

Development of Parachute Simulation Techniques in LS-DYNA[®]

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Abstract

Parachute design often relies heavily on historical experimental data, and parachute development frequently requires numerous test campaigns. Although both of these techniques eventually result in successful parachute systems, such an approach will rarely result in any true advance to parachute engineering knowledge. Consequently, an unusually high emphasis is placed on experienced parachute design personnel, and often similar lessons have to be re-learned over and over again.

Airborne Systems has been at the forefront of parachute modeling using Fluid Structure Interaction (FSI) techniques for the past 7 years. Significant advances have been made in parachute modeling using this powerful technology, many of which have been a direct result of US Army Natick Soldier Research, Development and Engineering Center funding and support. This paper presents the current "state of the art" parachute modeling at Airborne Systems using LS-DYNA. It discusses recent advances in simulating parachute performance and areas of future study. It documents fabric material modeling, wind tunnel class parachute analysis, parachute inflation studies, and comparisons with drop test data.

A description of the modeling methodology is included as well as the application of the technology in a number of real world parachute applications including the old T-10 and the new T-11 US Army mass tactical assault parachutes.

Introduction

Since 1919, when founder Leslie Irvin made the first ever free-fall parachute jump, Irvin Aerospace, now Airborne Systems, has been designing and manufacturing parachutes. In many ways, the methods used to develop parachutes can still be traced to the same techniques used over ninety years ago. Although materials and instrumentation have changed significantly parachute development still relies heavily on testing and more testing.

The inherently complex interaction of a highly deformable body and a fast moving compressible fluid has made a truly analytical design approach exceptionally difficult to accomplish. To appropriately simulate, and therefore understand and predict, this behavior requires an accurate method of assessing this complex relationship. Analysis of a parachute or a flow field without its associated partner is excluding the inherent interaction between the two. In saying this, there are many intermediate modeling steps that can provide performance and design guidance without requiring the computationally intensive FSI approach. In this term FSI is used to define the mutual interaction between a structure and a fluid, and not a more simple one-way interaction.

The author has previously published data that describes the use of Fluid Structure Interaction techniques within LS-DYNA to replicate parachute behavior [1]. That reference discusses the benefit of visualizing the flying shape and anticipating the performance of a newly designed tactical mass assault troop parachute, prior to fabrication and testing. The study exposed the inability to consider fabric permeability as an authentic limitation that would restrict the application of the methodology for a number of applications. This limitation has since been removed with the incorporation of the porous coupling within the `CONSTRAINED_LAGRANGE_IN_SOLID` card. Fabric testing is currently ongoing to gather the data required to enable his algorithm to modify permeability based on fabric strain. With the support of the US Army Natick Soldier Center many of the current parachute materials will be tested to provide a database of material properties.

Another limitation that has often been cited is the inability to consider the finite-mass inflation of parachute systems. This parachute term relates to the process of the payload slowing down during parachute inflation. A wind tunnel inflation of a parachute, where the air speed remains constant would be termed an infinite-mass inflation. Again, this limitation has recently been further studied thanks to support from the Natick Soldier Center, the results of which have indicated that such a finite-mass inflation simulation is possible. Current computational requirements have limited the applicability of this technique to small scale parachutes.

The following pages describe the state of the art parachute modeling at Airborne Systems using LS-DYNA and discuss their applicability to real world operations.

Modeling Approach

A multitude of finite element analysis techniques have been developed and employed, within the parachute community, to simulate various functions of a parachute system. This section describes a number of the LS-DYNA parachute analysis methods utilized by Airborne Systems and discusses how they are integrated into the design process.

Computational Structural Dynamics

This class of analysis involves applying distributed loading to a given parachute geometry. The canopy loading is normally in the form of a differential pressure that has been derived through test or based on similarity to past canopies. Figure 1 presents a contour plot of fabric running load on a ringsail parachute when subjected to a distributed pressure loading. The more complex structural analysis methods apply a time dependent loading that attempts to approximate the inflation process. These techniques produce valuable results when the canopy in question is historically well characterized. The canopy loading inputs rely upon wind tunnel test results or computational fluid dynamic outputs. For this reason, its applicability is reduced when considering new designs, new flight regimes for existing canopies, or parachute design modifications.

