Characterization of Water Impact Splashdown Event of Space Shuttle Solid Rocket Booster Using LS-DYNA

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ABSTRACT

The ALE capability in LS DYNA is used to predict splashdown loads on a proposed replacement/upgrade of the hydrazine tanks on the thrust vector control system housed within the aft skirt of a Space Shuttle Solid Rocket Booster. Two preliminary studies are preformed in working towards conducting a full comprehensive analysis: An analysis of the proposed tank impacting water without supporting structure, and an analysis of actual space capsule water drop tests conducted at NASA's Langley Research Center. Results from the preliminary studies provide confidence that useful predictions can be made by applying the ALE methodology to a detailed analysis of a 26-degree section of the skirt with proposed tank attached. Results for all three studies are presented and compared to limited experimental data. The challenges of using the LS DYNA ALE capability for this type of analysis are discussed.

INTRODUCTION

Reusing the Solid Rocket Boosters (SRB's) on NASA's Space Shuttle saves millions of dollars each launch. At the end of their mission cycle, the boosters separate from the shuttle's external tank, descend to earth via parachutes, and splashdown in the ocean for recovery. Typical splashdown velocities of 80 feet per second create significant impact loads to the SRB structure, particularly to the aft skirt and its components. Figure 1 shows the SRB's in launch configuration on the Space Shuttle with its External Tank. Figure 2 identifies the aft skirt on the SRB and depicts the orientation of the booster as it splashes down in the ocean.

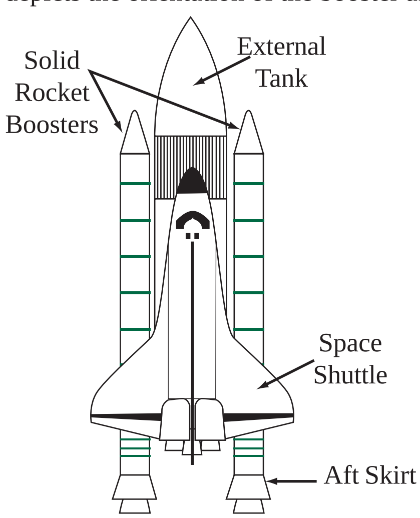


Figure1. Primary Components of Space Shuttle Launch Configuration

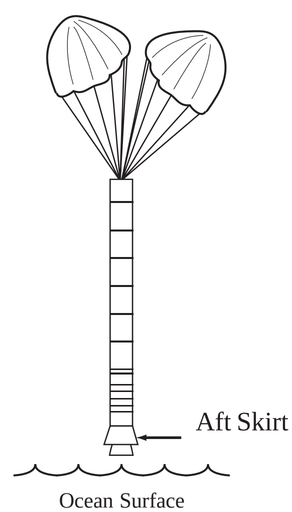


Figure2. Spashdown Orientation of SRB

Figure 3. Aft Skirt in NASA Assembly Facility Awaiting Integration to SRB

Figure 3 shows a photograph of an aft skirt awaiting integration to an SRB. Within the aft skirt of each SRB is a complex thrust vector control system (TVC), which mechanically directs the nozzle at the end of the booster to steer the shuttle during its initial ascent. The TVC consists of two hydraulic gimbal servo-actuators each independently powered by its own auxiliary power unit (APU) and hydraulic system. Hydrazine, currently used as the propellant for the TVC, is an extremely hazardous material. Safety concerns, regarding this, have provided motivation to

