21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar
23 - 26 May 2011, Dublin, Ireland

AIAA 2011-2591

Simulation of the Apollo Command Module Uprighting System using LS-DYNA

Scott J. Roland[1]
Airborne Systems North America, Santa Ana, CA 92704

This paper documents the recent simulation efforts conducted by Airborne Systems in accurately creating a simulation representative of the *Apollo Experience Report: Command Module Uprighting System* (NASA TN D-7081). As with the Mercury and Gemini command modules, the Apollo command module recovery was intended to be a nominal water landing. During its development, it was determined that the Apollo command module had two buoyantly stable states; however, only one of the two was allowed for many practical reasons including safe crew egress. The first of the buoyantly stable positions was such that the crew tunnel was clear of the water, the second of these positions was such that the crew tunnel was fully submerged beneath the surface of the water; thereby, making crew egress impossible. A self-contained system was developed to rotate the crew module from the latter of these stable positions (Stable II) to the stable position that would allow for proper crew egress (Stable I), while maintaining that position for a sufficient duration to allow for crew recovery. The commercially available finite element analysis code LS-DYNA was used to generate a simulation that accurately models the command module vehicle uprighting dynamics. Proper determination of the well-known Stable I and Stable II orientations subsequent to water impact are two of the preliminary milestones used to cross-check the validity of the simulation in properly capturing the characteristics of the command module. The behavior of the command module during the entire operational envelop is well documented; therefore, the accuracy and validity of the independently generated LS-DYNA simulation can be verified. Additionally, the buoyant characteristics of the command module are also independently verified using the Airborne Systems proprietary statically determinate buoyancy solving code, FloatStab. This paper illustrates the use of LS-DYNA in accurately simulating a critical subsystem performance and its effect on the whole of the system. This methodology could be expanded upon and extrapolated for a future crew or command module uprighting system design and prove to be a highly valuable tool for reducing the costs and risks associated with the design, development, and test phases of a comparable subsystem.

I. Introduction

One of the most important and difficult aspects of the Apollo missions was the safe rescue and recovery of the manned command module. After re-entry into the Earth's atmosphere, and descending under the main parachute canopies to a splashdown water landing, the command module and crew were transferred to a recovery ship. The time between splashdown of the command module and the beginning of recovery efforts could be as long as the 48-hr command module inhabitability requirement. Additionally it was determined that given the geometry and buoyant characteristics of the command module, there were two buoyantly stable states: vehicle upright (Stable I) and vehicle inverted (Stable II). Stable II was considered undesirable given crew comfort, crew safety, crew module ventilation, crew egress, post-landing recovery aid operation, and ease of transport to the recovery ship.

To alleviate the risks associated with the Stable II state, the use of a self-contained inflatable uprighting system consisting of three spherical bags, an uprighting bag inflation system, and retention system was proposed. To determine the efficacy of the proposed system, both scaled and full-sized model testing was undertaken spanning several months. Given the advancements in finite element analysis (FEA) modeling software and computational hardware capability since the Apollo era, the expensive and time consuming task of conducting these scaled and

[1] Systems Analyst, Airborne Systems, 3000 Segerstrom Ave., Santa Ana, CA 92704. AIAA Member.

full-scale model tests could potentially be eliminated, or reduced, in favor of a transient dynamic simulation that accurately captures the buoyant characteristics of the command module.

This paper recreates the findings of the Apollo Experience Report – Command Module Uprighting System[1], by using the transient dynamic commercially available FEA code LS-DYNA[2]; illustrating the feasibility of potentially replacing some of the testing efforts with simulation and analysis.

II. Apollo Command Module Uprighting System Characteristics

It is necessary to give an overview of the vehicle geometry and mass properties, as background information for the reader; additionally this information is used as inputs for the LS-DYNA simulation recreation efforts. The scope of this simulation effort was restricted to the Block II Apollo command module, though brief background is given on both design configurations. The geometry of the outer mold line (OML) of the Block II Apollo command module is shown in Figure 1.

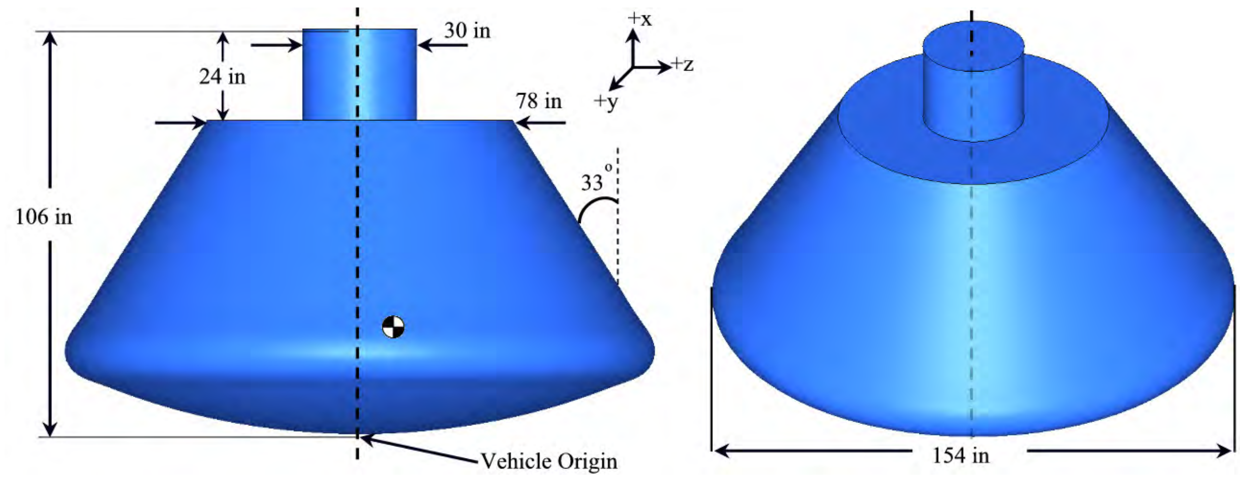

Figure 1. Apollo Command Module Pertinent Dimensions

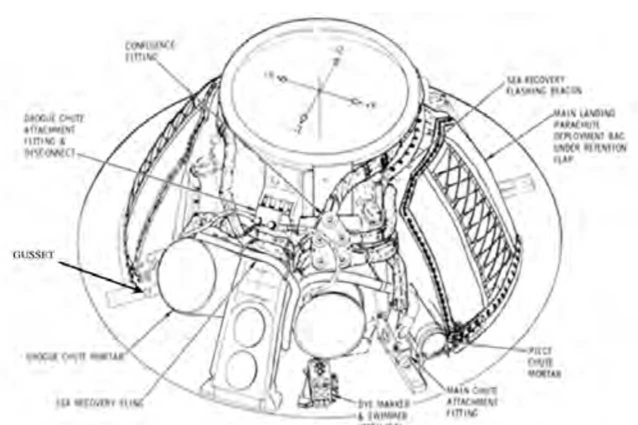

Figure 2. Apollo Command Module Main and Drogue Parachute Location

The Block I vehicle weight upon splashdown into the ocean was approximately 9,000 lbm, with the vehicle center of gravity located in the local vehicle coordinate system at (Xcg = 40.0 in, Ycg = 0.0 in, Zcg = 5.0 in), while the Block II vehicle weight upon splashdown was approximately 11,200 lbm with the center of gravity located at (Xcg = 37.5 in, Ycg = 0.0 in, Zcg = 5.5 in), these values are reiterated in Table 1. Additionally it should be noted that the main parachutes are stowed about the crew tunnel between four gussets as depicted in Figure 2. As mentioned previously, this simulation effort begins just as the command module splashes down into the ocean; hence, the drogue and main parachute geometries and weights are not included. Additionally, this study conservatively assumes a simplified common vehicle OML between the Block I and Block II configurations, as well as assuming all buoyancy contributions from the gussets and other geometric features around the crew tunnel can be neglected.

