The use of LS-DYNA to Simulate the Inflation of a Parachute Canopy

Benjamin A. Tutt* and Anthony P. Taylor.†
Irvin Aerospace Inc

This paper documents the results of an internal research and development effort by Irvin to ascertain the capacity of LS-DYNA to simulate the inflation of a parachute canopy. Recent application of Fluid Structure Interaction (FSI) techniques within LS-DYNA for the quasi-steady-state analysis of parachutes, water impact studies, and other dynamic events, have highlighted the potential of the tool to predict parachute opening performance. Currently, Irvin and others have restricted the application of FSI simulations to post-inflation parachute behavior. These simulations allow the parachute designer to visualize a canopy during the steady descent phase of operation. The ability to anticipate the aerodynamics throughout the canopy and to understand the associated effects of the airflow on the parachute performance have proven to be invaluable tools in the parachute development process. A similar ability to analyze the inflation of a parachute remains a more difficult assignment. The motivation behind this study was to gain a greater understanding of the flow dynamics of a flexible parachute. More specifically, the ability to visualize and characterize the flow-field and parachute parameters responsible for creating large opening forces could deliver a different perspective for parachute designers. The reliance on flight tests and past experiences can be expensive and time consuming. This paper presents the use of an Eulerian-Lagrangian penalty coupling algorithm and multi-material ALE capabilities within LS-DYNA to replicate the inflation characteristics of small round canopies in a water tunnel. Inflation loads, canopy shape, canopy breathing frequency, and fluid-flow patterns are discussed and compared with experimental results. A discussion concerning computational requirements and future model and technique enhancements is included. Also examined is the value of such techniques and the development of the methodology to include finite mass or actual flight scenarios.

Nomenclature

Re_{D0}	=	*Reynolds number (based on constructed parachute diameter)*
U	=	*flow velocity*
υ	=	*kinematic viscosity*
D_0	=	*parachute constructed diameter*

I. Introduction

THE inflation of a parachute can be described as a complicated, time dependent, interaction of structural and fluid dynamics. The combination of bluff body aerodynamics and a highly deformable structure, fabricated from a porous media, creates a truly complex and multifaceted environment.

A number of analytical or semi-empirical methods exist that permit the analysis of parachute inflation. Typically, these techniques depend upon prior knowledge of parachute performance. Terms such as parachute filling time and apparent mass are frequently used to explain parachute performance generalities. These expressions are a convenient means of grouping complex events under manageable segments. The use of these terms often requires a level of

---

* Systems Analyst, Analysis Dept.
† Director Business and Technical Development.

understanding normally achieved through testing or by extrapolation from a similar parachute or operating condition.

These methods have advanced significantly since their incorporation into the design process many decades ago. They are now included in the majority of force-velocity-trajectory codes, enabling a level of prediction for an entire parachute operational timeline.

The ability of these programs to predict parachute system performance is often sufficient for most applications. When designing a new parachute or modifying an existing design for use at new operating conditions, the semi-empirical relationships require the designer to make assumptions or extrapolate from available data. The performance of designed and proven parachutes is difficult to predict outside of the previous tested environment.

In many applications, opening forces establish the structural requirements of the parachute. The difficulties associated with characterizing the inflation process generally lead to excessive margin and therefore an inefficient design. The ability, not only to predict, but also to more accurately understand, the structural and fluid dynamics of a parachute and associated flow field, during inflation, should guide designers to a more efficient and reliable system.

The objective of this paper is to present the results of a recent study to assess the capability of the commercially available transient dynamic finite element program LS-DYNA[1] to simulate the inflation process of a parachute. A comparison between the simulated and test-bed performance is documented.

II. Simulation Methodology

A limited number of experimental studies have been performed that measure flow field and parachute parameters during inflation. Some data exists that equates flow around representative rigid shapes to parachute inflation performance. Numerous tests have been conducted using full-size parachutes, however, the only performance parameter normally acquired is force time history. Other studies have assessed the strength of a specific design during inflation without generating tangible data.

Desabrais[2] conducted a thorough and fully instrumented series of small-scale parachute inflation tests in the Worcester Polytechnic Institute free-surface water tunnel facility. The use of a water tunnel facilitates longer inflation times than would be present in a wind tunnel. The inflation profile of flat circular parachutes of two diameters, 15.2 and 30.5 cm, were analyzed in a series of flow velocities. The resulting Reynolds numbers ranged from $3.0 - 6.0 \times 10^4$. The experimental set-up enabled flow velocity to be measured and subsequent vorticity field to be computed. Canopy drag and geometry were also evaluated.

This study is aimed at assessing the ability to replicate the experiments undertaken by Desabrais within a simulation environment.

A number of finite element analysis techniques are available and have been used to shed light upon the parachute inflation process. A selection of these approaches are discussed below.