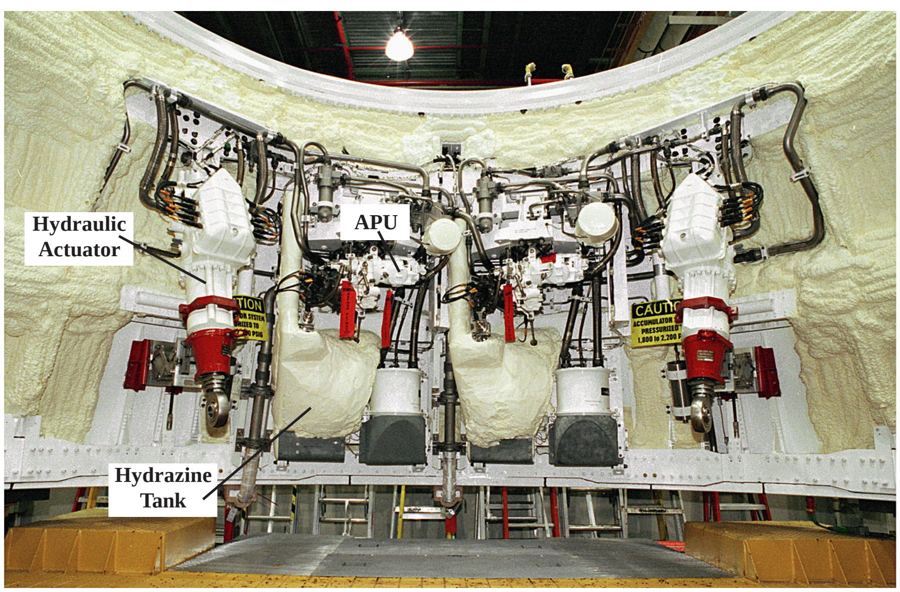


Figure 4. Thrust Vector Control System Inside Aft Skirt

propose a new propellant system using helium in place of hydrazine. Figure 4 is a photograph of the TVC system inside the aft skirt with the actuators, APU's and hydrazine tanks identified.

Experience with over 100 launches has enabled NASA to understand and minimize splashdown damage to current aft skirt and TVC components. The proposed helium tanks, however, are approximately six times the volume of the hydrazine tanks which could significantly change the splashdown impact loads on the TVC system. Consequently, a detailed analysis of the water impact event would be required in the design process of a new TVC system.

In an attempt to predict these new load conditions, LS-DYNA with its ALE capability is being employed to analyze a section of the aft skirt integrated with a proposed TVC helium tank as it undergoes a simulated splashdown event. The analysis results, presented here, are in general agreement with the limited qualitative and quantitative experimental data available for comparison. This provides sound encouragement that ALE LS DYNA capability will be useful for characterizing complex water impact problems such as this one.

Despite the relative success of this effort, this is only a small first step in developing the analysis capability for such problems. Several issues were brought to light during this project; First, more study is needed to better understand the limitations and/or validity of the material model used to define the water behavior in these analyses. Second, model sensitivities to the use of different boundary conditions should be investigated. Last, it should be noted that the use of a parallel solver could greatly reduce turn around time of such analyses.

APPROACH

This effort was broken into three analysis tasks. The first two were performed to establish a workflow methodology for conducting the ALE analyses with LS DYNA as well as develop a level of confidence that the DYNA results were reasonable ones. All of the analysis results presented here were run on a single processor Silicon Graphics Origin 2000 R10000 processor. The results from the first two analysis tasks yielded reasonable predictions, as will be discussed, and provided justification to commit the resources to perform a full-scale aft skirt analysis. It should be noted that attempts were made to analyze the full aft skirt analysis using parallel processors, however, an acceptable solution had not yet been obtained at the time of this writing.

The English system of units was used in the development of the analysis models (lb-in-sec). One of the most significant issues in this effort was the determination of material properties for water for the analyses. A literature search provided no historical data that would be useful for these purposes and a decision was eventually made to use the simplest of representations for water. The MAT_ELASTIC_FLUD card was used to characterize water behavior. Three parameters were explicitly defined on this card: Water density, bulk modulus, and a tensor viscosity coefficient. These values were 9.59e-5, 3.30e5,and .05 respectively. All other values on the card were left to their defaults. In addition, initial velocities for each analysis presented in this paper were set in the direction transverse and towards the free surface of the fluid mesh. No lateral initial velocities were assigned for any analysis.

In each case, symmetric boundary conditions were utilized to reduce the problem size. These constraints were applied to the ALE mesh in the same fashion as one would for a typical DYNA structural analysis. In other words, nodes that lie on a plane of symmetry were constrained to move only within that plane.

