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ANALYTICAL CHARACTERIZATION OF SPACE INFLATABLE STRUCTURES --- AN OVERVIEW

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ABSTRACT

One important challenge in implementing inflatable structures technology for future space missions is the development and validation of analysis and simulation methodologies. This paper reviews selected topics previously addressed by various researchers in this area. These include strength and modal analyses of inflated tubular structures, configuration analysis, inflation deployment dynamics, and membrane wrinkling analysis. In particular, several on-going efforts related to dynamic modeling of large, pre-tensioned, thin-film membranes that form the NGST Inflatable Sunshield are discussed in detail.

INTRODUCTION

Large space-based deployable structures are needed for a variety of applications. Such applications include radar antennas, solar arrays, sunshields, telescope reflectors, etc. Current concepts for large, conventionally mechanical, self-deployable space structures tend to be very expensive and mechanically complicated. Due to user requirements being very stringent (with respect to the very low-cost, high deployment reliability, low weight, and packaged-volume), new and innovative approaches to accommodate large space structures are demanded. Fortunately, a newly developed technology, called inflatable structure, can potentially revolutionize the designs and applications of large space structures. It is very likely that many of the NASA missions planed for the next decade will rely on space inflatable structures to achieve their launch volume and mass goals. This is especially true for missions that require relatively large in-orbit configurations to properly perform their assigned functions.

Recently, NASA, its industry and academia partners have been making significant progress in order to actually implement inflatable structures for space applications. In May 1996, a large inflatable antenna structure was successfully inflated in space[1,2]. Since this Large Antenna Experiment (LAE) was the first time to have a large inflatable space structure on orbit, a number of new technologies were demonstrated and evaluated. Due to the successful demonstrations of these new technologies and the large inflatable antenna, the large inflatable space structures are getting more and more attention. As a result, NASA is currently engaging in several space missions using inflatable space structures. One of these missions is the Inflatable Sunshield of the Next Generation Space Telescope (NGST) and another one is the Inflatable Synthetic Aperture Radar (ISAR)[3,4,5].

PREVIOUS ANALYSIS AND SIMULATION EFFORTS

Due to the demanding and the rapid development of the space inflatable structures, analysis and simulation efforts in several aspects of the space inflatable structures have been on going. These aspects include static and dynamic analyses of inflatable tubes, precision surface analysis, inflation procedure analysis, membrane wrinkling analysis, and etc. This section will briefly present several previous papers and reports with respect to above aspects.

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The first aspect is the static analysis of inflatable tubes. Following are several papers talking about the static analysis of inflatable cylindrical tubes.

Comer and Levy in their technical note "Deflections of an Inflated Circular-Cylindrical Cantilever Beam"[6] calculated the deflections and stresses of a beam with a tip load and a uniform load. The collapse load can also be obtained from the analysis.

Fichter in the NASA technical note "A Theory for Inflated Thin-wall Cylindrical Beams"[7] derived a set of non-linear equilibrium equations for the bending and twisting of pressurized thin-wall cylindrical beams. Three assumptions were made in this note for the derivation of equations. The first assumption was that any cross-section of the pressurized cylindrical beam remains undeformed under a system of loads; the second one was that the translations and rotations of a cross section are small; the last one was that the circumferential strain is negligible. Two numerical examples were solved after these differential equations were linearized.

Douglas in his paper "Bending Stiffness of an Inflatable Cylindrical Cantilever Beam"[8] investigated the structural stiffness of an inflated cylindrical cantilever beam, which is influenced by large deformations. The finite theory of elasticity and the theory of small deformation superimposed on large ones are employed to obtain explicit analytical results. This analysis accounts for changing geometry and changing material properties which occur during the inflation process.

Steeves in the report "A Linear Analysis of the Deformation of Pressure Stabilized Beams"[9] derived a set of governing differential equations for lateral deformation by using the principle of minimum potential energy. A simplified displacement approximation, which assumes the cross section remains undeformed, was then used to reduce the problem from two dimensions to one dimension. Green's function solutions for the cases of simply supported ends and clamped ends were developed.

