Development of an Airbag Landing System for the Orion Crew Module

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Abstract

Airborne Systems (formally Irvin Aerospace Inc) has developed an Airbag Landing System design for the Orion Crew Module of the Crew Exploration Vehicle. This work is in support of the NASA Langley Research Center Landing System Advanced Development Project. Orion is part of the Constellation Program to send human explorers back to the moon, and then onwards to Mars and other destinations in the Solar System. A component of the Vision for Space Exploration, Orion is being developed to also enable access to space following the retirement of the Space Shuttle in the next decade.

This paper documents the development of a conceptual design, fabrication of prototype assemblies, component level testing and two generations of airbag landing system testing. The airbag system has been designed and analyzed using the transient dynamic finite element code LS-DYNA®. The landing system consists of six airbag assemblies; each assembly contains a primary impact venting airbag and a non-venting anti-bottoming airbag. The anti-bottoming airbag provides ground clearance following the initial impact attenuation sequence. Incorporated into each primary impact airbag is an active vent that allows the entrapped gas to exit the control volume. The size of the vent is tailored to control the flow-rate of the exiting gas. An internal shaping structure is utilized to control the shape of the primary or main airbags prior to ground impact; this significantly improves stroke efficiency and performance.

Introduction

In January of 2004, US President George W. Bush announced a new Vision for Space Exploration setting the long-term goals and objectives for the Nation's space exploration efforts. Among these goals and objectives was the development and deployment of a new spacecraft capable of transporting humans to the International Space Station (ISS), the Moon, and eventually Mars. The subsequent Exploration Systems Architecture Study (ESAS) [1] identified an exploration framework that would enable NASA to achieve this goal of extending a human presence throughout the Solar System. The Constellation Program encompasses NASA's initial efforts to implement the framework developed during the ESAS. The Constellation Program currently consists of: a Crew Launch Vehicle (Ares I), and a Cargo Launch Vehicle (Ares V), the Orion Crew Exploration Vehicle (CEV), the Earth Departure Stage (EDS), and the Altair Lunar Lander. Figure 1 illustrates these primary components.

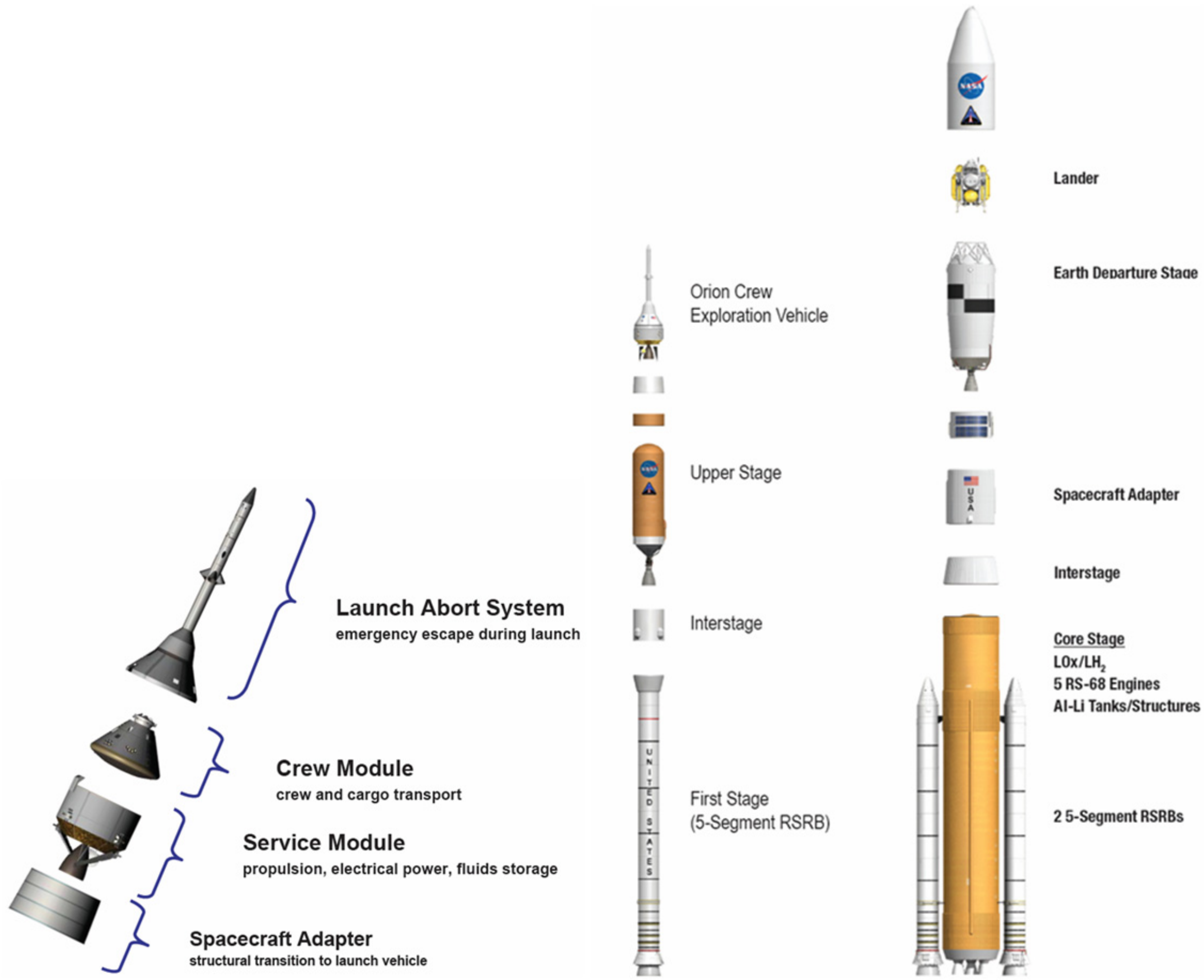

Figure 1: Primary Constellation Program Components

The ESAS also recommended a primary land landing mode for the Orion Crew Module when returning to Earth. This recommendation was made for ease and minimal cost of recovery, post-landing safety, and reusability of the spacecraft. The desire for a land landing capability lead NASA to task the Langley Research Center to investigate potential systems under the Landing System Advanced Development Program. As part of this program Airborne Systems has been under contract since February 2006 to demonstrate the application of airbags to land the Orion Crew Module. This paper discusses the role of LS-DYNA® in the design, development and analysis of an airbag landing system (ALS) for the Orion Crew Module. The ALS has undertaken the following development path:

- Concept Development to Generation 1 (Gen1) Flight System Design
- Generation 1 Prototype Drop Testing
- Generation 1 Prototype Inflation Testing
- Generation 2 (Gen2) Flight System Design
- Generation 2 Drop Testing

Airbag Landing System Design

ALS design was initiated with basic airbag sizing calculations and a review of mounting and stowage locations. When coupled with knowledge of the required performance envelope these parameters provide sufficient information to create initial LS-DYNA airbag system models.

