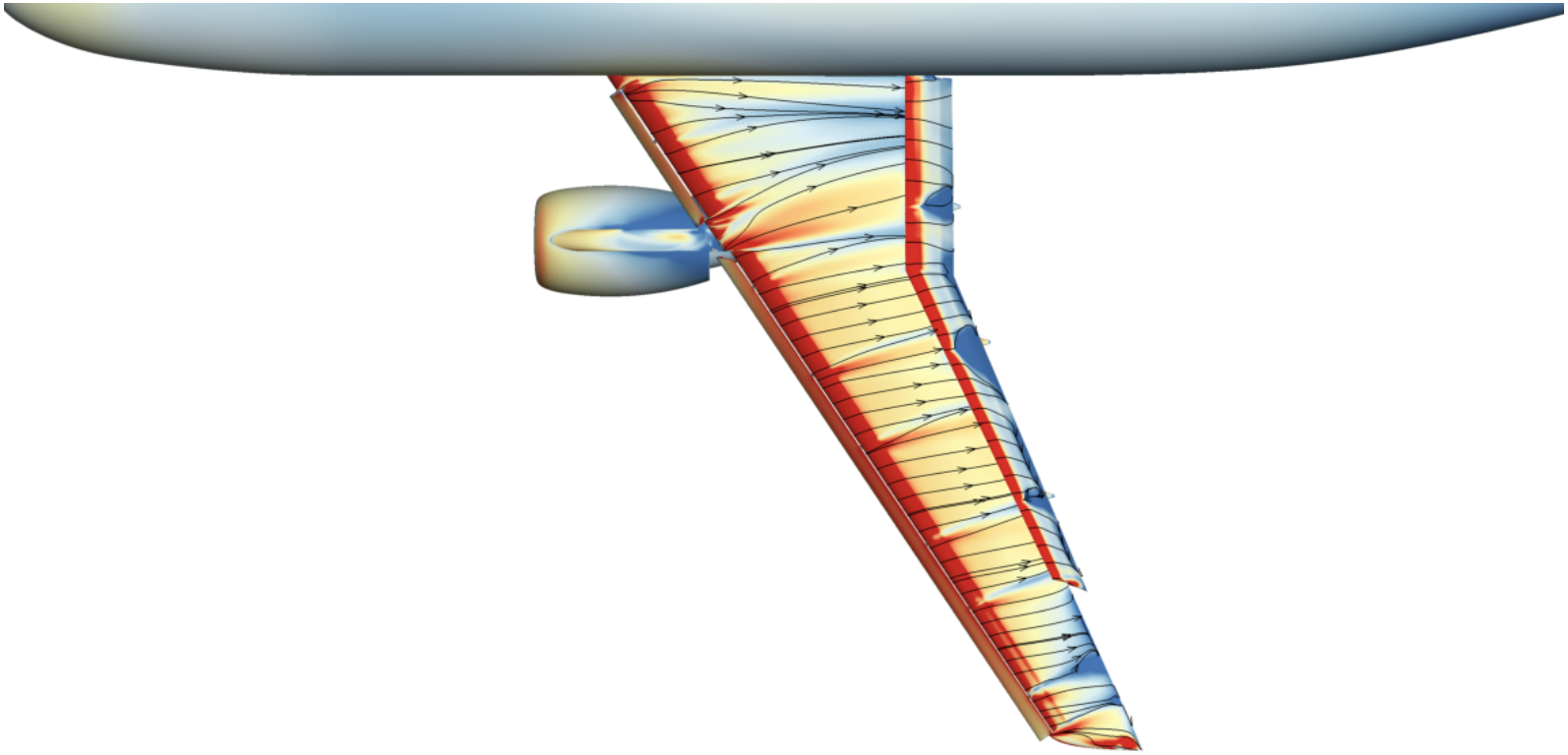

# *Gulfstream's Contributions to the 3rd AIAA High Lift Prediction Workshop*

*Nick Powell*

*June 25, 2018*

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# Outline

- Overview
  - 3rd High Lift Prediction Workshop
  - Solution Background
  - Grid Background
- HLCRM Results
  - Grid Convergence at $\alpha = 16^{\circ}$
  - Grid Convergence at $CL_{max}$
  - Boundary Layer (BL) Grid Dependency Study
  - Reynolds Number (RN) Dependency Study
- JSM Results
  - Comparison to Experimental Data
- Conclusions

# 3rd AIAA High Lift Prediction Workshop

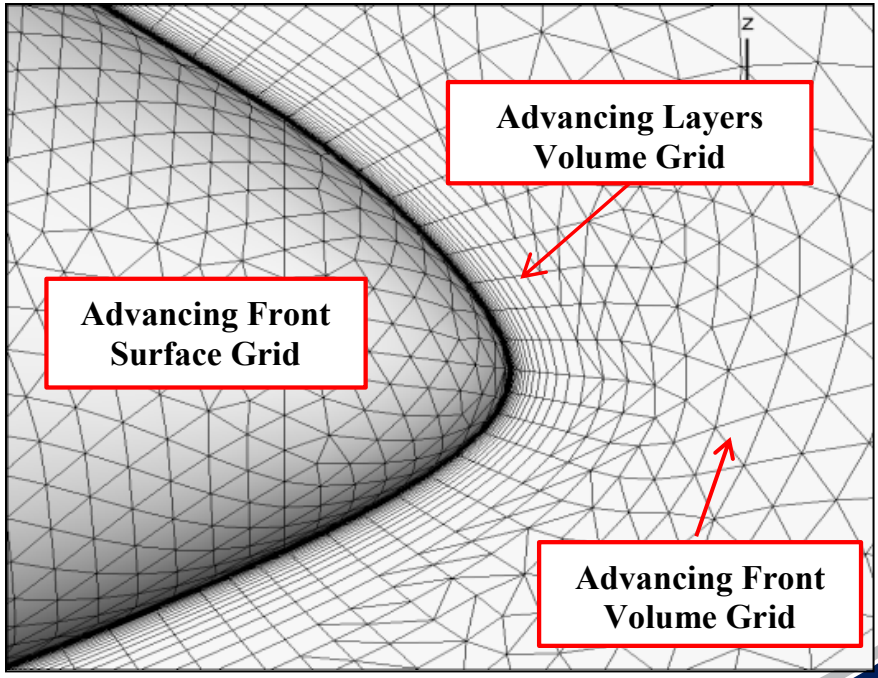
- Held at the 2017 AIAA Aviation Conference
- 36 Participants from 14 countries
- Focused on two geometries
  - NASA's High Lift Common Research Model (HLCRM)
  - JAXA's Standard Model (JSM)

# Solution Background

- Solver: FUN3D
  - Developed at NASA Langley
  - Finite volume RANS solver
  - Roe's flux difference splitting
  - Node-centered, unstructured, mixed-element
- Turbulence model: SA
- Convergence criteria
  - CL and CD variation within ± 0.1%
  - JSM grids required relaxed criteria to ± 1.0%
- Flow initialization
  - Cases were either submitted from scratch (free-stream initialization) or with restarts (initialized from previously resolved solutions at lower AOA)

# Custom Grid Background

- Custom grids were generated with HeldenMesh
  - Commercial unstructured grid generator similar to VGRID
  - Mixed element
  - Advancing front and advancing layers (BL) grid algorithms
  - Rapid grid generation through autonomous modeling and parallel processing
- BL grid parameters
  - Geometric growth rate ≤ 15%
  - Exponential growth rate of ~2.0%
  - Targeted a flat-plate $y^+ \simeq 1$
  - Approximately 30 points in the boundary layer at 50% MAC



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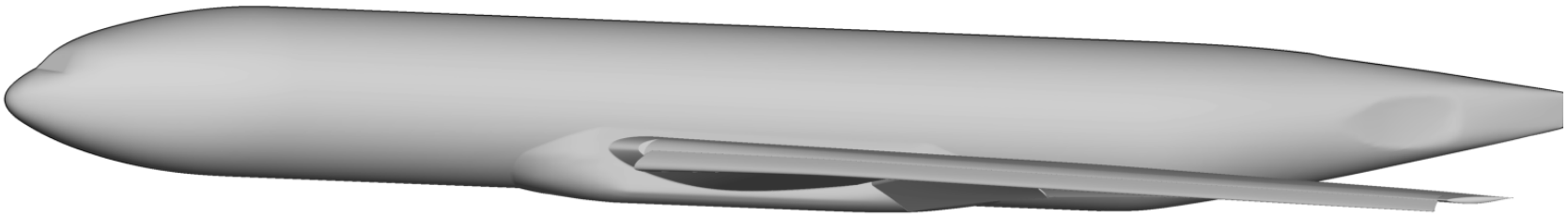
# NASA's High Lift Common Research Model

- Wing-body representing a modern 300 pax commercial airliner
- Full-Scale model
  - Mean Aerodynamic Chord (MAC): 275.8 in.
  - Wing-semi-span 1156.75 in. (96.4 ft)
  - Reference area: 4130 $ft^2$
- Slats and flaps included but not support brackets



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# HLCRM Cases

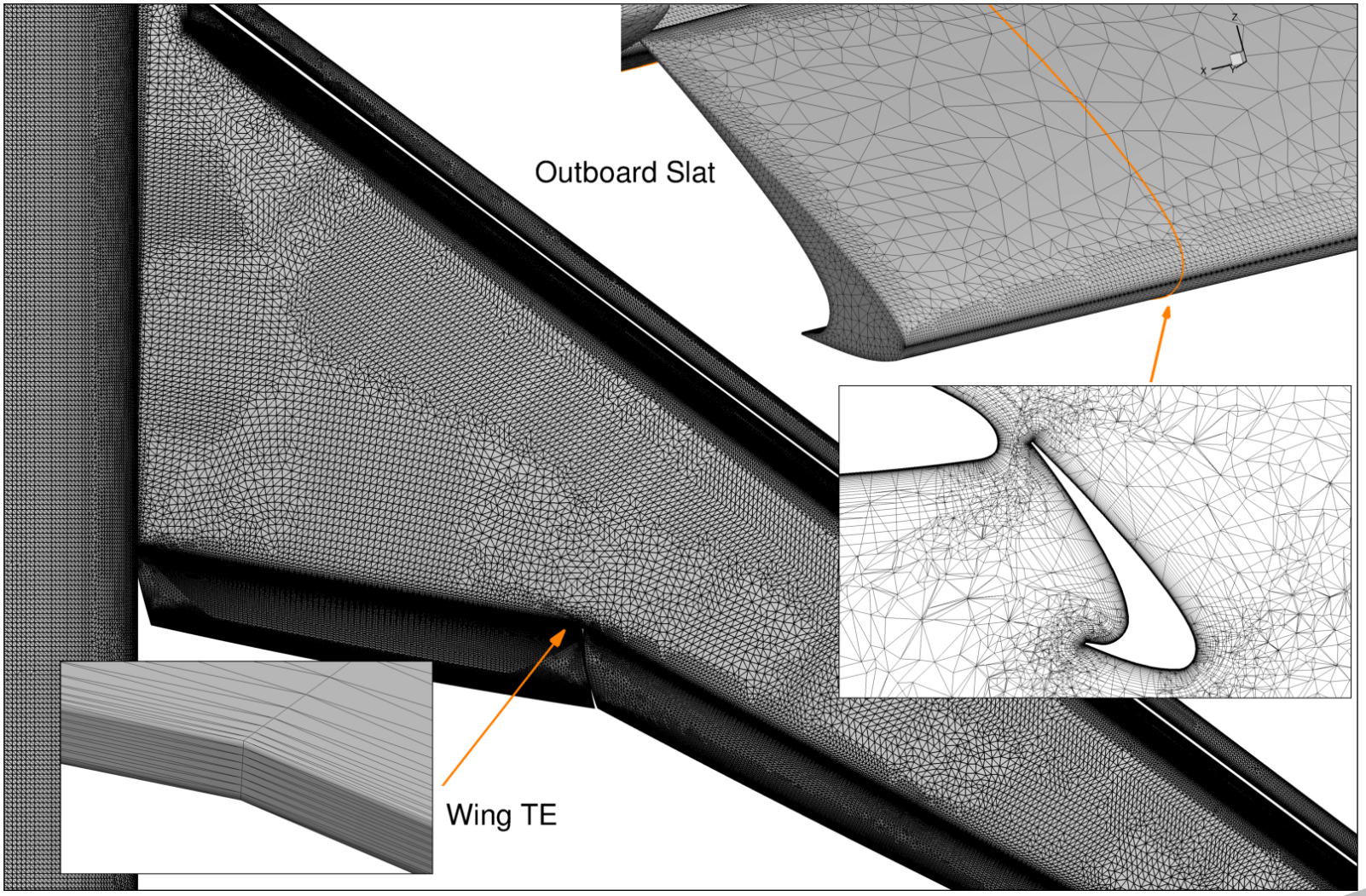
| HLCRM | Grid study at α = 8˚ | Grid study at α = 16˚ | Grid study polar to stall |
|---|---|---|---|
| 1a (full gap) | yes | yes | yes |
| 1b (full gap w adaption) | no | no | no |
| 1c (partial seal) | no | no | no |
| 1d (partial seal w adaption) | no | no | no |

| | |
|---|---|
| Free-stream Mach Number | 0.2 |
| Reynolds Number (based on MAC) | $3.26 \times 10^6$ |
| Reference Static Temperature | 518.67 ˚R |