Webber in his paper "Deflections of Inflated Cylindrical Cantilever Beams Subjected to Bending and Torsion"[10] derived a numerical way to calculate the beam deflections, wrinkling and collapse loads. Several tests were also carried out and correlated to the analytical results.

Because the inflatable beam is truly a two-diminsional problem, John A. Main et al. derived a model for the bending behavior of the inflated cylindrical beam that uses a two-dimensional Hook's Law to model the stress-strain behavior of the fabric.[11]

Instead of the static analysis of inflatable beams, dynamic analysis of inflatable beams has also been addressed in several papers. Following are two papers related to the dynamic analysis of inflatable cylindrical beams.

Main et al. in the paper "Dynamic Analysis of Space-based Inflatable Beam Structures"[12] tried to use Euler-Bernoulli beam theory to analyze the dynamic properties of inflatable beams. Two damping mechanisms, a purely viscous damping term and a longitudinal strain damping term, were added to the Euler-Bernoulli beam equation. Several tests were conducted to obtain the material properties and to correlate the test results with the analysis results. They also investigated the effect of the gravity on the inflatable structures.

Rybski, et al. in their paper "Robotic Manipulators Based on Inflatable Structures"[13] using Timoshenko beam theory calculated natural frequencies of a cantilevered inflatable beam and compared with experimental results.

Besides the static and dynamic analyses of inflated cylindrical beams, another analytical aspect of inflatable structures is the precision surface. Following are some papers in this area.

Grossman in his papers[14,15] derived equations for the analyses of loads and deformations of a space-based solar concentrator. The solar concentrator is composed of an off-axis parabolic membrane and an elliptical support rim.

Jekins *et al.* in the paper "Improved Surface Accuracy of Precision Membrane Reflectors Through Adaptive Rim Control"[16] simulated the surface profile by using the non-linear FEM code ABAQUS. The deviation of the surface from the equivalent parabola was also calculated.

Bishop in the paper "Shape Correction of Initially Flat Inflated Membranes by a Genetic Algorithm"[17] simulated the deformed shape of an initially flat membrane. The parabolic shape of the membrane can be obtained by the manipulation of the boundary conditions.

Moore, *et al.* in the paper "Evaluation of Catenary Suspension for Reducing Shape Errors in Inflatable Solar Concentrators"[18] used the finite element code

ALGOR to investigate the effect of the catenary on the precision of the solar concentrator surface.

In order to control the location and the orientation of space-based inflatable structures, the analysis of the inflation deployment dynamics has to be conducted prior to a real mission. Because the inflation deployment analysis involves large deformations, material nonlinearity, surface contact, maybe even material flow and coupled fluid-structure interacting, it is very complicated. So far, there is not much literature available in this area. Following are several relevant papers.

Tsoi[19] developed some very simple models to simulate the inflation procedures of different configurations. These configurations included fold-up and roll-up configurations, which are the most common methods for stowing the deflated structures. MATLAB codes were developed to simulate the inflation deployment of fold-up tubes, roll-up tubes and "z-star" toroidal stiffened spherical surfaces.

Fay and Steele in the paper "Bending and Symmetric Pinching of Pressurized Tubes"[20] conducted two experiments to quantify the forces necessary for large deformation of an inflated cylindrical tube made of a material with a high elastic modulus. Based on some assumptions and observations from these experiments, the potential energy of the deployment of a tube was derived.