Conceptual airbags are modeled in a theoretical, constructed geometry, and inflated at the beginning of the simulation; this approach enables airbag drawings and patterns to be taken directly from the LS-DYNA model at a later date. Airbag venting schemes are traded and suitable size vents are developed. During this initial design phase the Wang-Nefske definition of an airbag with vent area included in the card is utilized. This enables rapid assessment of system performance as a function of separate variables without having to incorporate physical vents into the model.

As the airbag geometry and configuration evolved the location of the airbag vent or vents became important. Airborne Systems has learned through a number of past programs that physical blockage of the vent, or flow rate impediment, can occur through vent proximity with the vehicle, landing surface or adjacent bags. LS-DYNA has the capability to evaluate the influence of vent blockage on the mass flowrate through the vents. Studies were performed to optimize the location of the airbag vents by tracking the location of airbag material nodes as a function of time for a variety of landing scenarios.

LS-DYNA Model Description

The Crew Module (CM) was assigned a rigid body material property to decrease the computational overhead associated with modeling a deformable structure. The relatively large deflections of the fabric structure as compared to those of the CM generally make the rigid body approximation both reasonable and conservative. As the CM structure evolves, a deformable vehicle, including material plasticity, will be incorporated into the LS-DYNA model. Figure 2 illustrates the evolution of the rigid body in the LS-DYNA model.

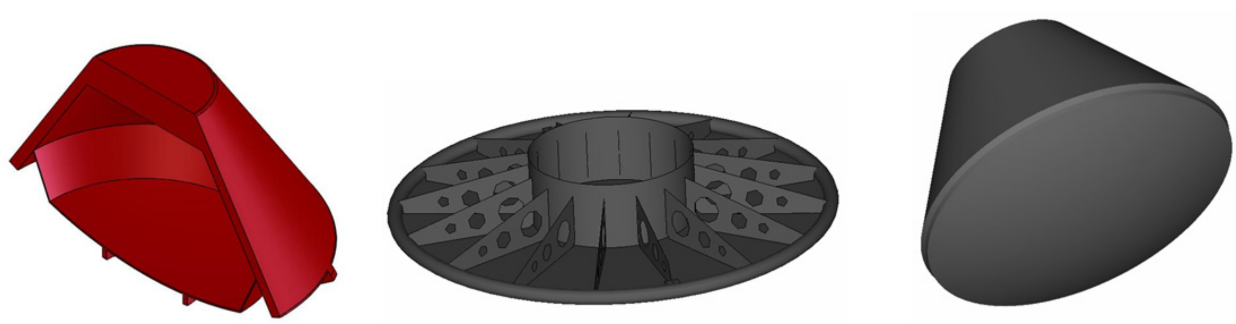

Figure 2: CM Evolution- From Gen1, through Gen1 Testing, to Gen2 (left to right)

Throughout Gen1 of the landing system development the ground was also assigned a rigid body property. The definition of a landing site and the availability of material properties was still in flux during these early stages of the program. As the program matured, a variety of landing surface material definitions were developed. The Gen2 airbag design was evaluated using these *MAT_SOIL_AND_FOAM material models. A static and dynamic coefficient of friction along with a decay coefficient, which describes the relation between static and dynamic values as a function of relative contact velocities, was defined between the airbags and the ground.

Figure 3 illustrates the Gen2 airbag configuration. The configuration is comprised of six individual airbag assemblies with each assembly containing four core components:

- A primary impact, main venting airbag
- A non-venting, anti-bottoming airbag
- A main venting airbag internal shaping structure
- A fast acting, low leak rate active vent

