National Aeronautics and
Space Administration

FREE-FLIGHT CFD SIMULATIONS OF BALLISTIC RANGE AND FLIGHT TESTS

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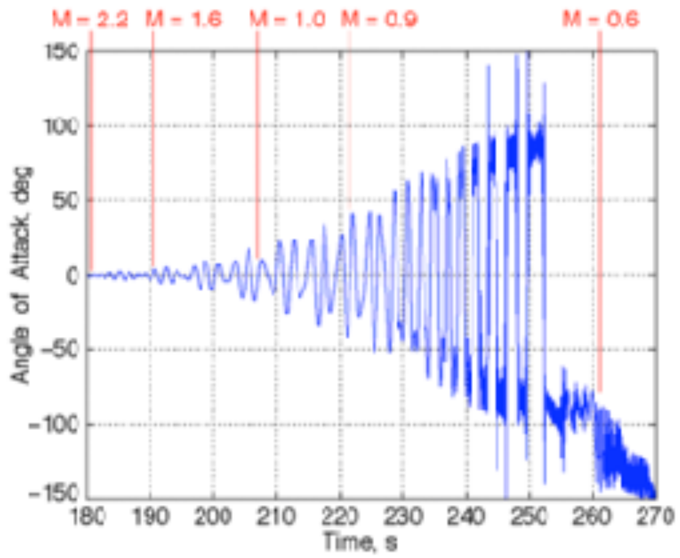
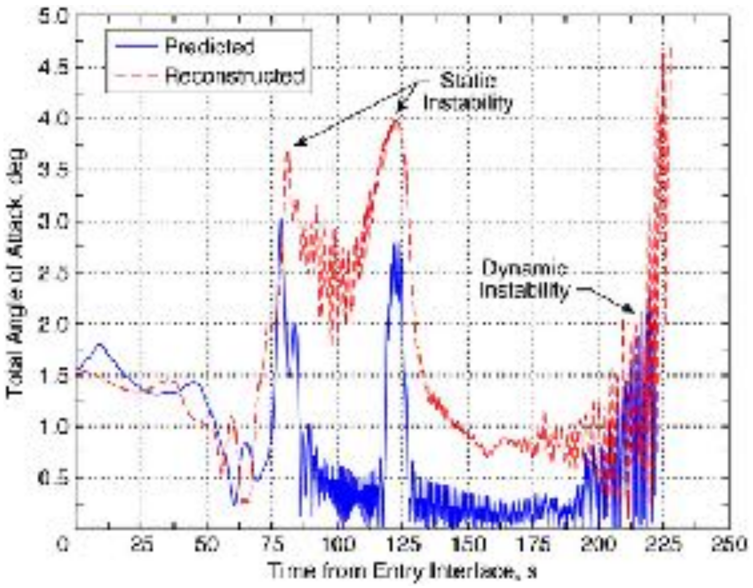
Blunt Body Dynamic Stability

Genesis Sample Return Capsule (Desai, 2008)



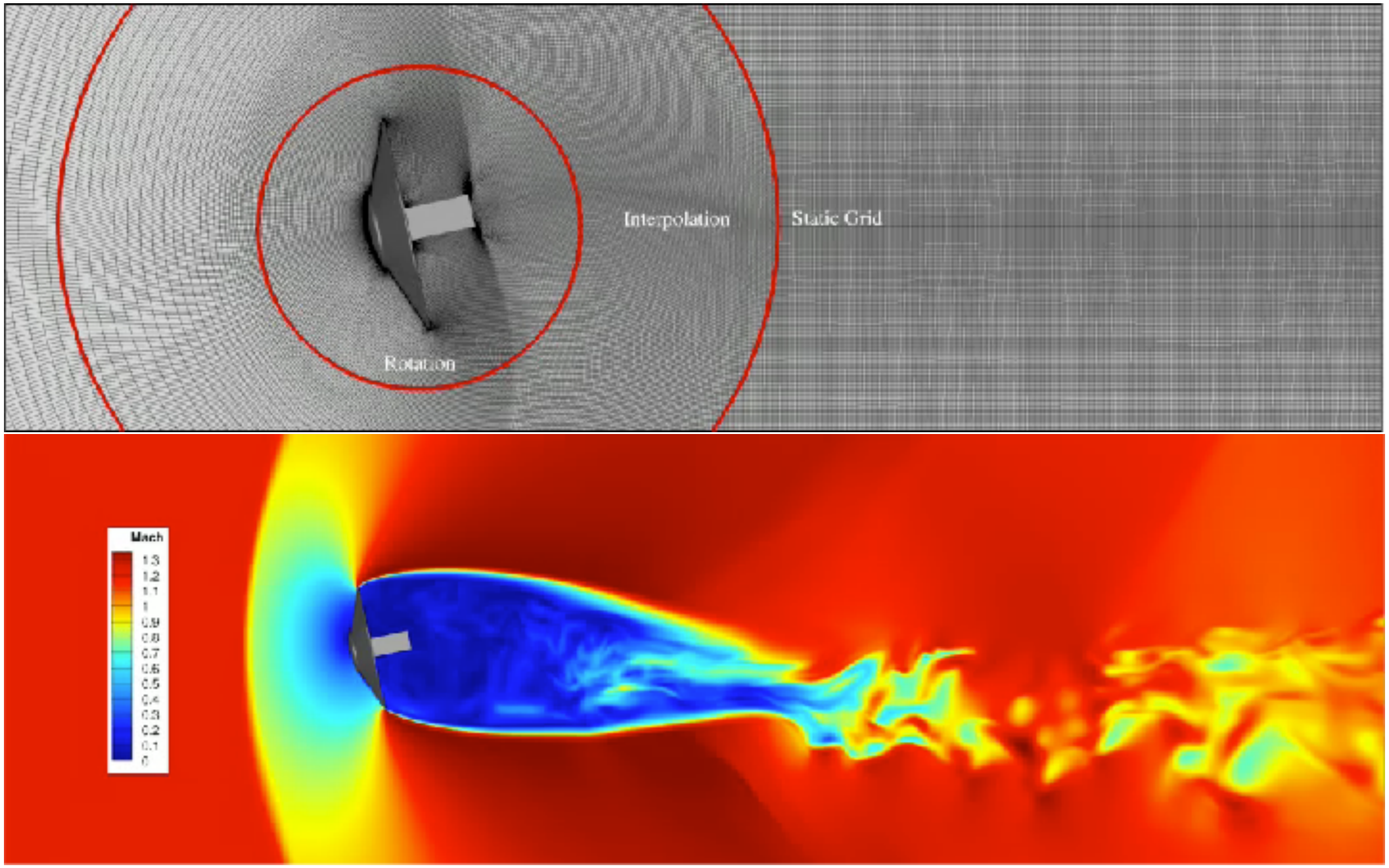
Mars Phoenix Lander (Desai, 2011)



- **Blunt-body capsules very effective at reducing heating to the surface**
- **Dynamic instabilities often arise at low-supersonic and transonic Mach numbers**
- **Dynamic stability characterized exclusively through experiment — forced-, free-oscillations, and ballistic range — however each have drawbacks resulting in uncertain predictions**
  - **In all cases, flight similitude parameters are difficult to achieve**

- CFD an integral part of *static* aerodynamic characterization and design.
- Would be desirable to have similar capability for *dynamic* aerodynamics

US3D Free-Flight Solver

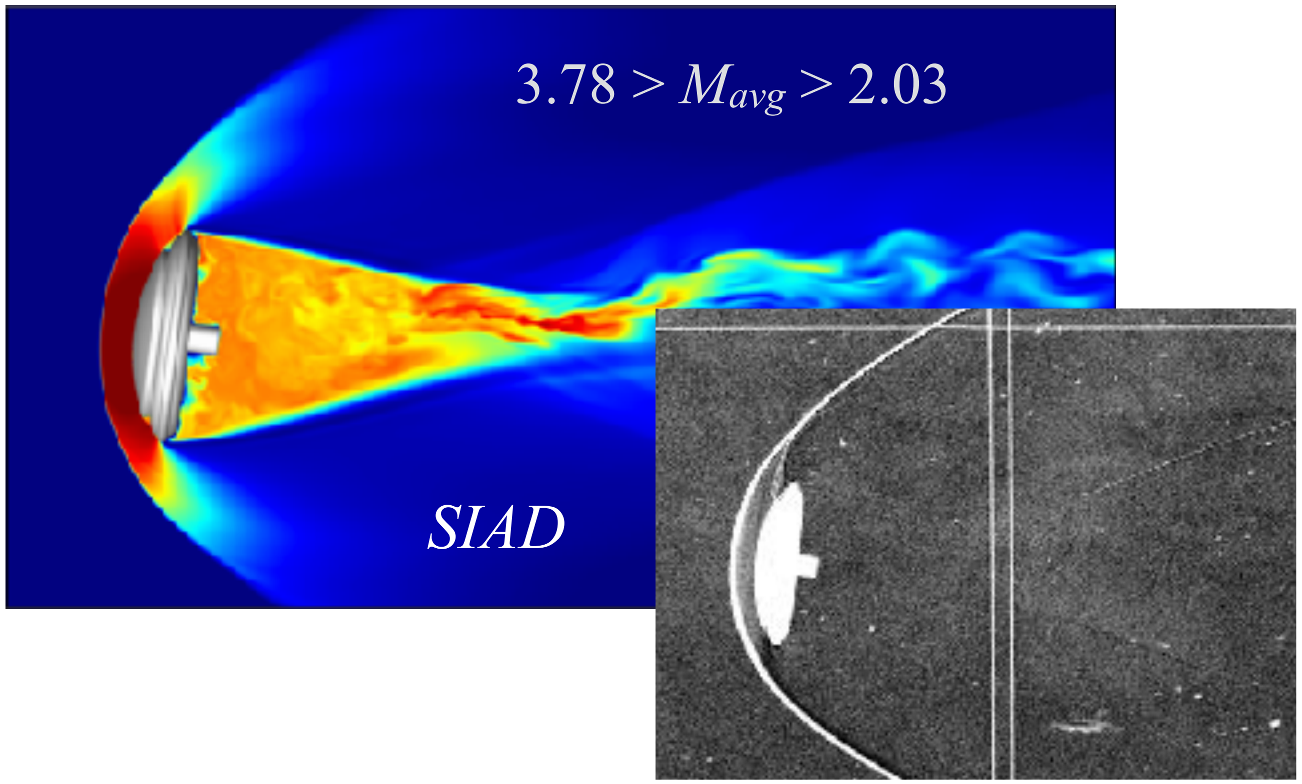


Free-flight Solver Loop:

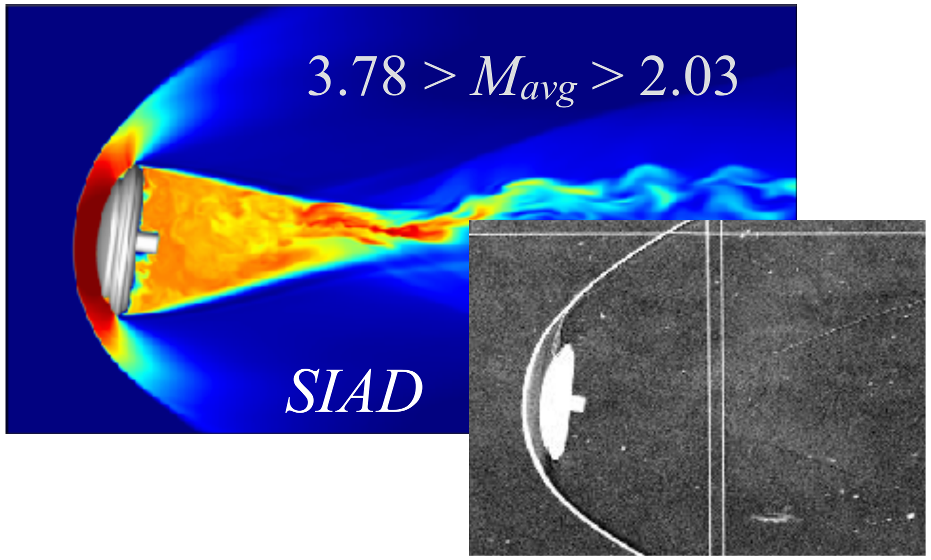
- **US3D flow solution provides forces and moments**
- **Moments are integrated to determine rigid body rotation**
- **Grid is deformed in interpolation region to accommodate rigid body rotation**
- **Lift and drag are integrated to determine frame velocity**

- **US3D requires body-fitted mesh**
- **Mesh deformation employed to model 3-DOF (pitch, yaw, roll) motion**
  - **Inner mesh undergoes rigid body rotation with vehicle**
  - **Intermediate region blends inner rigid body rotating mesh to outer static region by interpolating node displacements**
- **Frame velocity applied to discrete governing equations when translation dynamics (i.e. acceleration, deceleration) are required**

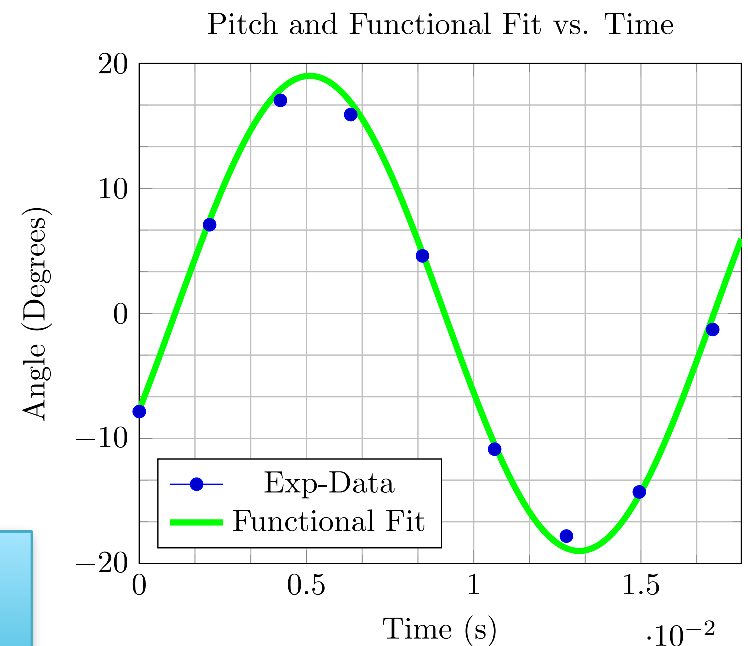
Validation Efforts to Date

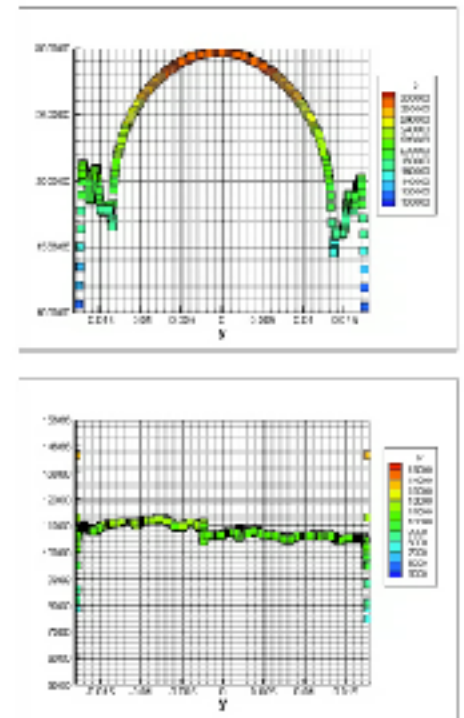


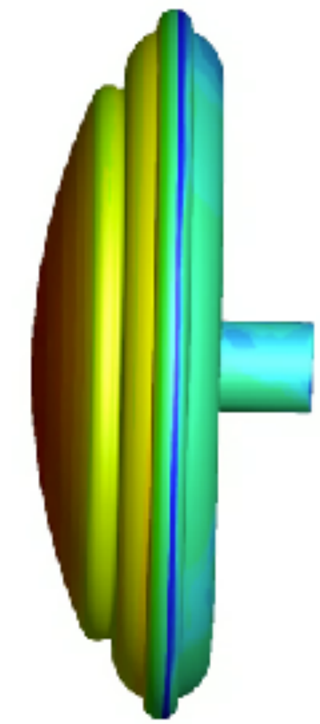
Free-Flight CFD in Supersonic Regime



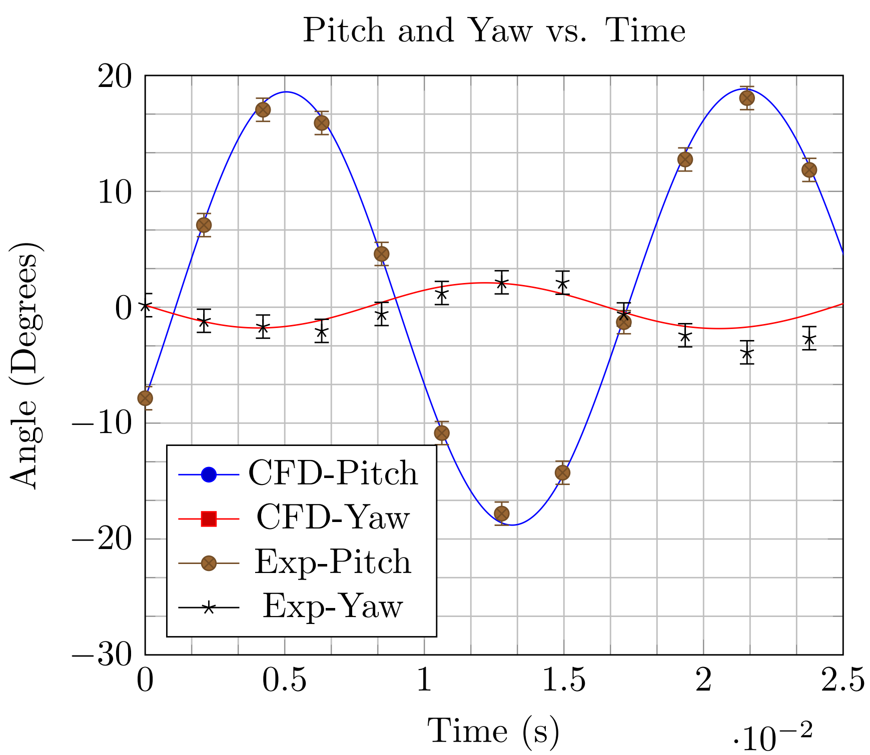
Fit data and taking the first derivative for tip-off rates