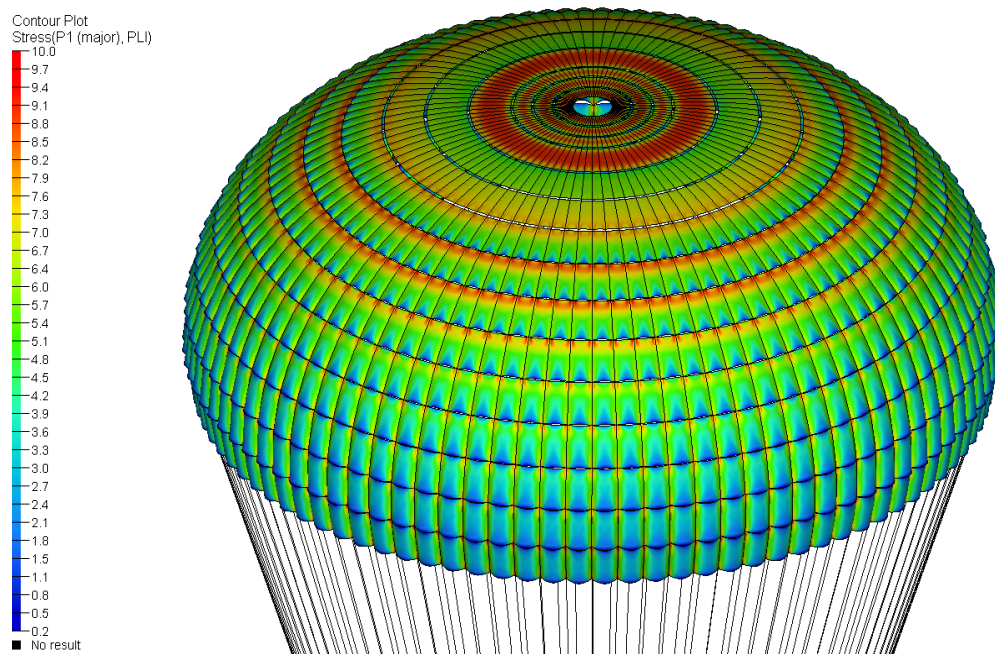


Figure 1: Example of Computational Structural Dynamics

This technique has been used recently to assess the impact of parachute damage to overall mission survivability. Understanding the potential consequences of parachute damage enables the designer to incorporate mitigation considerations into the parachute design.

One example of this is the Parachute Assembly System for the Orion Crew Module. The Orion parachute landing system architecture includes three main ringsail parachutes, similar to Apollo, and two smaller drogue parachutes. The drogues are stronger and heavier parachutes that are

used to slow the Crew Module to a lower dynamic pressure that enables the larger main parachutes to survive inflation.

Drogue parachutes are constructed from individual fabric ribbons that are assembled to produce a highly porous, but strong parachute, that can withstand high dynamic pressure environments. LS-DYNA was used to analyze a structural model of a drogue parachute that had sustained damage during deployment; a potential scenario during extreme testing. The objective of the modeling was to identify the inherent damage tolerance in the parachute design and guide placement of heavier rip-stop ribbons at locations in the parachute to avoid catastrophic failure. The images in Figure 2 illustrate stress contours on a drogue parachute that had sustained damage in several locations.