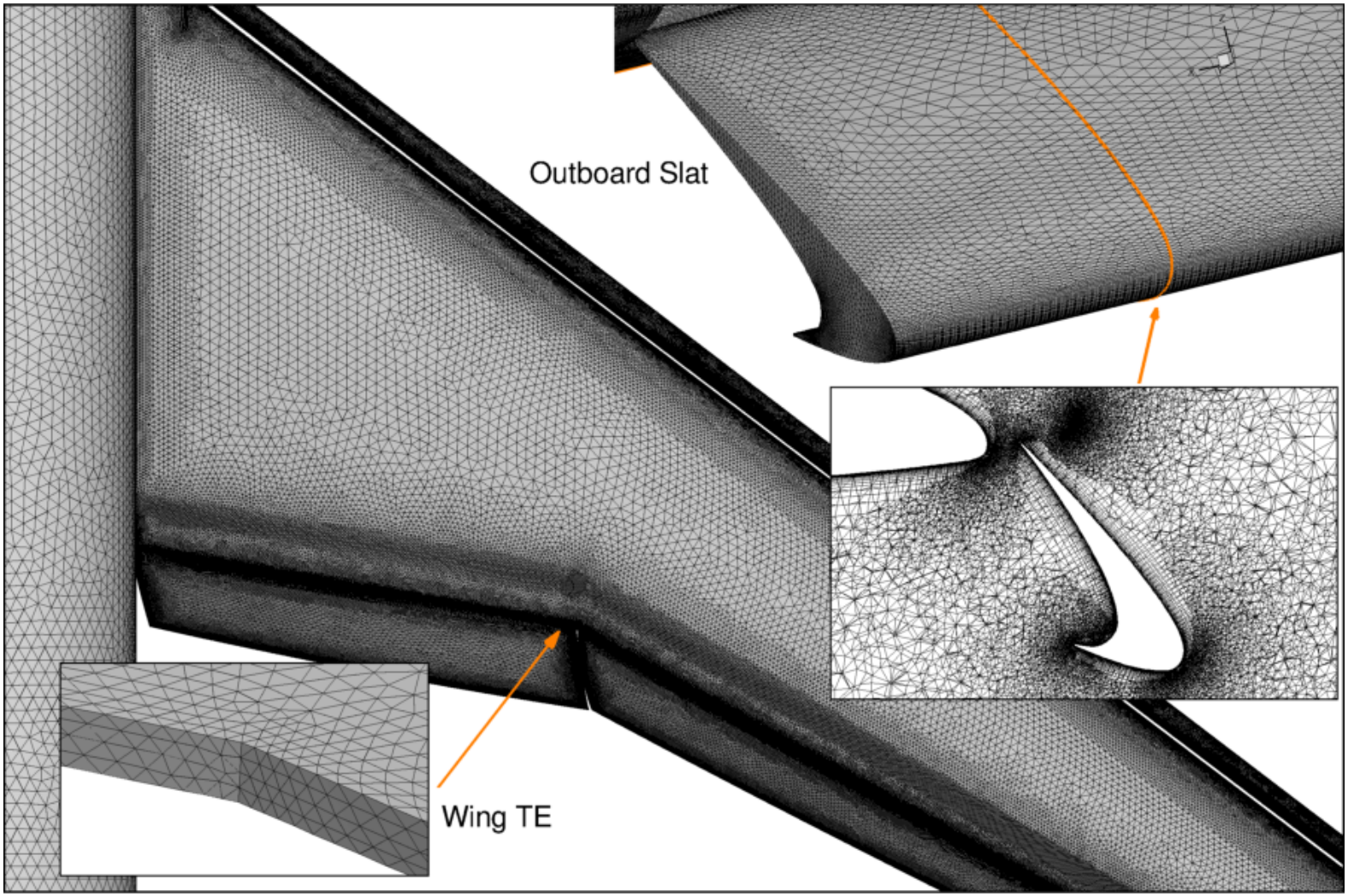
# Grid Specifications

| Series/ ID | Case/ Config | Type | Number of Points (M) | Number of Cells (M) | Grid Developer | Tool |
|---|---|---|---|---|---|---|
| B2 | 1a | Mixed (prism dominant) | 8, 26, 70, 206 | 22, 65, 170, 541 | Pointwise | Pointwise |
| GAC HLCRM | 1a | Mixed (prism dominant) | 30, 33, 41, 55, 78, 131 | 88, 106, 132, 174, 250, 425 | Gulfstream | HeldenMesh |

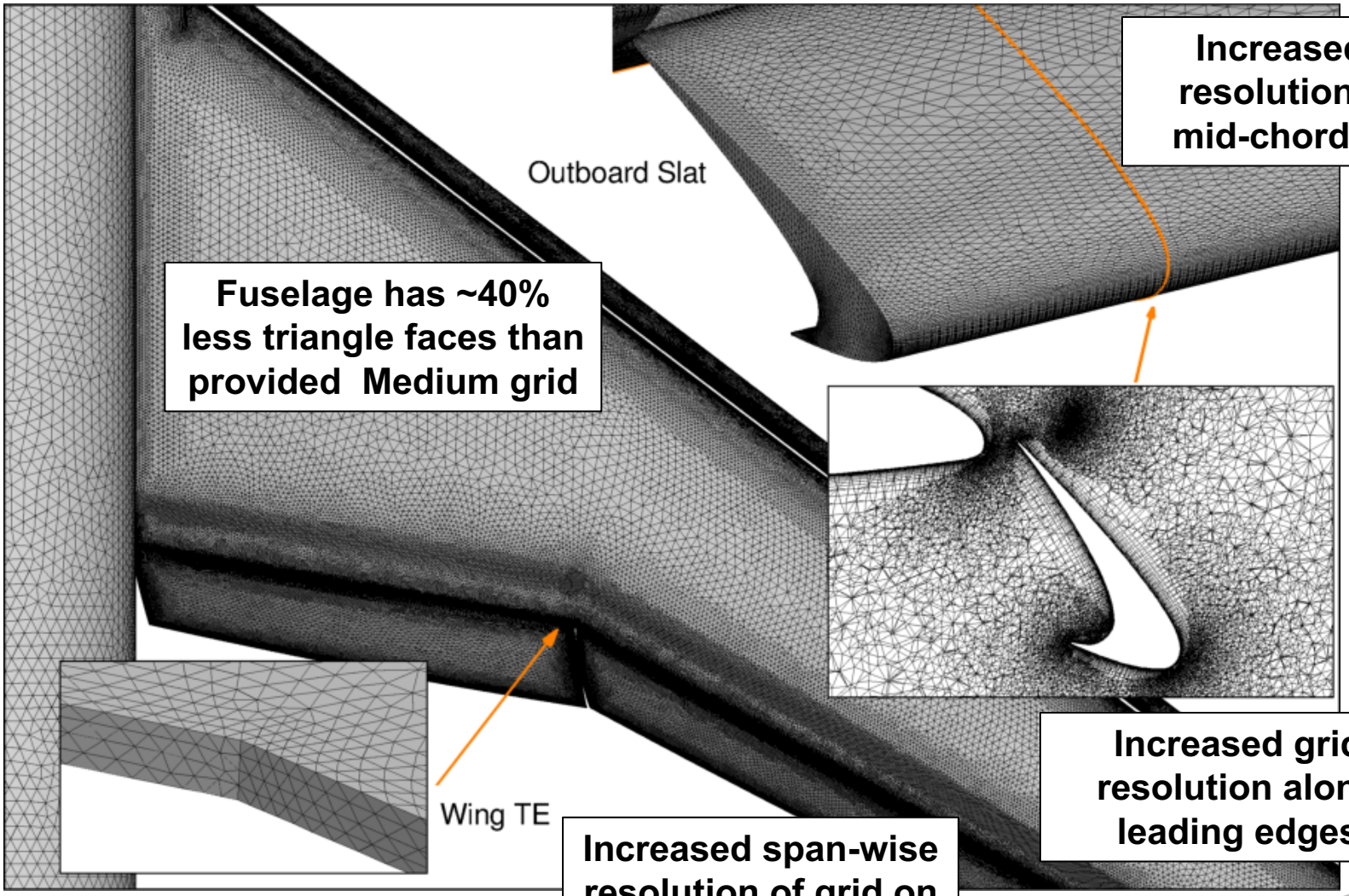
# Provided HLCRM Medium Grid



# GAC Custom HLCRM Medium Grid



# GAC Custom HLCRM Medium Grid




**Increased grid resolution along mid-chord of slat**

**Fuselage has ~40% less triangle faces than provided Medium grid**

**Increased grid resolution along leading edges**

**Increased span-wise resolution of grid on wing TE**



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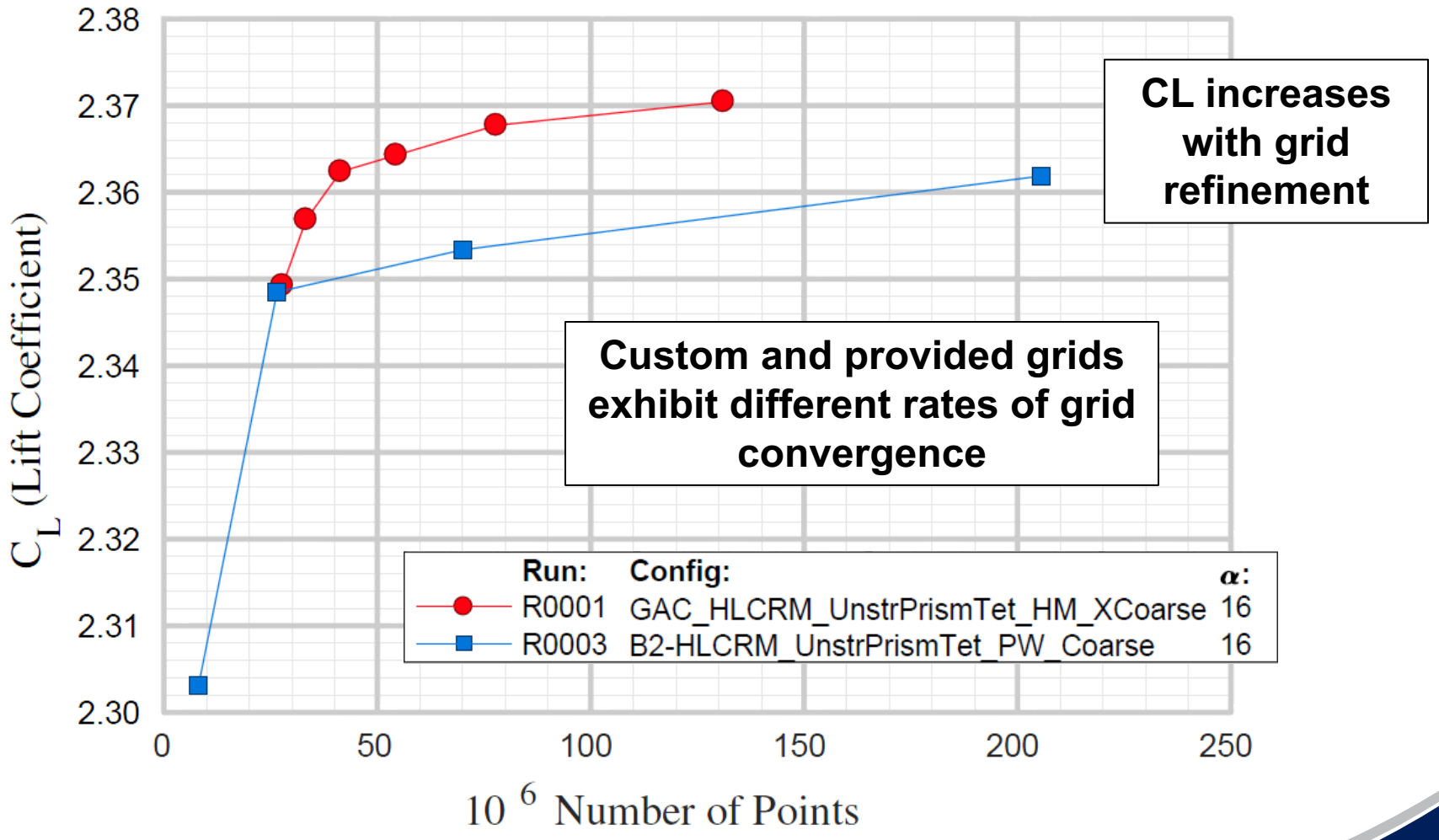
# Grid Convergence at 16˚ AOA