Salama *et al.* in their paper "Simulation of Airbag Impact Dynamics for Mars Landing"[21] represented a simplified low-order impact simulation model. Simulations were conducted using the Automatic Dynamic Analysis Mechanical Systems (Adams) software. A set of differential equations for this mechanical system was given in this paper, which includes mass flows, volumetric changes, pressures, forces, etc. Some of these differential equations could be further developed to simulate the inflation deployment. Before they made this model, they had attempted to construct a high fidelity, large deformation, finite element model that included detailed geometry and properties of the lander and airbag tendons, skin fabrics and gas system. Unfortunately, this effort didn't work because it required enormous time and computing resources to obtain useful results and numerical conditioning problems seemed to grow with the number of degrees of freedom in the model. These drawbacks could still impact inflation deployment analysis if one attempts to use non-linear finite element software with large quantities of degrees of freedom.

Haung *et al.* in their paper "The Numerical Simulation of the Inflation Process of Space Rigidized Antenna Structures"[22] successfully simulated the inflation procedure of a Space Rigidized Antenna Structure. The software used by E. Haung *et al.* is the industrial explicit dynamic finite element code PAM-CRASH. The code PAM-CRASH was initially developed to simulate the deployment process of an airbag for passenger safety in a motor vehicle. Because this deployment procedure and the inflation procedure of a space based inflatable structure bear many similarities, software developed for the deployment of an air bag could be employed to simulate the inflation procedure of an inflatable structure.

The industrial explicit dynamic finite element code PAM-CRASH also has been used by several other authors to simulate the deployment procedures of motor vehicle passenger air bags[23,24,25]. Besides PAM-CRASH, there are several other explicit non-linear finite element codes that have been used to simulate the deployment procedures of air bags. DYNA3D[26] is one of them and DYTRAN[27] is another one.

Besides using finite element codes to simulate the air bag deployment procedures, several researchers have derived some gas dynamic equations, thermodynamic equations, and analysis methodologies[28,29,30,31]. Those equations and methodologies could be used to simulate the inflation procedures of space based inflatable structures.

Although the inflation deployment of a space based inflatable structure is similar to the deployment of an airbag, they do have some differences. For example, space based inflatable structures are usually much larger and more complicated than motor vehicle airbags; the durations of the inflation procedures of space based inflatable structures are usually much longer than that of motor vehicle airbags; the deployment control mechanisms used by space based inflatable structures are usually not applied to motor vehicle airbags. Therefore, efforts are still needed if one wants to simulate the inflation deployments of space based inflatable structures using explicit non-linear finite element codes initially developed to simulate the deployment procedures of motor vehicle airbags.

The NGST Inflatable Sunshield[3,4] and Inflatable SAR[3,5,32] are two of the currently planned space inflatable demonstrations. Figure 1 shows the 1/2-scale engineering model of the inflatable sunshield. The inflatable sunshield is composed of several layers of membrane which are stretched at four corners by four inflatable tubes. Figure 2 depicts the 1/3-scale engineering model of the inflatable SAR. The inflatable SAR utilizes an inflatable planar frame to support and stretch multiple layers of RF membranes.

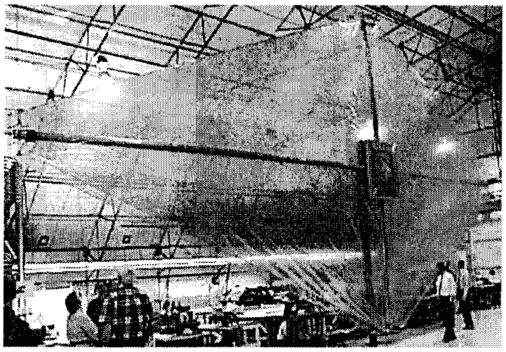
Figure 1. 1/2-Scale Engineering Model of the Inflatable Sunshield

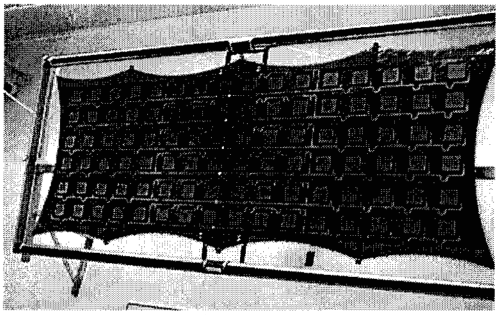
Figure 2. 1/3-Scale Engineering Model of the Inflatable SAR