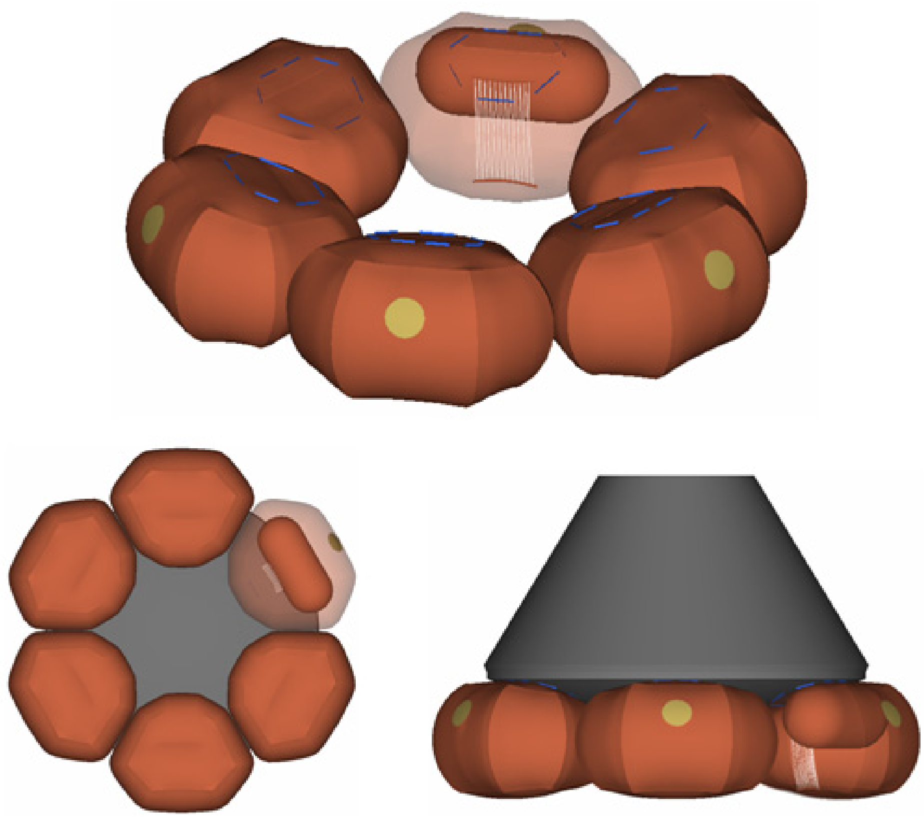

Figure 3: Gen2 Airbag Configuration

The main airbags are sized to provide sufficient stroke to decelerate the CM and maximize the contact area with the CM structure. The height of the airbag is predominantly based upon providing sufficient stroke for the parachute failure vertical velocities and minimizing rebound velocity for a nominal landing scenario. Maximizing the airbag/CM contact area minimizes the pressure applied to the base of the CM during the primary impact stroke, and improves the efficiency of the airbag stroke. These features, in combination with the vent size and vent trigger pressure, are tailored to ensure deceleration levels are within the specified limits.

The main airbags extend beyond the outer mold line (OML) of the CM to improve pitch and yaw stability during the primary landing stroke. This feature is particularly important when the CM exhibits pitch and yaw departures in a high crosswind landing environment. As the vehicle contacts the ground during these scenarios, the capsule begins to pitch/yaw and the portion of the airbag that extends beyond the CM conforms to the OML and provides a restoring moment.

The role of the non-venting anti-bottoming airbags (AB airbags) is to protect the aft bulkhead from ground impact, and prevent the CM from rolling over.

AB airbag size, shape, and location are based on the following design principles-

- The airbag size originates from the requirement to maintain a minimum dynamic ground clearance of 8 in during the nominal landing scenarios. The particular cases within this group that drive the airbag diameter are those incorporating a 3 sigma high vertical velocity. The size was then marginally increased to account for the main airbag failure landing scenarios where the primary impact is taken by the AB airbag inside the failed main airbag.

- Several performance features have guided the shape of the AB airbags. Perhaps the primary consideration is an efficient pressure vessel shape; the AB airbags have to withstand peak pressures in excess of 30 psi for the more exotic parachute failure landing cases. An inefficient shape would require heavier material to withstand the same fabric stresses. Another key design feature was integration into the main airbag, more specifically: the AB airbag had to perform without detracting from the performance of the main airbag. In addition, the requirement for a successful landing if a single AB airbag failed dictated that adjacent airbags are capable of providing sufficient redundant protection. The resulting AB airbag shape is a cylindrical body with hemispherical endcaps that provides sufficient aft bulkhead protection without restricting the airflow out of the main airbag.

- The location of the airbags, at the perimeter of the CM, is driven by the requirement to protect the aft bulkhead during the landing sequence. Locating the airbags as far outboard as possible enables protection of the entire bulkhead during maximum pitch orientations and crosswind scenarios. This placement of the AB airbags also establishes a flat bottomed system with as wide and stable base as possible.

The internal shaping structure is integrated into the main airbag to maximize stroke efficiency by pre-deforming the airbag. The reduction in airbag height also reduces the propensity for CM roll-over during high crosswind velocities by effectively reducing the system CG location.

The vent assembly is completely constructed from flexible fabric materials; this ensures that the vent conforms to the shape of the inflated airbag without prematurely venting the entrapped gas. This design also enables flexibility in the packing process. The vent assembly is fabricated from a latex gas barrier, loose fabric structural disc, and a fabric petal configuration. Two pyrotechnically actuated cutters are incorporated into a fabric retaining loop that is used to close the fabric petals.

The venting sequence is as follows:

- Following deployment and full inflation, pressure transducers, connected to each of the main venting airbags, continually monitor control volume pressure.
- When the pressure in a single main venting airbag exceeds a pre-defined pressure for a cumulative time (to eliminate spurious data) an electronic signal is sent to the dual pyrotechnically-actuated cutters located at the vent assembly of that specific airbag.
- The two cutters (only one required for successful operation) sever the fabric retaining loop.
- The fabric petals begin to open, the structural fabric disc is ejected and the latex expands and bursts.

This performance is simulated in LS-DYNA using the pressure venting option in the Wang-Nefske airbag definition.

The airbags are defined using 4-noded fully integrated Belystchko-Tsay membrane elements. The airbag meshes include no triangular elements. The presence of 3-noded elements can introduce areas of unrealistically high fabric stress due to the limited rotation permitted at the 3 nodes, compared to the 4-noded elements. The *MAT_FABRIC material model is used to assign representative fabric properties to the airbag elements. Utilization of accurate material properties is always important but incorrect material allocation in these models generates secondary inaccuracies; assigning overly stiff fabric properties generates a smaller volume than experienced in reality, this equates to less gas inside the airbag for a given pressure. The volume of gas in the airbag is a measure of the work the airbag can do during the deceleration stroke. Accurately capturing the mass, volume and pressure of the gas inside the airbag is essential in predicting performance.

As described above, a Wang-Nefske airbag definition is used to characterize the airbag behavior and blockage is taken into account when the vent area contacts either the ground or the vehicle, using the OPT flag. No flow impingement due to the internal anti-bottoming airbag is simulated.

The vents are constructed from separate parts, allowing that individual part to be assessed for blockage and the mass flowrate through the vent reduced appropriately.

The airbags are considered to have been inflated by a gas of a composition of air and to have reached a temperature of 60F when ground impact occurs. This assumption is based on the utilization of an aspirator based inflation system, and a nominal return trajectory.

A flow coefficient of 0.7 has been applied to the vent area of each main airbag. This value has been derived through historical test data, and reinforced through Gen1 testing.

The internal shaping structure is modeled using seatbelt elements and slipring elements. This technique accurately simulates the lacing design used to restrict the naturally spherical shape of a pressure vessel.

