Force and Moment Analysis for the High Reynolds Number Wind Tunnel Test of the Space Launch System at Ascent Conditions

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Outline

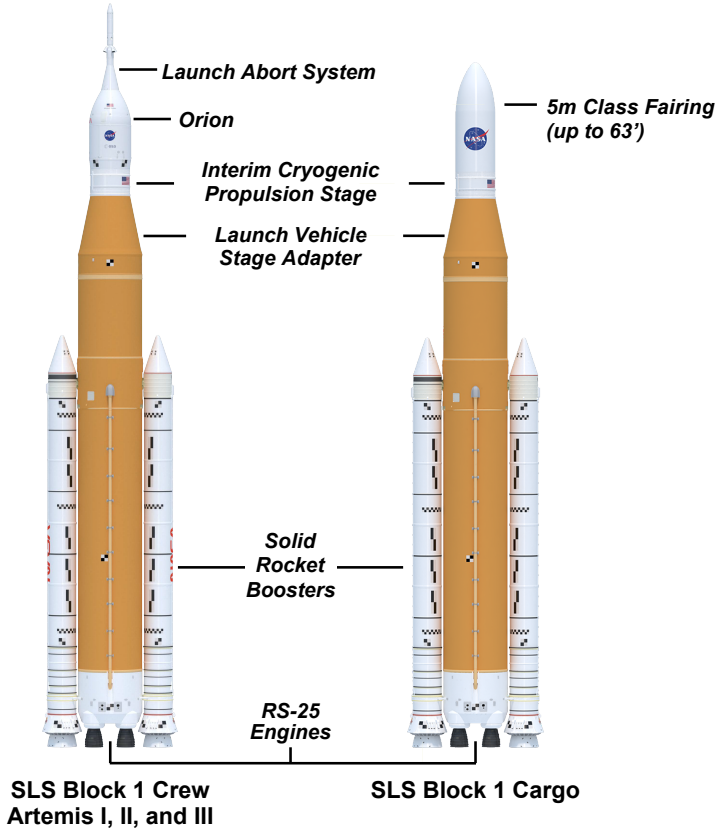
- Background
- Test facility and experimental setup*
- Data corrections and response surface modeling
- Reynolds number effects
  - Force and moment coefficients
  - Surface pressure coefficients
- Summary and conclusions

*More details can be found in the companion paper by David Chan, et al., "*Overview of the High Reynolds Number Ascent Wind Tunnel Test of the Space Launch System at the National Transonic Facility*"
AIAA Paper 2023-0425

Background

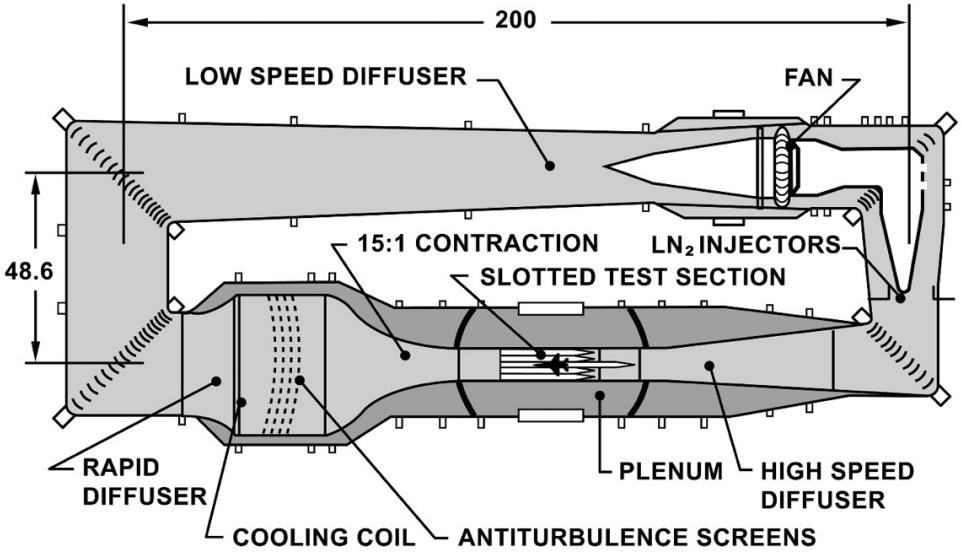
- Motivation
  - Wind tunnels typically used for SLS testing are limited to diameter-based Reynolds numbers (Re_D) 1-2 orders of magnitude lower than flight conditions
  - CFD simulations at ground test and flight conditions have been only data available to assess and account for Reynolds number effects

