



Recent Validation of Low Speed Aerodynamic Analysis for the Space Launch System

DATAWorks April 2026

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Introduction

- Space Launch System (SLS) is the family of rockets used for the Artemis missions
 - Made up of a Centerbody and two Solid Rocket Boosters (SRBs)
 - Forebody changes between configurations
- Low Speed Aerodynamics
 - Prelaunch ground wind loads
 - Early stages of flight
- In preparation for new Artemis missions, we are validating some of the assumptions used to analyze the aerodynamics

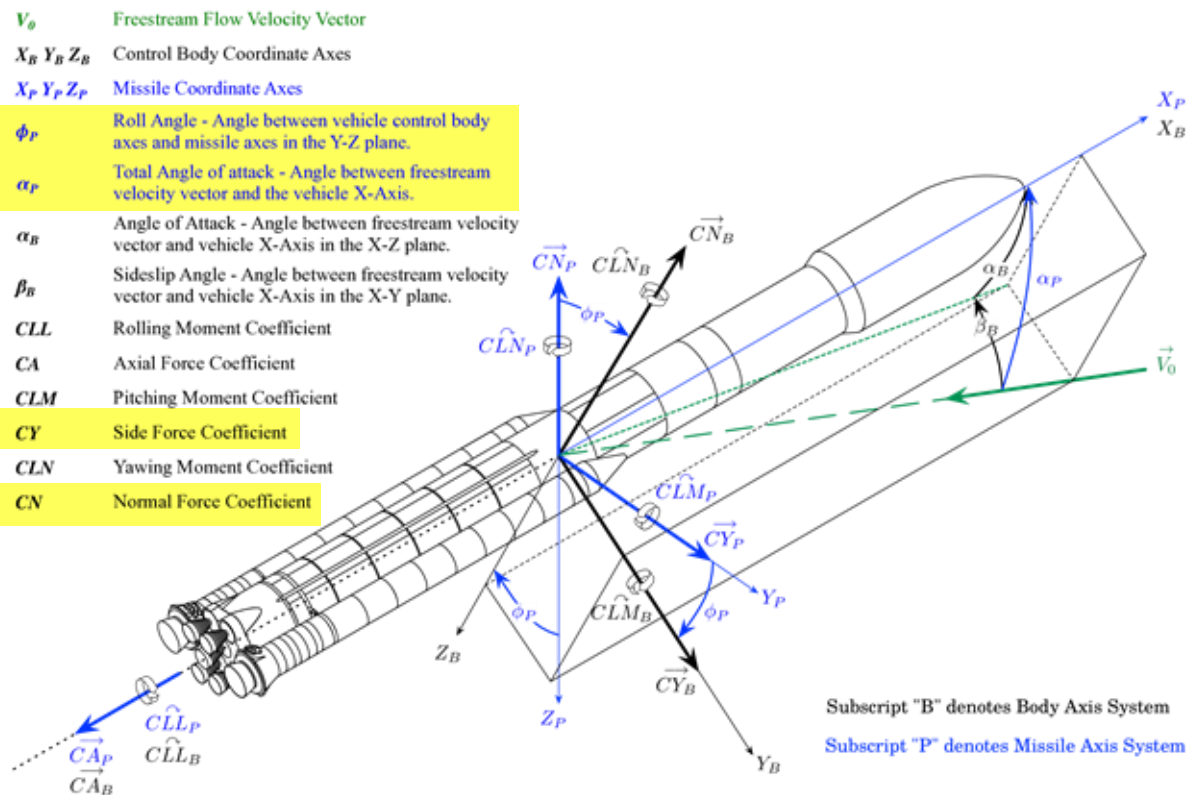
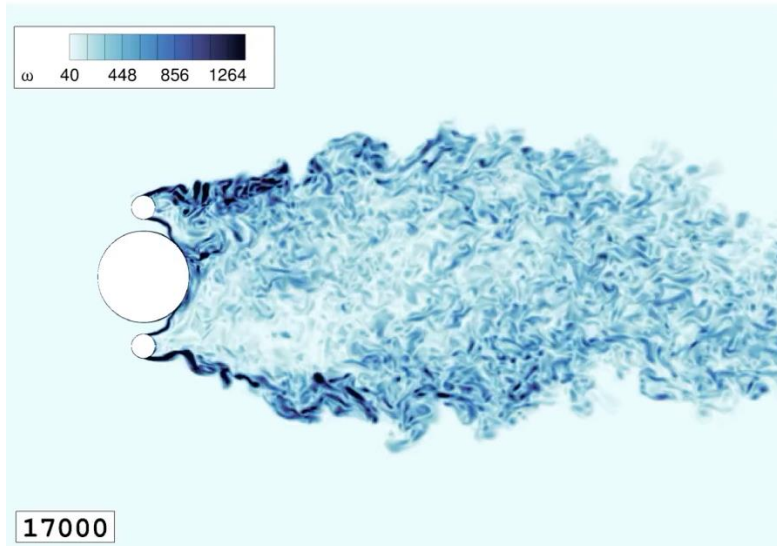


NASA/Joel Kowsky



Introduction

- Dominated by large unsteady wakes
- Full vehicle incidence (α_P) and azimuthal ϕ_P freestream range
- Multimodal phenomenon





Introduction

Two End Users

- Guidance, Navigation, and Controls
 - Mostly use integrated aerodynamic loads
 - Uncertainty Quantification (UQ) delivered as probability distribution
- Loads Team (Structural analysis)
 - Mostly use distributed aerodynamic loads
 - UQ more concerned with “worst case”
 - Usually delivered as alternate states



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Two Analysis Tools

- Wind tunnel testing
 - NASA Langley 14- by 22- Foot Subsonic Tunnel
 - Integrated loads
 - Total vehicle, and SRBs
 - Individually metric mobile launcher tiers



Introduction

Two

- Guidance
- Mission
- Launch
- Load
- Mission
- Launch



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Figure from: Walker et al. “Experimental Identification of Bistable Flow States on the Space Launch System at Liftoff Conditions” AIAA Scitech 2022 doi: 10.2514/6.2022-3665



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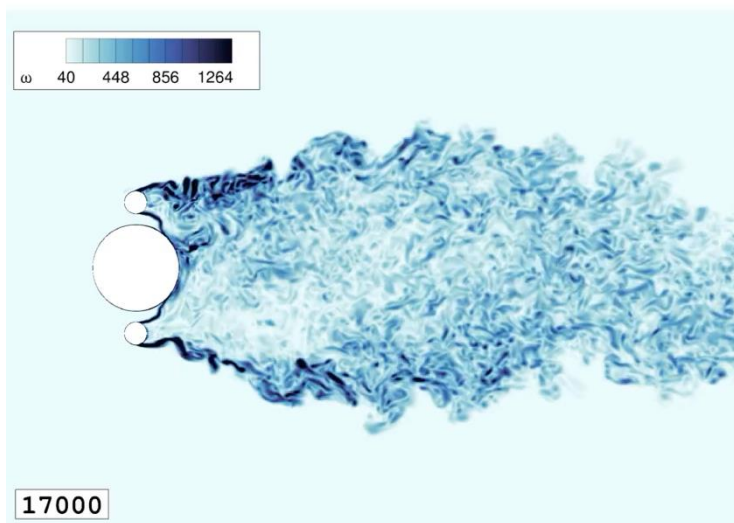
- Wind tunnel testing
 - NASA Langley 14- by 22- Foot Subsonic Tunnel
 - Integrated loads
 - Total vehicle, and SRBs
 - Individually metric mobile launcher tiers
- Computational fluid dynamics (CFD)
 - CREATE-AV Kestrel CFD solver
 - Distributed loads
 - Flow field characteristics



Introduction

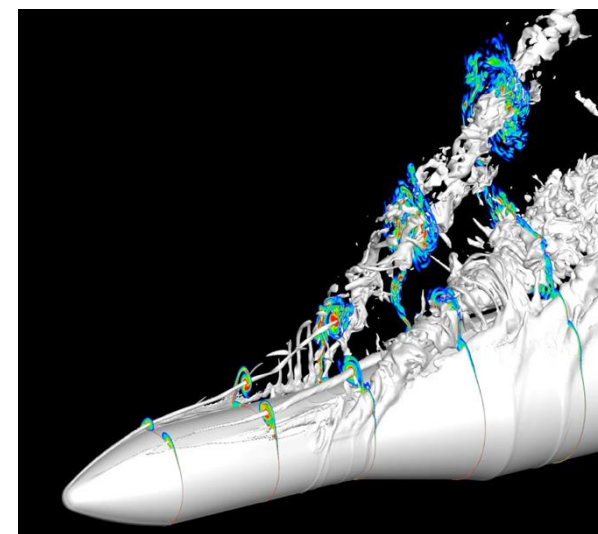
- Coandă Effect

- Gap flow between booster and core can attach to either side
- Four possible states



- Asymmetric Vortices

- Vortex system on the nose can separate on either side creating large side loadings
- Appears on both cargo and crew variants
 - More coherent on cargo configurations
- Two-ish states



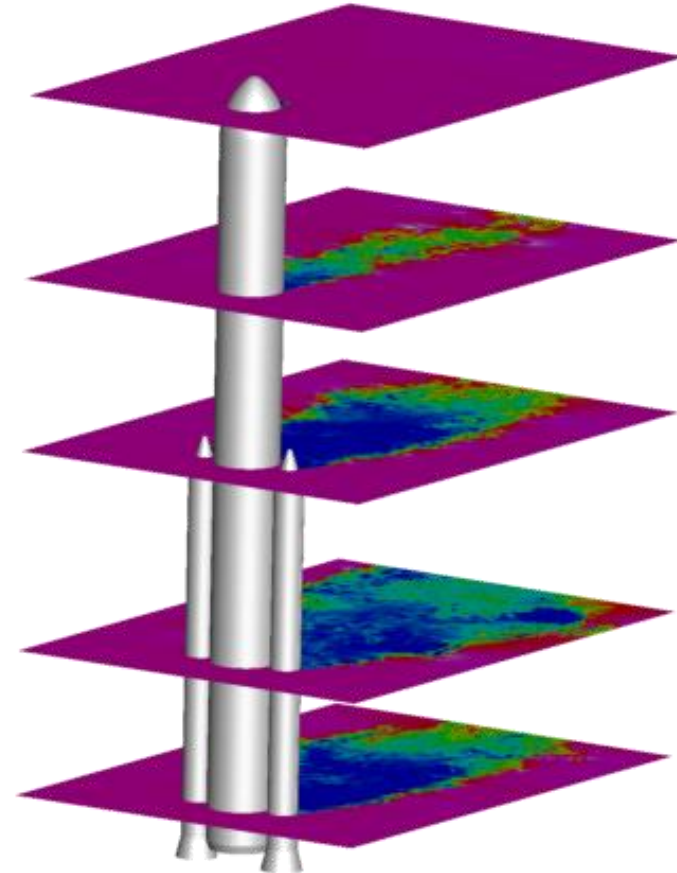
Asymmetric Vortex From: Pomeroy et al. "Sensitivity of Space Launch System Low-Speed Aerodynamic CFD Results to Kestrel Flow Solver Inputs" NASA/TP-20230003697



