Water Landing of Space Flight Re-entry Vehicles Using Abaqus/Explicit

Summary

Space flight re-entry vehicles impart highly dynamic loads on the crew and/or payload during a water landing. To understand the behavior of the vehicle/payload system as it makes impact, a predictive framework that can simultaneously model the structure, the highly deformable landing medium (water or soil), and their interaction is required. The coupled Eulerian-Lagrangian (CEL) method in Abaqus/Explicit provides the means for capturing these complex physical phenomena. In this Technology Brief, the simulation of a re-entry vehicle water landing will be demonstrated, and strong agreement with test results will be shown.

Background

Understanding the landing characteristics of a manned space flight re-entry vehicle is critical to ensuring the safety of the crew. Historically, vehicles have been subjected to both water (Apollo missions in 1960s) and ground (Russian Soyuz capsule) landing, where the vehicle speed is reduced by parachute deployment prior to impact. Re-entry vehicles have also been used to return research materials from space. The landing medium in these cases is typically soil. In all cases the structure must be appropriately designed to limit the loads imparted to the crew and the payload.

The behavior of a re-entry vehicle in an impact landing scenario is dependent upon:

1. the orientation (pitch and roll angles) of the vehicle immediately prior to landing,
2. the vertical and horizontal velocities before impact,
3. the mass of the vehicle, and
4. the properties of the landing medium.

Numerical simulation using CEL technology in Abaqus/Explicit is an efficient method for studying the factors mentioned above. In this Technology Brief, we deploy the CEL method to model the impact characteristics of a prototype Apollo Command Module [1].

Modeling Approach

The schematic of the Apollo Command Module is shown in Figure 1. The center of gravity and vehicle axes are identified in the figure. The moment of inertia of the re-entry vehicle is specified in a local coordinate system attached to the vehicle axes at the center of gravity.

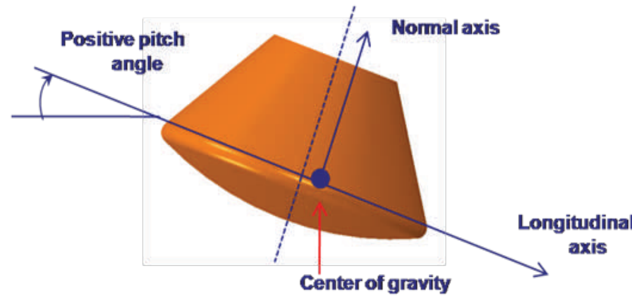

Figure 1: Prototype Apollo Command Module

Key Abaqus Features and Benefits

- Coupled Eulerian-Lagrangian method to simulate fluid-structure interaction in a single model
- Abaqus/Explicit general contact capability greatly simplifies the specification of contact interactions
- Output filtering to reduce noise from explicit dynamics simulation

Geometry and Model

Table 1 lists the geometric and inertial parameters for the full scale Apollo Command Module. While the experiments were conducted at ¼ scale using appropriate Froude number scaling, the Abaqus/Explicit CEL models are built full-scale. The geometric models and the finite element mesh for the simulation are generated in Abaqus/CAE. The initial configuration is shown in Figure 2. The

Parameters	Full Scale Model
Mass	267.3 slugs
I_{xx} (Roll)	4100 slug ft^2
I_{yy} (Pitch)	3890 slug ft^2
I_{zz} (Yaw)	3080 slug ft^2
Max Diameter	151.5 in
Height	86.2 in

Table 1: Apollo Command Module full scale inertial and geometric properties

re-entry vehicle is modeled as a rigid body. The Eulerian mesh of the landing medium is defined so that the effects of the boundaries are minimized.

The simulation involves Eulerian-to-Lagrangian contact between the fluid (modeled in an Eulerian framework) and the re-entry vehicle (modeled in a Lagrangian framework). Such complex contact interactions are easily modeled in Abaqus/Explicit using a penalty-based general contact approach.

Material Properties

Water has typically been chosen as the landing medium for manned space flights. The constitutive behavior is that of an incompressible viscous fluid; in Abaqus/Explicit the linear U_S-U_P Hugoniot form of the Mie-Grüneisen equation of state is used.

