

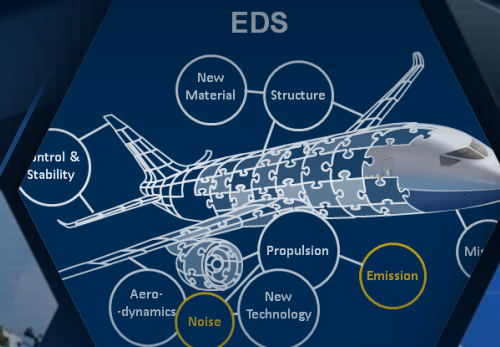
# A Methodology for Actuating RCS Jets in a Continuous, Time-Accurate CFD Simulation

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Presented by: Bradford Robertson

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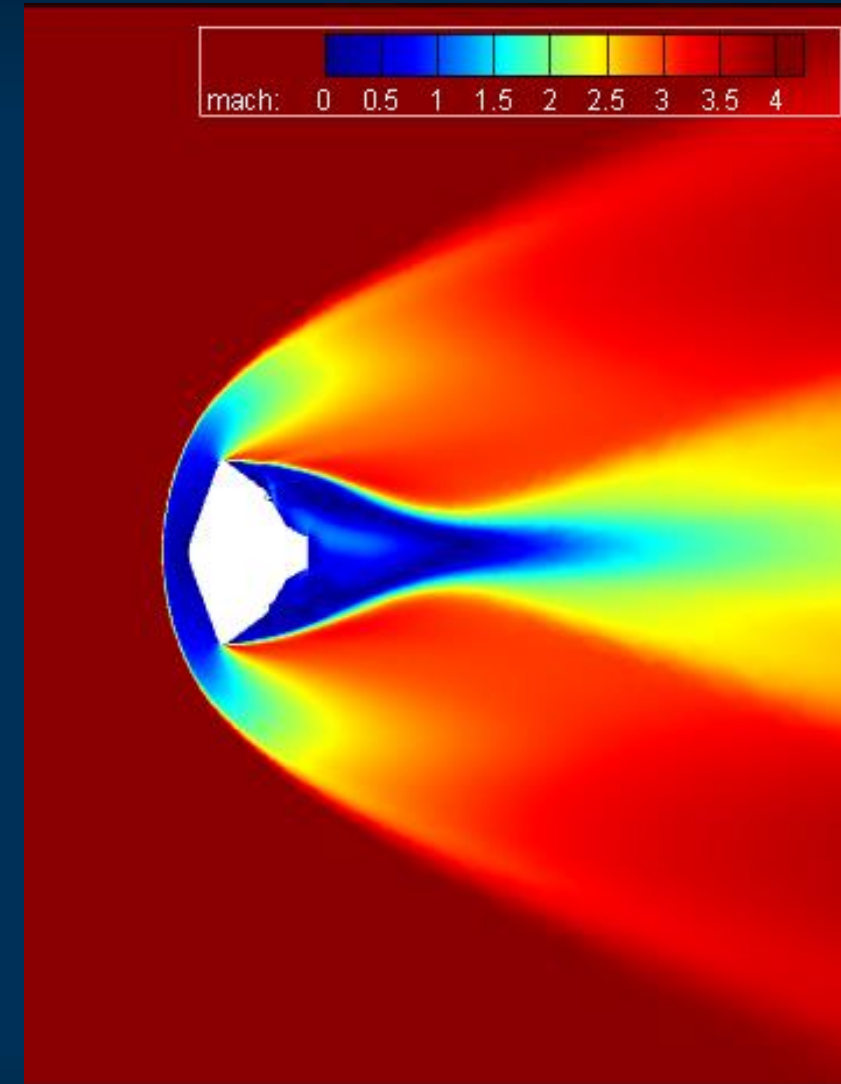
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# Overview of EDL RCS problem

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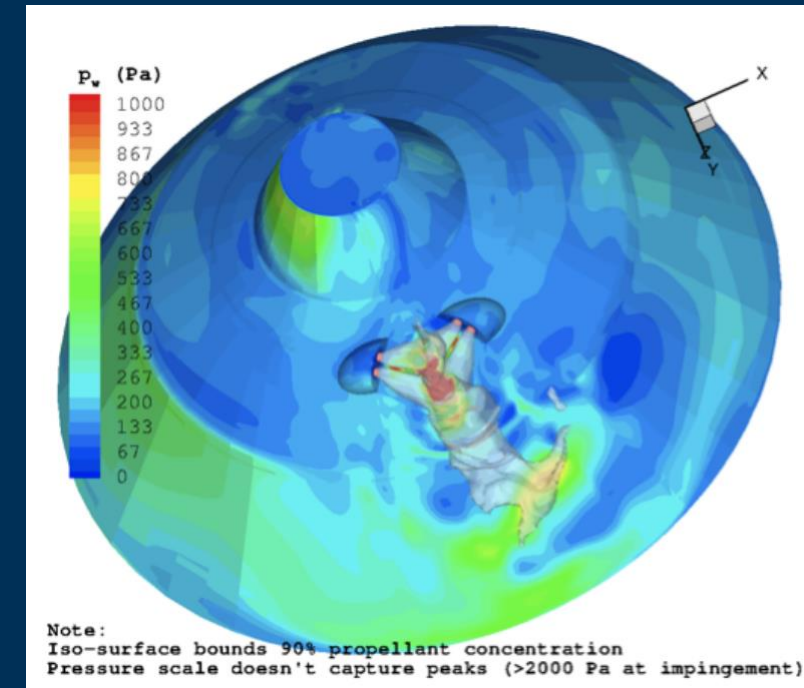
- As interest in exploring mars continues to grow, the development of better tools to model the entry descent and landing(EDL) vehicles becomes more important
- EDL vehicles
  - blunt bodies which aerodynamically show a strong bow shock and an elongated wake
  - Reaction control systems(RCS) often use monopropellant hydrazine thrusters for roll control [5,7]
- The blunt body combined with the RCS creates a complex, difficult to characterize environment in the wake of the vehicle
- Characterizing the aerodynamics of these vehicles is critical to their design and controllability [2,3]
- Traditionally, CFD simulations are used in combination with experiments to understand the aerodynamics of these systems [3–6]