- Objectives
  - Assess the aerodynamics of the SLS Block 1 Cargo for the largest range of Reynolds numbers obtainable at the National Transonic Facility
  - Obtain six-component aerodynamic force and moment data
  - Obtain static surface pressure data



NASA Langley National Transonic Facility

- Cryogenic test facility
  - Closed-circuit
  - Continuous flow
- Test section
  - 8.2 feet x 8.2 feet x 25 feet
  - Slotted floor and ceiling
    - 6% open
- Air mode capabilities
  - Mach 0.1 to 1.10
  - Maximum Re_∞ = 20x10^6/ft
  - 80°F to 130°F
- Nitrogen mode capabilities
  - Mach 0.1 to 1.20
  - Maximum Re_∞ = 145x10^6/ft
  - -250°F to 80°F



Linear dimensions in feet

Experimental Setup

- 1.75% scale SLS Block 1 Cargo test article
  - As large as possible to allow for detailed protuberances
  - Small enough to stay under 0.5% blockage ratio recommended by NTF
- Test section installation
  - Arc sector
  - Roll mechanism
  - Sting mounted
- Instrumentation
  - Internal six-component balance
  - 124 pressure ports
    - Base and cavity pressures
    - Surface pressures
- Boundary layer tripping
  - Air mode ($Re_D < 4x10^6$)
    - Free transition: *Trip* = 0
    - Trip dot rings: *Trip* = 1
  - Nitrogen mode ($Re_D \geq 4x10^6$)
    - Trip dot rings: *Trip* = 2

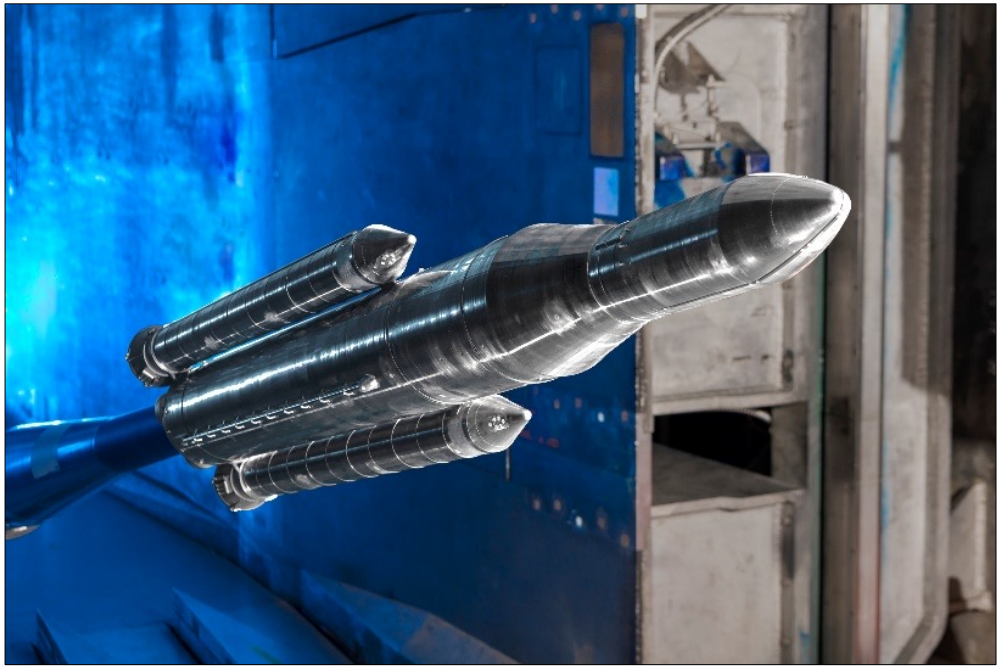


Photo Credit: NASA

Data Corrections

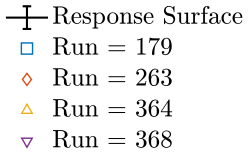
- Standard facility corrections
  - Flow angularity
  - Transonic Wall Interference Correction System (TWICS)
    - Mach
    - Dynamic pressure
    - Pitch angle
    - Lift, drag, and pitching moment
- Base and cavity corrections
  - Base pressure environment in wind tunnel does not represent flight conditions
  - Corrections computed using base and cavity pressures
    - Axial force and yawing moment
- Mach setpoint
  - Small changes in Mach number can have large impacts on axial force
  - Axial force correction accounts for difference between nominal and actual Mach setpoint
- Roll-dependent bias
  - Standard SLS correction when using pitch-roll model positioning
  - Accounts for minor systematic biases that are measured by rolling the model at 0° angle of attack
  - Correction applied to all forces and moments

