DEVELOPMENTS IN THE APPLICATION OF LS-DYNA TO FLUID STRUCTURE INTERACTION (FSI) PROBLEMS IN RECOVERY SYSTEM DESIGN AND ANALYSIS

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INTRODUCTION

Irvin Aerospace Inc. has used the LS-DYNA Explicit Finite Element Analysis (FEA) tool for over five years for that analysis of static and dynamic fabric problems. The references provide many examples of this previous work. Our first application was the analysis of airbag landings for several spacecraft programs, including Reusable Launch Vehicles (RLV's), various Unmanned Air Vehicles (UAV's), Military Airdrop Systems, and planetary exploration systems. These programs are thoroughly covered in the references, including comparisons between simulation and test. Our database of test to simulation comparisons and understanding model details where simulation does or does not apply continues to grow. Additional static and dynamic simulations include various pressurized fabric beams and fabric impact analysis; these are also covered in the references, including another paper presented at this conference.

In the past year, Irvin has begun to explore the FSI capability within LS-DYNA through the explicit Navier-Stokes solver, the ALE solutions technique, and the various coupling options. This capability begins to provide Irvin with a capability, which in our industry is currently only available in Government Labs. The interaction of fluid systems and fabric is both the most basic of recovery system (parachute) problems, and perhaps the most difficult fluid structure interaction problem to solve. By beginning with simple problems, and continuously increasing the complexity, we have created early examples of where this simulation technology may lead. Along the way, we will include model size, solution time, and project to problems that will be solvable in the next two years. Additionally, we will report on required algorithmic enhancements and our suggestions on how to approach these. We will also present examples where we begin to apply the recently added Incompressible Navier-Stokes solver in LS-DYNA 960.

Unfortunately, we will not report on comparisons to test data as, at the time of this writing, these are not available.

DISCUSSION

The term Recovery System, along with Aerodynamic Decelerator Systems, are the broad names that our industry uses to describe systems, that use deployable fabrics to land valuable cargo. These applications run the entire spectrum from spacecraft to military cargo delivery. Human cargos, such as aircraft escape (ejection seat, etc) and Airborne Mass Assault (Paratrooper), both occupy an important part of the spectrum.

Preliminary simulations presented herein include results from the simulation of both ballistic and gliding parachutes. Specific Parachute system problems, such as the impact of dynamic loading of steady state parachutes, as happens during vehicle position change, or rapid release or rapid retraction, are presented. These issues are among the hardest for conventional analysis techniques and, conveniently, are some of the easiest with current FSI tools.

Finally, the multi-material aspects of the LS-DYNA fluid solver are used to explore water entry simulations. These simulations are of great interest, from historical programs such as Apollo, which had no such simulation, to current and future programs, including flight experiment and spacecraft recovery programs.

We close with a discussion of additional capabilities required and desired, including further fluid related outputs and post processing, and additional solver algorithms such as fabric porosity.

Parachute Simulations

Several examples of the analysis of parachutes in flight are presented. At this emergent stage, we concentrate on parachutes that are simple to simulate, the cross type parachute being perhaps that simplest. We believe that through ever increasing complication in our problems, we will continue to expand these simulation techniques to the wide range of potential applications.

The parachute simulations presented in this section were primarily conducted at ¼ symmetry. Total element and node counts were on the order of 250,000. Simulation run times, on modern PC's, were on the order of 2-12 hours, depending on overall simulation time.

Simple Cross Parachute. Figure 1 presents a simple simulation of a parachute type shape in a fluid flow field. The cross parachute type was chosen for its simple geometry, both in terms of mesh construction and final inflated shape.

The parachute is drawn in its constructed shape, and placed in the flow field, which is an extreme simplification as compared to a flaked, folded and packed parachute in a pre-inflation condition. We believe that simulation of the latter is at least several years away and may require free particle techniques before significant results are available.

