ON THE APPLICATION OF EXPLICIT FINITE ELEMENT ANALYSIS AND COUPLED FLUID/STRUCTURE SIMULATIONS AS THEY APPLY TO ESCAPE AND RECOVERY SYSTEMS

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INTRODUCTION

In recent years, the significant development of commercially available Explicit Finite Element simulations and Coupled Fluid/Structure simulations – often called Fluid Structure Interaction (FSI) – have begun to penetrate the aerospace industry and, to some extent, the realm of recovery systems, parachutes, and related equipment. We are largely the beneficiaries of the automotive industry in terms of simulation capability. The significant advances in modern PCs and PC workstations have also made entry level and (recently) highly detailed engineering solutions affordable as never before.

Irvin Aerospace Inc (Irvin) has played a leading role in the development and application of these tools as they relate to recovery systems and, more recently, escape and survival systems. This paper will present an overview of various simulations that have been completed with these tools and provide some insight into the level of engineering analysis and simulation validation currently ongoing – at Irvin and others.

DISCUSSION

Some of the recovery system simulations reviewed herein include the following:

1. Doors and Covers
   - Thruster door interaction
   - Thruster, door, fluid interaction
2. Airbags for Landing Impact
   - Includes roll-over mitigation
   - Secondary impacts
3. Water Entry
   - Generic spacecraft
   - With airbags for attenuation
4. Parachutes and Other Decelerators
   - Sub-sonic parachutes
     - De-spin of a payload
     - Parachute control applications
     - Parachute performance
     - Post-inflation dynamic loading of parachutes
     - Canopy stability
   - Supersonic parachutes
     - 2D ribbon parachutes
     - 3D ribbon parachute simulations
     - Other higher mach parachutes
   - Ballutes and other high Mach stabilizers/ decelerators

We will close with a discussion of where we believe this technology is headed and what significant simulations may be possible in the next two to five years.

RECOVERY SYSTEM DOOR DEPLOYMENT

Perhaps one of the most important and least analyzed areas of recovery system design is the initial deployment of a door or cover. Often this is completed with thrusters or other release devices and can be critical to the proper operation of the recovery system.

Two areas of analysis are particularly interesting: the transfer of energy from thruster to door and the initial path of the door through the flow field near a vehicle. In both cases, tests are relatively expensive and test support through analysis is increasingly valuable. In the latter (flow field) case, analysis may also provide the only reasonable interpolation/extrapolation to other flight conditions that may be very expensive to test.

DOORS AND THRUSTERS

The simplest example of a door/thruster simulation involves the modeling of the thruster as a non-linear spring, such as force displacement data, or a force time history at the thruster impact location. The significant advantage of this approach, when combined with a flexible door model or with even higher fidelity, a metallic model that considers plastic deformation, is the immediate insight into the losses in imparted energy due to door deformation.

Figure 1 provides an example of a previously flat door, following the simulation of a thruster event. In Figure 2, we compare the basic thruster energy imparted to the door with 1) the door considered a rigid body and 2) the door modeled including elastic and plastic deformation. Clearly, the reduction in imparted energy is extremely significant.