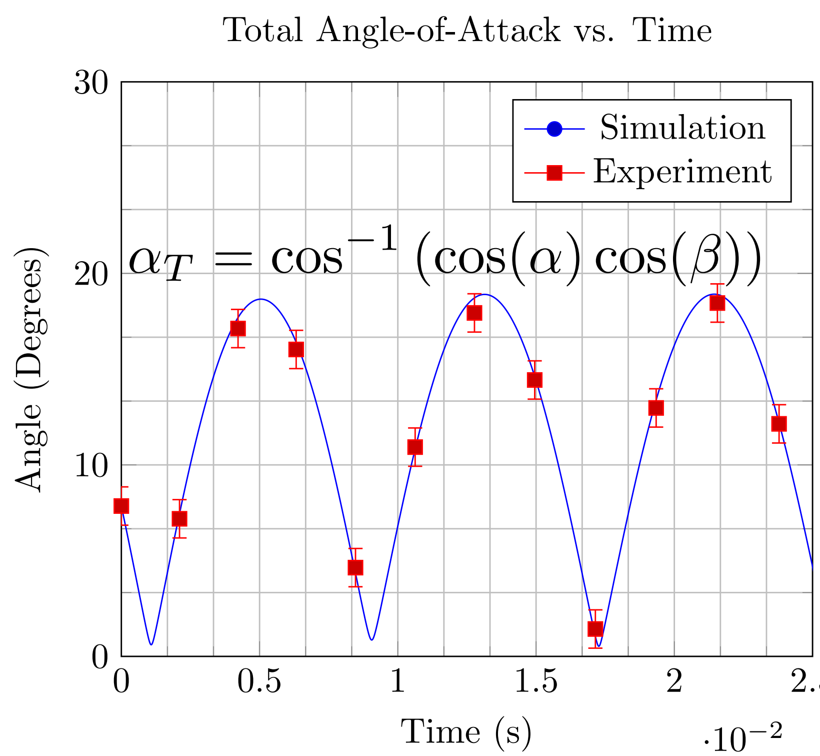


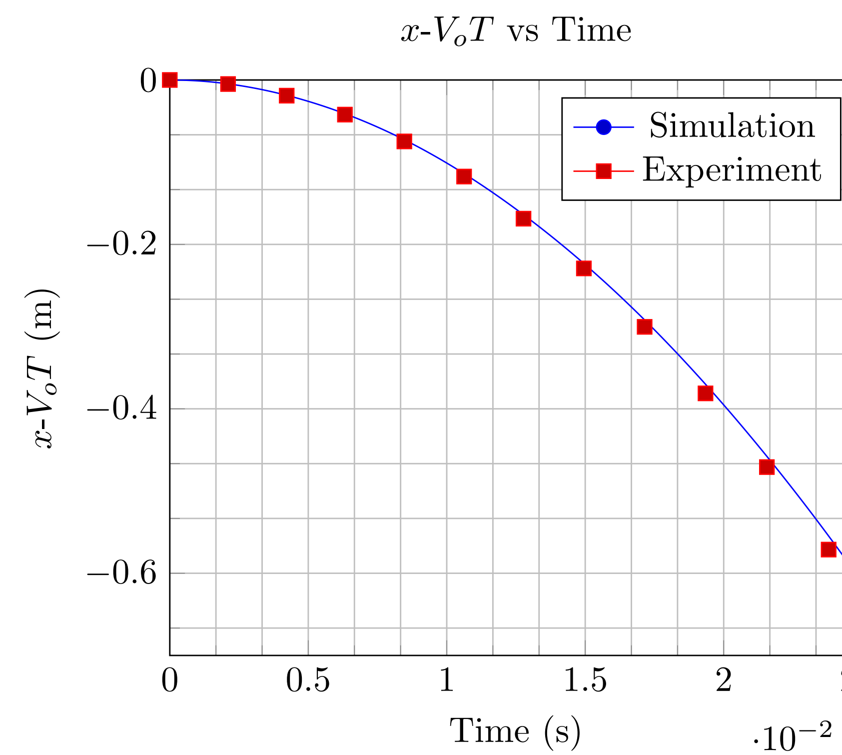




Simulation data for pitch, yaw, total angle of attack and downstream distance is compared against experimental data







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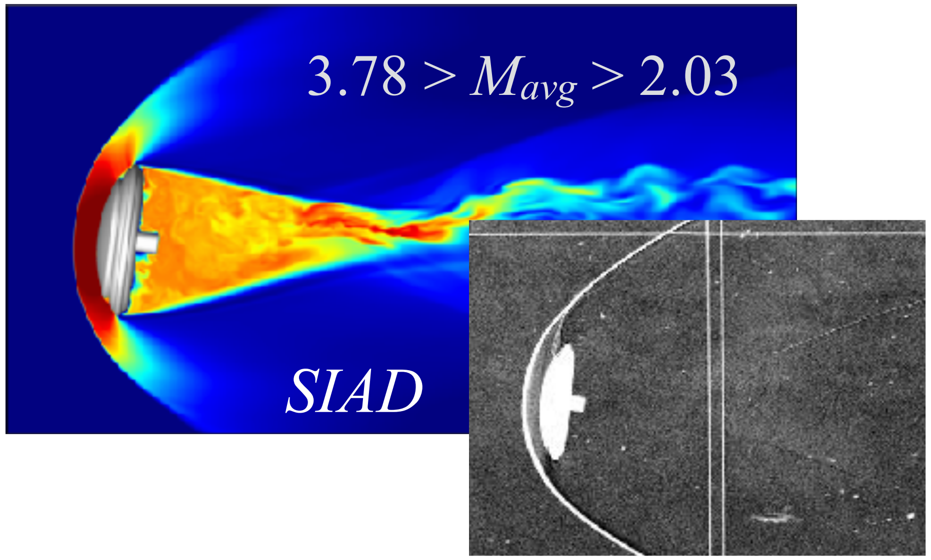
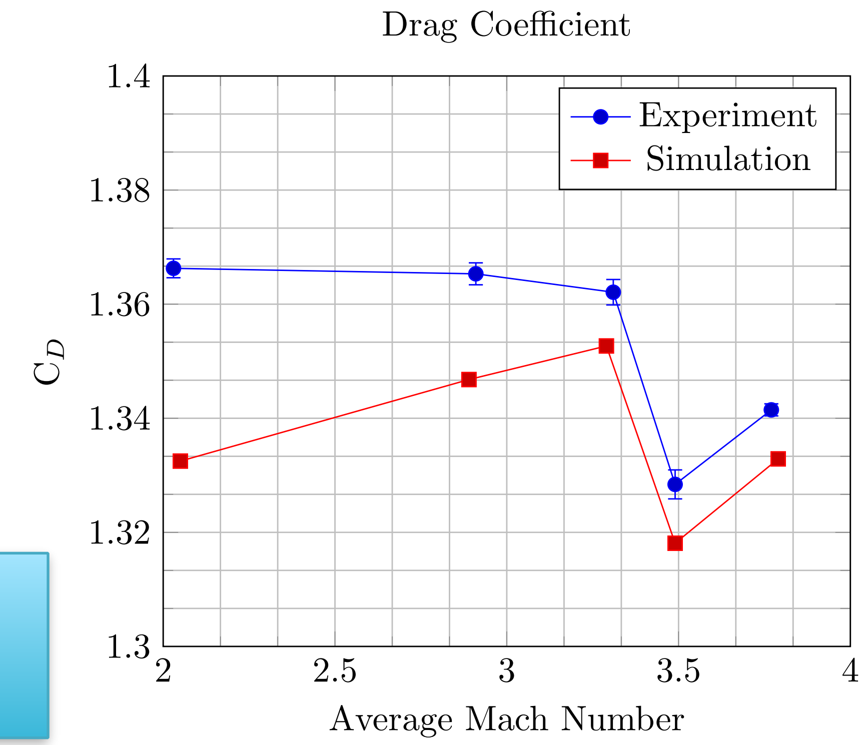
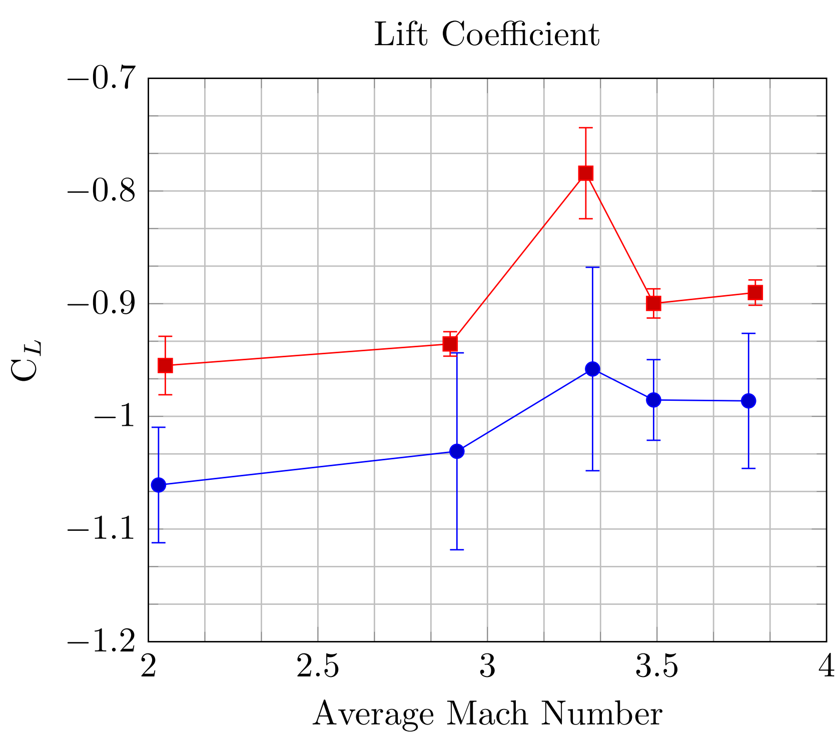
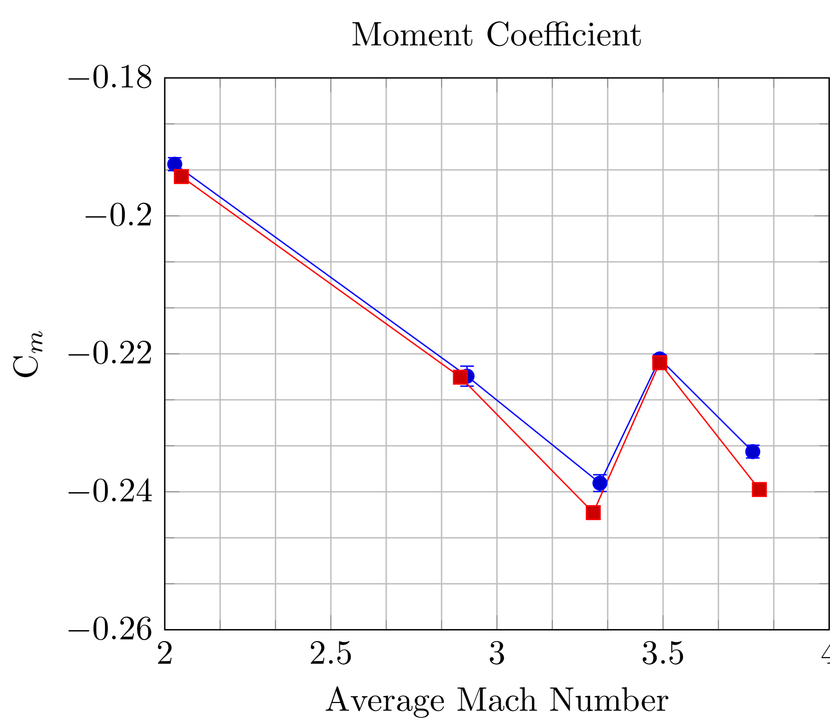
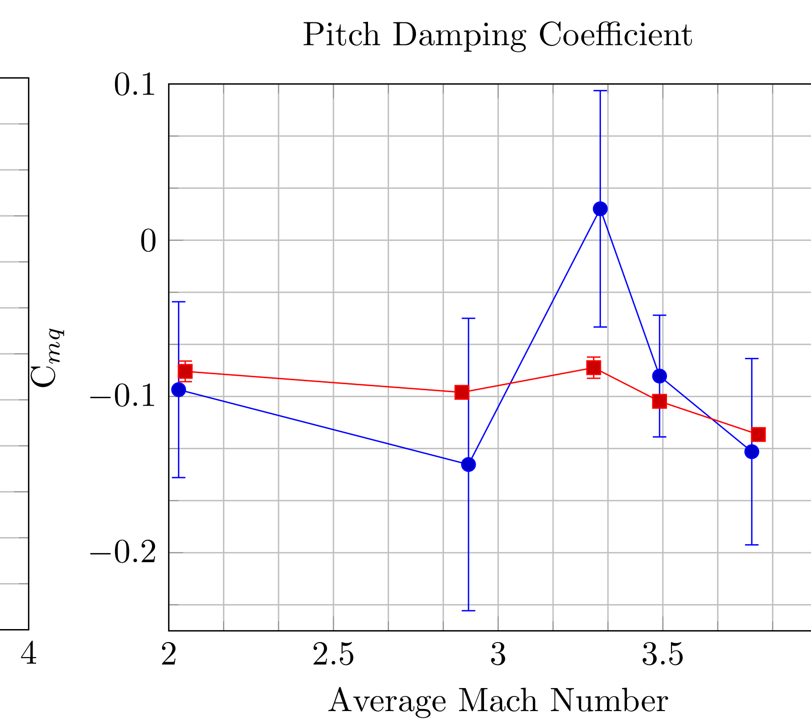