Analysis Overview

Two Validation Efforts

1. Reynolds Number, Re_D , Effects
 - 0.6, 3.0, and 10 million
 - Centerbody Diameter
 2. Quasi-Steady State Assumptions (QSSA)
 - Dynamic case based on Artemis 1 trajectory
- Simplified rocket (Threebody-5)
 - CREATE-AV Kestrel CFD flow solver
 - Finite Volume, Cell centered
 - Cartesian offbody solver with adaptative mesh
 - Hybrid RANS-LES
 - SA with IDDES





Reynolds Number Validation

- Analysis $Re_D \approx 0.6 \times 10^6$
- Flight $Re_D \approx 12 \times 10^6$
- Two major concerns
- Does the location of flow separation change?
 - This may change integrated forces and moments
 - Smooth cylinders are very sensitive to this
- Does the Coandă effect manifestation change?
 - This may change integrated and distributed forces
 - Characteristics of gap flow are expected to change with Re_D



Reynolds Number Validation – Flow Separation

- $Re_D \approx 0.6 \times 10^6$ is typically in the transcritical regime for 2D cylinder flow
 - Subcritical regime, flow is well behaved
 - Transcritical regime, flow changes rapidly with Re_D
 - Supercritical flow behavior “asymptotes” and relatively constant with Re_D
- Wind tunnel testing uses grit to increase effective Re_D
- CFD run fully turbulent
 - no laminar to turbulent boundary layer transition modeled

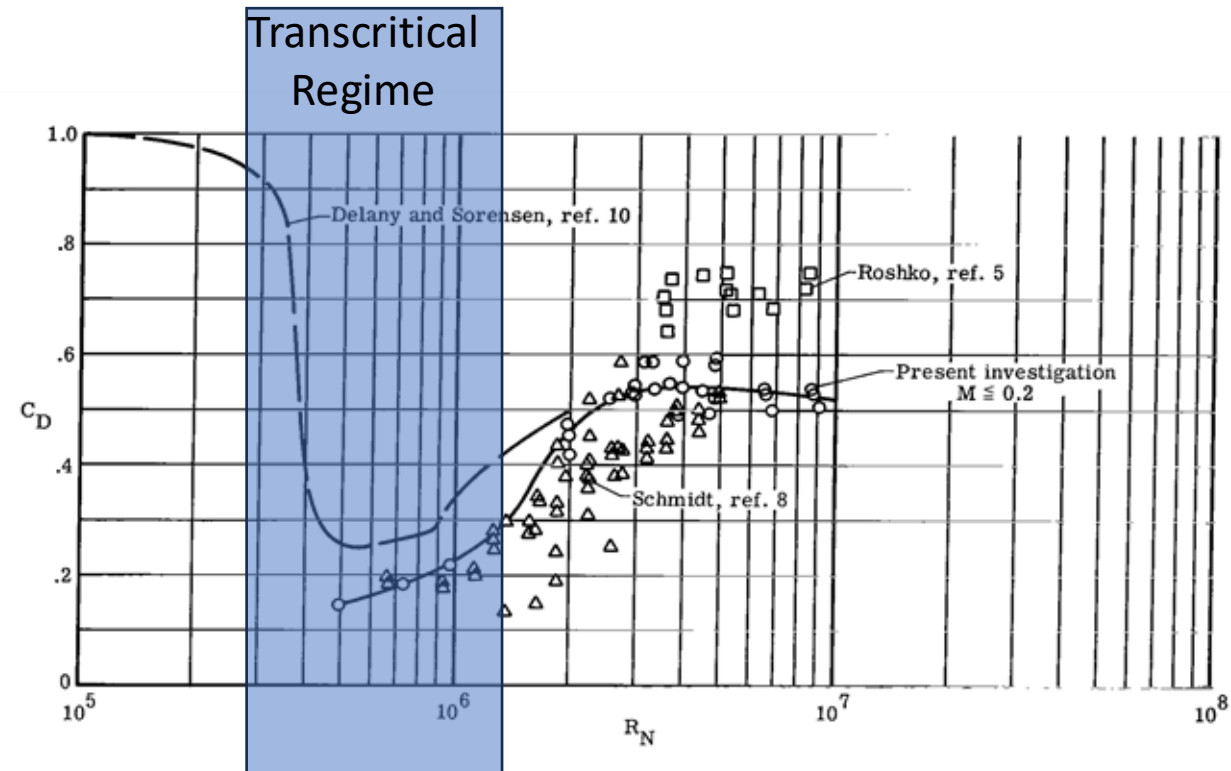
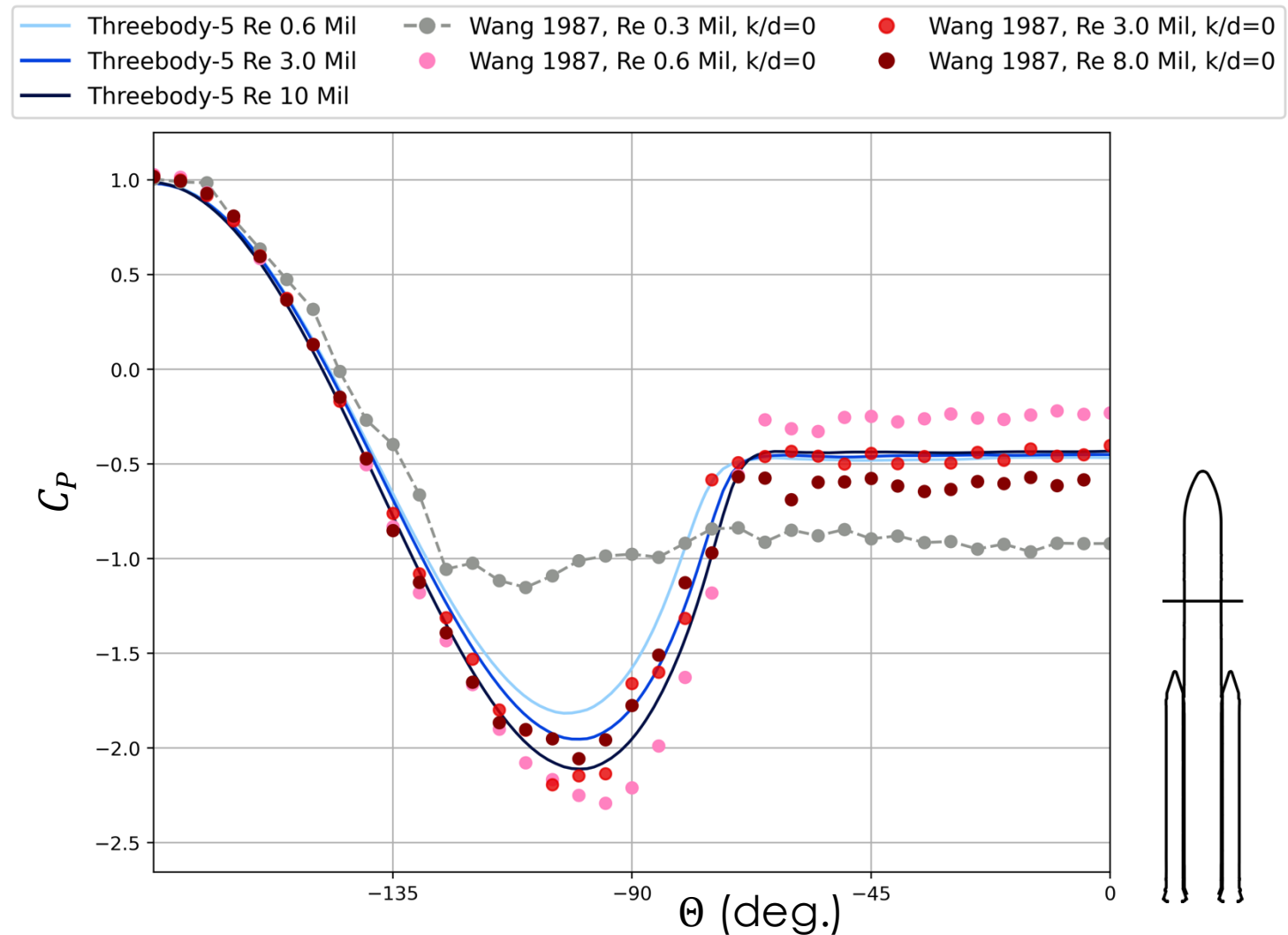


Figure from: Jones et al. “Aerodynamic forces on a stationary and oscillating circular cylinder at high Reynolds numbers” 1969 NASA TR-R-300