However, this technique does allow the quasi-steady state simulation of inflated parachute shapes, which provide multiple areas for significant investigation and advancement in this industry. Figure 1 presents a views of the cross parachute during inflation and in its final inflated shape, with the flow field around it. Figure 2 presents a view of the parachute shape alone, with a comparison to a typical inflated shape of a cross parachute in flight. While we did not have the fore sight to exactly replicate the shape of the flight parachute, the shape comparisons are sufficiently close to suggest a successful simulation.

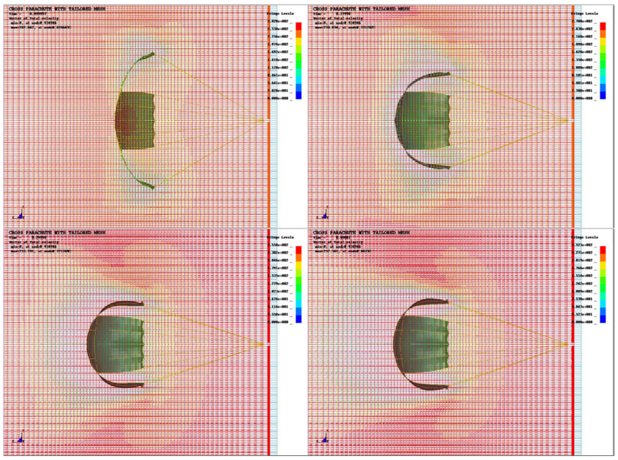


Figure 1. Simple Cross Parachute Simulation

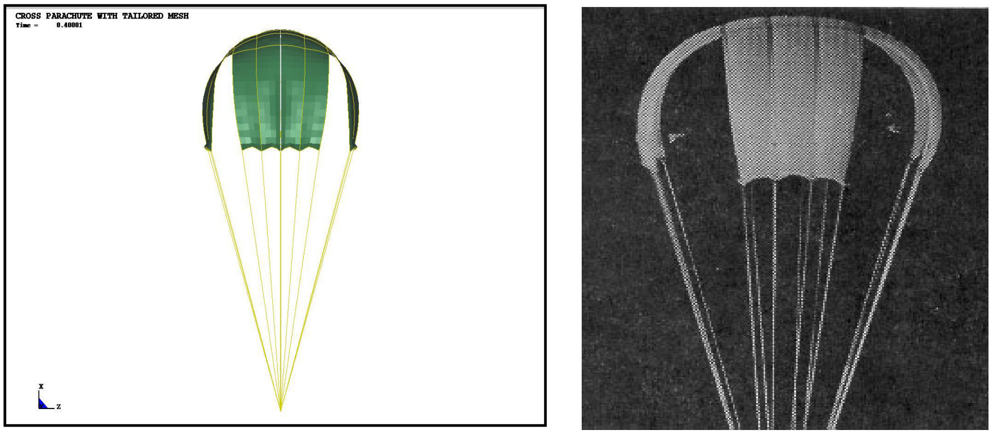


Figure 2. Cross Parachute Simulation and Flight

Test Comparison

Dynamic Loading of Cross Parachute. One of the most interesting, and perhaps most easily investigated areas, of parachute dynamics is the dynamic loading of parachutes following full inflation. Dynamic events such as the retraction of a load – pulling between load and parachute, or the re-orientation of a load – releasing the load, and catching it again at new attachment locations are of great interest to designers. Retraction is often studied and sometimes used as a means to provide soft, low speed landing of a fragile load. By pulling between parachute and load just prior to ground impact, payload velocity can be greatly reduced. Re-orientation is often used to change the payload attitude from initial parachute deployment to final landing condition.

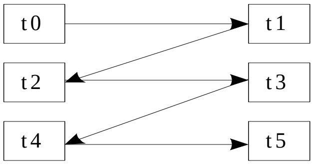
Unfortunately, both of the events can be highly load dependant. They are also both extremely difficult to analyze. Simple mass and spring models ignore significant shape changes that occur within the parachute. Finally, they are extremely difficult to explain to customers, who rightly expect detailed and accurate analysis.