Many methods have developed from what can be classed as Computational Structural Dynamics, CSD, techniques. These methods involve applying known or derived pressure distributions to instantaneous parachute geometry. The resulting displacement of the canopy can then be assessed and an iterative process used to evaluate the entire inflation. The accuracy of this method is reliant upon the quality of the canopy loading description.

Computational Fluid Dynamics, CFD, techniques are commonly used to provide inputs to a CSD simulation. This method can be used to assess flow around a rigid body and can provide a pressure distribution for structural analysis.

An alternative technique, often referred to as Fluid Structure Interaction, FSI, literally combines these two approaches, CSD and CFD. This approach permits a flexible structure to react and deform in response to a surrounding flow field. The subsequent effect of this motion on the flow field is then assessed in a closed-loop type environment. For some time, FSI techniques have shown potential for visualizing and explaining a number of parachute performance characteristics. Recently, the combination of code improvements and the availability of suitable computing resources have allowed Irvin to realize some of this potential.

Irvin has utilized the transient dynamic finite element program LS-DYNA for over 8 years for the analysis of fabric structures and parachute system hardware. Such techniques have lead to reduced testing requirements and more efficient solutions to a number of parachute system requirements. Over the past 4 years, Irvin has investigated the FSI capability within LS-DYNA; leading to successful replication of Apollo Command Module water landing tests[3] and an investigation into the apparent mass of parachutes.[4] Ongoing work has helped determine steady-descent phase performance characteristics of parachutes. The intuitive response to these studies was to establish whether a similar process could be applied to bring a comparable insight to the parachute inflation process.

The simulation approach developed for this study can be divided into two separate components: the creation of packed or pre-inflation parachute geometry and the subsequent inflation of that geometry.

A. Pre-inflation Phase

The initial phase, creating a packed geometry, is physically simplistic but numerically, is significantly challenging. It is well known that the process of packing a parachute within a deployment bag, or in this case a rigid cylinder, significantly effects the manner in which it deploys. From a numerical, or mathematical point of view this process incorporates a number of challenging tasks. Two of these are identified below:

I. The close proximity of parachute material in the packed state requires the definition of contact algorithms that inhibit adjacent elements from becoming entangled.

II. The proportions of the parachute must remain consistent. Whether the parachute is flat, packed or inflated, the geometry should represent the same parachute.

A number of techniques were assessed in an attempt to create a repeatable and numerically stable method for generating geometry representative of the parachute in the deployment cylinder. Figure 1 illustrates a sample of the pre-inflation shapes created. As can be seen from Fig. 1, the effect of using different packing techniques is substantial.

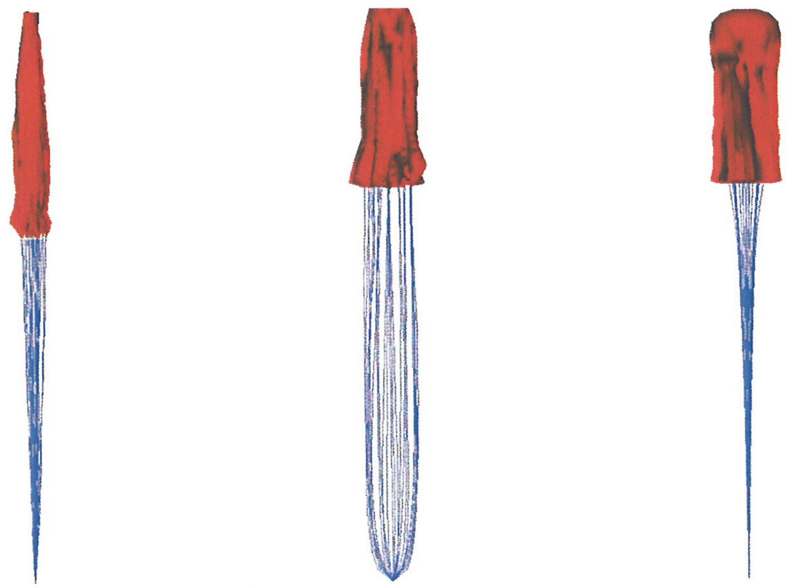

Figure 1. Sample packed parachute geometry.

The method chosen to create the packed geometry used in the inflation process was a dynamic structural simulation. This simulation involved applying a load to the canopy over a period of time. The canopy and suspension lines were represented by elements described by a Lagrangian formulation. Figure 2 depicts the parachute geometry prior to the inflation phase.

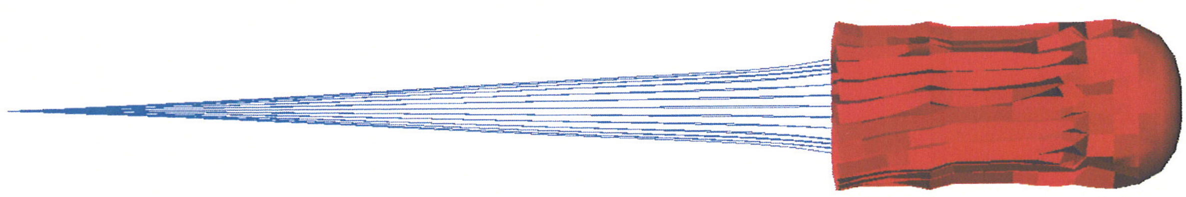

Figure 2. Final 15.2 cm diameter packed parachute geometry.