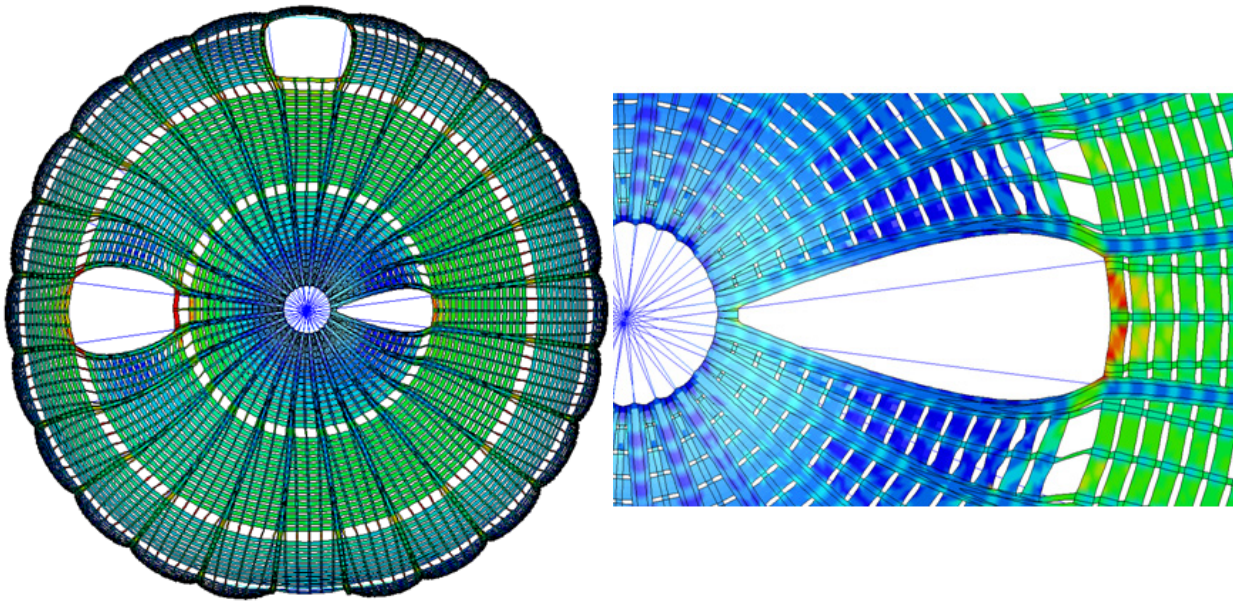


Figure 2: Parachute Damage Tolerance Investigation

This is an exciting area of parachute analysis within LS-DYNA and Airborne Systems contend this class of simulation could be applied to almost any parachute type and provide useful results that have the potential to improve survivability for both personnel and cargo applications.

The models are constructed using the MAT_FABRIC material model, utilizing the non-linear stress vs. strain behavior, as well as the anisotropic definition when necessary. Simulations typically take several hours on a high-end PC workstation. The primary challenge with this class of model is to ensure that the initial parachute geometry is correct and accurately replicates the constructed shape of the parachute.

Computational Fluid Dynamics

CFD can be thought of as FSI but with only one-way communication. Some insight into parachute aerodynamics can be gained from CFD analysis of flow around a rigid body that approximates the instantaneous geometry of a parachute in flight. However, the inherent instabilities associated with bluff body aerodynamics and the uncertainty associated with inflated

shape suggests that this technique has limited applicability when characterizing the performance of a parachute. The presence of re-circulation and the accompanied reverse flow in the wake of the bluff body indicate the potential of such flow conditions to create asymmetric instabilities.

Analysis experience at Airborne Systems has suggested that CFD models can provide valuable insight into instantaneous parachute performance characteristics, especially for parachutes that cannot be fully analyzed using FSI techniques; due to the high computational overhead. This technique has also proven beneficial when considering the wake of a forebody; a particular concern for interplanetary missions.

The model depicted in Figure 3 is a section through half a ribbon parachute. . The parachute center is in the top middle of the image and air is flowing past it from the left. The parachute was defined as a rigid body and the constraint coupling (CTYPE=4) was activated in the `CONSTRAINED_LAGRANGE_IN_SOLID` card. This approach essentially results in a compressible CFD simulation.