Helium Tank Water Impact Analysis

The first analysis modeled a half section of the proposed helium tank impacting a volume of water as an independent structure. The primary purpose of this analysis was to establish that the ALE methodology was working properly and to develop an idea as to what fidelity of mesh would be necessary to get reasonable results. The mesh, shown in Figure 5, consisted of 77184 elements and 82228 nodes. Symmetry was used to model half of the problem. The tank, made of shell elements, was defined as elastic steel 0.5" thick. An initial velocity of 960 inches/sec was assigned to the tank.

Reentry Capsule Water Impact

The second analysis was based on an experimental program conducted at NASA's Langley Research Center in 1959, reference 1, to define the water landing characteristics of a space capsule similar to that used for the Mercury Program. The primary focus of the research was to establish peak decelerations for various splashdown orientations of the capsule for both full and 1/12-scale test articles.

These experiments were conducted using several different initial conditions, however, only one case was selected for DYNA analysis: A full-scale capsule impacting a body of water at 360 inches per second. The full-scale capsule was 10.5 feet in height, 7.0 feet in diameter at the base, and weighed 2150 lb. Figure 6 depicts the capsule and fluid mesh created for this analysis. As with the previous problem, symmetry was used to reduce the problem size by half. This model consisted of 84836 elements and 90066 nodes. Primary interest was in predicting the

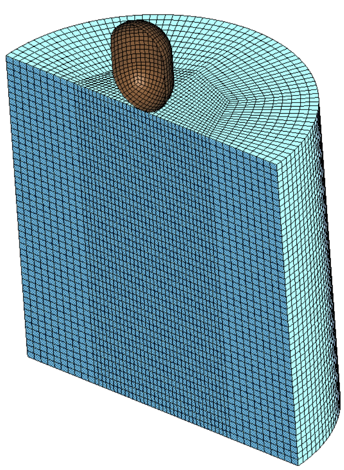


Figure 5. Mesh for Helium Tank Water Impact Analysis

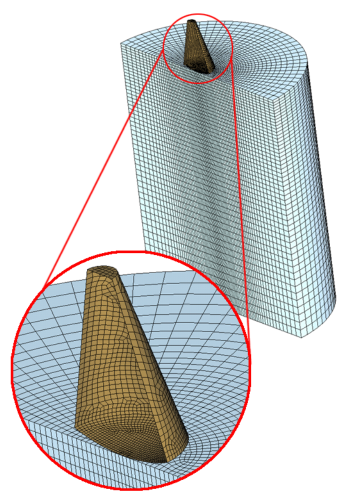
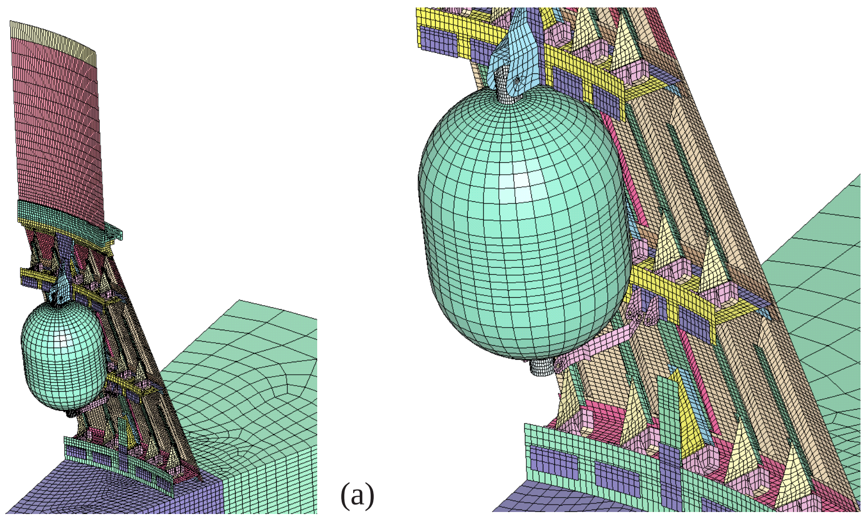


Figure 6. Mesh for Reentry Capsule Water Impact Analysis

capsule deceleration; hence, the capsule was modeled as a rigid body with an accelerometer element added to it.