Reynolds Number Validation – Flow Separation

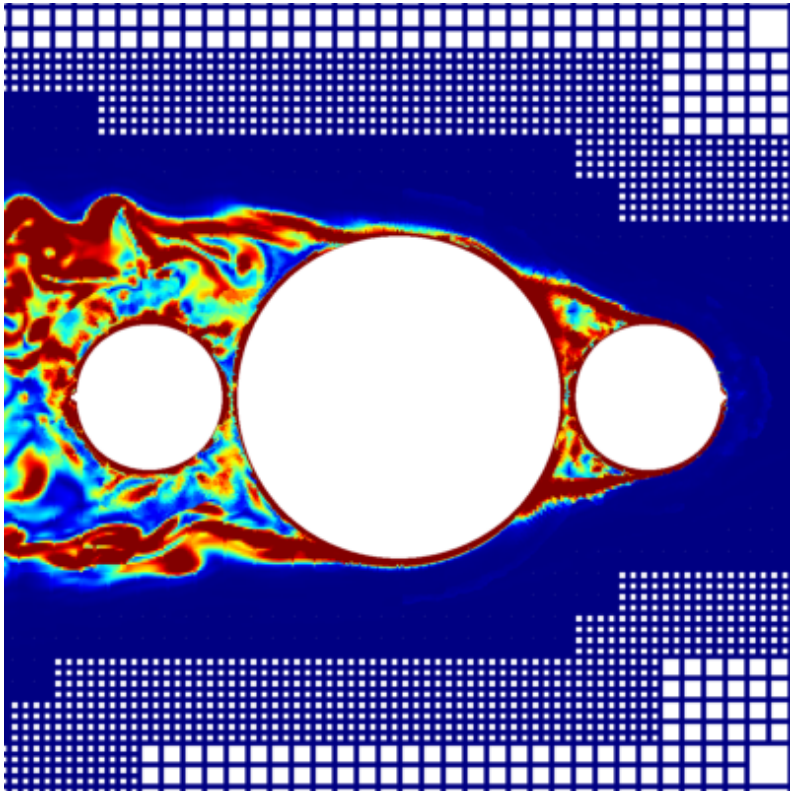
- Compare surface pressure
 - Experimental data from Wang 1987*
 - Full span cylinder model
 - Most cylinder like section of Threebody-5
 - 3D effects
- Separation pattern matches supercritical flow
- Back pressure and minimum pressure agree well with experiment



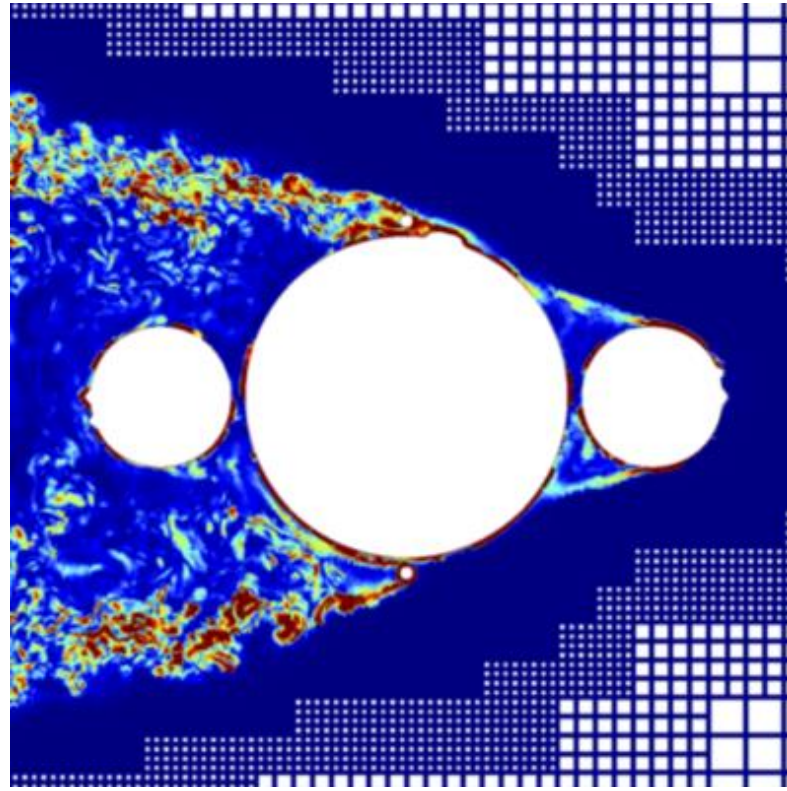
*Wang and Shih. "High Reynolds Number Flows around Smooth and Rough Cylinders. Volume 1. Mean Surface Pressure Distribution." Tech. rep. PRI-PV-87-R001-VOL-1. Office of Naval Research, 1987



Reynolds Number Validation - Flow Separation



Threebody $Re_D \approx 0.6 \times 10^6$



Actual SLS $Re_D \approx 0.6 \times 10^6$

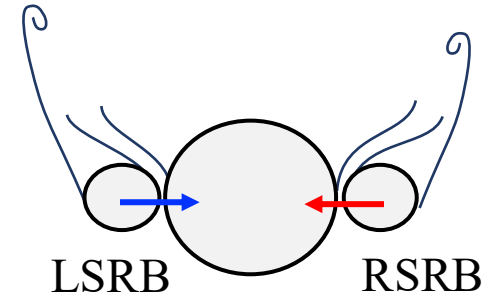


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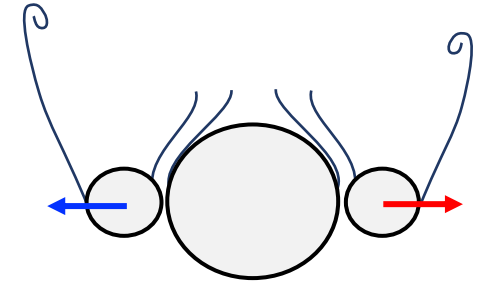


Reynolds Number Validation – Coandă

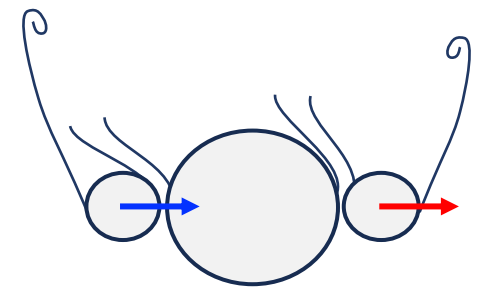
- As flow passes between the centerbody and boosters it can attach to either side
 - Gives four possible flow states
- Primarily an issue for prelaunch with winds from the south
- Can cause wide range of loadings
- Seen in both computational and experimental data
- Random occurrence of states



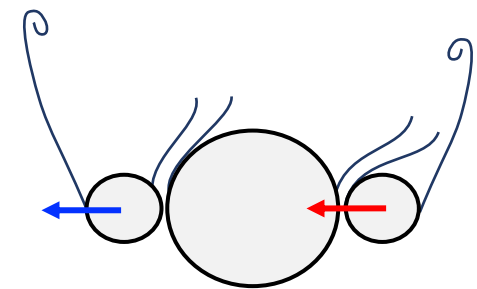
(a) Symmetric Booster (SB)



(b) Symmetric Core (SC)



(c) Asymmetric Left (AL)

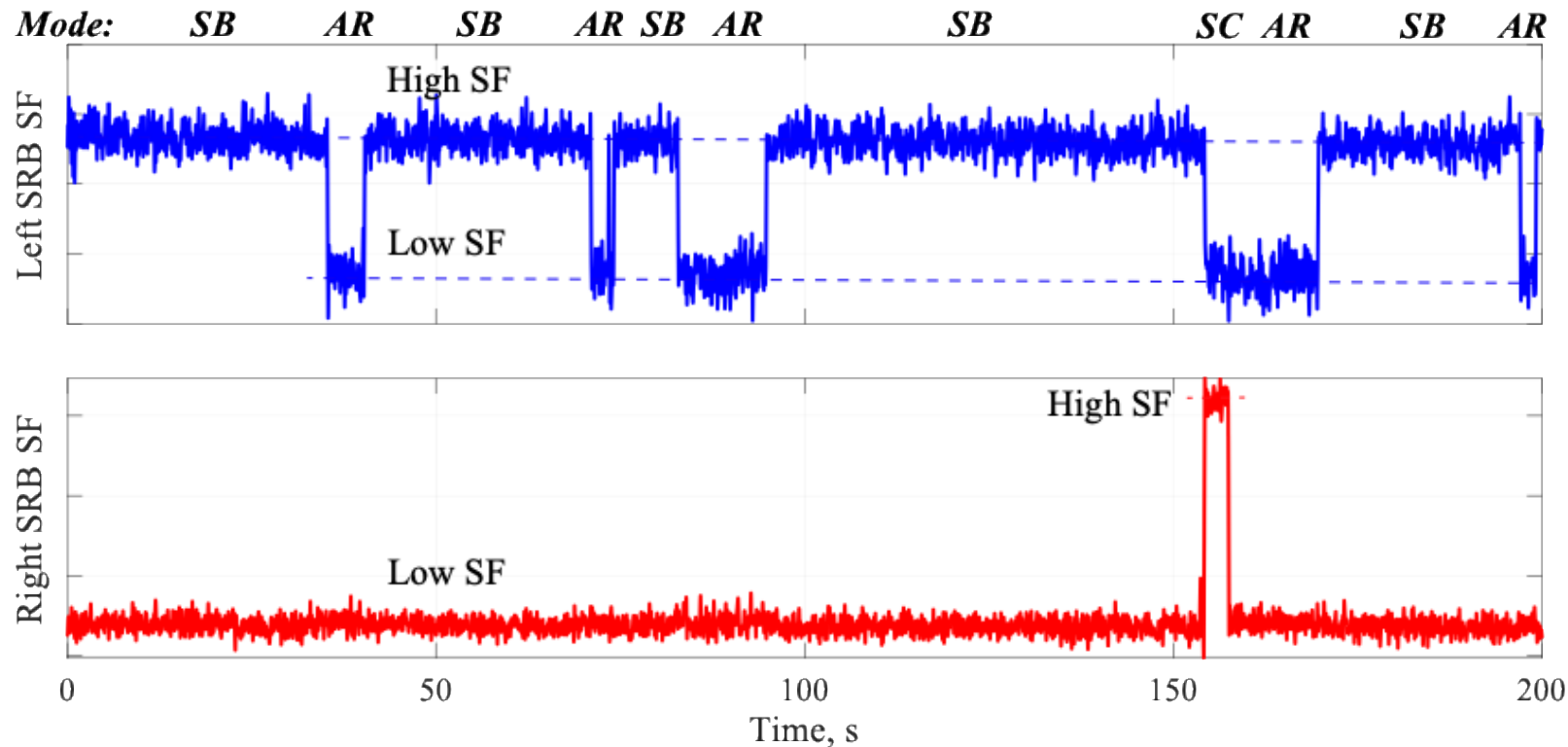


(d) Asymmetric Right (AR)

Figure from: Mears et al. "Asymmetric Flow State Switching in the Space Launch System Block 2 Liftoff Environment". AIAA SCITECH 2024 doi:10.2514/6.2024-0466.