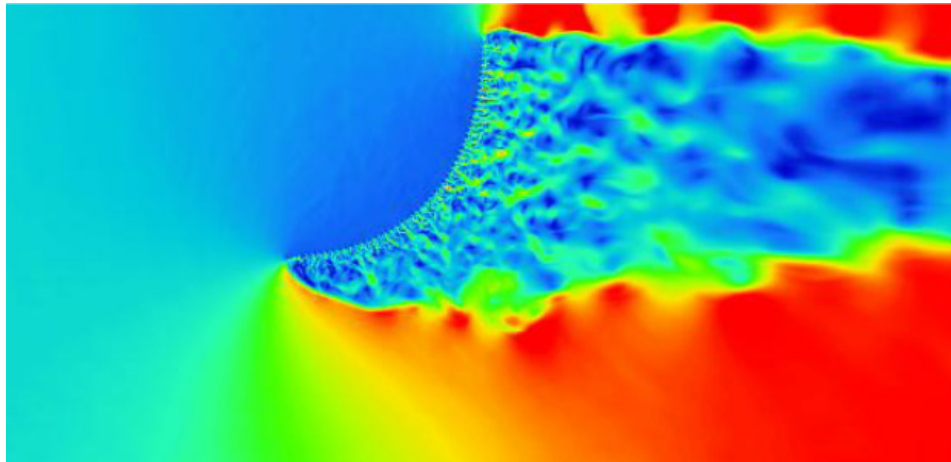


Figure 3: CFD Parachute Model

Fluid Structure Interaction- Highly Deformable Structure

This broad term has been used to describe a number of modeling approaches each of which have succinct computational and operational differences. In general terms, FSI techniques involve the coupling of structural and fluid dynamics. The methods utilized to achieve this coupling are dependent upon the codes used and to some extent the analysis application. The approach used by LS-DYNA is to perform both the structural and fluid computations with the same code. Although data does still have to be transferred between the structure and the fluid the obvious benefit of this scheme is that no inter-code data transfer is necessary.

It is possible to use LS-DYNA in a number of alternative ways to simulate this highly dynamic fluid, and structural event. However, the large deformations associated with parachute behavior limit the applicability of the Lagrange formulation for both the parachute and the flow field, and in our experience the runtime requirements of SPH or meshfree methods currently limit their efficiency.

The FSI models comprise a fluid, which is solved by using an Eulerian formulation [2] on a Cartesian mesh, that overlays a parachute structural mesh that is discretized by Lagrangian 4-node membrane elements based on the Belytschko-Lin-Tsay formulation [3], and 2-node cable elements.

The multi-material Eulerian formulation permits material flow through a mesh which is fixed in space. Individual elements are allowed to contain a mixture of different materials. This method completely avoids any mesh distortions for the fluid domain. The incorporation of an Eulerian-Lagrangian coupling algorithm permits the interaction of flow field, Eulerian formulation, and the parachute, Lagrangian definition, within the same simulation.

Previous parachute analysis identified the inability to account for parachute fabric permeability as a distinct limitation of the original penalty coupling method. A second coupling method, termed the porous coupling method, was proposed by Airborne Systems to Livermore Software Technology Corporation (LSTC), the developers of LS-DYNA. The implementation, verification and validation of this coupling method is discussed in Ref [1]. The following is a numerical description of the coupling approach.

In an explicit time integration solution, the calculation of nodal forces is the primary procedure within each time step. When considering the simulation of a parachute, nodal forces are calculated for both the fluid and structure. The forces due to the coupling are then computed, these forces only affect the nodes that are on the fluid - porous structure interface. For each structure node, a depth penetration \vec{d} is incrementally updated at each time step, using the relative velocity \vec{v}_{rel} at the slave and master node. For this coupling, the slave node is a parachute structure mesh node, but the master node is not a fluid mesh node. It can be thought of as a fluid particle within a fluid element, with mass and velocity interpolated from the fluid element nodes using finite element shape functions. The location of the master node is computed using the isoparametric coordinates of the fluid element.