B. Inflation Phase

The inflation phase involved applying a flow velocity to the geometry shown in Fig. 2. It is possible to use LS-DYNA in a number of ways to simulate this highly dynamic event. Available computational resources restrict the use of either Smooth Particle Hydrodynamics (SPH), or mesh free techniques. Numerical instabilities due to element distortions limit the applicability of using a Lagrangian formulation for the flow field. An alternative technique for the fluid domain is a multi-material, Navier-Stokes based, Eulerian formulation. This formulation permits material flow through a mesh, fixed in space, whose elements are allowed to contain a mixture of different materials. This method completely avoids any mesh distortions for the fluid domain. The Eulerian formulation is not completely free from shortcomings. The user must be aware of the propensity for dissipation and dispersion inaccuracies connected with the fluxing of mass across element boundaries. The Eulerian mesh is required to span the entire range of activity associated with the Lagrangian structure. In addition, the size of these Eulerian elements must be sufficient to permit flow into the closed mouth of the canopy while in the packed condition. This can surmount to a large number of elements and hence a high computing cost. One method used to obviate the related increase in element count was to grade the fluid mesh. This technique utilizes small elements where appropriate and transitions to larger elements where less fidelity is acceptable. Figure 3 illustrates the fluid domain with and without the initial canopy geometry.

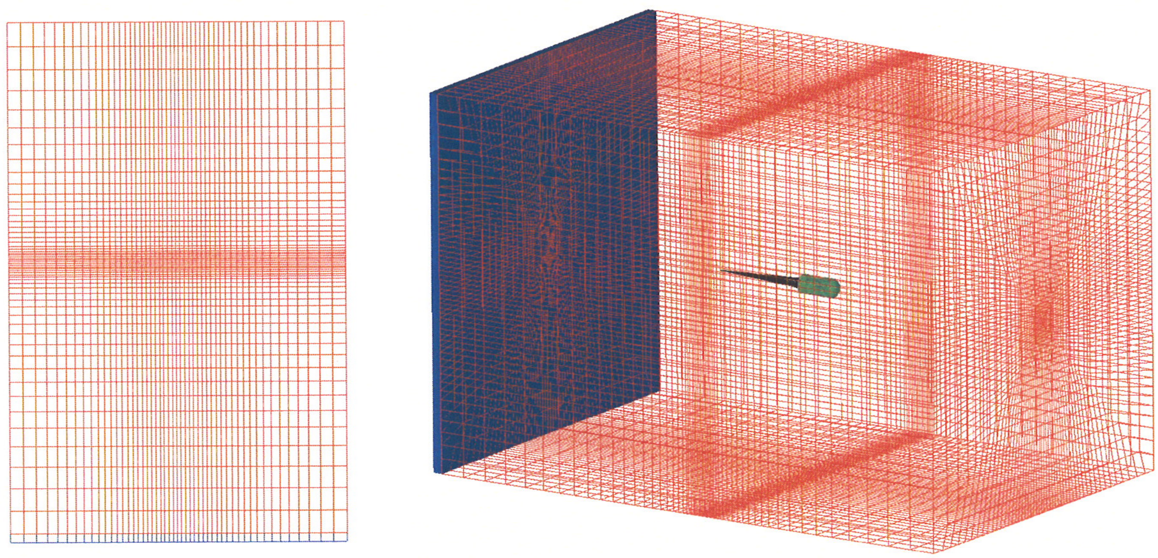

Figure 3. LS-DYNA parachute inflation model.

The incorporation of an Eulerian-Lagrangian penalty coupling algorithm permits the interaction of the fluid (Eulerian) and structure (Lagrangian) parts within the same simulation. The use of a penalty-based coupling algorithm significantly reduces the energy conservation errors connected with alternative constraint-based techniques. Constraint-based methods consume kinetic energy at coupling interfaces, an inappropriate technique when considering this type of application.

The fluid domain is constructed in such a manner that a continuous source of water, at a controllable velocity, flows from one end of the fluid domain and exits at the opposite end, much the same way as it would in a water tunnel. Boundary conditions are imposed upon the fluid domain that reflects those observed in the water tunnel experiments.

The models were constructed using HyperMesh, a member of the HyperWorks Suite developed by Altair Engineering, and executed using LS-DYNA version 970, revision 3535, running on a 3 GHz, 32-bit PC workstation. Post-processing activities were performed using HyperView, another member of the HyperWorks Suite, and EnSight version 8.0, developed by CEI. EnSight was primarily used to view the parachute in the flow field while HyperView enabled the monitoring of model performance and evaluation of time history ASCII files.