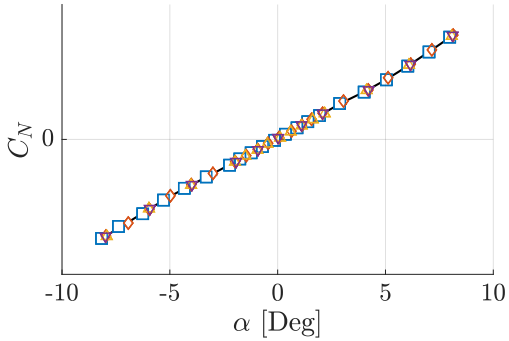
Response Surface Modeling

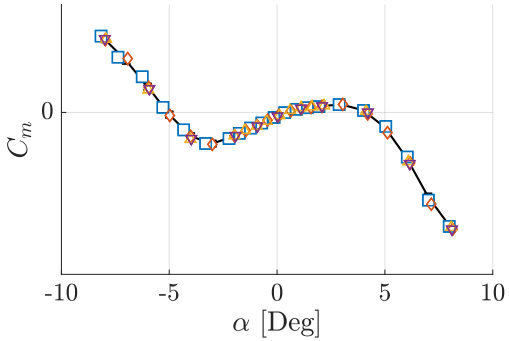
- Response surfaces used to help simplify Reynolds number effect comparisons
- Response surfaces computed using thin-plate splines in Matlab
  - All relevant repeat data used for generating response surfaces
    - Response surface not required to pass through training data
  - Two inputs
    - Angle of attack (α)
    - Sideslip angle (β)
  - One output
    - Single force or moment coefficient
  - Unique response surfaces computed for each Mach and Reynolds number
- Uncertainty quantification
  - Balance accuracy
    - Calculated as part of balance calibration prior to test
  - Modeling and repeatability
    - Computed as the difference between acquired data and response surfaces
  - Balance and modeling error root-sum-squared for combined uncertainty
  - 95% confidence bounds used as error bars on figures to follow

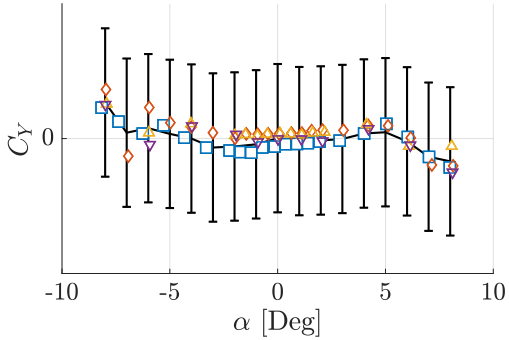
Response Surface Example

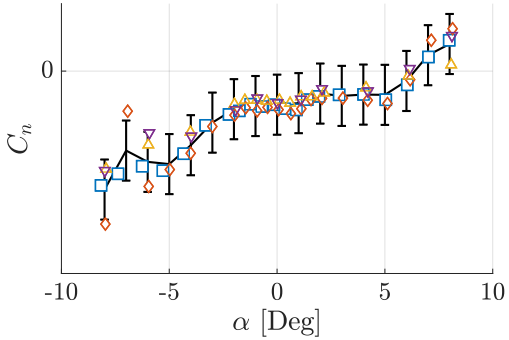
- Pitch sweeps
- $Re_D = 30x10^6$
- Mach = 0.90