System Performance Analysis

The design and analysis of the airbag system was a continual closed loop process. For Gen2 an initial design was assessed and enhanced based upon the results of a landing matrix of 60 scenarios. This matrix included nominal landings, emergency entry landings, parachute failure, and airbag deployment or inflation failure. The nominal landing scenarios include variations in CM pitch and yaw angle at impact, vertical velocity under all 3 parachutes, horizontal velocity caused by winds, and local ground slope. The airbag system is required to operate successfully throughout all the possible landing scenarios without modification or prior knowledge of that landing scenario.

Figure 4 details the airbag numbering sequence, and definition of the velocity vectors.

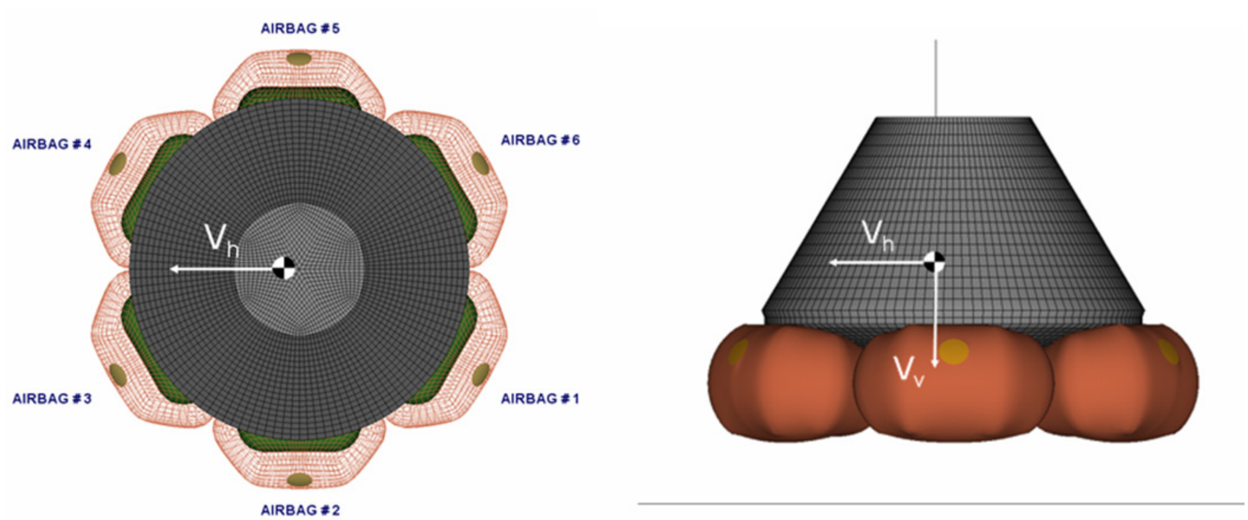

Figure 4: Airbag System and Landing Velocity Definitions

Model element count varies based on the landing surface. The basic airbag model contains almost 20,000 elements. Model run-time varies based on required simulation time, landing surface and compute hardware. Airborne Systems utilize a mix of Dell Workstations and SGI compute nodes. LS-DYNA version 971-7600 was used throughout the program. Altair HyperMesh was used for mesh generation. Altair HyperView, CEI EnSight, and LS-PREPOST were used for post-processing.

Figure 5 and Figure 6 detail airbag and CM time history data for a nominal landing scenario- 0 degree CM pitch, 0 degree CM yaw, 0 degree ground slope, 25.1 ft/s vertical velocity, and 0 ft/s horizontal velocity.

