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Recent Advances in Structural Modeling of Parachute Dynamics

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Abstract

This paper describes several new advances in the structural modeling and computer simulation of parachute systems. The theoretical formulation is briefly discussed and several applications are presented. The first topic is the modeling of contact phenomena in parachute systems. The application problems include gore-to-gore contact in a single round canopy due to control operations, contact of a single round canopy with a flat rigid surface, and multiple parachute contact in a three parachute cluster. A method to model initially folded canopies is illustrated in the cluster problem. The second topic is the development of a geometrically nonlinear anisotropic constitutive relation for membranes. This result is used to simulate the behavior of a pneumatic muscle actuator in a soft landing parachute system.

Introduction

Computer modeling of parachute systems has advanced significantly in the past five years. Fully coupled fluid-structure interaction simulations can now be routinely performed and their results compare favorably with experimental and test results[1]. Within the next several years, computer simulation will become an integral part of the parachute design process.

During the advancement of these simulation methods, numerous challenges specific to parachute systems have been identified. For example, Accorsi *et al*[2] have shown that it is critical to account for fabric "wrinkling" in modeling parachute dynamics.

Collaborative research between the University of Connecticut, U.S. Army Soldier Systems Center, and Rice University has focused on advancing the state-of-the-art in modeling parachute dynamics. In this paper, the following recent advances in structural modeling are presented:

- Modeling of contact in parachute systems
- Modeling of initially wrinkled membranes
- Modeling of geometrically nonlinear anisotropic membranes

Each of these advances is briefly described and their application to parachute problems is demonstrated by examples. In general, the simulation of parachute systems requires the coupling of a structural dynamics model for the canopy, suspension lines, and payload with a fluid dynamics model for the surrounding airflow. To test the new developments in the structural model presented here, the simulations are performed using only the structural model with prescribed fluid forces (pressure and drag). Since the structural model is considerably smaller than the fluid model, this approach simplifies the evaluation of the performance of the structural model. At the same time, however, the results from these simulations are preliminary because of the approximate modeling of the fluid forces.

The theoretical foundation of the existing structural finite element model has been previously presented by Accorsi *et al*[3] and is based on a total Lagrange formulation for the geometrically nonlinear and transient behavior of membrane, cable, and mass point elements. Additional features have been developed specifically for modeling parachutes systems and have been presented previously by Benney *et al*[4,5]. The structural model includes a general geometrically nonlinear "wrinkling" algorithm that models the loss of tension in thin membranes [2,6].

Contact Problems

To date, the application of contact algorithms to decelerator problems has been limited to simulation of airbags [7]. Contact phenomena, however, occur between gores of a single canopy and between multiple canopies in a parachute cluster. The importance of canopy contact on opening and stability is not well understood and difficult to study experimentally. Computer simulation of canopy contact provides an excellent tool to investigate this problem.

The modeling of contact in a parachute undergoing large dynamic displacements is a challenging problem. In general, implementation of contact into a structural dynamics model requires the following tasks:

- Search and projection algorithms
- Contact force and stiffness mechanics
- Enforcement of contact constraints
- Nonlinear time integration algorithms with contact

The theoretical formulation of these tasks and their verification are presented by Gupta [8]. A general search and projection algorithm for membrane elements is used that automatically locates contact points in the model. After contact is detected, the contact forces and stiffness are calculated using the geometrically nonlinear formulation of Laursen and Simo[9]. The penalty method or augmented Lagrange method is used to enforce the contact constraints. These three components are used within a nonlinear implicit time integration scheme. Implicit methods are chosen for two reasons. First, implicit methods employ iterative convergence checking at each step that insures satisfaction of the dynamic contact equilibrium equations. Second, implicit methods are unconditionally stable so that a large time step can be used. Since parachute applications typically occur over long time durations, restrictions on the time step are undesirable.

Gore-to-Gore Contact in a Round Canopy

This example is motivated by the desire to perform coupled fluid-structure interaction (FSI) simulations on parachute systems subjected to control operations. Specifically, the use of pneumatic muscle actuators (PMAs) within a parachute system is currently being evaluated[10]. In an FSI simulation, fluid elements surround the structural model and are attached to it on the canopy surface. When a riser pull or extension is performed, localized folding and gore overlapping occurs that results in a volume inversion of the fluid elements and numerical failure of the fluid dynamics model. In this example, contact mechanics is applied to eliminate this problem.

Figure 1 shows the inflated configuration of a C-9 parachute with four risers in steady terminal descent. Figure 2 shows the parachute configuration after extension of one riser. The localized folding is evident. Figure 3 shows the skirt profile prior to riser extension. Figure 4 shows the steady state skirt profile after riser extension when contact is not used. Without contact, the structural model will freely pass through itself as evident in this figure. Although the extent of overlap is small and will not significantly affect the global response, this small overlap instantly renders the fluid model singular. Figure 5 shows the steady state skirt profile after riser extension when contact is used. In this case, the overlap is prevented. Additional effort will be needed for FSI simulations to insure that a minimum gap is maintained that is suitable for the fluid mesh.

Contact Between a Round Canopy and a Flat Surface

This example begins with the same parachute system as the previous problem. After riser extension, the parachute system is then steered into a flat rigid surface. After contacting the surface, the extended riser is shortened to steer the system away from the surface. The configuration of the parachute system at five points during this maneuver is shown in Figure 6. Figure 7 shows the horizontal displacements of a node located on the payload and on the leading edge of the skirt versus time. The contact period is most clearly seen as the flat region in the skirt node displacement that lasts for approximately 0.5 seconds. As expected, the payload displacement is delayed and survives the maneuver without "hitting the wall". Figures 8 and 9 show the horizontal and vertical velocities, respectively. In this example, the terminal vertical velocity is about 26 fps and a horizontal velocity of about 10 fps is obtained prior to contact. In both figures, the velocity of the skirt node is very erratic during contact whereas the payload velocity remains smooth.