In Figures 3 and 4, we have completed some simplified simulations of this dynamic event. In Figure 3, we take the same cross parachute presented above and, following the parachute inflation and damping phase, provide a simple representation of a retraction. This is accomplished by providing the node at the confluence of the suspension lines with a prescribed motion, effectively pulling on the suspension lines, similar to a retraction event. Figure 3 provides several images of the flow field during this event and, to a trained aerodynamicist, the resulting shapes and field velocities are quite attractive.

Similarly, in Figure 4, we provide a simple re-orientation event simulation by first releasing and then pulling on the confluence node. This is done again through a prescribed motion on the node. Again, the flow field images are quite exciting, with a ‘classic’ wake re-contact being simulated.

In Figure 5 we present comparisons of suspension line forces for these two events.

Figures 3 and 4 should be read as:



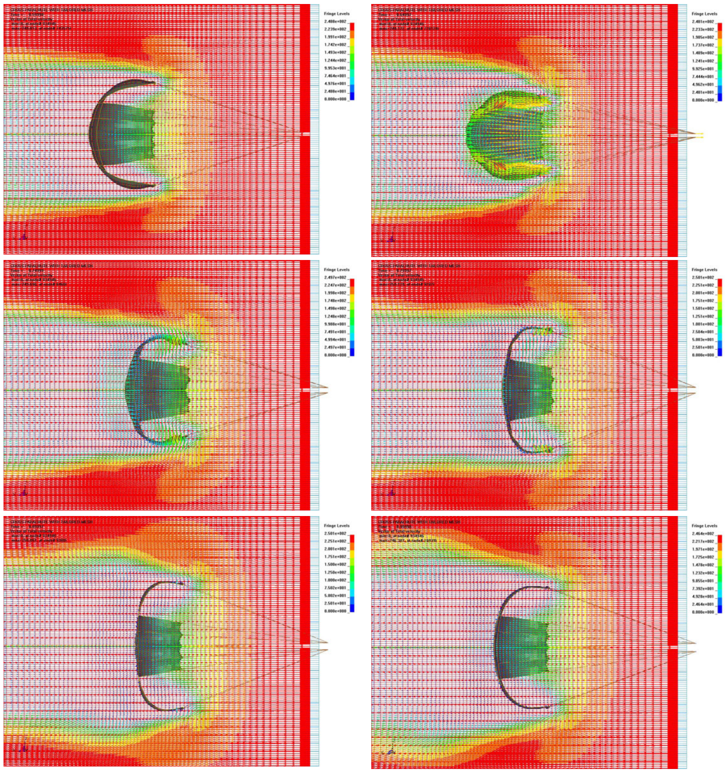


Figure 3. Cross Parachute Under Retraction Load

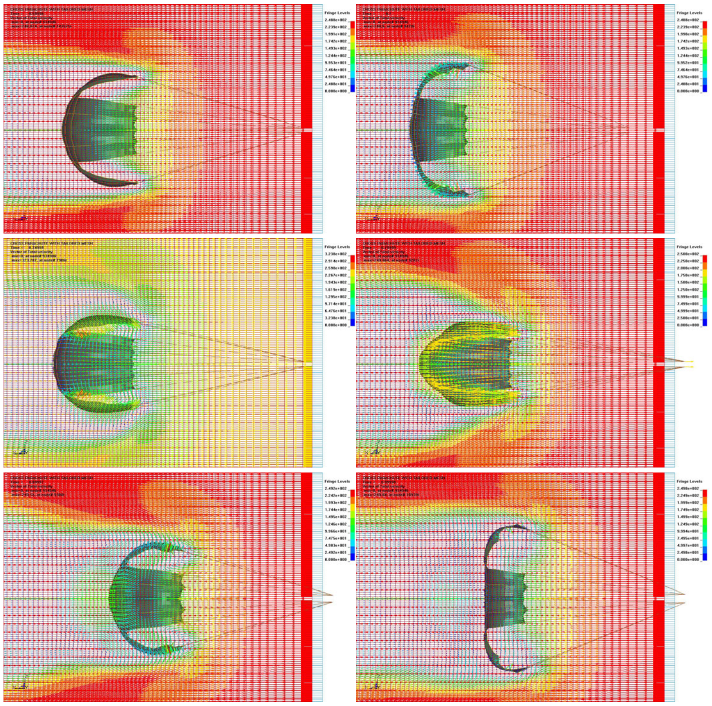


Figure 4. Cross Parachute Under Release then Retraction Load

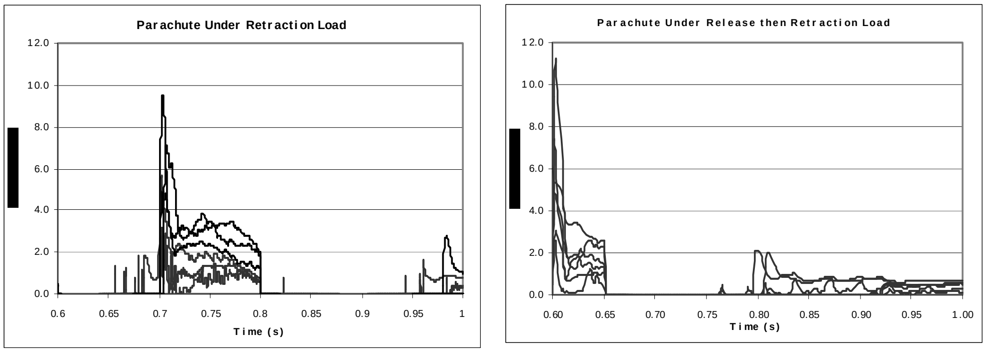


Figure 5. Suspension Line Force Comparison

Advanced Cross Parachute. An advanced version of the cross parachute involves the connection of the tips of the cross arms to form a skirt region similar to a conventional round parachute. This approach provides improved inflation control of the parachute and retains or improves the stability of the conventional cross. Figure 6 presents an image of such a parachute – currently being developed by the U.S. Army as a modern paratrooper parachute – in flight test.

Figure 7 presents an early attempt at a simulation of this parachute in flight. In our first attempts, the arms of the parachute were folded at 90 degrees to the parachute crown with only the bottom nodes joined between arms. However, due to the fluid coupling, this configuration resulted in the nodes along the arm acting as if glued together. Figure 8 shows this initial mesh and Figure 8a shows a consequent solution where the arm was bent 45 degrees and then 90 degrees.. This initial mesh created the results in Figure 7. While these results are representative, we still observe a residue of the mid-arm 90 degree bend, probably associated with the fluid coupling in a cross flow direction. In future attempts, we will use multiple slighter angles or continuous curvature to eliminate this feature.