Coandă State Switching in the Tunnel



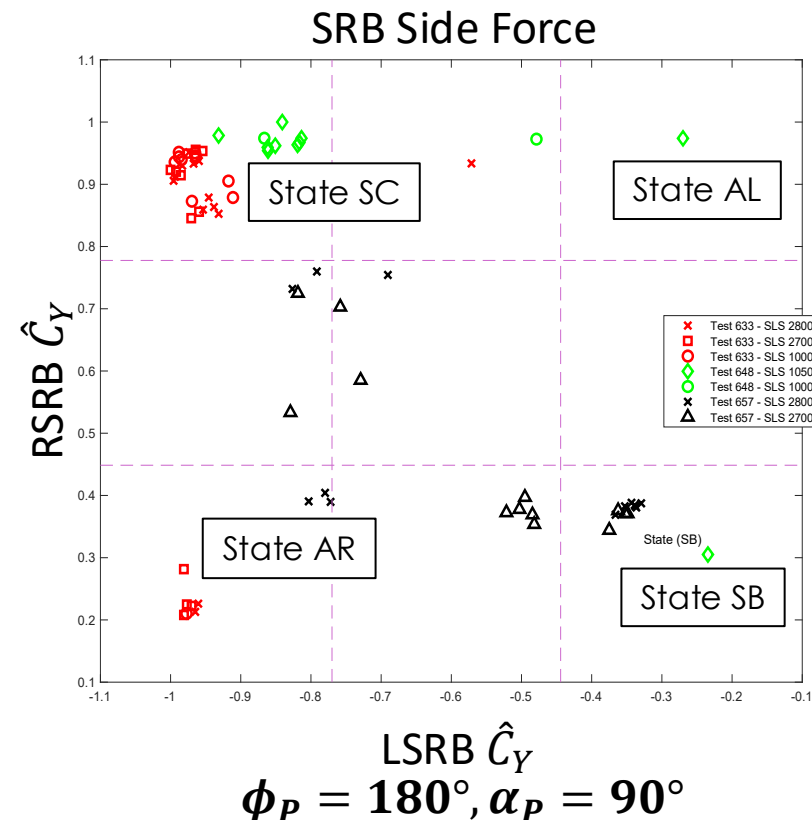
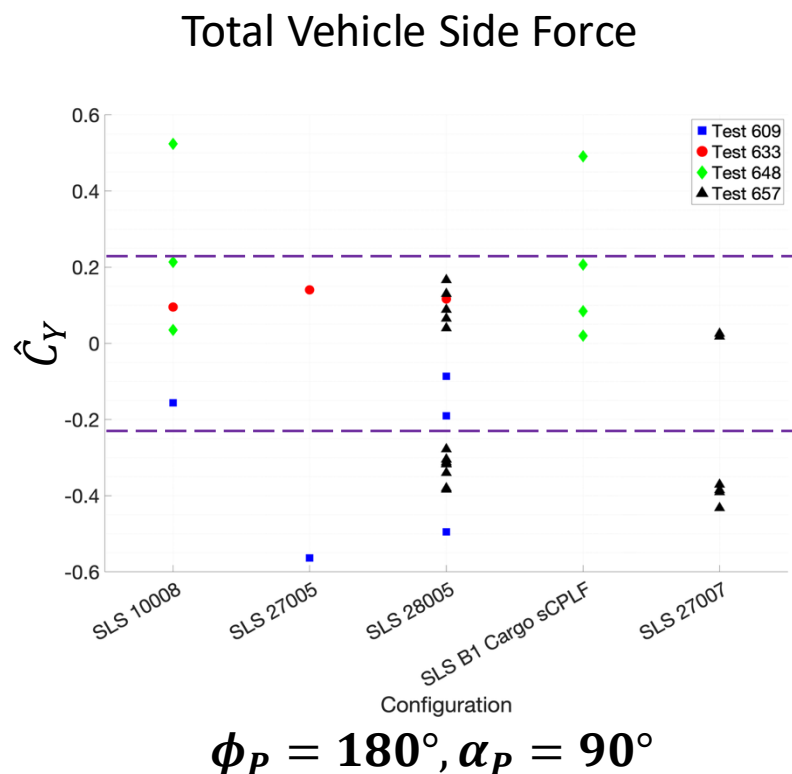
- Long series experimental data at $\phi = 162.5^\circ$ shows state can change randomly
- This data series is about 25 times longer than typical practice

Figure from: Mears et al. "Asymmetric Flow State Switching in the Space Launch System Block 2 Liftoff Environment". AIAA SCITECH 2024 doi:10.2514/6.2024-0466.



Coandă Uncertainty Quantification

- While some states are rare, pooling across various configurations allows characterization
- Partial states are possible
- Total vehicle loads fall into 3 clusters
- Focus on capturing extremes



Figures from: Wignall et al. "Experimental and Computational Examination of the Coandă Effect on the Space Launch System at Liftoff Conditions". AIAA SCITECH 2023 doi:10.2514/6.2023-0648.

- Distributed loading largely the same process
- Collect data from all relevant CFD
- Use engineering judgement to select representative cases
 - Balance local extremes with integrated extremes
 - Resulting moments also considered
- Create alternate line loads by blending representative loads with nominal simulations
 - Account for minor variations between configurations

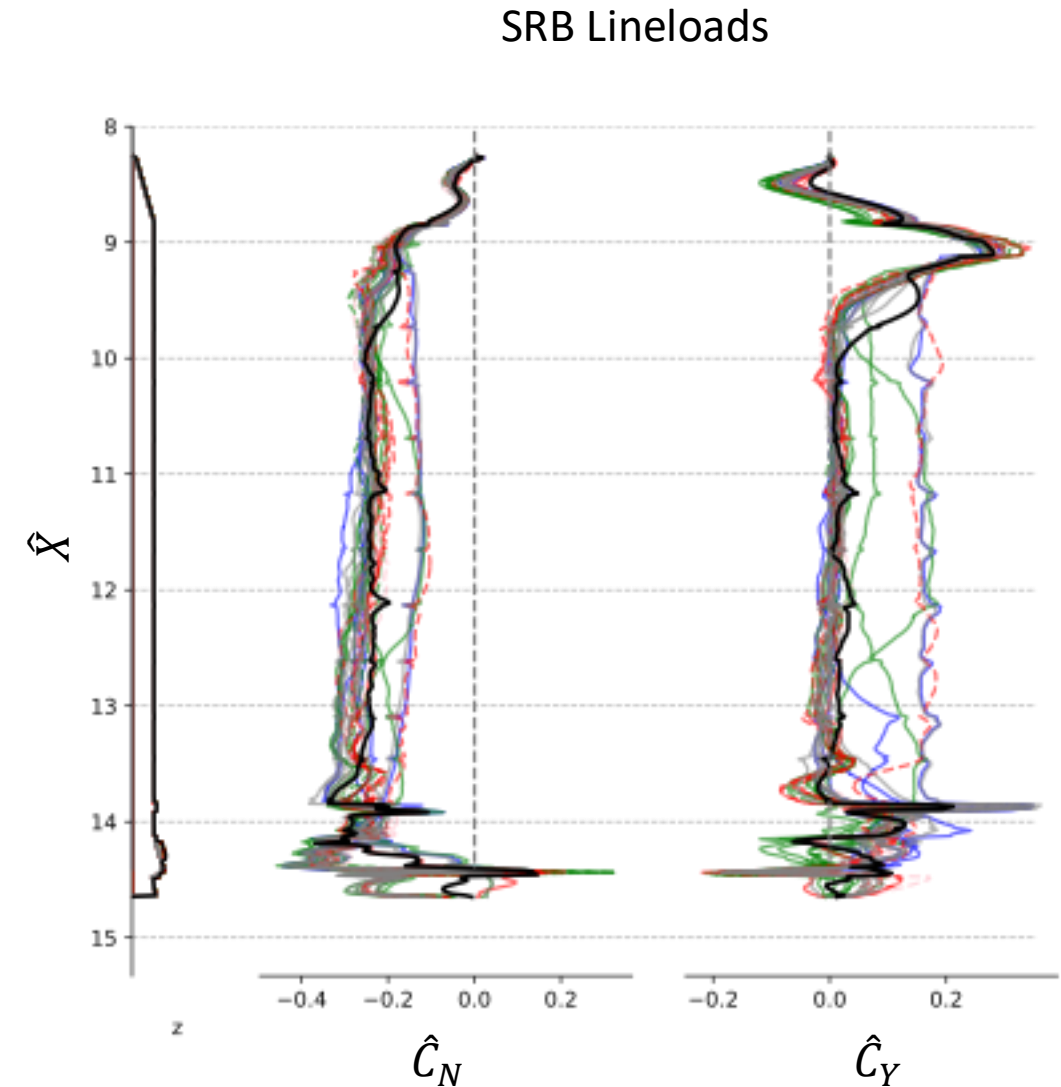
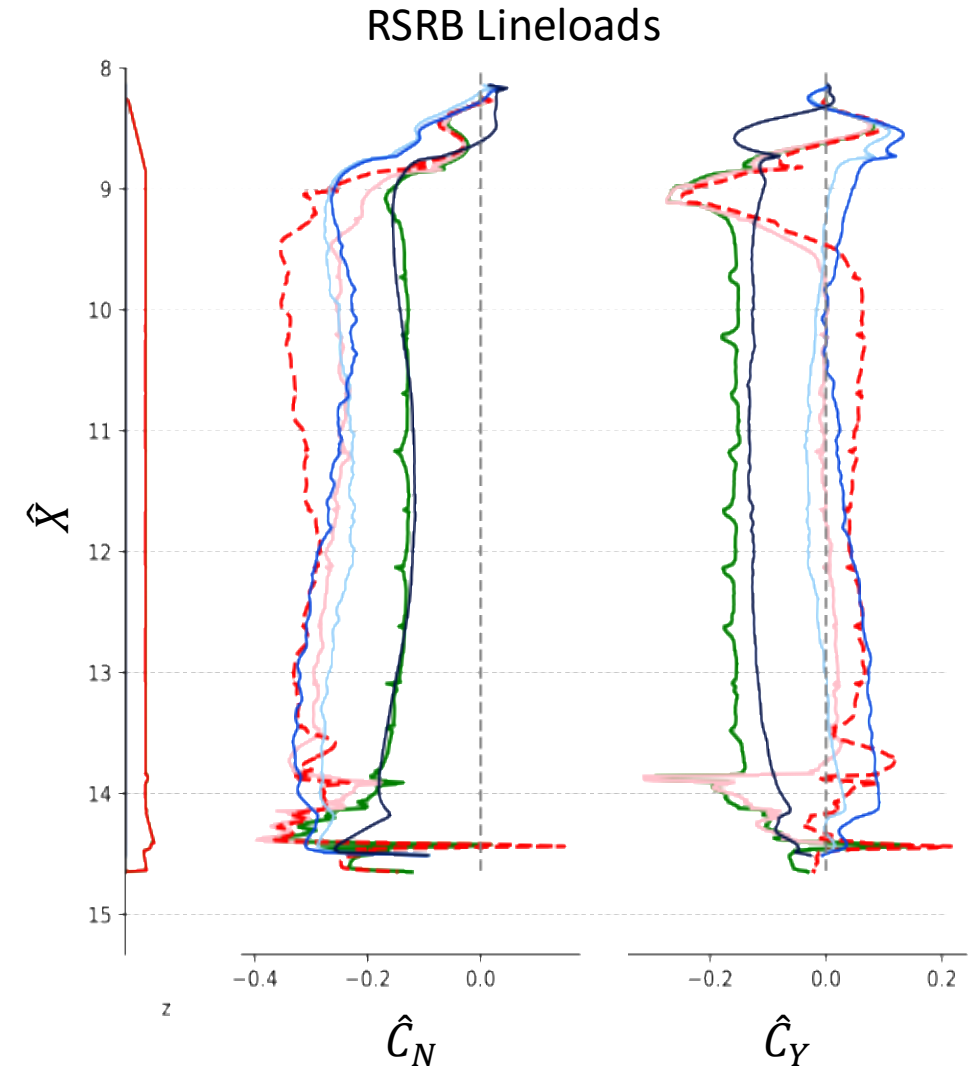
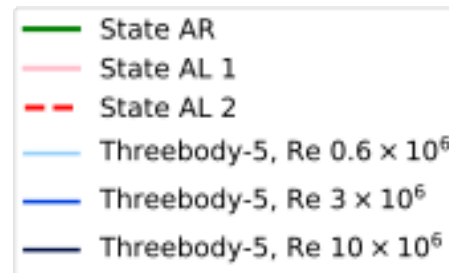