III. Simulation Results

A. 15.2 cm Diameter Canopy, 20 cm/s Flow Velocity

The inflation characteristics of a, 15.2 cm diameter, flat circular parachute were analyzed at a flow velocity (U) of 20 cm/s. A Reynolds number, based on the constructed diameter, can be calculated using Eq. (1), where υ is the kinematic viscosity of water (0.01 cm^2/s). The equation yields a Reynolds number of 2.98×10^4.

$$\mathrm{Re}_{D_0} = \frac{U \cdot D_0}{\upsilon} \tag{1}$$

Figure 4 displays time history data for the inflation of the parachute. The force data along the centerline of the parachute is presented. The instantaneous parachute diameter is computed from the coordinates of two points on the skirt of the parachute canopy. Figure 5, reproduced from the Desabrais paper, shows the force-time and diameter-time test data for the associated inflation experiment. It is clear that the simulation has captured the general inflation characteristics well, large opening shock, over expansion and subsequent breathing of the canopy. The maximum predicted parachute diameter is within 8% of that observed in the experiment. The cyclical nature of the canopy breathing also correlates well. Peak to peak maximum diameter comparisons yield a prediction accuracy of within 4%.

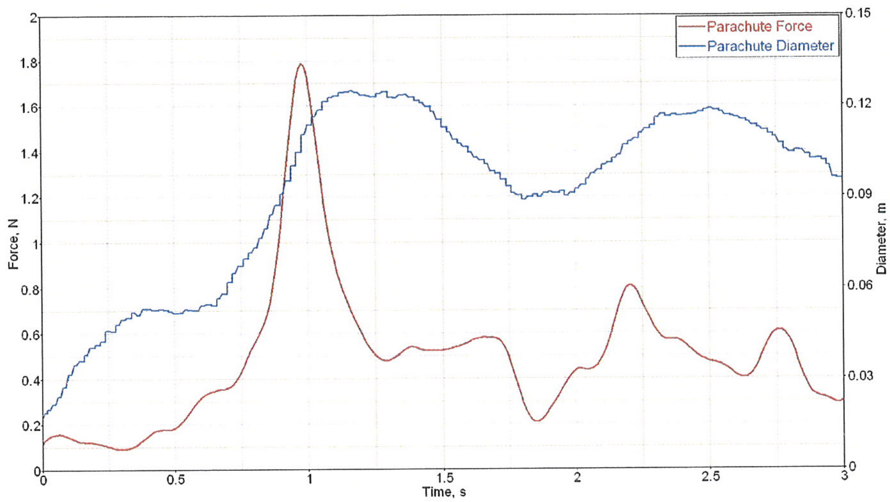

Figure 4. Force and diameter time history data of the 15.2 cm diameter parachute inflation simulation.

The peak inflation force observed during the simulation is higher than that recorded during the water tunnel experiments. No attempt was made to use the same or similar data filtering techniques as performed during the experiments.

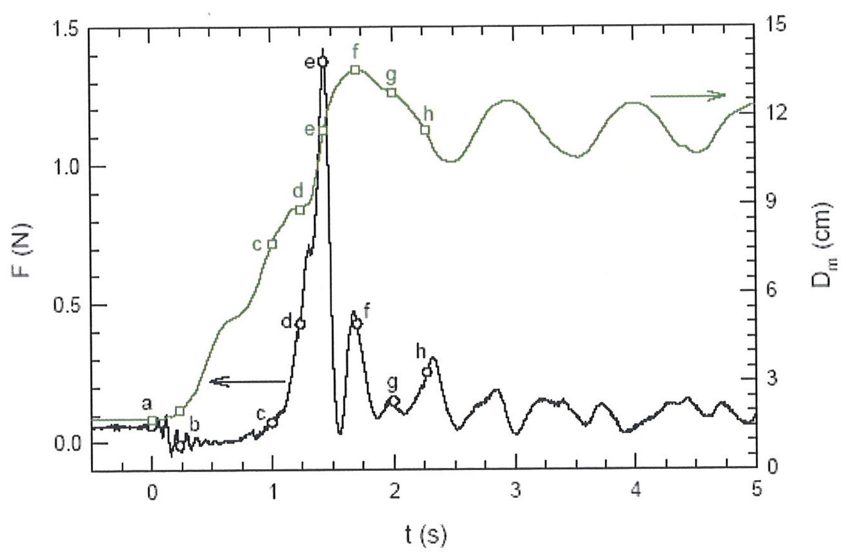

Figure 5. Force and diameter time history data of the 15.2 cm diameter parachute inflation experiment.