Upon splashdown of the command module, the crew would manually trigger a release of compressed gas that would inflate the bags, uprighting the command module from Stable II to Stable I, if inverted. The Stable I and Stable II positions are described in Figure 3. The angles, ψ_1, ψ_2 are 5 degrees and 160 degrees, respectively.

During the initial design and development stages of the Apollo command module uprighting system, for the Block I design, the plan was to retrofit a pre-existing command module to incorporate the inflation tanks, all tubing, and the packed uprighting bags. During the Block II design phase, volume was allocated beneath the packed main parachutes, as depicted in Figure 2, to allow for the packing of the uprighting bags and the accompanying inflation equipment. The original Block I proposed uprighting system design using three polyurethane impregnated Dacron cloth uprighting bags, was maintained for the Block II design efforts. Each of the 43-in bags were constructed from geodesic patches to form 43-inch diameter spheres, while the smaller Block II +Z-bag was constructed using banana peel patches. In both designs, the uprighting bags were located in the +Y, -Y, and +Z quadrants on the upper deck of the command module as shown in Figure 2 and Figure 5.

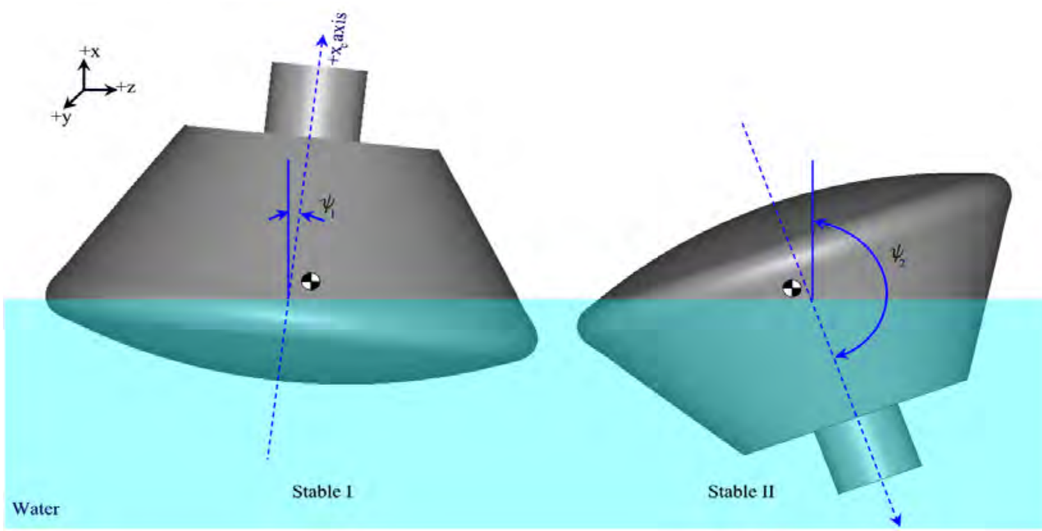

Figure 3. Apollo Command Module Stable I and Stable II Definitions

The uprighting bags were maintained in their respective positions by implementing a series of fan patches attached around the surface of the spherical bags while being anchored to the gussets. Because the mass increased as the design of the command module matured from Block I to Block II design, the Block I uprighting system could not be used for Block II as-is. Given the change in mass between the command module designs, the system was requalified, during which it became obvious that the Block II command module design was much less stable than the original Block I design—primarily due to a shift in C.G. location. As a result, when assessing a one-uprighting bag failure case, the vehicle would not upright out of its Stable II position. To alleviate this concern, the +Z uprighting bag was decreased in size from 43-in to 34-in to achieve less roll moment in the case of either the +Y or –Y uprighting inflation bag failures. The other change was requiring the crew relocate from couches to the aft bulkhead, thereby shifting the C.G. of the crew module and allowing the uprighting event to occur. A few photos from the recovery of each of these vehicles are shown in Figure 4 and help illustrate the differences between the Block I and Block II configurations, as well as depicting the uprighting systems fully deployed.

BLOCK I: Apollo 6 Uprighting System & Recovery (Uprighting Bags Deflated)

BLOCK II: Apollo 11 Uprighting System & Recovery (Smaller 34-in Bag on Left)

Figure 4. Apollo Block I and Block II Command Modules Depicting Uprighting Systems

The nominal uprighting bag layout for each of the vehicle configurations are shown in Figure 5, the only difference from the standpoint of initial configuration is the presence of the 34-in diameter uprighting bag (+Z) in the Block II configuration.

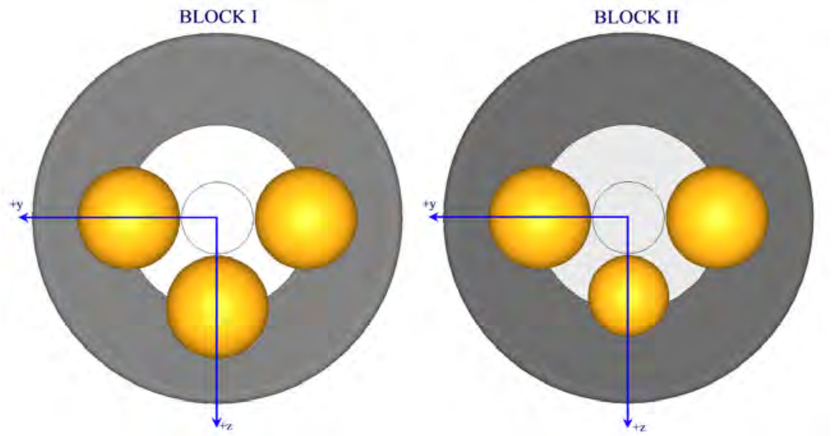

Figure 5. Uprighting Bag Layout for Apollo Command Module Block I and Block II Configurations

The mass properties in Table 1 are valid for all Block I configurations (including any of the one-uprighting bag failure cases); however, the nominal mass properties for Block II are only valid for the zero-uprighting bag failure case. As mentioned previously, in the case of a bag failure for the Block II configuration, the crewmembers must shift from the couch to aft bulkhead in order to shift the center of gravity further toward the aft bulkhead (or the vehicle origin as shown in Figure 1). To account for this shift in center of gravity in the LS-DYNA simulation, the initial center of gravity is shifted such that it would fall into an acceptable "Two-bag uprighting zone" as depicted in Figure 6.

