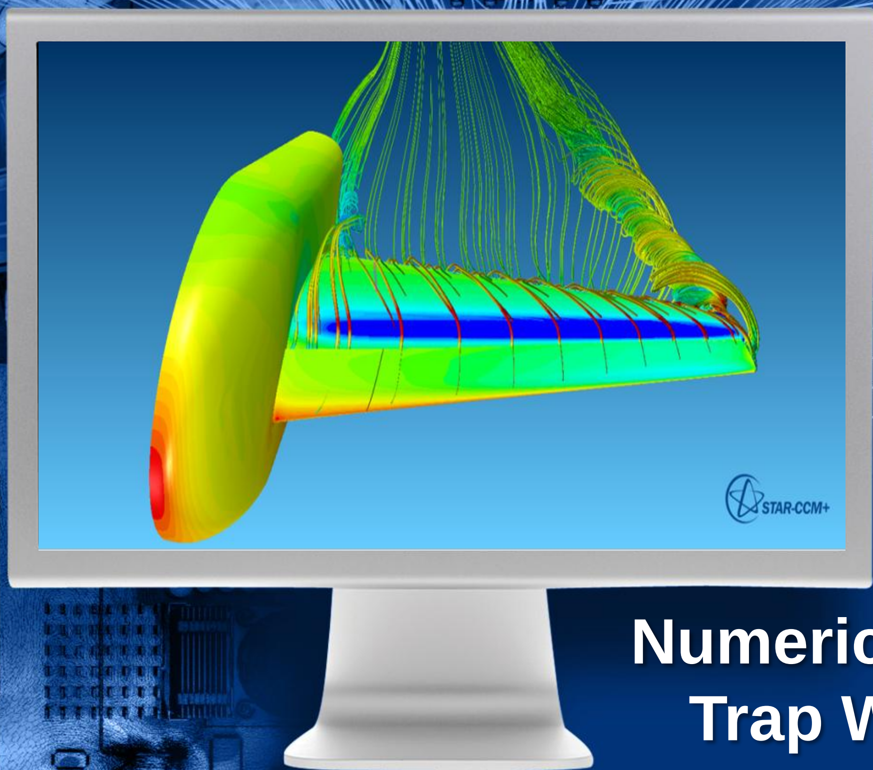


Numerical Simulation of High Lift Trap Wing Using STAR-CCM+

Prashanth S. Shankara, Deryl Snyder
CD-adapco

Outline

- Motivation
- Cases overview
- Solver & boundary conditions
- Mesh
- Results – Config 1 without brackets
- Results – Config 1 with brackets
- Conclusion

Motivation

- **Investigation of STAR-CCM+ high lift aerodynamics prediction capability**
- **Model high-lift physics in a manner well-suited for industrial design use**
  - Automated and unstructured polyhedral mesh
- **Performance of γ-Re_θ transition model**

High Lift Aerodynamics

- **Aerodynamics of 3D swept wings in high-lift configurations is very complex**
  - Separation
  - Unsteadiness
  - Confluent boundary layers
  - Transition
  - Vortical flow
- **AIAA HiLiftWS1 (2010)**
  - Assess capabilities of current-generation codes
    - Meshing
    - Numerics
    - Turbulence Modeling
    - High-performance computing

NASA 'Trap Wing' model

- **Tested in 1998-1999, 2002-2003 at NASA Langley and NASA Ames wind tunnels**
- **Re~4.6 M**
  - No turbulent trips – transition is a factor
- **Data collected**
  - Aerodynamic forces/moments
  - Pressure distributions
  - Transition location
  - Acoustics

Trap wing in NASA LaRC 14x22 WT

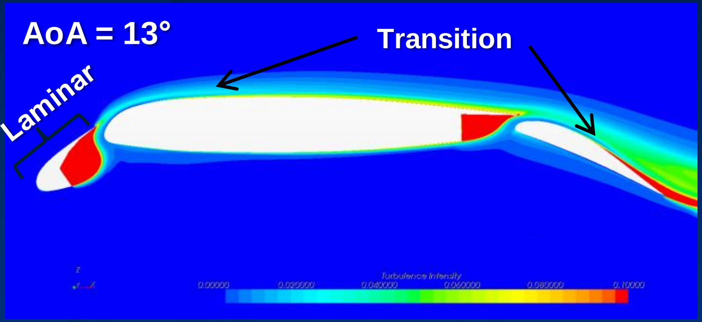
STAR-CCM+

- STAR-CCM+ v6.06.011
  - Mesh, Solve, Post-process
- Density-based coupled solver
  - Low Mach number preconditioning
  - Algebraic Multi-Grid (AMG) acceleration
- 2^{nd}-order spatial discretization
- Steady-state RANS equations
  - Implicit pseudo time-marching scheme
- SST (Menter) k-ω turbulence model
  - Integrated to the wall
- **γ-Re_θ Transition Model**
- **Arbitrary unstructured polyhedral mesh**

γ-Re_θ Transition Model

- **Without transition modeling**
  - Lift coefficients generally under-predicted
  - Late stall prediction

