NASA/TM—2003-212093

Finite Element Simulation of a Space Shuttle Solid Rocket Booster Aft Skirt Splashdown Using an Arbitrary Lagrangian-Eulerian Approach

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January 2003

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Acknowledgments

The author would like to thank Mike Pereira and Kelley Carney, NASA Glenn Research Center, Dallas McFadden, Richard Knockelman, and Pete McFadden, United States Alliance, and Khanh Bui, Livermore Software Technology Corporation, for their contributions to this work, which greatly enhanced my efforts to characterize this problem.

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ABSTRACT

Explicit finite element techniques employing an Arbitrary Lagrangian-Eulerian (ALE) methodology, within the transient dynamic code LS-DYNA, are 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 performed prior to the full aft skirt analysis: An analysis of the proposed tank impacting water without supporting aft skirt structure, and an analysis of 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 duty 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 SRBs integrated with the external tank and space shuttle orbiter vehicle in launch configuration. Figure 2 identifies the aft skirt on the SRB and depicts the orientation of the booster as it splashes down into the ocean.

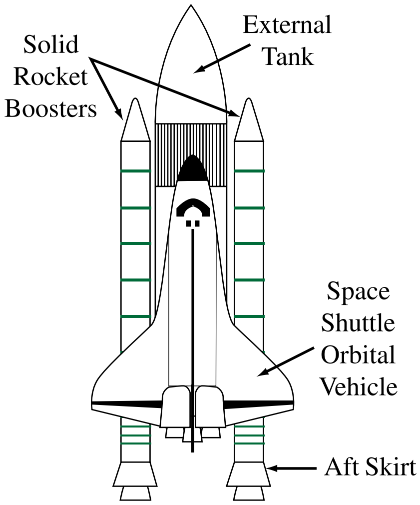

Figure 1. Primary Components of Space Shuttle Launch Configuration.

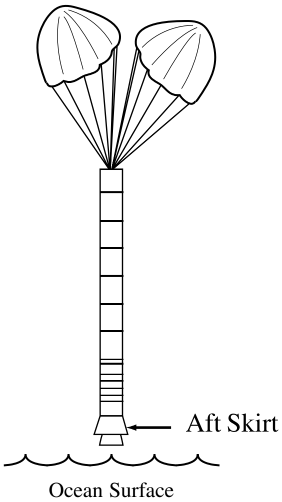

Figure 2. Spashdown Orientation of SRB.

Figure 3 shows a photograph of an actual aft skirt awaiting integration to an SRB (personnel in this figure provide a reference for scale). Each SRB aft skirt houses 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. Figure 4 is a photograph of the TVC system inside the aft skirt with the actuators, APUs and hydrazine tanks identified. Hydrazine, currently used as the propellant for the TVC, is an extremely hazardous material. Safety concerns, regarding this hazard, have provided motivation to propose a new propellant system using helium in place of hydrazine.