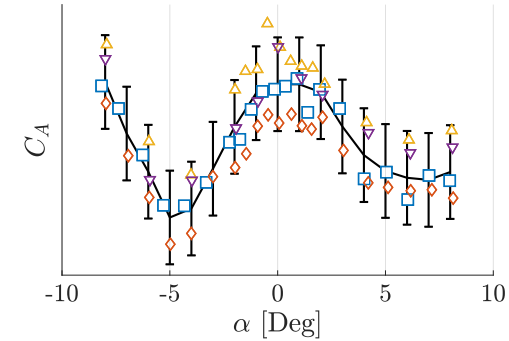


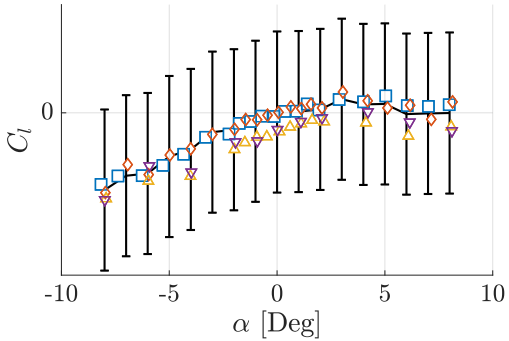






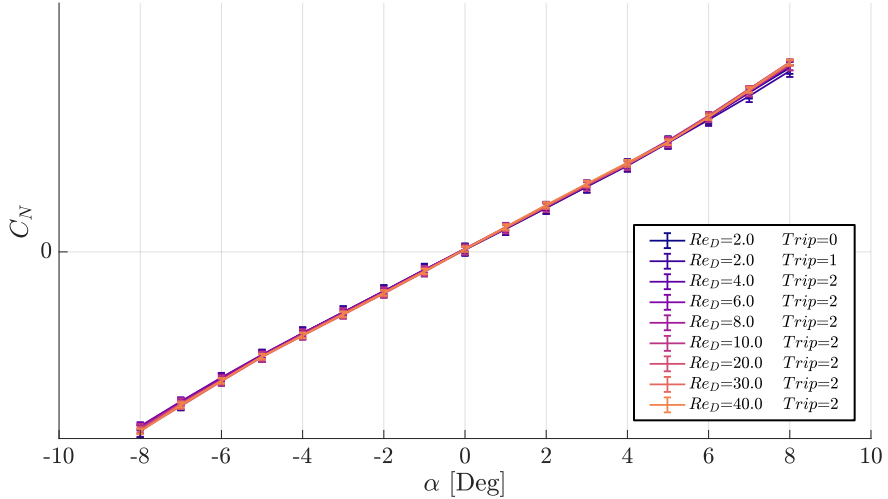


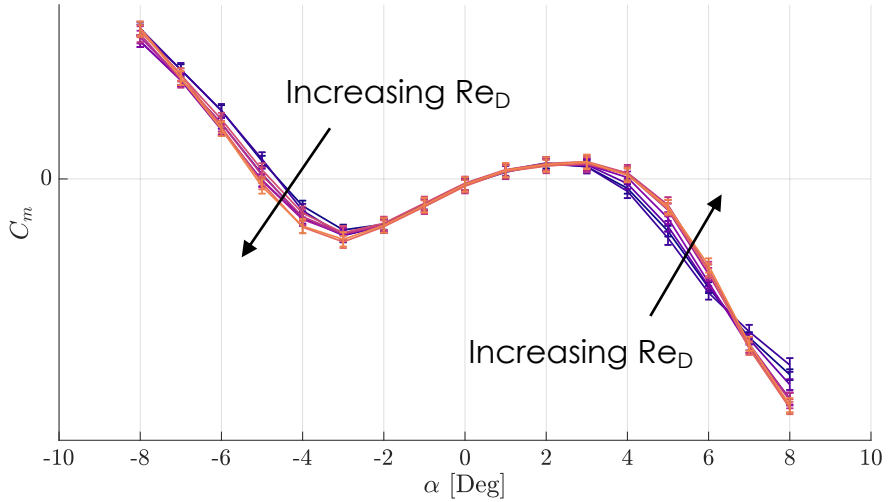




Reynolds Number Effects on Force and Moment Coefficients

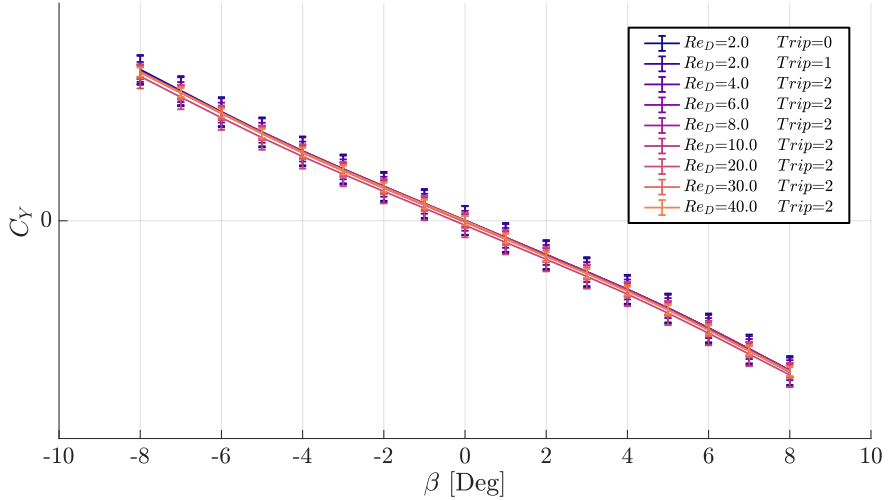
- Longitudinal coefficients
- Mach = 0.90
- Legend Re_D in millions (x10^6)
- Trip dot configurations
  - 0 – Free transition
  - 1 – Air mode sizing
  - 2 – Nitrogen mode sizing
- Key findings
  - No significant Re_D effect on normal force coefficient – C_N
  - Significant Re_D effect on pitching moment coefficient – C_m
    - Re_D trends potentially continue for Re_D greater than 40x10^6
    - Effects seen across entire pitch range