If \vec{d}^n represents the penetration depth at time $t = t^n$, it can be incrementally updated using Eq.(1):

$$\vec{d}^{n+1} = \vec{d}^n + \vec{v}_{rel}^{n+1/2} \cdot \Delta t \quad \text{Eq. (1)}$$

In $\{1\}$ $\vec{v}_{rel}^{n+1/2} = \vec{v}_s^{n+1/2} - \vec{v}_f^{n+1/2}$ in which the fluid velocity \vec{v}_f is the velocity at the master node location and the structure velocity \vec{v}_s is the velocity at the slave node location. The coupling acts only if penetration occurs i.e. $\vec{n}_s \cdot \vec{d}^n < 0$, where \vec{n}_s is built up by averaging the normals of structure elements connected to the structure node.

The porous coupling forces are derived from the integration of the Ergun [4] equation on the shell volume Eq.(2):

$$\frac{dp}{dz} = a(\mu, \epsilon) \vec{v}_{rel} \cdot \vec{n}_s + b(\rho, \epsilon) (\vec{v}_{rel} \cdot \vec{n}_s)^2 \quad (2)$$

in which \hat{z} is the local position along the fiber direction of the shell element and ε is the porosity, defined as $\varepsilon = \frac{v_{void}}{v_{total}}$, μ and ρ are the dynamic viscosity and density, respectively.

The coefficient $a(\mu, \varepsilon)$ is the reciprocal permeability of the porous shell or viscous coefficient, and $b(\rho, \varepsilon)$ represents the inertia coefficient. For flows under very viscous conditions the second term in Eq.(2), which represents the inertia effects drops out and the Blake-Kozeny equation for laminar flow in porous media is obtained. At high rates of flow it is the first term or viscous term which drops out, and the Blake-Plummer equation for turbulent flow in porous media is obtained.

These coefficients can be derived from the Ergun theory:

$$a = \frac{150\mu(1-\varepsilon)^2}{D^2\varepsilon^3} \quad (3)$$

$$b = \frac{1.75\rho(1-\varepsilon)}{D\varepsilon^3} \quad (4)$$

Where D is a characteristic length defined by: $D = \frac{6(1-\varepsilon)V}{S}$ with V , the volume of the canopy and S , the “wetted” surface of the parachute.

At this point it is worth discussing the use of the terms porosity and permeability. The Ergun equation describes the magnitude of porous flow velocity at a given differential pressure based upon two coefficients. It is an equation derived to explain a number of porous flow conditions, which has been used to describe soil mechanics and biomedical applications. In the above description, the flow coefficients assume the Lagrangian structure to exhibit constant porosity, not to be confused with a constant permeability. For the application of interest in this study porosity is a characteristic of the parachute fabric, whereas permeability is a description of the flow velocity through the parachute fabric at a given condition. Many materials can be highly porous without being permeable.

It should be noted that the porosity of some fabrics can change significantly with applied load and this area is the subject of further research.

It is only within the last 5-6 years that this “direct method” of computing the fluid and structure within the same code with a coupling algorithm has emerged as a viable way of simulating parachute performance. The application of Eulerian formulations can lead to a propensity for energy dissipation and dispersion inaccuracies connected with the fluxing of mass across element boundaries. In addition, the Eulerian mesh is required to span the entire range of activity associated with the Lagrangian structure. In many applications, this can result in a large size mesh and hence a high computing cost. Many of these potential difficulties have been managed through algorithm development and vast improvements in computing power.