Table 1. Block I and Block II Command Module Nominal Mass Properties

Nominal Block I CM				Nominal Block II CM			
Mass [lbm]	x_{cg} [in]	y_{cg} [in]	z_{cg} [in]	Mass [lbm]	x_{cg} [in]	y_{cg} [in]	z_{cg} [in]
9000	40.0	0.0	5.0	11200	37.5	0.0	5.5

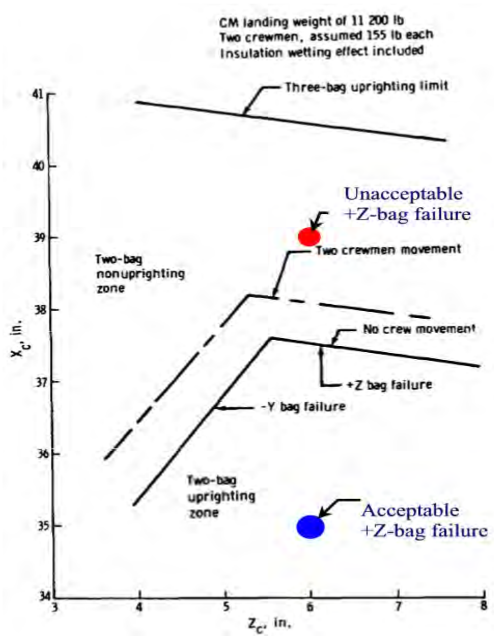

Figure 6. Block II Apollo Command Module Uprighting Curves. *Blue-Crewmember CG shift, Red-No Crewmember CG Shift*

III. Simulation Methodology and Overview

The primary simulation tool used in this analysis was the commercially available transient dynamic FEA solver LS-DYNA from Livermore Software Technology Corporation (LSTC). An Arbitrary Lagrangian-Eulerian numerical approach was used in this analysis such that the Eulerian fluid (water) was initially evacuated from the Lagrangian domain (crew module), to allow for the buoyant characteristics to take effect at the initialization of the simulation. This also allows for an accurate portrayal of the rotational characteristics of the crew module as a result of the buoyant forces. The simulation establishes a new solution at each individual time step such that it becomes the input for the next time step, while also accounting for momentum and energy conservation considerations and the inertial effects from the prior time steps.

As a secondary source of verification of performance, the Airborne Systems developed finite element simulation tool FloatStab[3] was implemented in this effort. FloatStab uses a discretized finite element model of the CM OML and user inputs of the CM mass and CG location to calculate the waterline for given, pitch, roll and yaw orientations. Once the water-line is identified, the buoyancy moments can be calculated. The process can be rapidly completed for numerous combinations of pitch, roll, and yaw angles.

As a demonstration of the application and accuracy of the FloatStab simulation tool, the Block I Apollo command module stability data was analyzed and reproduced, showing a good correlation, as shown in Figure 7. Though the Apollo command module data only spans 180 degrees of pitch, FloatStab accurately predicts both the Stable I and Stable II points, as well as the theoretical dynamically stable points at approximately 80 degrees and 275 degrees.

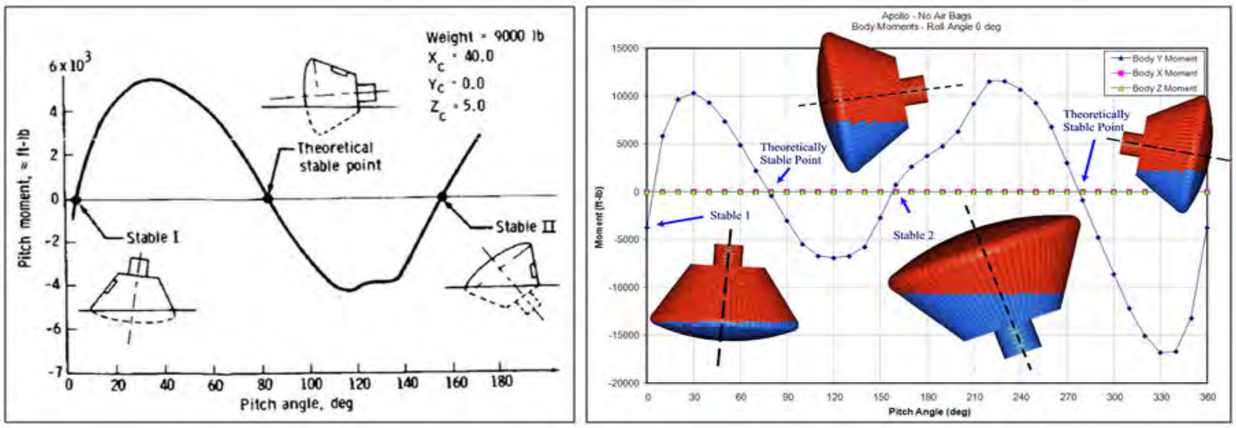

Figure 7. Comparison between Apollo Command Module Pitch Moment and FloatStab Predictions

In all scenarios evaluated within this effort, besides the determination of Stable I, the command module begins with a pitch angle of 180 degrees, as illustrated in Figure 8. By beginning the simulation with the vehicle positioned as such, the inherent buoyant force of the vehicle with the uprighting bags (where applicable) is allowed to reposition the vehicle to its natural final pitch angle position.

Before discussing the simulation results, a brief discussion on the dimensions of the finite element model contents as well as the Eulerian domain dimensions is warranted.

The entire Eulerian mesh consists of 147,500 first-order hexahedral Arbitrary Lagrangian-Eulerian Multi-Material Elements, made up of 156,060 nodes. The Eulerian domain space is divided up between two different fluids: air and water. In an effort to limit any edge effects due to the domain space on the system performance and simulation results, the majority of the Eulerian domain consists of water. The Eulerian domain is divided into the two distinct fluids; the air domain consists of 52,500 elements and 57,222 nodes, while the water domain is consisting of 95,000 elements and 98,838 nodes. Moreover, the dimensions of the Eulerian domain can be seen in Figure 8. Conversely, the Lagrangian command module consists of 5,904 two-dimensional fully-integrated membrane elements and 5,906 nodes.

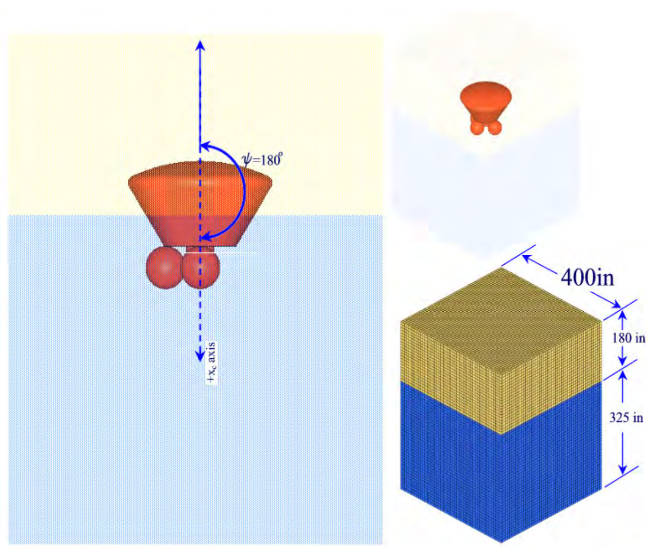

Figure 8. Initial Starting Condition for Uprighting System Evaluation Simulations and Dimensions of Eulerian Domain.