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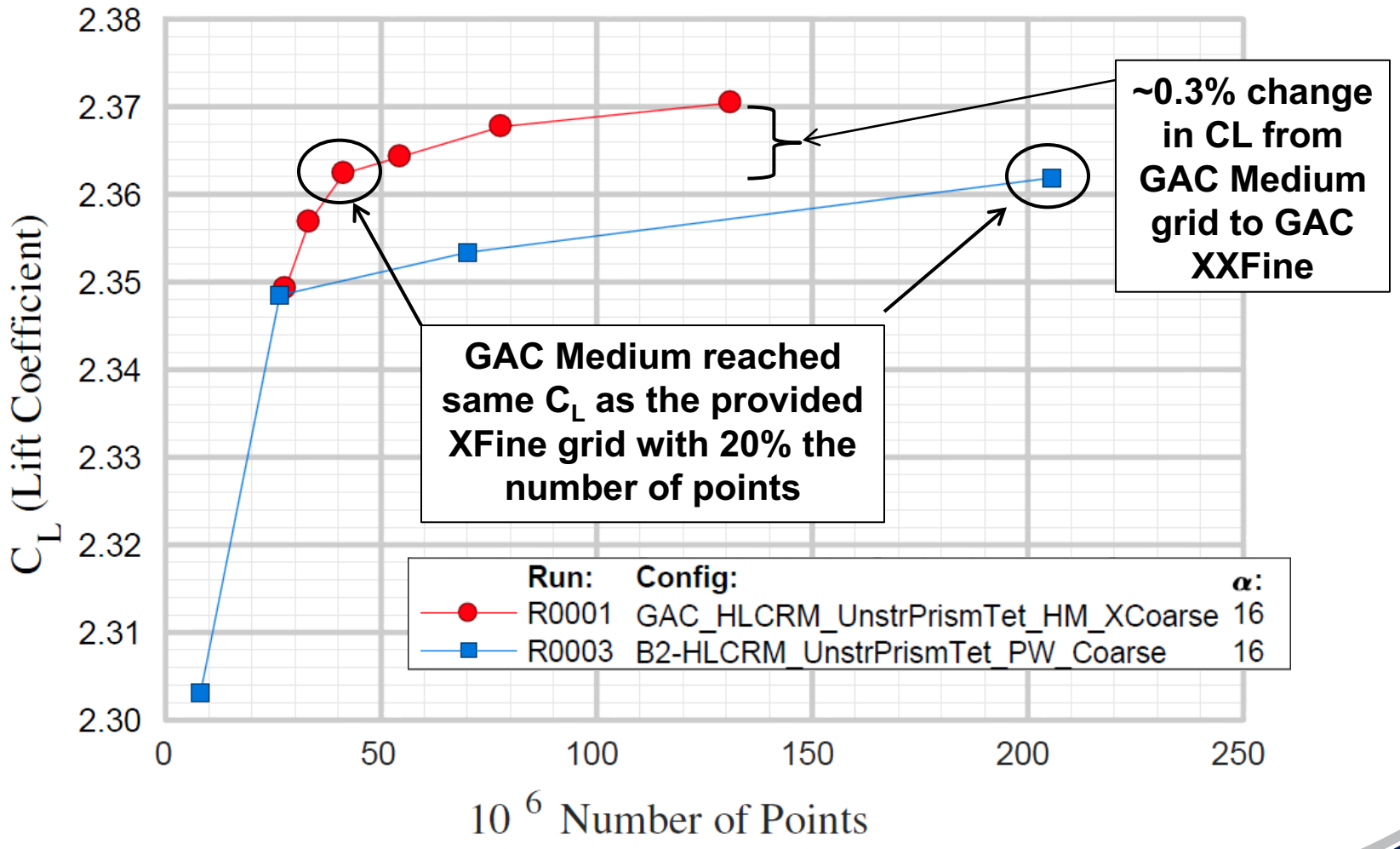
# Grid Convergence at 16˚ AOA



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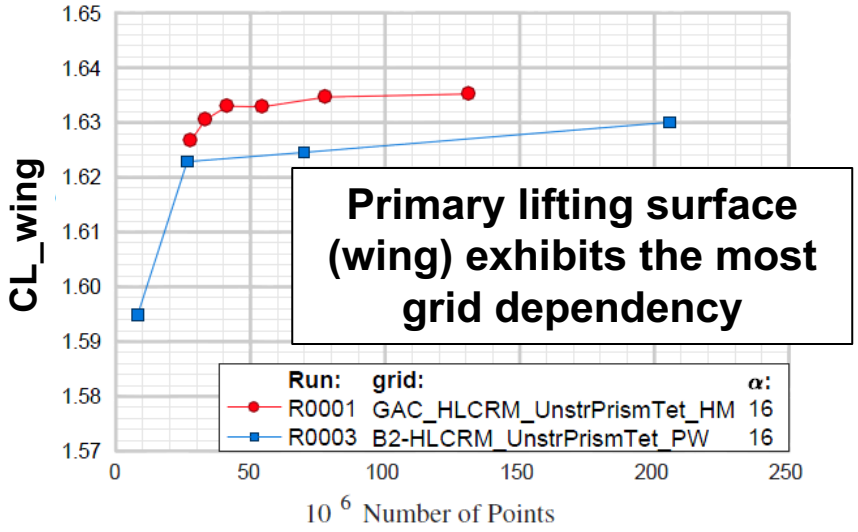
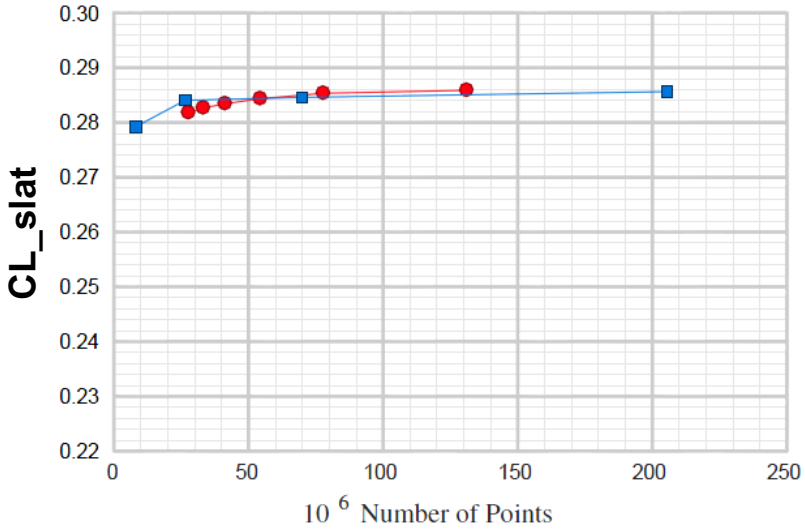
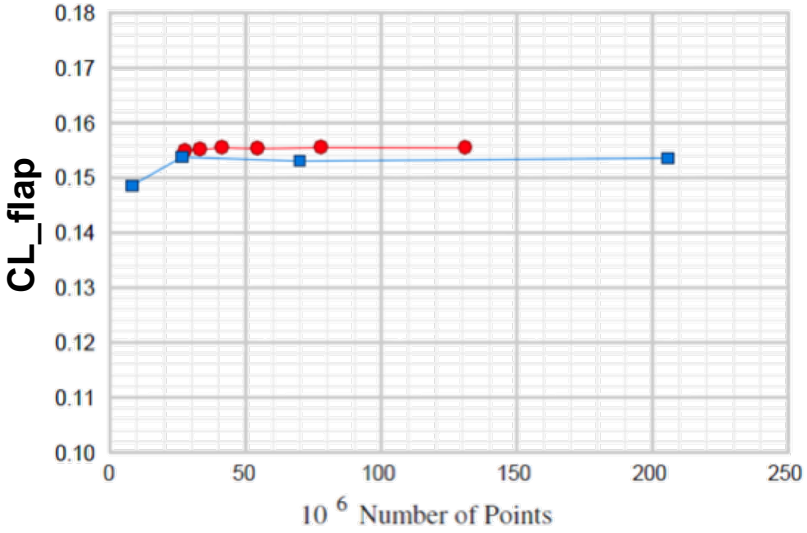
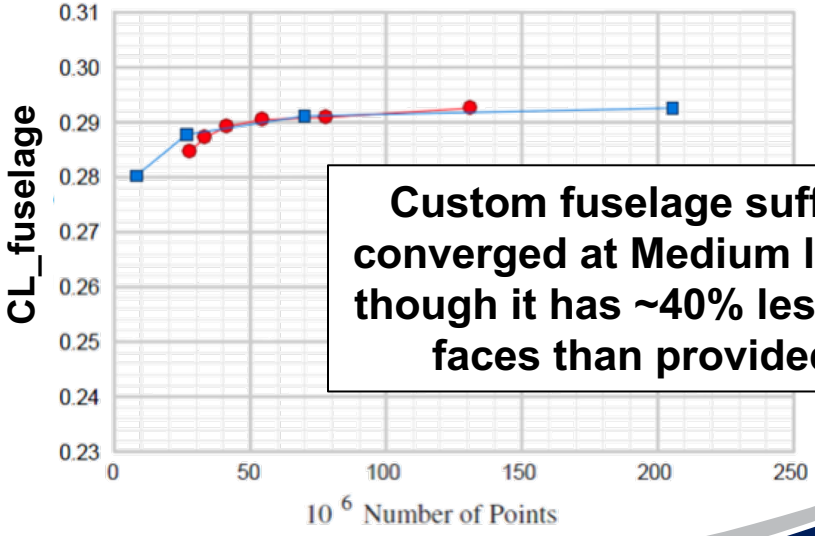
# Grid Convergence by Aircraft Component




**Primary lifting surface (wing) exhibits the most grid dependency**




**Custom fuselage sufficiently converged at Medium level even though it has ~40% less triangle faces than provided grid**



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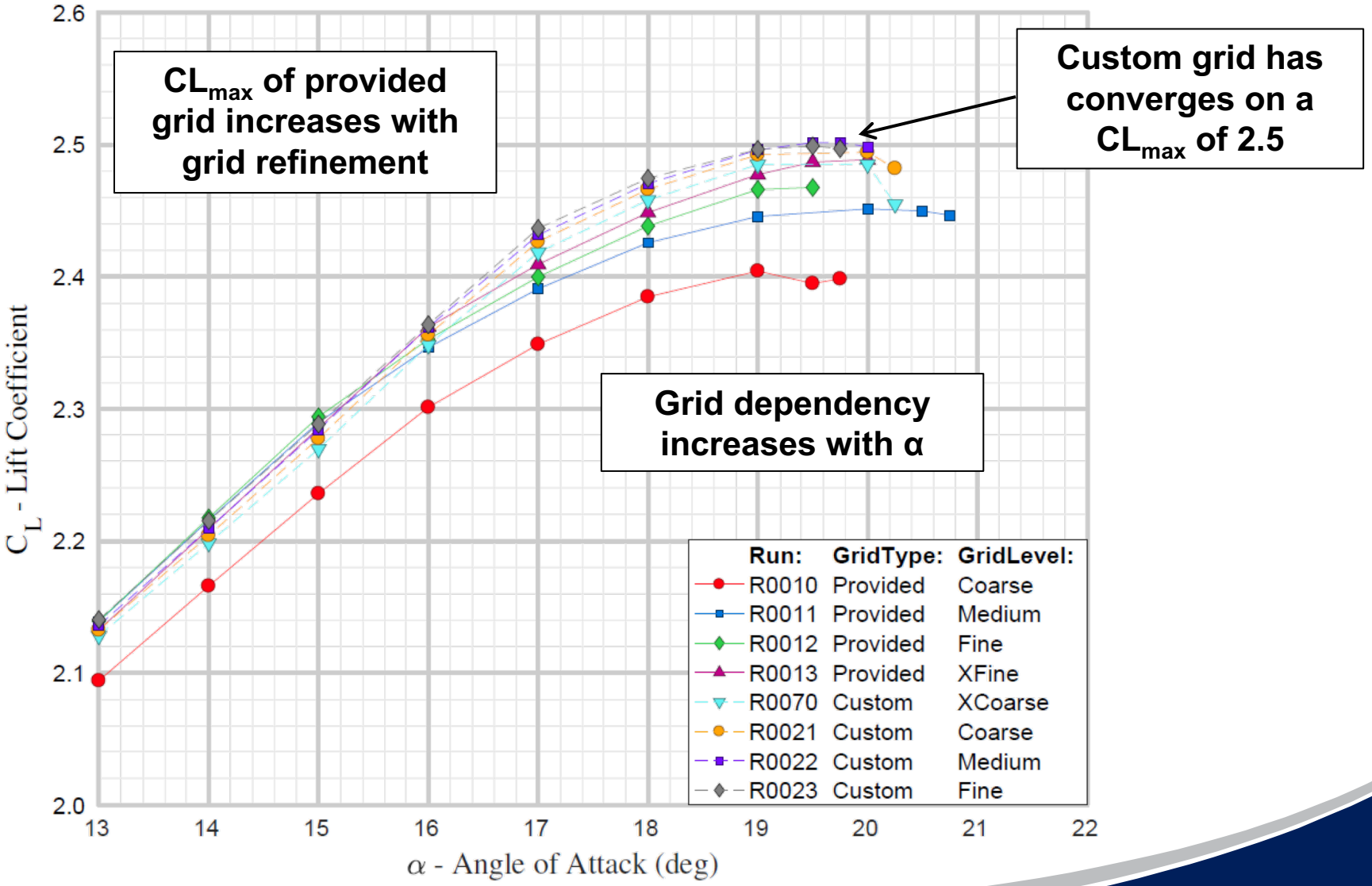
# Grid dependency on $CL_{max}$



# Exceptions to the 3rd HLPW Gridding Guidelines

- Custom grid set does not grow by increments of 3X between grid levels
  - Global source terms were scaled by 20% between grid levels
- Custom grid set does not grow uniformly in all directions
  - Advancing-layer initial height and growth rates were kept constant across the grid set

| Grid Designation | $10^{-6}\ N^{-2/3}$ | | $10^{6}\ N$ | |
|---|---|---|---|---|
| | Provided | Custom | Provided | Custom |
| XCoarse | -- | 10.9 | -- | 27.8 |
| Coarse | 24.8 | 9.7 | 8.1 | 33.3 |
| Medium | 11.3 | 8.4 | 26.5 | 41.4 |
| Fine | 5.9 | 7.0 | 69.9 | 54.5 |
| XFine | 2.9 | 5.5 | 205.6 | 77.9 |
| XXFine | -- | 3.9 | -- | 131.1 |