Full Scale Aft Skirt Analysis

The final analysis performed in this investigation was of a 26-degree section of an SRB aft skirt with the proposed helium tank integrated into the structure. The mesh for the aft skirt analysis, seen in Figures 7a and 7b, contained 164537 nodes and 161133 elements. The majority of the structural model was made up of shell elements, which lay on the geometric centerlines of the plate structure they were representing. In some areas, plates were welded or bolted together on the skirt to stiffen the local structure or join panels together. These instances were modeled by connecting the joined panels with very stiff beam elements whose lengths were determined by the distance between the centerlines of those panels. Over 8000 beams were used in this model. Contact between fluid and structure was limited to the aft skirt outer skin, the three main circumferential stiffening rings, and the helium tank. The initial velocity of the skirt was 960 inches per second. The aft skirt was modeled entirely as an elastic material using aluminum



(a) (b)

Figure 7. Mesh for Full Scale SRB Aft Skirt Water Impact Analysis

material properties with the exception of the helium tank attachment pins which we modeled as elastic Steel.

DISCUSSION OF RESULTS

All three analysis problems proved to be well conditioned and contact between the fluid and solid was obeyed in each case

Some of the results presented are LS POST images taken at various times. Graphically representing the deformation of the water surface, which is somewhat non intuitive, is accomplished by applying "History Variable #2" to the fringe component. This variable, found under the miscellaneous pick on the FCOMP menu, represents the volume fraction of the water in the ALE mesh. To use an iso-surface to visualize the free surface deformation of the fluid, the minimum and maximum fringe ranges for this component were set to .5 and .51 respectively through the user interface pick on the RANGE menu and the iso-surface visualization pick selected.

Helium Tank Water Impact Analysis

Running the analysis to .1653 seconds took just over 38 hours. The predicted cavity formed in the water by the impacting tank was compared to high-speed photographic images of a ball bearing being dropped into a vessel filled with water. No scientific effort was made to establish scaling or similarity parameters between the predicted and measured events but it was noteworthy to see the striking resemblance of the two cavity formations. It was considered to be a positive outcome that the most basic numerical representation of water used with a DYNA ALE

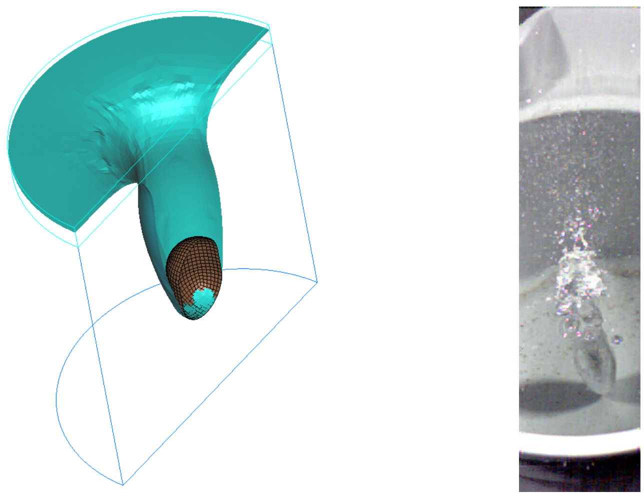


Figure 8. Comparison of DYNA Analysis of Helium Tank Water Impact with High Speed Film Image of Ball Bearing Impact in Water Bucket

analysis appeared to be capturing the general behavior of a water/structure impact. Figure 8 shows a side-by-side comparison of the DYNA prediction with a high-speed image.