MSL Static solution

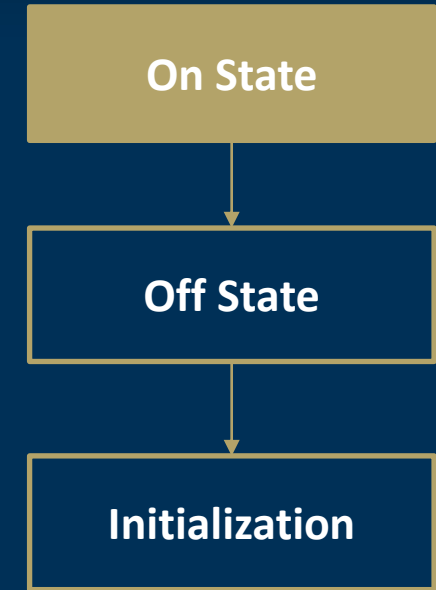
# Limitations of current practices

- Current CFD modeling [3–6]
  - steady state or dynamic simulations where the jet is assumed to be on for the entire duration of the simulation
  - fixed attitude, speed, and environment
  - validated against experimental results from wind tunnel tests
- Limitations [2,3,7]
  - lack the ability to effectively model true dynamic behavior of the system as it descends through the atmosphere
  - the complexity of the grid required in the wake of the vehicle to capture the flow interactions leads to significant uncertainty in the results of the simulations
- These issues lead to the need to implement control deadbands on the Phoenix lander [5,8]
- Integrated models as a solution
  - There has been significant work on integrating CFD and rigid body dynamics(RBD) simulations to allow for the free flight modeling of these systems[9,10]
  - Some initial work has been done on completing a coupled CFD-RBD-flight control system simulation on the Army-Navy generic finner missile [11]
    - demonstrated issues with using a pure step function to actuate the jet
    - implemented an undefined ramp function to resolve numerical stability issues
- This work defines a detailed methodology for actuating a RCS jet in a time accurate CFD simulation focusing on the application to EDL vehicles



**MSL aftbody pressure distribution for candidate RCS configuration[3]**

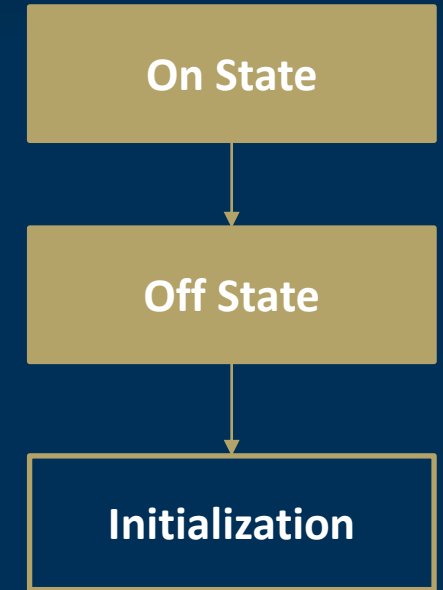
- The methodology is broken into three steps: the on state, the off state, the initialization
- The on state is implemented first
  - Converts the time from when the jet reaches to final pressure ratio to the end of the simulation
- Boundary condition definition:
  - Subsonic inflow boundary condition
  - Controlled by temperature and pressure ratios seen in eq. (1) and (2) which are defined by the total plenum state with respect to the free stream
  - Determined based off literature review, experiment or manufacturer
- This state is used
  - To determine the appropriate flow settings for the simulation
  - For the grid study



$$PR_{t,bc} = \frac{p_{total,plenum}}{p_{static,freestream}} \quad (1)$$

$$TR_{t,bc} = \frac{T_{total,plenum}}{T_{static,freestream}} \quad (2)$$

- Covers the time from when the simulation is started to when the first command is sent to change the temperature and pressure ratio
- Boundary condition definition
  - Ideally modeled with an inviscid wall boundary condition
  - The boundary condition type cannot be changed mid-simulation to accommodate jet actuation
  - The subsonic inlet boundary condition which needed for when the jet is actuated must be used to model the off state
  - To determine the appropriate temperature and pressure ratios for the off state
    - First run a time accurate simulation of the system with the wall boundary condition
    - Then sample the chamber close to the boundary to the far left of center, center and the right of center to extract the temperature and pressure
    - Calculate the temperature and pressure ratios using eq. (1) and (2)
    - Run a simulation with the subsonic inlet boundary condition with the calculated temperature and pressure ratios to verify the off state is sufficiently similar to the on state



- Initialization covers the period between when the first command is sent to change the temperature and pressure ratios and when the final temperature and pressure ratios are reached
- Boundary condition definition:

- Three different ramping functions are explored for the pressure ratio

- Step function:

$$PR_{t,bc}(t) = PR_{off}; t < t_{start} \quad (3)$$

$$PR_{t,bc}(t) = PR_{on}; t \geq t_{start}$$

- Linear ramping function:

$$PR_{t,bc}(t) = (PR_{on} - PR_{off}) / (t_{end} - t_{start}) * (t - t_{start}) + PR_{off}; \quad t_{start} \leq t \leq t_{end} \quad (4)$$

- Exponential ramping function

$$PR_{t,bc}(t) = (PR_{on} - PR_{off}) * \left( 1 - \text{Exp} \left[ -\frac{t - t_{start}}{\tau} \right] \right) + PR_{off}; \quad t_{start} \leq t \leq t_{end} \quad (5)$$

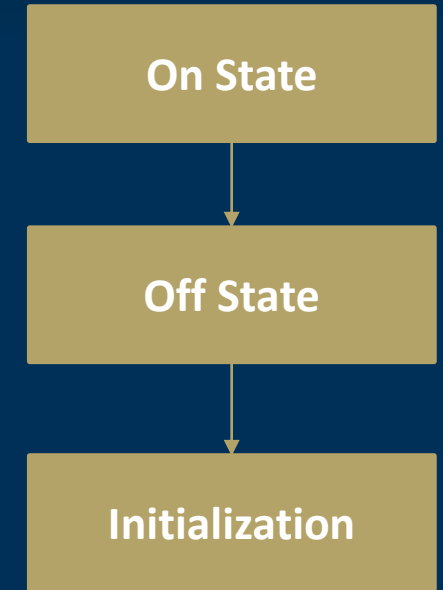
- Each function is implemented as a part of a piecewise function in which is preceded by the previously defined off state and followed by the on state

