave insight into the deployment sequence, the effect of anchoring the sail, and the effect of internal friction between sail elements. Details of the model and simulation results are presented. The presentation includes a video showing the deployment of the sail.

INTRODUCTION: The Nanorover Solar Sail is a concept being investigated at JPL for the deployment of small rovers that may be used for extra-terrestrial exploration. The Solar Sail is comprised of rings with progressively smaller diameters such that the entire sail can be folded and stored in a very compact form. The rings are arranged in the form of "fronds" attached to a spine. When deployed, the sail is propelled by solar wind pressure on a kapton membrane stretched across the rings. Under space application, the sail will operate in vacuum under zero gravity. A demonstration model of the solar sail is planned for use in proof of concept studies on a suitable platform.

PART DESCRIPTION – PROTOTYPE SAIL: The prototype sail will have six principal spines emanating in a hexagonal array from a central hub. Each spine has fronds containing rings attached on either side. When deployed, the fronds fan out from the central hub and the spines to form an array extending about 25m in diameter. The full sail will have over 4000 rings. The largest rings, which are located at the principal spine, are 12-in in diameter, and the subsequent rings decrease in diameter by 1/16-in each.

PART DESCRIPTION - DEMONSTRATION MODEL: A demonstration model is planned for use in proof of concept studies. The demonstration model simulates a single spine of the prototype sail, and has eight fronds, each consisting of six rings. The fronds are divided into two sets of four fronds, one attached to either side of a ring on the spine. The demonstration model thus has a total of 52 rings. The spine is made up of four rings of 9-in diameter. The diameters of the rings on the frond decrease progressively by 1/16 each. The first ring on the frond attached to the spine is 8.9375-in in diameter, and the last ring on the frond is 8.625-in. The sail demonstration model is shown in Figure 1.

Figure 1. Solar Sail 52-Ring Demonstration Model

Each ring is made of a tube 0.012-in OD and 0.006-in ID made from 416 stainless steel. The rings are butt-welded to one another. A typical pair of rings with the butt weld is shown in Figure 2. The rings are subjected to twisting when they are in the folded position. The resulting torsional resistance of the rings provides the spring stiffness that propels the sail during deployment. Each ring has a central aluminized Kapton membrane 0.00025-in thick (300A) as shown in Figure 2.

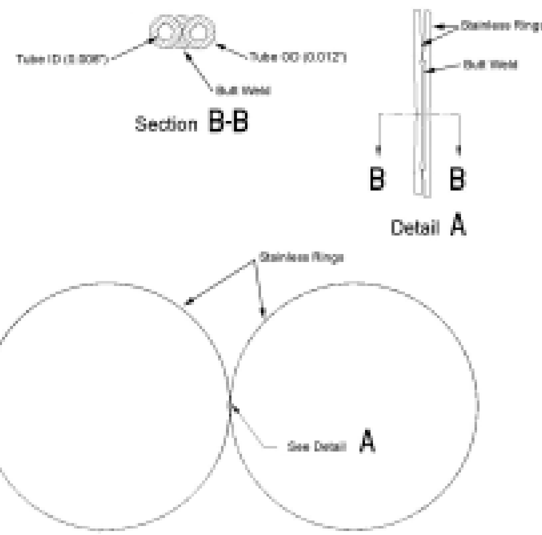


Figure 2. Solar Sail: Typical Pair of Butt-welded Adjacent Rings

From the completely open or deployed position, the rings fold on top of one another in “jelly roll” fashion and eventually on to the spine ring to which the frond is attached. When all the fronds have been folded, the rings of the spine are folded in “accordion” fashion. The demonstration model extends to approximately 100-in by 60-in when deployed.

The demonstration model is intended to be exercised on the earth on a suitable platform such as the KC-135 or the space shuttle, and as such, it will operate in air and under a range of gravitational environments from normal gravity to microgravity.