Figure 6. XT-11A Parachute Photo

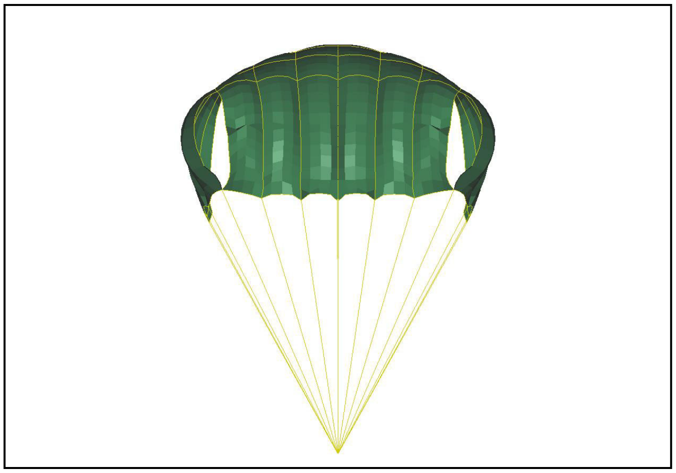


Figure 7. Simulation Result of Advanced Cross Parachute

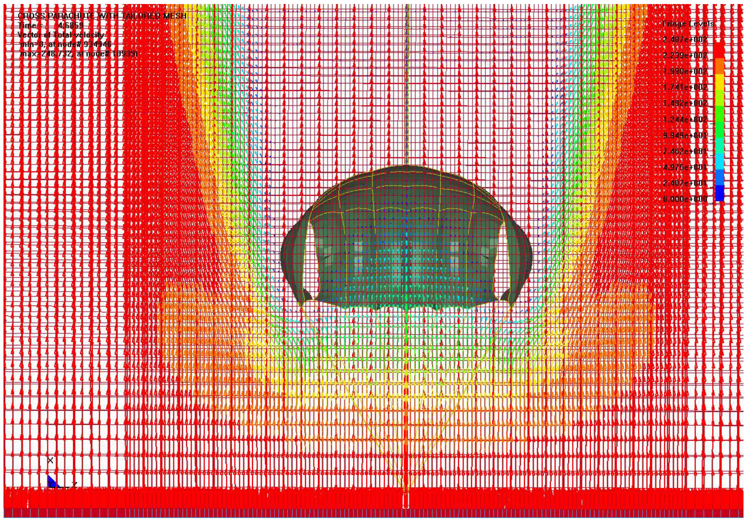


Figure 8. Flow Field Around Advanced Cross Parachute

Round Parachutes. The large majority of parachutes for military and recovery applications are constructed in a round shape for ballistic flight. Our early attempts at simulating these were based on military cargo parachutes. These are constructed from a flat circular pattern that provides excessive slack at the base, or skirt, of the parachute. In our attempts to simulate these configurations, the excessive slack causes fabric-to-fabric contact, with the potential for fluid mesh being trapped between the fabric layers. In our experience, there are no current algorithms capable of handling this scenario.

In future simulations, we will concentrate on highly shaped, round parachutes that eliminate the fabric-to-fabric contact, as these are the business of modern constructions versus WWII class technology.

Gliding Parawing Parachute. Another class of parachute of recent interest is the twin keel parawing. This classic parachute, researched in the 1960s, was recently reviewed as a low-cost method to provide gliding cargo flight for controlled precision delivery. As a portion of this study, we investigated our ability to simulate this parachute in gliding flight, with the expectation that future simulations would investigate performance enhancements.

The parawing is a flat constructed parachute with various length lines to provide a flying shape. Figure 9 presents our initial parachute mesh. Suspension lines were modeled as non-linear, discrete springs, with virtually no compressive stiffness. This allowed the use of the discrete element initial length option to contract/extend suspension line lengths from the linear geometry presented above to the desired flying geometry for which the device was built. This approach greatly reduced the model construction time as opposed to drawing and meshing curved surfaces that represent the combination of parachute surface and suspension line geometry.

Figure 10 presents a comparison of simulation results and flight test geometry. The geometric shape is, again, compelling. The gap in the middle of the parachute is anomalous and under investigation. Repeated checks have confirmed that the proper symmetry constraint is applied to these and all nodes; however, a gap exists.

As mentioned above, the purpose of the simulation was to investigate performance improvement (lift to drag ratio) through local stiffening of the parachute. During our investigation, we also became aware that the model could provide additional insight, such as parachute line loads, and particularly line loads during control surface deflections that are difficult to measure. Another potential area of investigation is the re-shaping of the wing through suspension line length changes.