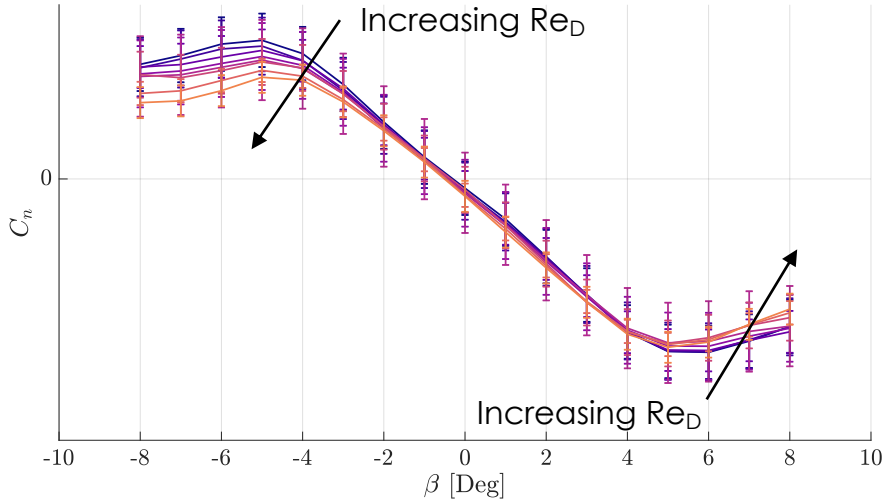




Reynolds Number Effects on Force and Moment Coefficients

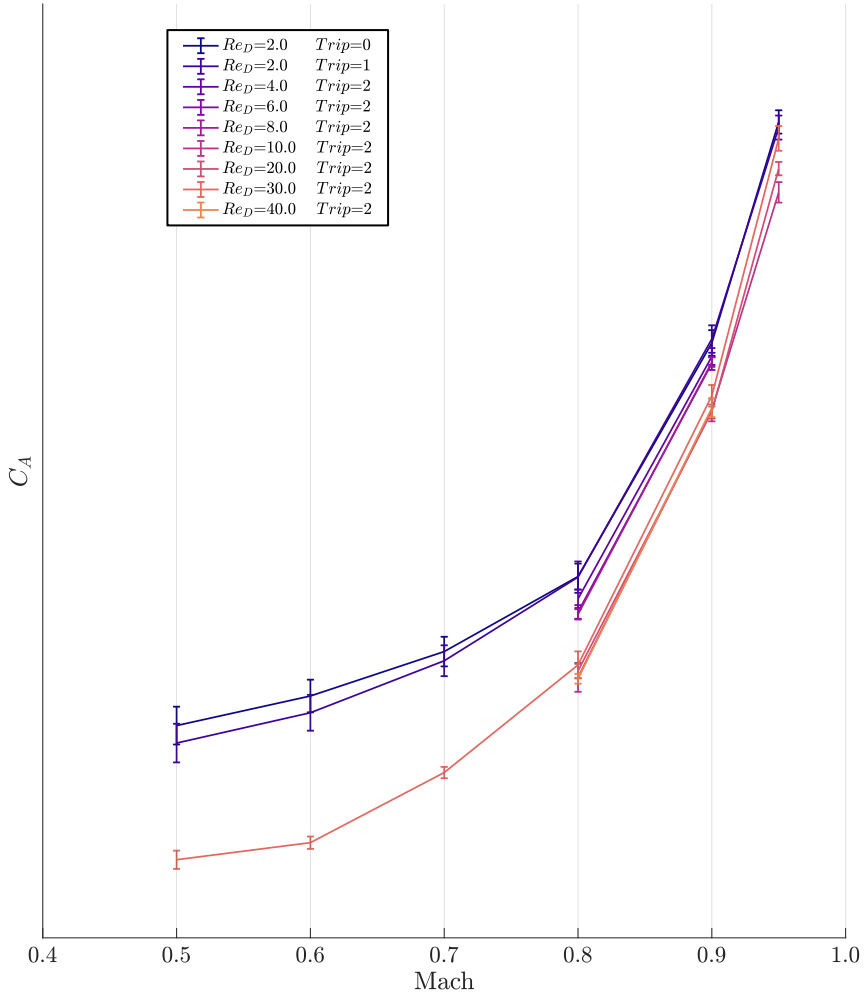
- Lateral coefficients
- Mach = 0.90
- Legend Re_D in millions (x10^6)
- Trip dot configurations
  - 0 – Free transition
  - 1 – Air mode sizing
  - 2 – Nitrogen mode sizing
- Key findings
  - No significant Re_D effect on side force coefficient – C_Y
  - Significant Re_D effect on yawing moment coefficient – C_n
    - Re_D trends potentially continue for Re_D greater than 40x10^6
    - Larger impact at higher sideslip angles