ADAMS ANALYSIS:

ANALYSIS APPROACH

An ADAMS model of the solar sail demonstration model was constructed to serve as the basis of the analysis. A dynamic simulation was performed to study the deployment dynamics of the sail model. Total time for the sail to completely open up from the folded position, sequence of opening and closing of the individual rings, and the influence of ring-to-membrane damping and air damping on the response characteristics were investigated.

ANALYSIS MODELS

The model was comprised of interconnected rings in the configuration of the sail demonstration model. Each ring consisted of a toroid representing the stainless steel tube and a circle representing the Kapton membrane. The mass of the Kapton membrane was included in the model by modifying the density of the rings, but the membrane was not a structural part of the model. This is representative of the prototype sail, because the membrane is not pre-loaded and does not contribute structural stiffness. A systematic nomenclature was developed such that each element of the model had a descriptive name defining its location on the sail model. Figure 3 shows the arrangement of the rings in the model, illustrating the nomenclature.

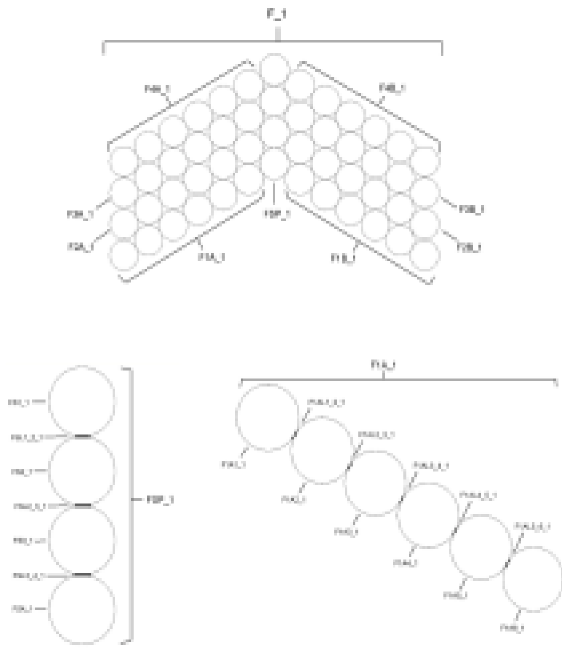


Figure 3. Solar Sail 52-Ring ADAMS Model: Arrangement of Rings and Nomenclature

The rings were mated together using a weld part. A revolute joint was provided at each ring interface comprising a spring-dashpot element with torsional stiffness and damping properties. Each ring could be modeled with a large number of segments to accurately represent the torsional stiffness of the rings. This approach was experimented with and found to be too unwieldy to use. Therefore, the rings were modeled as rigid elements, and the torsional stiffness of the rings was represented by the spring constant of the revolute joint. The assigned spring constant was derived by first developing a finite element model (Figure 4). This model represented a single typical ring with 72 bar elements. The torsional stiffness of the ring was obtained from the finite element analysis as 1.23E-4 in-lb/deg. The damping constant was initially assigned a trial value of 1.23E-5 in-lb.sec/deg. A revised value for the damping constant was obtained from air damping tests on a generic 6-Ring model as described later.

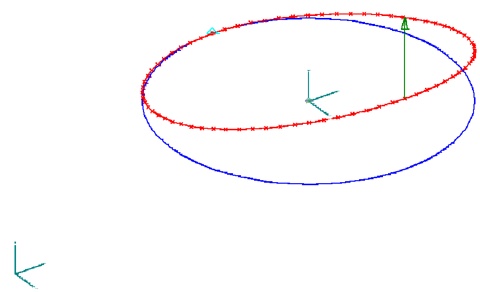


Figure 4. Solar Sail : One Ring FEA Model

The friction between the sail ring and the kapton membrane of an adjacent ring could potentially affect the sail deployment because the ring rubs against the membrane while opening. The frictional resistance was modeled by a contact region using a sphere and a plane. ADAMS allows for specifying separate static and dynamic friction coefficients. In the present analysis, the same value was used for both static and dynamic friction coefficients, but this value was varied over a wide range.