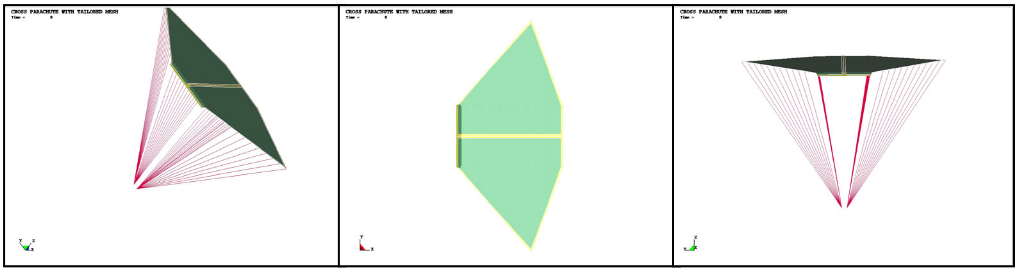


Figure 9. Parawing Initial Geometry/Mesh

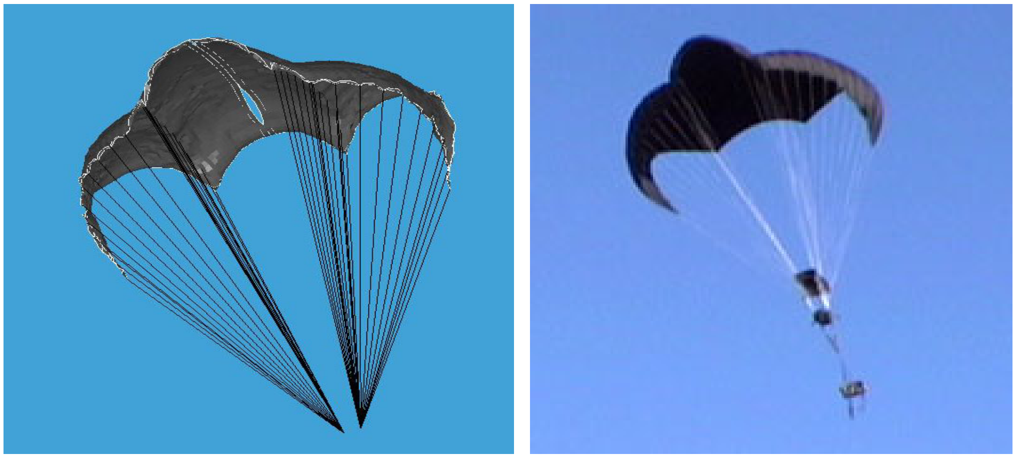


Figure 10. Comparison Simulation and Flight Test

Water Entry Simulations

The multi-material capability in the ALE solver provides an excellent tool for the analysis problems, such as the water landing of recovered vehicles. Taking the system approach to recovery system design, Irvin recognizes that the trade between water impact velocity and parachute size is extremely important in these landing cases. The faster the allowable water impact, the smaller the required parachutes. For certain vehicle shapes, the trade study becomes higher order than this. For instance, the Shuttle Solid Rocket Booster (SRB) recovery system is sized to minimize the slap-down landing of the booster following the initial water entry and rebound. A relatively high water impact velocity serves to minimize the slap-down following initial impact.

Figure 11 presents images from a water entry simulation of a spacecraft recovery concept. This concept was explored during the mid-1990s as a technique to return valuable engine parts from an otherwise expendable launch vehicle. Figure 12 presents several images from demonstration testing performed on this vehicle concept. We are currently working to compare simulation and test data.