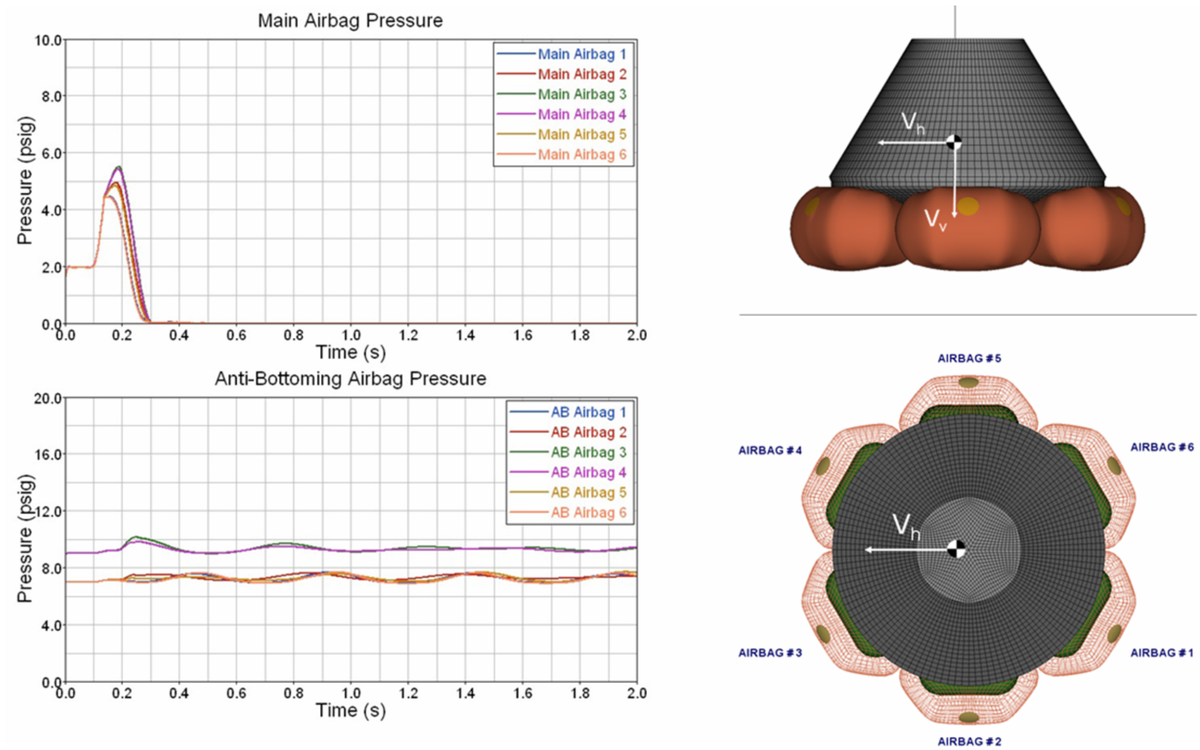

Figure 5: Airbag Pressure Time History Data

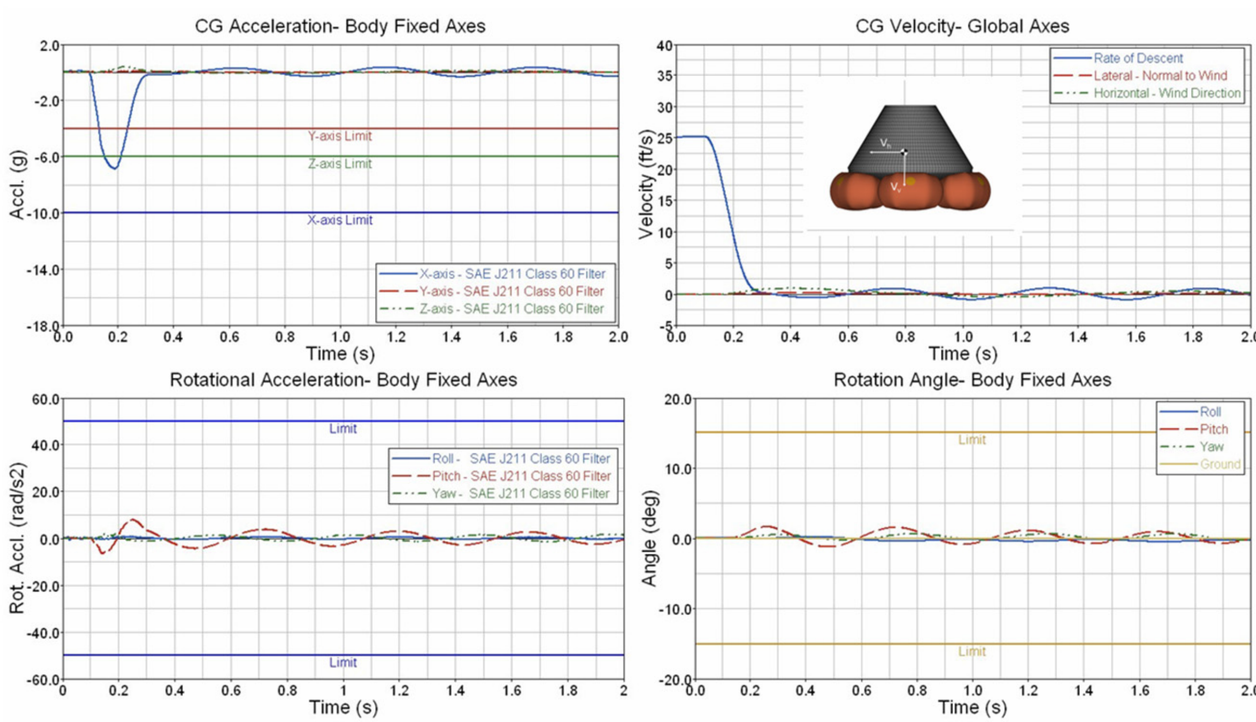

Figure 6: CM Time History Data

In addition to assessing the landing dynamics of each scenario, the LS-DYNA model permits information regarding fabric strength requirements and attachment loads to be evaluated. Figure 7 displays the fabric stress contours for a vertical velocity only landing on a hot day and with 3 sigma low parachute performance. A hot day and 3 sigma low parachute performance reduces the relative drag force of the parachute system and therefore increases the vertical velocity of the CM at ground impact.

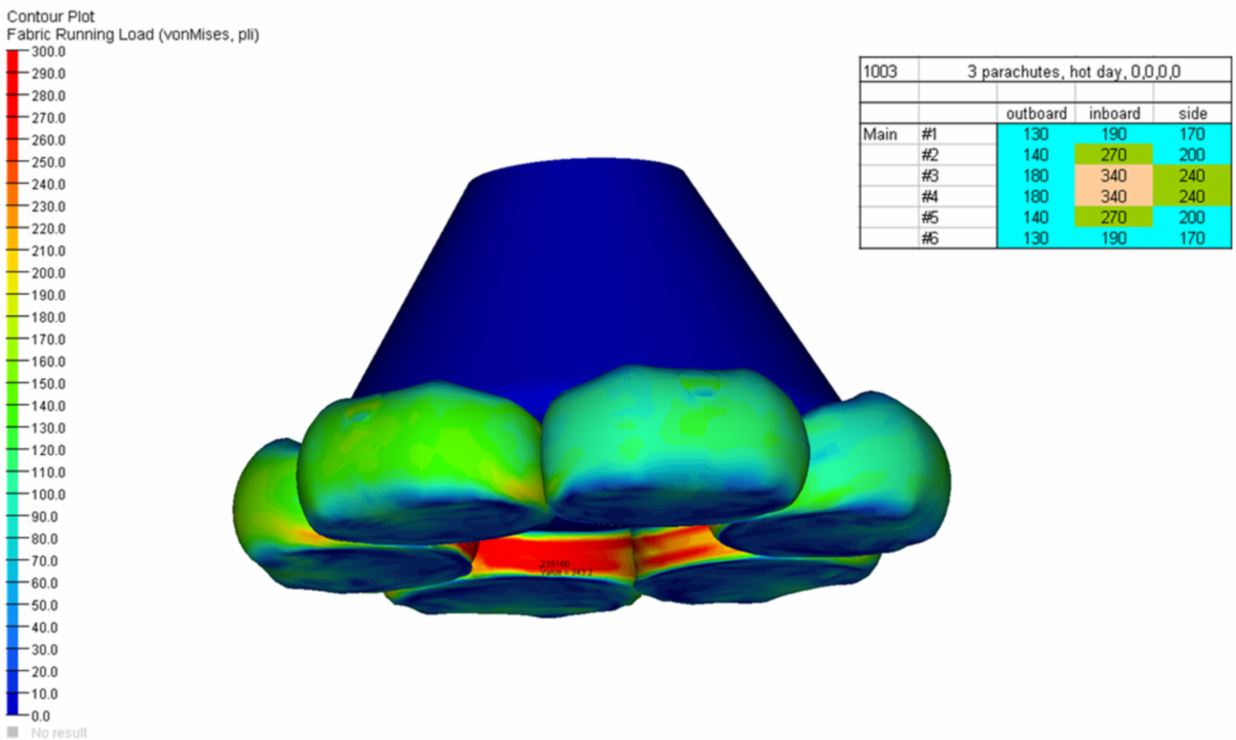

Figure 7: Gen2 Fabric Stress Contours

The stress contours were used to assess the fabric material strength required. The assessment was performed for every landing scenario, for all six main airbags and AB airbags. Additionally, each airbag was separated into sections to assess whether different strength materials could be integrated into each airbag. Clearly, for space operations mass is an important design driver, and the ability to save system mass by utilizing the most appropriate fabric strength and therefore weight where possible can have significant benefits elsewhere on the spacecraft.