**Solving an XXFine grid for the Provided grid set would be prohibitively expensive**

**For 50 million more points, custom grid set has 2 more grid levels**

# Advancing Layer (Boundary Layer) Grid Dependency Study

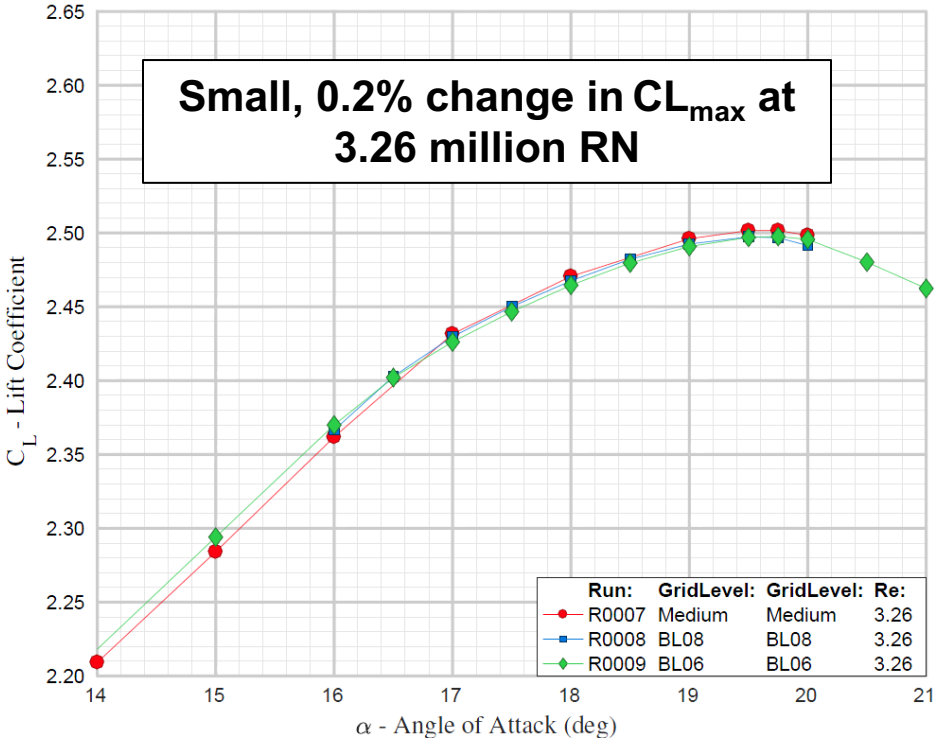
- Advancing Layer algorithm

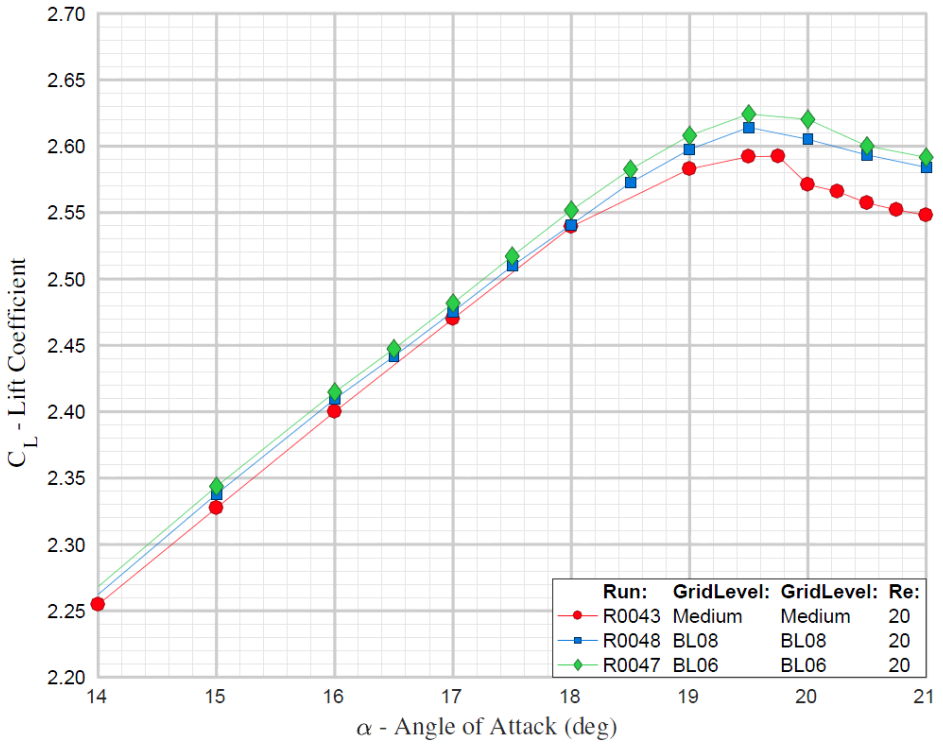
$$\Delta n_j = \delta_1\left(1 + r1(1 + r2)^{j-1}\right)^{j-1}$$

  - $\delta_1$ = initial grid height off of surface
  - r1 = geometric growth rate
  - r2 = exponential growth rate

| Grid Designation | δ1 | r1 | r2 | Approx. # of Points in BL at 50% MAC |
|---|---|---|---|---|
| Medium | 0.00160 | 0.15 | 0.02 | 31 |
| Medium_BL08 | 0.00128 | 0.12 | 0.02 | 36 |
| Medium_BL06 | 0.00096 | 0.09 | 0.02 | 43 |

# BL Grid Dependency at 3.26 M RN and 20 M RN




**BL grid exhibits significant grid dependency at 20 million RN**



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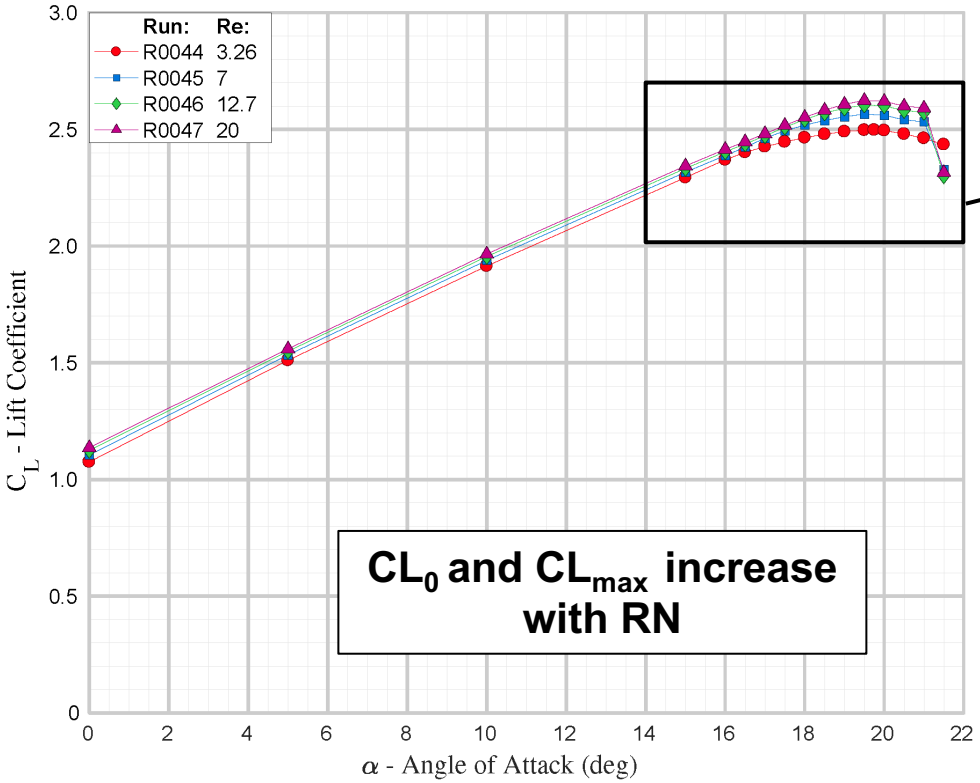
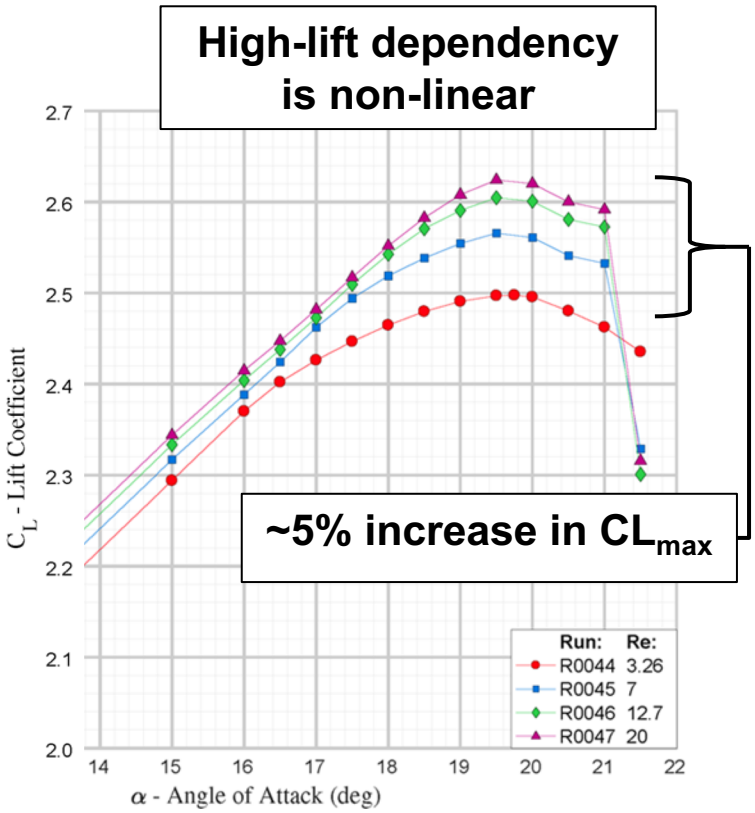
# Reynolds Number Study

- Polar up to stall
  - Restarted solutions from previous α after α = 16˚
- Reference temperature and reference chord kept constant
- Utilized custom HLCRM medium grid with fine BL – “BL06” to avoid grid dependency at high RN

# Lift Dependency on Reynolds Number



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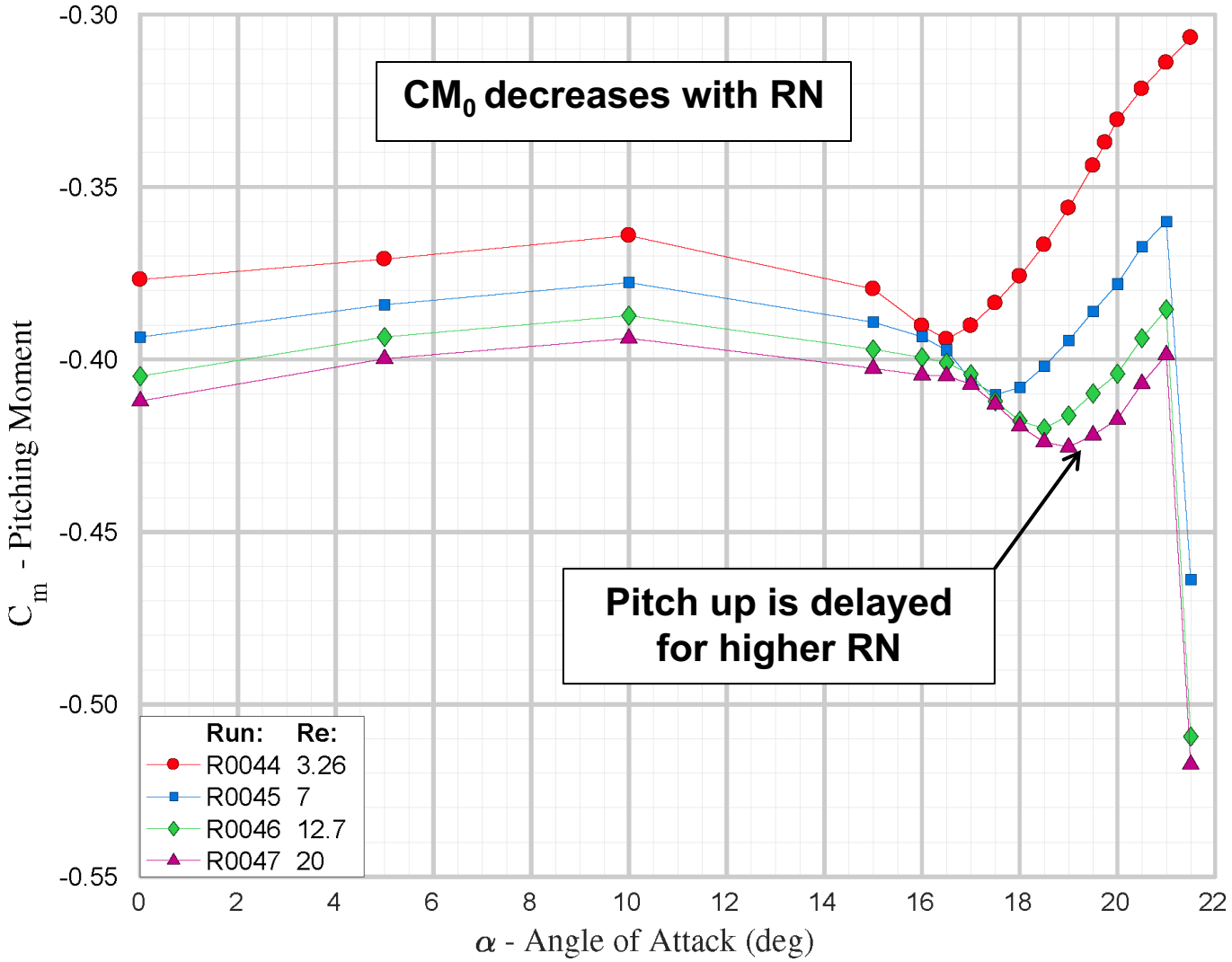
# Pitching Moment Dependency on Reynolds Number