Reynolds Number Effects on Axial Force Coefficient

- $\alpha = \beta = 0°$
- Legend Re_D in millions ($x10^6$)
- Trip dot configurations
  - 0 – Free transition
  - 1 – Air mode sizing
  - 2 – Nitrogen mode sizing
- Key findings
  - Significant Re_D effect on axial force coefficient
  - Effects are Mach-dependent
  - Maximum effect seen by $Re_D = 10x10^6$
  - Extrapolating results past Mach 1.0 might not give meaningful estimations

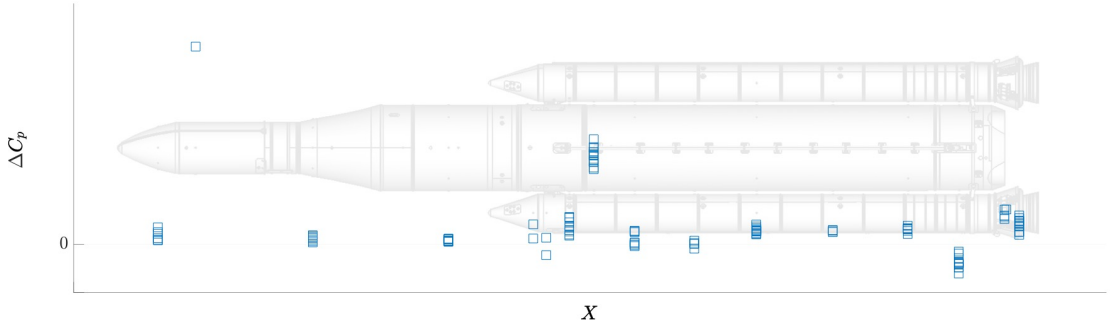


Reynolds Number Effects on Pressure Coefficients

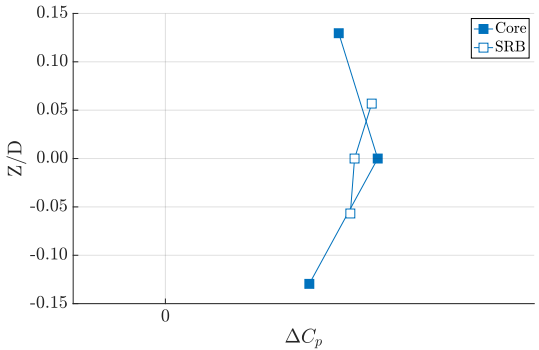
- $\alpha = 0°$
- $\beta = 0°$
- Mach = 0.90