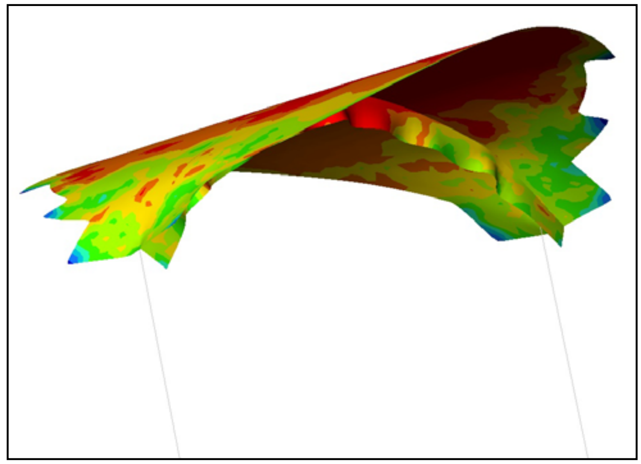

Figure 1. Door Ejection Result – Deformed Shape Due to Thrusters

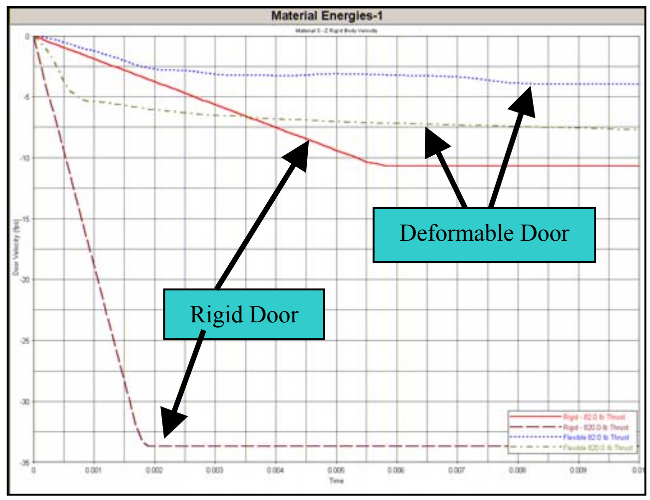

Figure 2. Door Ejection Result – Door Velocity, Rigid Versus Deformable

Unfortunately, while we have several examples of deformation results, simulation versus testing, we have not had time to seek customer permission to use these images. This is unfortunate as the simulation results, in several cases, match nearly identically to the dynamic test results.

DOORS AND FLOW FIELDS

Another interesting investigation area involves the incorporation of door/thruster models, as discussed above, into a simulation of the fluid flow around the vehicle and separating door. This allows the full simulation of the door separation event, and we know that some door events, particularly in the base region of a large vehicle, interaction with the flow field can be particularly challenging.

Figure 3 provides views of such a simulation for the separation of a forward door from a generic missile configuration. In general, results are reasonable and the door separates cleanly. However, the flow field near the missile body indicates a rather large boundary layer. We expect that further fluid mesh refinement would improve this aspect of the simulation. We believe that this simulation results in a slightly conservative prediction, as a closer energized flow would aid the door/vehicle separation. Additionally, we feel that flow in the base region of a vehicle, where door separation is most critical, would be largely unaffected by a potentially thick boundary layer in the fluid simulation.

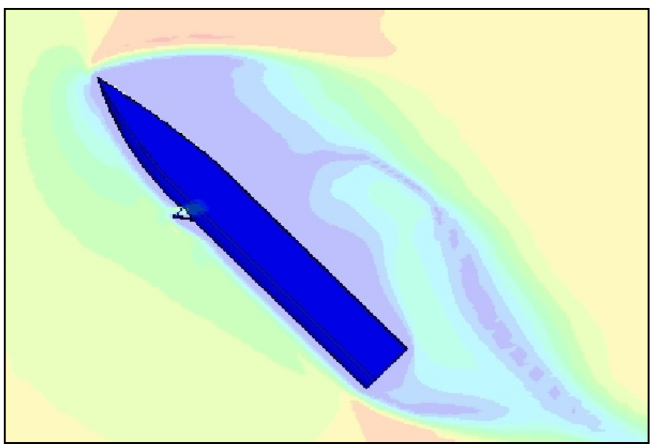

Figure 3. Door Separation in Flow Field

AIRBAGS AND LANDING IMPACT

Irvin has been using the LS-DYNA tool for simulation of vehicle landing airbags for over six years. References 1 through 9 provide previous papers published by the authors and other Irvin personnel in this area. These papers include significant work in the comparison and validation of simulation and test.

Lessons learned and incorporated into every program include the requirement to model airbag details, such as attachment structure, and the importance of airbag vent location and potential blockage. Our moderately sophisticated airbag models include the physical location of the vent and computations to account for blockage between the airbag vent and the ground plane or vehicle structure. Further sophistication includes effects such as soil compliance/deformation.

Figure 4 provides a view of an airbag simulation for landing a generic spacecraft. Figure 5 presents the results of soil deformation following the landing of a vehicle with deformable skids.