Figure 11. Simulated Spacecraft Water Landing Testing

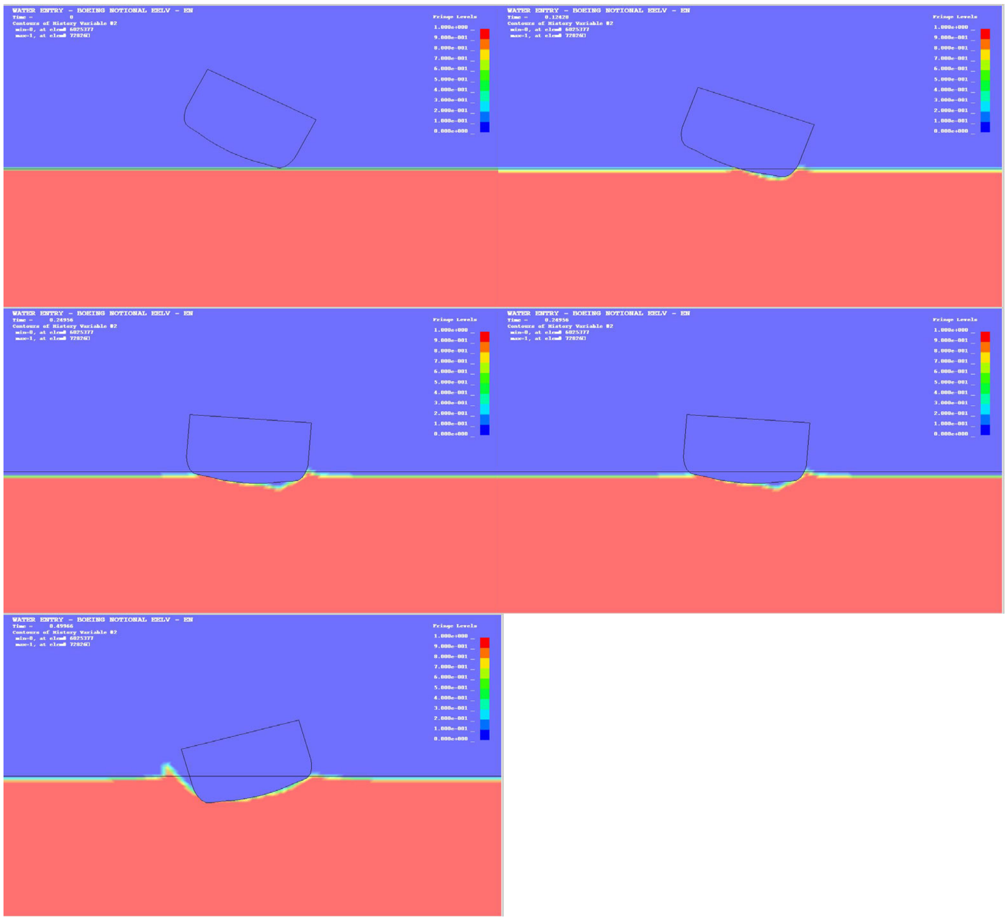


Figure 12. Spacecraft Water Landing Simulation

Vehicle Wake Simulations

Another area of critical importance to improved recovery system analysis is the detailed understanding of vehicle trailing wake an its effect on parachute performance. In many instances, the wake of a vehicle can reduce parachute drag, through reduced fluid dynamic pressure, by 25% or more. Many of our customers do not possess tools for such analysis, and only discover a requirement for such data following the completion of all wind tunnel testing.

Figures 13 and 14 present simple examples of these simulations, and how they would provide significant engineering data. In the first, we again have a cross parachute that is closely trailing a cylindrical fore body. At moderate transonic Mach, we are concerned about the vehicle wake effect on the parachute. Preliminary simulations indicate that this is rather significant and we continue to investigate.

In Figure 14, we present two views; the first is a simple fore body followed by a conceptual parachute design. The concept of this supersonic parachute is to remain behind the vehicle generated shock wave while avoiding the low energy flow directly behind the fore body. The second portion of Figure 14 illustrates that this is accomplished. The parachute segments are behind the primary shock waves but avoid the deep core wake directly behind the vehicle.

Another example of desired wake simulation is the ability to quickly assess the velocity deficit behind an aircraft configuration. This parameter is critical to the design of spin stall recovery parachutes and the required data is rarely available from customers. Additionally, they are rarely able to provide CFD predictions, particularly in the commercial aviation business. We are currently working to assess the viability of the LS-DYNA fluid solvers to provide this information.