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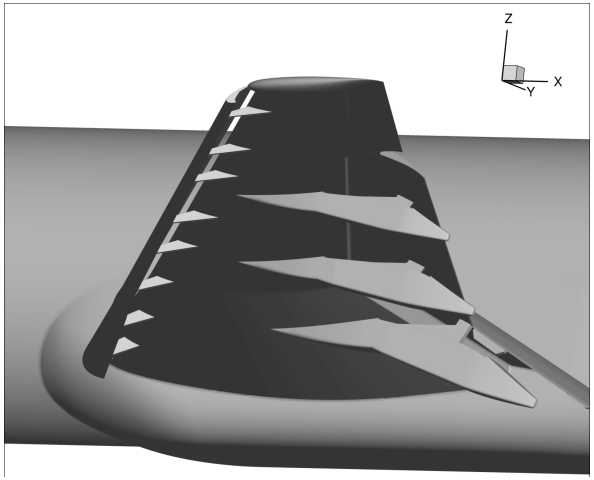
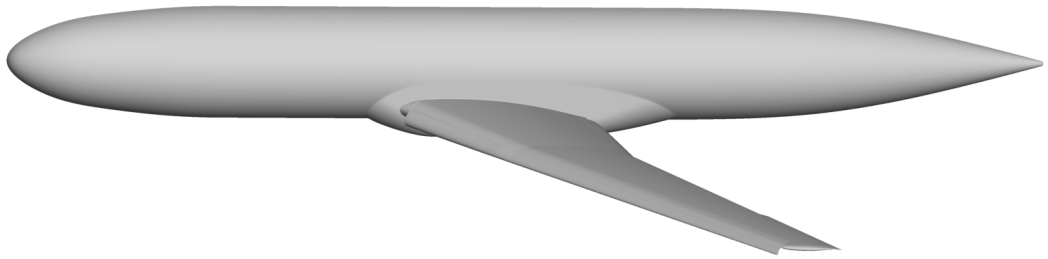
# Case 2: Comparison with Experiment using the JSM

- JAXA's Standard Model
  - Wing-body representing a modern 100 pax commercial airliner
  - 17% Scaled Model
    - Mean Aerodynamic Chord (MAC): 529.2 mm
    - Wing-semi-span: 2300 mm (~7.4 ft)
    - Reference area: 1,123,300 $mm^2$ (~12 $ft^2$)
- Comparison to Experimental Data
  - Data obtained from JAXA's 6.5m X 5.5m wind tunnel run at 1.93 million RN



# HLPW Case 2

| JSM | Polar | Polar, specified transition | Polar, with transition prediction |
|---|---|---|---|
| **2a (no nacelle)** | yes | preliminary | no |
| **2b (no nacelle w adaption)** | no | no | no |
| **2c (with nacelle)** | yes | no | no |
| **2d (with nacelle w adaption)** | no | no | no |

| | |
|---|---|
| Free-stream Mach Number | 0.172 |
| Reynolds Number (based on MAC) | $1.93 \times 10^6$ |
| Reference Static Temperature | 551.79 ˚R |

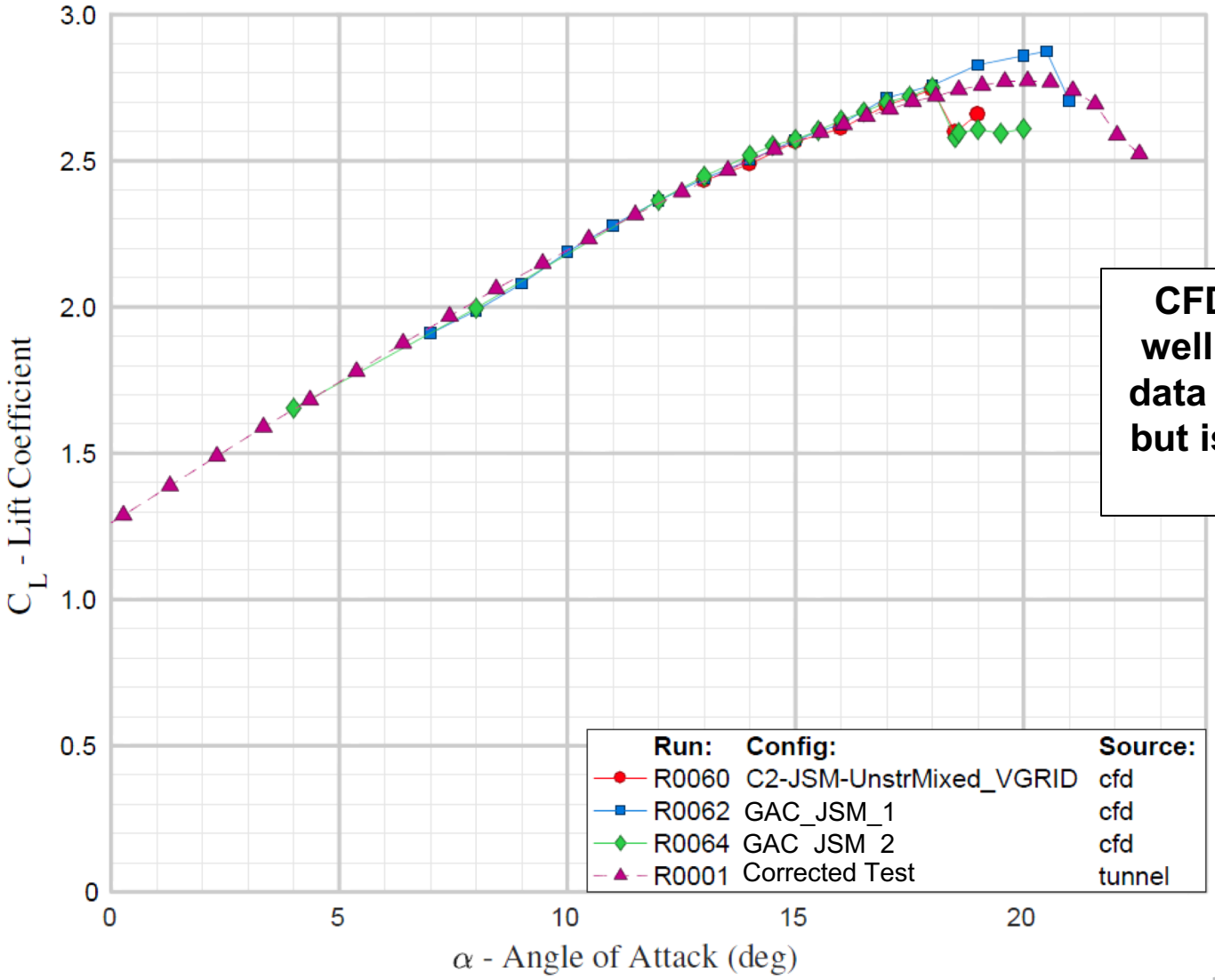
# Grid Specifications

| Series/ ID | Case | Type | Number of Points (M) | Number of Cells (M) | Developer | Tool |
|---|---|---|---|---|---|---|
| C2 | 2a,2c | Mixed (prism dominant) | 16, 21* | 52, 65* | S/G** | VGRID |
| GAC JSM 1 | 2a,2c | Mixed (prism dominant) | 63 | 192 | Gulfstream | HeldenMesh |
| GAC JSM 2 | 2a,2c | Mixed (prism dominant) | 31 | 85 | Gulfstream | HeldenMesh |

*** Without and with nacelle**
**** Spaceship Company and Gulfstream Aerospace**

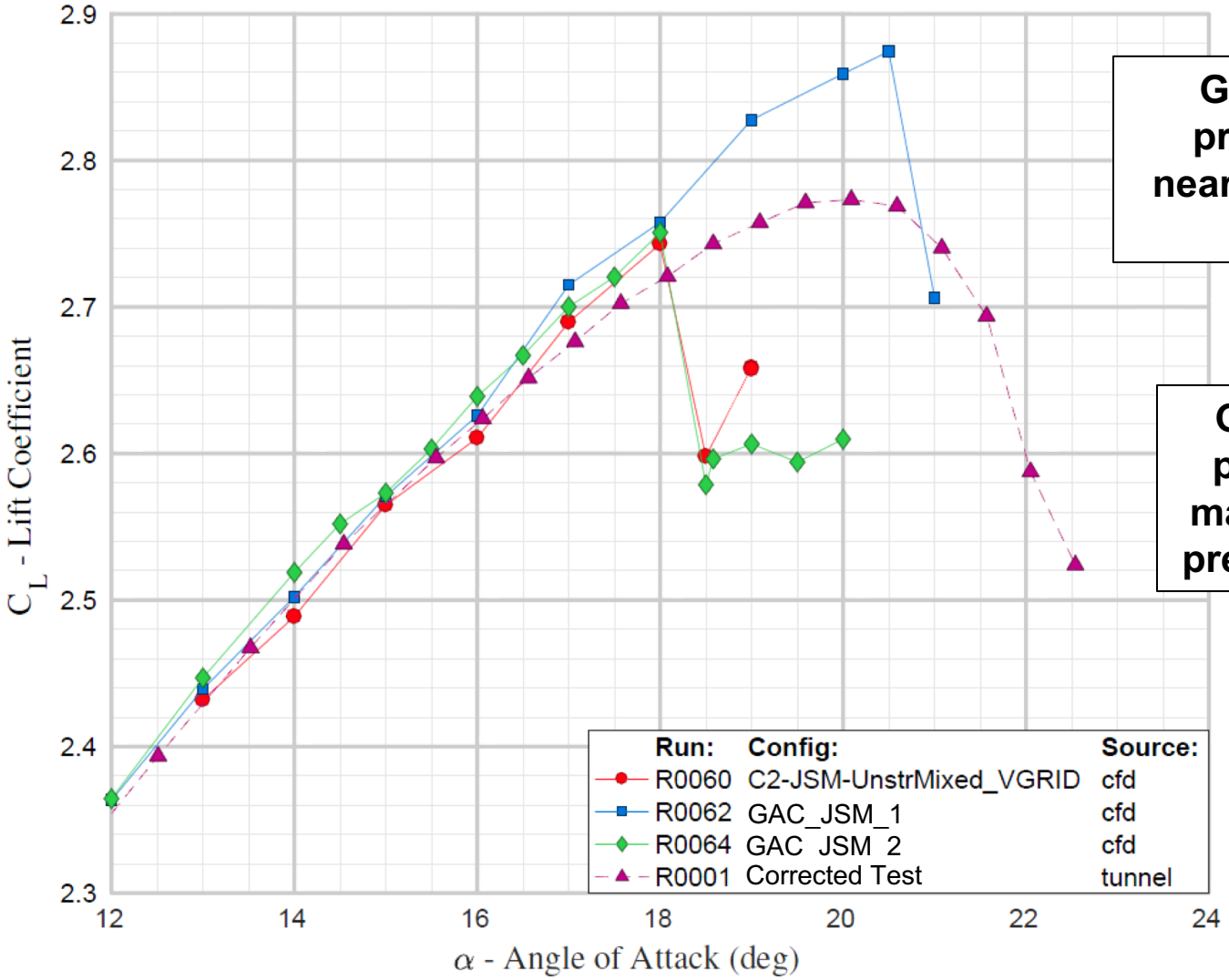
**GAC JSM 2 utilized grid parameters from the custom HLCRM Medium, which were adjusted to account for aircraft size, model scale and grid units**