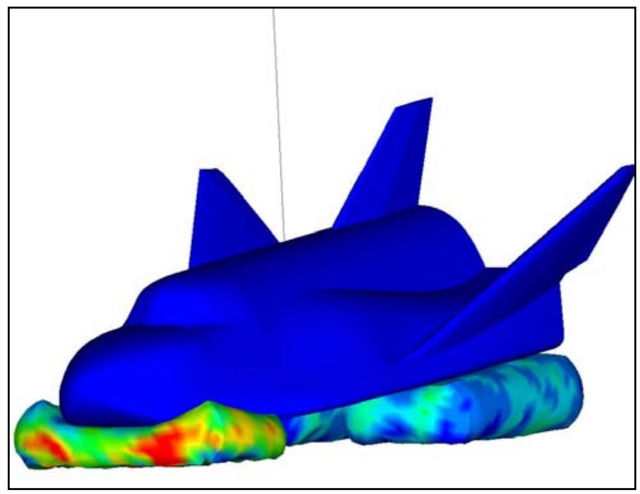

Figure 4. Generic Spacecraft with Ground Impact Attenuation Airbag System

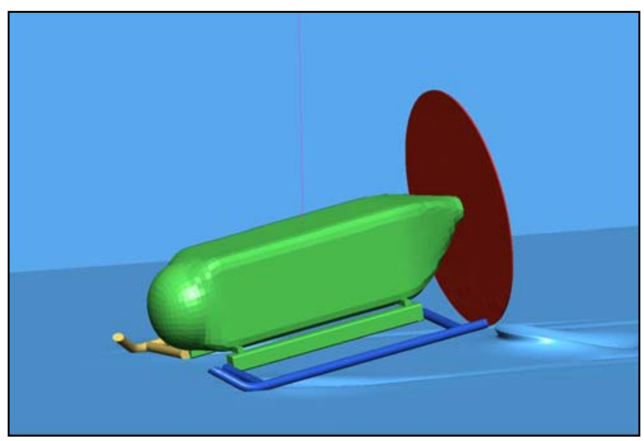

Figure 5. Landing of Vehicle into Compliant Soil

WATER ENTRY

Another significant aspect in the assessment of recovery and escape systems is the performance of such vehicles during water landing. Irvin has invested significant time and energy into the completion and validation of water landing simulations using the LS-DYNA Arbitrary Lagrange Eulerian (ALE) fluid simulation. This tool allows for the simulation of multiple fluids, such as an air/water interface, and the coupling of the fluid simulation with a structural simulation, such as a vehicle.

Irvin has recently completed a series of validation simulations – a scaled Apollo capsule – that compare favorably with historical (Apollo program) test data. These results will be the subject of a future paper(s).

Figure 6 provides an example of a water entry simulation for a generic spacecraft vehicle during water entry. The simulation graphic presents fluid density, with red representing high density (water) and blue, low density (air). In this simulation, the entry vehicle is completely rigid, structural deformations were not considered significant for this analysis.

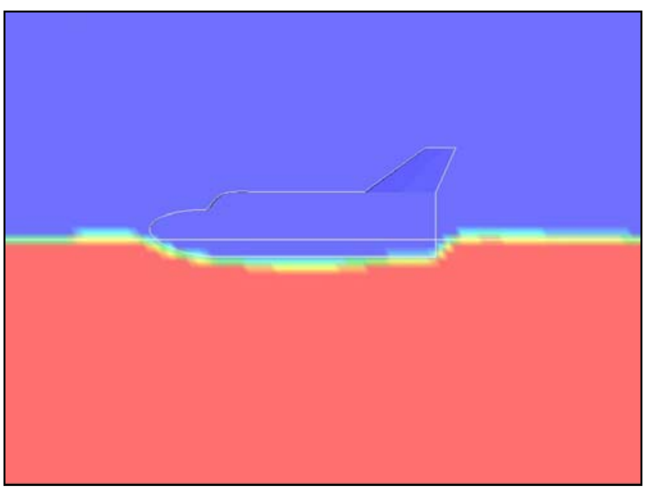

Figure 6. Nominal Landing of a Generic Spacecraft into Water

In Figure 7, we present the results of another generic shape during water landing. The contours remain the same. In this case, the highly deformable airbags are used for reducing the water impact acceleration. Our first desire was to assess the capability to complete such simulations, both in terms of model creation and execution time; these were both entirely acceptable. An additional result was the preliminary indication that land landing devices (such as airbags) provide similar impact attenuation for water landing. Figure 8 provides a qualitative comparison of water landing results, with and without airbags. These results are indicative of the marked performance improvement observed when airbags are inflated prior to water landings.

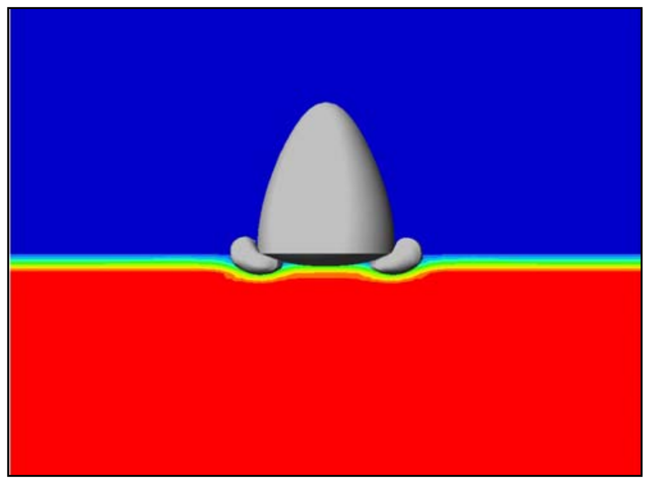

Figure 7. Generic Spacecraft Water Landing With Inflated Airbags

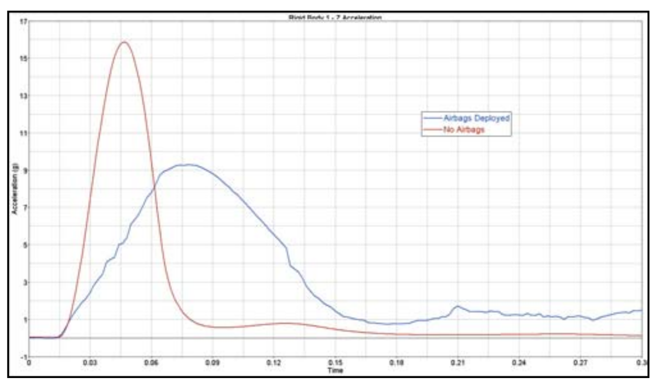

Figure 8. Vehicle Vertical Acceleration of Similar Generic Spacecrafts with and without Airbag Attenuation