Reentry Capsule Water Impact

This analysis was run out to .2145 seconds taking just 13.5 hours to complete. As with the previous analysis, this problem was well behaved throughout the run. Attention to the results of this analysis was focused on the Z-acceleration (direction transverse to the water surface) predictions from the seatbelt accelerometer element. Details, provided in reference 1, for the accelerometer that measured the downward acceleration on the full scale test, stated that it could measure up to 100 g, had a natural frequency of 640 Hz, and was damped to 65% of critical damping. The recording equipment, which read the data, did so at 600 Hz. Figure 9 shows an acceleration plot as a function of time, which compares data from the Langley full-scale capsule drop tests to both raw and filtered accelerometer predictions from this analysis. Curve A is the raw unfiltered analysis data. Curves B through E are filtered from Curve A data using a Butterworth filter at various frequency limits. Curve F has been plotted from the observed data in reference 1. Clearly, the data from the Langley experiments had been filtered in some fashion, however, no discussion was provided in reference 1 as to how it was done. It was reasoned that by applying a filter to the DYNA data and increasing its frequency cutoff incrementally until all of the higher frequency oscillations not seen in the observed data were removed, that a comparison of the experiment and the predictions could be made. The Butterworth filter using 50-60 Hz limits (Curves C and D) yielded curves that were remarkably close to the

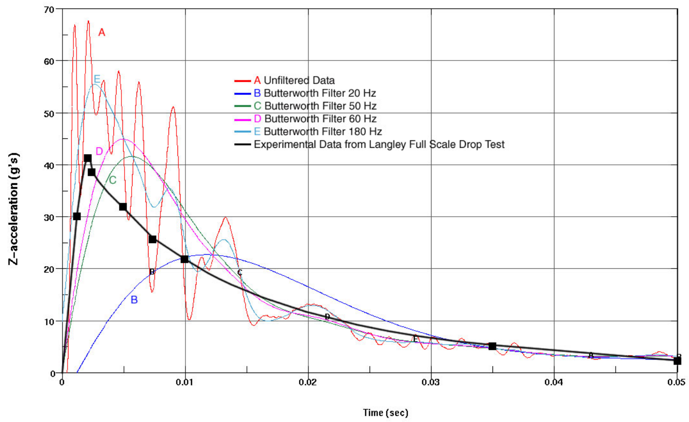


Figure 9. Comparison of Predicted and Measured Acceleration Data for Langley Capsule Drop Tests

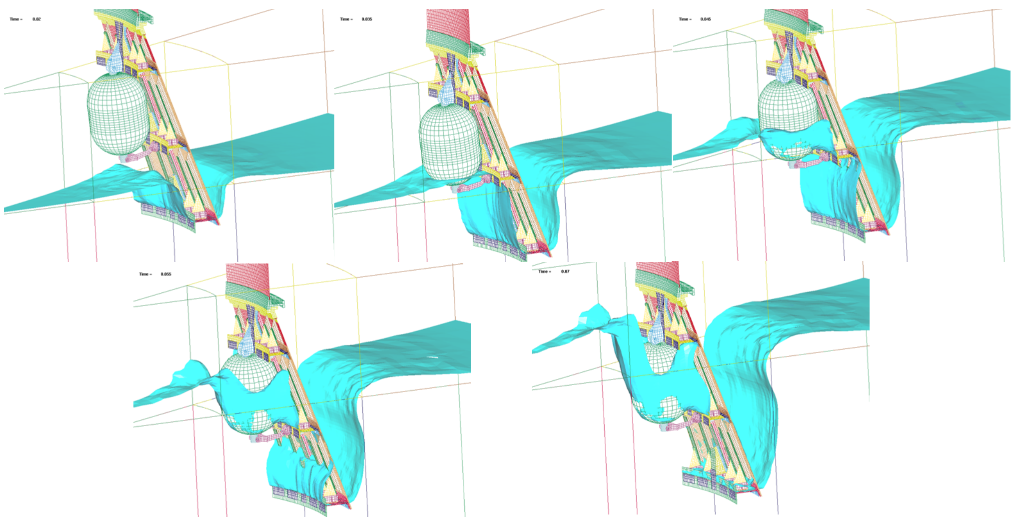


Figure 10. Five Animation Images at Various Time Steps from Full Aft Skirt Analysis