- Ramp duration is determined based on literature review, manufacturer information or experimentation

- Temperature ratio is always defined by a step function:

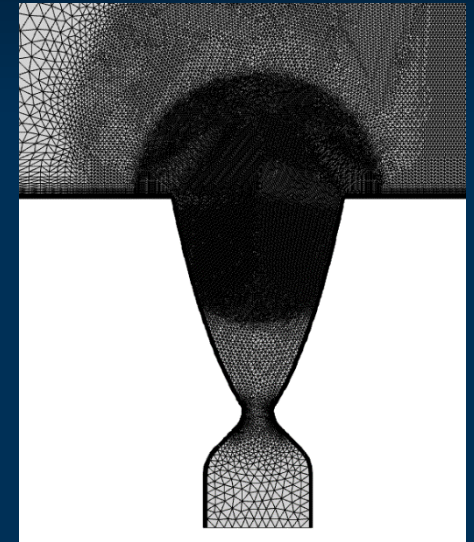
$$TR_{t,bc}(t) = TR_{off}; t < t_{start} \quad (6)$$

$$TR_{t,bc}(t) = TR_{on}; t \geq t_{start}$$

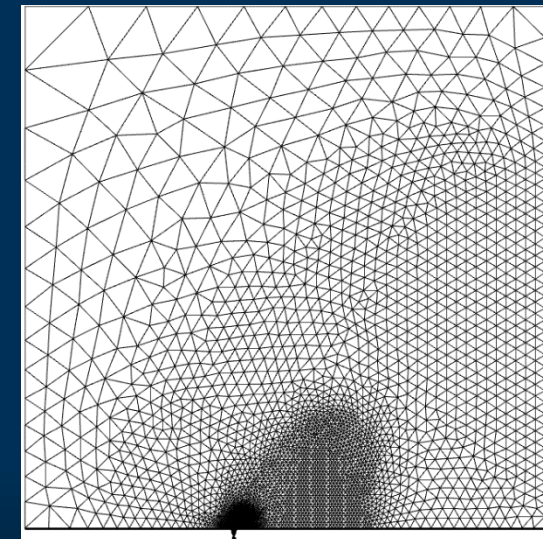


# Test case set up

- The large complex grid required to effectively capture the jet wake interactions motivated the use of a test grid which isolates the RCS jet from the rest of the problem
- Jet in a flat plate subjected to a supersonic cross flow was selected due to its suitability and history of being used as a test case to model the RCS problem[14]
- RCS geometry definition
  - Based on a 400N monopropellant hydrazine thruster
  - Nozzle geometry is based on procedure described by Rao et. al.
  - Combustion chamber given a representative length based on literature review
- Grid boundaries set to be at least 40 nozzle diameters from the nozzle entrance in all directions to ensure the ability to capture flow phenomenon of interest
- 8 million node tetrahedral grid generated in capstone
  - Boundary layer define for flat plate, nozzle, throat and chamber walls
  - Tight grid control was found to be necessary around the entrance to the jet and shortly down flow