# JSM Results




**CFD Correlates fairly well with experimental data in the linear region but is inconsistent near stall**

# JSM Results near Stall




**GAC_JSM_1 over predicts $CL_{max}$ but nearly matches $\alpha_{max}$ of the test data**

**GAC_JSM_2 and the provided grid almost match $CL_{max}$ but under predict tunnel $\alpha_{max}$ by 2˚**



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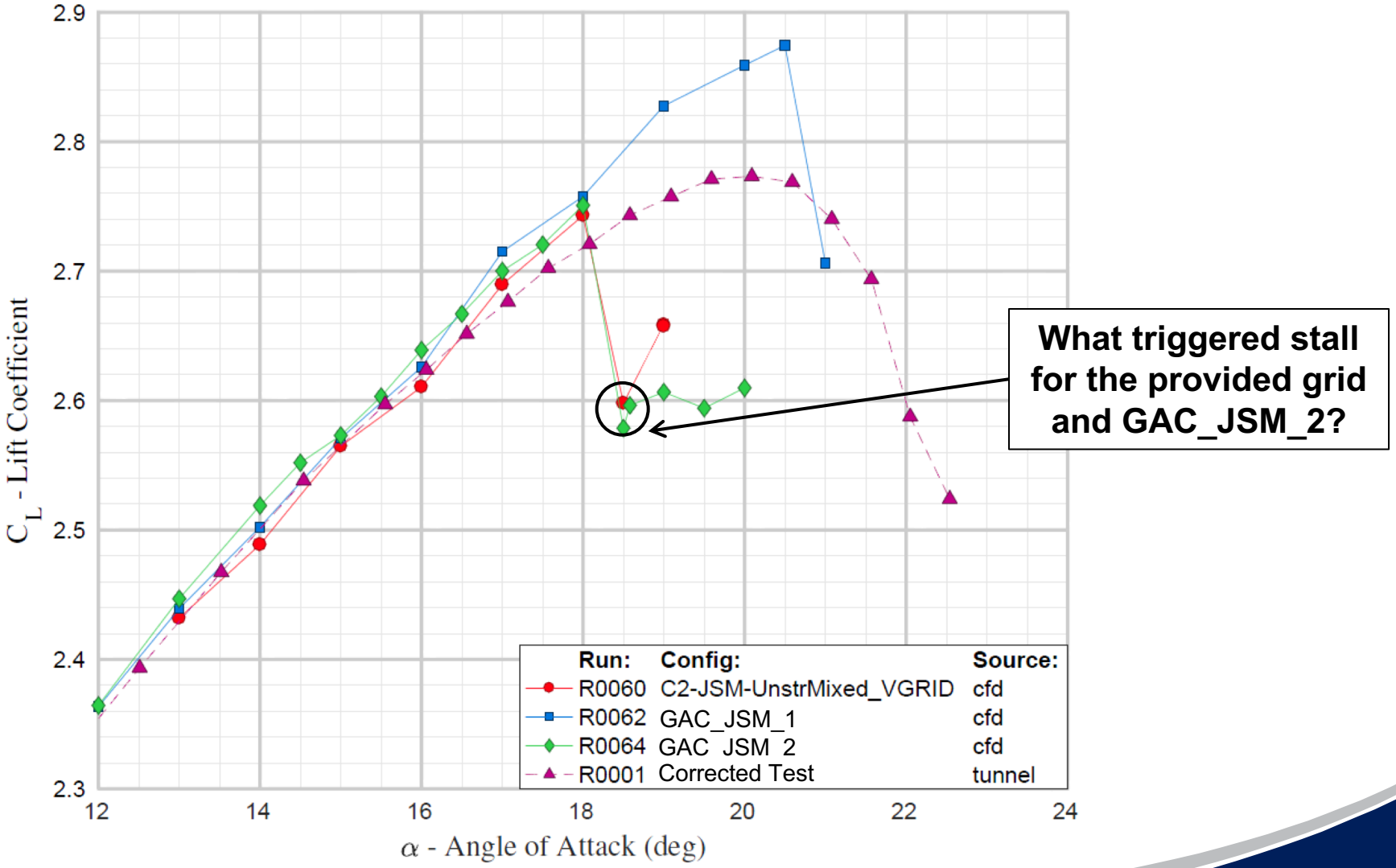
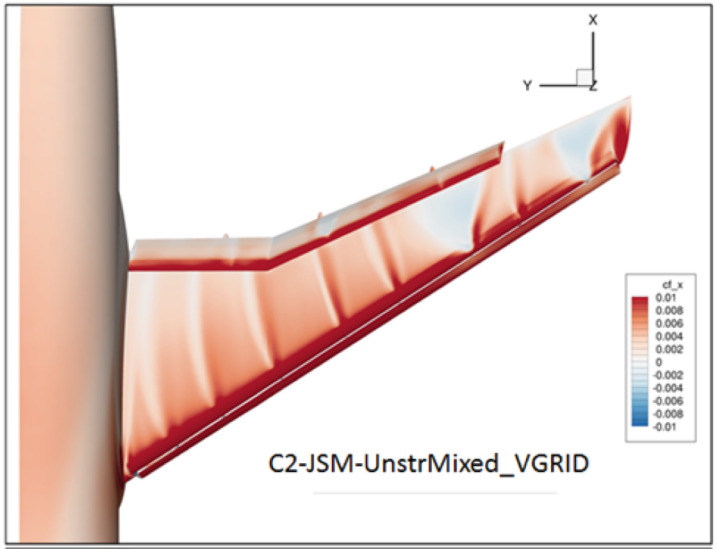
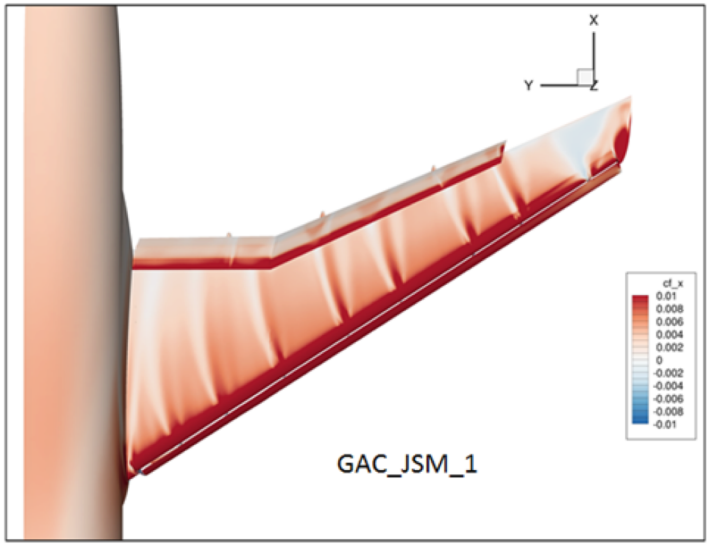
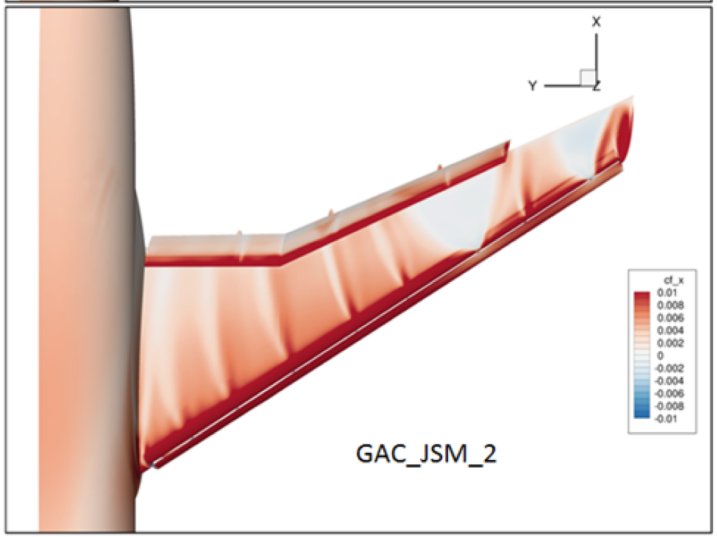
# JSM Results near Stall

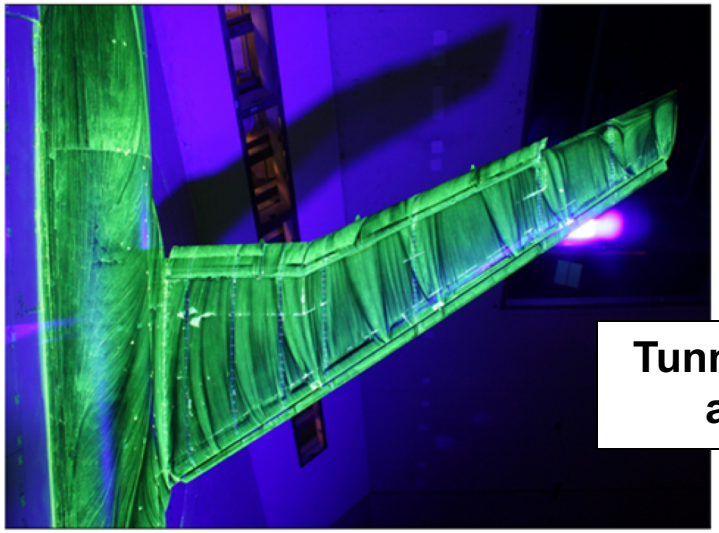


# Flow Visualization Comparisons



**Skin Friction Coefficient at α = 18.5˚**

**Red: Positive**
**White: Neutral**
**Blue: Negative**

**Tunnel Oil Flow at 18.58˚**



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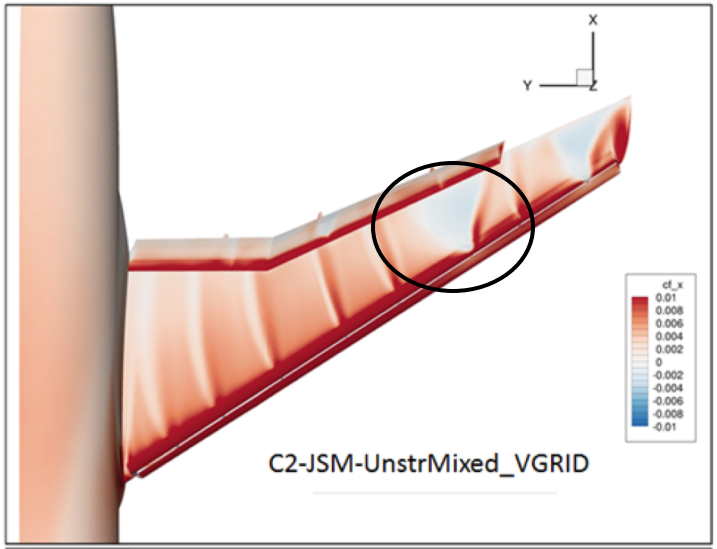
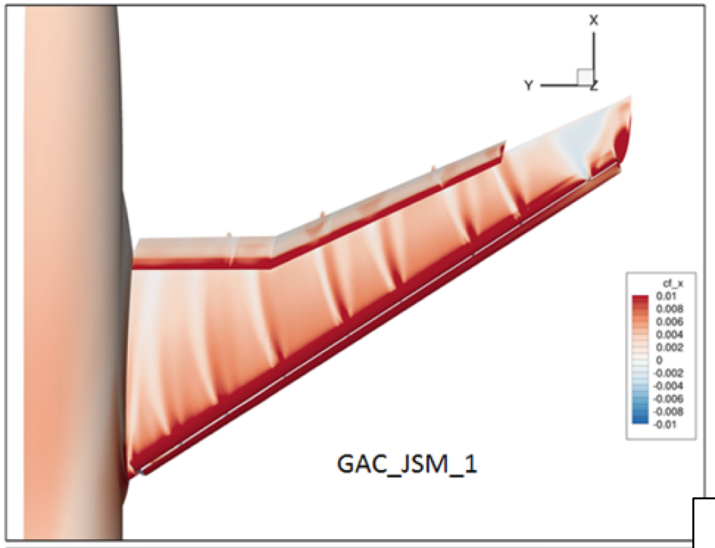
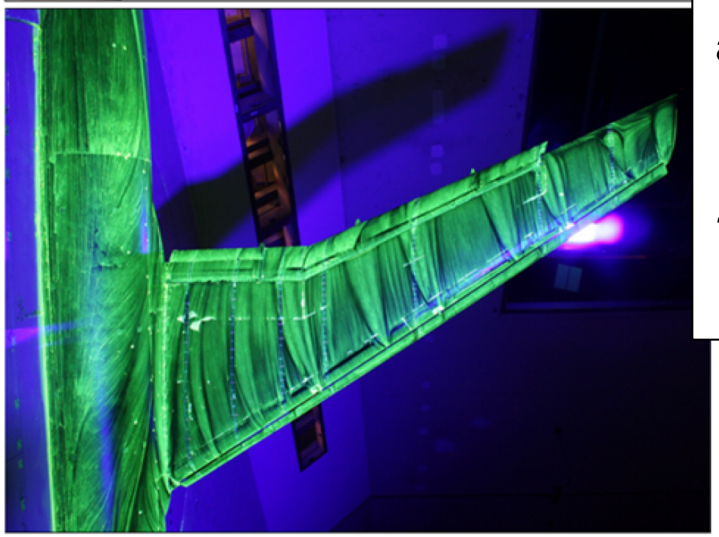
# Flow Visualization Comparisons