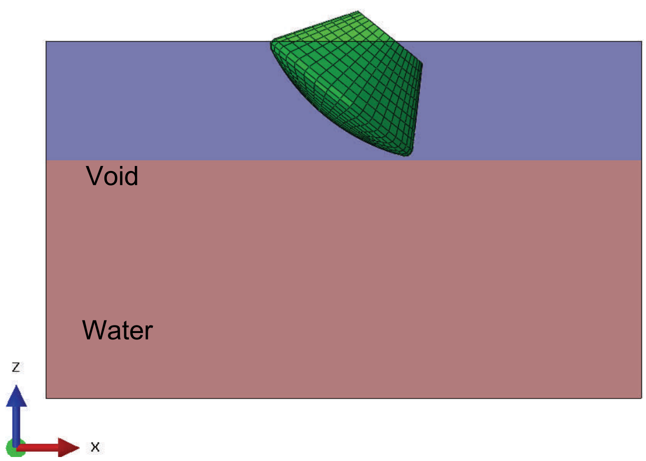

Figure 2: Initial configuration

To improve the performance of the simulation, the bulk modulus of the water is chosen to induce an appropriate amount of numerical compressibility. The re-entry vehicle is also modeled as a rigid body.

Loading, Initial & Boundary Conditions and Simulation Steps

Gravity loading is applied to the entire model, and the re-entry vehicle is given an initial velocity. In order to confine the water within the Eulerian domain boundaries, a zero normal-velocity boundary condition is specified on the bottom and side surfaces of the Eulerian domain. An initial condition on the Eulerian volume fraction is specified to initialize the Eulerian domain with unperturbed water at $t = 0$.

To compare with experimental measurements, acceleration time history output is obtained in the coordinate system attached to the vehicle axes. Output is obtained at every increment and passed through a Butterworth filter. The cut off frequency of the filter is lowered successively to reveal the low frequency components characterizing the structural response. Typically, the choice of cut off frequency is dependent on the experimental methodology used to collect data but in absence of such information, a simplistic approach is adopted.

Results and Discussion

Five simulations were performed to study the splashdown behavior under different initial configurations of the re-entry vehicle. These configurations are characterized by different pitch angles, thus placing the vehicle in a variety of tilted positions at impact. Four simulations were performed with zero initial horizontal velocity, and the fifth simulation was performed with both horizontal and vertical velocity components. For the fifth case, the size of the Eulerian domain is extended by 60 % in order to allow for the re-entry vehicle to splash and skid over water before stabilizing. The initial configurations were chosen from a wide set of experimental conditions reported in [1]. For each case, normal, longitudinal and angular (Figure 1) accelerations are compared with the reported experimental values. Table 2 lists the test and simulation results for various cases.

As can be seen from the comparison, Abaqus/Explicit captures the peak accelerations seen during the splashdown event. Figure 3 depicts time histories of the acceleration components for different configurations.

Figure 4 shows iso-surface plots of the volume fraction of water during splashdown for the impact case with horizontal velocity (case # 5).

A plot of peak accelerations versus vehicle pitch angle is shown in Figure 5. This type of information can help engineers design the optimal orientation of the vehicle for splashdown.

Conclusions

The current work demonstrates a methodology for simulating the splashdown event of re-entry vehicles in water. The strength of the CEL method in this application lies in

Case		**1**	**2**	**3**	**4**	**5**
Vertical Velocity (ft/sec)		31.8	31.2	30.4	29.8	30.4
Horizontal Velocity (ft/sec)		0	0	0	0	49
Pitch (Deg)		14	25	30	39	20
Test	Normal (g)	31.1	12.4	7.2	4.1	16.6
	Longitudinal (g)	6.3	4.9	2.9	1.9	5.7
	Angular (rad/sec^2)	155	72	54	29	121
Simu-lation	Normal (g)	31	12.7	7.5	4.4	16.6
	Longitudinal (g)	6.9	4.2	2.3	1.7	7.5
	Angular (rad/sec^2)	152.8	87.1	52.5	34.9	123.8

Table 2: Comparison of computed and experimental maximum accelerations measured at the capsule center of gravity (along vehicle axes)

its ability to simulate the rigid body dynamics of a re-entry vehicle and its interaction with the fluid medium, all within the framework of a single finite element model. The simulation provides the means to investigate the peak accelerations faced by the crew or the payload during water landing. This information can also be used to study re-entry procedures, including such effects as vehicle orientation prior to landing. While water is chosen as the landing medium in the current work, the simulation can be easily extended to study landing characteristics on sand or clay. Also, the simulation can be extended to study the deformation of the vehicle during impact.