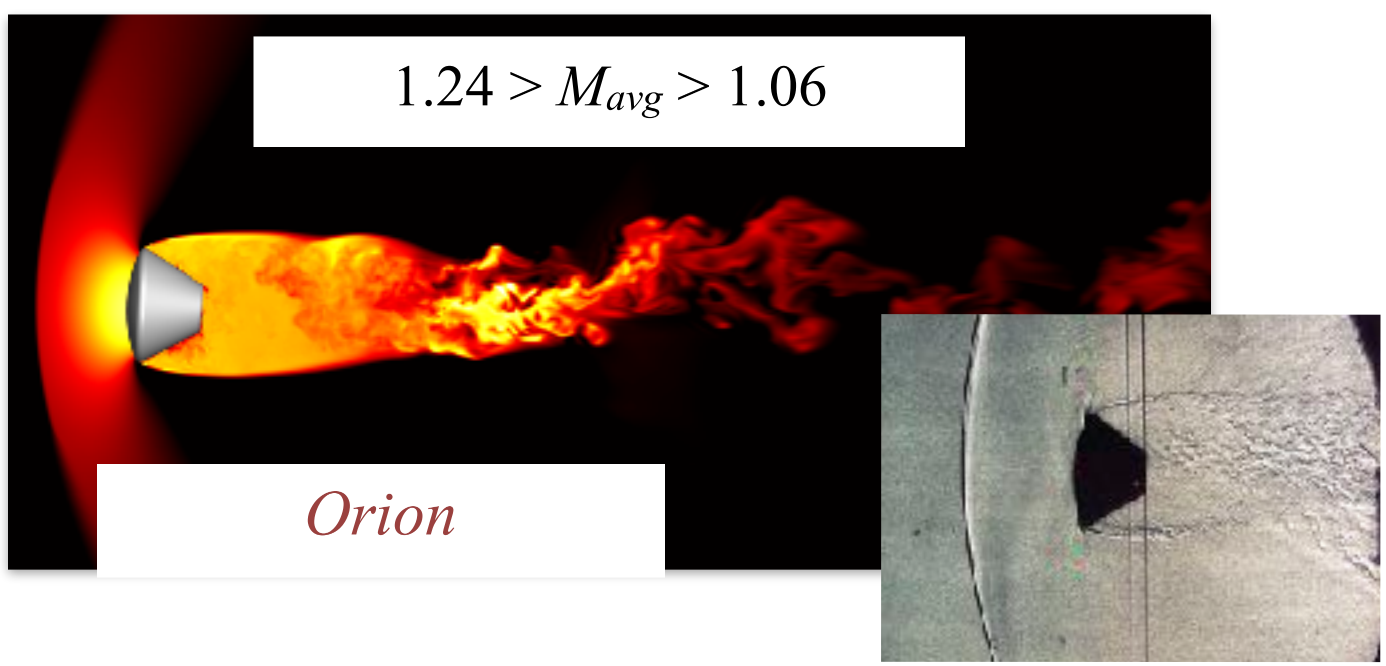
Compared against Derived Aero-Coefficients



