Water Impact Prediction Tool for Recoverable Rockets

Extended Abstract Submitted For

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Introduction

Reusing components from a rocket launch can be cost saving. NASA's space shuttle system has reusable components that return to the Earth and impact the ocean. A primary example is the Space Shuttle Solid Rocket Booster (SRB) that descends on parachutes to the Earth after separation and impacts the ocean. Water impact generates significant structural loads that can damage the booster, so it is important to study this event in detail in the design of the recovery system. Some recent examples of damage due to water impact include the Ares I-X First Stage deformation as seen in Figure 1 and the loss of the SpaceX Falcon 9 First Stage.

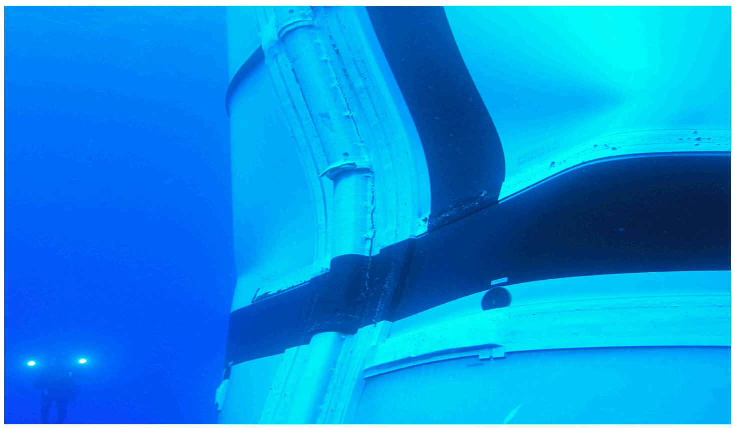

Figure 1: Ares I-X First Stage Deformation from Water Impact

To ensure that a component can be recovered or that the design of the recovery system is adequate, an adequate set of structural loads is necessary for use in failure assessments. However, this task is difficult since there are many conditions that affect how a component impacts the water and the resulting structural loading that a component sees. These conditions include the angle of impact with respect to the water, the horizontal and vertical velocities, the rotation rate, the wave height and speed, and many others.

There have been attempts to simulate water impact. One approach is to analyze water impact using explicit finite element techniques such as those employed by the LS-Dyna tool [1]. Though very detailed, this approach is time consuming and would not be suitable for running Monte Carlo or optimization analyses.

The purpose of this paper is to describe a multi-body simulation tool that runs quickly and that captures the environments a component might see. The simulation incorporates the air and water interaction with the component, the component dynamics (i.e. modes and mode shapes), any applicable parachutes and lines, the interaction of winds and gusts, and the wave height and speed. It is capable of quickly conducting Monte Carlo studies to better capture the environments and genetic algorithm optimizations to reproduce a flight.

Technical Overview

The simulation tool is based on TREETOPS (TT), which is a time history simulation of the motion of complex, multi-body, flexible structures with active control elements [2]. Developed for NASA throughout the 1970's and 1980's, it can capture large rotations and non-linear events. The name TREETOPS refers to the class of structures which may be simulated by the program, i.e., those having a tree topology as shown in Figure 2.

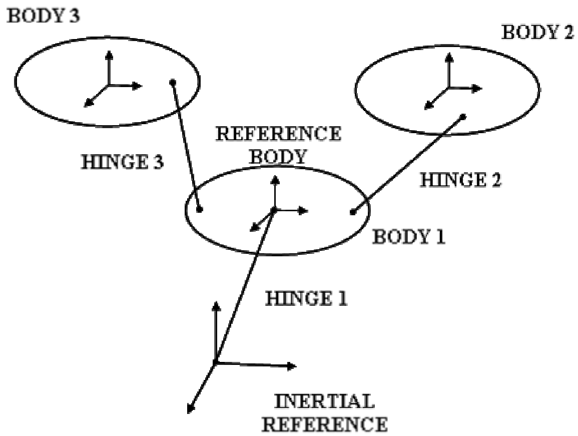

Figure 2: TREETOPS Tree Topology

A 3-D surface model is used within TREETOPS to model fluid (air and water) interaction. The model breaks the composite body surface into planes or facets to approximate the body external surface shape geometry as shown in Figure 3. Many axial stations are required to properly give the booster the required force and moment fidelity needed to simulate the "slap-down" loading event and allow for detailed wave shape definitions.