It can be observed that both structures are composed of multiple layers of very thin membrane which are stretched (pre-tensioned). The membrane itself does not have out-of-plane stiffness. The out-of-plane stiffness of the membrane is caused by the pretension, which is called the differential stiffness. Differential stiffness is a function of the membrane in-plane stress distribution. According to Cook[51], the work due to the pretensioning is given as:

$$U_\sigma = \int_A \left(\frac{1}{2} w_{,x}^2 N_x + \frac{1}{2} w_{,y}^2 N_y + \frac{1}{2} w_{,x} w_{,y} N_{xy} \right) dA$$

$$= \frac{1}{2} \iint \begin{Bmatrix} w_{,x} \\ w_{,y} \end{Bmatrix}^T \begin{bmatrix} N_x & N_{xy} \\ N_{xy} & N_y \end{bmatrix} \begin{Bmatrix} w_{,x} \\ w_{,y} \end{Bmatrix} dxdy \qquad (1)$$

where:

$$\varepsilon_x = \frac{1}{2} w_{,x}^2 \qquad (2\text{-}1)$$

$$\varepsilon_y = \frac{1}{2} w_{,y}^2 \qquad (2\text{-}2)$$

$$\gamma_{xy} = w_{,x} w_{,y} \qquad (2\text{-}3)$$

are membrane strains associated with small rotations $w_{,x}$ and $w_{,y}$ of the membrane mid-suffice. N_x, N_y, N_{xy} are membrane forces and can be expressed as:

$$N_x = \int_{-t/2}^{t/2} \sigma_x dz \qquad (3\text{-}1)$$

$$N_y = \int_{-t/2}^{t/2} \sigma_y dz \qquad (3\text{-}2)$$

$$N_{xy} = \int_{-t/2}^{t/2} \tau_{xy} dz \qquad (3\text{-}3)$$

In equations (3), σ_x, σ_y, and τ_{xy} are stresses.

Equation (1) can be further expressed as

$$U_\sigma = \frac{1}{2} \{\mathbf{d}\}^T [\mathbf{k}_\sigma] \{\mathbf{d}\} \qquad (4)$$

and $[\mathbf{k}_\sigma]$ is called the differential stiffness matrix of this element.

Due to the effect of Poisson's Ratio of the membrane material and because the membrane material can not carry any compressive loads, wrinkles are formed when a portion of the membrane is subjected to localized compression. Wrinkles will redistribute the stresses and, therefore, the differential stiffness will also be changed.

Static analyses of wrinkled membrane have been previously addressed by several researchers. Manuel Stein and John M. Hedgepeth in their NASA technical note "Analysis of Partly Wrinkled Membranes"[33] presented a theory to predict the stresses and deformations for partly wrinkled membranes. Solutions were given for three problems: 1) in-plane bending of a stretched rectangular membrane; 2) bending of a pressurized cylinder; 3) rotation of a hub in a stretched infinite membrane.

Mikulas in his NASA technical note "Behavior of a Flat Stretched Membrane Wrinkled by the Rotation of an Attached Hub"[34] analyzed the wrinkling behavior of a stretched membrane subjected to torsional loading through an attached hub.

Miller and Hedgepeth in their technical note "An Algorithm for Finite Element Analysis of Partly wrinkled Membranes"[35] developed a numerical algorithm that retains the simplicity of form characteristic of linear elastic case, but is consistent with the nonlinear Stein-Hedgepeth wrinkle model. A so-called equivalent elasticity matrix that relates stresses and elastic strains within an element was given. The equivalent elasticity matrix varies among slack status, taut status, and wrinkled status.