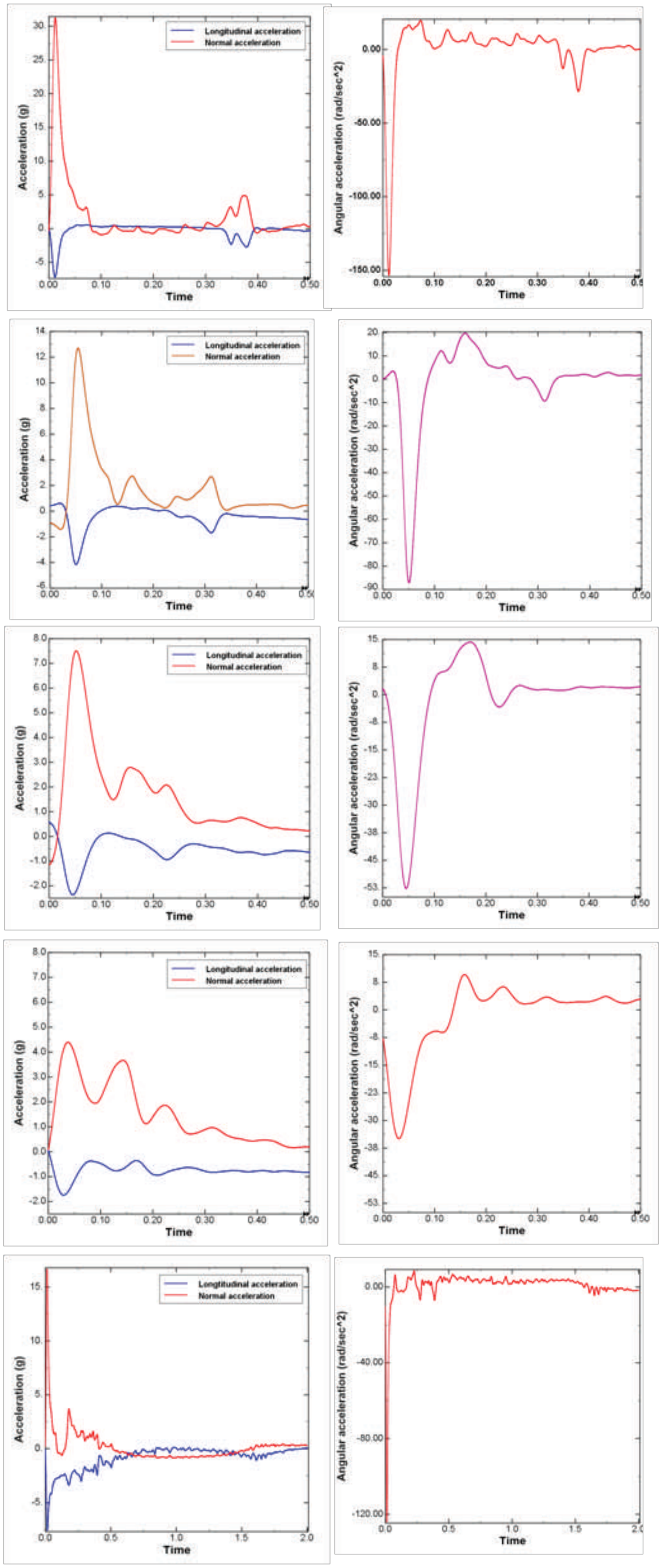

Figure 3: Longitudinal, normal and angular accelerations of the re-entry vehicle for Cases 1, 2, 3, 4, & 5