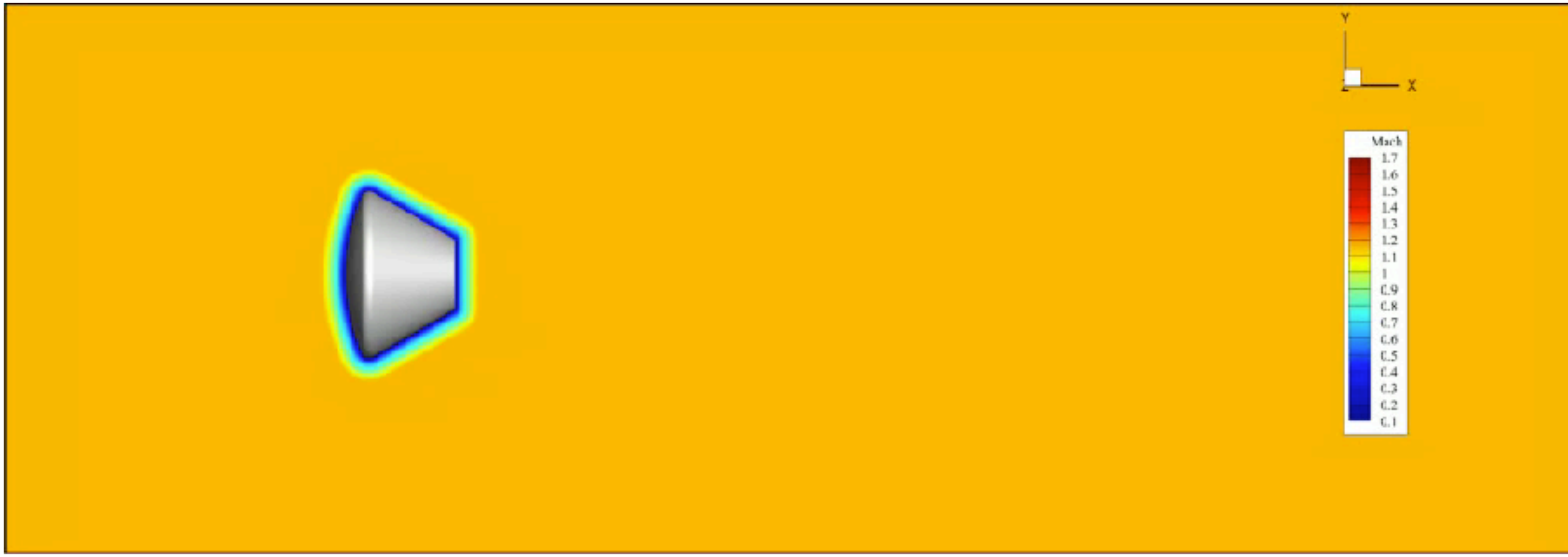


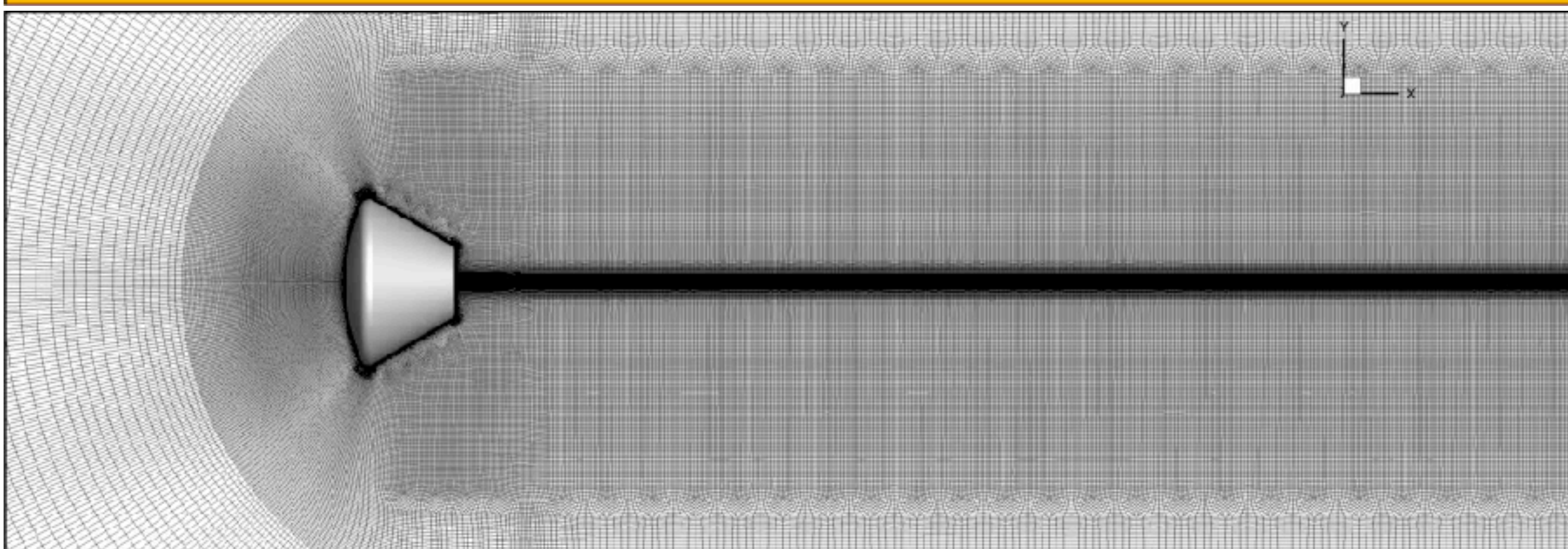


Validation Efforts to Date

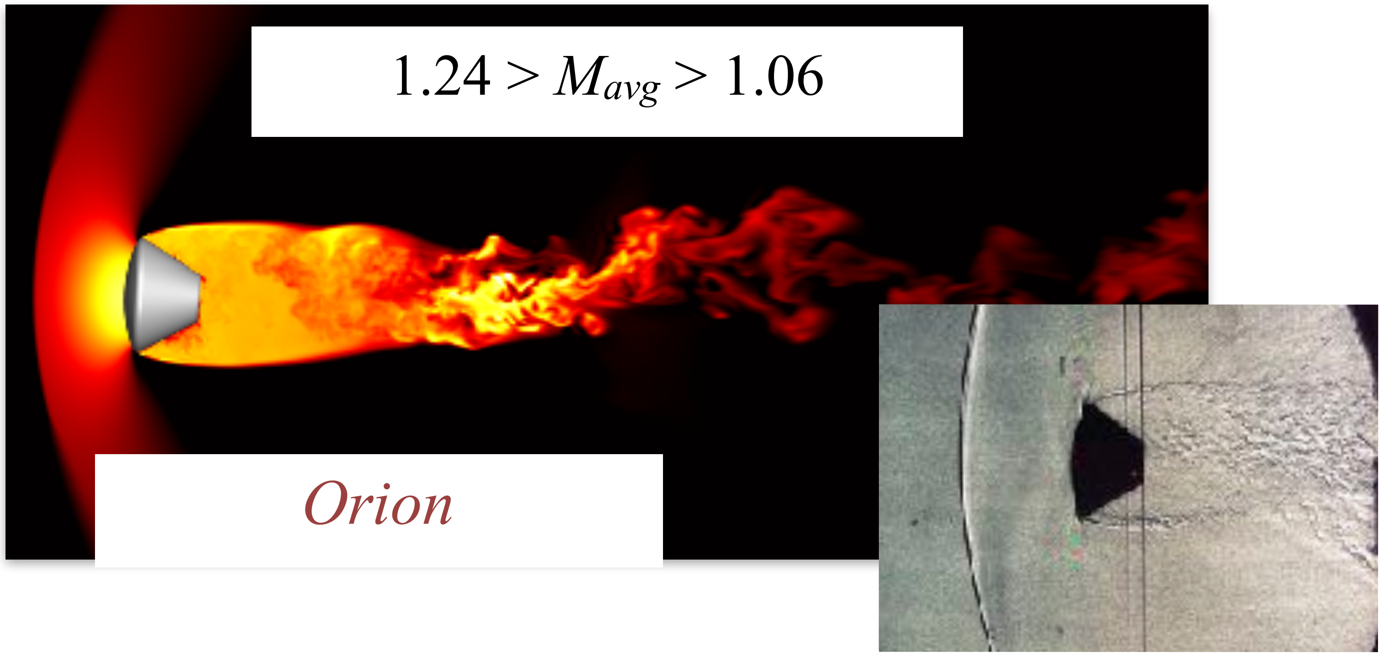


Mesh Deformation Improvements



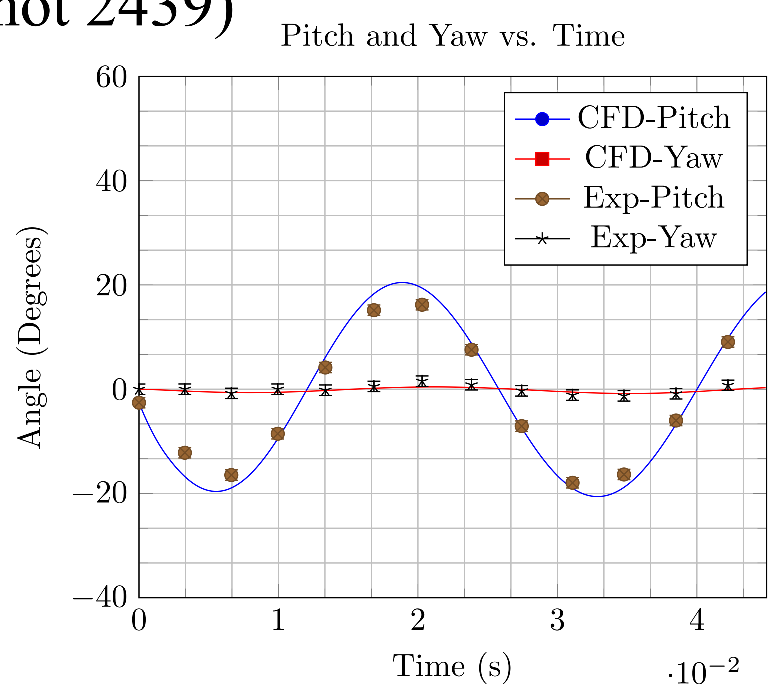


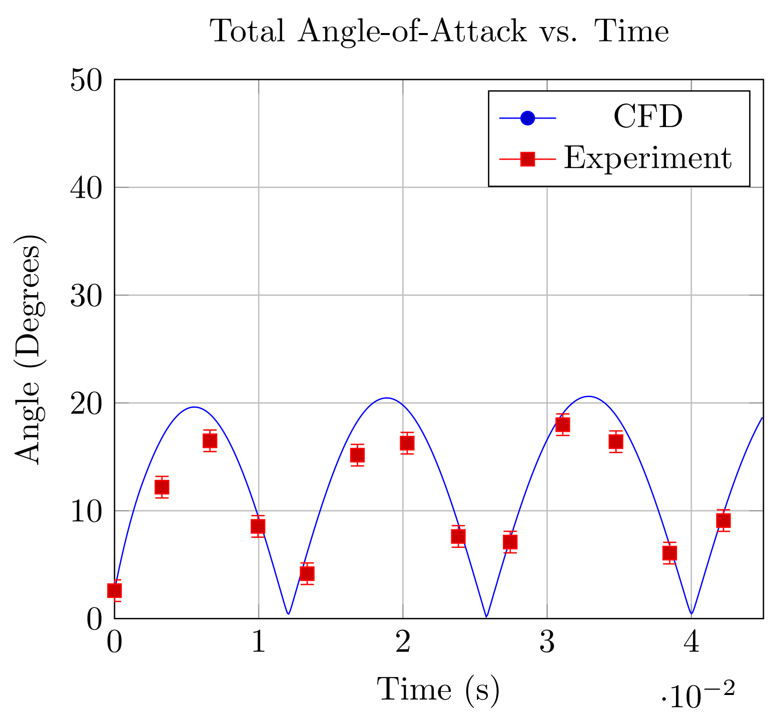
Recent Results

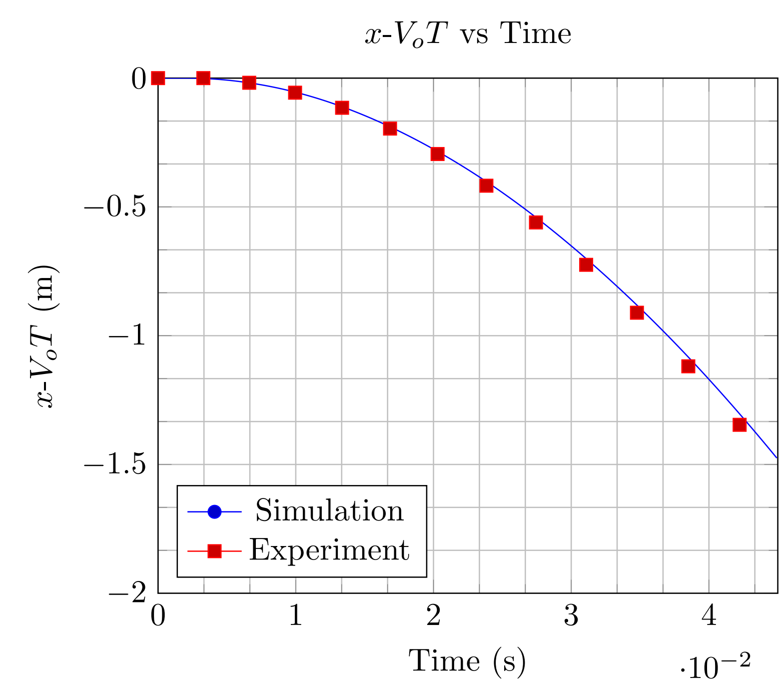


US3D Total : Time 20.61 hrs

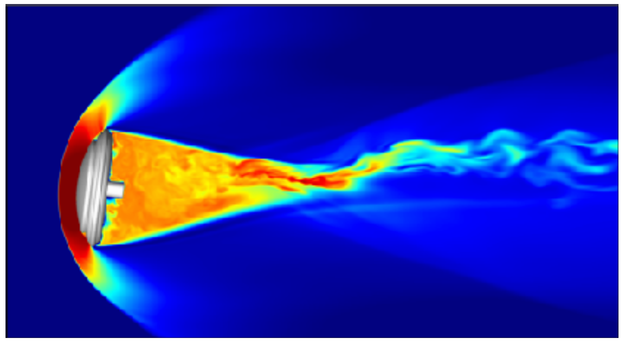
Mach = 1.24
(Shot 2439)