PARACHUTES AND OTHER DECELERATORS

Our research into the application of FSI to parachutes and other decelerators is both diverse and rather new (past two years). In the parachute arena, our investigations are almost entirely related to the post inflation dynamics of parachutes. Areas of investigation include:

1. The ability of parachutes to arrest the spin of various bodies.
2. Glide performance of various parachute designs, and their response to control inputs.
3. Stability and drag optimization for parachute designs.
4. Response of parachutes to post-inflation dynamic loading.
5. Performance of Ribbon Class parachutes at high Supersonic Mach.
6. Performance of other decelerators such as ballutes.
7. General validation of these simulations, providing confidence in the results obtained.

We will provide examples of recent research in most of these important areas of investigation.

DE-SPIN

The de-spin of certain payloads, such as missile components, is often a design consideration. While design experience with other programs indicates that a cross parachute is an effective de-spin device, a rigorous analytic proof is rather difficult and testing is rather expensive. Therefore, a simulation of such an event is useful. Figure 9 provides views from one such simulation. In this case, the generic fore body and parachute are both spinning at the initial spin rate. The parachute is initially not included in the fluid coupling definition, allowing the vehicle wake to establish at the parachute location. After the wake develops, the parachute is introduced to the fluid coupling and completes a quasi-inflation. The results in Figure 10, spin rate versus time, indicate that the parachute has significant de-spin control and arrests the spinning payload in fractions of a second.

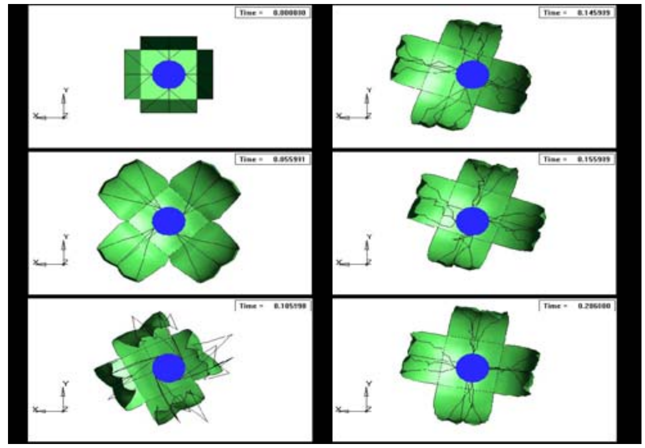

Figure 9. Bottom View of Cross Parachute De-Spin Capability

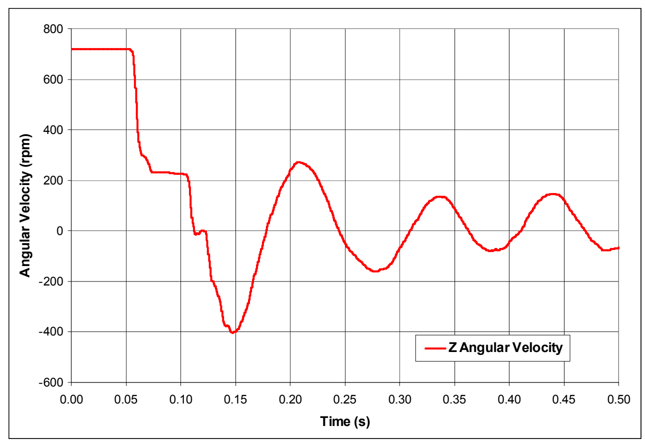

Figure 10. Z Axis Rotational Velocity – Shows Arrest and Counter Rotation of the Fore Body

PARACHUTE STABILITY

One of the most interesting areas for FSI investigation of parachutes is the balance and trade between parachute stability and parachute drag performance. Often, the introduction of slots or other vents will improve parachute stability at some sacrifice to parachute drag performance. Unfortunately, today, this trade is left largely to past history and trial and error. The test costs of the trial and error approach often eliminate the opportunity for full optimization.

Clearly, a computed analysis approach would provide significant insight and design guidance. Additionally, the same trade study applies for parachutes in a cluster; however, we suspect that the optimization point is entirely different for single and clustered parachutes. A parachute cluster is a significant issue for systems such as Crew Escape Modules.