Figure from: Wignall et al. "Experimental and Computational Examination of the Coandă Effect on the Space Launch System at Liftoff Conditions". AIAA SCITECH 2023 doi:10.2514/6.2023-0648.



Coandă and Reynolds Number

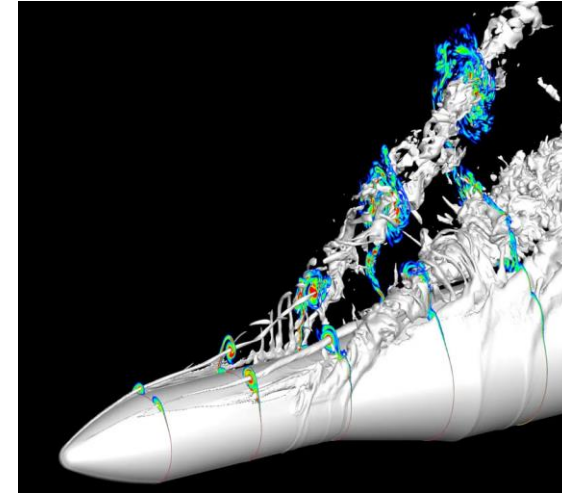
- $Re_D \approx 10 \times 10^6$ case has an attached booster state
- Compare to representative cases
 - Navy Blue to Dark Green
- Results of Reynolds number validation showing no major issues with difference between analysis and flight values



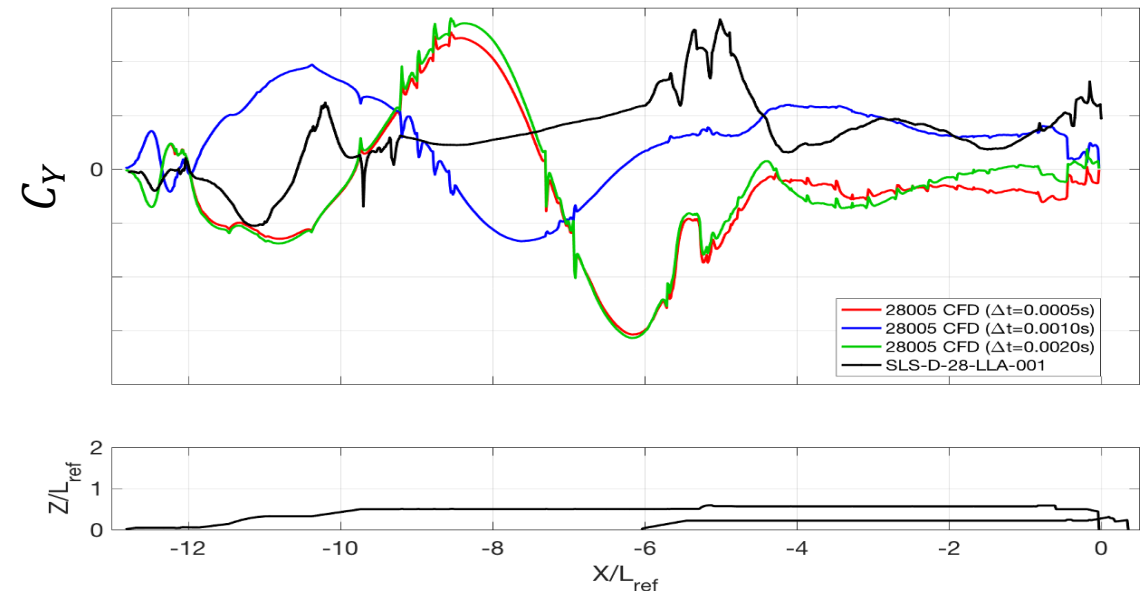


Asymmetric Vortices

- Asymmetric Vortices can form on either side
 - Also possible to have symmetric vortices
- Creates side force loads with same magnitude as normal force loads
- Stable once formed
- Which side tends to be function of small asymmetries
- Little data on how they behave dynamically
- These effects are sometimes called “phantom yaw”



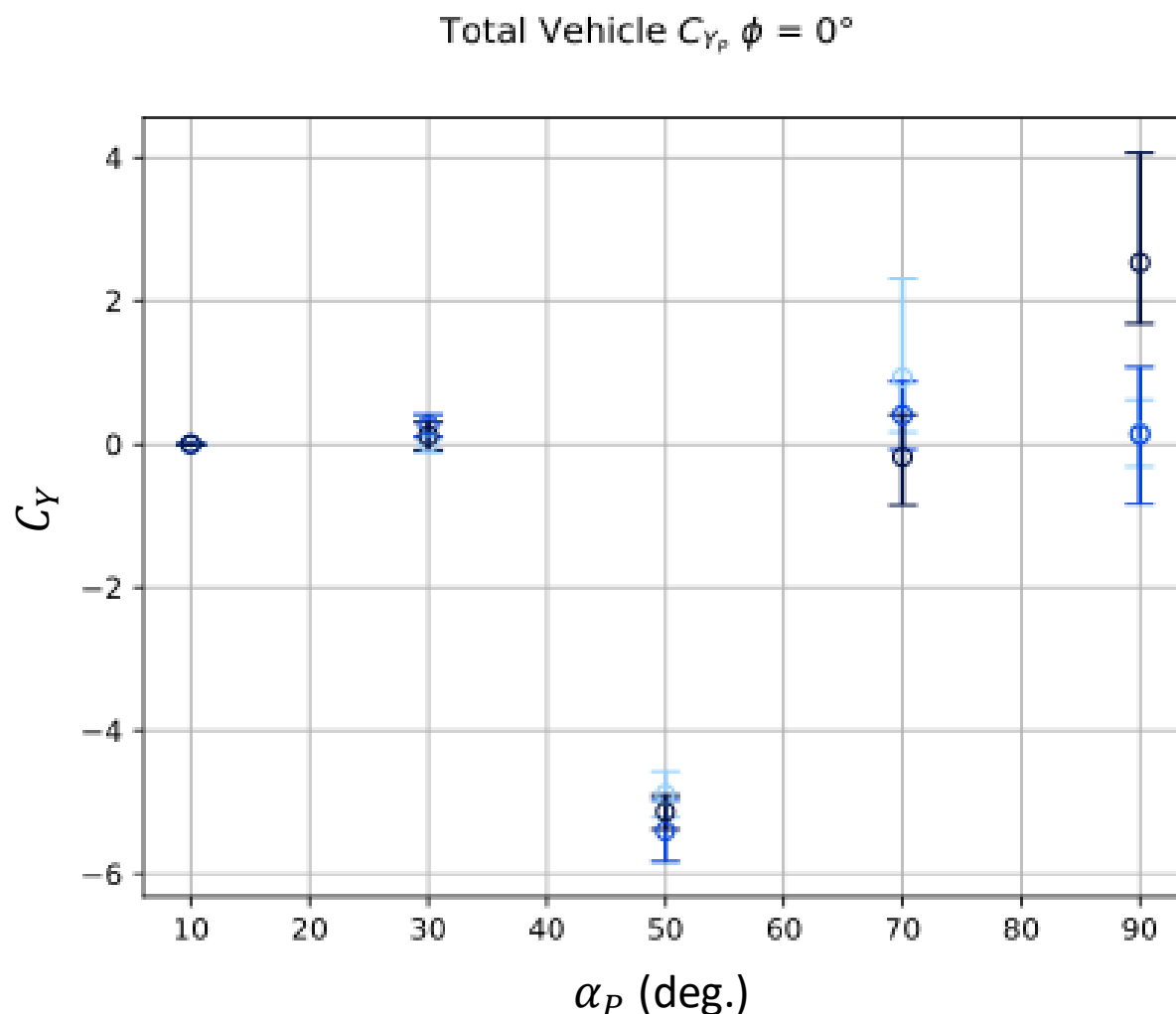
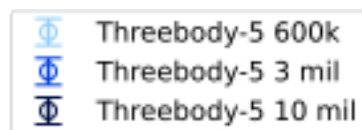
SLS-28005 LO/T Side Force Stack Line Load at $\alpha_T=50^\circ$, $\phi_A=0^\circ$