Jenkins and Leonard in their paper "Nonlinear Dynamic Response of membranes: State of the Art"[36] reviewed all nonlinear analysis methods of membrane structures. Their attention was focused on formulation of field equations, wrinkling analysis, fluid/structure interactions, material non-linearities, and computational methods.

Li and Steigmann in their paper "Finite Plane Twist of an Annular Membrane" [37] analyzed the finite deformation of an annular membrane induced by the rotation of a rigid hub. Equations were derived based on the so-called direct theory of elastic membranes.

Gorman and Singhal in their paper "A Superposition-Rayleigh-Ritz Method for Free Vibration Analysis of Non-Uniformly Tensioned Membranes,"[38] developed an analytical technique for obtaining accurate stress distributions in corner-tensioned rectangular membranes. The analysis was further extended to demonstrate how the Rayleigh-Ritz energy method, in conjunction with the computed initial stress distributions, can be employed to obtain membrane free vibration frequencies and mode shapes.

Haseganu and Steigmann in the paper "Analysis of Partly Wrinkled Membrane by the Method of Dynamic Relaxation"[39] used the dynamic relaxation method to analyze partly wrinkled membranes. The wrinkle is taken into account by using a so-called relaxed strain energy which takes different forms in different regions of strain space, according as the state of strain corresponds to a tense, wrinkled or completely slack condition. When the relaxed energy function is used, compressive stresses are excluded automatically. Numerical experiments indicated that the equilibria generated are insensitive to the initial data in calculations based on the relaxed energy.

Lin and Mote[40,41,42,43] used a modified von Karman's nonlinear plate equations and tensioned Kirchhoff plate equation to describe the motion of a wide, axially moving web with small flexural stiffness under transverse loading. Airy stress functions are determined in closed form for webs under arbitrarily prescribed, in-plane edge loading. Two criteria predicting the wrinkling were given. The first criterion is for isotropic, compressible rectangular webs under uniform in-plane principal stresses, and the second one is for isotropic, incompressible membranes. The onset of wrinkling in a web under non-linearly distributed, in-plane, edge tension was predicted. They have also tried to predict the parametric stability of a rectangular web under constant, uniform, longitudinal tension plus periodic shear excitation.

Kang and Im in the paper "Finite Element Analysis of Wrinkling Membrane"[44] proposed a scheme for finite element analysis of wrinkling. This scheme is applicable to both anisotropic and isotropic membranes. Numerical examples suggested that this scheme retains good convergence behavior even for a large loading step within the range of small strain deformations.

Tabarrok and Qin in the paper "Dynamic Analysis of Tension Structures"[45] described a finite element method for the determination of free and forced vibration analysis of tension structures. Equations of motion for curved membranes were derived by using the Hamilton's law. Linearized equations are determined by considering small amplitude oscillations about the position of static equilibrium. More accurate equations are determined by taking into account geometrical non-linearities in the displacement-strain relations.

DYNAMIC ANALYSIS OF THE INFLATABLE SUNSHIELD

The Next Generation Space Telescope (NGST) is a major NASA astrophysics mission to be flown in the later part of the next decade. In order to passively cool the telescope to below 60 K for maximum science return, a 32-meter by 14-meter multiple-layer inflatable sunshield is included in the baseline NGST architecture. In-orbit dynamic behavior of the inflatable NGST Sunshield needs to be analyzed for the mission.