- $\Delta C_p = C_{p,ReD=30} - C_{p,ReD=2}$

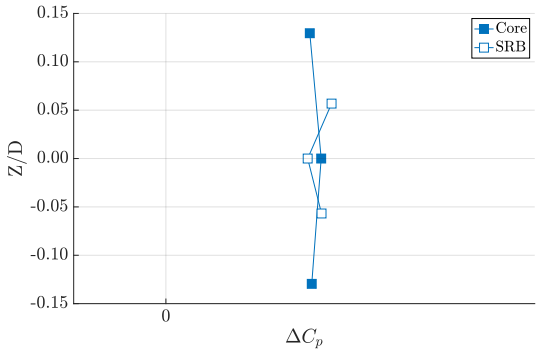
- Key findings
  - Large difference seen on cargo fairing shoulder likely due to shift in lambda shock footprint
  - Large differences seen near SRB forward attach hardware
  - Differences are generally symmetric between top and bottom of vehicle



Axial Distribution



Left Booster Gap



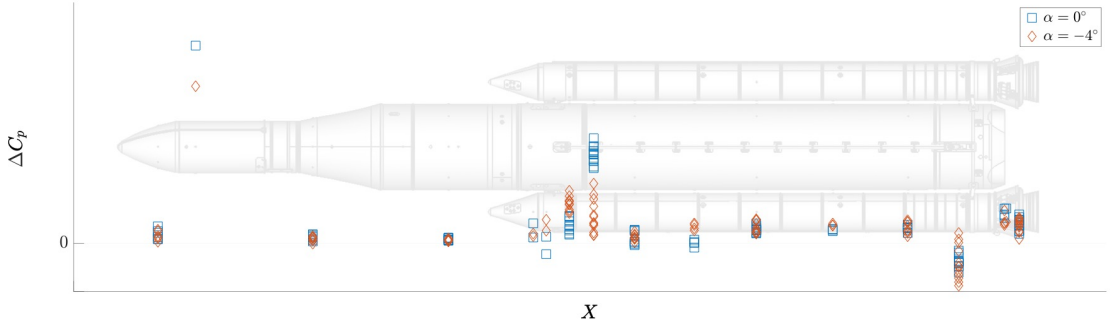
Right Booster Gap

Reynolds Number Effects on Pressure Coefficients

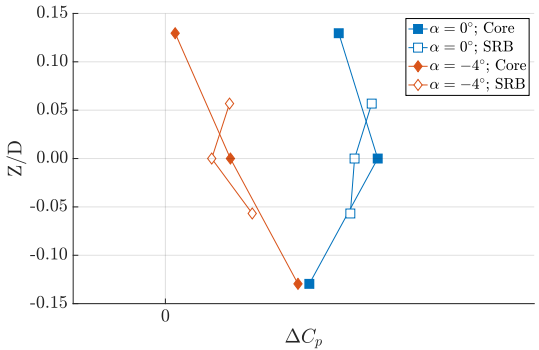
- $\alpha = 0°$ (Blue) and $\alpha = -4°$ (Orange)
- $\beta = 0°$
- Mach = 0.90

- $\Delta C_p = C_{p,ReD=30} - C_{p,ReD=2}$

- Key findings
  - Large differences seen near SRB forward attach hardware
  - Top and bottom asymmetry now evident in pressure coefficient difference
  - Change in wake development near SRB likely impacts pitching moment due to effects localized to aft half of the model



Axial Distribution



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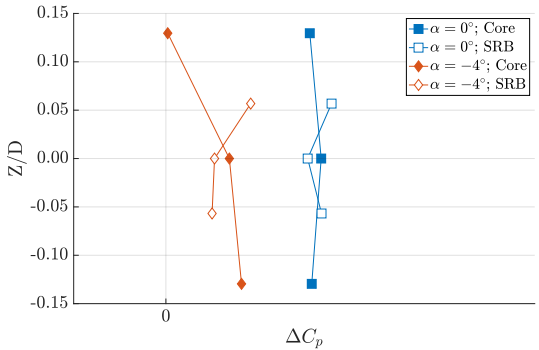