FSI Parachute Examples

The wind tunnel type environment enables parachutes to be studied in a more controlled condition. Similarly, the numerical wind tunnel equivalent enables the designer to understand more about the parachute performance characteristics, particularly useful for comparisons with the steady descent phase of operation. This modeling approach also provides the capability to compare simulation results directly with test data. Steady state drop test conditions can be replicated by constraining the payload and defining the appropriate flow velocity in the simulation. The force generated by the parachute in the simulation can then be compared to the payload weight used in the drop test. There are differences between the two conditions that the user needs to be aware of but this approach is still very useful in understanding certain parachute parameters. Figure 4 depicts the velocity vectors on a section cut through the fluid surrounding the T-11 main parachute (top), and pathlines defining the flow of air through the side slots. This parachute was assessed in a wind tunnel type model. This parachute is now in full rate production and a US Army study has revealed that the parachute has reduced injuries by 73% compared to its predecessor; the T-10. This is partially due to the FSI modeling performed using LS-DYNA during its development phase.

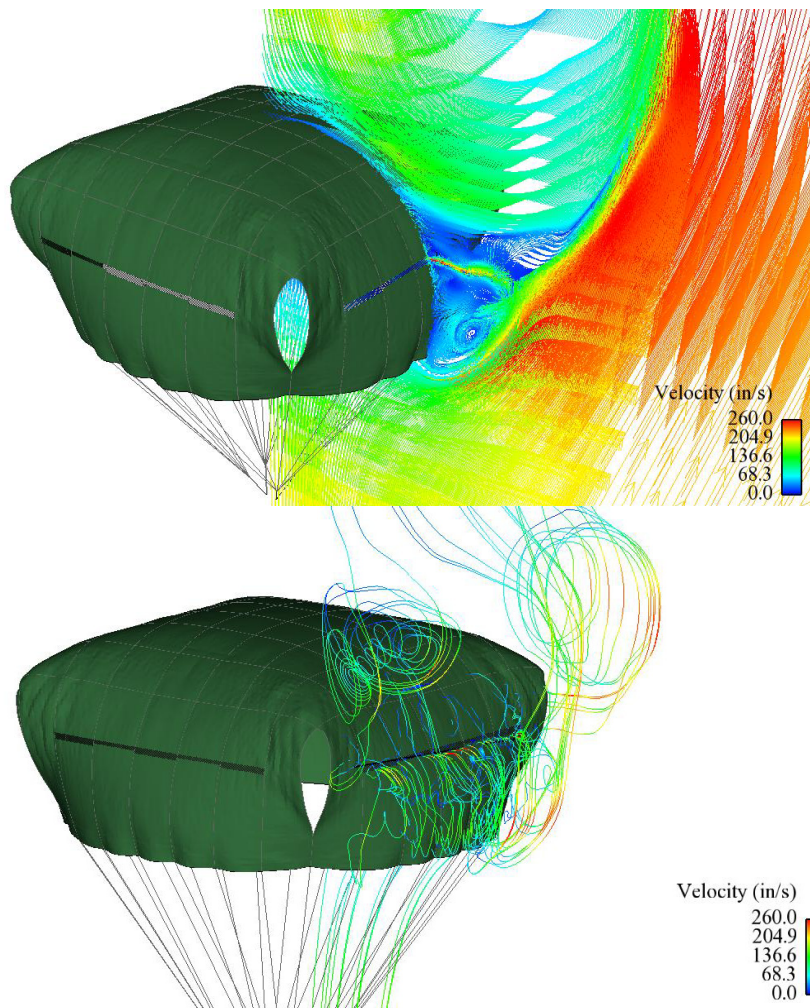


Figure 4: T-11 Main Parachute Analysis

Another area of recent advancement is the simulation of finite-mass parachute inflation. The objective of this work was to utilize experimental work conducted by Natick Soldier Center to aid validation studies of simulation technology. The particular experimental series considered throughout this report was the indoor vertical parachute tests [5] conducted at the Space Power Facility (SPF) at the NASA Glenn Research Center (GRC) Plum Brook Station in Sandusky, Ohio. The test series comprised dropping scaled parachutes in a controlled environment surrounded by a multitude of instrumentation.