We tried to use the commercial finite element software MSC/Nastran[46,47] to analyze the dynamic behaviors of the inflatable sunshield. Dynamic analysis for an inflatable structure usually is unique in two aspects. First of all, the inflatable sunshield is composed of several layers of large membranes that are supported and stretched (pretensioned) by four inflatable/rigidizable booms. The out-of-plane stiffness of these stretched membranes, called differential stiffness, is a function of the membrane pretension and must be first dealt with in the modeling. Second, when a portion of the membrane is subjected to localized compression, wrinkles will be formed, which in turn will redistribute the stresses and will induce geometry changes. The first aspect, differential stiffness, is related to the large deformation and geometric non-linearity. The second aspect, wrinkling, is taken care of in this analysis by material non-linearity. It is assumed that the Young's Modulus of the membrane equals E while it is in tension, and equals to a very small number while it is in compression. This means that the membrane elements can not take any in-plane compressive loads

The modeling process developed for dynamic characterization of the inflatable sunshield can be divided into several steps. The first step is using the thermal loads to elongate four supporting booms. The elongation of these booms will stretch and pretension the membranes. Because the pretensioning of the membrane is a large deformation procedure, non-linear static analysis must be used to obtain the stress distributions in the membranes. It is known that a membrane element only has in-plane stiffness. After the stress distribution of pretensioning is obtained, the differential stiffness can be calculated based on the membrane stresses. Thereupon, the out-of-plane stiffness of a membrane can be obtained. The second step of the analysis is to perform a modal analysis with both structural stiffness and differential stiffness. The third and final step is to make a frequency response run, from which the transfer functions of the system can be obtained and used for the orientation control of the space telescope. One assumption was made before the vibration analysis. The assumption was that the magnitude of the vibration deformation is very small, and thus, stress distribution and differential stiffness would not be effected. Three models are given as below.

1) One Layer Membrane Model with Fixed Center

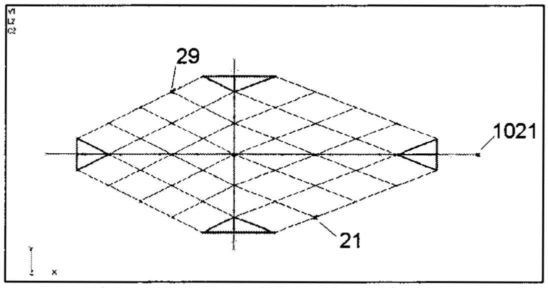

Figure 3. One Layer Model of the Inflatable Sunshield

Figure 3 shows the one layer model of the inflatable sunshield. The total length of the model is 32.8 meters. The total width of the model is 14.2 meters. The thickness of the membrane is 0.0001016 meter (4 mils). This model consists of 40 membrane elements and 32 Beam elements. The membrane material is Kapton. In order to simulate the wrinkling, the elasticity modulus of the Kapton is non-linear (E=3516000000 Pa when stress is positive, E=1 Pa when stress is negative). The center of the sunshield is fixed. The pretensioning loads are applied as the thermal expansion of four beam elements. Both membrane and beams are pre-loaded. Pretensioning forces are 100 Newtons in the x direction and 115 Newtons in the y direction (in figure3, x coordinate is in horizontal direction, y coordinate is in vertical direction, and z direction is in out of plane direction).

Figure 4 gives the z direction displacement response of node 1021 (node 1021 is shown in Figure 3). The excitation is in z direction and on node 1021. The magnitude of the excitation force is one Newton. Figure 5 shows the y direction displacement response of node. The excitation is in the y direction and on node 1021. The magnitude of the excitation force is one Newton. Figure 6 gives the z direction displacement response of node 29 (node 29 is on membrane and is given by Figure 3). The excitation is in the z direction and on node 1021. The magnitude of the excitation force is one Newton. For all response curves, horizontal-axes are frequencies and the unit is Hz.

For all of the frequency response analyses, the overall structural damping coefficient is 0.1. There are five calculating frequencies per each natural frequency; one is identical to the natural frequency and the frequency band spread is +/- 10%.