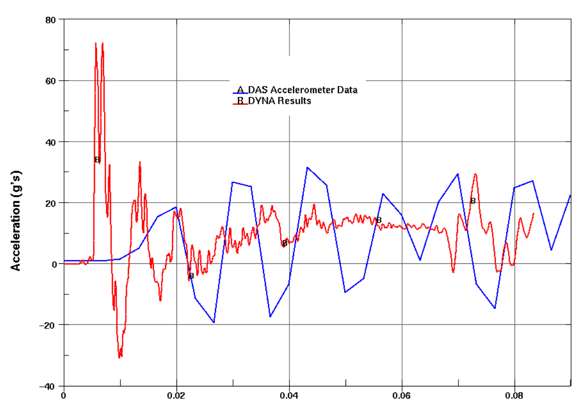


Figure 11. Comparison of Predicted and Measured Acceleration Data for Full Aft Skirt Splashdown

Langley experimental data providing a relatively high degree of confidence in the applicability of the DYNA ALE methodology to this class of problems.

Full Scale Aft Skirt Analysis
Running this analysis to .09 seconds took 510 hours to complete. The analysis was well behaved up to .03 seconds at which point a notable increase in hourglass energy was observed. The analysis was allowed to continue for the purposed of generating data for this publication, however, additional work is currently ongoing to obtain a reasonable analysis model. Figure 10 shows five instances throughout the analysis. Note that the model predicts the secondary water impacts on the middle and upper channel sections of the skirt. Figure 11 is a graph comparing measured and predicted accelerometer data. The measured data was taken from an onboard data acquisition system (DAS) on the left hand booster from the STS-106 mission. No filtering was applied to the DYNA predictions and it is unknown what, if any, filtering was applied to the measured data. With the exception of the initial spike in the DYNA data, it can be argued that there is general agreement between analysis and prediction. The Sampling rate of the DAS data was substantially less than that of the analysis and in order to make a stronger case for agreement between results, a higher DAS sampling rate would be desired.

Expertise in applying filtering techniques to accelerometer data is a necessity in order to make quality assessments as to the validity of analysis predictions for problems of this nature, particularly when comparing measured and computed data. Future work on this problem will employ a filtering technique in order to make better engineering judgments from the data.

SUMMARY

Using LS DYNA with its ALE capability to characterize a Space Shuttle Solid Rocket Booster splashdown event with reasonable results has been demonstrated suggesting that this analysis technique could yield valuable insight to water impact problems. Future work is anticipated on analyzing the latter part of the SRB splashdown event in which the booster falls on its side and the forward skirt at the top of the booster is subjected to severe water impact loads.

Several issues are worthy of mention at this juncture; 1) The water model used in this analysis was a very rudimentary one as no verified material models were available for our use in this problem. It would be of significant value should a more robust characterization of water be developed for this class of problems. 2) The computational demands of a problem of this nature are immense as demonstrated by the full aft skirt analysis. Computational constraints for this effort demanded that we hold our model to under 200,000 elements, however it ultimately would be desired that we increase the resolution of our ALE mesh by a factor of 8 to 10 in order to obtain a better solution. Further investigation is in order to develop a parallel solution procedure enabling a model of higher resolution. 3) Early considerations in setting up the meshes for these analyses included the use of non-reflecting boundary conditions on the ALE mesh. Some problems were created in using these and it was decided to apply basic planar constraints to the planes of symmetry to simplify the problem. It is possible that a better-conditioned analysis might be obtained using the non-reflecting constraints and this issue should be considered in future analyses of this type. 4) Data filtering is imperative for correct interpretation of such highly transient results. Without a strong fundamental understanding of filtering techniques, the quality of engineering decisions made from impact analyses is reduced.

ACKNOWLEDGEMENTS

The authors would like to thank Mike Pereira and Kelley Carney of NASA Glenn Research Center, and Dallas McFadden, Richard Knockelman, and Pete McFadden of United Space Alliance for their contributions to this work, which greatly enhanced our efforts to characterize this problem.

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