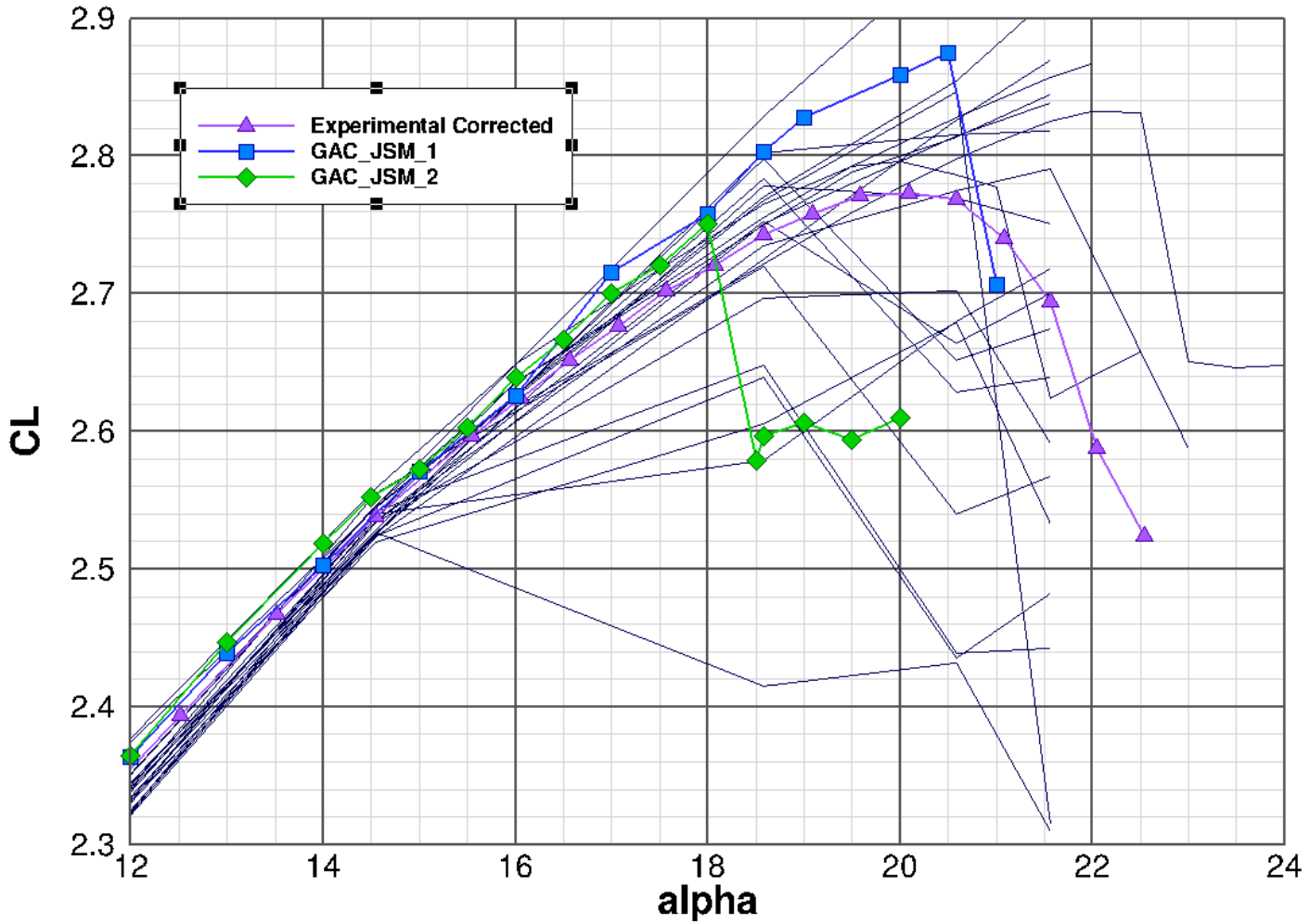







**Provided grid and GAC_JSM_1 grids exhibit large separation just aft of the 3rd most outboard slat bracket**

# Custom JSM Results Compared to Other Participants

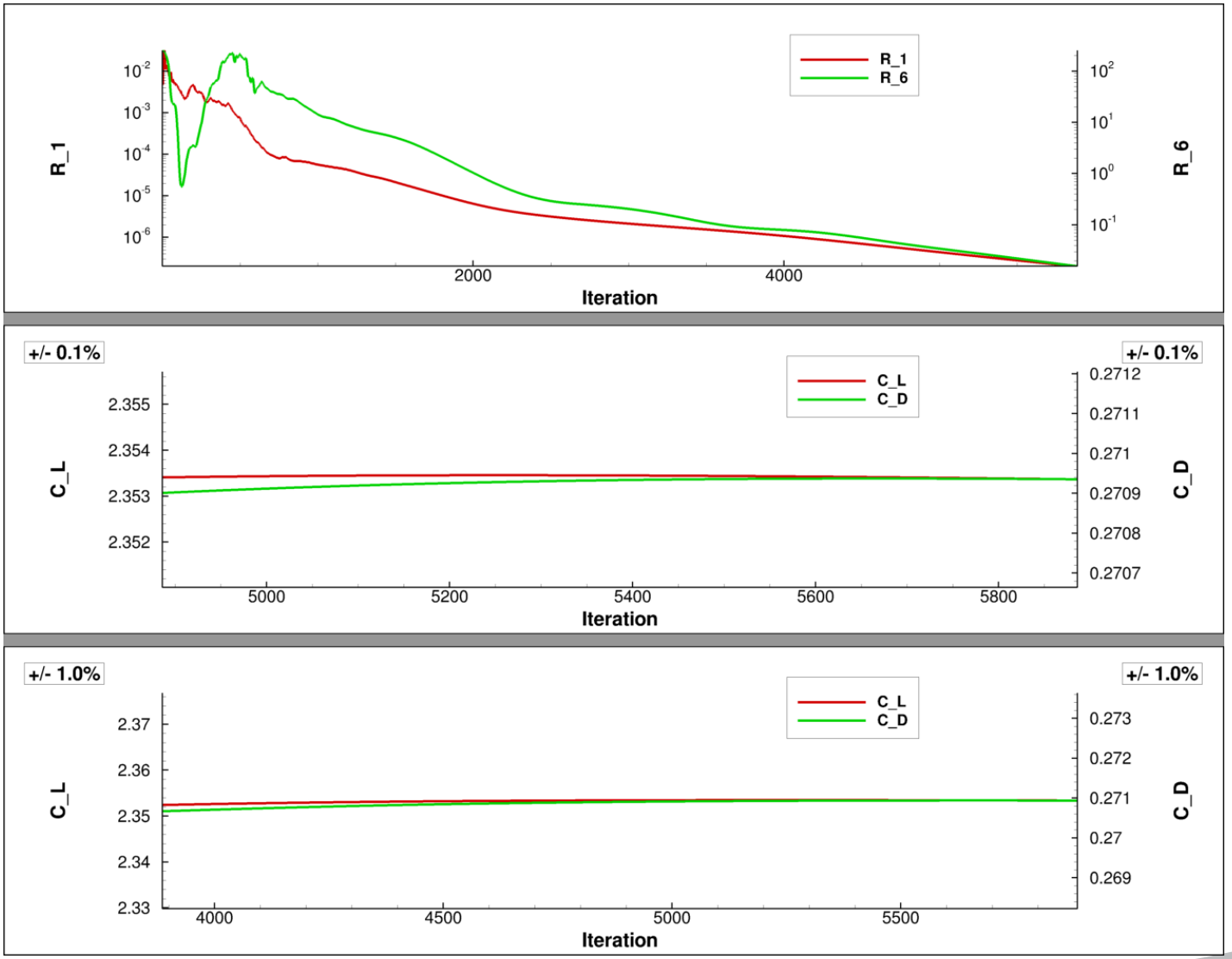


# Conclusions

- It is important to analyze high-lift grid dependency up to stall
  - Grid dependency increased with α
  - $\alpha_{max}$ can be highly grid dependent (as seen with the JSM) and can account for a substantial loss in $CL_{max}$
- It is import to analyze high lift dependency on Reynolds Number
  - Test data was gathered at low RN, which is typical due to the cost constraints of obtaining high RN data
  - RN dependencies were non-linear near stall
- Starting grid distribution and size are key to the success of a grid convergence study
  - With 80% fewer points, the custom medium grid obtained the same result as the provided extra-fine grid
  - By starting with a finer medium grid, we were able to use smaller increments and solve two more grid levels for a relatively small cost

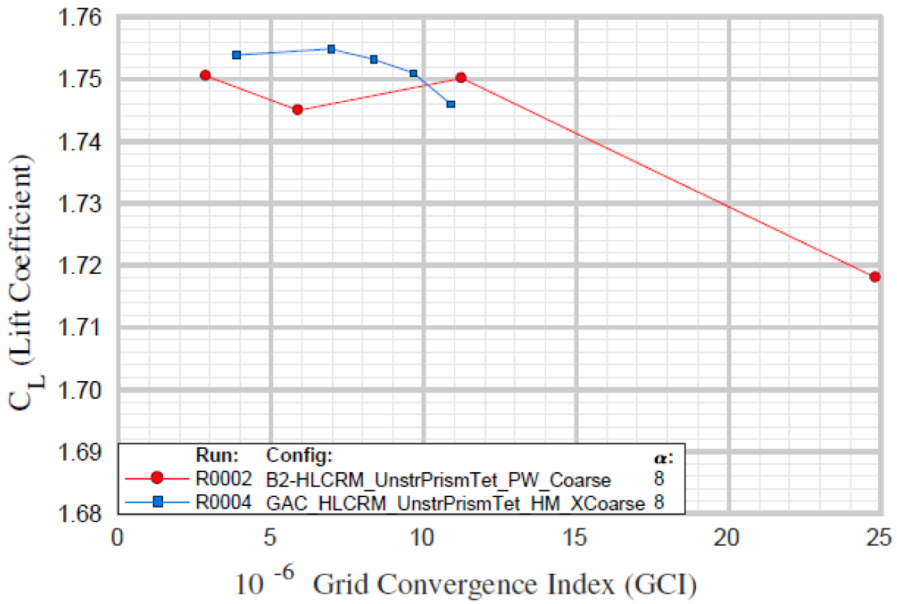
# Questions?