This very important research area is one of the newest in our internal investigations. The requirements for fluid mesh size in the region of a slot or vent, and the requirement for full symmetry models to capture the full interaction between parachute and shed vortices, dictates very large models. We are currently working with models of approximately one million nodes/elements but suspect that significant results will require 10 million element class models. These will be possible shortly through with further computer advances and proposed corporate investment in additional computer resources. Additionally, our corporate and government research partners may provide opportunities for additional computer resources.

At this point, our principle investigation is into the FSI modeling of parachute shapes/designs that are expected to be unstable. For instance, flat circular, and most solid parachute construction techniques have a level of oscillation. Our approach to date has been to complete simulations of parachutes that we expect to be unstable. This first allows definition and review of the fluid boundary conditions for these simulations and, most importantly, the volume of the fluid mesh versus the size of the inflated parachute.

Having completed simulations of unstable parachutes, we will begin to apply standard techniques, such as slots and vents, to further stabilize the parachute (in the simulation).

In Figure 11, we present an example of an FSI simulation of a parachute that is expected to be relatively unstable. The velocity vector plots of the flow field, we believe, provide an indication of vortex shedding interacting with the parachute structure. Additionally, the motion of the parachute indicates a level of oscillation. Clearly, these are very early results in a simulation that could provide significant input to future design efforts.

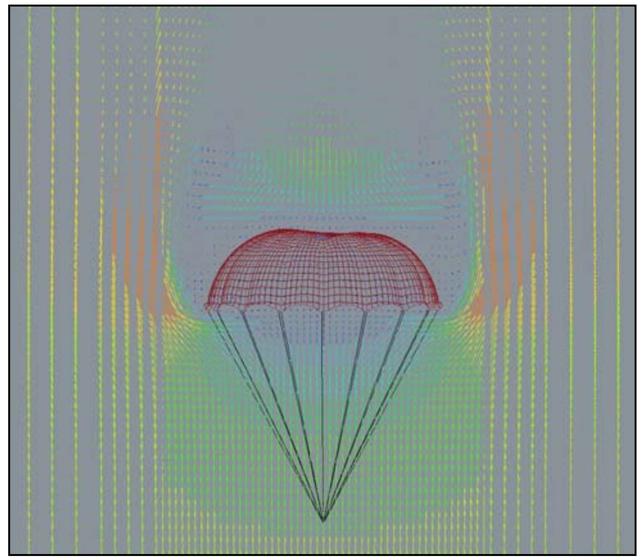

Figure 11. Beginnings of Non-Symmetric Loading

POST INFLATION DYNAMIC LOADING

Post inflation dynamic loading of parachutes has been one of our earliest areas of investigation. The model size requirements of these simulations are not as complex as those involving flow through slots and other performance related assessments. The motivation for this investigation is largely related to the re-orientation of a vehicle following parachute inflation and prior to landing. The recovery of large spacecraft is a typical example.

We know from more traditional multi-body trajectory class simulations and from testing that typical simulations of the re-orientation event over-predict loads by about 15%. Additionally, we know that if these maneuvers are not properly designed, the re-orientation loads can be higher than initial parachute inflation loads, making careful consideration critical.

As a result, we have begun an investigation of post-inflation dynamic loading of parachutes. In these early investigations, we are considering a retraction event, which is a simplification of the more complex re-orientation event. Re-orientation can be described as a release of the parachute followed by the retraction of the parachute.

Figure 12 provides an example of a simple re-orientation simulation, using a point mass representation of the parachute. These results indicate loads approximately 15% higher than the test results. In Figure 13, we present fluid and structural results from a retraction event using a ¼ symmetry cross parachute. In Figure 14, we present a comparison of trajectory class simulations versus the FSI results. These results are presented for several parachute scale sizes. In this analysis we are working to identify the drag surface related forces versus the inertial forces related to the volume of trapped air in the parachute.

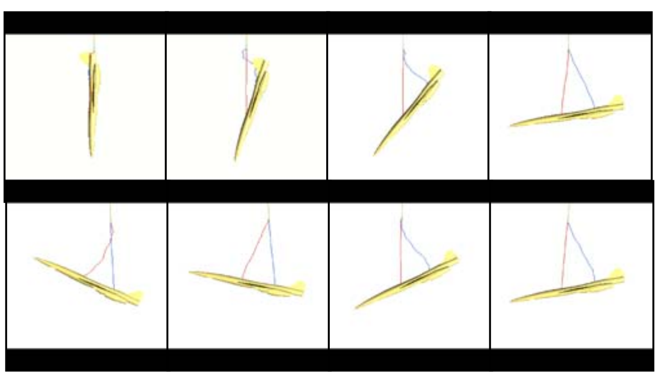

Figure 12. Simple Re-Orientation Simulation

In Figure 15, we modify the trajectory results by adjusting the mass of the parachute (due to the enclosed air); this result provides a high fidelity match across the entire scale range. Thus, we can conclude that the apparent mass, or mass of the air trapped in the parachute, was the difference between the FSI simulation and testing versus the simpler multi-body or trajectory simulations.