It is noticeable that the initial (packed) diameter of the simulated and actual parachute are not the same. The ratio of deployment tube diameter to constructed parachute diameter remained constant at 7% during the inflation experiments. The ratio used for the 15.2 cm diameter simulation was 11%. This larger ratio is directly related to element size and the associated simulation run-time. As the diameter of the packed parachute decreases, the number of fluid mesh elements required to describe flow into the mouth of the canopy increases. The decision to use a larger initial parachute diameter ensured that reasonable and realistic simulation run-times, using existing resources, were attained.

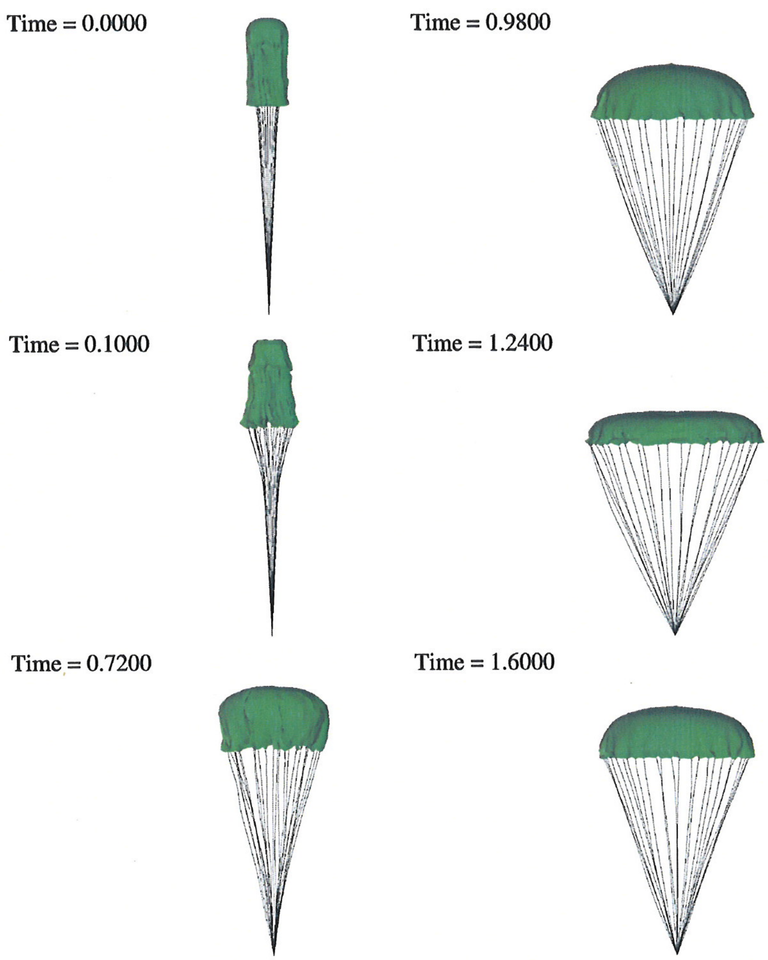

Figure 6. Parachute inflation images, 15.2 cm parachute.

Figure 6 illustrates the predicted canopy geometry at key stages within the inflation process. Again, these shapes correlate well with those observed during the experiments. The stiffness effects of scaling are noticeable; the inflation is different than those observed during full-scale parachute testing. The radial movement of the skirt prior to crown inflation is commonly observed in small-scale parachute inflation experiments. This is believed to be a consequence of the inability to scale the stiffness of the canopy fabric. This is another interesting area that would be simple to investigate using FSI simulations.

It should also be noted, that during the water tunnel experiments a restraining cable was placed along the centerline of the parachute and through the apex of the canopy. This constrained the canopy in the lateral direction, eliminating any instabilities normally associated with flat circular parachutes. A similar method was developed for the simulations depicted in Fig. 6.

An additional simulation was performed where this restriction was removed. After inflating, the canopy moved towards one side, at approximately 20 degrees the canopy stopped and began to move back towards the center. This appears to replicate the behavior expected from a flat circular parachute.

Clearly, these simulations have the capability of providing a great deal of information to the user. An interesting flow feature is the location and distribution of vortex cores. These identify areas of flow circulation and help trace the development of the parachute wake. Figure 7 illustrates the location of vortex cores for this simulation. It is apparent that no vortex ring had been generated when the peak force was experienced. It can also be seen, that as the canopy breathes, the transition of the vortex ring downstream is affected. At times, it is sucked back towards the canopy.