Contact in a Parachute Cluster

In this example, steady state contact between three half-scale C-9 parachutes in a cluster is simulated. A novel approach was developed to generate the inflated configuration prior to contact. As shown in Figure 10, three configurations are used. The reference state corresponds to the unstressed cut pattern of the parachute. The initial state corresponds to the starting time where the parachute may be initially folded or "wrinkled". The third state corresponds to the configuration at the current time. In the total Lagrange formulation, the current time is referred back to the reference state with the difference between the initial and reference state used as the initial displacements.

For the three parachute cluster, the reference and initial states are shown in Figures 11 and 12, respectively. The reference state corresponds to the cut patterns of three overlapping parachutes. The initial state corresponds to three truncated conical models. Without knowledge of the reference state and wrinkling, this model would behave like a conical canopy as opposed to a round canopy. Figure 13 shows the inflation of the cluster from the initial state. Since the true folding of the canopy is not modeled, the inflation behavior may not be accurately modeled. This approach, however, provides an easy technique to generate the inflated configuration of the cluster prior to contact.

The side and top views of the cluster canopies during contact are shown in Figures 14 and 15, respectively. The deviation from a round shape due to contact is apparent in the side view. In the top view, highly localized folding occurs in the lower left canopy in the contact region. Localized folding, such as this, is typically observed in actual clusters. Due to the relatively coarse finite element model used, the localized folding is quite jagged. In the current simulation, this canopy ultimately collapses after the localized folding begins. Figure 16 shows the meridian of one canopy through the contact zone center when the simulation is performed with and without contact. It is seen that significant retardation of the inward motion has occurred at this point in the simulation due to contact. Similarly, the skirt profiles of the three canopies without and with contact are shown in Figure 17 and 18, respectively.

Anisotropic Material Modeling

The woven fabrics used in parachute systems are, in general, anisotropic and may undergo large displacements and rotations. Our focus is to develop an anisotropic membrane model for use in simulating pneumatic muscle actuators (PMAs) that are currently being used for control of parachute systems[10]. For this application, the material also experiences large relative rotations between the braided fibers that must be modeled. The material model developed is also suitable for canopy fabrics that typically experience much less relative fiber rotation.

The basic approach is shown in Figure 19. A detailed discussion is given by Zhang[11]. In the total Lagrange approach, the current stresses and strains are referred back to the reference state, so the material properties are also written in this state. In the reference state, the material properties are first written in the material system. This is the system that corresponds to the physical properties of the material, such as the fiber directions in a PMA. Next, the material properties are rotated to the global system by a standard fourth order tensor transformation using the three-dimensional direction cosines of the material axes. Finally, the material properties are transformed to the current curvilinear coordinate system of each element integration point using the current curvilinear base vectors.

PMA Verification Problem

The geometrically nonlinear anisotropic membrane model was first verified by comparison with the inextensible PMA model presented by Brown et al[10]. The initial unstressed model is shown in Figure 20 and corresponds to a cylindrical membrane folded completely flat. The PMA is fixed at one end, loaded axially by distributed forces at the other end, and internally pressurized. The steady state contracted configuration of the PMA is shown in Figure 21. A comparison of the finite element results with the inextensible theory is shown in Figure 22 over a wide range of pressures and contractions. The agreement between these is, in general, very close.

PMA Demonstration Problem

The motivation for this problem is to simulate the behavior of a new soft-landing system that incorporates a PMA between the payload and suspension lines that provides rapid contraction and reduced impact at landing. The model in terminal descent is shown in Figure 23 and consists of an inflated T-10 canopy, suspension lines, an un-inflated PMA, and payload. Although the PMA appears as a single line, it is actually modeled by 642 membrane elements in an initially flat configuration. Figures 24 and 25 show two configurations after pressurization of the PMA. Initially, the PMA contracts but remains straight, then it buckles as the payload continues to decelerate. A close-up view of the PMA cylinder is shown in Figure 26. The vertical velocity of the payload during the time of PMA pressurization is shown in Figure 27 for two cases. In the first case, the canopy pressure is held constant at the steady state pressure. In the second case, the canopy pressure is doubled during PMA pressurization. Both cases show significant reduction in the payload velocity. The velocity reduction is larger when the canopy pressure is increased. It is expected that the impulsive contraction of the PMA will result in rapidly increased dynamic canopy pressure, but the magnitude of the increase is unknown. Therefore, a more realistic model for this problem should include coupling with a fluid dynamics model.

Conclusions

Contact phenomena in parachute systems are currently not well understood and difficult to study experimentally. The successful application of contact mechanics to a parachute structural model demonstrates that computer simulation can be an effective tool to study these phenomena. The next step in this process is to perform coupled fluid-structure interaction simulations that include contact mechanics.

The use of pneumatic muscle actuators (PMAs) for control of parachute systems is currently under development. Computer simulation can be an effective tool to study the behavior of parachute systems incorporating PMAs. The behavior of a PMA can be modeled using a geometrically nonlinear anisotropic membrane element. As with contact, the next step in this process is to perform coupled fluid-structure interaction simulations that account for the dynamic pressure changes induced by the PMA.