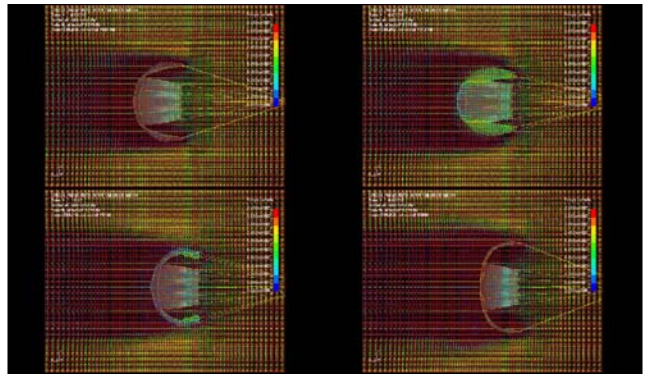

Figure 13. Retraction of Parachute in Flow Field

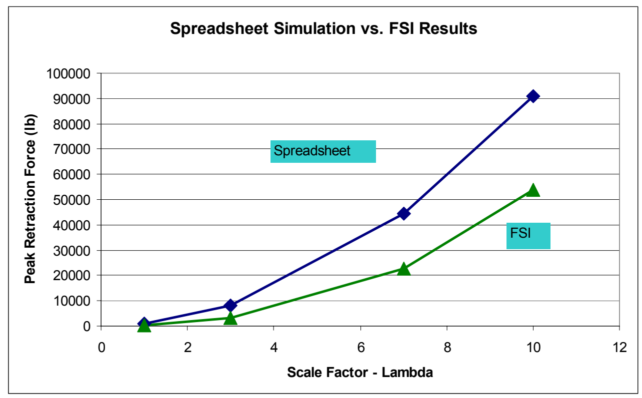

Figure 14. Multi-body and FSI Results, Classical Treatment of Air Included in the Parachute

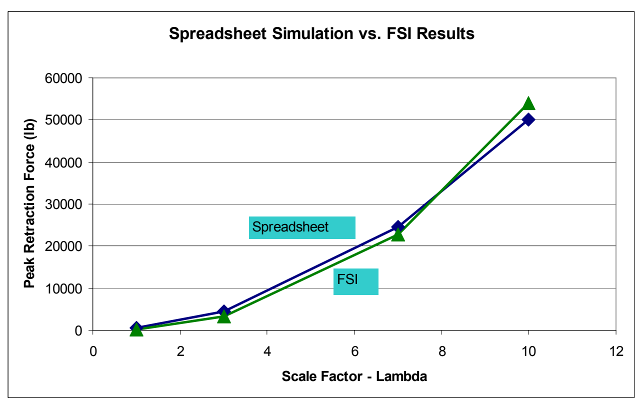

Figure 15. Same Multi-body Simulation – Parachute Air Mass Adjusted to Match FSI Result – Same Volume Formula Used for all Scale Factors

These simulation and techniques, the basic mathematical approach, and the FSI results, are discussed thoroughly in Reference 10.

RIBBON PARACHUTES AT SUPERSONIC MACH

Another extremely interesting area of investigation is the flight stability of drogue class parachutes such as conical ribbon and hemisflo parachutes at higher Mach number. There are indications in the historical parachute database that this class of parachute fails to perform correctly at Mach numbers above approximately three. Actually, the indication is that the parachutes rapidly experience structural failure due to dynamic instability related to shock interaction. Additionally, the historical database is 1960s era, not completely understood and developed prior to any modern (low elongation) fibers such as Kevlar.

Thus, a simulation tool that provides insight into these flight stability phenomena would be of interest for several reasons; 1) to provide additional guidance into the flight performance of potential designs, 2) to provide insight into the effects of modern materials in the older test results, and 3) to be used as design guidance in the development of future, higher Mach parachute designs.

In this area, we are again somewhat limited by practical model size. However, two-dimensional models have provided a wide range of early developmental simulation and we are rapidly approaching the realm of (axis-symmetric) 3D simulations. We believe that these will provide initial insight into the inflation instability issue, as this is largely a relationship between parachute inlet normal shock position and the flying shape of the parachute.

The figures and results presented in this paper are first-generation simulation results. These are instructive and illustrate the basic results and capability. We are currently completing a second generation of these models as a portion of our internal research; however, these results are not available at the time of this writing.

Figure 16 provides a flow field velocity vector plot from a 2D simulation of a ribbon parachute. In this simulation, the ribbons are rigid. We completed this result to check the fidelity of the flow field around the ribbons. Clearly, the vortex and reverse flow regions behind the ribbons provide a preliminary validation of the fluid and structural mechanisms for this model. In other words, the flow through the parachute and around the ribbons looks correct.