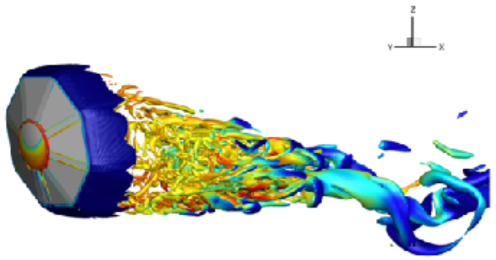




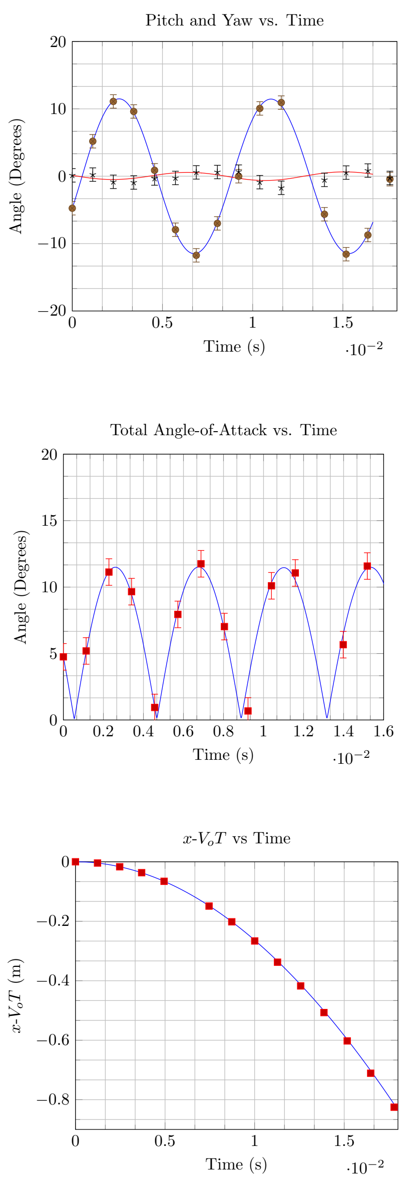


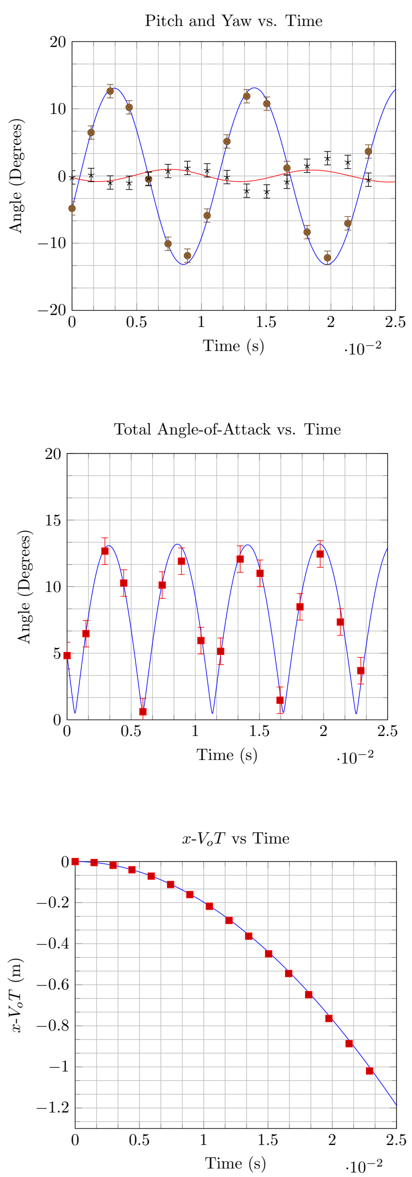
Supersonic to Transonic

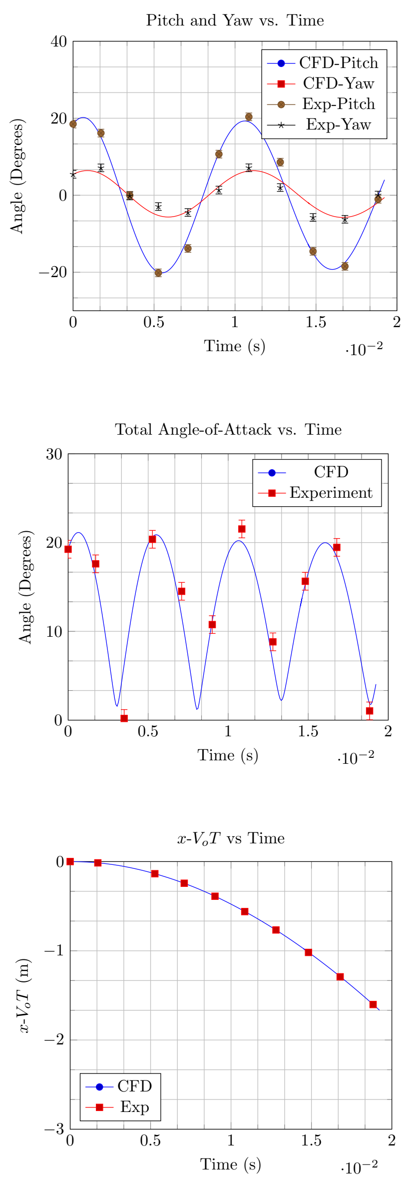


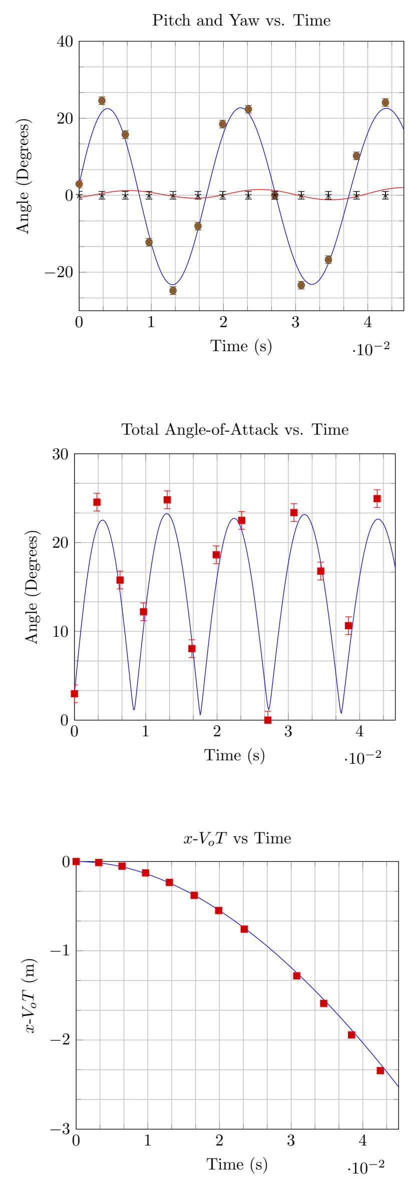


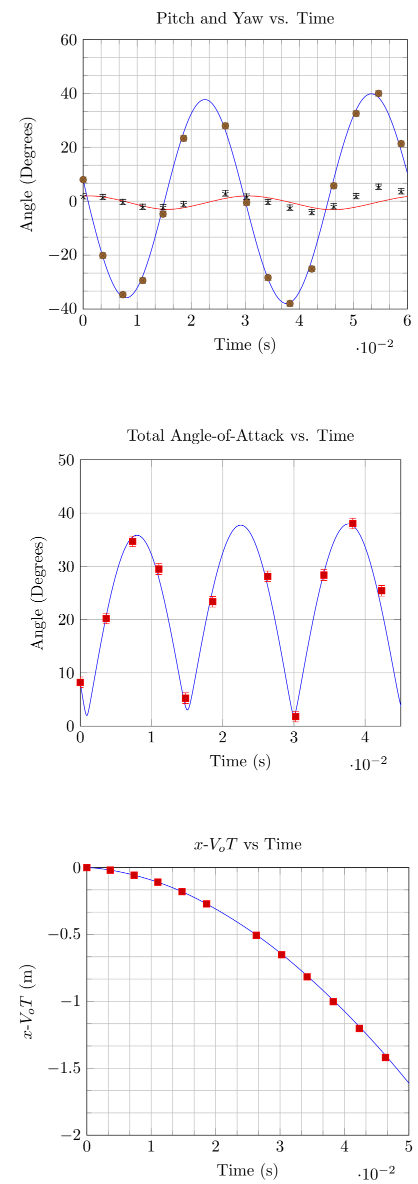
Mach: 3.78 *Mach*: 2.91 $Mach = 2.36$ $Mach = 1.23$ *Mach*: 1.13 *Mach*: 1.06