Acknowledgements

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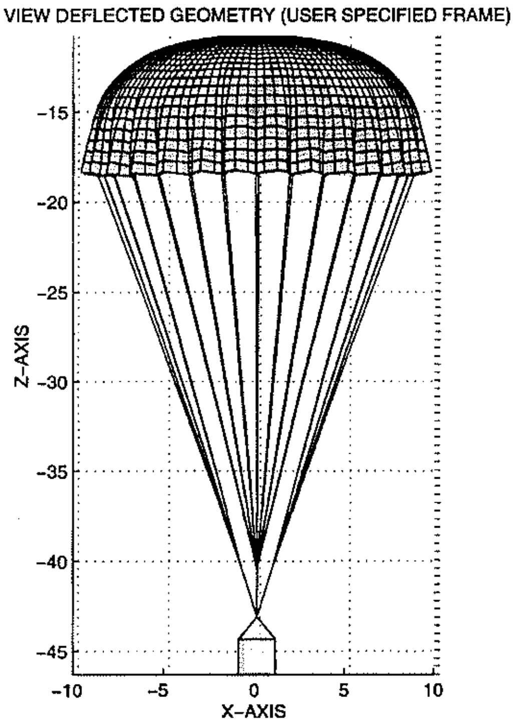

Figure 1: Initial Inflated Configuration

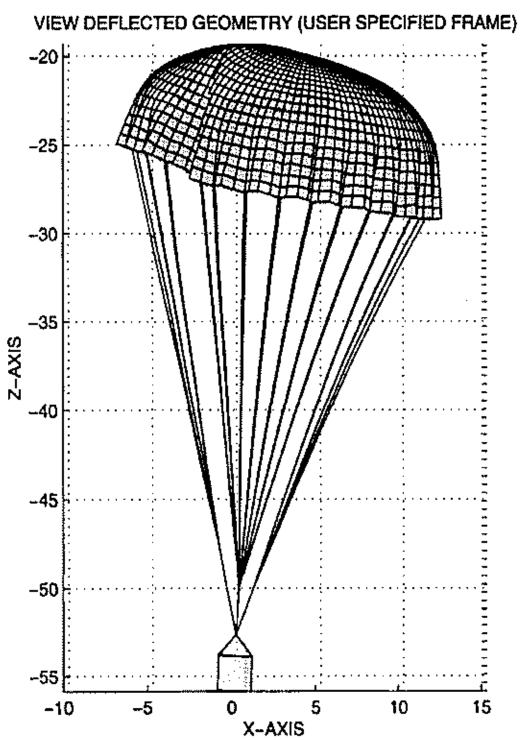

Figure 2: Configuration after Riser Elongation

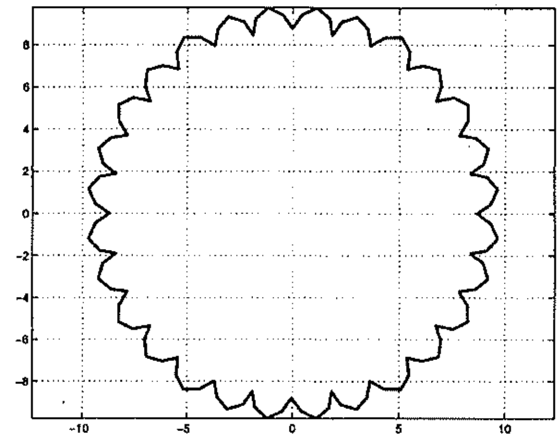

Figure 3: Skirt Profile at Inflated Configuration

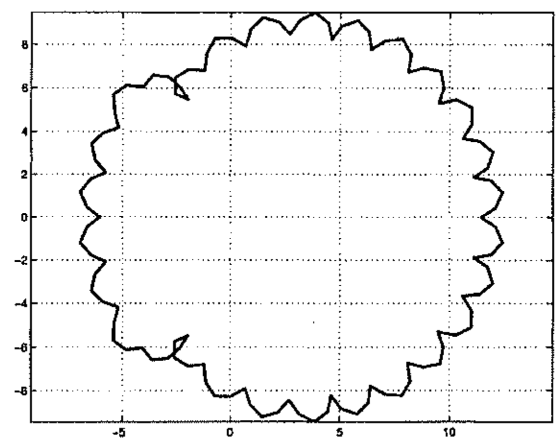

Figure 4: Steady State Skirt Profile without Contact