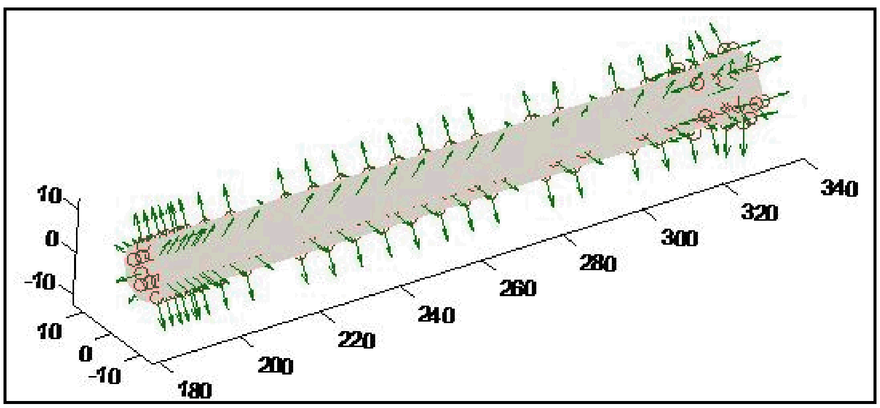

Figure 3: Surface Model for Fluid Interaction

As represented in Figure 4, surfaces interact with a flowing stream of air or water to produce forces and moments on one or more of the bodies that make up a TT model. Static pressure forces model the buoyancy. Dynamic pressure forces model the drag which is similar to the form a water drag model would take. Drag and buoyancy are dependent upon the time of occurrence and the angle of impact. Therefore, the fluid affects the structure instead of a simplified time history force application.

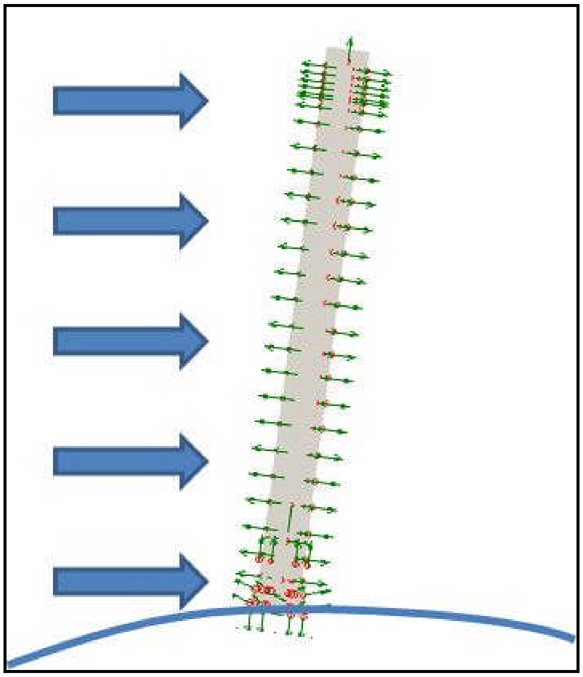

Figure 4: Air and Water Interaction Representation

Structural information (modes and mode shapes) is extracted from the component finite element model (FEM), which is in the water impact configuration. Typically, the models have several hundreds of thousands of degrees of freedom which would overwhelm the simulation. Thus, the corresponding model is dynamically reduced using Guyan or Craig-Bampton methods. Modal truncation studies are conducted to assure capture of the correct loads.

The parachute model is built upon three key items. First, the geometric dimensions of radius and length are needed. These parameters are used for modeling the parachute and line as bodies, as well as generating the 3-D surface model. Next, the coefficient of drag is needed to model the forces that the parachute applies. Finally, the trapped air mass is used to provide the mass properties.

Results

One use of the water impact tool was to reconstruct the accelerations of the SRB from Space Shuttle flight STS-89 using a Genetic Algorithm (GA), which is a numerical optimization algorithm inspired by both natural selection and natural genetics. The GA approach was selected over gradient based optimization since there may be multiple local solutions. The conditions at impact were known – the vertical and horizontal velocities, the sea conditions, and the wind speed. Accelerometers were placed on the SRB to capture accelerations. Key parameters were allowed to be adjusted by the GA so that the simulation captured the key accelerations and the appropriate times. Figure 5 below shows those key points circled – the axial acceleration at initial impact, the lateral accelerations at initial impact and slapdown, and the time between initial impact and slapdown. The GA fitness function was defined to capture those accelerations and time. After several thousand generations, the fitness function converged to a reasonable set of conditions that produced a fitness value of 0.922 out of 1.0.