Asymmetric Vortices Integrated Forces UQ

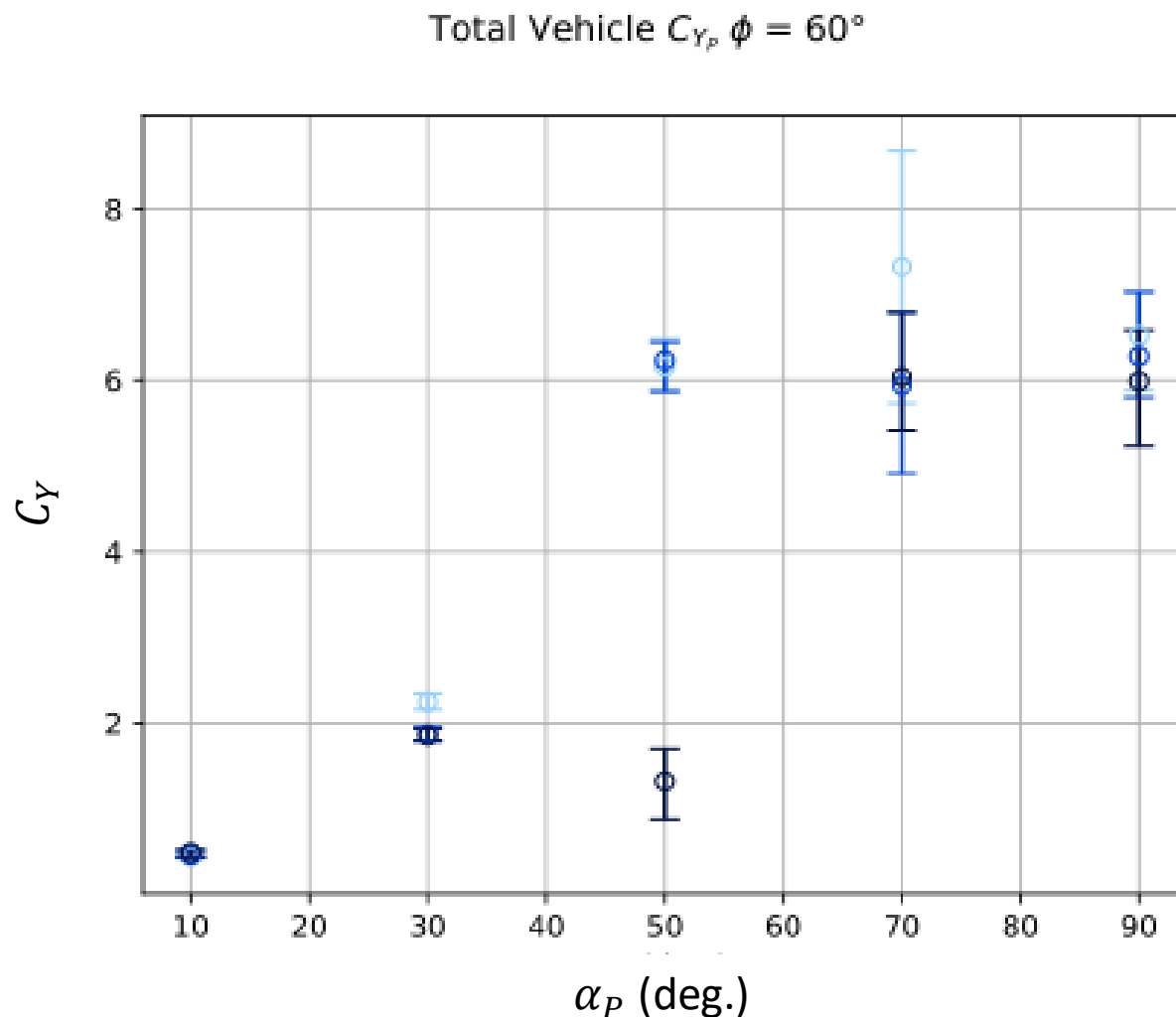
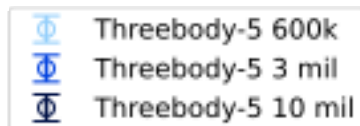
- Focus on giving alternate nominal values at easy to flip roll angles
 - $\phi = 0^\circ, 90^\circ, 180^\circ, 270^\circ$
- Uncertainty bars shows range over CFD time averaging window





Asymmetric Vortices Integrated Forces UQ

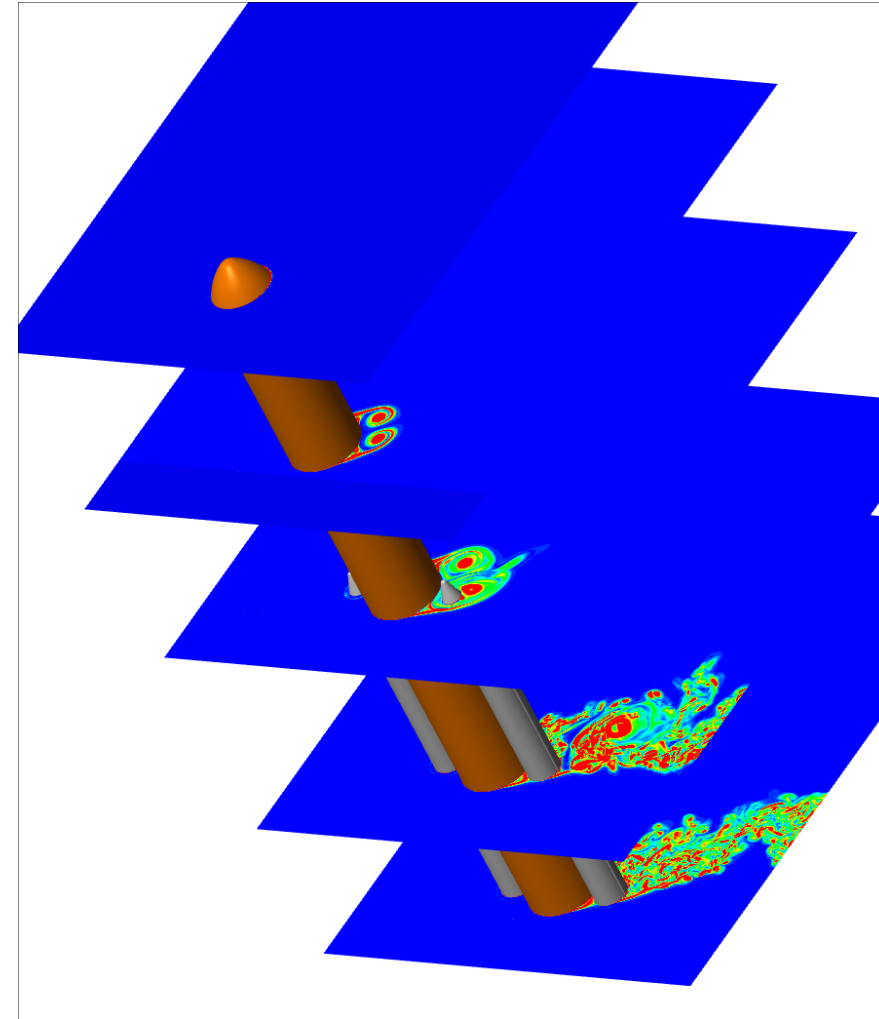
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- Because of interaction of SRBs at oblique roll angles, ϕ , it is difficult to estimate the opposite state