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

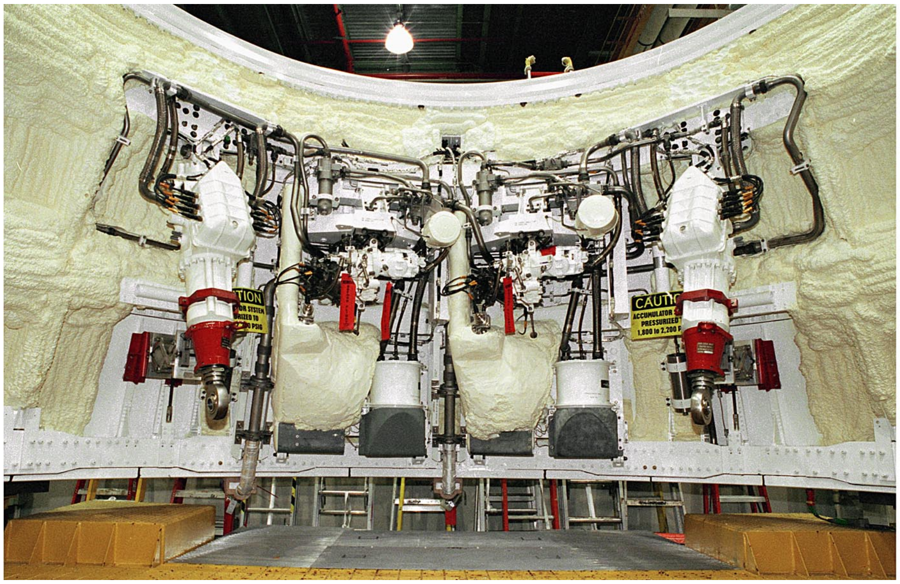

Figure 4. Thrust Vector Control System Inside Space Shuttle SRB.

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 and would significantly change the exposure characteristics of water impact loads to the system should they be implemented. As a consequence, a new detailed analysis of the water impact event with the new helium tanks would be required during the design stage.

Only recently has the ALE capability in LS-DYNA$_1$, an explicit finite element code (ref. 1), become feasible for analyzing water impact problems. The primary objective of this work is to establish the practicality of using such methods to model the SRB splashdown event in a timely fashion. To demonstrate this, LS-DYNA is used to analyze several different types of water impact problems. The analysis results, presented here, are in general agreement with the limited qualitative and quantitative experimental data available for comparison. This provides encouragement that the LS-DYNA ALE capability will be useful for characterizing complex water impact problems such as this one.

Modeling Approach and Analysis Results

The Arbitrary-Lagrangian-Eulerian method utilizes two mesh types in an analysis: The Lagrangian mesh, associated with the typical finite element analysis, distorts as it responds to the loading and boundary conditions in the analysis. The Eulerian mesh, conversely, remains fixed throughout the analysis and tracks material as it moves throughout the mesh. Combining these two meshes together in a single analysis provides the ability to predict the interaction between fluid and structural elements. The ALE approach was suited perfectly for this analysis with the SRB structure being modeled with the Lagrangian mesh, and the water being modeled with the Eulerian mesh.

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 to develop a level of confidence that the LS-DYNA results were reasonable. 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 recourses to perform a full-scale aft skirt analysis.

One of the most significant issues in this effort was the determination of material properties and the respective constitutive models to be used to characterize water for the analyses. LS-DYNA enables the user to choose from a variety of material models for property definitions, however, in the absence of an advanced material model for water, the most rudimentary characterization of water was made for these analyses using the LS-DYNA MAT_ELASTIC_FLUID definition. Three parameters were explicitly defined on this card: Water density, bulk modulus, and a tensor viscosity coefficient. Density and elastic modulus values, taken from the literature, were 9.59e-5 lbm/in^3, 3.30e5 lb/in^2, respectively. A tensor viscosity value of .05 was assigned based on recommendations from the Livermore Software Technology Corporation, and a default value for cavitation pressure of 1.0E20 lb/in^2 was used.

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 ALE structural analysis. In other words, nodes that lie on a plane of symmetry were constrained to move only within that plane. Eight-node bricks were used for all of the Eulerian fluid meshes which consisted of water and void. A void region must be defined to represent the air above the fluid free surface in order to accommodate the splash effect upon impact. For ease of visualization, elements representing voids in the models are not shown in the figures to follow. The Eulerian mesh sizes were somewhat driven by the Lagrangian meshes in these problems. Once the structural mesh was developed, the fluid mesh was created with the same general element sizes in order to avoid contact problems that can occur with elements that have noticeable disparity in their sizes.

Initial velocities of the impacting structure for each analysis presented in this paper were set in the direction vertically towards the horizontal free surface of the fluid mesh. No lateral initial velocities were assigned for any analysis.

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 four-node shell elements, was defined as elastic steel 0.5” thick. Elastic modulus, density, and Poisson’s ratio were 28.0e6 lb/ in^2, 7.24e-4 lbm/in^3, and 0.3 respectively. An initial velocity of 960 inches/sec was assigned to the tank.