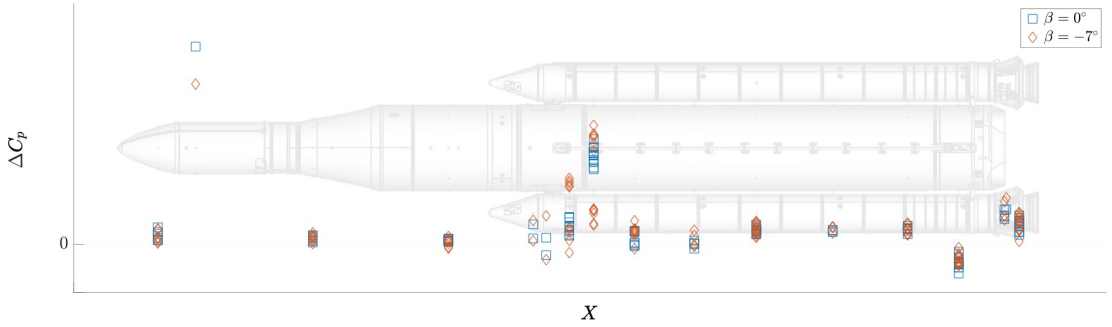
Right Booster Gap

Reynolds Number Effects on Pressure Coefficients

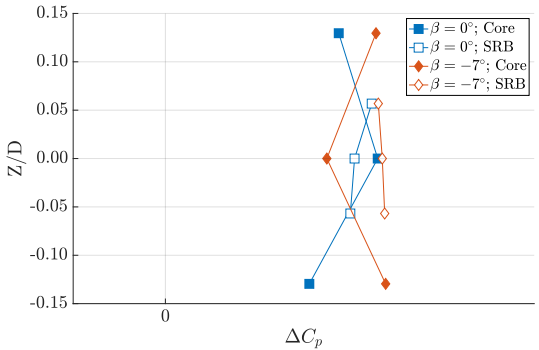
- $\alpha = 0°$
- $\beta = 0°$ (Blue) and $\beta = -7°$ (Orange)
- Mach = 0.90

- $\Delta C_p = C_{p,ReD=30} - C_{p,ReD=2}$

- Key findings
  - Large differences seen near SRB forward attach hardware
  - Left and right asymmetry now evident in pressure coefficient difference
  - Change in wake development near SRB likely impacts yawing moment due to effects localized to aft half of the model



Axial Distribution



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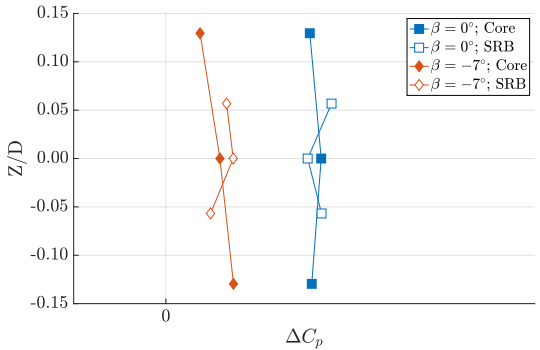

Right Booster Gap

Summary and Conclusions

- SLS Block 1 Cargo vehicle tested at NASA Langley National Transonic Facility
  - Re_D ranging from $2x10^6$ to $40x10^6$
  - Mach numbers ranging from 0.50 to 0.95
- Force and moment coefficients
  - Normal and side force coefficients had no measurable sensitivity to Re_D
  - Pitching and yawing moment coefficients were sensitive to Re_D
    - Largest effects at higher angles of attack and sideslip
    - No threshold seen indicating Re_D effects may increase past $40x10^6$
  - Axial force coefficient sensitive to Re_D
    - Axial force coefficient generally decreased at higher Re_D
    - Re_D effect threshold reached by $10x10^6$ for Mach 0.80 and 0.90
    - Re_D effect trend started to reverse at Mach 0.95
- Pressure coefficients
  - SRB forward attach hardware showed high sensitivity to Re_D
  - Flow state at forward attach point influences flow field development for aft half of vehicle