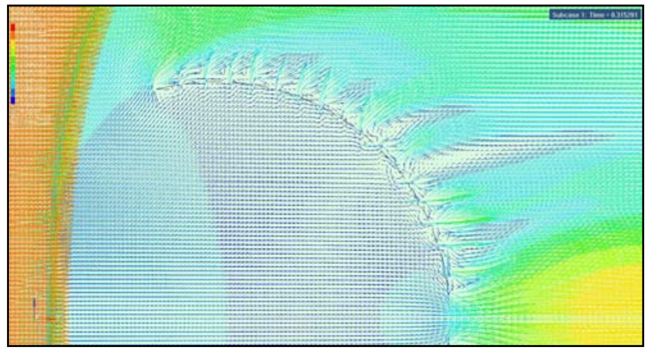

Figure 16. 2D Flow Field through Rigid Representation of a Ribbon Parachute

Figure 17, provides views from a similar model, however, here the parachute structure is fully flexible. In this simulation, the parachute porosity (gaps between ribbons) is too large, and the parachute does not reach a flying shape. This result is consistent with one of the known unstable flight modes for supersonic ribbon parachutes.

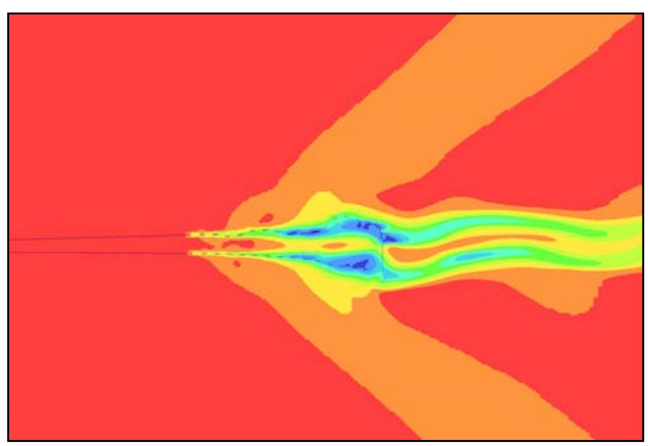

Figure 17. A Ribbon Parachute with Excessive Geometric Porosity

In Figure 18, the parachute porosity is corrected and the parachute reaches an inflated and stable flying shape.

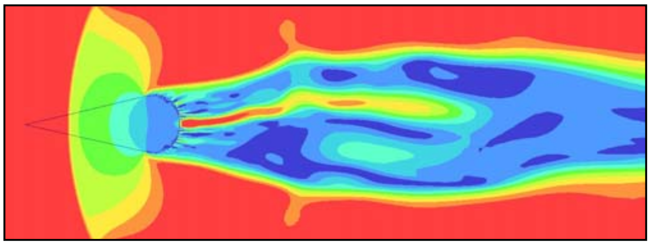

Figure 18. Fluid Flow Through an Inflated Ribbon Parachute

These preliminary results have encouraged Irvin to proceed with a second generation of 2D models, and shortly an axis-symmetric 3D model. We hope to present results from these simulations in the coming year.

BALLUTES

Another class of decelerators is the Ballute (balloon parachute). In this discussion, we use this term to describe a large range of inflatable decelerators. These devices might be either attached or trailing a vehicle (as on a riser) and can be either pressurized by a gas supply or from ram-air inlets built into the decelerator structure.

These devices are of particular interest for higher Mach deceleration and stabilization, as well as for rapid deployment. Attached ballutes provide very fast stabilization or drag augmentation due to the rather short deployment train. They also function at higher Mach than classic parachute designs

To our knowledge, Irvin is the only commercial manufacturer researching the simulation of such devices. While our efforts are rather preliminary, they indicate the ability of FSI tools to provide basic engineering results. Among these are the resulting flying shape and stress patterns of such as device. We believe that future simulations will also serve to assist in prediction of overall performance, such as drag enhancement or resulting stability of a fore body/Ballute combination. In the case of trailing devices, the assessment of Ballute performance, in the wake flow field of the fore body, will be of significant interest.

Figure 19 provides some preliminary simulation results for an attached Ballute and a generic fore body. The fluid flow represents a super-sonic Mach.