- **Predicts laminar-turbulent transition in the boundary layer**
  - Correlation-based model formulated for unstructured CFD codes
    - Uses locally computed vorticity-based Re
  - In conjunction with SST k-ω turbulence model
  - Models transport of Momentum Thickness Re (Re_θ) and Intermittency (γ)
  - Turbulence Intensity and Intermittency as transition identification parameters

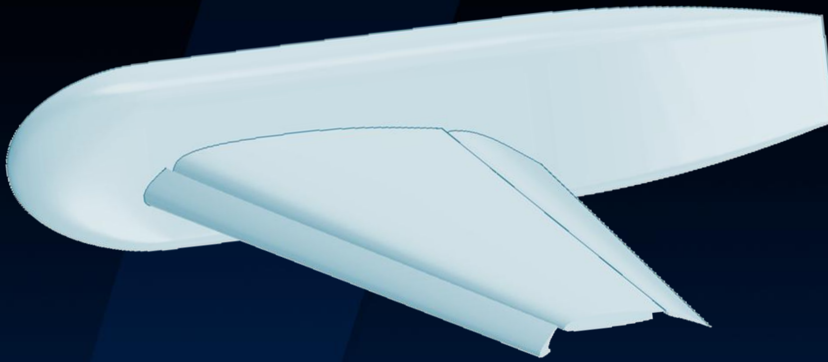


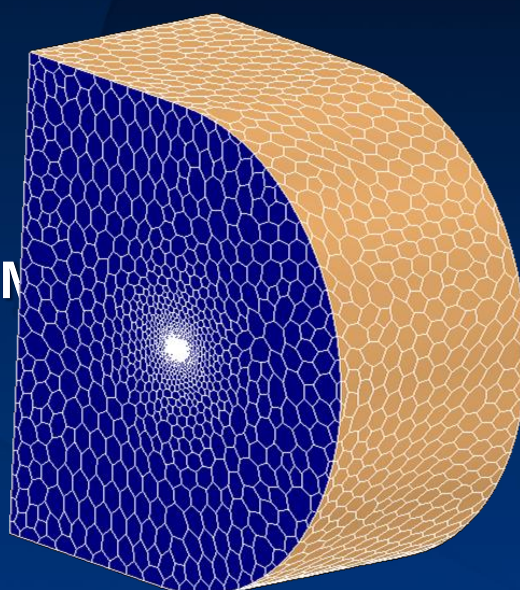
Cases

- **Case 1 – Configuration 1, No brackets**
  - Slats at 30° and flap at 25°
  - Three mesh sizes (coarse, medium, fine)
  - Angles of attack varying from 6° to 37°
- Case 2 – Configuration 1 with brackets
  - α – 6°, 13°, 21°, 23°, 25°, 27°, 28°
  - Medium mesh (No grid convergence study)

Boundary conditions

- **No-slip wall conditions**
  - No transition location specified
- **Symmetry plane**
- **Freestream**
  - Mach 0.2
  - T = 520R
  - P = 1 atm
  - Re = 4.3M based on MAC
  - α = 6, 13, 21, 28, 32, 34, 35, 36, 37 deg
  - Turbulence intensity = 7.5e-4 (WT data)
- **Farfield boundaries created in STAR-CCM**
  - Extends 100MAC in all directions





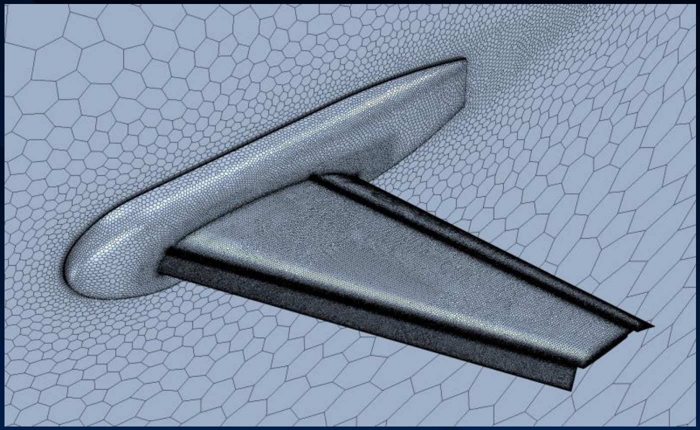
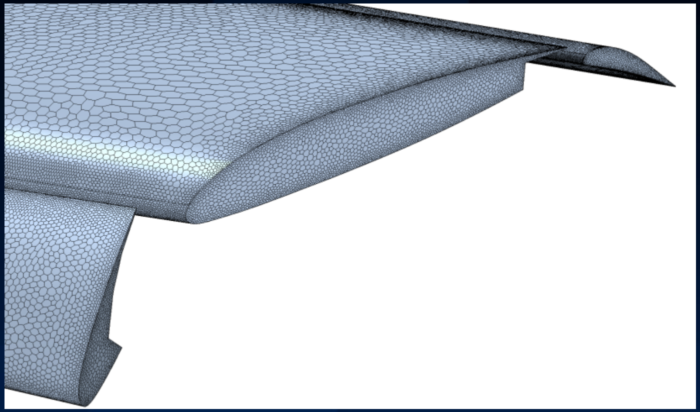
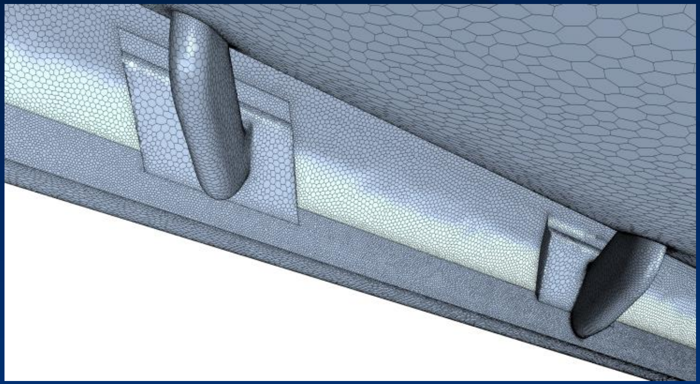
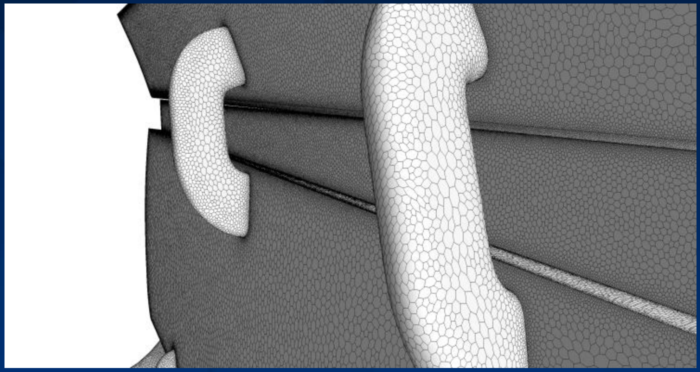
Computational Mesh Overview