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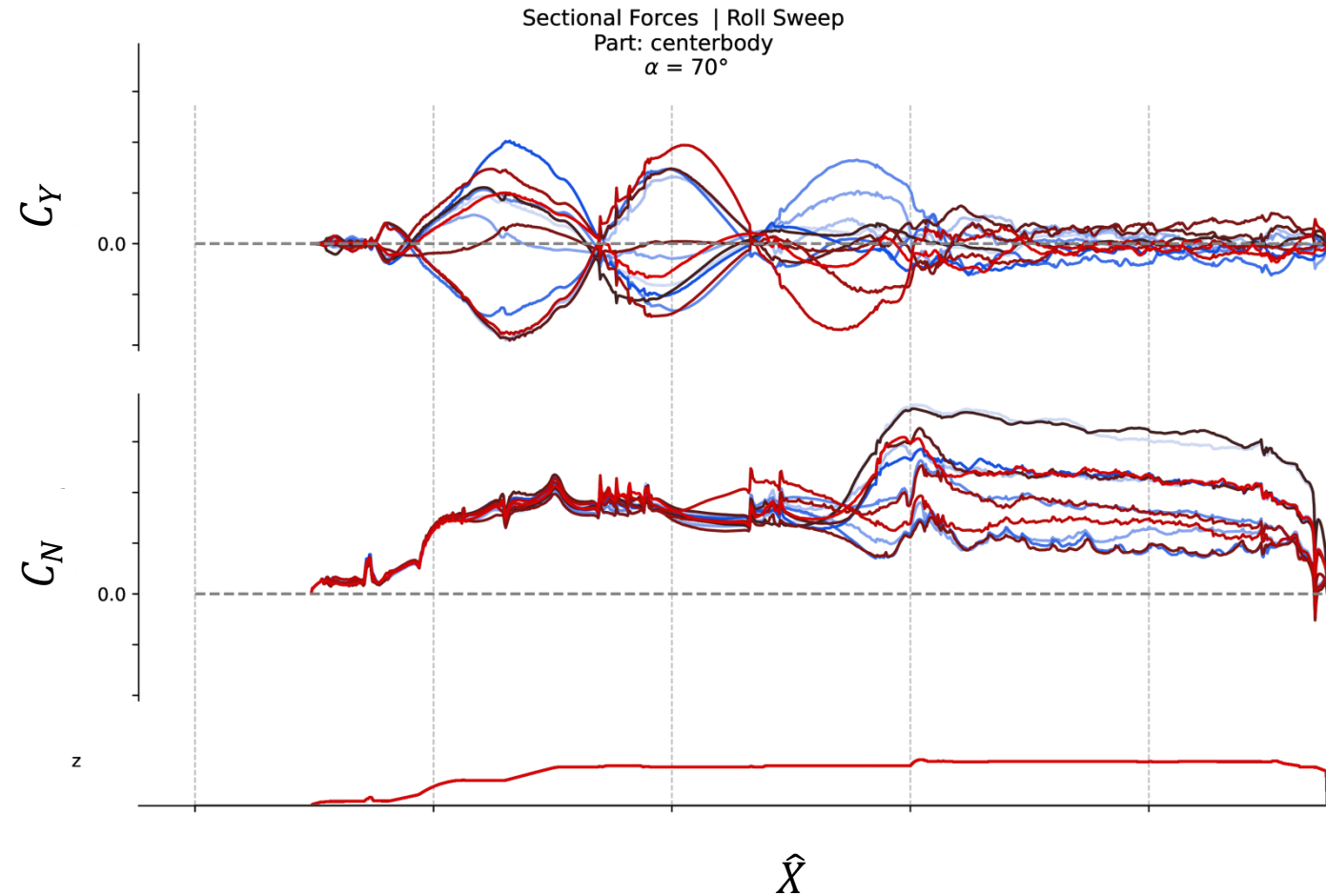
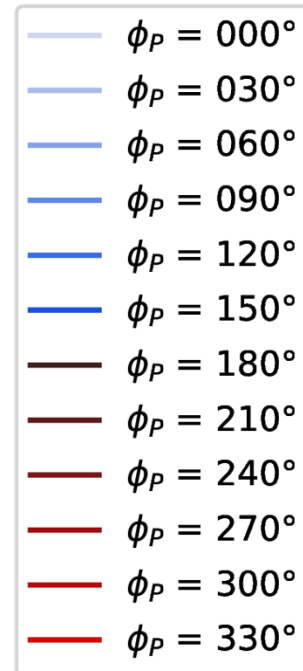


$$\alpha_P = 50^\circ, \phi_P = 60^\circ, Re = 0.6 \times 10^6$$



Asymmetric Vortices Lineloads UQ

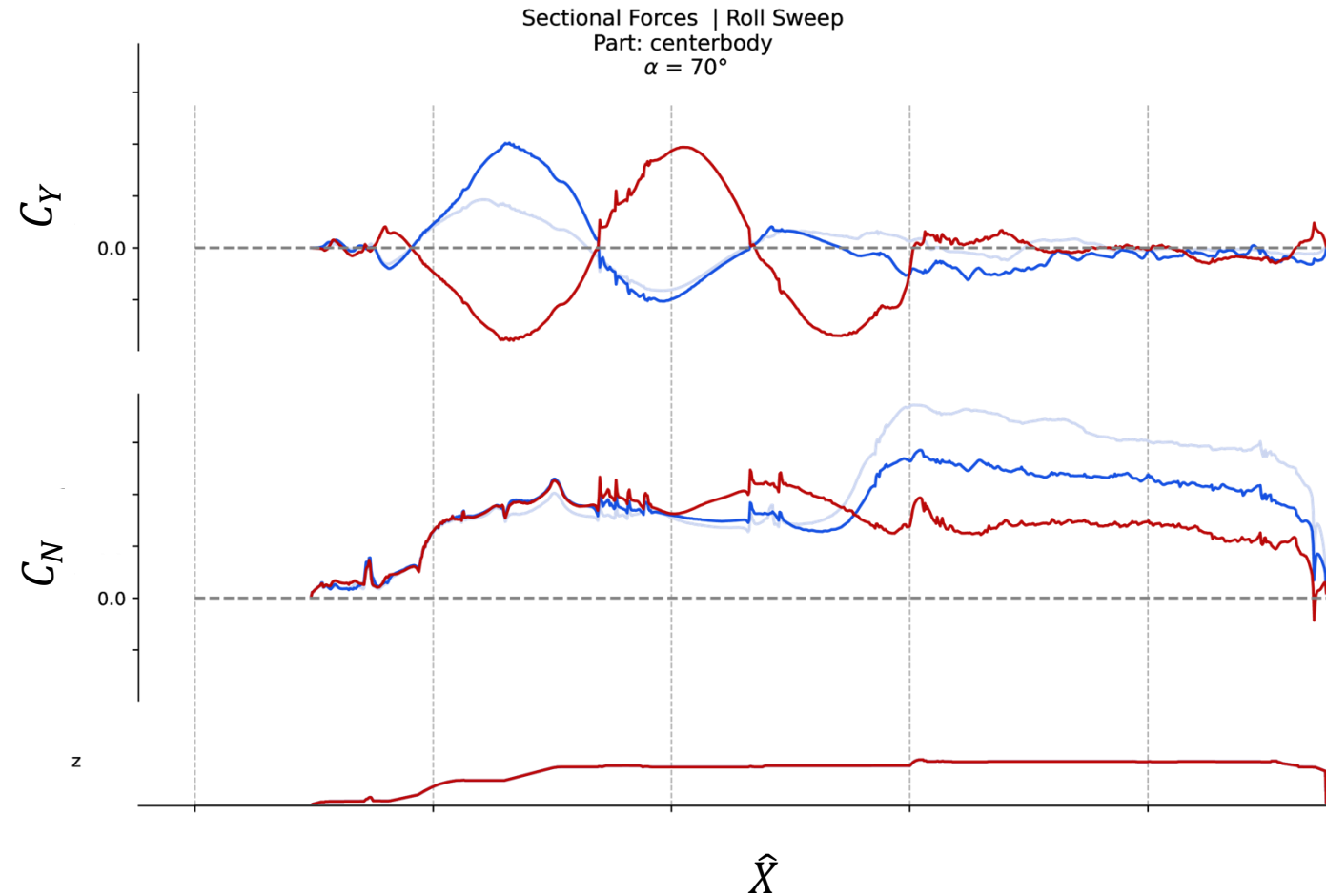
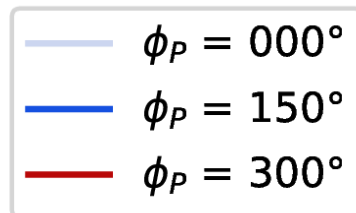
- Size and strength changes with angle of attack
- At each angle of attack find representative cases





Asymmetric Vortices Lineloads UQ

- Size and strength changes with angle of attack
- At each angle of attack find representative cases
- Merge nominal lineload with high loading cases





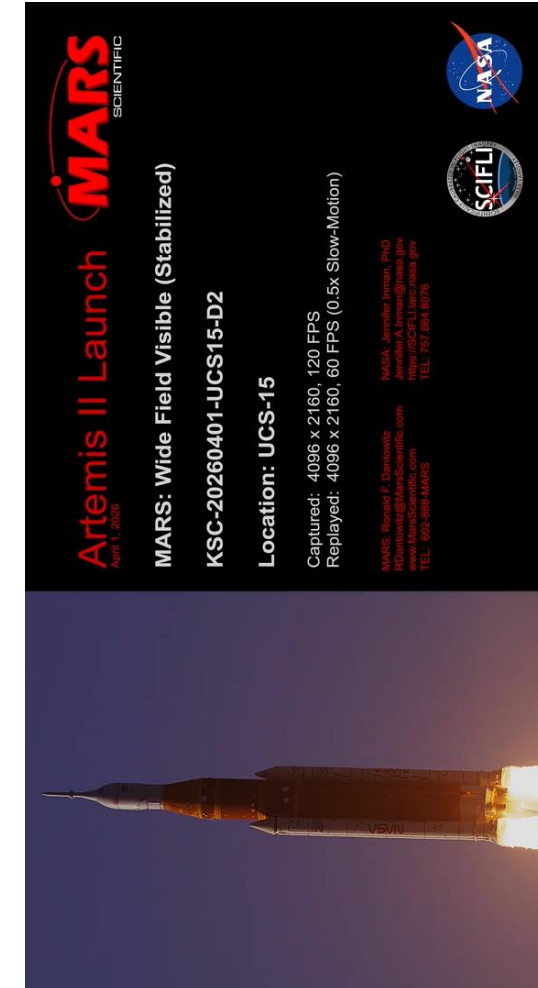
Quasi-Steady State Assumption (QSSA)

- Assumes that results from analysis done at constant input parameters can be used in downstream dynamic analysis
- Assumes changes in flow are faster than changes in inputs
- No data on how long asymmetric vortices take to form and/or dissipate
- Use an accelerating vehicle simulation to test this assumption



Moving Body Simulation

- Want to approximate changes in flow field during early stages of flight
- Vehicle goes from 90° angle of attack to about 10° over the course of 5 seconds
- Goals:
 - Does the asymmetric vortex system have time to form?
 - Do dynamic forces match steady state loads?