IV. LS-DYNA and FloatStab Simulation Results

A summary of the Block II Apollo uprighting scenarios assessed in this analysis is presented in Table 2. Whenever possible, the results of the simulation animation are compared to screenshots from the Apollo Experience Report in order to offer further validity of the behavior and dynamics of the uprighting system performance, as predicted by the LS-DYNA simulation. As a method of simplification, in each of the uprighting scenarios, the uprighting bags begin the simulation fully inflated. Integrating a method of inflating the uprighting bags into the LS-DYNA simulation would only act to further emulate the actual event and is certainly an avenue for future development of this methodology.

Table 2. Summary of all Apollo Command Module Uprighting System Simulation Efforts

Apollo Block II CM	
A	Stable II
B	Nominal
C	+Z-Bag Fail
D	+Y-Bag Fail

A. Apollo Block II, Stable II (Case A)

As a baseline case to test the validity of the LS-DYNA simulation methodology, the Block I Apollo command module Stable II pitch angle predictions were verified. To offer further validation, the Stable II pitch angles were corroborated using FloatStab.

Figure 9 shows the time-lapsed results from the animation of the LS-DYNA Stable II predictions, with the time advancing from left to right. Furthermore, the result of the simulation showing the command module in both the Stable I and Stable II states while floating in the water are shown in Figure 10. The successful prediction of these primary pitch angle states is an important step in instilling confidence going forth with the rest of the uprighting simulation.

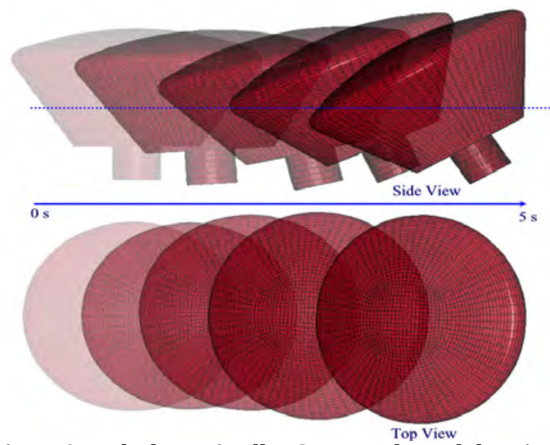

Figure 9. Block II Apollo Command Module Time Lapsed Stable II Simulation Result

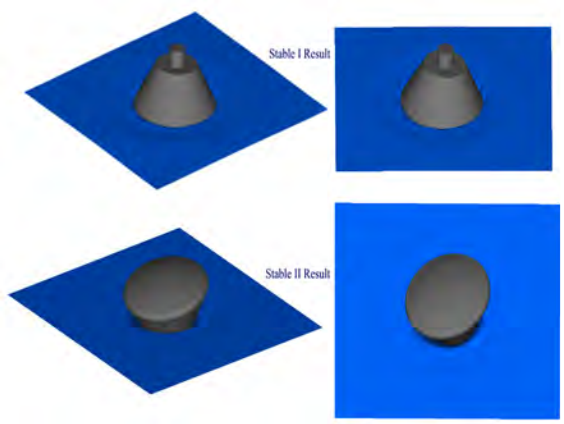

Figure 10. Block II Apollo Command Module Stable I & Stable II Simulation Result

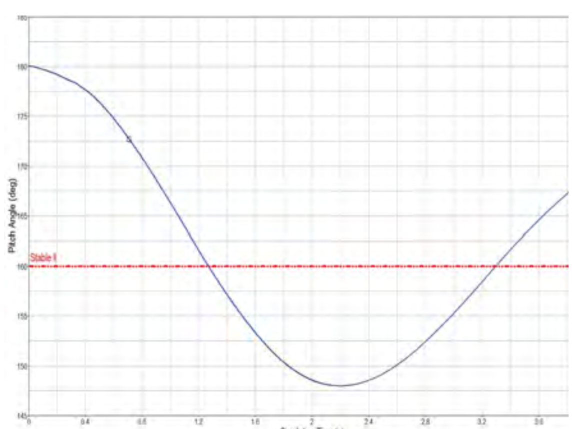

Figure 11. Block II Apollo Command Module Stable I & Stable II Simulation Result

In addition to the qualitative results depicted in Figure 9 and Figure 10, a plot of pitch angle time history for the Stable II simulation result is shown in Figure 11.

As mentioned previously, the FloatStab simulation results for the predictions of the Block I Apollo command module Stable I and Stable II pitch states are illustrated in Figure 7. Given the good correlation between the FloatStab and LS-DYNA results with those discussed in the Apollo Experience Report, the remainder of the cases for the Block II configuration were analyzed.

B. Apollo Block II Command Module, Nominal (Case B)

The nominal uprighting case is shown in Figure 12, showing that the three uprighting bags provide sufficient buoyant force to upright the vehicle from its initial 180 degree pitch angle.

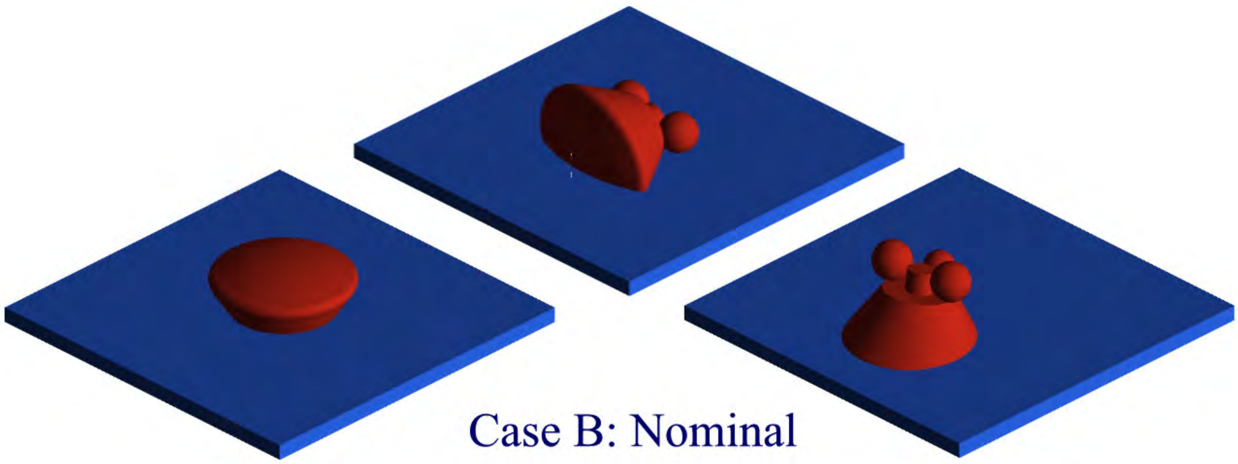

Figure 12. Apollo Command Module Uprighting System Performance, Nominal Condition (Left-to-Right)

In addition to simply illustrating the uprighting process for the simulation results, the results are directly compared to photos from the Block II Apollo command module testing as described in the Apollo Experience Report.