The Eulerian fluid mesh generated for this task replicated only a small section of interest within the Plum Brook SPF. To construct a fluid mesh of suitable density to fill the entire volume of test chamber would far exceed the available computational power. : Computational Mesh and SPF Relative Scale Figure 6 illustrates the relative size of the computational mesh and the cross sectional area of the SPF. The SPF test chamber is 100-ft in diameter and 120-ft high at the center of the chamber.

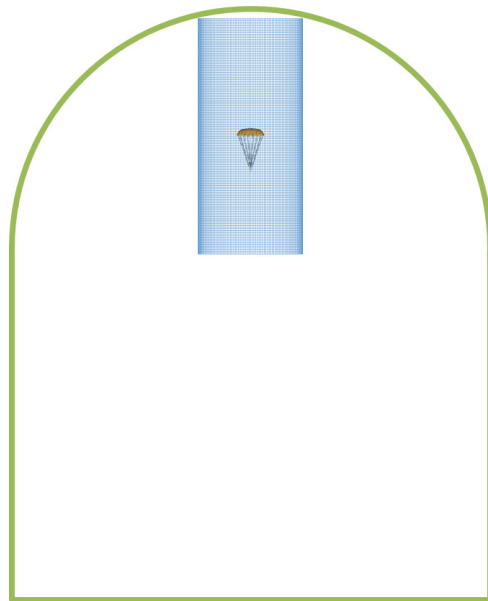


Figure 6: Computational Mesh and SPF Relative Scale

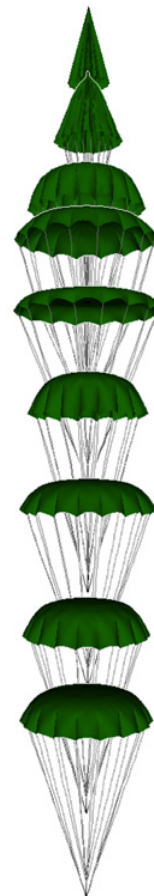


Figure 6: Parachute Inflation

Capturing the initial inflation shock loading of the parachute canopy was necessary to fully and accurately model the inflation process and any resulting parachute dynamics. This process involved effectively modeling the initial deflated parachute canopy shape (tests began with the parachute in a straight line, not packed in a bag).

In order to accurately model the initial parachute canopy shape, Airborne Systems had to develop a methodology for taking the parachute planform from drawings, allow it to deform appropriately and then export that geometry for use as the initial deflated parachute canopy geometry in the FSI model. The key to this process was ensuring that zero strain was present in the deformed shape, otherwise this would be carried forward to the initial drop test geometry.

As illustrated by **Error! Reference source not found.**, the parachute starts in its free hanging position, then rapidly inflates. It is shown to progress into an over inflation shape, almost flat, and then deflate and once again over inflate. This phenomenon is referred to as breathing and is a well documented feature of flat circular parachutes.

This model utilized in excess of 1M hexahedral solid elements, and 4,000 membrane shells. Total run-time was on the order of days.

The capability to replicate this behavior is impressive and further research is currently ongoing to shed further light on similar performance parameters observed during the testing.

Conclusions

Parachute analysis using LS-DYNA continues to push back some of the technical boundaries and shed light on some interesting phenomena concerning the interaction of a highly deformable thin structure with fast moving compressible fluids.

Demonstration of the applicability of LS-DYNA to simulate finite mass parachute applications was a significant advancement during the work outlined in this paper. Airborne Systems contend that the extent of the qualitative similarities is very encouraging and clearly illustrates the value of LS-DYNA in such applications, current work is aimed at comparing the data compiled from the tests with the model results. The qualitative comparisons presented in this document indicate that the numerical modeling technique identified both an accurate parachute opening force and also replicated the breathing phenomenon. It seems appropriate to conclude that the LS-DYNA modeling technique captured the general behavior of the parachutes. This is the first known application of LS-DYNA to simulate finite mass type parachute performance and compare the results with experimental data.

The authors appreciate the continued efforts by LSTC to improve the scalability of the MPP version of LS-DYNA for ALE applications.

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