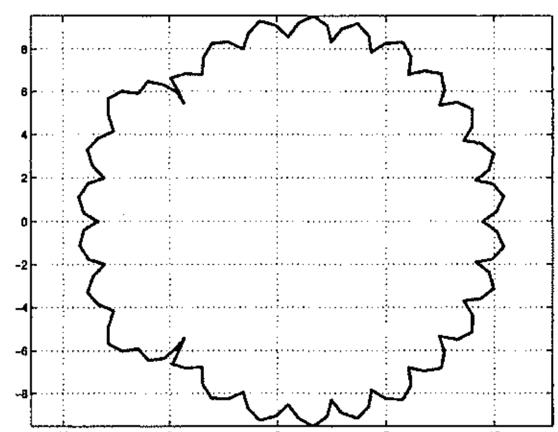

Figure 5: Steady State Skirt Profile with Contact

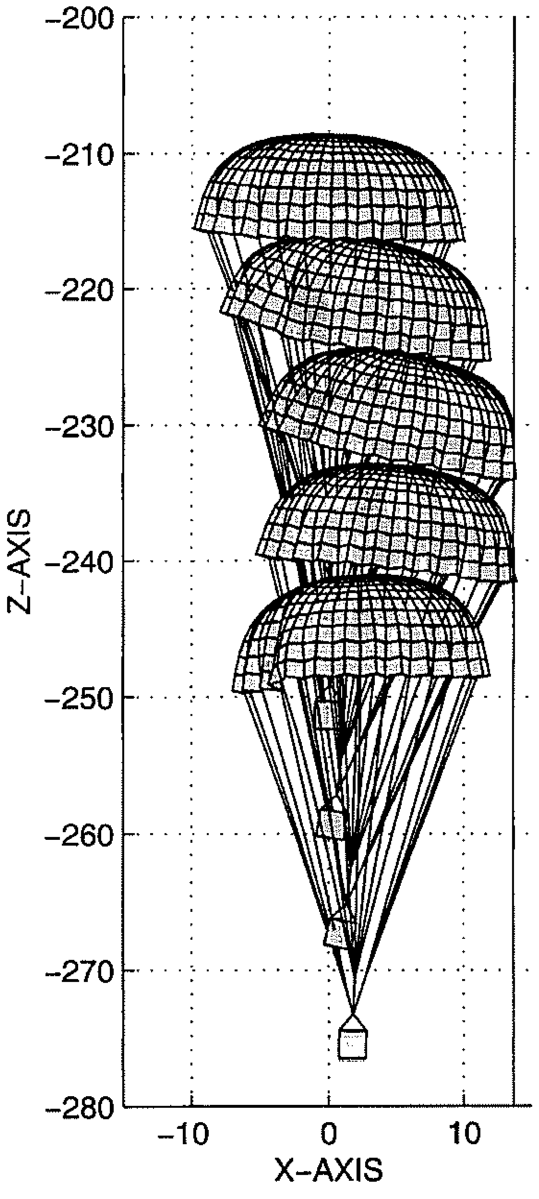

Figure 6: Contact of Canopy and Wall

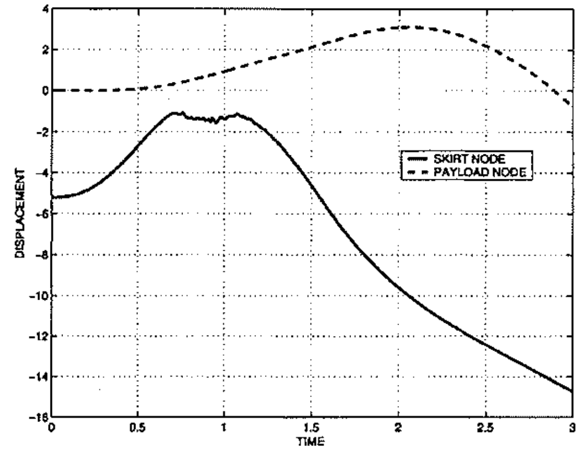

Figure 7: Horizontal Displacements versus Time

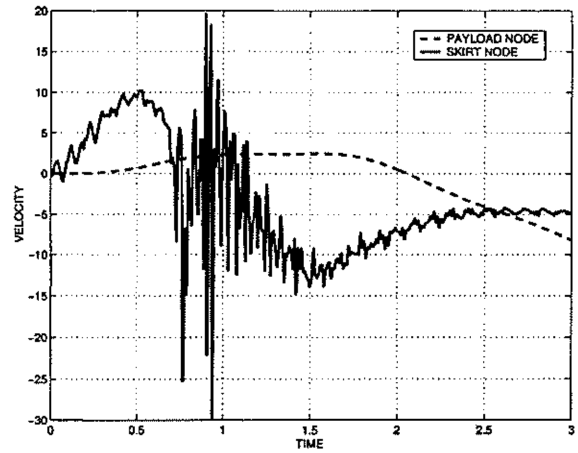

Figure 8: Horizontal Velocities versus Time

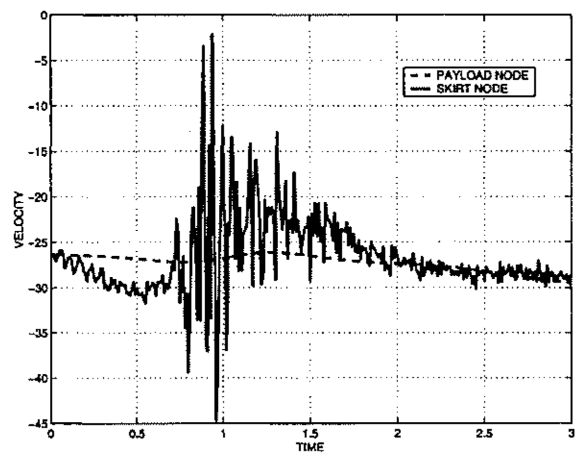

Figure 9: Vertical Velocities versus Time