The method for connecting the airbags to the aft bulkhead was similar to the lacing technique used for the internal shaping structure. A lacing methodology enables the loads to be transferred from the airbags into the CM without point loading any components. This was critical when considering the high horizontal velocity landing cases where the CM wants to slide off the airbags and impart substantial load into the attachments.

Fabrication

Once the airbag landing system design had matured and stabilized the LS-DYNA model was used to generate the airbag patterns. This technique ensures that what is fabricated is as close to the analyzed geometry as possible. An iterative step was included that took the final flat patterns and reconstructed the airbags to further ensure the appropriate geometry was being fabricated. Figure 8 displays a Gen2 main airbag flat pattern. The Gen2 airbags were fabricated from polyurethane coated Vectran fabric and constructed using radio-frequency welding.

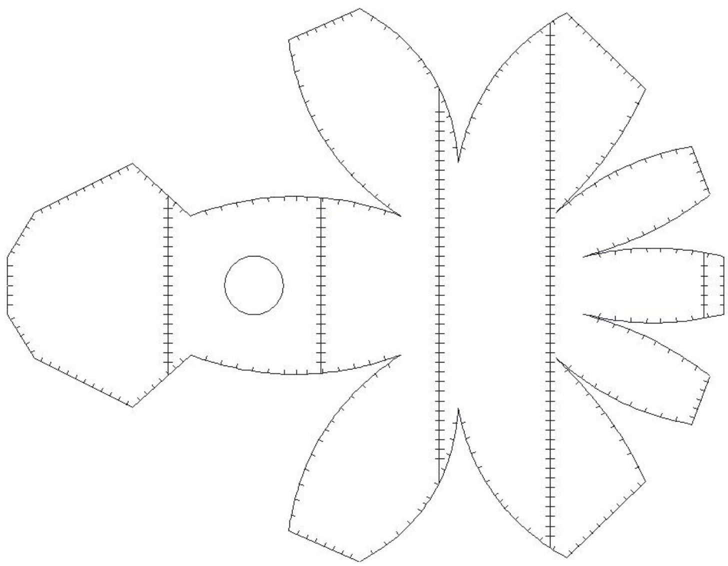

Figure 8: Gen2 Main Airbag Flat Pattern

Figure 9 illustrates both the Gen1 and Gen2 drop test systems. The Gen1 drop test article is a flat-bottomed vehicle whose diameter is full-scale but only half full-scale mass. This resulted in only using 3 of the proposed 6 airbag assemblies. Gen1 testing started in December 2006 and finished in July 2007. The Gen2 drop test article is full-scale, weighing 16,000 lb, and includes the curved aft bulkhead. Gen2 testing began in February 2008 and is currently ongoing.

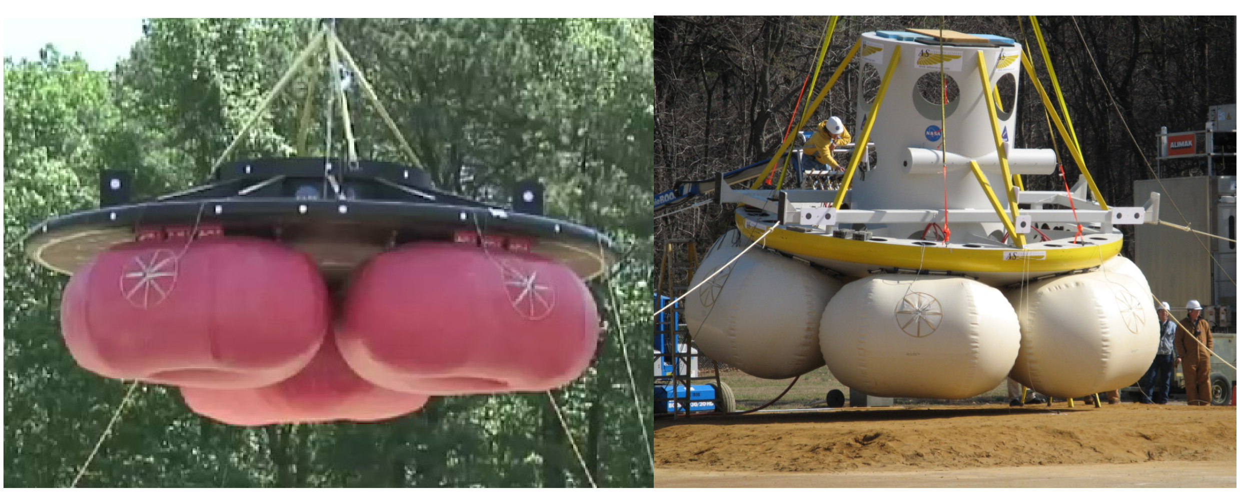

Figure 9: Gen1 and Gen2 Drop Test Systems

Testing and Model Correlation

The Landing and Impact Research Facility at NASA Langley Research Center was used for both the Gen1 and current Gen2 drop testing. The Gen1 drop testing encompassed 8 drop tests.

Figure 10: NASA LaRC LandIR Facility

Figure 11 displays side views of the initial impact from two drop tests. The images illustrate the operation of the active vent; both images show the bursting of the latex disc, the image on the right clearly indicates how the trailing airbag has not impacted the ground and has not yet vented.