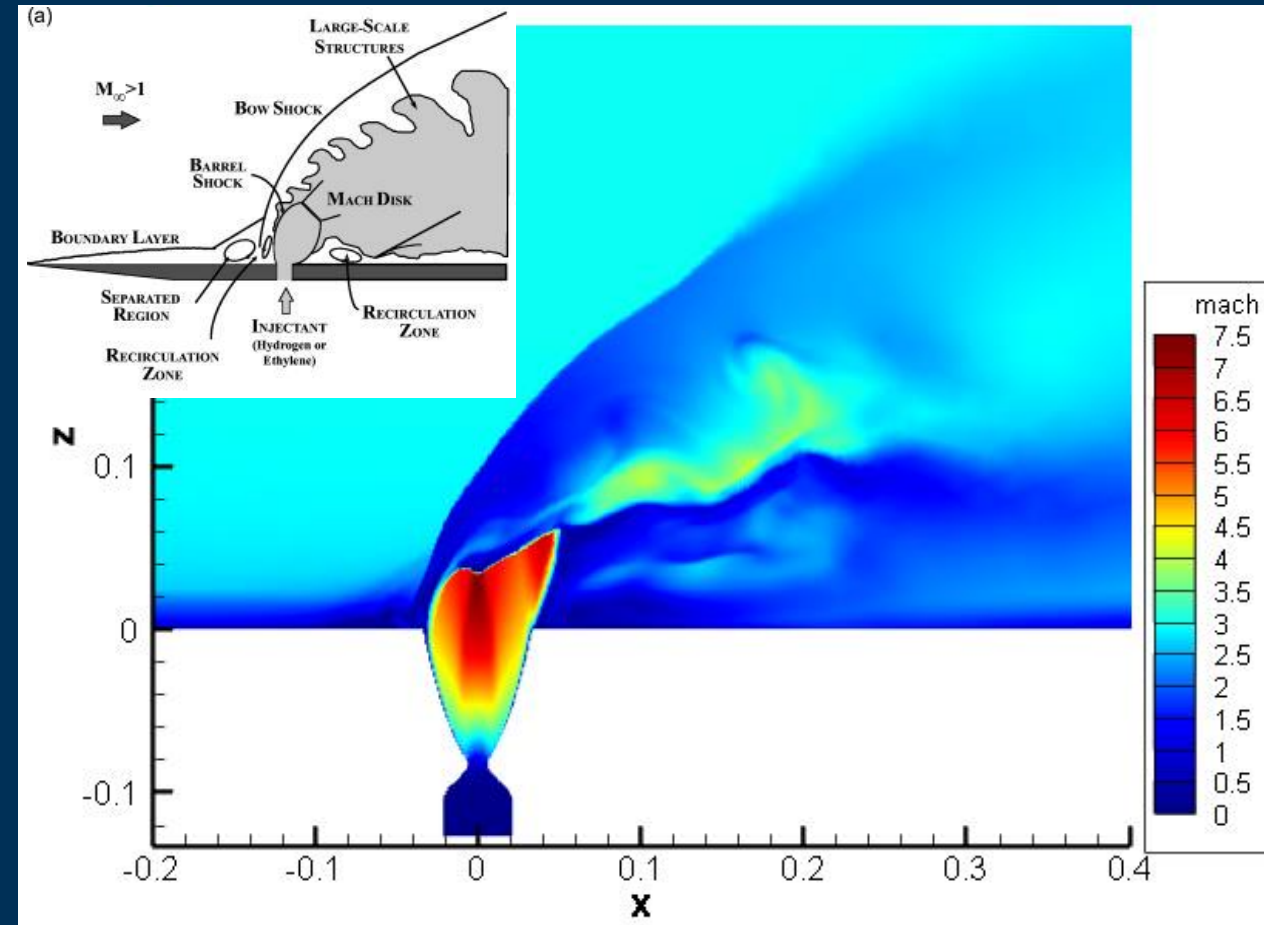


Detailed grid around jet

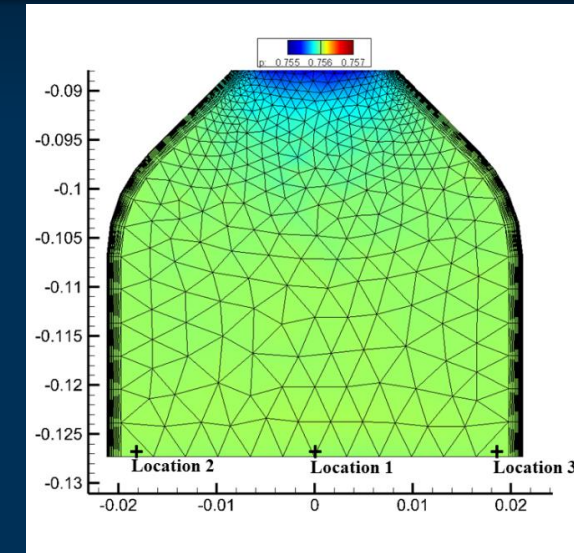


Grid cross-section

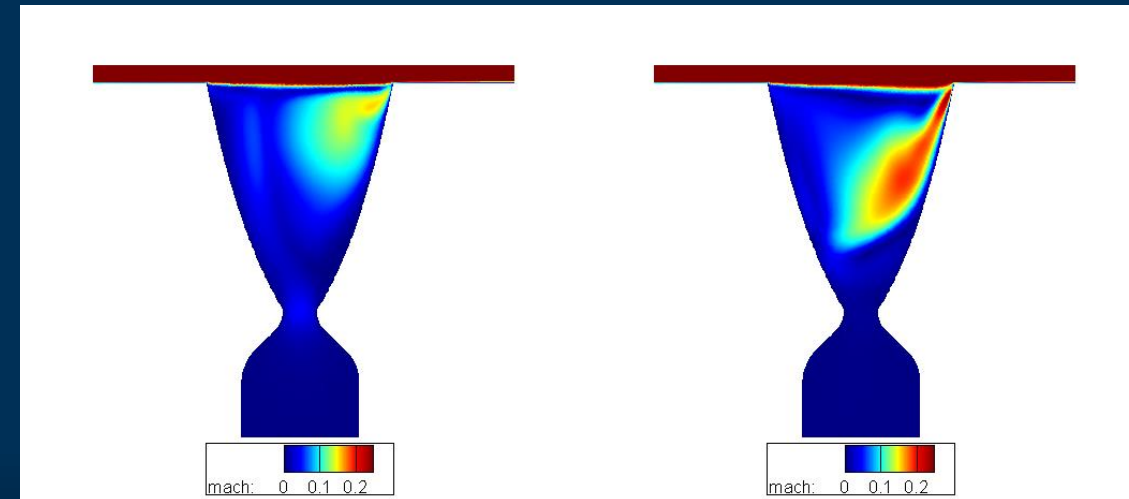
- Simulation freestream conditions
  - Martian atmospheric temperature, pressure, and density at an altitude of 10km[15]
  - Run in air
  - Mach 3
  - Reference length of 0.07m based off of nozzle exit diameter
  - Reynolds number of approximately 30,000
- Simulation settings
  - Turbulence model DES
  - Flux construction Roe
  - Flux limiter: van albada
- On state boundary conditions
  - Pressure ratio: 270
  - Temperature ratio: 6.5
- Verified in a time accurate simulation run for 3000 steps
  - Expected flow phenomenon are present
  - Good convergence of residual behavior



- Establishing the boundary condition
  - A simulation was completed with an inviscid boundary condition at the jet inlet
  - The converged simulation was used to take samples at the indicated locations of the pressure and temperature
  - These were then used to calculate the off state temperature and pressure ratios
    - Temperature ratio: 2.34
    - Pressure ratio: 1.05
- Verifying the boundary condition
  - The calculated temperature and pressure ratios were implemented with the subsonic inlet boundary condition
  - Simulation was run for the same amount of time as previous simulation and then compared
  - Given lack of significant flow and similarity of results the off state was deemed to be sufficient