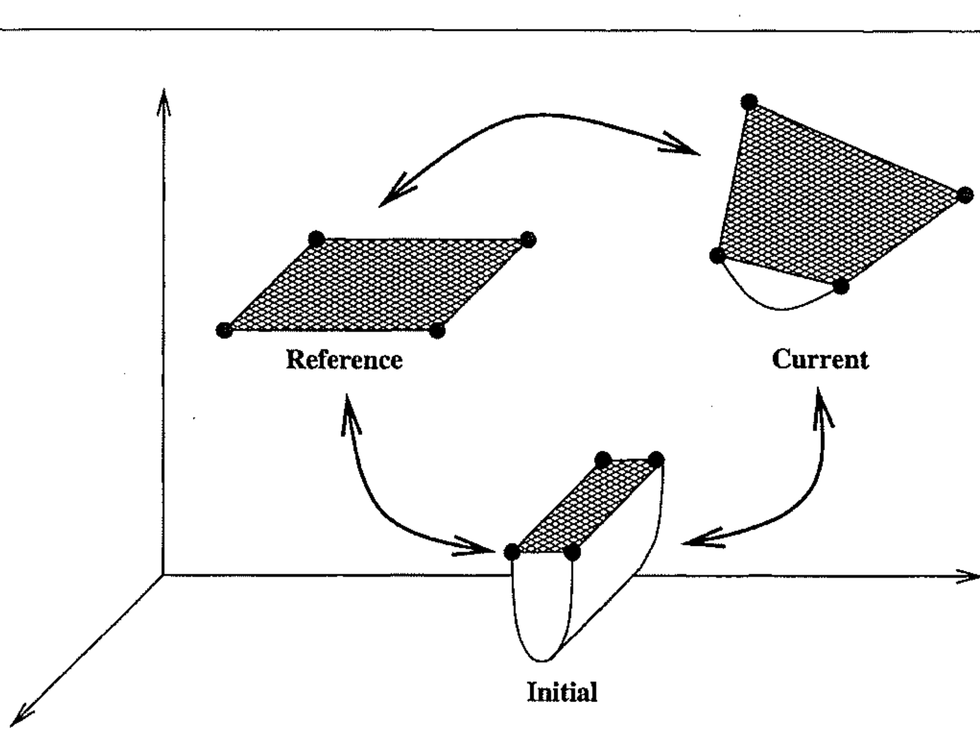

Figure 10: Three Configurations used for Initially Wrinkled Model

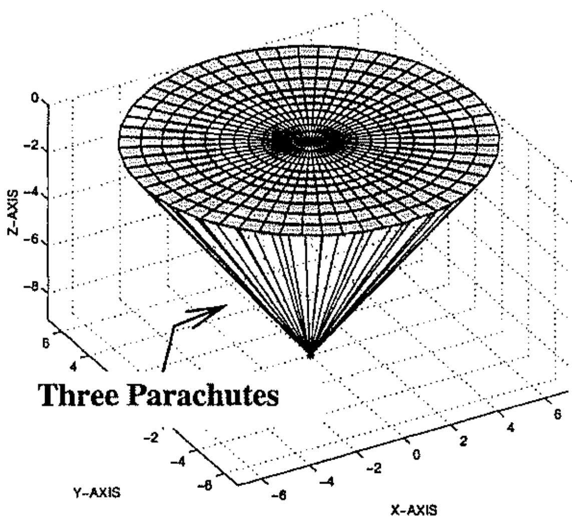

Figure 11: Cluster Reference Configuration

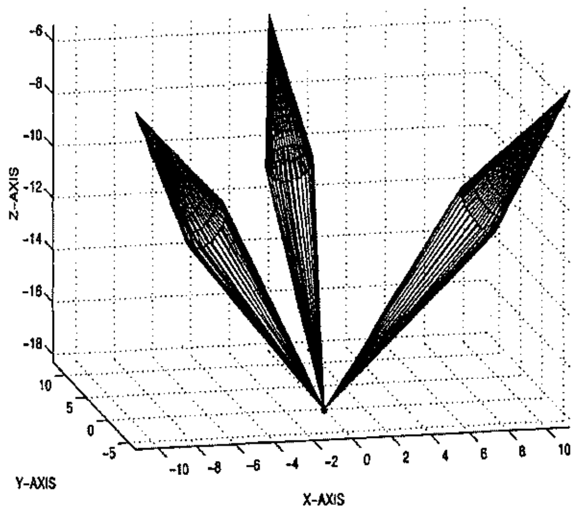

Figure 12: Cluster Initial Configuration

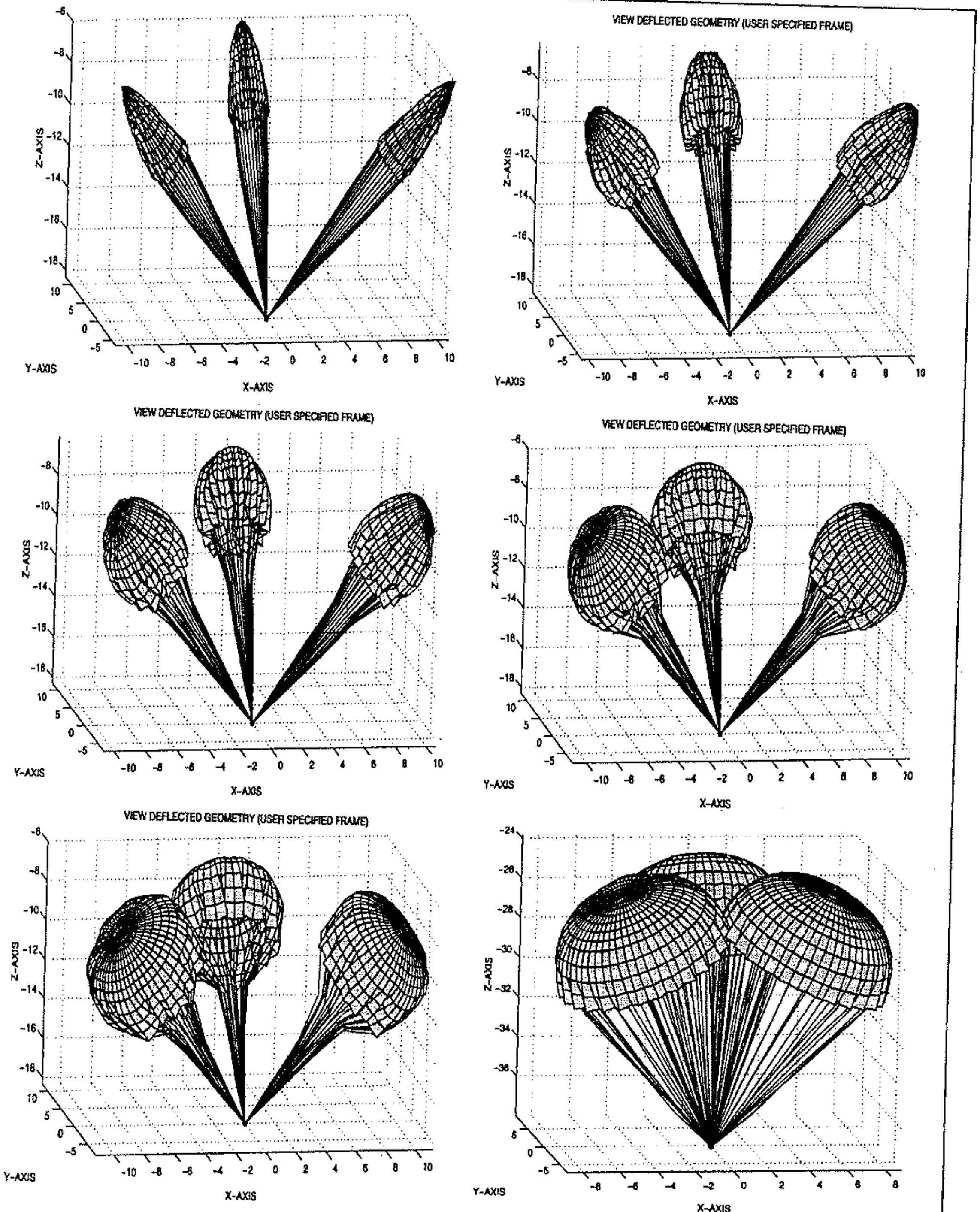

Figure 13: Inflation of Cluster from Initially Wrinkled Configuration