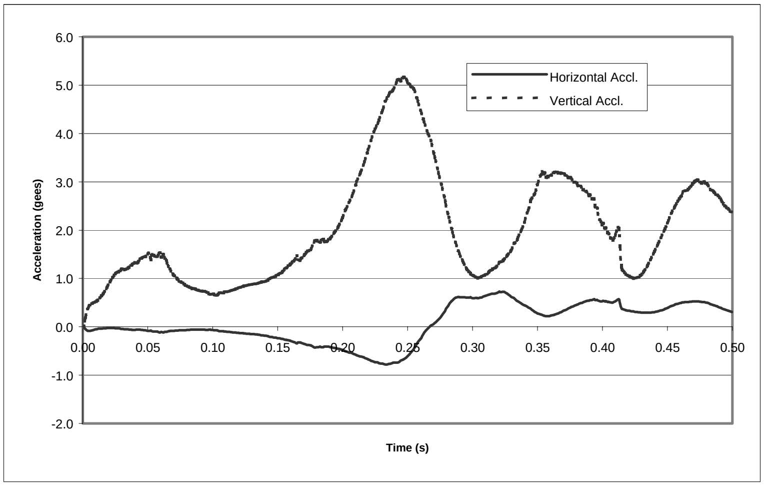


Figure 13. Vehicle Accelerations During Water Landing

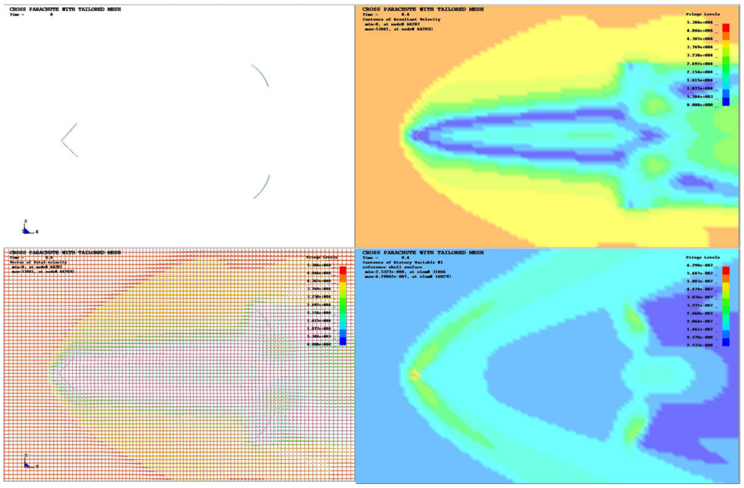


Figure 14. Multi-body Wake Flow Interaction

SUMMARY AND CONCLUSIONS

As presented in the references, we have provided multiple papers regarding the performance and wide application of LS-DYNA the structural tool. Herein, we present early applications using the fluid solver(s) and coupling fluids and structures. Many more will come in the next few years.

The tools provided in the current releases offer several levels of fluid application. The first is what we often call “poor man’s CFD”. That is not to diminish the tool, but rather to point out that for enterprises that desire a basic CFD capability and do not wish to predict drag on long endurance aircraft, this provides a significant capability. That is particularly true if you already own the package.

More impressive is the simple coupling between fluid and structure, and the multiplicity of simulations that this affords. In the parachute area, we are currently approaching a capability that the U.S. Army has spent years to develop. We are working cooperatively with the Army, looking for ways to validate and enhance the commercial tool – LS-DYNA.

This however, leads to the vision statement. We are working to establish test data and validation cases for certain types of simulations and suggest that progress in this area is far too slow. Until basic levels of validation are available, the use of these tools to support major design decisions will be uncomfortable at best.

Additionally, available post-processors from all vendors with which we are familiar need to recognize the fluid aspects of this tool. Plots of dynamic pressure, pressure coefficient, and even integration of these into body forces and moments are sorely needed. We hope for these advancements soon.

We are encouraged by the ever expanding capabilities and look forward to further use, further applications and further capabilities with LS-DYNA.

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