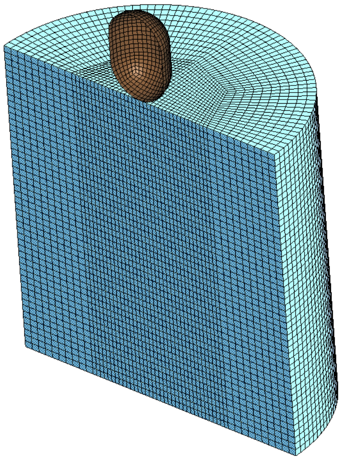

Figure 5. Mesh for Helium Tank Water Impact Analysis.

Results

Running the analysis to .1653 seconds took just over 38 cpu 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 analysis appeared to be capturing the general behavior of a water/structure impact. Figure 6 shows a side-by-side comparison of the DYNA prediction with a high-speed image.

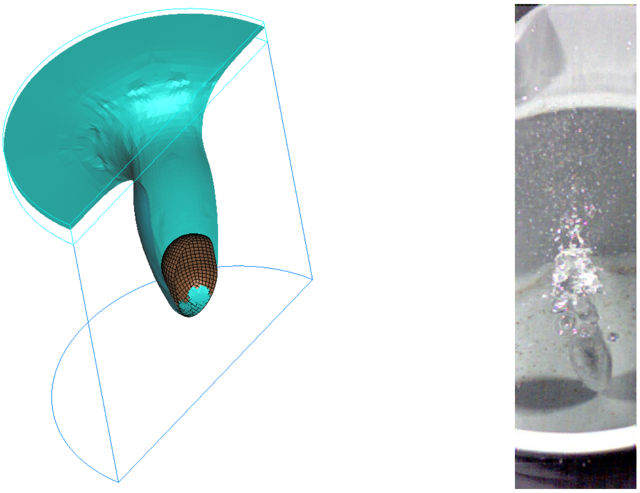

Figure 6. Comparison of DYNA Analysis of Helium Tank Water Impact with High Speed Film Image of Ball Bearing Impact in Water Bucket.

Reentry Capsule Water Impact

This second analysis was chosen for both the simplicity of the problem and the existence of experimental observations. It was based on an experimental program conducted at NASA’s Langley Research Center in 1959,[2] 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 7 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 capsule deceleration; hence, the capsule was modeled from four-node shells as a magnesium rigid body with an accelerometer element added to it. Elastic modulus and density for the capsule were 6.5e6 lb/ in^2, 1.674e-4 lbm/in^3 respectively.

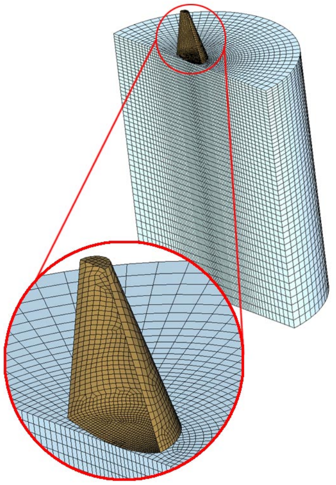

Figure 7. Mesh for Reentry Capsule Water Impact Analysis.

Results

This analysis was run out to .2145 seconds taking just 13.5 cpu 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 capsules Z-acceleration (direction transverse to the water surface) predictions. Details, provided in reference 2, 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 8 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 B is the raw unfiltered analysis data, curve A is the raw data filtered with a Butterworth filter at 50 Hz and curve C has been plotted from the observed data in reference 2.