Sampling locations

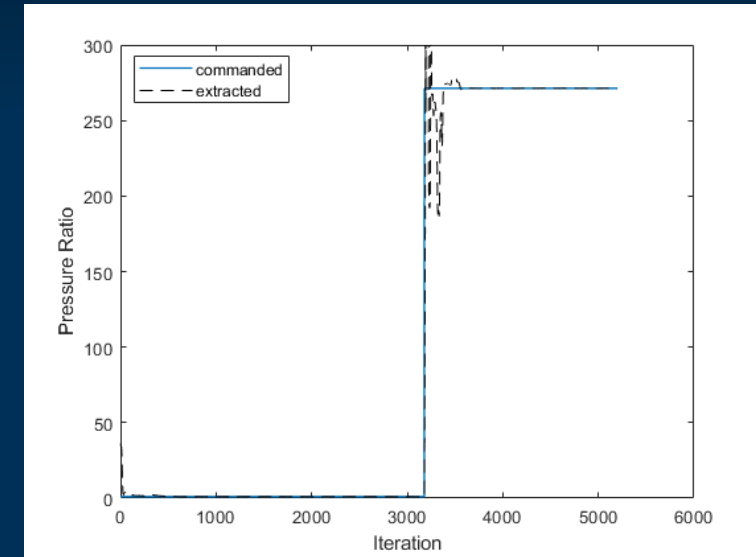


Idealized Off State

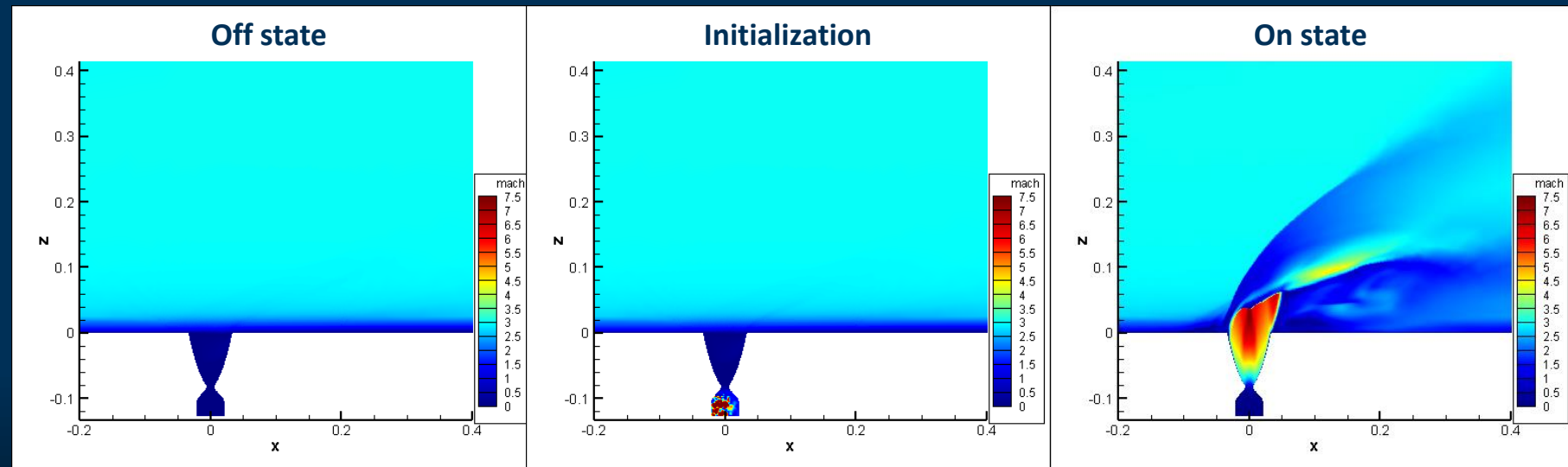
Approximated Off State

# Test case initialization: Step function

- The step function implemented steps from a pressure ratio of 1.05 in the off state to 270 in the on state
- The simulation has difficulty achieving the instantaneous pressure change at the boundary
  - Not accompanied by the need for pressure or density corrections
  - Does show nonphysical flow behavior
- Simulation is able to achieve the commanded pressure ratio at the boundary after  $\sim 75$  steps
- Once the pressure is reached no further problems are seen in the flow or simulation
- Demonstrates that there may be some benefit to the simulation in a gentler transition between states

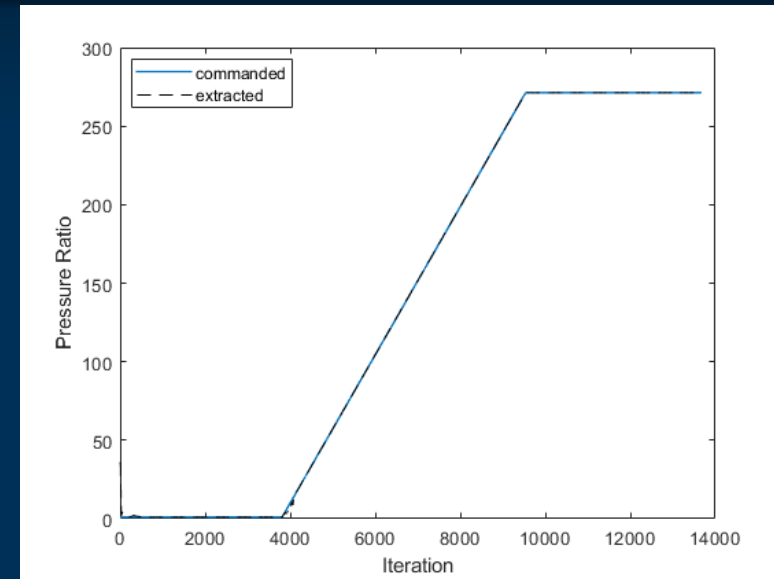


Extracted vs. commanded pressure ratio

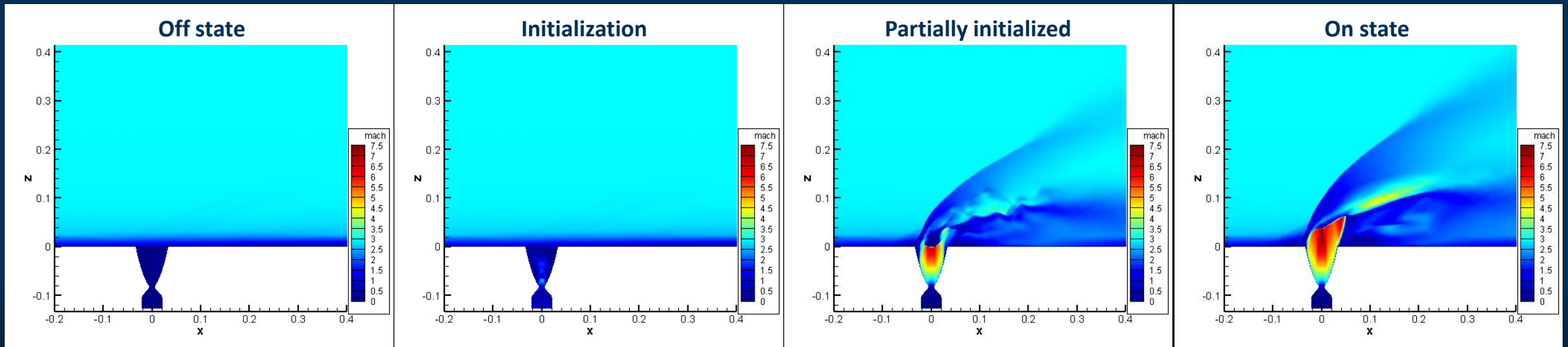


# Test case initialization: Linear ramp function

- The linear ramp function implemented ramps from a pressure ratio of 1.05 in the off state to 270 in the on state over 20ms
- The extracted pressure ratio at the boundary from the simulation is able to follow the commanded pressure ratio increases almost exactly
- The non-physical flow behavior in the chamber at the initialization of the jets has been resolved
- The rest of the flow looks as expected
  - Good behavior out of the implemented DES turbulence model
  - Good stability in the on state with defined shock structure

