Ares I-X First Stage Separation Loads and Dynamics Reconstruction

Extended Abstract Submitted For

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Lee Demory – Dynamic Concepts, Inc.

Bill Rooker – Dynamic Concepts, Inc.

Marc Jarmulowicz – Dynamic Concepts, Inc.

John Glaese, PhD – Dynamic Concepts, Inc.

Huntsville, Alabama

Introduction

The Ares I-X flight test provided NASA with the opportunity to test hardware and gather critical data to ensure the success of future Ares I flights. One of the primary test flight objectives was to evaluate the environment during First Stage separation to better understand the conditions that the J-2X second stage engine will experience at ignition [1]. A secondary objective was to evaluate the effectiveness of the stage separation motors. The Ares I-X flight test vehicle was successfully launched on October 29, 2009, achieving most of its primary and secondary test objectives. Ground based video camera recordings of the separation event appeared to show recontact of the First Stage and the Upper Stage Simulator followed by an unconventional tumbling of the Upper Stage Simulator. Closer inspection of the videos and flight test data showed that recontact did not occur. Also, the motion during staging was as predicted through CFD analysis performed during the Ares I-X development.

This paper describes the efforts to reconstruct the vehicle dynamics and loads through the staging event by means of a time integrated simulation developed in TREETOPS, a multi-body dynamics software tool developed at NASA [2]. The simulation was built around vehicle mass and geometry properties at the time of staging and thrust profiles for the first stage solid rocket motor as well as for the booster deceleration motors and booster tumble motors. Aerodynamic forces were determined by models created from a combination of wind tunnel testing and CFD. The initial conditions such as position, velocity, and attitude were obtained from the Best Estimated Trajectory (BET), which is compiled from multiple ground based and vehicle mounted instruments. Dynamic loads were calculated by subtracting the inertial forces from the applied forces. The simulation results were compared to the Best Estimated Trajectory, accelerometer flight data, and to ground based video.

Simulation Overview

Within the TREETOPS environment, the Ares I-X vehicle was modeled as two separate rigid bodies initially connected by four stiff springs. One body represented the First Stage (FS) Solid Rocket Motor (SRM), while the second represented the Upper Stage Simulator (USS). The Ares I-X geometry differed from the Ares I launch vehicle in several areas, most notably in the separation plane and location of the interstage frustum after separation. The simulation was created with Ares I-X specific mass properties for each body estimating the mass at separation.

During the separation event, multiple forces are acting on the vehicle. The SRM is still producing a relatively small amount of thrust. Before separation, the Booster Deceleration Motors (BDMs) fire to pull the FS away from the USS. After separation, the Booster Tumble Motors (BTMs) fire to impart a tumbling motion that slows the FS as it reenters the atmosphere. Forcing functions for each of these solid rocket motor firings were applied during the simulation.

Because the Ares I-X used a four-segment SRM rather than the Ares I five-segment, the separation event occurred at a much lower altitude. Therefore the aerodynamic forces were more significant causing the post-separation tumbling motion of the USS. Aerodynamic forces were applied to both the FS and USS. These forces were determined from models generated by wind tunnel testing as well as Computational Fluid Dynamics (CFD).

Simulation Results

To verify that the TREETOPS simulation emulates the dynamics of the actual Area I-X flight, outputs from the simulation were compared to BET data, accelerometer outputs from Developmental Flight Instrumentation (DFI), and ground based video. These comparisons show good correlation as seen in Figures 1-4.