Figure 11: Gen1 Drop Testing Images

Figure 12 through Figure 15 compare acceleration, velocity, and pressure time history data from the drop tests and the LS-DYNA model predictions. The LS-DYNA model was not modified following the drop test, except to include the actual drop test conditions i.e if the CM impacted at 9 degrees instead of the anticipated 10 degrees this was incorporated into the model.

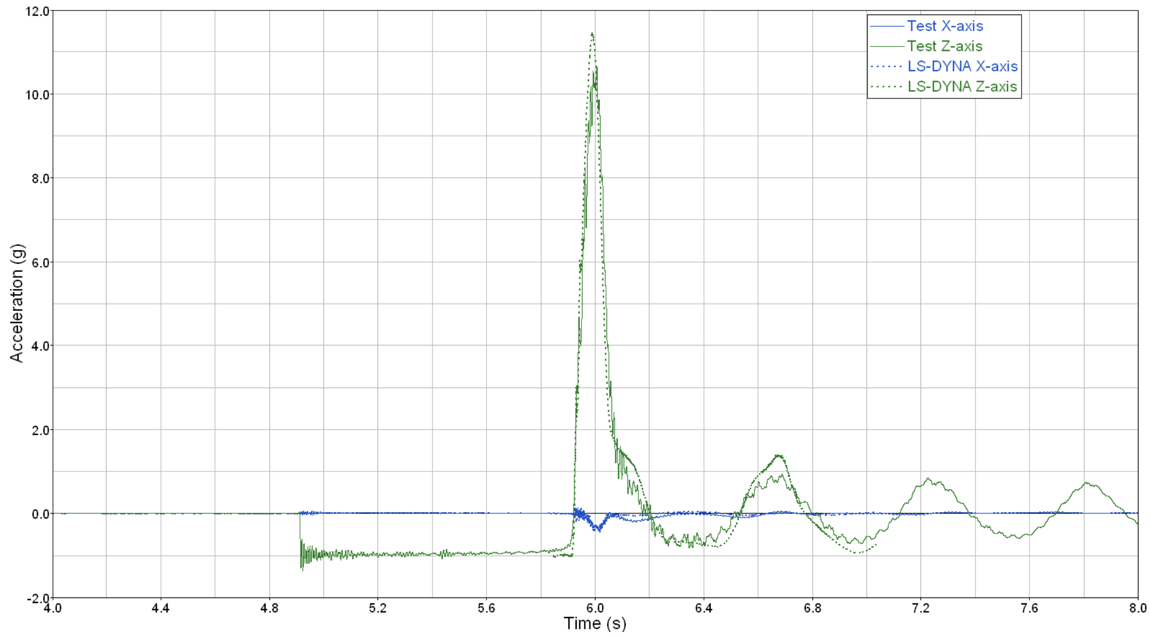

Figure 12: Vertical Velocity Drop Test- Test Data and LS-DYNA Model Prediction- Acceleration Time History

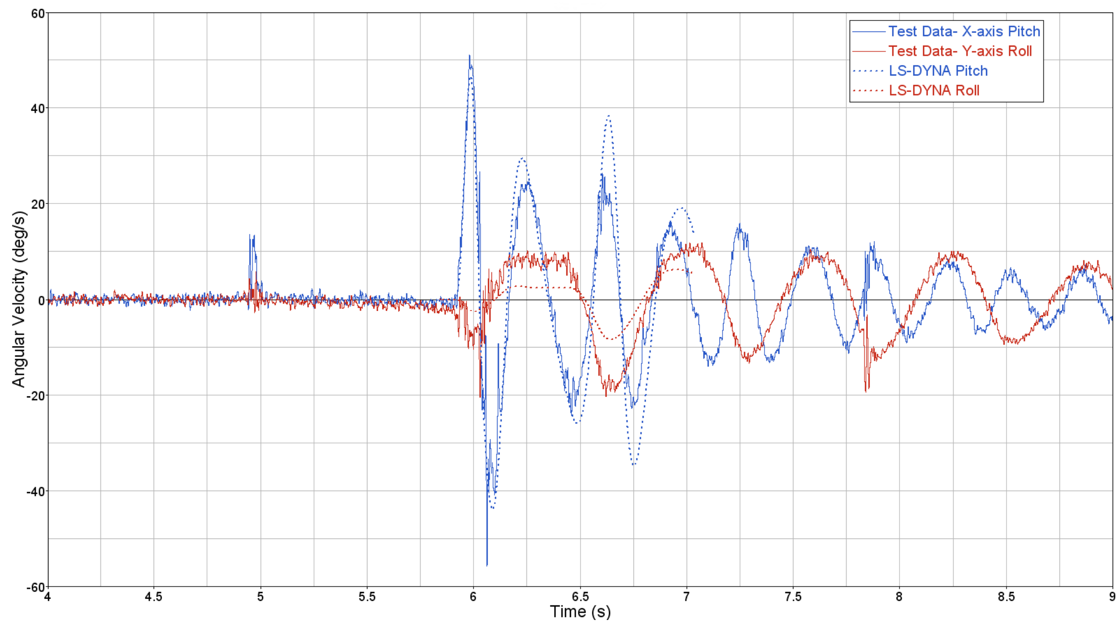

Figure 13: Vertical Velocity Drop Test- Test Data and LS-DYNA Model Prediction- Angular Velocity Time History