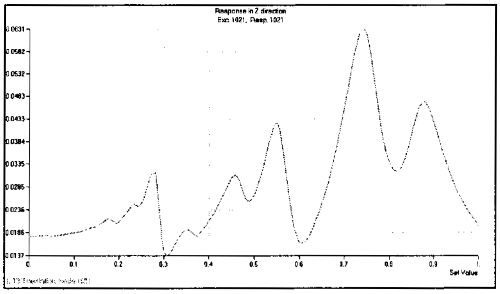

Figure 4. Magnitude of displacement response. Both excitation and response are on 1021 and in z direction

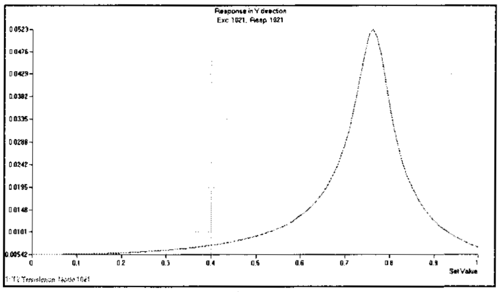

Figure 5. Magnitude of displacement response. Both excitation and response are on 1021 and in z direction

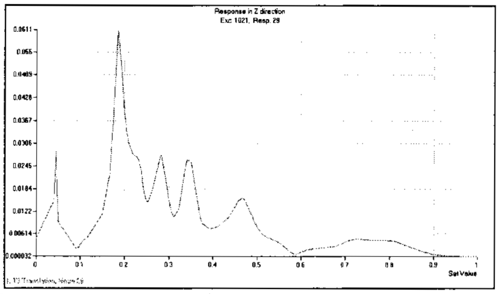

Figure 6. Magnitude of displacement response. Excitation is on node 1021 in z direction, response is on node 29 and in z direction

2) One Layer Membrane Model With Base Acceleration

This model is similar to the previous one. The only difference between this model and the previous model is that there is a large mass (50000 Kg, the weight of the unit is 47.59Kg) connected to the center of the unit as the bass. The center point is only free in the z direction. The large mass (the bass) is excited by a 50000 Newton force.

Figure 7 gives the acceleration response at node 1021 (z direction). Figure 8 gives the acceleration response at node 21 (z direction). Locations of these nodes are given in figure 3.

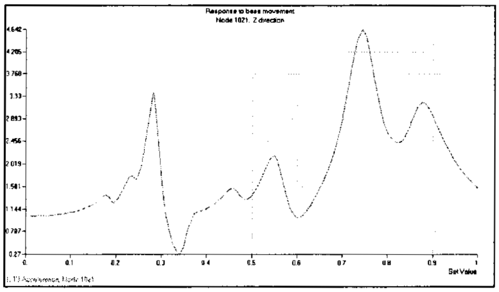

Figure 7. Magnitude of acceleration response at node 1021 to base movement

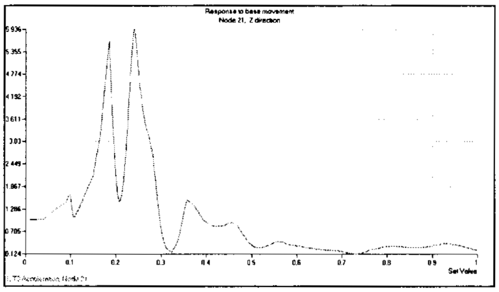

Figure 8. Magnitude of acceleration response at node 21 to base movement

3) Four Layers Membrane Model With Base Acceleration

This model has four layers of membrane. Figure 9 shows the model. This model has 160 membrane elements and 84 beam elements. Figure 10 shows all of these beam elements. There is a large mass (50000 Kg, the weight of the unit is 65.05Kg) connected to the center of the unit as the bass. The center of each layer of membrane and the center of the system are connected by a rigid element. The large mass is fixed in x and y directions and is also fixed for all rotational degrees of freedom. In the z direction, the large mass is connected to the ground by a very soft spring element (K=0.49 N/m). Therefore, the natural frequency induced by the mass-spring system is very low (0.0005 Hz). The large mass (the bass) is excited by a 50000 Newton force.