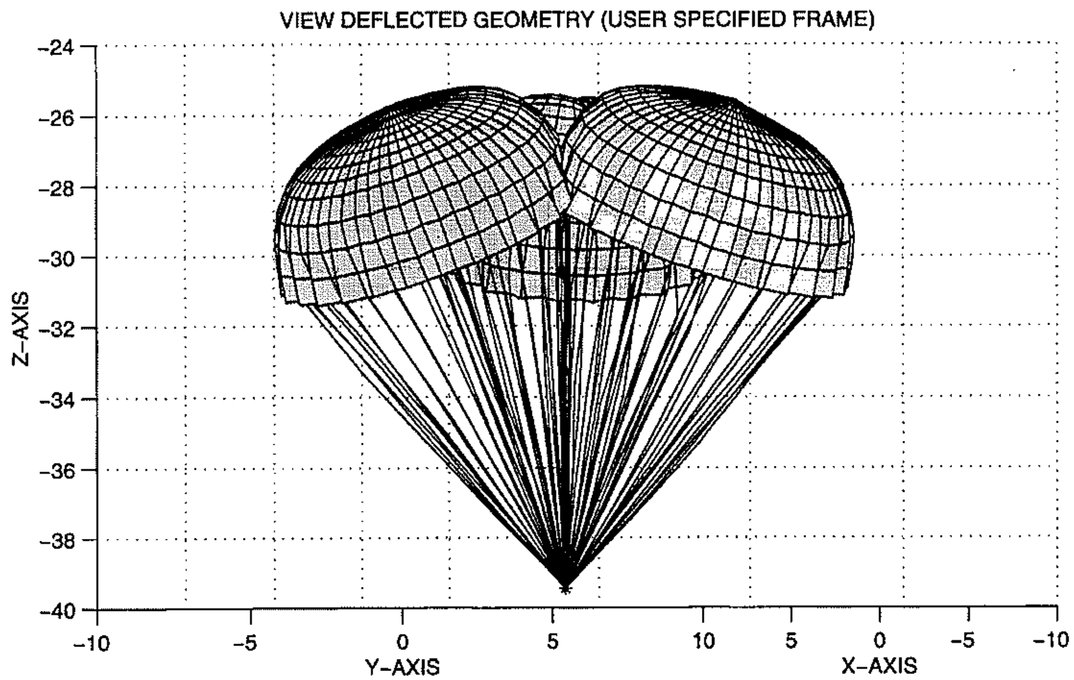

Figure 14: Side View of Cluster in Contact

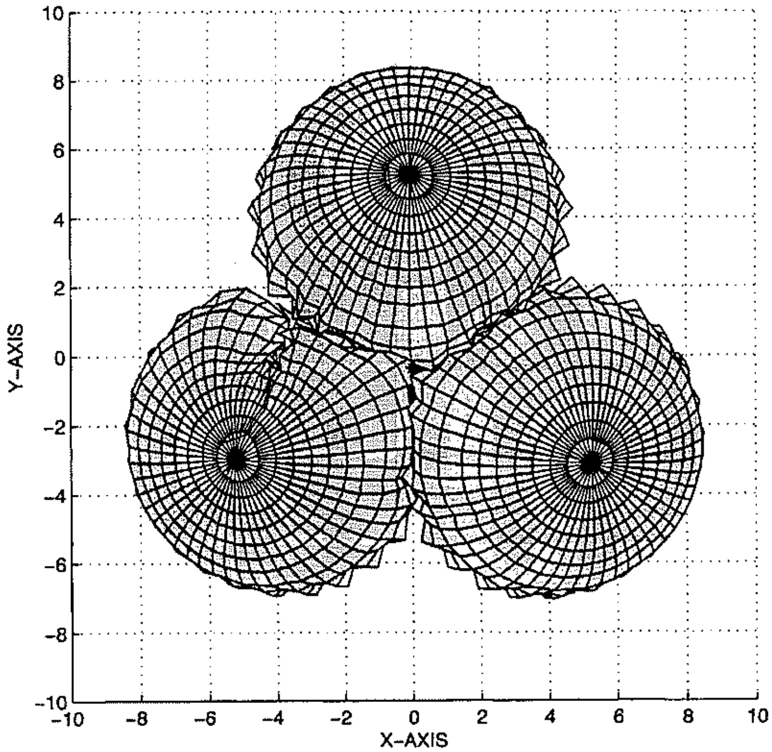

Figure 15: Top View of Cluster in Contact

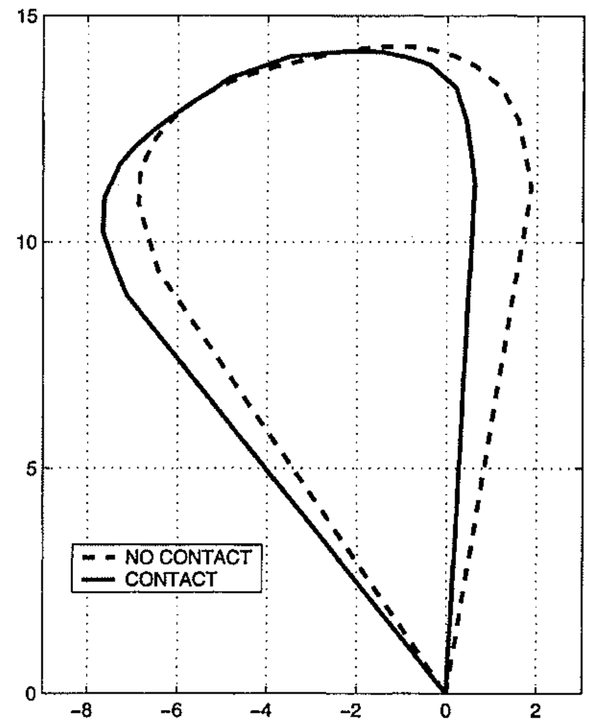

Figure 16: Meridian Profile of Parachute with and without Contact

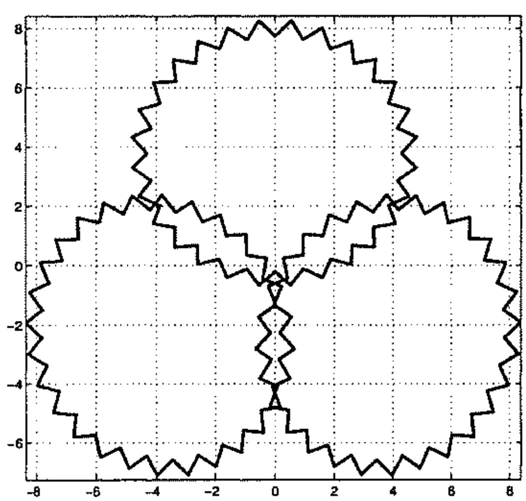

Figure 17: Skirt Profile without Contact

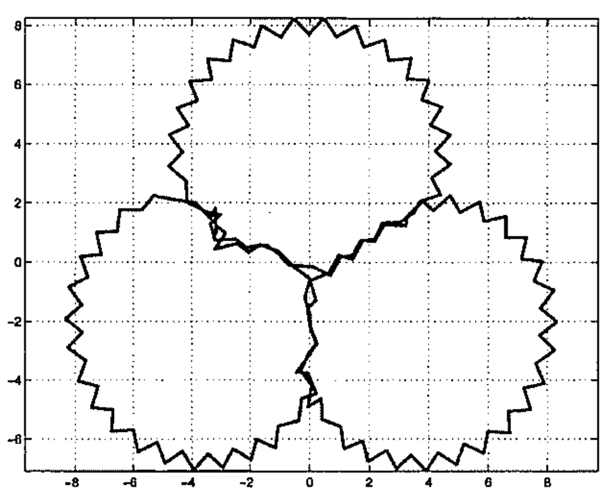

Figure 18: Skirt Profile with Contact