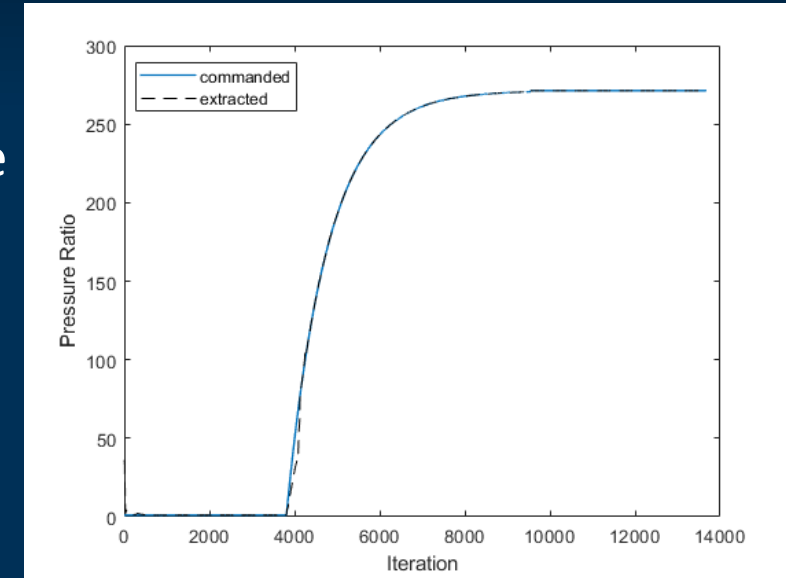


Extracted vs. commanded pressure ratio

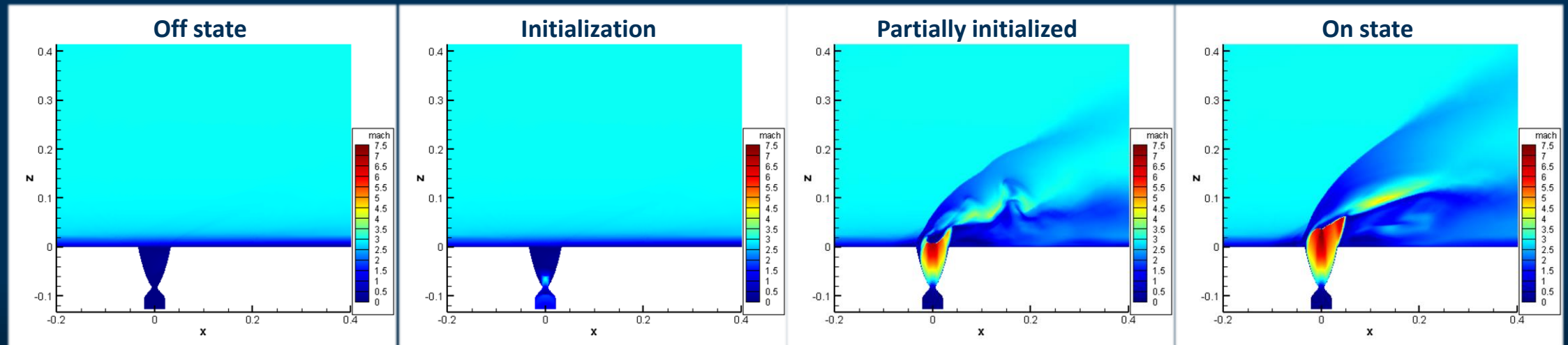


# Test case initialization: Exponential ramp function

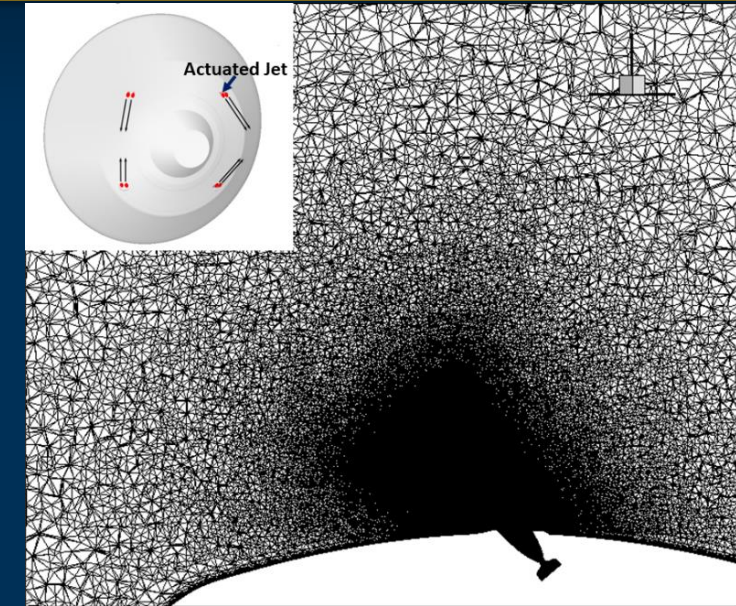
- The exponential ramp function increases the pressure ratio over 20ms
- The extracted pressure ratio boundary values demonstrate some difficulty in keeping up with the prescribed rate change but there is no divergence as seen in the step function
  - This may indicate that for a particular CFL and time step there is a max rate change that can be achieved before stability issues are seen
- In spite of the slight rate divergence the flow appears as expected at initialization of the nozzle and once again good flow behavior is seen throughout the rest of the simulation