PROTOTYPE SAIL MODEL

At the inception of this task, it was envisioned that the ADAMS model of the prototype sail comprising 4000+ rings could be generated by building the 52-Ring model in parametric form and developing an automated process of duplication to extend it.

Given the differences in the ring sizes and the complexity of the joint definition, however, a simple automated procedure could not be developed for extending the 52-Ring demonstration model to the prototype model. Therefore, it was decided to focus on the dynamic simulation of the 52-Ring model to be followed by a subsequent study to explore automated procedures for generating the prototype 4000-Ring ADAMS model in an expedient manner. The follow-on study would also establish the hardware and software requirements for the dynamic simulation runs on the prototype sail model, and investigate optimization of the hardware and software resources.

RESULTS

AIR DAMPING EFFECTS

The prototype sail would be deployed in space and would therefore operate in vacuum. The demonstration model would be exercised in an environment with air. The air resistance would be expected to significantly affect the deployment time and dynamics, and therefore the influence of air damping needs to be quantified. A simple laboratory test was performed, in which a 6-Ring generic sail model was released from the fully folded position inside a building, and the time required for it to reach a fully open configuration was measured. The configuration of the tests is shown in Figure 5. The test article had 7 rings representing 6 rings on a frond and the associated spine ring. For purposes of comparing with the analytical simulation, deployment time is defined as the time at which the two rings at the extremity of the frond cross their initial position, and are parallel to the plane of the sail in its rest position.

Figure 5. Solar Sail 6-Ring Model: Air Damping Test Set up

In the ADAMS model, air resistance is not directly modeled, but its effect is included via the damping constant at the ring revolute joints. The 6-Ring analytical model was iterated, varying damping constant values to get the deployment time of the model to match the observed test results. The simulation of the 52-Ring model was repeated using a damping constant value inferred from the 6-Ring model runs to define the final results of this study.

DEPLOYMENT DYNAMICS OF ANCHORED AND FREE SAIL

In the prototype application, the sail would be deployed in free space, whereas in demonstration tests, the sail model may have to be anchored because of space limitations or other constraints. The free and anchored configurations have distinctly different effects on the deployment dynamics. In the free deployment case, the opening of the sail has to occur in such a manner as to keep the center of mass of the entire system at the same location in space. On the other hand, when the sail model is anchored, the center of mass of the system moves as the sail opens. As a result, the total deployment time for the two configurations is significantly different, and the free sail deploys in substantially less time than the anchored sail. This difference was clearly demonstrated in the ADAMS simulations of the 52-Ring model as well as in the 6-Ring model tests. The tests also showed that the deployment time was sensitive to the manner in which the model was anchored, and varied from 4.3s to 6.3s, compared with a deployment time of 2.8s for the free model.

The difference in deployment times may have a bearing on the platform to be used for the demonstration tests. If the deployment time is sufficiently short (under about 40s), the demonstration can be performed on the KC-135. If the deployment time is longer than what can be accommodated on the KC-135, the space shuttle would have to be used for the demonstration tests.