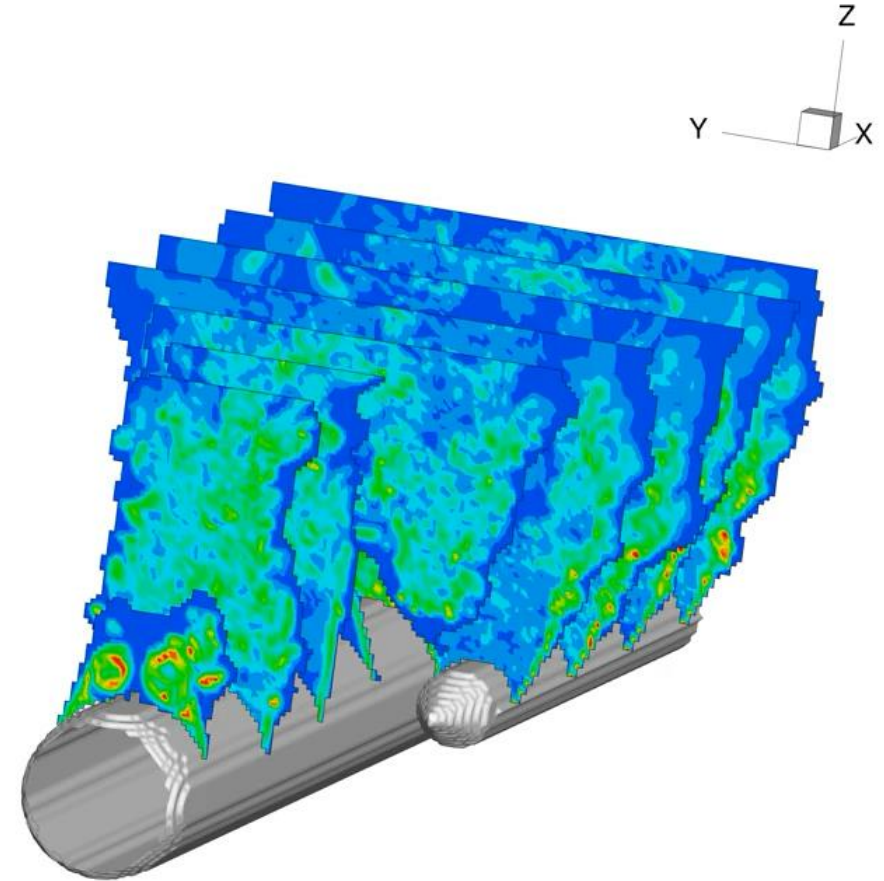


NASA/SCIFLI



Moving Body Simulation Early Results

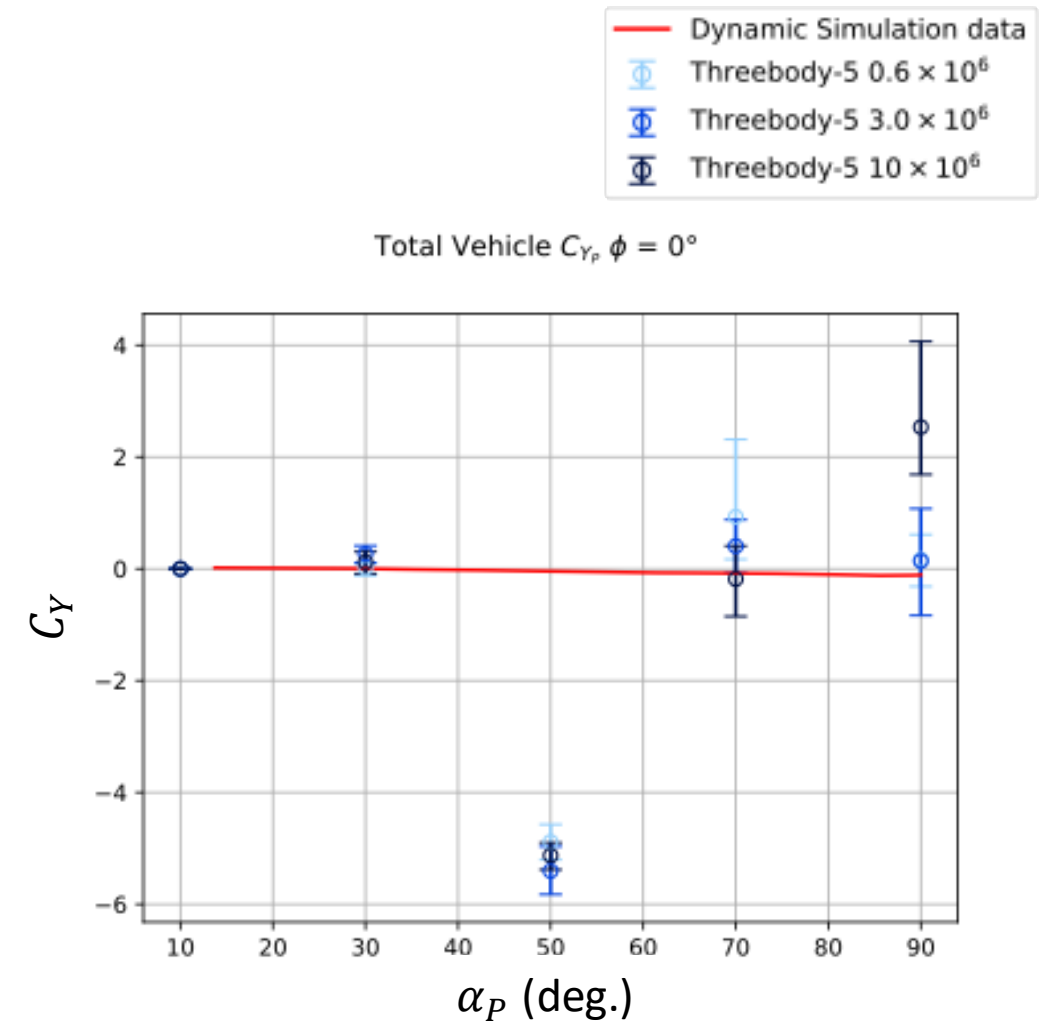
- Preliminary off body flow visualization shows asymmetric vortex system early in the simulation
- Showing contours of vorticity at fixed x values
- Appears to burst part way through





Moving Body Simulation Early Results

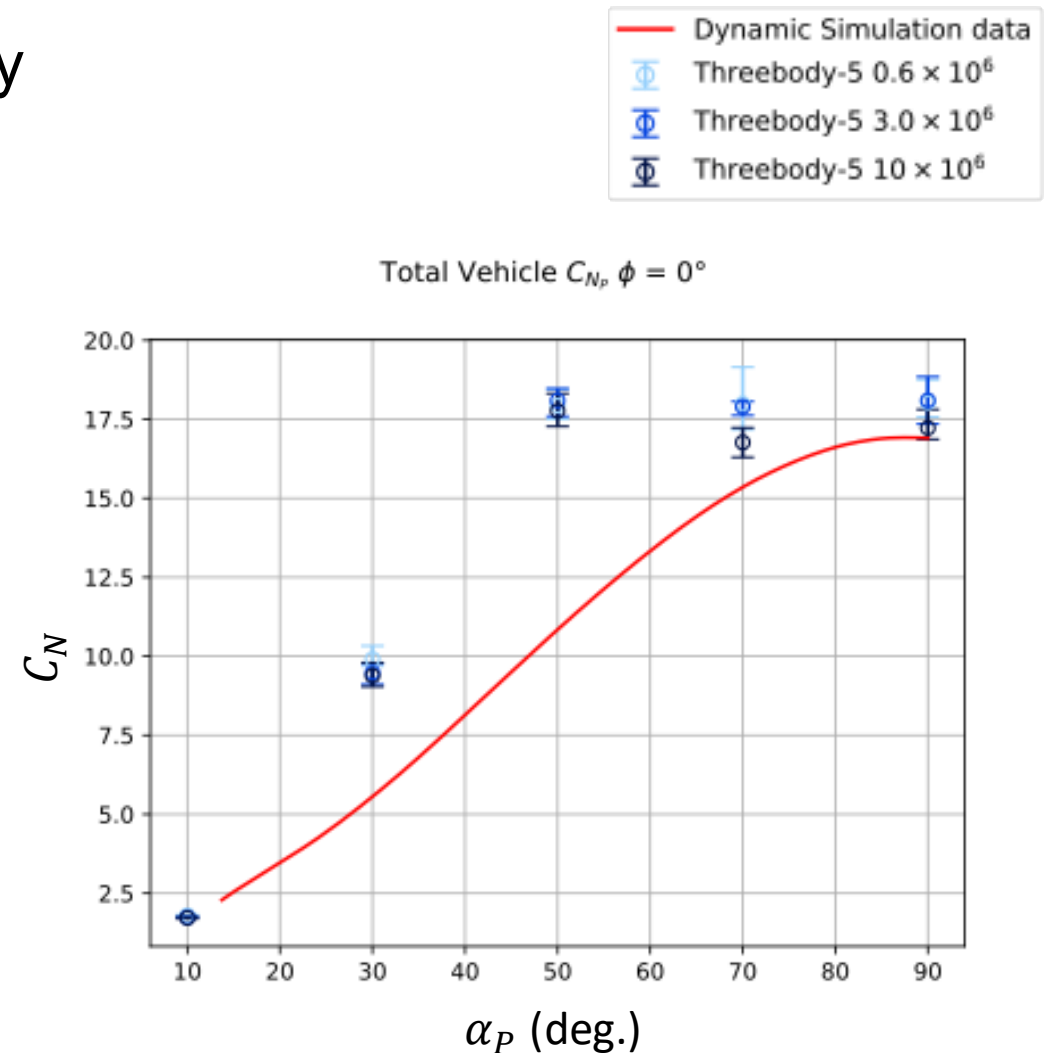
- See no signs of asymmetric vortices when looking at side force
- More visualization and analysis of flow domain to be done
- So far it seems that there is not sufficient time for an asymmetric vortex system to form and affect the vehicle





Moving Body Simulation Early Results

- Normal force shows a more interesting story
- See significant differences in forces at mid α_P (30° to 70°)
- Approaching same value at $\alpha_P = 10^\circ$
- Evidence that QSSA needs to be examined closer
- Need to understand the physics that lead to this difference
- Need to see if these results hold true for distributed loads as well





Summary

- Uncertainty quantification is hard for multimodal phenomenon
 - Use adhoc methods to characterize rare/hard to control observations
- Validation efforts for the SLS program are continuing
- Reynolds number validation shows few concerns regarding difference between flight and analysis conditions
 - Flow separation driven by geometric protuberances
 - Coandă effect does not appear sensitive to Reynolds number
- Early results show quasi-steady state assumptions may not be valid
 - Asymmetric vortex system may not have sufficient time to influence forces
 - Significant difference in integrated forces between stationary and dynamic simulation
 - Distributed loads still need analysis



Questions?



Backup



Vorticity Start and Stop Frames