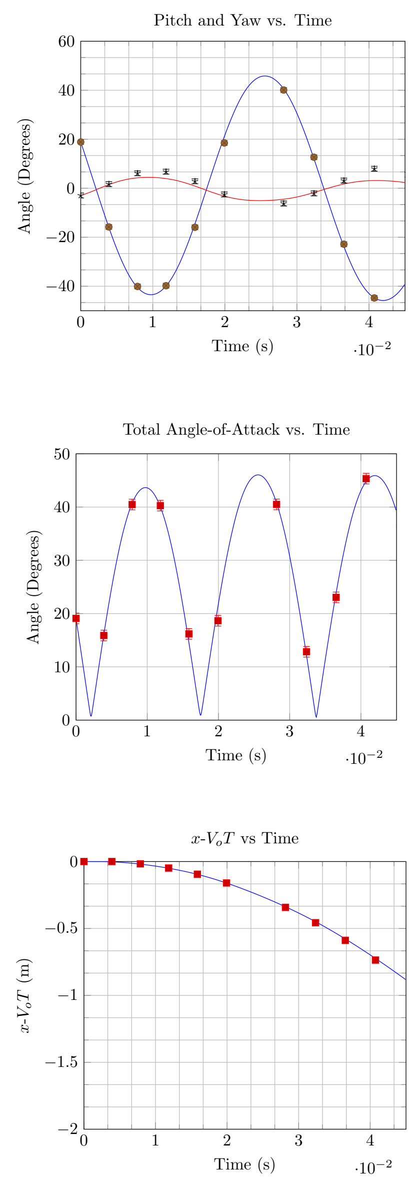






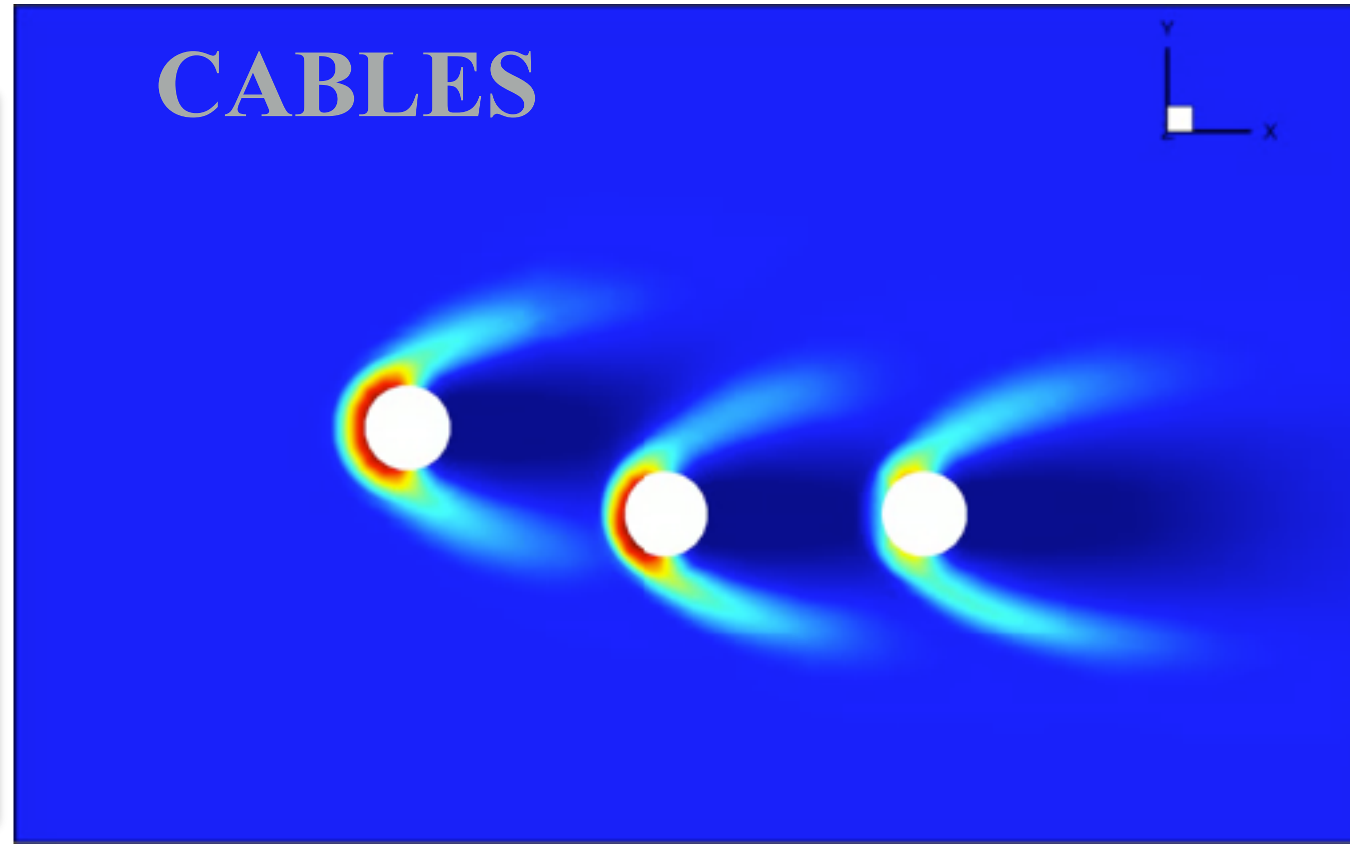




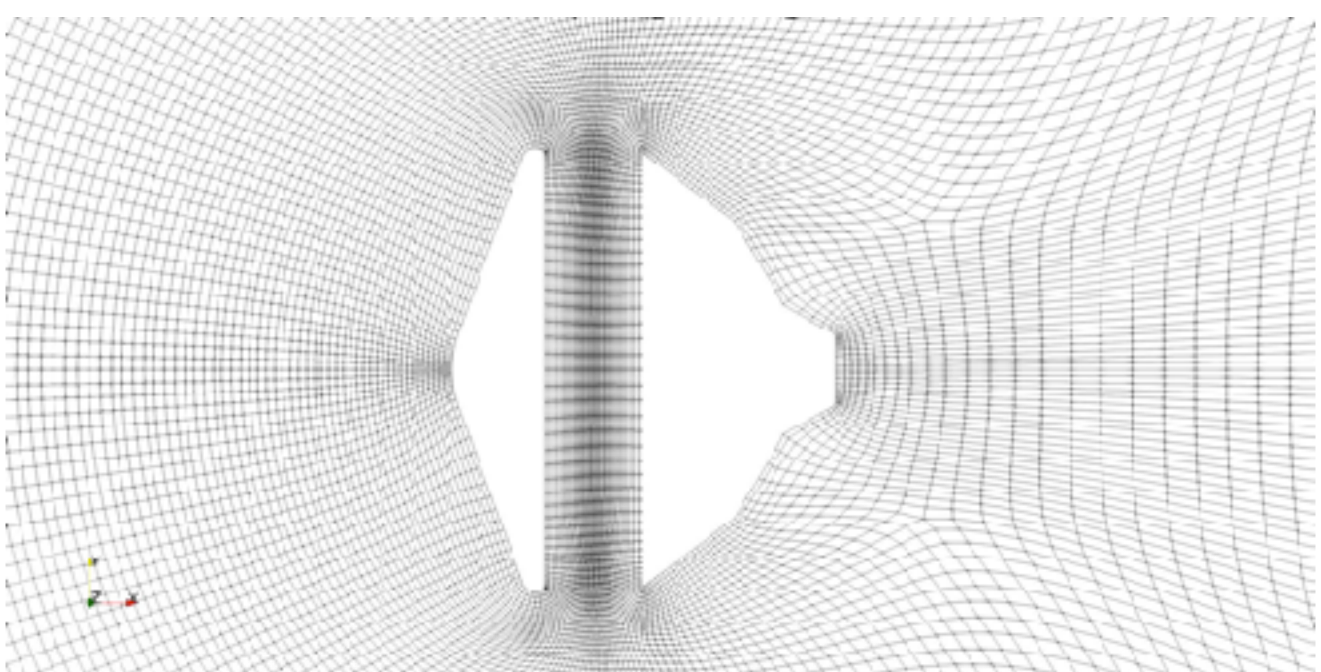


Multi-Body Dynamic Capabilities

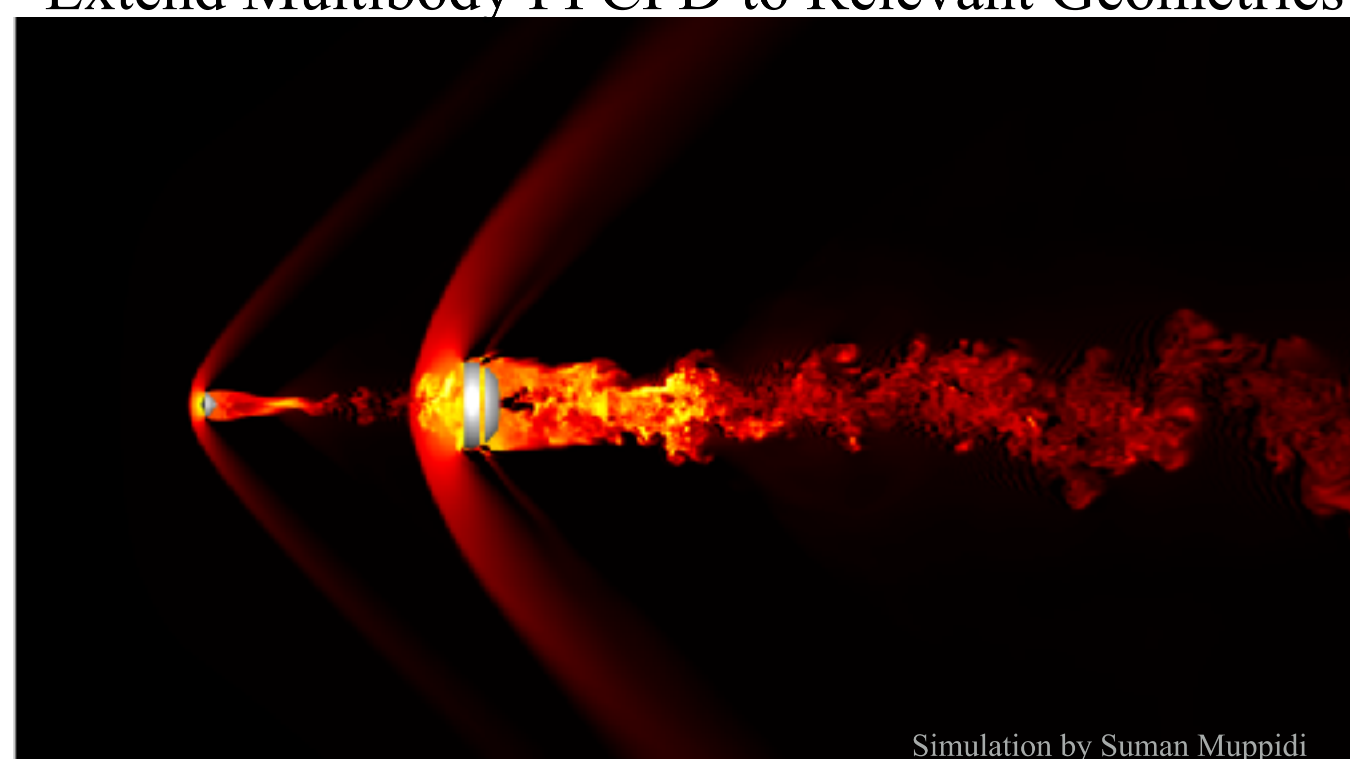
- CABLE module allows motion of multiple bodies to be coupled to each other
  - Forces are transferred via tension within virtual cable
  - Capability will be extended to rigid parachute simulations to study wake interactions
- Multi-body capability allows the study of separation events where recontact is of interest