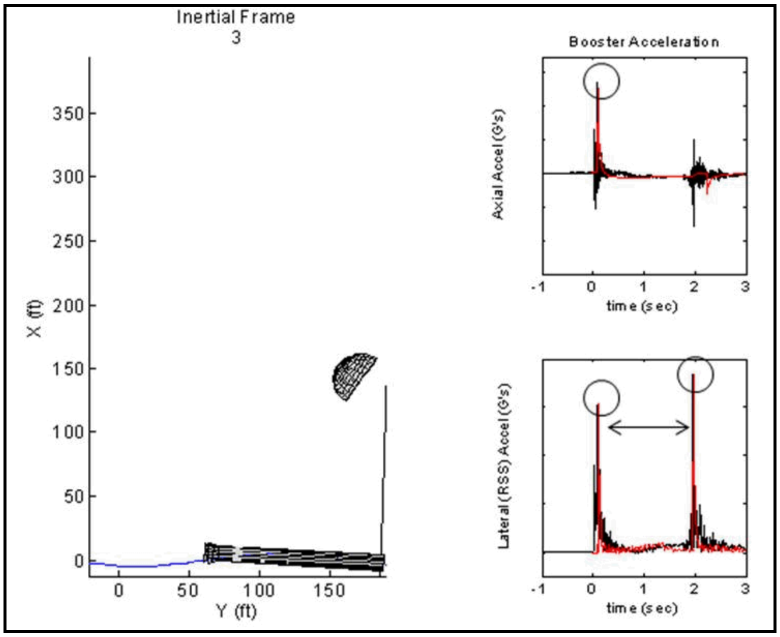

Figure 5: STS-89 SRB Acceleration Regeneration using Genetic Algorithm

Another use of the tool was to reconstruct the loading conditions of the Ares I-X First Stage booster that led to buckling of the aft motor case. Estimates of the conditions were provided by NASA and these values were applied to the simulation. The resulting loads were processed through a buckling solution within the booster FEM. Figure 6 shows the buckling mode shape compared to the actual booster post-flight condition. These results indicate that the water impact tool is a reasonable predictor of vehicle response to water impact conditions.

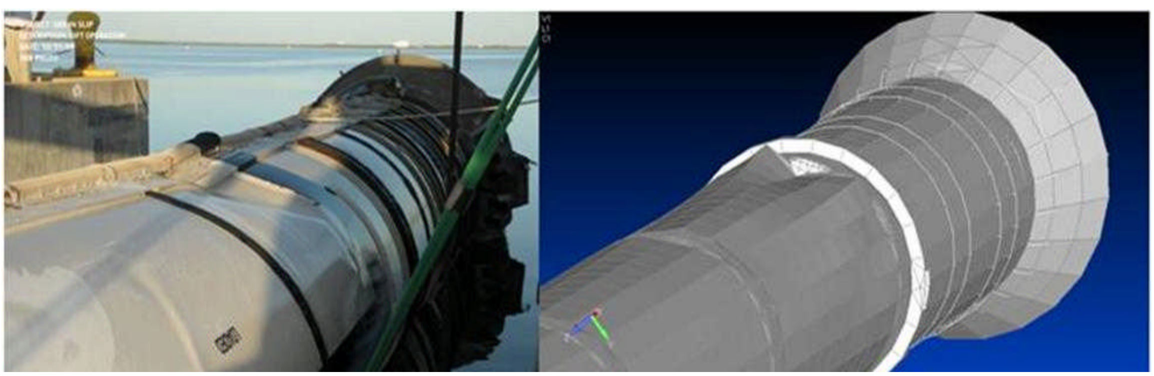

Figure 6: Ares I-X Buckling Reconstruction

Conclusion

The water impact tool yielded results that approximately match actual NASA flight data. The objective was to create a simulation tool that captures the physics of water impact and can run quickly. These loads are necessary for the purpose of designing components and to predict if conditions would cause failures. The tool is flexible enough to allow modeling of varied component configurations and application of any aspect of the water environment. Thus, the tool will enable NASA to capture more accurate structural loads for any current or future components.

References

[1] Wang, John T., Lyle, Karen H., *Simulating Space Capsule Water Landing with Explicit Finite Element Method*, AIAA-2007-1779, Apr. 23-26, 2007.

[2] NASA, *TREETOPS USER'S MANUAL: A Control Simulation For Structures With A Tree Topology*, Revision 8.

Water Impact Prediction Tool for Recoverable Rockets

Bill Rooker[1], John Glaese, PhD.[2], and Joe Clayton[3]
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The measurements taken during Shuttle flights and the Ares I-X test flight provide a unique opportunity to assess the accuracy of the models and methods used to analyze the loads and accelerations during water impact of recoverable rockets. In this paper, the methods used for reconstructing the loads and accelerations during water impact are described. The results generated are compared to measured values, leading to insight into the accuracy of the water impact prediction tool techniques.