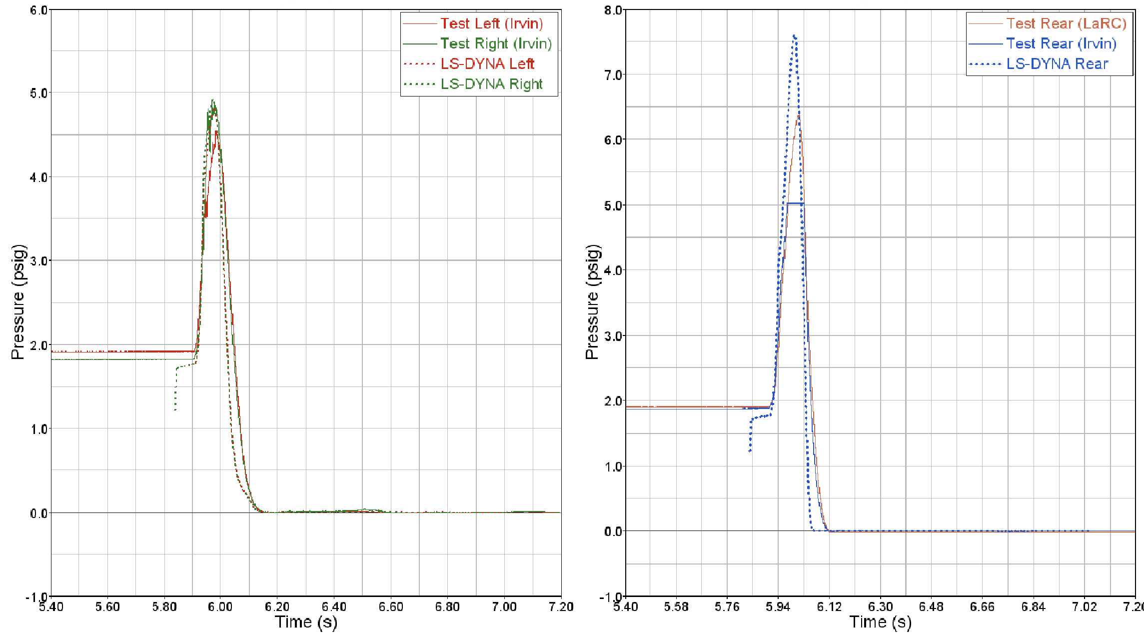

Figure 14: Vertical Velocity Drop Test- Test Data and LS-DYNA Model Prediction- Airbag Pressure Time History

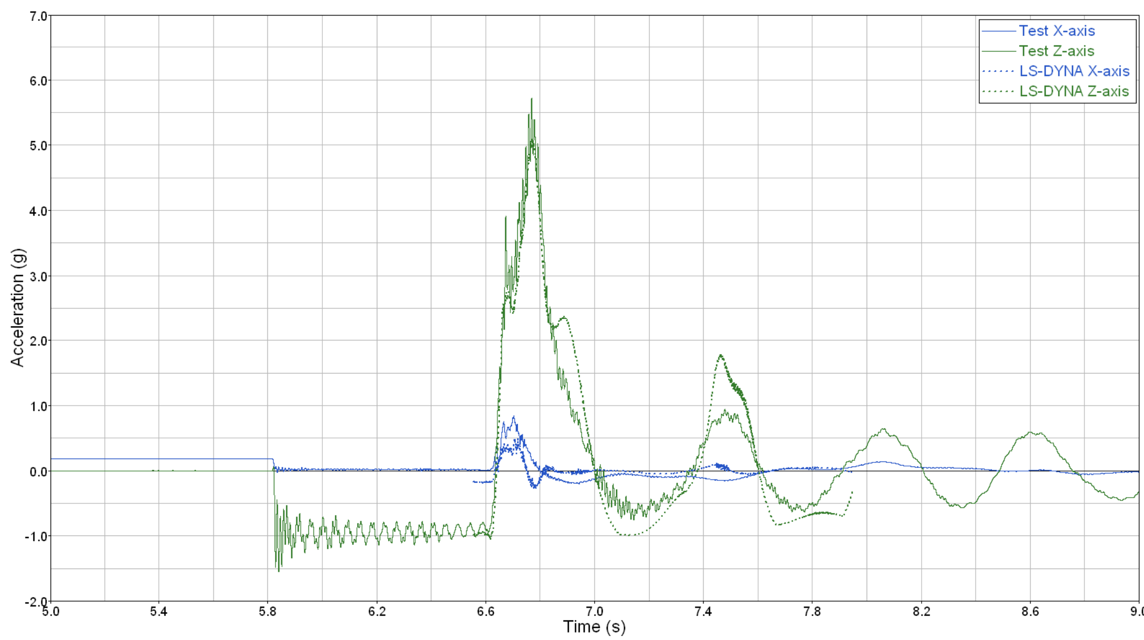

Figure 15: Vertical Velocity, 10 Degree Pitch Drop Test- Test Data and LS-DYNA Model Prediction- Acceleration Time History

The comparisons illustrate a high level of correlation between the test data and the model predictions. The remaining drop tests exhibited a similar level of correlation.

Conclusions

This paper has described the use of LS-DYNA to design and analyze an Airbag Landing System for the Orion Crew Module in support of NASA's Landing System Advanced Development Project.

Over two test series, the Gen1 ALS has been subjected to eight drop tests. Every drop test has resulted in a crew survivable landing; within acceleration limits and no roll-overs. It should be noted that two of the drop tests resulted in minor component level failures of the fabric attachment technique. The reasons for these failures were promptly identified and have already been resolved. These issues were connected with human and process errors rather than LS-DYNA model inaccuracies.

The model also proved useful in understanding the landing event more fully. It first identified a time delay observed in one of the pressure transducers during the first test series, and later helped understand a back pressure anomaly within the inflation system.

The drop testing identified a feature of the LS-DYNA model that would benefit from further development. Currently, vent blockage is simulated as a reduction in exit mass flowrate from an airbag when the vent area is in contact with another component. This leaves two potential vent blockage (perhaps more accurately described as vent flowrate reduction) scenarios that are not accounted for in the model.

- The first, and perhaps most influential during the test series, is the inability of the model to account for a flowrate reduction when the anti-bottoming airbag moves to cover the vent from the inside. This was recognized as a feature during the conceptual design phase but was not developed further due to the large distance between the vent and the AB airbag in the Gen1 design. Animations of the Gen1 design suggested that the main airbag would have finished venting before the AB airbag could reach the vent. However, this distance reduced significantly when the airbags were modified to mate with the flat-bottomed test vehicle.

- The second scenario that could reduce flowrate from the airbag vent is proximity to the ground. Proximity to the ground could impinge upon the gas flow from the vent and produce a form of back pressure that would act to reduce the net mass flowrate.

Two Gen2 drop tests have been successfully completed as of writing this paper. Both tests where once again crew survivable and as predicted by the LS-DYNA model. Within the next month the airbag landing system will be further evaluated by more demanding drop test conditions.

References

[1] "NASA's Exploration Systems Architecture Study", NASA-TM-2005-214062, November 2005