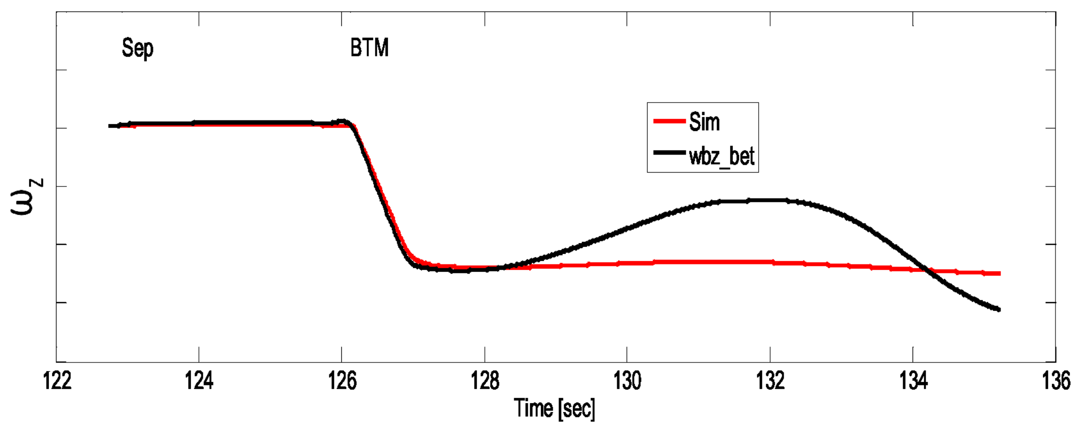

Figure 1: FS Rotation Rate about Body Z Axis

Figure 1 above shows the comparison of the FS rotation rate about the body Z axis. The simulation is well correlated to the BET data up to when the BTMs fire. However, the correlation decreases around 128 sec presumably since the simulation did not incorporate wake aerodynamics.

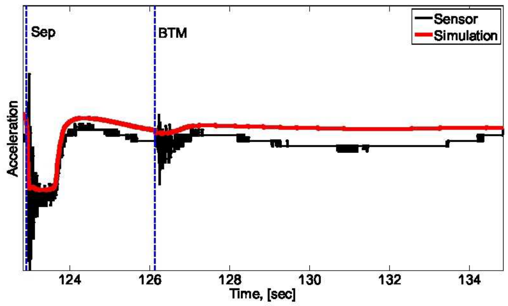

Figure 2: Axial Accelerometer vs. TREETOPS

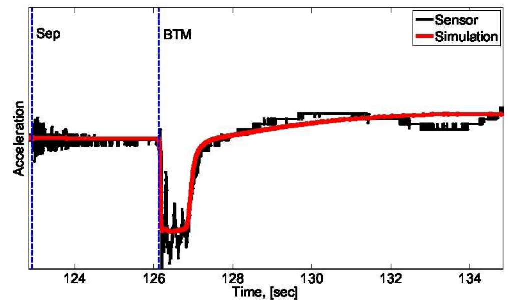

Figure 3: Lateral Accelerometer vs. TREETOPS

Figures 2 and 3 above show the correlation between the simulation acceleration output and two physical accelerometers mounted on the aft skirt of the vehicle. Very good correlation between the simulation and the sensor outputs is observed.

Figure 4 below shows a comparison of the simulation dynamics, as well as the FS BET animated and overlaid on a ground based flight video. This work was primarily done to demonstrate the correlation of the USS simulation to the actual USS flight dynamics. Because the USS did not carry any instrumentation, the ground based flight video is the only available resource to study the USS motion.

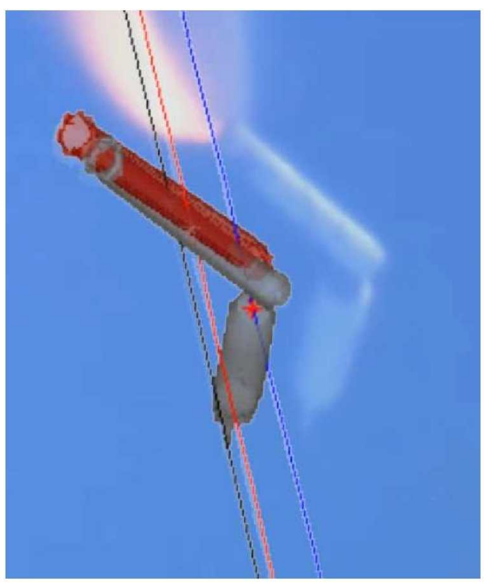

Figure 4: TREETOPS (grey) and FS BET (red) animation overlaid on ground based flight video