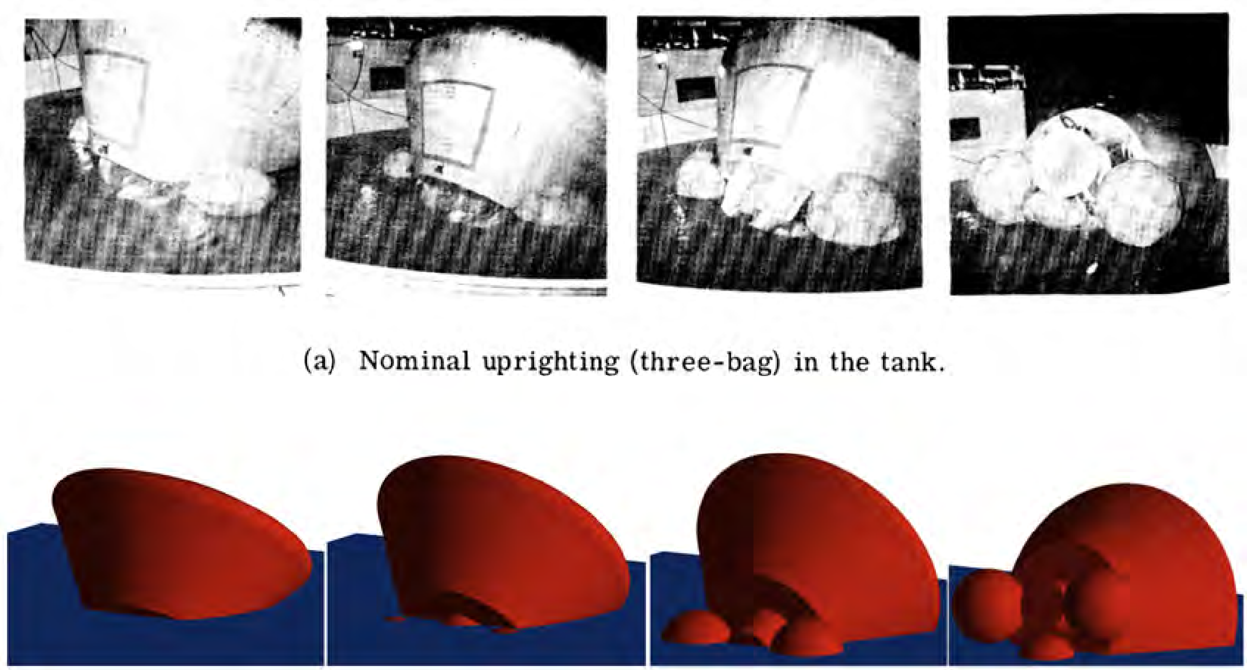

Figure 13. Comparison between Apollo Experience Report Uprighting System and LS-DYNA Simulation Predictions

There is an obvious correlation between the simulation and the actual performance of the command module as depicted in Figure 13. Some additional information regarding the temporal nature of the uprighting event for the actual Apollo command module could further the validity and correlation of the simulation predictions.

C. Apollo Block II, +Z-Bag Fail (Case C)

As discussed previously, in the case of a bag failure, upon splashdown the crewmembers need to shift their positions, and thereby the C.G., to facilitate the uprighting of the command module. As such, the center of gravity is shifted in the simulation prior to initialization.

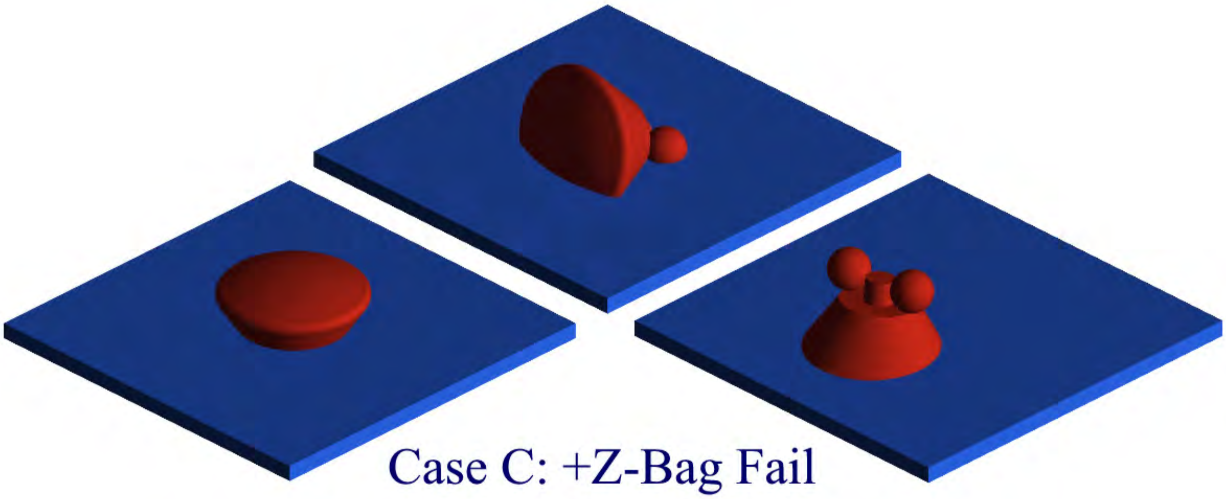

Figure 14. Apollo Command Module Uprighting System Performance, +Z-Bag Failure (Left-to-Right)

Additionally, some photos were provided in the Apollo Experience report showing this uprighting condition being tested and verified while at sea. Though these photos are slightly more washed out than those depicted in Figure 13, the performance characteristics and comparison to the simulation results are evident.

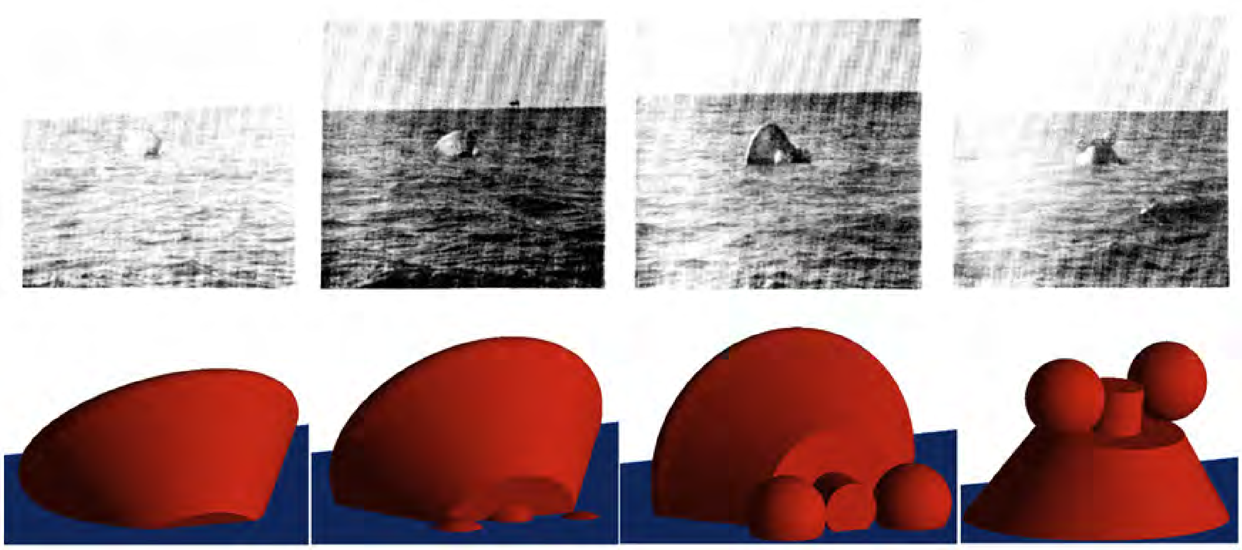

Figure 15. Comparison between Apollo Experience Report Uprighting System and LS-DYNA Simulation Predictions