Separation Events



Extend Multibody FFCFD to Relevant Geometries



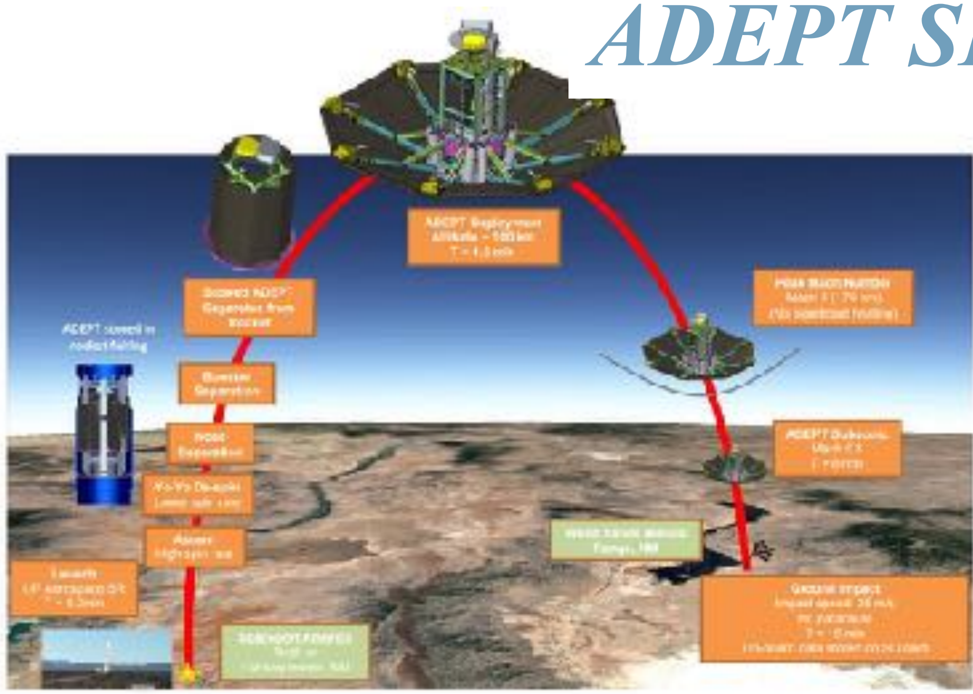
Summary

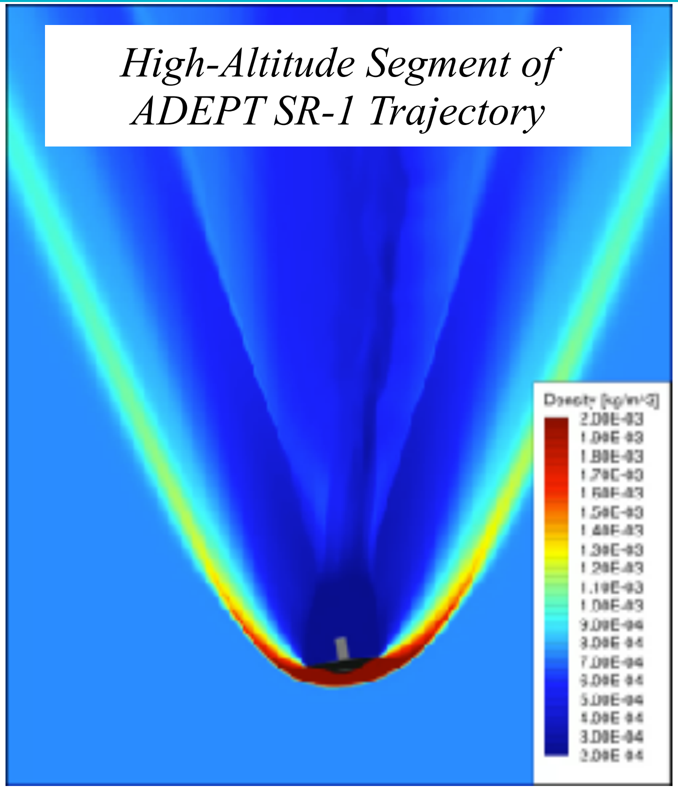
- Free-Flight CFD has been implemented into US3D and verified against experiment for single body geometry over a span of Mach numbers 3.7-1.06
  - Simulation is in excellent agreement with experimental data for the full range of Mach numbers
    - Roughly 5 percent error in total alpha
- Multi-body capability allows for investigation of flight dynamics of multiple rigid objects in proximal free-flight
  - Additional tool to constrain motion which approximates cable coupling has been implemented
- Trajectory code integrates FFCFD and atmospheric codes such as EarthGRAM to approximate changing free stream conditions and the effect on flight performance across an entire trajectory
  - Solver has been applied to full-scale trajectory
    - High altitude portion shows stable flight dynamics
    - Lower altitude shows total amplitude growth

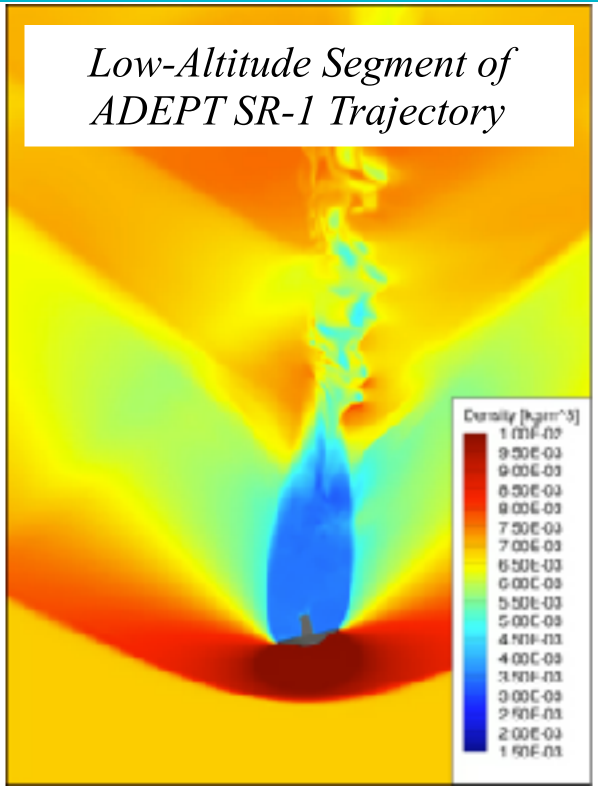
Backup

Changing Free-Stream Conditions

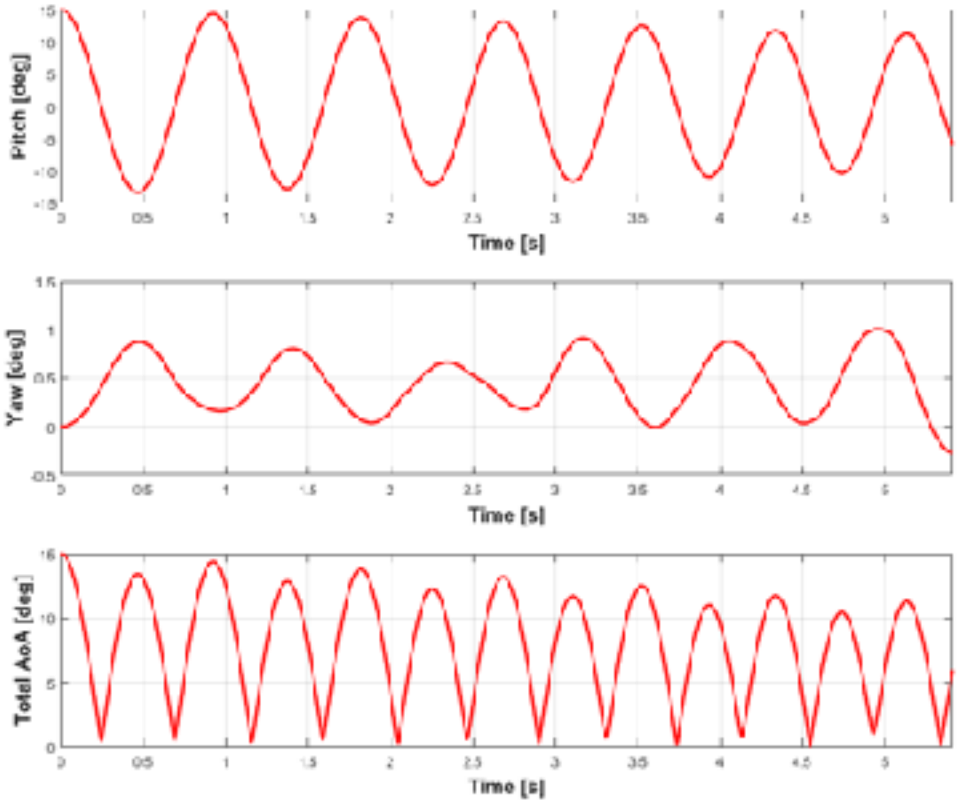
ADEPT SR-1



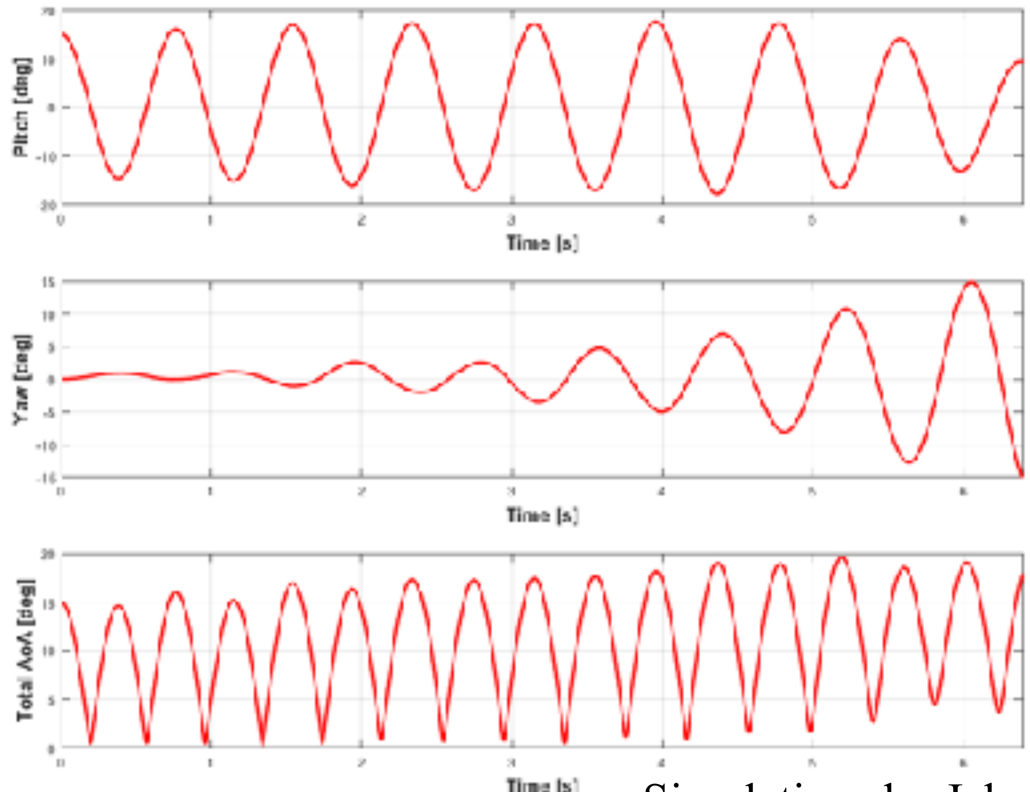




High Altitude



Low Altitude



Simulations by Jake Hergert