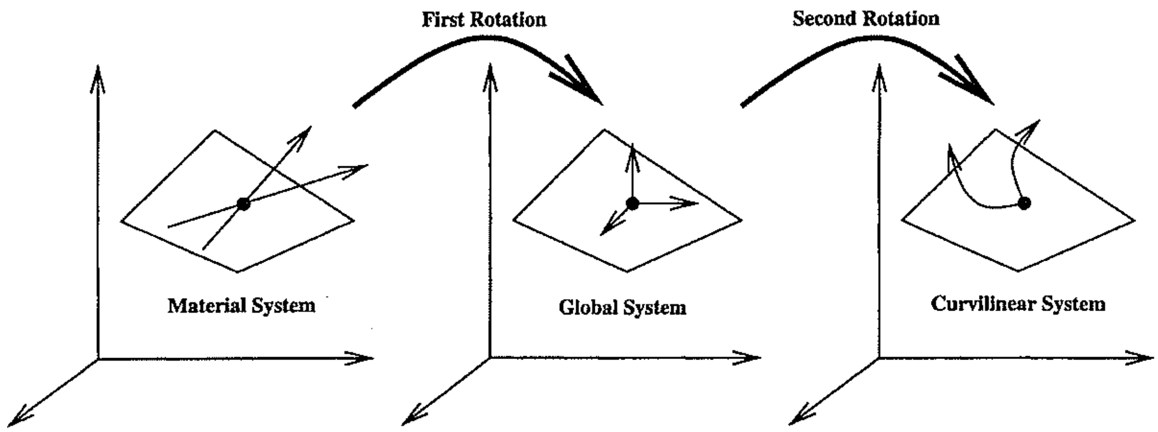

Figure 19: Coordinate Systems for Anisotropic Membrane

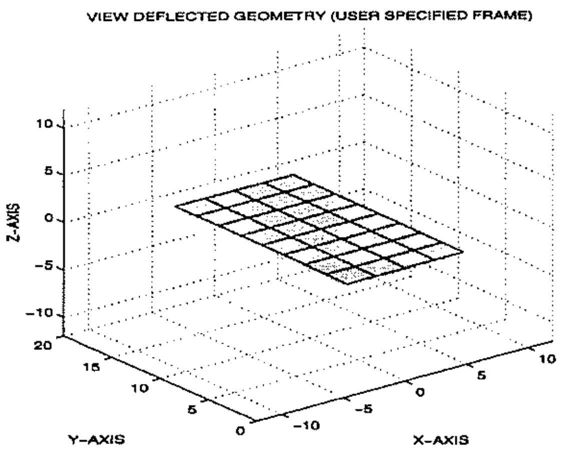

Figure 20: Initial Configuration of PMA

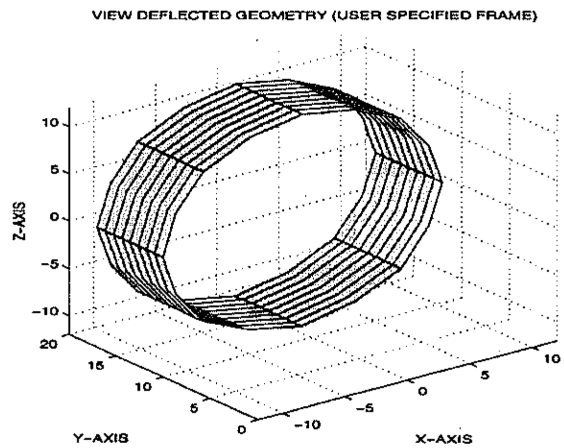

Figure 21: Final Configuration of PMA

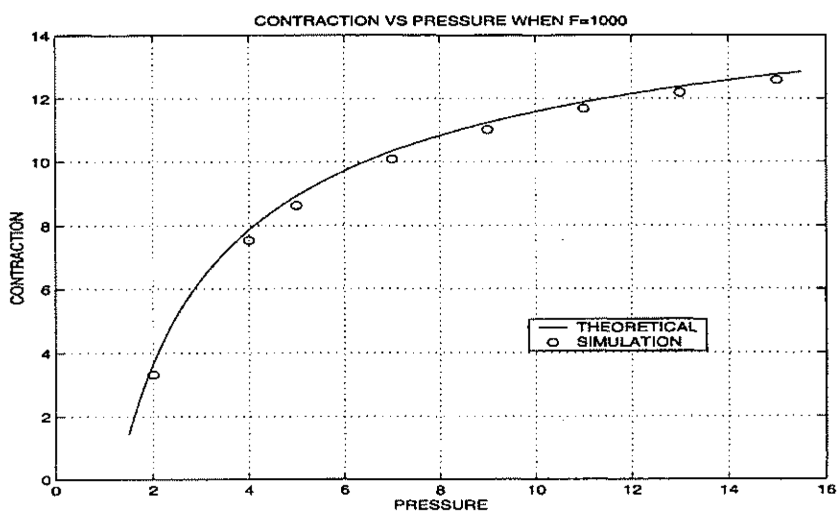

Figure 22: Verification of Anisotropic Membrane Results

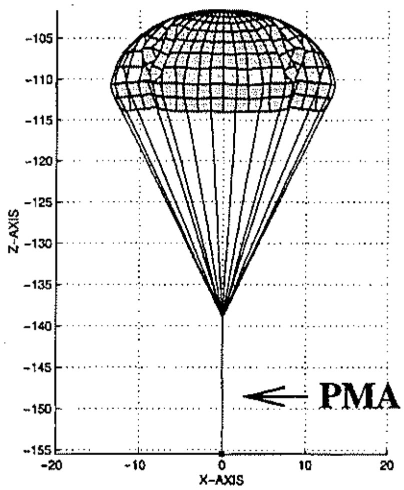