Section Loads Calculations

The section loads for the separation analysis were calculated by subtracting inertial forces from the applied forces (known as the "F-ma" approach*)* to determine the internal loads and then summing the internal loads over the length of each of the two bodies. TREETOPS was used to determine the force distribution over the bodies as a function of time. Next the rigid body accelerations were calculated using the geometric rigid body modes as shown in Equation 1

$$\{RB\_Accel\} = \left[\left[\phi_{rbm}^{T}\right]*[Mass]*\left[\phi_{rbm}\right]\right]^{-1} * \left\{\left[\phi_{rbm}^{T}\right]*\{FM_{ext}\}\right\} \quad (1)$$

where ϕ_{rbm} is the geometric rigid body modes and $\{FM_{ext}\}$ is the external Force/Moment output from TREETOPS. The accelerations found in Equation 1 were used to calculate the internal forces and moments using Equation 2.

$$\{FM_{\text{int}}\} = \{FM_{ext}\} - \left[[Mass]*\left[\phi_{rbm}\right]\right]*\{RB\_Accel\} \quad (2)$$

The section loads at a particular station, *i*, were then calculated using Equations 3 and 4,

$$\{Shear\}_i = \sum_{j=1}^{i-1}\{Force\}j \quad (3)$$

$$\{Moment\}_i = \sum_{j=1}^{i-1}\left(\{Moment\}_j + \{Force\}_j * \{x_j - x_i\}\right) \quad (4)$$

Section Loads Results

Some results of the Ares I-X Loads reconstruction are shown below. These section loads plots correlate well to previous Ares 1 loads analyses. This correlation reinforces the fact that the BTM's are the dominant loads driver for the staging event. Figures 5-7 below show section load plots for axial shear as well as shear and moment in the plane of the BTM firing.

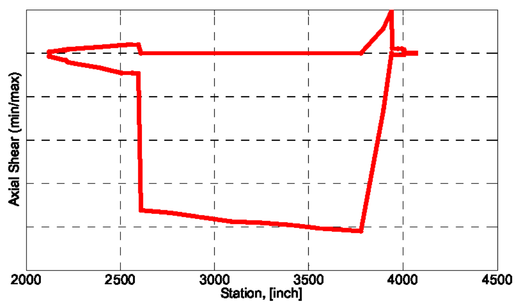

Figure 5: Post-Separation Axial Shear

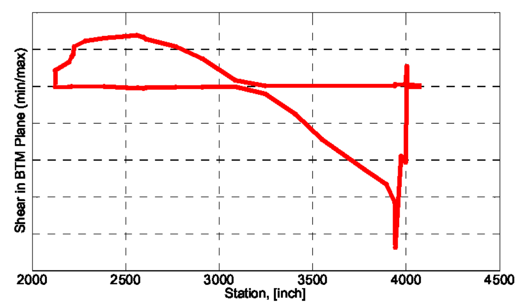

Figure 6: Post-Separation BTM Plane Shear

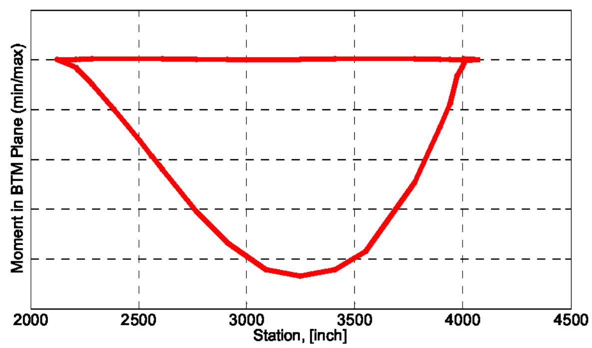

Figure 7: Post-Separation BTM Plane Moment

Conclusion

The Ares I-X first stage separation reconstruction yielded results that matched the BET and DFI accelerometer data for the FS, and ground-based flight video for the USS. TREETOPS was proven to be useful for simulating this type of reconstruction which consists of multiple bodies which are rotating through large angles. The simulation modeled the thrust from the SRM, USMs, BDMs, and BTMs, as well as aerodynamic effects.

Shear and bending moment plots were generated from the simulation output. The results of this loads analysis were aligned with previous Ares I analyses, concluding that the BTM firings are the loads driver for the FS during the separation event.

References

[1] NASA, *Constellation Program: Ares I-X Flight Test Vehicle "The first flight of a new era"*, NASA document FS-2009-03-007-JSC.

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