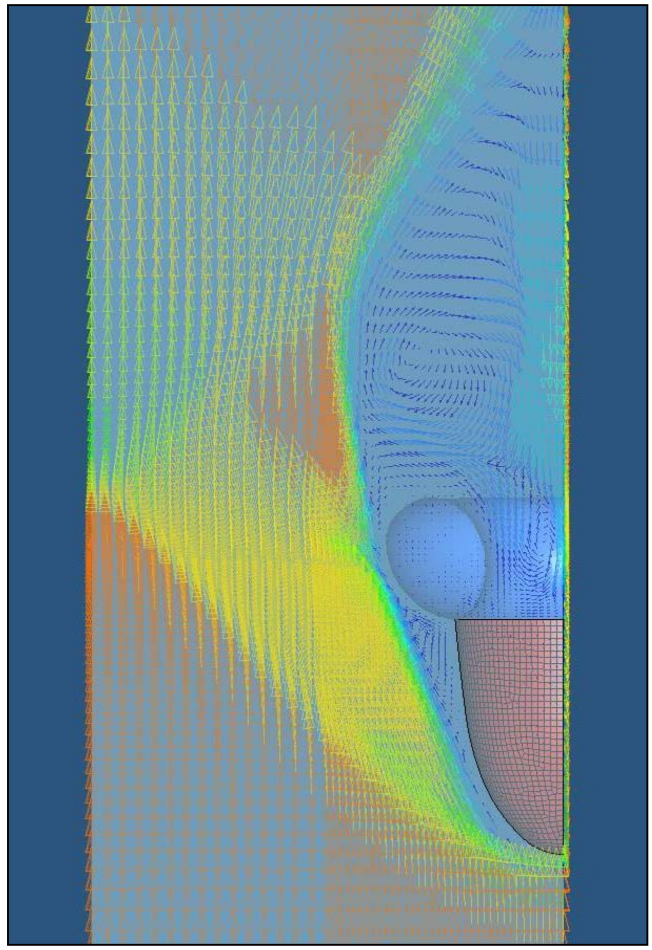

Figure 19. Flow around a Generic Fore Body and Attached Ballute at Supersonic Mach

CONCLUSIONS

Herein, we have presented a wide range of simulations that apply directly to recovery and escape systems. In general, we believe that these are unique in our industry, particularly at the commercial level.

Of these simulations, some have become routine and well understood, such as airbags and doors. Others are now emerging as serious engineering tools, such as the water landing simulation. Still others, such as the performance aspects of parachutes, are developmental but will begin to directly influence design in the next few years.

Beyond these there remains a series of problems that are well suited to computer simulation. As a leader in this technology field, we look forward to years of technological advancement, serving to further increase the understanding of all aspects of our small but important industry.

We continue to work in detail with software providers to create all the tools required for our expanding simulation desires. This includes special algorithms and capabilities in the basic solvers and additional capabilities for both pre and post processing of models.

Meanwhile, our software providers continue to advance the capabilities they provide. In many areas we are the grateful recipients of capabilities desired by the automotive industry. In others, the unique aspect of our problems is motivation enough for new capabilities. In the near future, we expect additional fluid solvers and further enhancements in material models and fluid post-processing. Meanwhile, the acceleration of computer capabilities will further serve to complete increasingly advanced simulations.

In summary, the future is bright; the computer is coming to the parachute industry!

REFERENCES

1. McKINNEY, J. and TAYLOR, A. “Use of LS-DYNA to Simulate the Airbag Landing Impact Attenuation of the Kistler K-1 Reusable Launch Vehicle”, 5th LS-DYNA Users Conference, 1998.
2. TAYLOR, A., GARDINIER, D. and SABBERTON, A. “Design Optimization of the Beagle II Mars Lander Airbags through Explicit Finite Element Analysis”, AIAA 99-1743, LS-DYNA Users Conference.
3. TAYLOR, A. “Design Optimization of the Beagle II Mars Lander Airbags through Explicit Finite Element Analysis - An Update”, 2000 LS-DYNA Users Conference.
4. TAYLOR, A. “The Case for Explicit Finite Element Analysis of Fabric Systems, A Presentation of Real World Applications”, AIAA 2001-2002.
5. TAYLOR, A. “The Case for Explicit Finite Element Analysis of Fabric Systems, A Comparison to Test Data”, AIAA 2001-2003.
6. TAYLOR, A. BENNEY, R. and BAGDONOVICH, B. “Investigation of the Application of Airbag Technology to Provide a Soft Landing Capability for Military Heavy Airdrop”, AIAA2001-2045, May 2001.
7. DELURGIO, P., et al. “Recovery System for the Evolved Expendable Launch Vehicle”, 14th ADS Conference Proceedings, AIAA 97-1513. June 1997.
8. TAYLOR, A. and DELURGIO, P. “An Overview of the Landing System for the K-1 Launch Vehicle, Parachutes and Airbags”. AIAA 97-1515. June 1997.
9. TUTT, B. and TAYLOR, A. “Applications of LS-DYNA to Structural Problems Related to Recovery Systems and other Fabric Structures”, 7th International LS-DYNA Users Conference, May 2002.
10. TAYLOR, A. “An Investigation of the Apparent Mass of Parachutes Under Post Inflation Dynamic Loading through the use of Fluid Structure Interaction Simulations”, AIAA 2003-2104.