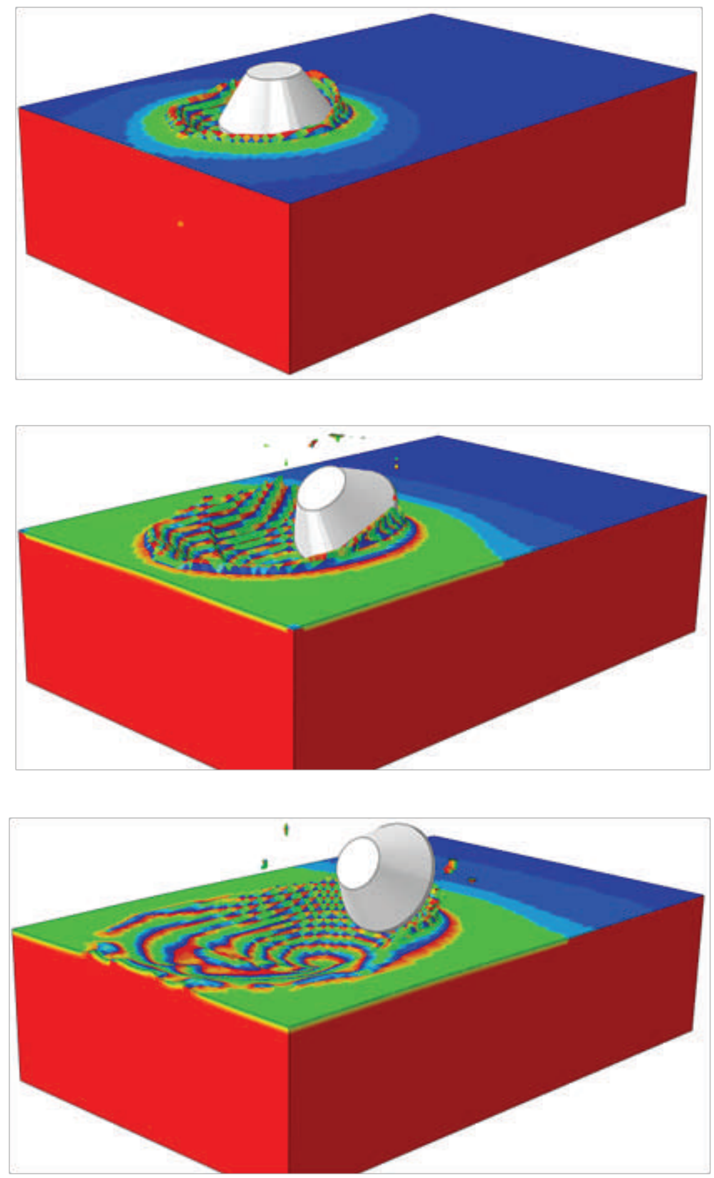

Figure 4: Iso-surface plots of the volume fraction of water during splashdown for Case 5 at time t = 0.2, 0.5 & 0.9 s

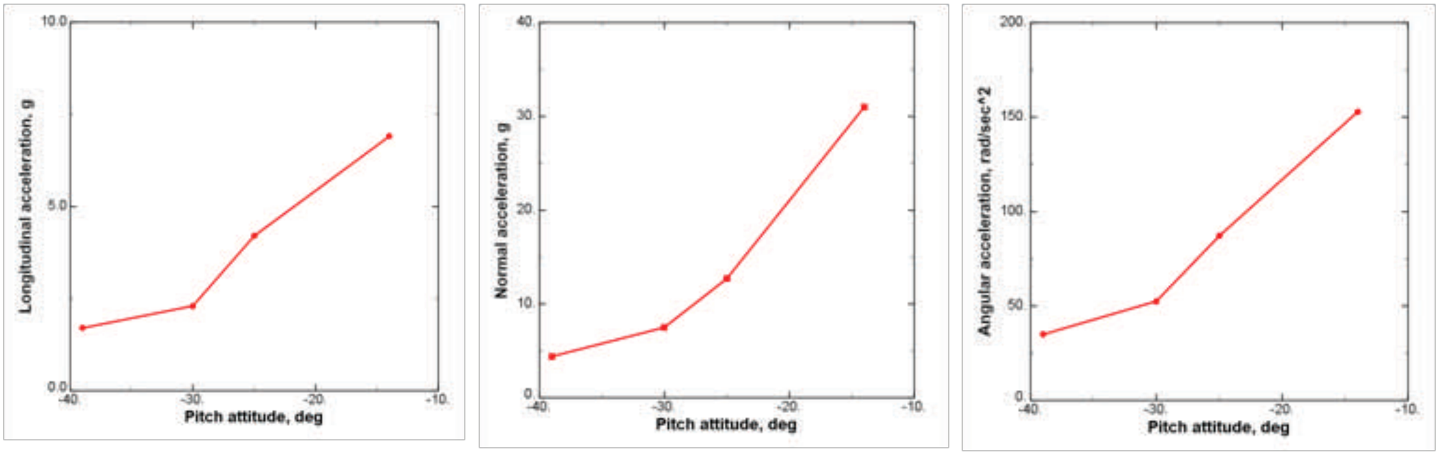

Figure 5: Peak longitudinal, normal and angular accelerations versus vehicle pitch

References

1. Stubbs, S. M., “Dynamic Model Investigation of Water Pressures and Accelerations Encountered During Landings of the Apollo Spacecraft,” Langley Research Center, NASA, TN D-3980, 1967.

Abaqus References

For additional information on the capabilities reported in this technology brief, please refer to the following Abaqus 6.11 documentation references:

- ‘Eulerian Analysis,’ Section 14.1
- ‘Defining general contact interactions in Abaqus/Explicit,’ Section 34.4.1
- ‘Output to the output database,’ Section 4.1.3