- **Polyhedral unstructured mesh**
  - Three different mesh sizes for grid refinement study
  - Wide range of angles of attack on a single mesh
  - Arbitrary geometry shapes used for focused refinement
- **25 prism Layers**
  - First cell y+ < 1.0

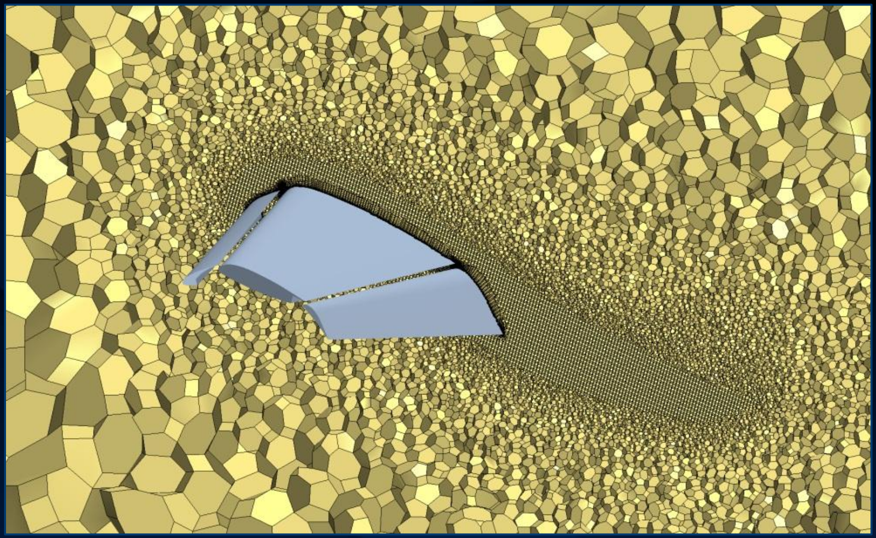
Parameter	Coarse	Medium	Fine	Med. (brackets)
No. of cells	10M	22M	34M	20M
No. of surface faces	46M	112M	184M	
Target prism layer height	$0.032C_{ref}$	$0.032C_{ref}$	$0.032C_{ref}$	$0.032C_{ref}$
Cells across trailing edge	6	10	12	10
Near-wall cell height (m)	5e-6	3.3e-6	1e-6	3.3e-6