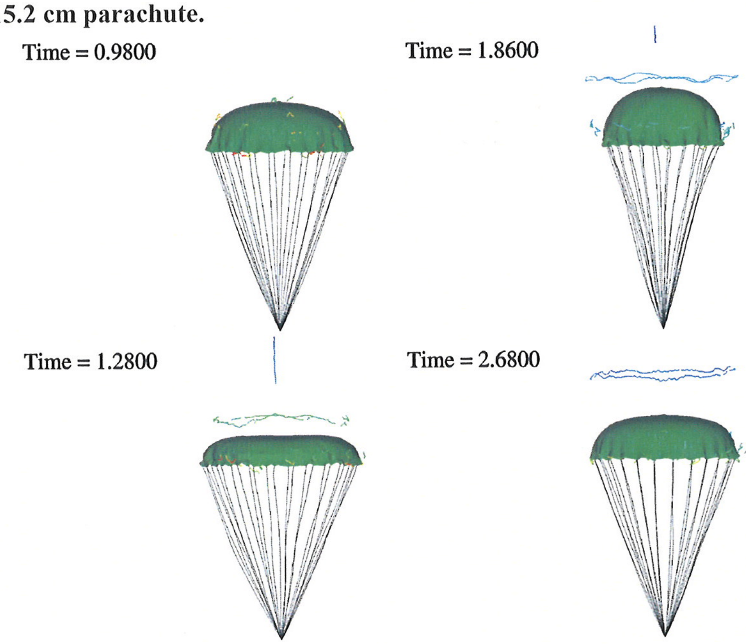

Figure 7. Location and distribution of vortex-cores during parachute inflation.

Pressure contours provide more details concerning the flow field during inflation. The images displayed in Fig. 8 represent the pressure field up to the peak inflation force. Figure 9 depicts the pressure field post-peak inflation force and during the over-inflation phase. The colors towards the red end of the spectrum represent increased pressure and those closer to the blue end correspond to reduced pressure areas.

These figures visualize the development of the pressure field and help to describe the force experienced in the suspension lines, see Fig. 4. The rapid reduction in pressure within the canopy, during the over inflation phase, is worthy of note. As the parachute approaches its maximum diameter, the shape of the canopy becomes shallower, and the internal pressure is lost to the external flow.

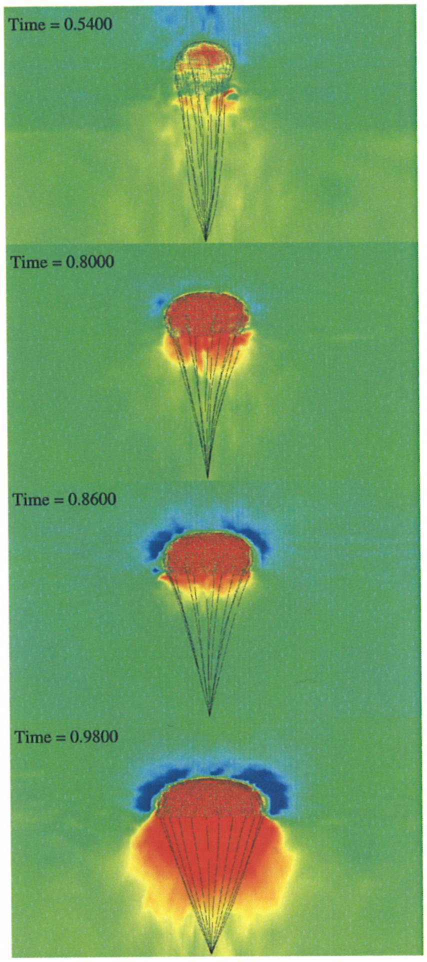

Figure 8. Pressure contours during inflation.

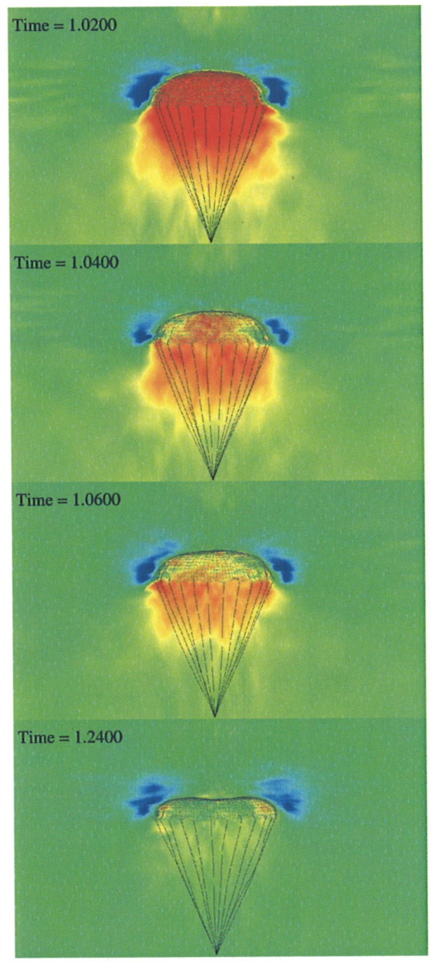

Figure 9. Pressure contours during over-inflation.

B. 30.5 cm Diameter Canopy, 20 cm/s Flow Velocity

The majority of this study considered the development of the technique as opposed to replicating the entire test series. However, following the encouraging results gained from the comparison with the 15.2 cm canopy, a larger diameter canopy was also considered. A 30.5 cm diameter canopy was packed and inflated the same manner as the smaller canopy. Figure 10 illustrates the packed geometry prior to inflation.