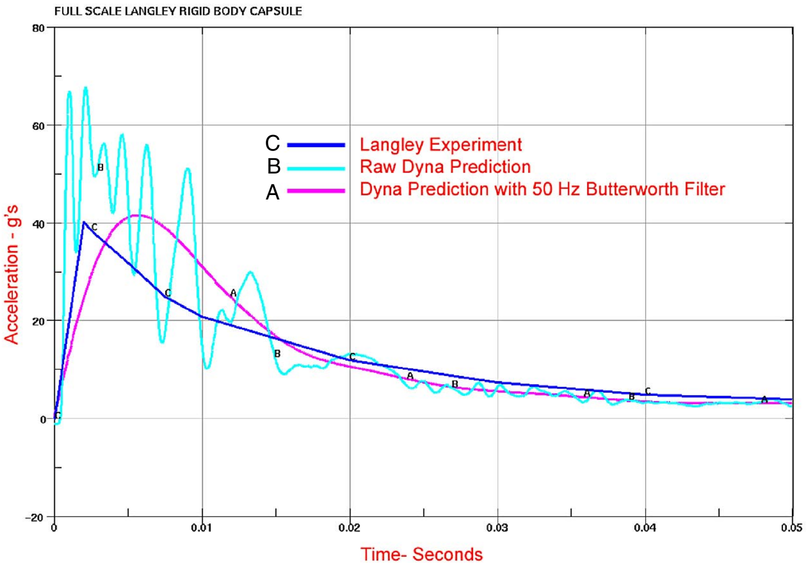

Figure 8. Comparison of Predicted and Measured Acceleration Data for Langley Capsule Drop Tests.

Clearly, the data from the capsule drop tests had been filtered in some fashion, however, no discussion was provided in reference 2 as to how it was done. It was reasoned that by applying a filter to the DYNA predictions 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 yielded curves that were very close to the 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

Results of the helium tank and reentry capsule analyses provided confidence that it would be worthwhile to pursue a full scale aft skirt analysis. A mesh was constructed 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 9a and 9b, 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 add more strength to the overall structure. 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 for the material properties. Density, elastic modulus, and Poisson's ratio, were 2.656e-4 lbm/in^3, 10.5e6 lb/in^2, and .33 respectively.

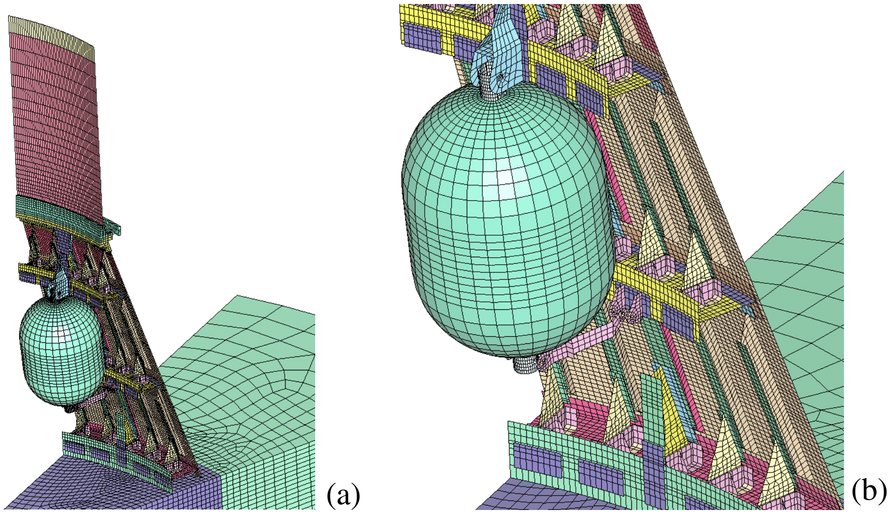

Figure 9. Mesh for Full Scale SRB Aft Skirt Water Impact Analysis.

Results

Running this analysis to .09 seconds took 510 cpu hours to complete. The analysis was well behaved up to .03 seconds at which point a notable increase in hourglass energy was observed indicating that remeshing portions of the mesh might be necessary. Figure 10 shows five instances from the analysis. Note that the model predicts the secondary water impacts on the middle and upper channel sections of the skirt. Post impact inspection of the aft skirt has indicated the existence of these secondary water impacts. 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.[3] This data was provided electronically from SRB engineers at Kennedy Space Center. 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 with data filtering techniques of 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.