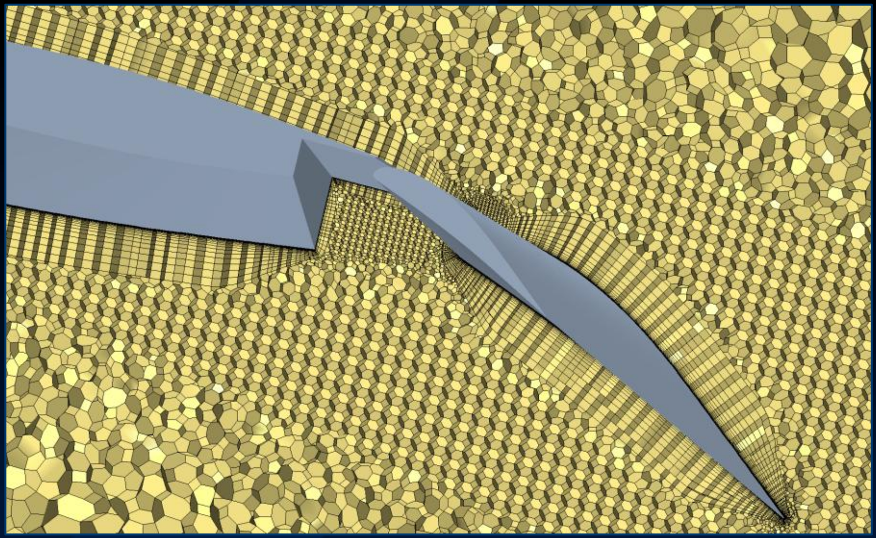
Mesh – Surface

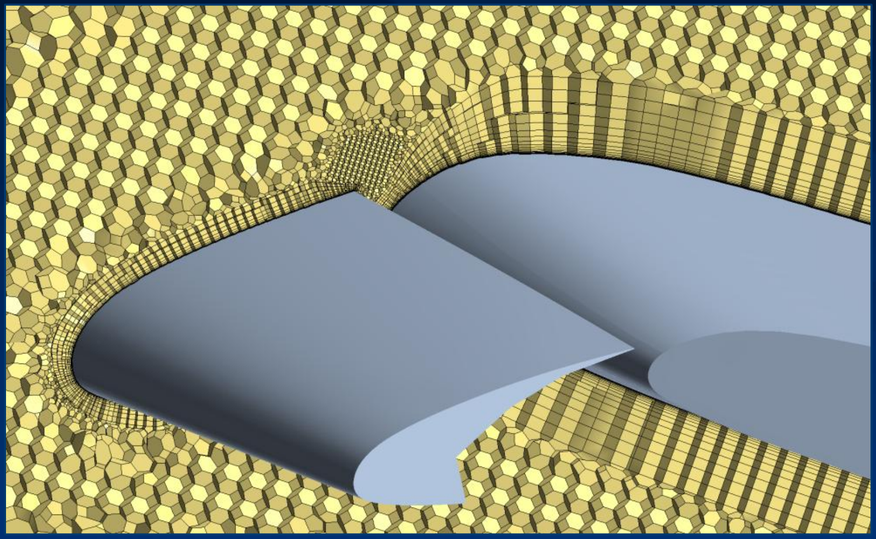
- Surface faces refined on curvature, sharp edges, near tip