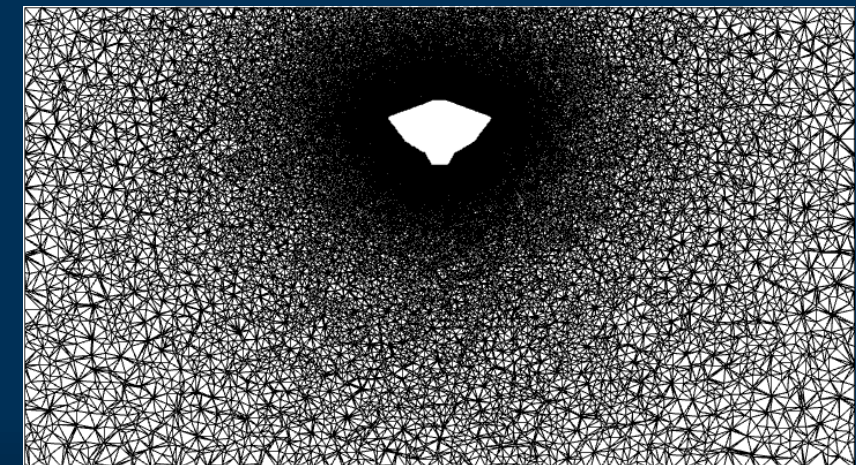
Extracted vs. commanded pressure ratio



- The completion of the test case set the stage for a demonstration of the methodology on the MSL vehicle
- A 35 million node mixed element grid was provided by NASA Langley
- Each simulation is started with a static simulation to provide better flow stability
- Freestream conditions
  - Karlgaard et al. trajectory reconstruction at of the MSL flight 692 seconds used to determine the atmospheric properties[21]
  - Mach 3.9
  - Temperature 201K
  - Reynolds number of  $1.53e6$
  - Run in air
- CFD settings
  - Turbulence model: DES
  - Flux construction: dissipative LDFSS
  - Flux limiter: van albada

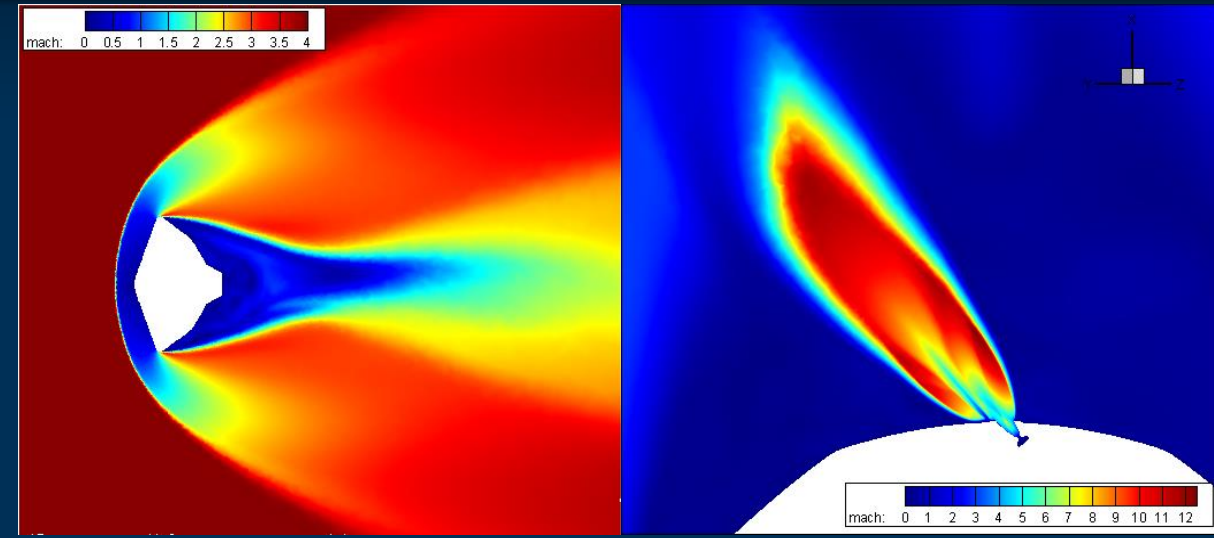


Jet detail



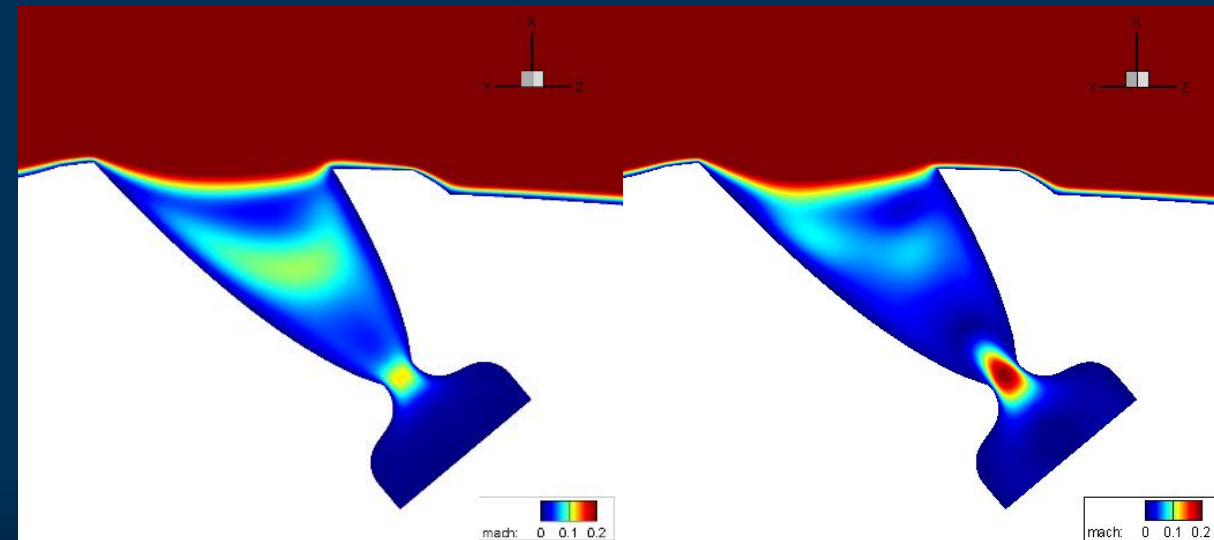
Full grid

- The on state simulation completed showed good overall stability
  - Provides insight into the performance of a step function due to step from off state to on state at the beginning of the simulation
  - Grid density was not sufficient to capture the jet wake interactions on the upper left hand side of the plume
  - The flow does show an anomaly to the left hand side of the opening of the jet which is addressed by the implementation of a ramp
- The off state establishment
  - Ran simulation with inviscid wall boundary condition
  - Sampled as per previously described sampling method
  - Calculated pressure and temperature ratio
    - Pressure ratio: 0.43
    - Temperature ratio: 3.65
  - Comparison deemed sufficient for demonstration