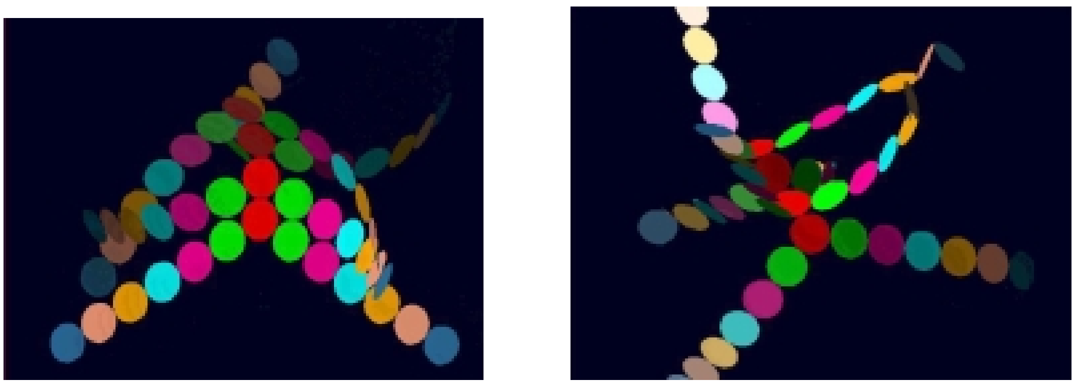
DEPLOYMENT TIME

The ADAMS model of the 52-Ring sail was used for a dynamic simulation in both the anchored and free configurations. The initial simulations were performed using a generic trial value of 1.23E-5 in-lb.sec/deg for the damping constant at the revolute joints. The simple definition of deployment time used with the 6-Ring model is not directly applicable to the 52-Ring model because of the considerably more complex dynamic response. A mathematical definition of deployment is possible in terms of a threshold value for the system energy, but was not pursued in the present effort. Instead, the animations of the responses were visually scanned for the state of motion during and at the end of the simulation. It was clearly evident that some motion of the 52-Ring model was still present at 50s for the free configuration, and at the end of the simulation time of 60s for the anchored configuration.

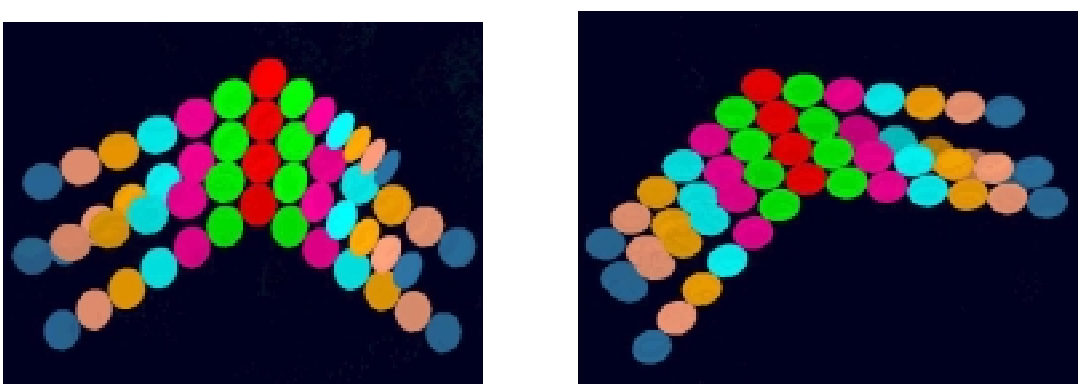
The anchored simulation was performed with one of the spine rings fixed. The simulation showed that the two fronds attached to the fixed spine ring came to rest early. Figure 6 shows the configuration of the sail in both the free and anchored modes at various stages of deployment.

ANCHORED MODEL **FREE MODEL**

Deployment Initiation



Configuration at Intermediate Time



Near Full Deployment Configuration

Figure 6. Solar Sail 52-Ring Model Dynamic Simulation Results

After the test results became available, the 6-Ring model was iterated on to determine a damping constant that gave a simulation time close to the observed time of 2.8s for the free 6-Ring model. Figure 7shows the variation of deployment time with damping for the simulations performed on the 6-Ring model. Based on these results, a damping constant value of 8.0E-5 in-lb.sec/deg was selected for the final simulation**.** The ADAMS simulation of the 52-Ring model was repeated for the free sail configuration with the new damping value. The simulation showed that the 52-Ring model had nearly approached a state of equilibrium in less than 30s.