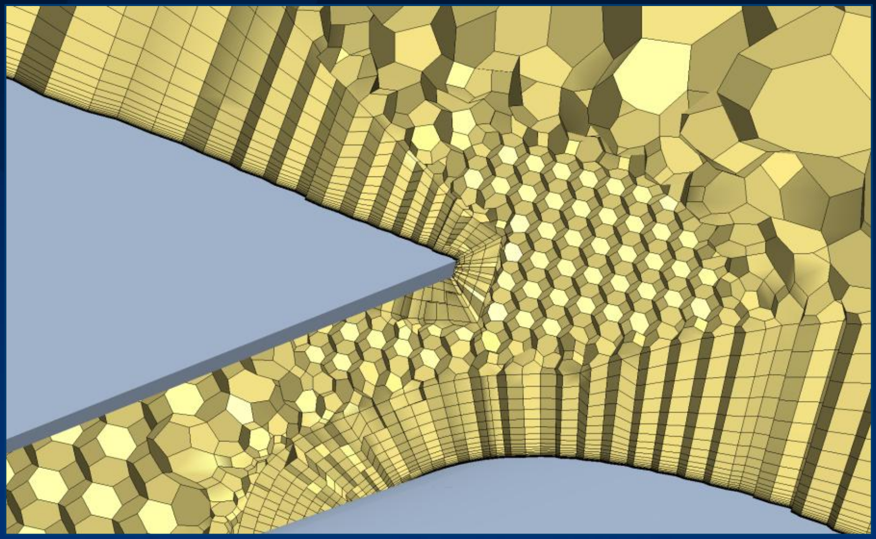





Mesh – Volume





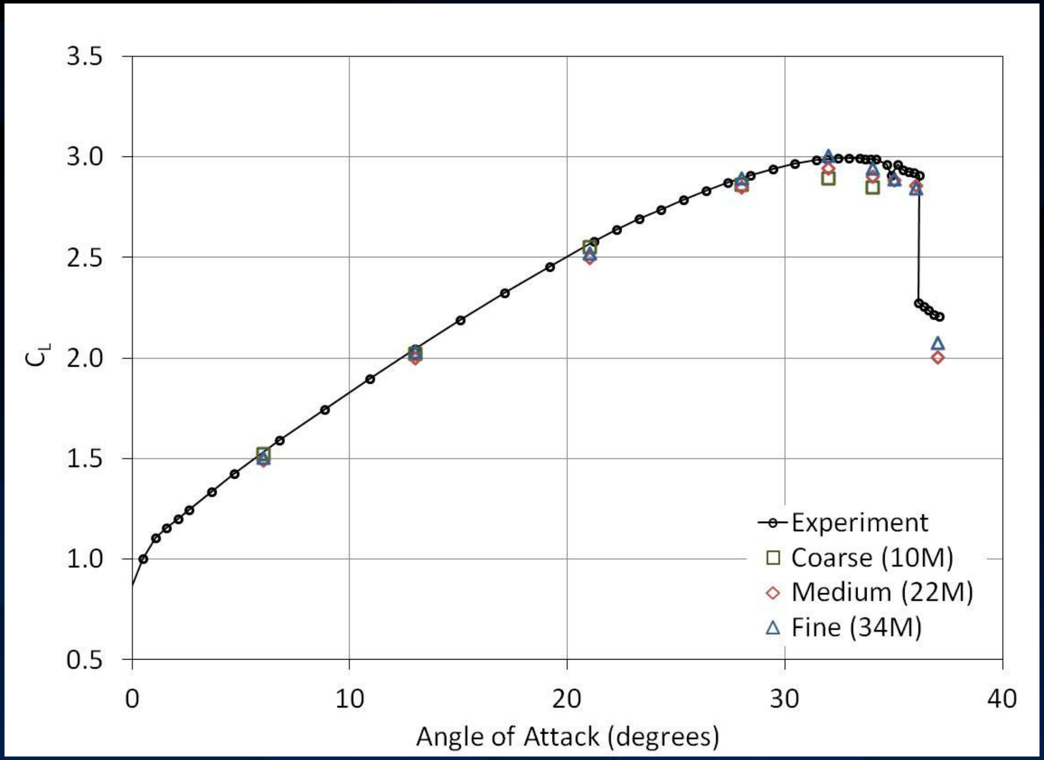




Solution Strategy

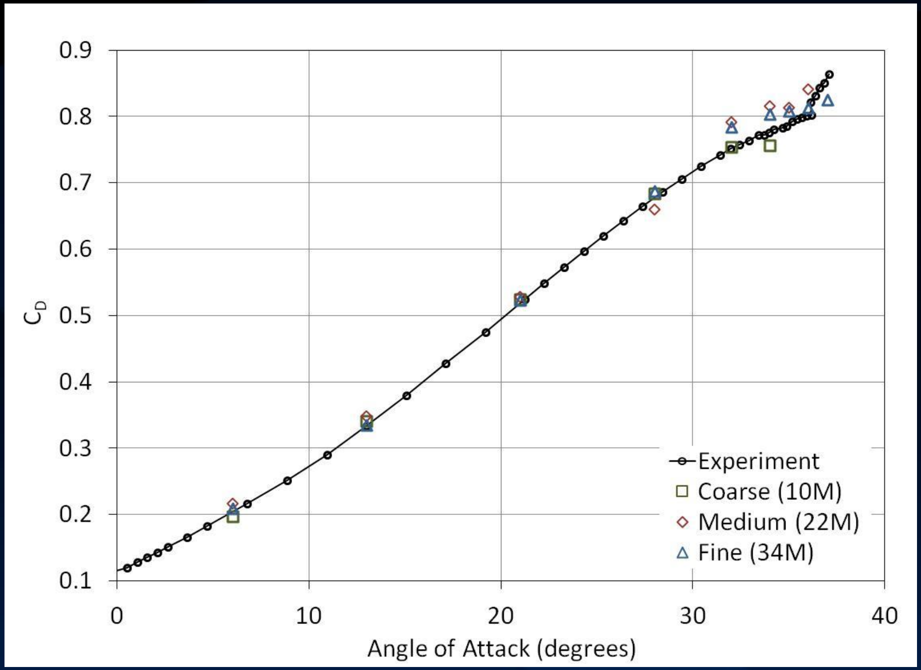
- Solution strategy
  - For α = 6° to 28°
    - Initialized via grid-sequencing technique
    - Obtain a stable solution without transition model
    - Introduce transition model
  - For α = 32° & 34°
    - Initialized from previous angle of attack
    - Obtain a stable solution without transition model
    - Introduce transition model
  - For α = 35°, 36° & 37°
    - Initialized from previous angle of attack

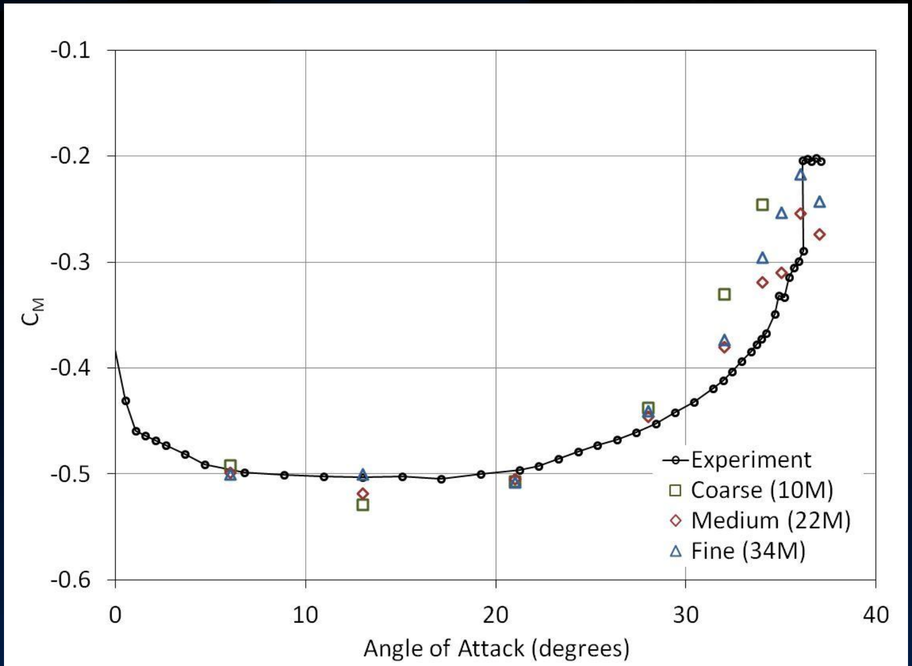
Lift Coefficient



- Both medium and fine mesh predicts post-stall region well
- Results improve with mesh refinement
- C_{LMax} deviation
  - Coarse mesh: 3.3% (low)
  - Medium mesh:1.6% (low)
  - Fine mesh: 0.4% (high)