As with the nominal (Case B) simulation predictions, additional information regarding the temporal nature of the uprighting event could help further validate and correlate these LS-DYNA simulations predictions.

D. Apollo Block II, +Y-Bag Fail (Case D)

The +Y-Bag failure is the worst-case bag failure scenario and the primary driver behind the crew relocation requirement. Rather than a nearly pure pitching moment uprighting case, the asymmetric buoyancy behavior creates a roll-moment that is coupled with a slightly weaker pitch-moment to facilitate the uprighting event. Due to the reduction in pitching moment associated with the elimination of the +Y-bag, this event slightly lags the other uprighting cases, as shown in Figure 17; however, it is evident that the LS-DYNA simulation accurately predicts that the system will still upright given these initial conditions.

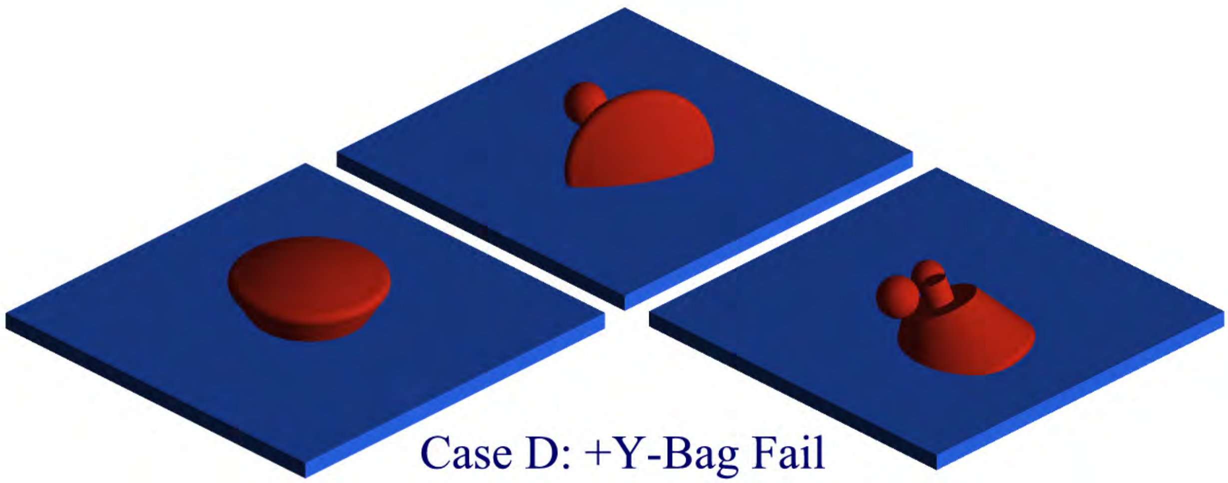

Figure 16. Apollo Command Module Uprighting System Performance, +Y-Bag Failure (Left-to-Right)

E. Graphical Representation of Uprighting System Performance

In addition to the results of the simulation animation, the pertinent rotational displacement and velocity data with respect to the local coordinate system at the center of gravity of the vehicle is shown in Figure 17 through Figure 21.