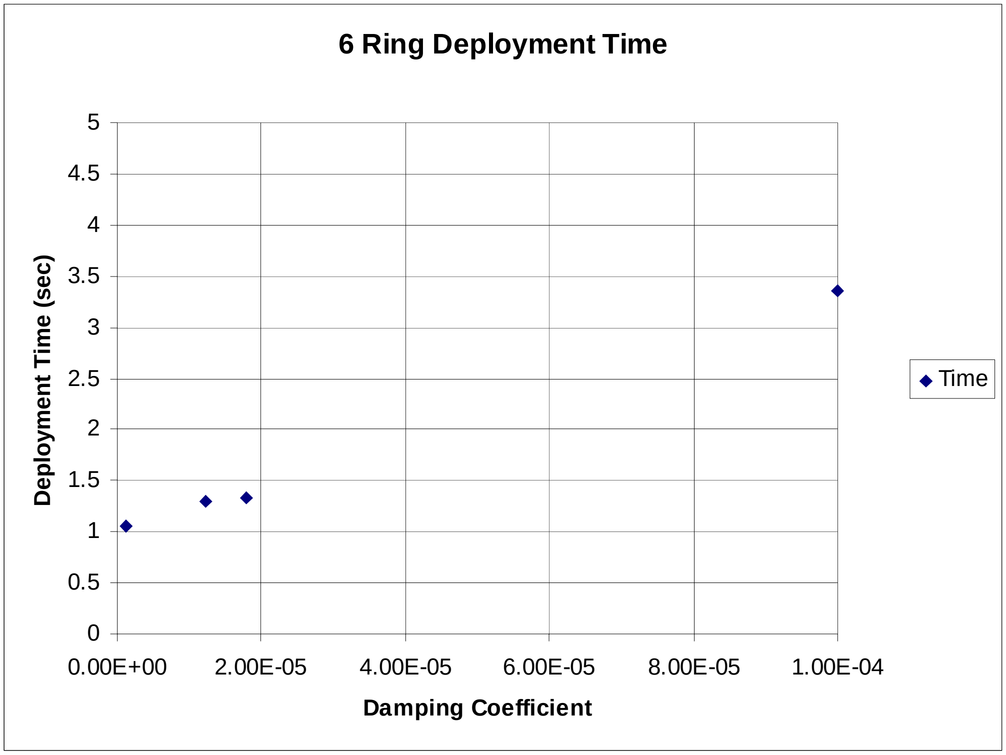


Figure 7. Solar Sail 6-Ring Model : Variation of Deployment Time with Damping

DEPLOYMENT SEQUENCE - SECONDARY COLLISONS

The ADAMS simulations for both the free and anchored configurations showed that the rings on adjacent fronds run into one another during the early stages of deployment. These are termed secondary collisions. ADAMS has the capability to detect and consider collisions of elements of a model provided potential colliding bodies are identified at the outset in the simulation. In the present analysis, the rings comprising the sail were identified for contact at the beginning of deployment, so that the break of contact of rings at the initiation of deployment could be tracked. However, no provision was made for detecting subsequent contact among the rings. Therefore, while the simulations produced in this task visually show the occurrence of secondary collisions, these are not accurately accounted for in the analysis.

PARAMETRIC ANALYSIS OF RING/MEMBRANE FRICTION

This analysis was performed with a simplified 6-Ring generic model. The results of this analysis showed the ring/membrane friction to be a relatively insensitive parameter for the sail deployment dynamics. Motion of the ring is initiated when the static friction force at the interface between the ring and the membrane of the next stationary ring is overcome. The simulation showed that when the static friction force was exceeded, the ring was already oriented at a very high angle relative to the membrane, and broke contact almost instantaneously. Therefore, the ring rubs against the membrane of the next stationary ring only very briefly. As a result, deployment of the sail is not significantly affected by the friction between ring and membrane.

RESULTS PRESENTATION

The results of the dynamic simulation of the 52-Ring model were captured in the form of an ADAMS animation. Electronic files in AVI format were generated for a dynamic graphic display of sail deployment. A video was generated showing the ADAMS dynamic simulation of both the free and anchored sail configurations.

FUTURE WORK

A future effort is planned to investigate the feasibility of a dynamic simulation of the full 4000+-Ring sail. The present effort showed that this simulation will push the capabilities of ADAMS to the limit, both in terms of model building and computer resources for simulation. Therefore, the next task will seek to devise methods to automate model building and to optimize resource utilization during simulation. A dynamic simulation of the full 4000+-Ring sail will be undertaken once these techniques are developed.

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