Figure 23: Configuration Prior to PMA Pressurization

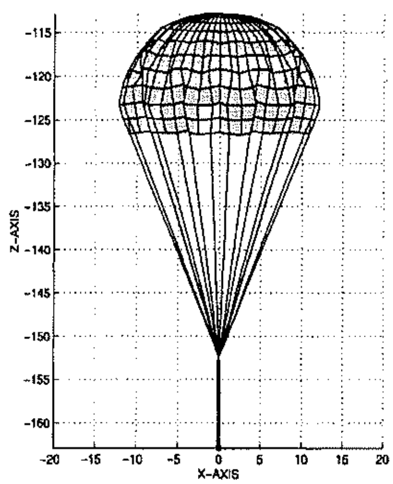

Figure 24: First Configuration during PMA Pressurization

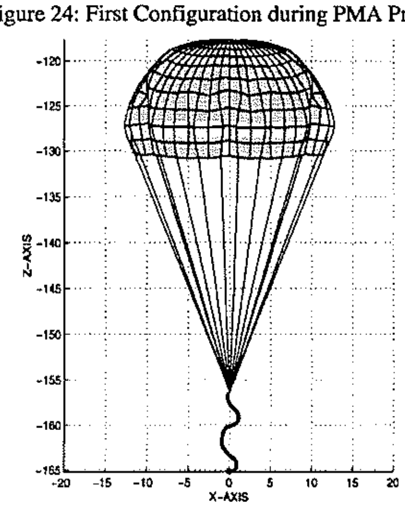

Figure 25: Second Configuration during PMA Pressurization

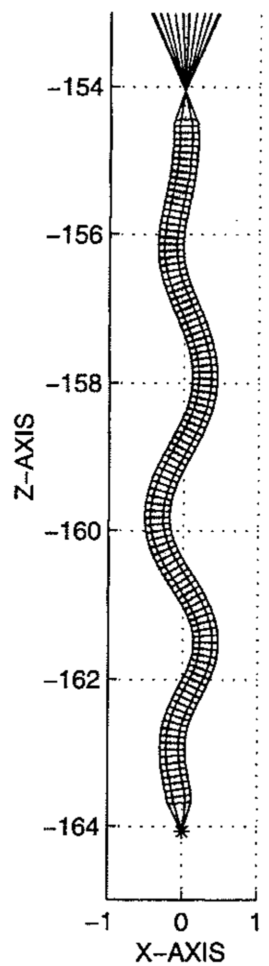

Figure 26: Close-Up View of Pressurized PMA

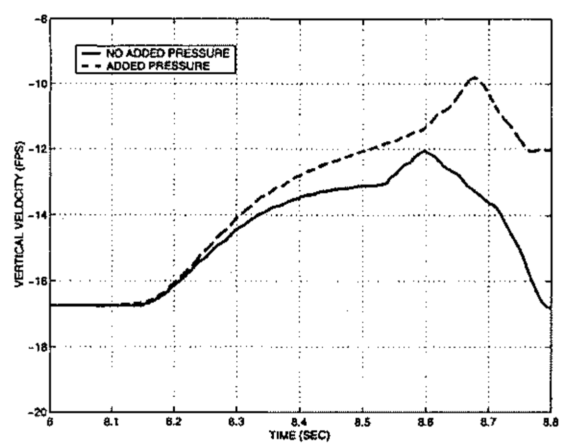

Figure 27: Payload Velocity during PMA Pressurization