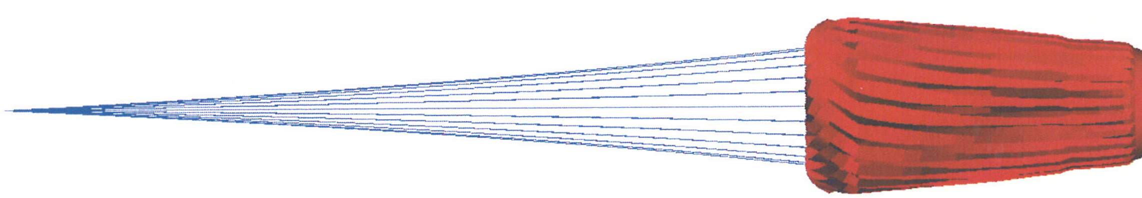

Figure 10. Packed parachute geometry.

Figure 11 displays the force and diameter time history data. Again, the simulation appears to replicate the inflation characteristics well. The most interesting feature of this simulation is that, as observed during the water tunnel experiment, the inflation looks significantly more like a full-size parachute. Figure 12 illustrates key stages

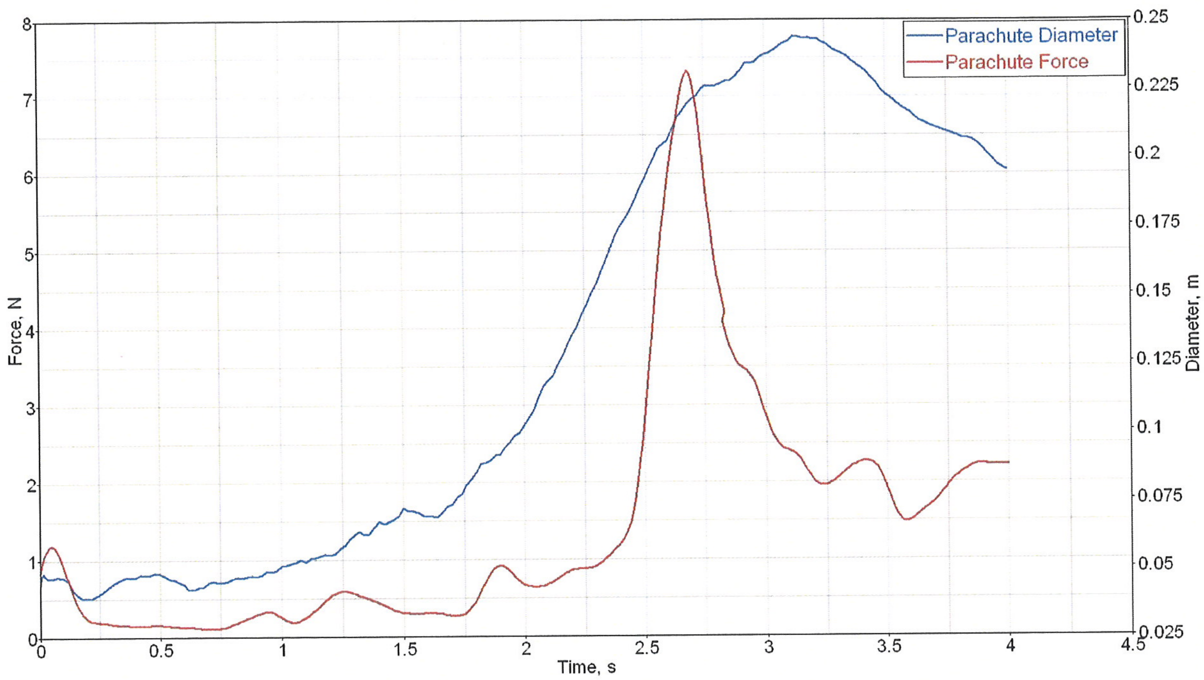

Figure 11. Force and diameter time history data for the 30.5 cm diameter parachute inflation.

during the inflation of the 30.5 cm diameter canopy. It is clear that the crown begins to inflate considerably earlier than observed during the 15.2 cm diameter simulation. This is particularly important as it suggests the simulation correctly accounts for the stiffness scaling effects.