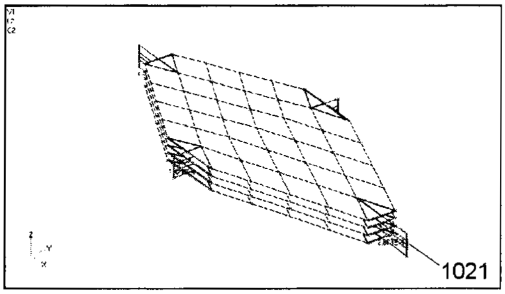

Figure 9. Four layers model

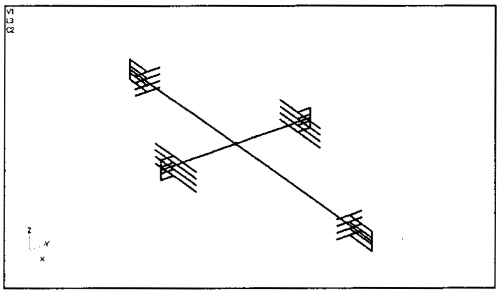

Figure 10. All beam elements

Figure 11 gives the acceleration response at node 1021 (see Figure 9 for the location of node 1021).

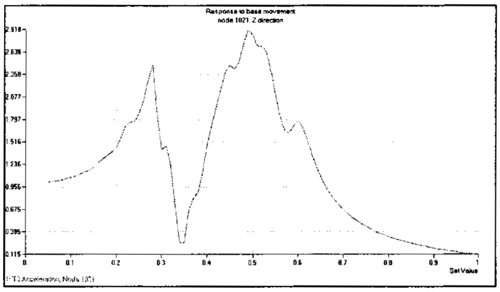

Figure 11. Magnitude of acceleration response at node 1021 to base movement

There is one drawback to this methodology. This methodology uses non-linear material property

(E=3516000000 Pa when stress is positive, E=1 Pa when stress is negative) to simulate the membrane wrinkling. MSC/Nastran is a commercial software and only checks the stresses in the local coordinate system of each element. The criterion of the wrinkling is that minor principal stress goes to zero[44]. The inaccuracy induced by this drawback can be minimized by refining the mesh of membrane elements.

Aaron L. Adler and Martin M. Mikulas at the University of Colorado are working on another methodology to analyze the inflatable sunshield using MSC/Nastran[48]. They are writing a program that has an interface with MSC/Nastran. This program updates the stiffness matrix after each iteration and makes sure that the minor principal stress of each element will not be negative.

Besides Aaron L. Adler and Martin M. Mikulas, Sebastien Lienard at GSFC and Andy Kissil at JPL are working on this project as well. Sebastien Lienard uses bar elements in Nastran to simulate the membrane[49]. Andy Kissil uses the software IMOS to analyze the sunshield [50]. The advantage of using IMOS is that it is in the Matlab environment, therefore, it is very easy to manipulate the analysis. His model uses IMOS plate element. The bending factor is set to a high value to remove the bending flexibility from the model low frequency characteristics. The shear stiffness can then be tuned to match the correct differential stiffness due to preload. An IMOS model, which is very similar to the one in Figure 3, has been made and the first four natural frequencies are: 0.23018 Hz, 0.32047 Hz, 0.44065 Hz, and 0.54409 Hz.

CONCLUSION

Rapid development of space inflatable structures is pulling the analysis and simulation methodologies. Although some previous efforts for the analysis of inflatable structures have been given, some analytical tools and methodologies still need to be developed. Based on our understanding, there are two aspects that need further developments. The first one is the dynamic analyses of deployed structures. Usually this kind of analysis involves membrane pre-loading and wrinkling. The second one is the inflation deployment dynamic analysis. This kind of analysis usually involves large deformations, material nonlinearity, surface contact, deployment control mechanisms, and possibly material flow and coupled fluid-structure interacting. Therefore, more efforts are still needed for the analysis and simulation of space-baced inflatable structures.

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