Notice to readers:
The predicted performance and certain other features and characteristics of the Ares I-X launch vehicle are defined by the U.S. Government to be Sensitive But Unclassified (SBU). Therefore, details have been removed from selected plots and figures.

Nomenclature

A	=	Projected surface area
C_d	=	Coefficient of drag
F	=	Force
g	=	Gravitational constant
ρ	=	Density

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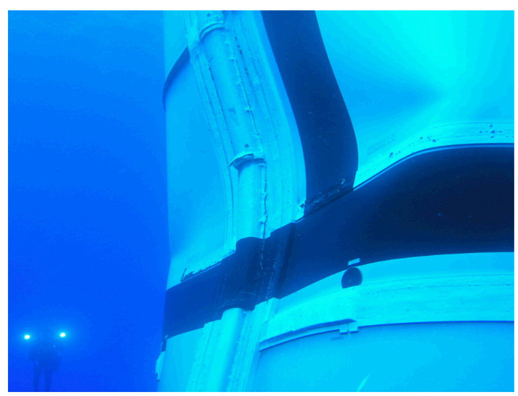

Figure 1. Ares I-X First Stage Deformation.

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The purpose of this paper is to describe a multi-body simulation tool that runs quickly and that captures the environments a component might see during water impact. The simulation incorporates the air and water interaction with the component, the component dynamics (i.e. modes and mode shapes), any applicable parachutes and lines, the interaction of winds and gusts, and the wave height and speed. It is capable of quickly conducting Monte Carlo studies to better capture the environments and genetic algorithm optimizations to reproduce a flight.

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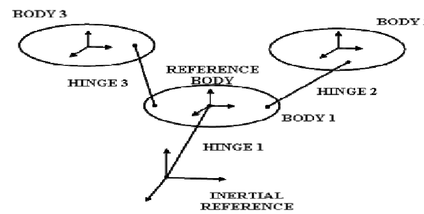

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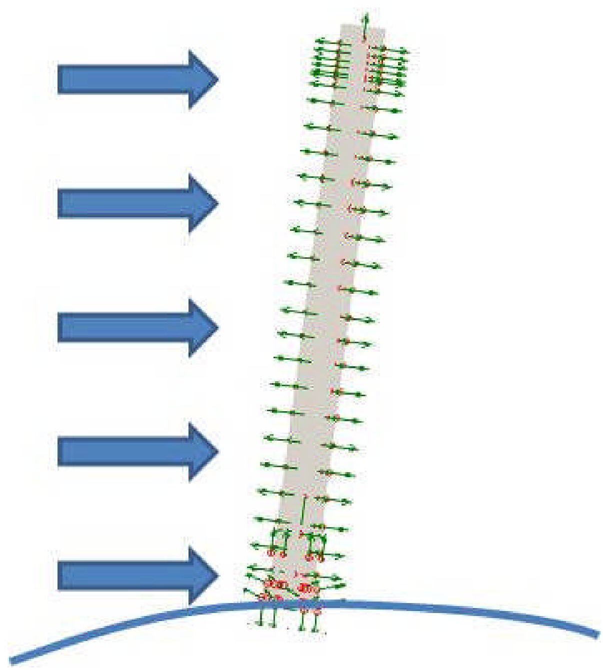

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$$F = \rho V_{disp} g \tag{1}$$

$$F = \frac{1}{2}\rho V^2 C_d A \text{ where } \mathrm{C_d} \text{ adapted for impact} \tag{2}$$

III. Results

One use of the water impact tool was to reconstruct the accelerations of the SRB from Space Shuttle flight STS-89 using a Genetic Algorithm (GA), which is a numerical optimization algorithm inspired by both natural selection and natural genetics. The GA approach was selected over gradient based optimization since there may be multiple local solutions [3]. The conditions at impact were known – the vertical and horizontal velocities, the sea conditions, and the wind speed. Accelerometers were placed on the SRB to capture accelerations. Key parameters were allowed to be adjusted by the GA so that the simulation captured the key accelerations and the appropriate times. Figure 4 shows those key points circled – the axial acceleration at initial impact, the lateral accelerations at initial impact and slapdown, and the time between initial impact and slapdown. The GA fitness function was defined to capture those accelerations and time. After several thousand generations, the fitness function converged to a reasonable set of conditions that produced a fitness value of 0.922 out of 1.0.