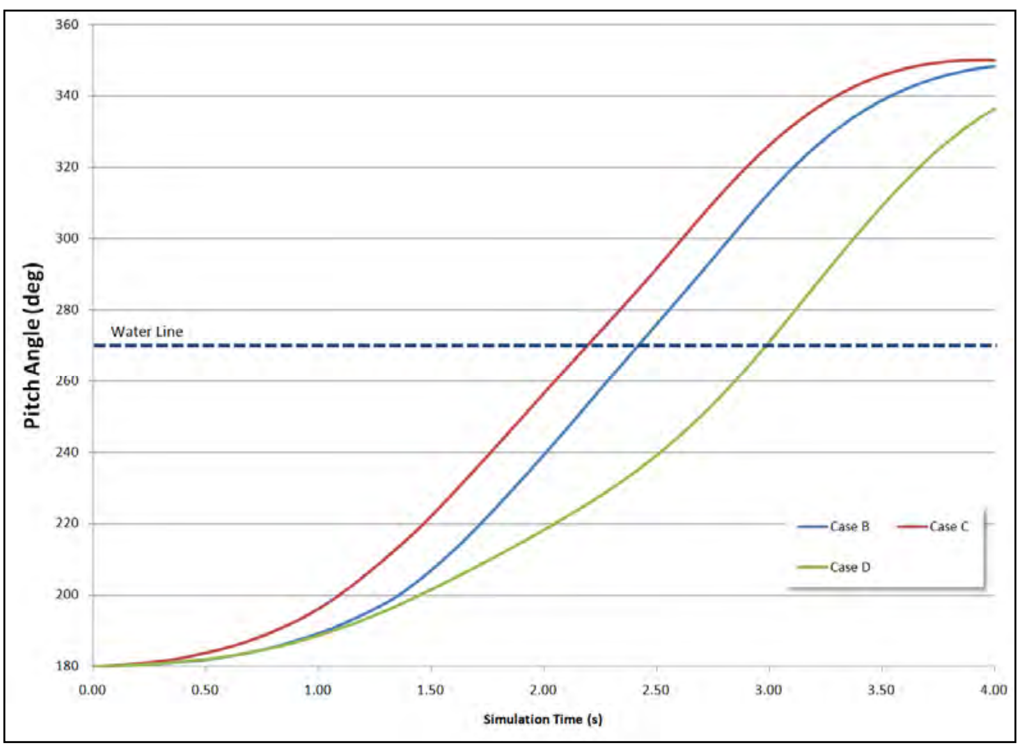

Figure 17. LS-DYNA Predicted Pitch Angle Time History

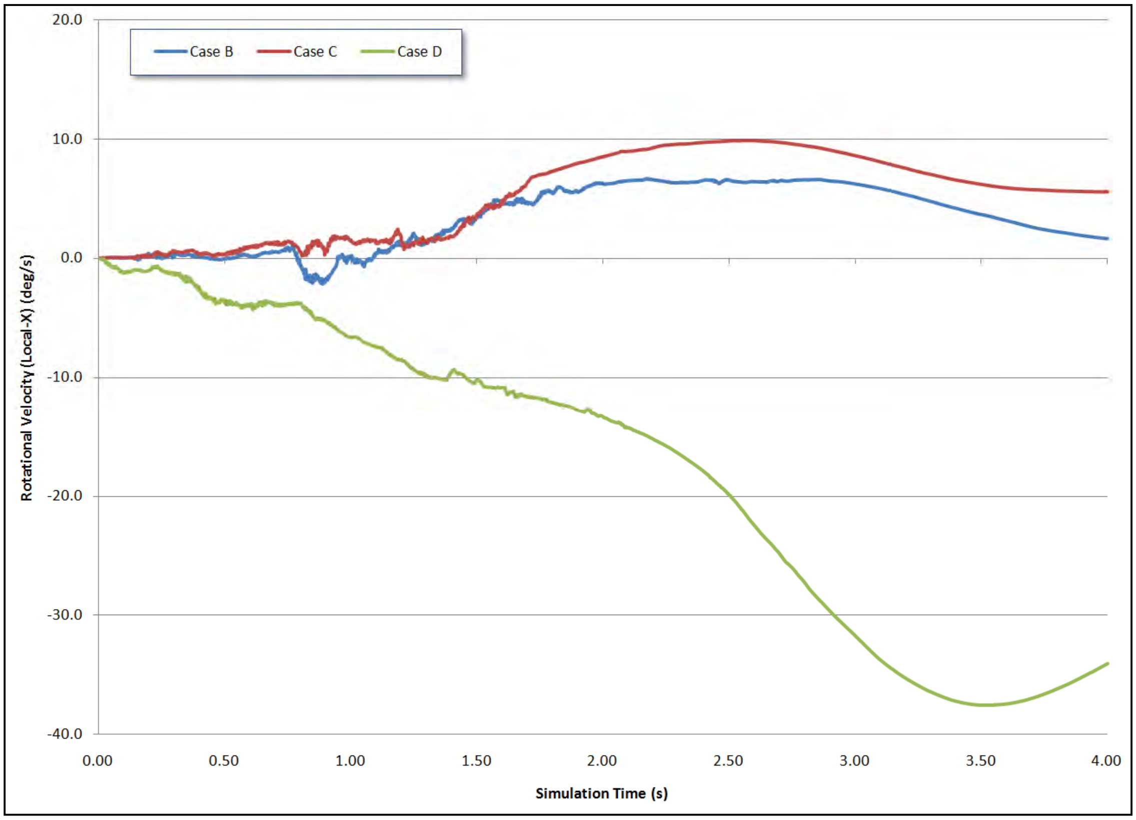

Figure 18. LS-DYNA Predicted Local-X Rotational Velocity

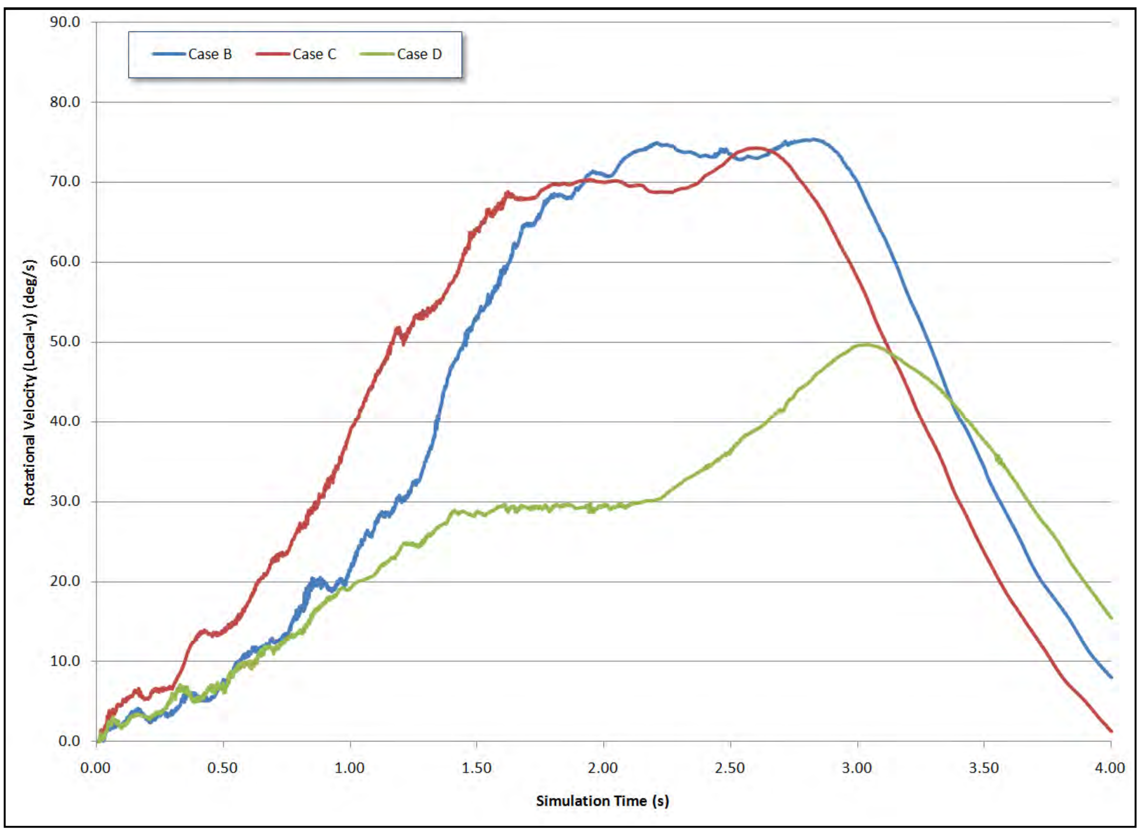

Figure 19. LS-DYNA Predicted Local-Y Rotational Velocity

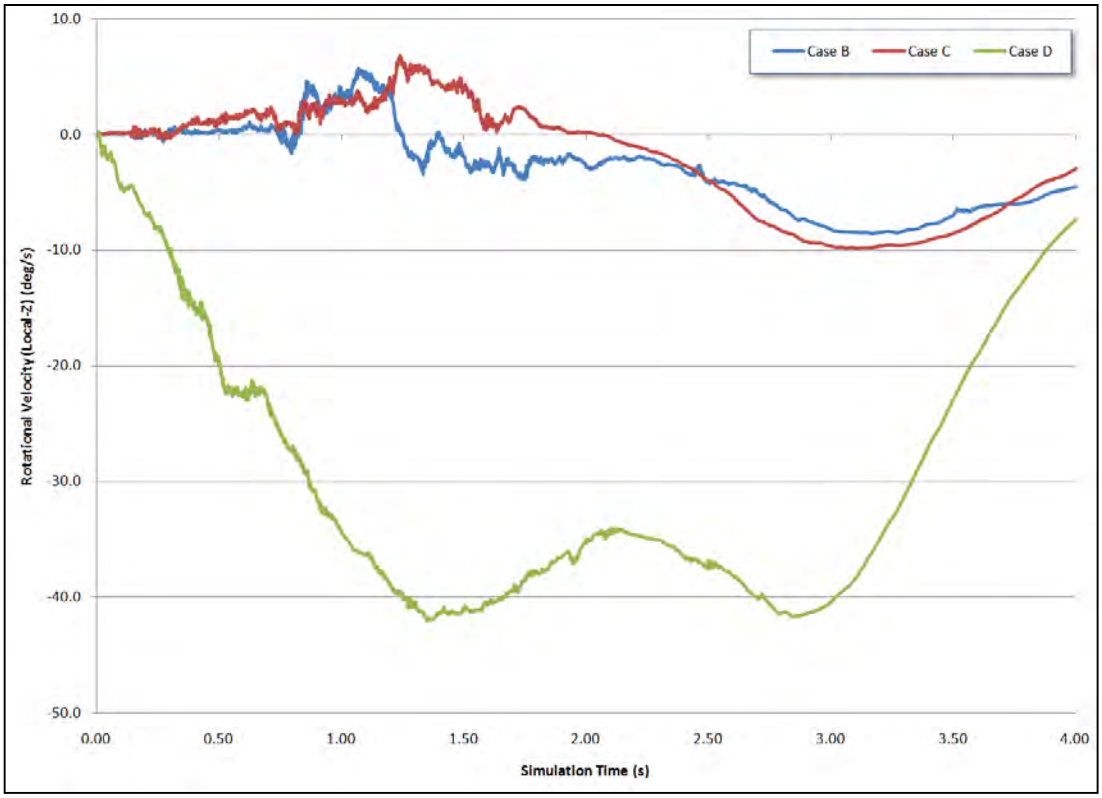

Figure 20. LS-DYNA Predicted Local-Z Rotational Velocity

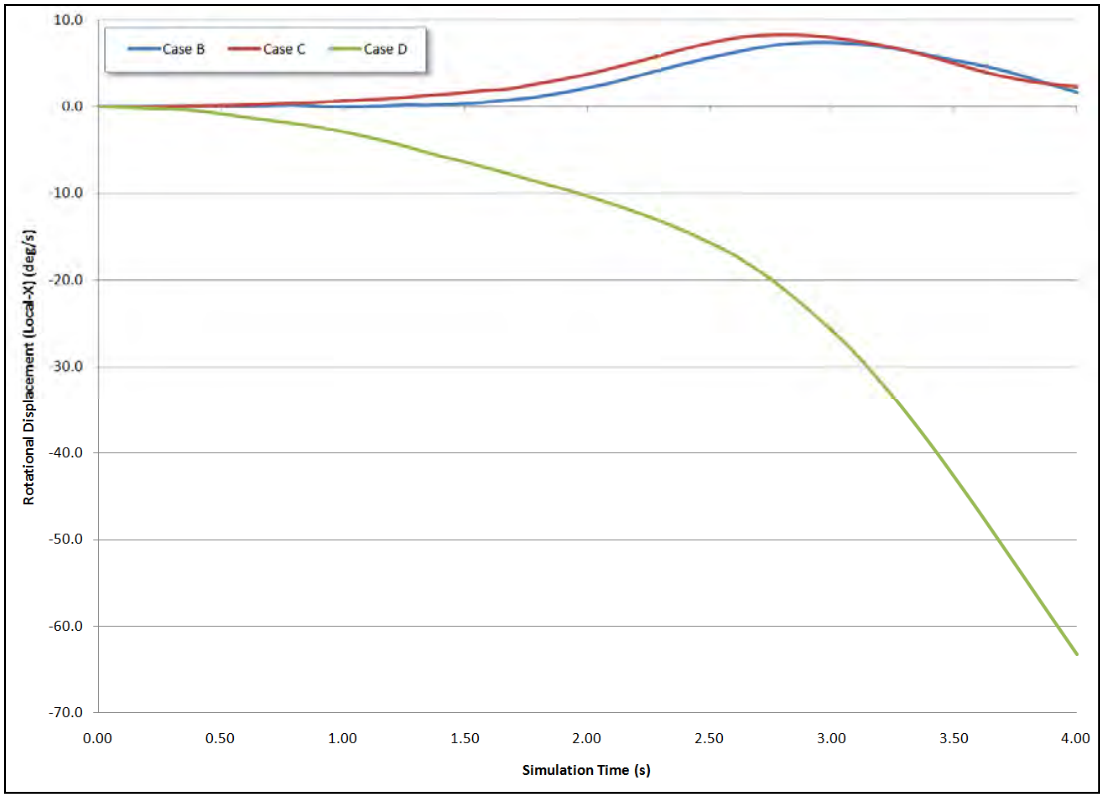

Figure 21. LS-DYNA Predicted Local-X Rotational Displacement

As expected, the nominal uprighting (Case B) and the +Z-Bag out uprighting (Case C) events are similar in overall performance. By introducing the asymmetry involved in the +Y-Bag out uprighting (Case D) event, the result is a completely different uprighting behavior, as thoroughly depicted in Figure 21. The differing behavior of the crew module during Case D uprighting is fully expected given the asymmetric buoyant restoring force associated with the loss of one of the Y-uprighting bags.

V. Conclusions

This paper has presented the use of the commercially available transient dynamic finite element analysis code LS-DYNA using an Arbitrary Lagrangian-Eulerian algorithm to replicate and validate the Apollo command module uprighting system test data and performance descriptions as described in the Apollo Experience Report – Command Module Uprighting System.

This simulation effort was originally intended to be the first in a series of Airborne Systems internal simulation developments pertaining to better defining the uprighting system performance using LS-DYNA. Even these preliminary results show that this methodology is certainly feasible. One of the advantages to implementing an analytical simulation methodology rather than solely relying on testing is the cost savings that could be realized once the simulation has been validated and the outputs from the simulation are supported by test data.