Drag & Moment Coefficient

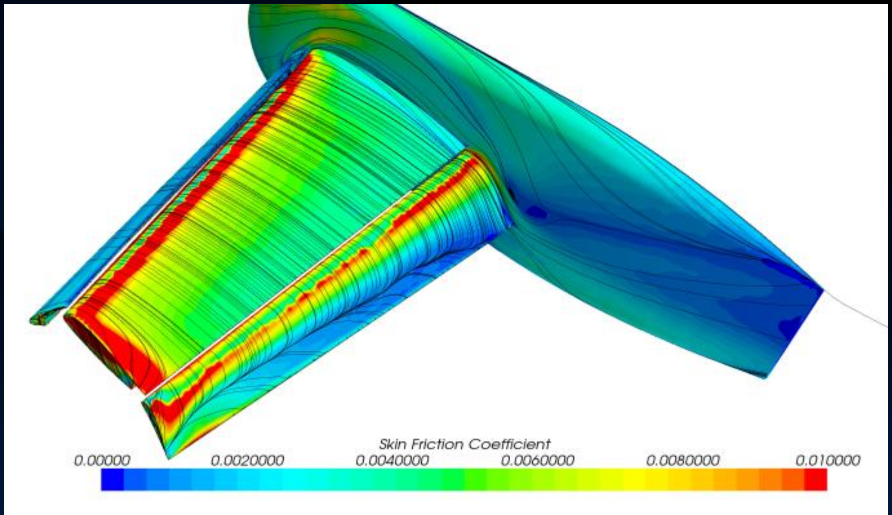




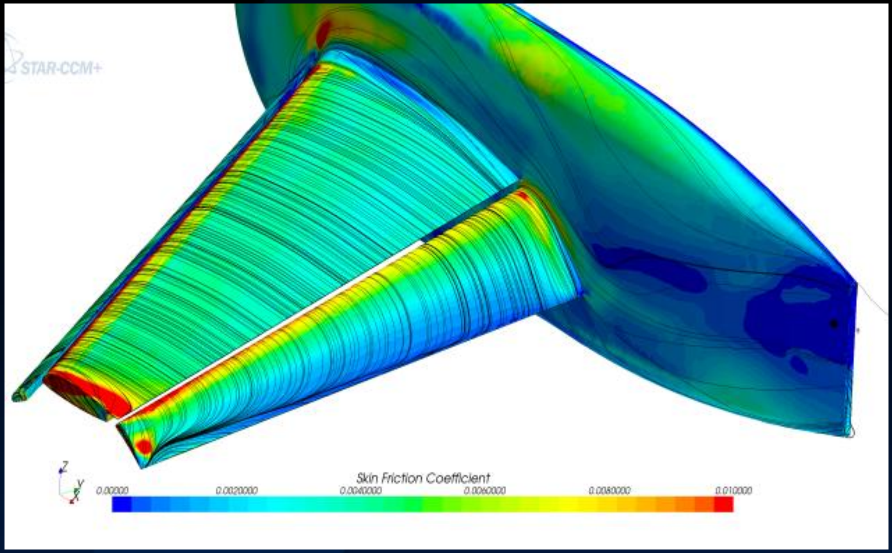
- Drag
  - Excellent agreement for fine grid (within experimental error)
  - Medium grid predicts slightly higher C_D after α = 28°
  - Coarse grid also performs well up to α = 32°
- Moment
  - C_M showed the most deviation from experiments – harder to predict
  - Performance improves with mesh refinement