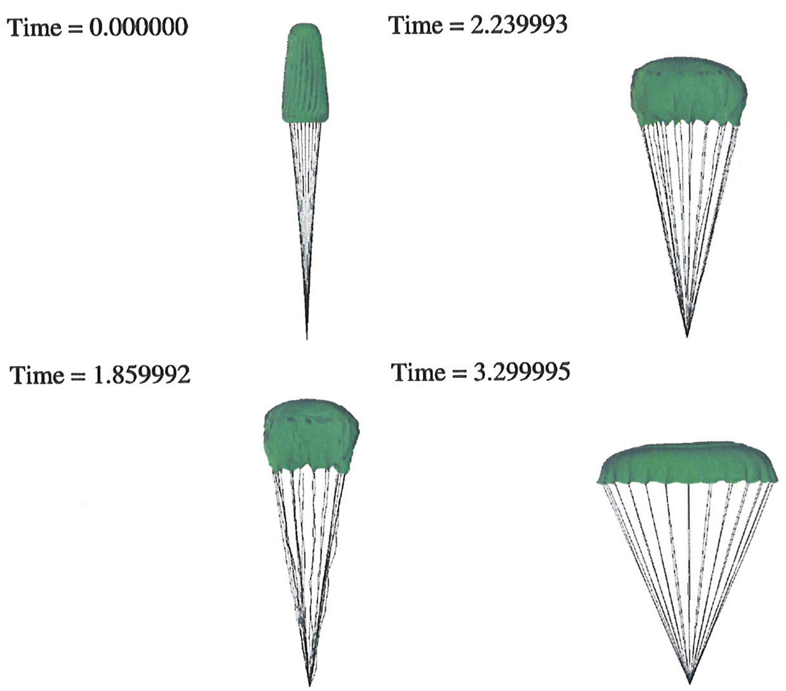

Figure 12. Parachute inflation images, 30.5 cm parachute.

IV. Current Limitations and Future Enhancements

As discussed throughout this paper, computational resources are the prime driver in the quality and accuracy of the results gathered from the simulations. The size of the model is directly related to the quantity of fluid elements located around the mouth of the canopy. Increasing the number of elements used in the vicinity of the canopy mouth more accurately captures flow into the parachute. The simulations discussed within this paper incorporate a fluid domain that is essentially a compromise between model accuracy, and model size/runtime. A consequence of placing a greater number of elements around the mouth of the canopy is that these elements become small, therefore the model timestep falls appropriately, and accordingly the runtime increases.

The simulation of the smaller parachute consisted of 150,000 fluid elements and required 5 days to produce 3 seconds of inflation time.

The replication of this methodology with full-scale parachutes, or with air as the flow media, is believed to be solely reliant upon computational resources. The extension of this technique to incorporate parachute deployment from a deployment bag (D-bag) should also be possible. This will prove to be challenging, as an accurate representation of the parachute geometry, within the D-bag, would be required.

When extending this methodology to full-scale parachutes, another limitation of the parachute simulation technique is encountered. Currently there are no suitable means of including fabric permeability. The density and viscosity of the water make the assumption of zero porosity valid for the water tunnel simulations described within this paper. Although geometric porosity can be assessed with this approach, a reliable method to evaluate fabric permeability is still required. Efforts are ongoing between Irvin and developers to incorporate a suitable technique, current plans include algorithm testing in summer 2005.

An additional limitation of the modeling technique is the lack of coupling between the risers/suspension lines and the fluid. Although this deficiency would not have a substantial affect on the parachutes discussed in this study, as dynamic pressure and number of suspension lines increases this will become more important. It should be noted that methods are available for incorporating line-induced drag in the simulations. However, the computational resources required to evaluate such methods have left the technique unproven.

V. Conclusion

This paper presents a method for conducting FSI simulations using the commercially available transient dynamic finite element analysis program LS-DYNA. The aim of this study was to assess the capability of LS-DYNA to replicate water tunnel inflation tests. It has been shown that a suitable methodology has been developed to replicate the inflation experiments. The results of a comparison with two of the experiments have highlighted the ability of the simulation to accurately replicate parachute performance characteristics during the inflation process. The accuracy of the over-inflation phase and subsequent cyclic breathing is particularly encouraging.

This study has displayed the potential of LS-DYNA to assist the parachute designer in further understanding the interaction of parachute and flow field during the inflation process. The ability to visualize this interaction and identify significant parachute parameters is believed to be a considerable breakthrough.

The cost and time associated with testing a new or modified parachute for structural integrity during inflation is constantly increasing. The outcome of these tests is often a success or failure and very little advance in engineering knowledge is achieved. Consequently, this results in performance prediction difficulties when extending the operational envelope of a parachute. The extension of this simulation methodology to full-size parachutes and a finite mass inflation can result in an improved understanding of inflation forces.

References

[1]Hallquist, J. O., "LS-DYNA Theoretical Manual," Livermore Software Technology Corporation, 1998.

[2]Desabrais, K. J., "Velocity Field Measurements in the Near Wake of a Parachute Canopy," Worcester Polytechnic Institute, 2002.

[3]Tutt, B. A., and Taylor, A. P., "The use of LS-DYNA to Simulate Water Entry Characteristics of Space Vehicles," 8th International LS-DYNA User's Conference, 2004.

[4]Taylor, A. P., "An Investigation of the Apparent Mass of Parachutes under Post Inflation Dynamic Loading through the use of Fluid Structure Interaction Simulations," 17th AIAA Aerodynamic Decelerator Systems Conference, 2003.