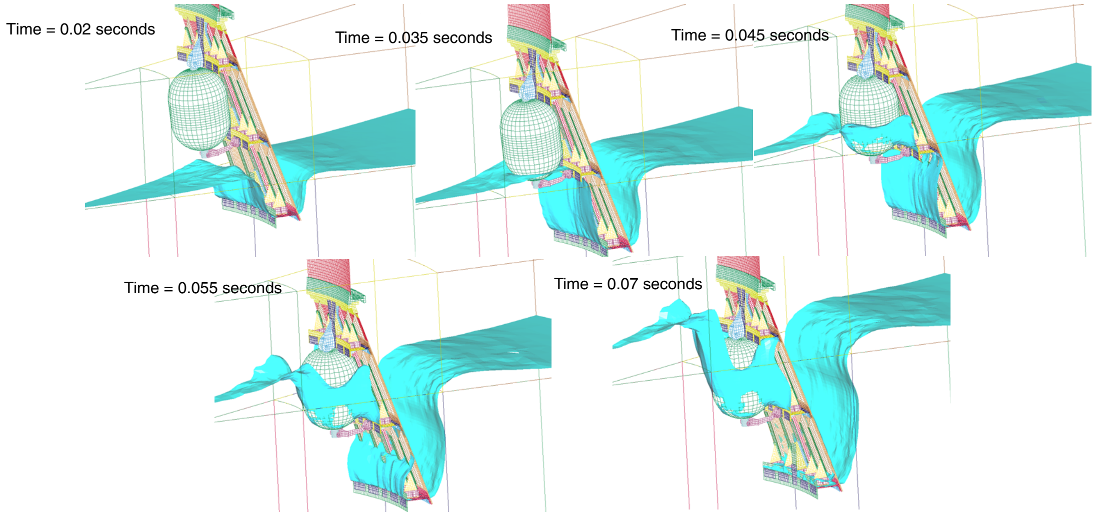

Figure 10. Five Animation Images at Various Time Steps from Full Aft Skirt Analysis.

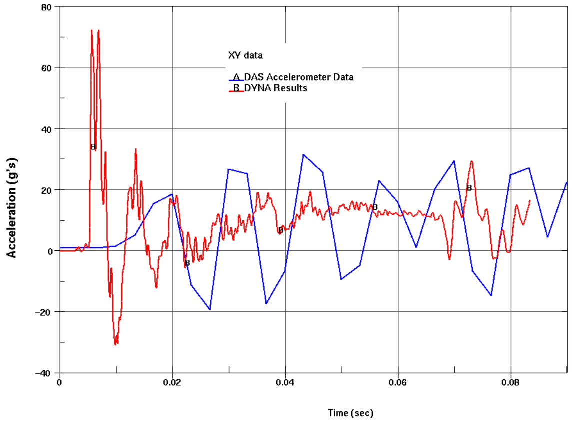

Figure 11. Comparison of Predicted and Measured Acceleration Data
for Full Aft Skirt Splashdown.

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 potentially subjected to severe water impact loads.

Several issues were brought to light during this project; 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. In order to keep the analysis turnaround times to a reasonable level, the models in this effort were held 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 (numerically removing non-pertinent frequency data from the experimental and computational results) 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.

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2. McGehee, J.R. and Hathaway, M.E. (1959). “ Water-Landing Characteristics of a Reentry Capsule” NASA Memo 5-32-59L NASA Langley Research Center, Langley Field, VA.
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** January 2003	**3. REPORT TYPE AND DATES COVERED** Technical Memorandum

4. TITLE AND SUBTITLE Finite Element Simulation of a Space Shuttle Solid Rocket Booster Aft Skirt Splashdown Using an Arbitrary Lagrangian-Eulerian Approach	**5. FUNDING NUMBERS** WBS–22–721–26–13
6. AUTHOR(S) Matthew E. Melis	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135–3191	**8. PERFORMING ORGANIZATION REPORT NUMBER** E–13745
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546–0001	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER** NASA TM—2003-212093

11. SUPPLEMENTARY NOTES

Responsible person, Matthew E. Melis, organization code 5930, 216–433–3322.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Categories: 15, 39, and 34 Distribution: Nonstandard Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.	**12b. DISTRIBUTION CODE**

13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS Explicit finite element; Fluid structure; Arbitrary Lagrangian-Eulerian; ALE; Splashdown water impact; Solid rocket booster; SRB	**15. NUMBER OF PAGES** 14
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102