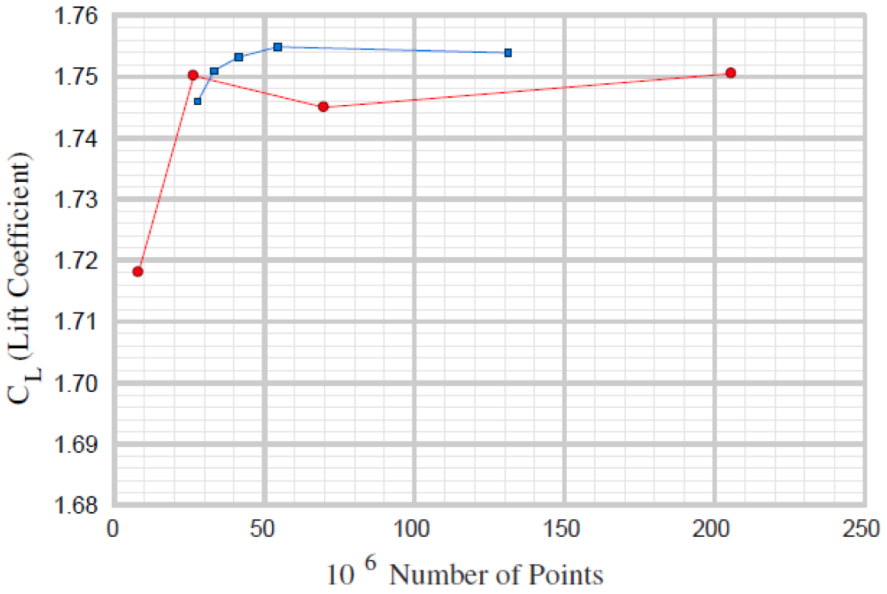
# Solution Convergence




**HLCRM Committee Fine Grid at 16°**

# Grid Convergence at 8° AOA



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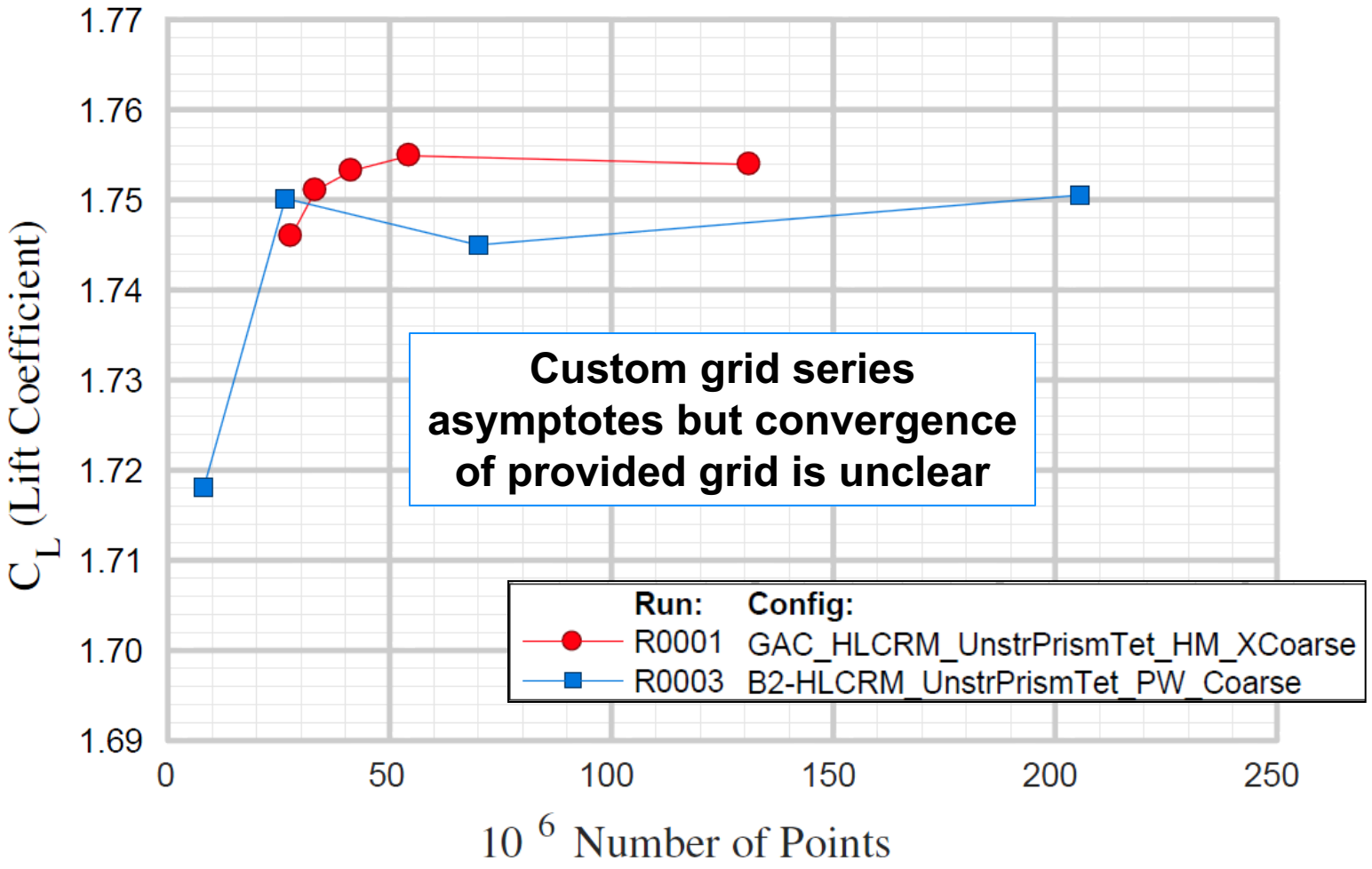
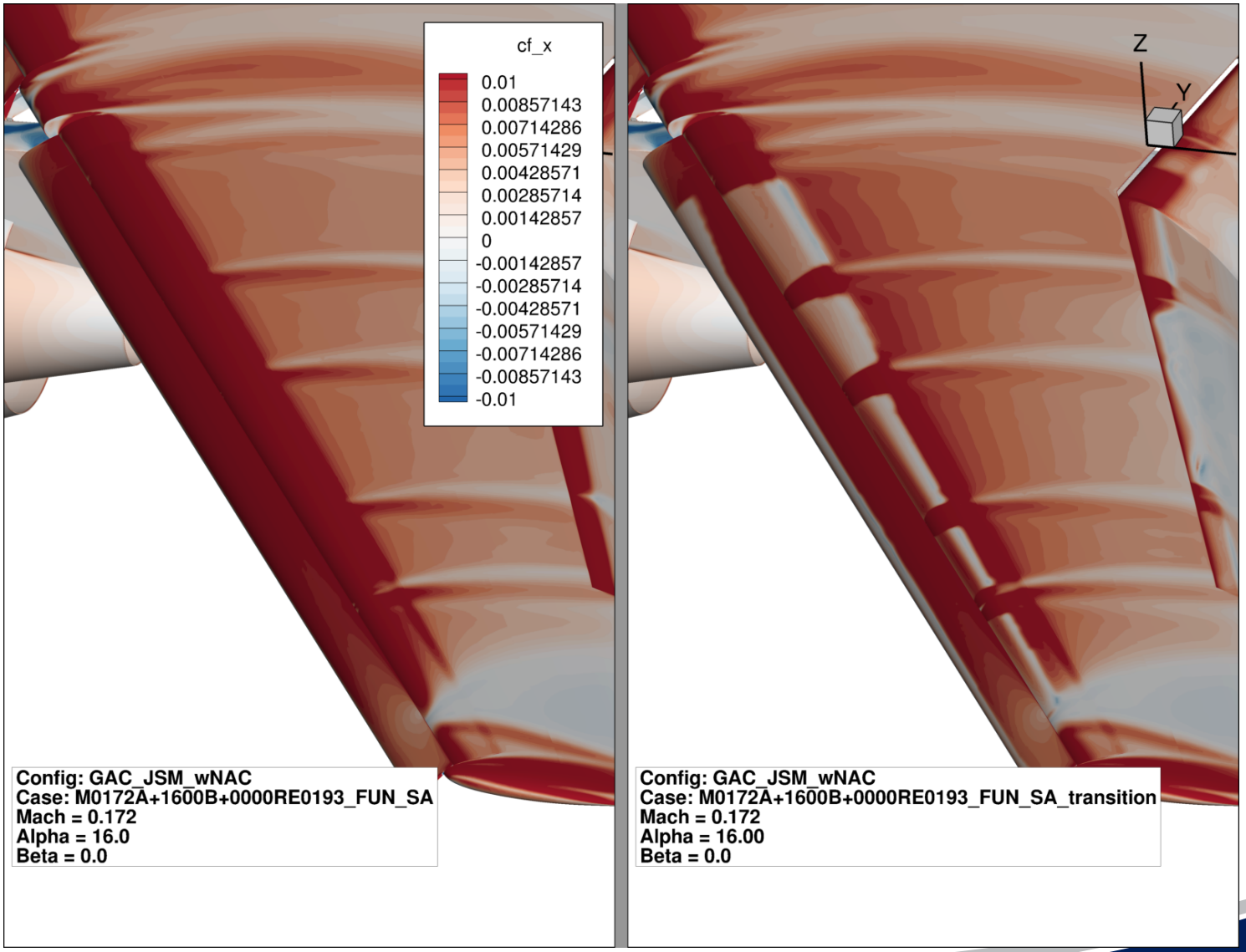
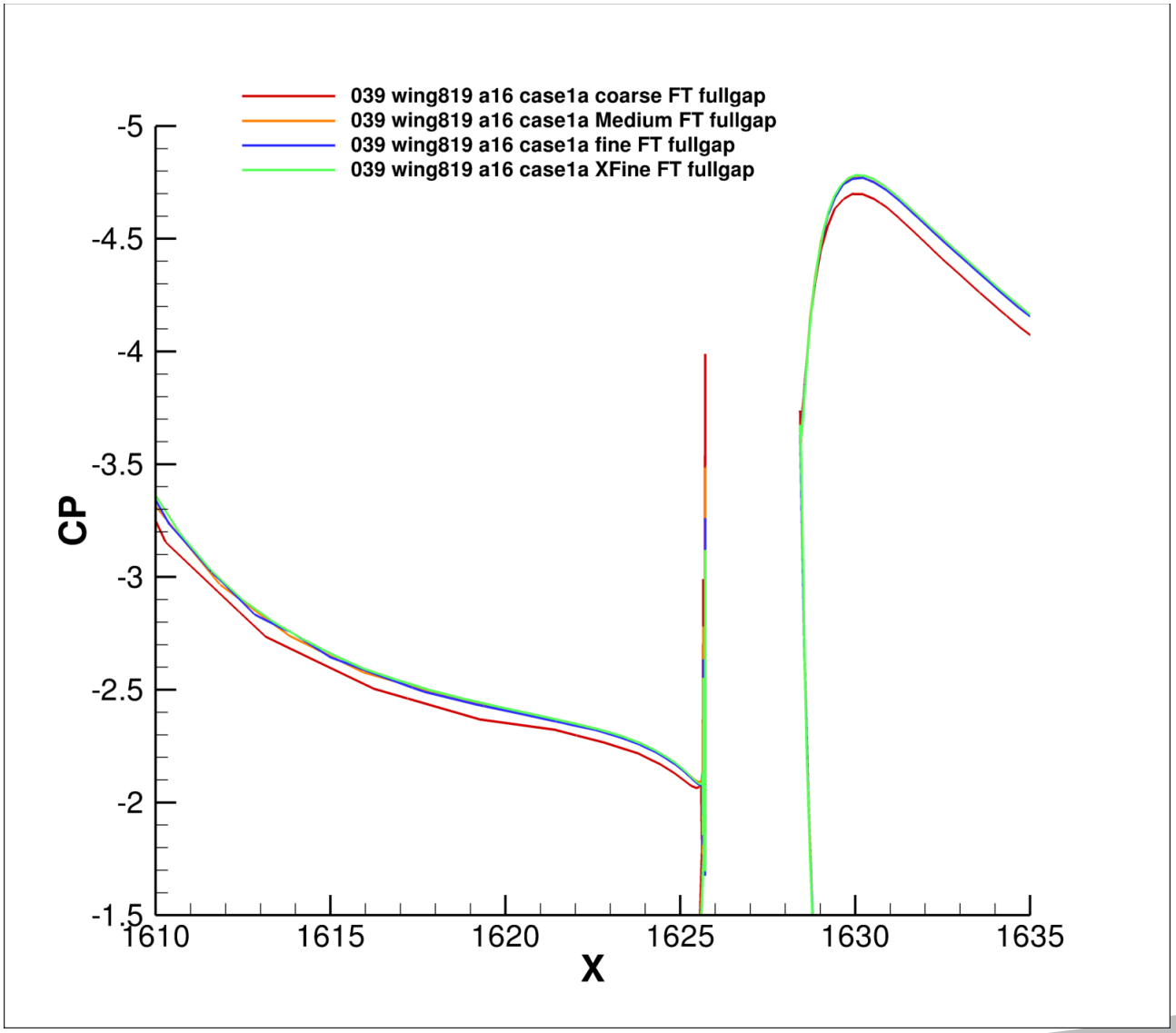
# Grid Convergence at 8˚ AOA



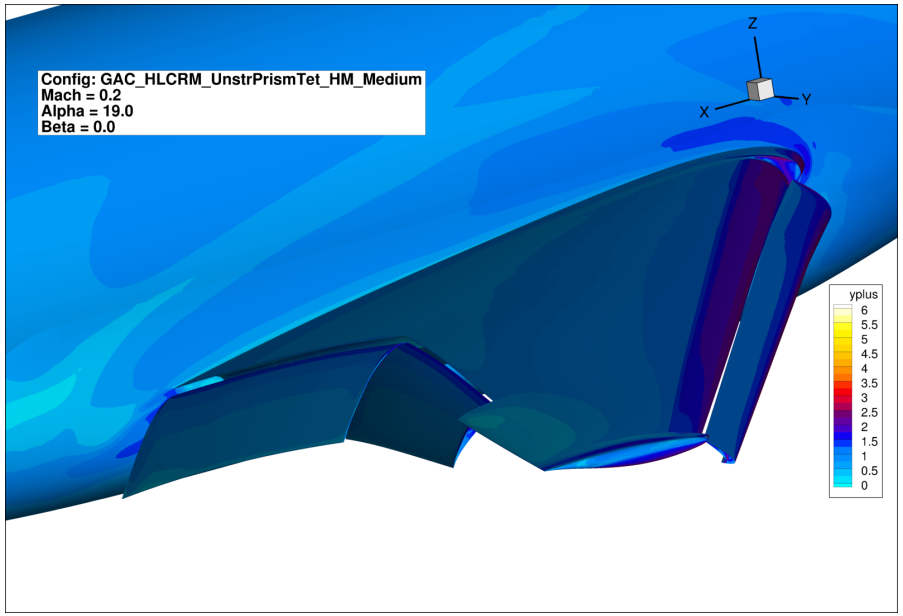
# Transition Tripping

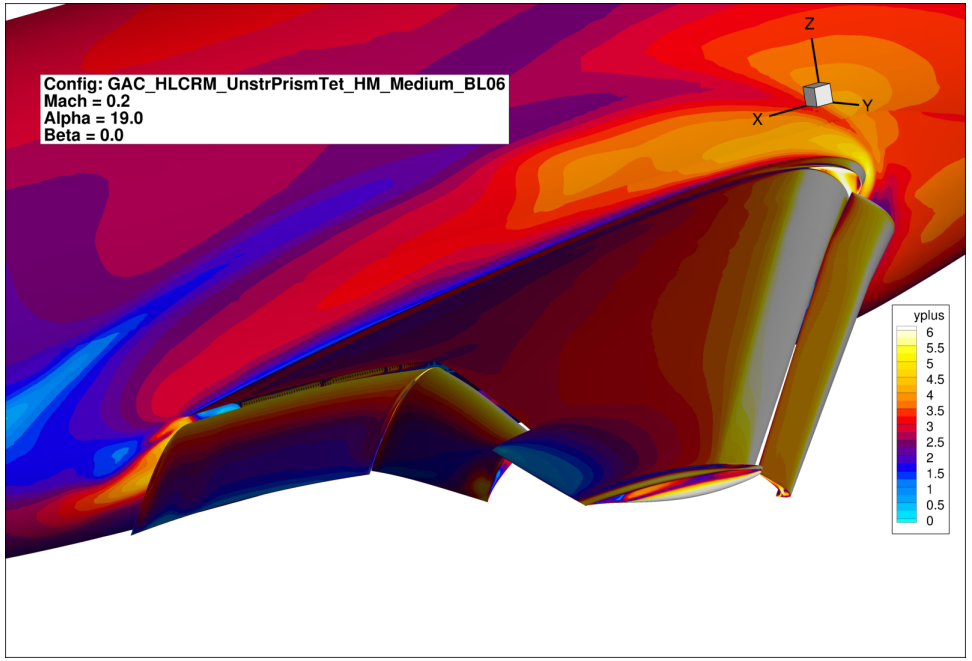


# Grid Convergence and Wing LE Pressure Peak



# Y+ at α = 19˚ for 20 million RN



# Custom JSM w/Nac vs. Corrected Test Data