Additionally, this simulation methodology could be leveraged to easily perform feasibility studies on potential designs. For instance, given that the Apollo command module required that the crew be conscious and able to move from the couches to the aft bulkhead in the case of an uprighting bag failure. However, if a design were conceptualized that required the ability to perform the uprighting procedure independent of the crew's ability to shift the center of gravity, this simulation methodology could be used to explore the design space available to determine feasibility. Furthermore, given the current accelerated state of the commercial space industry, the necessity for design and development of a command module uprighting system is far more relevant than it has been since the Apollo era. From this, having a low-risk, test-proven simulation tool to assist in these efforts is likely to be very desirable.

Overall, this methodology could be adapted to assess the buoyant impacts of any number of uprighting systems. The potential for this uprighting simulation methodology to increase cost savings, define operable margins and reduce lead time over testing is evident, while maintaining the ability to perform design feasibility studies and provide accurate and verifiable results is clearly shown in the course of this paper.

References

[1]White, R. B., "NASA TN D-7081: Apollo Experience Report – Command Module Uprighting System," National Aeronautics and Space Administration. 1973.

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

[3]Taylor, A., "FLOATSTAB – A Tool for the Rapid Analysis of Floatation Stability Following Water Landing," AIAA-2005-1630, 18th AIAA Aerodynamic and Balloon Technology Conference and Seminar, 2005.Munich, Germany.