Effect of Transition Model

α = 13°

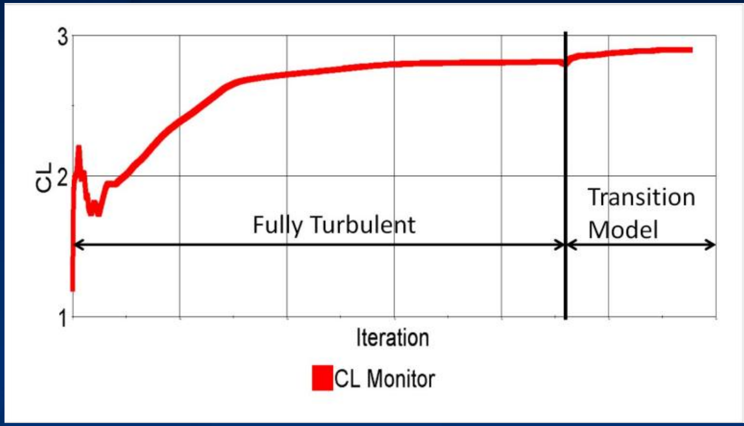


Transition Model

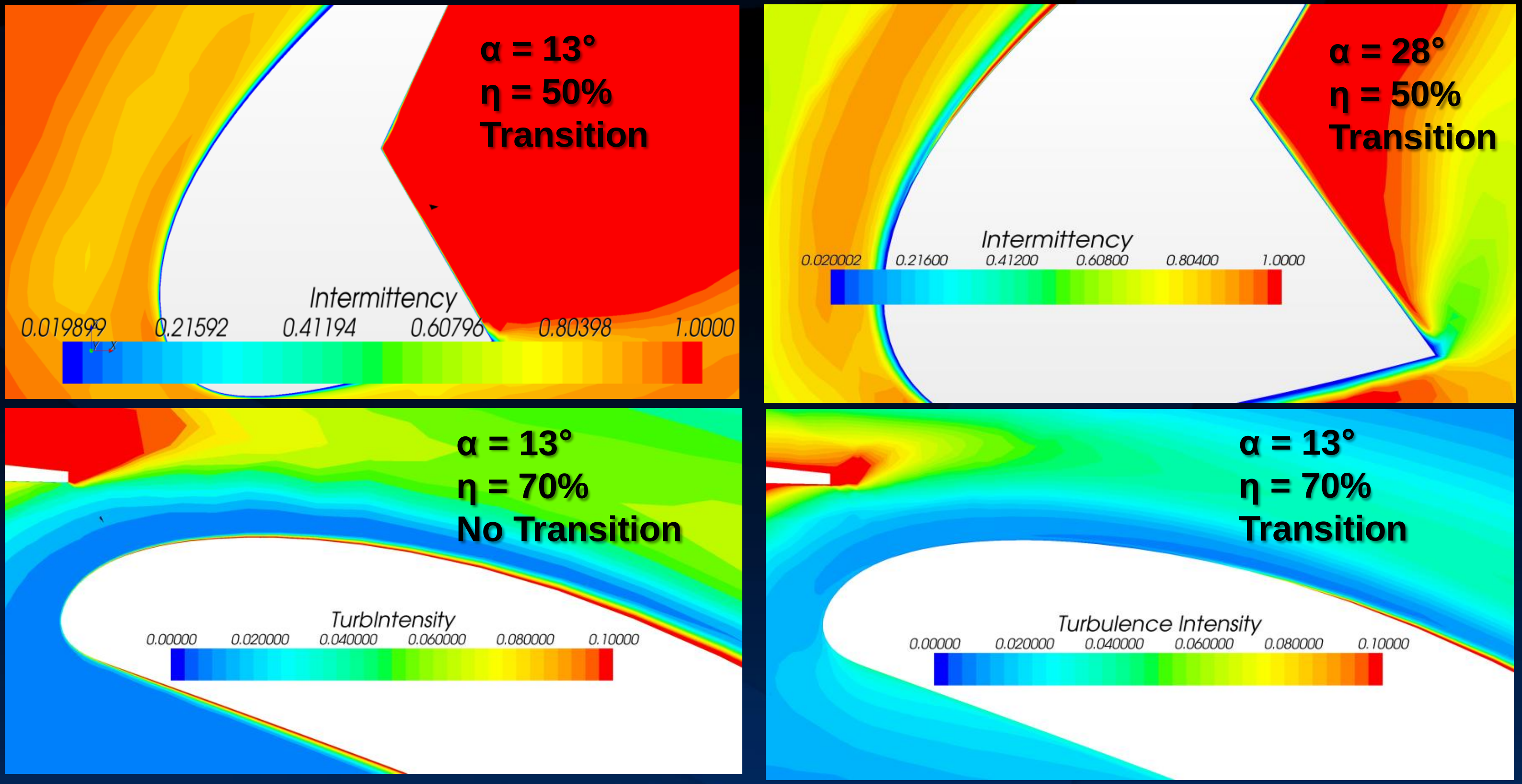


No Transition Model

- Transition model increases lift coefficient
- Transition model predicts larger flap separation
- Flap side-of-body (SOB) separation bubble only predicted with transition model
  - Insufficient mesh resolution in this area for fully turbulent case
- Skin friction coefficient on surface shows transition location