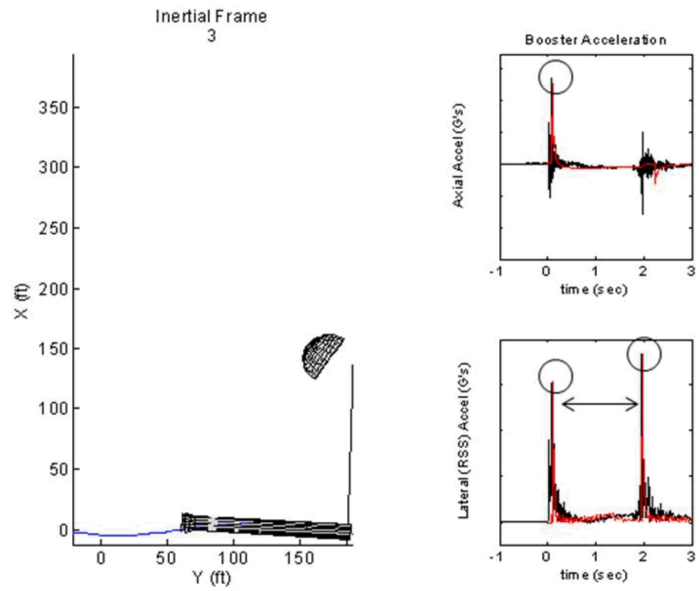

Figure 4. STS-89 SRB Acceleration Regeneration using GA.

Another use of the tool was to reconstruct the loading conditions of the Ares I-X First Stage booster that led to buckling of the aft motor case. Estimates of the conditions were provided by NASA and these values were applied to the simulation. Shear and bending moment diagrams along the length of the vehicle centerline were generated and compared against loads seen by Shuttle SRBs. As shown in Figure 5, Ares I-X saw relatively higher loads along the length of the vehicle. Since Ares I-X used an SRB for the first four segments, this is a good indicator that the loads were high enough to cause buckling.

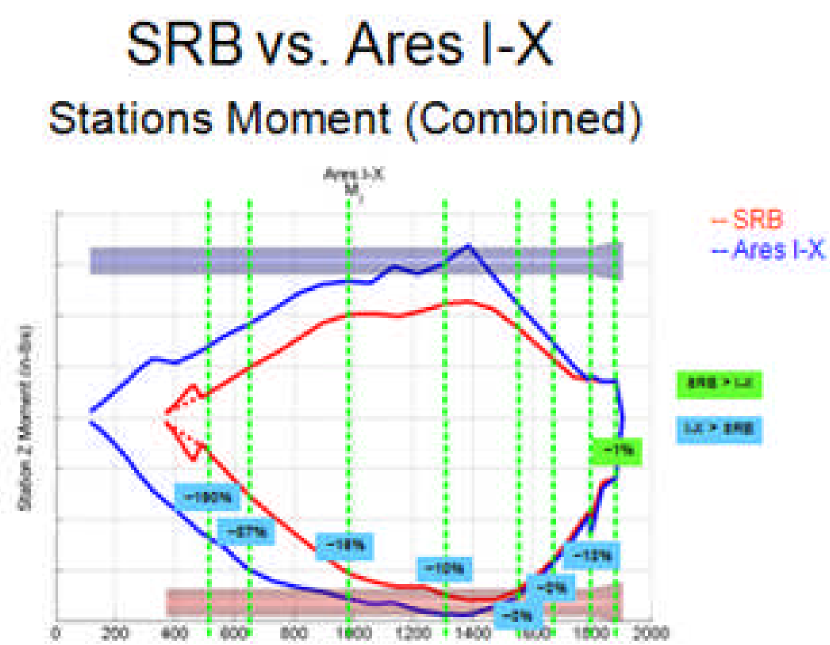

Figure 5. SRB vs. Ares I-X Moment.

The resulting forces and moment time histories were processed through a buckling solution within the booster FEM. Figure 6 shows the buckling mode shape compared to the actual booster post-flight condition. These results indicate that the water impact tool is a reasonable predictor of vehicle response to water impact conditions.

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The authors would like to acknowledge our NASA sponsors Mike Murphy and Christy Gattis for this project.

References

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[2] NASA, *TREETOPS USER'S MANUAL: A Control Simulation For Structures With A Tree Topology*, Revision 10, with modifications and additions by John Glaese.

[3] Coley, David A., *An Introduction to Genetic Algorithms for Scientists and Engineers*, World Scientific, Singapore, 1999.