Vehicle flow

Nozzle detail

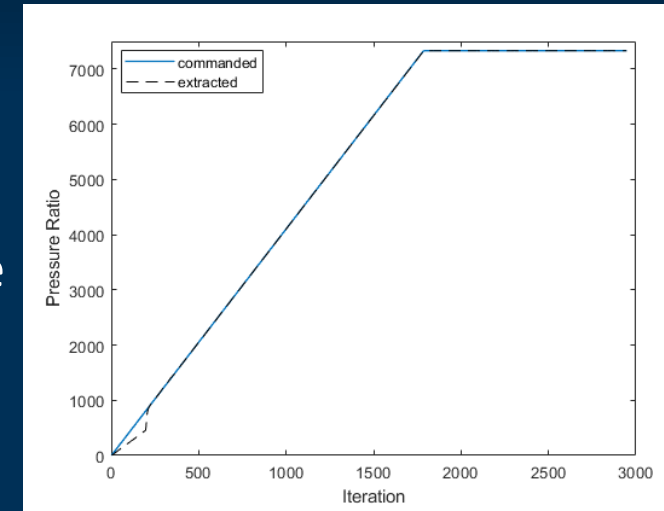


inviscid wall

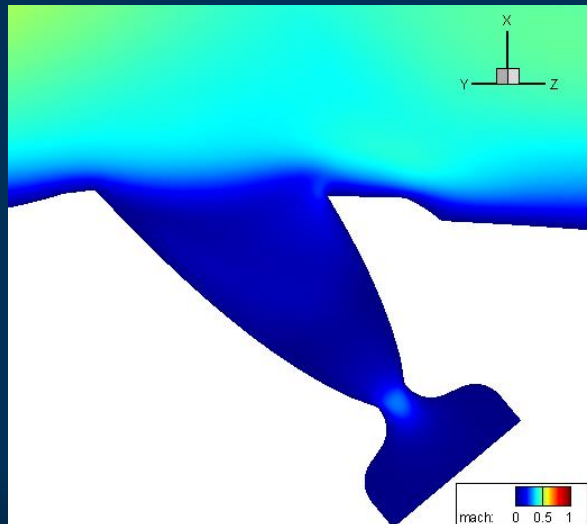
subsonic inlet

# MSL demonstration: linear ramp

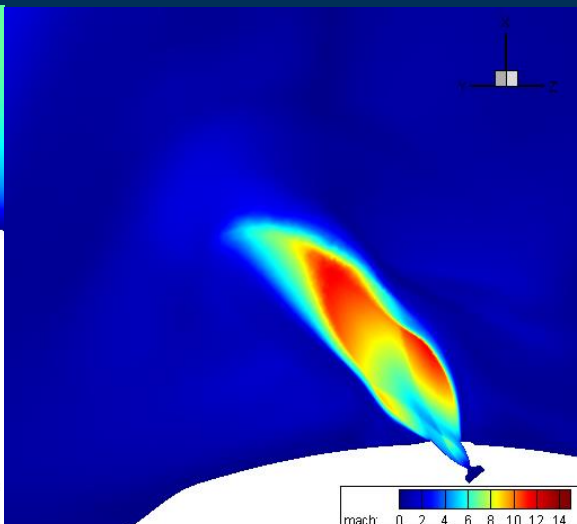
- A linear ramp was implemented over 20ms
- The simulation shows some difficulty in achieving the prescribed rate of increase at the beginning but this resolved in the first 150 iterations
- The implementation of the ramp resolves the flow anomaly seen in the previous runs which implemented a step in pressure
- Demonstrating the potential utility of implementing a ramping function for flows with complex interactions



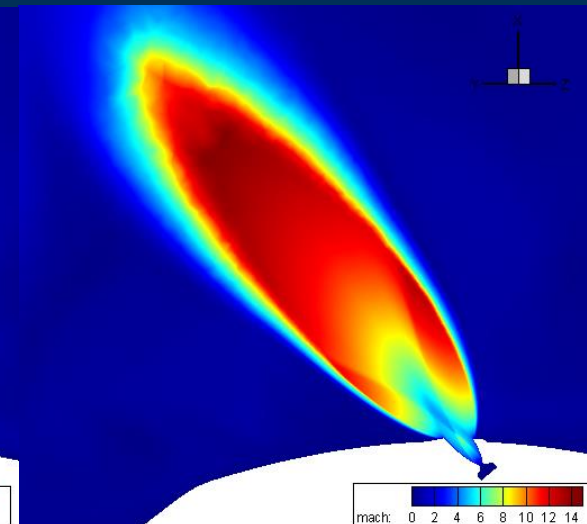
Extracted ramp



Initialization



Partially initialized



On state

- The methodology demonstrated successfully allows for actuation of RCS jets during a time accurate CFD simulation setting the stage for further integration with CFD-RBD-FCS simulations
- Implementation on the test case demonstrated
  - Simulation setting selected for the on state are able to achieve good results during the off state and initialization of the jet in spite of the wide range of flow phenomenon present
  - The implementation of a ramping function not only allows for better modeling of real world system responses but produces greater simulation stability over a step function
  - For a particular set of flow setting there is likely a maximum rate of increase achievable for the pressure ratio
- MSL demonstration
  - Showed successful implementation of the methodology to demonstrate a linear ramping function on the RCS jets imbedded in the vehicle
  - Demonstrated the value of implementing a ramping function when actuating jets in complex scenarios to allow for more accurate results

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