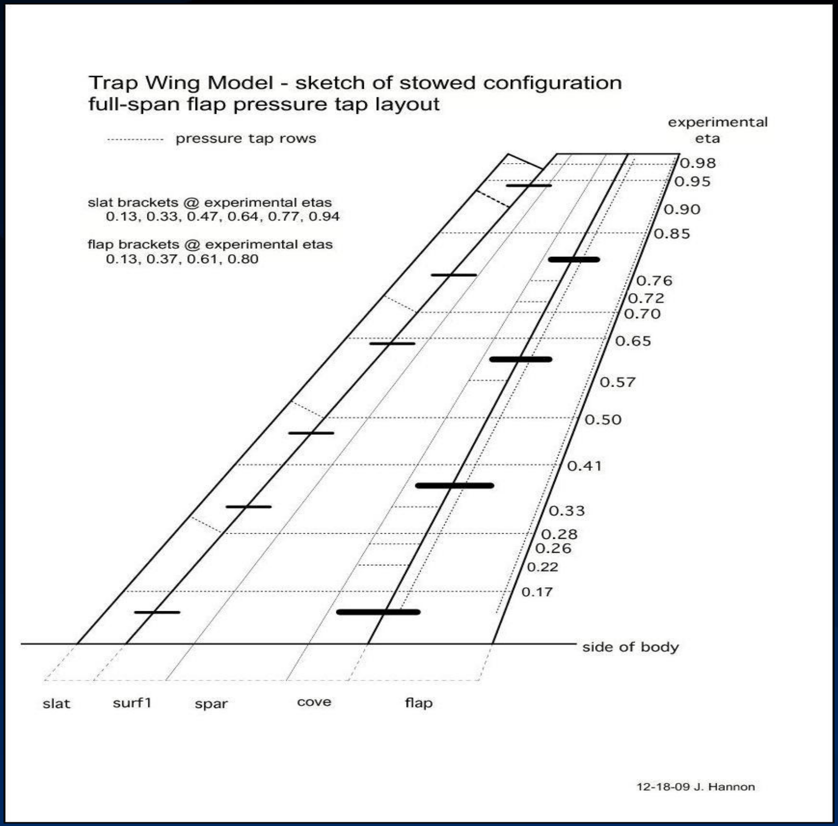


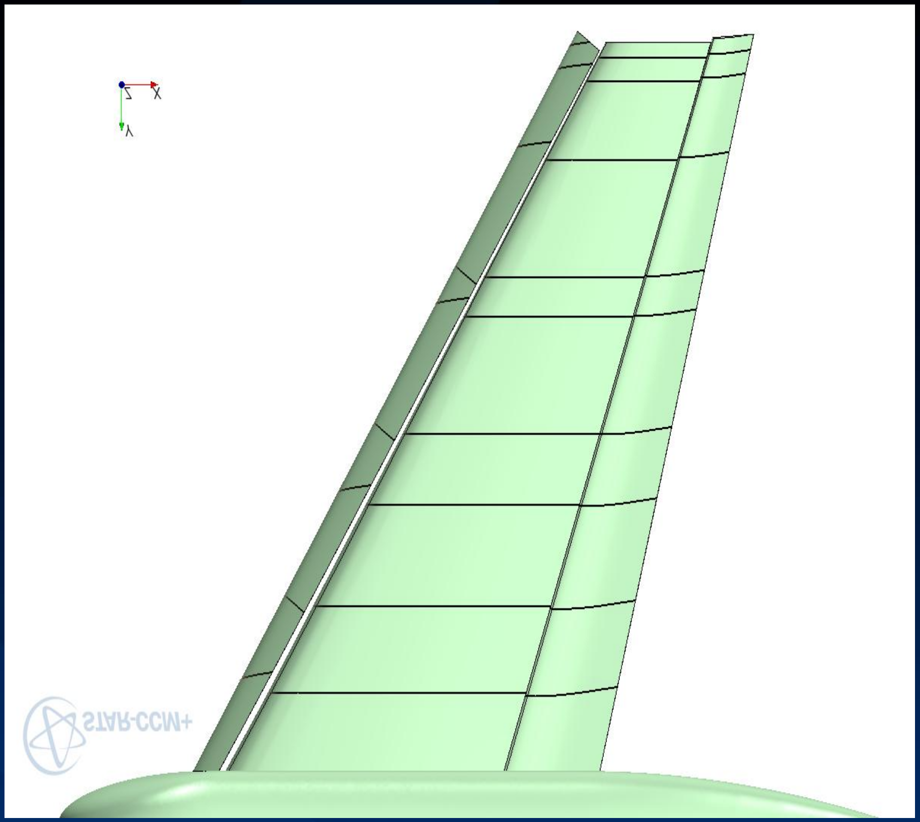
Effect of Transition Model



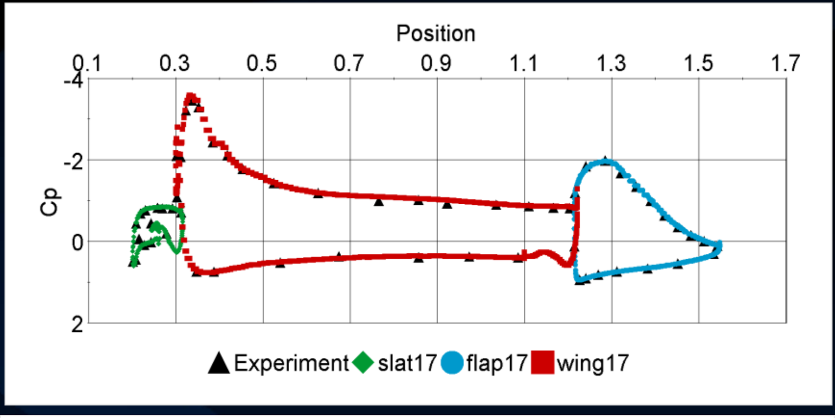
- Intermittency (γ) is used to identify flow transition
  - A value of 0 is laminar flow and 1 is turbulent flow
- At 13°, flow over slat is laminar; at 28°, clear laminar-turbulent transition is seen from the γ-Re_θ model
- Transition model captures transition on flap, yielding more accurate prediction of flap separation

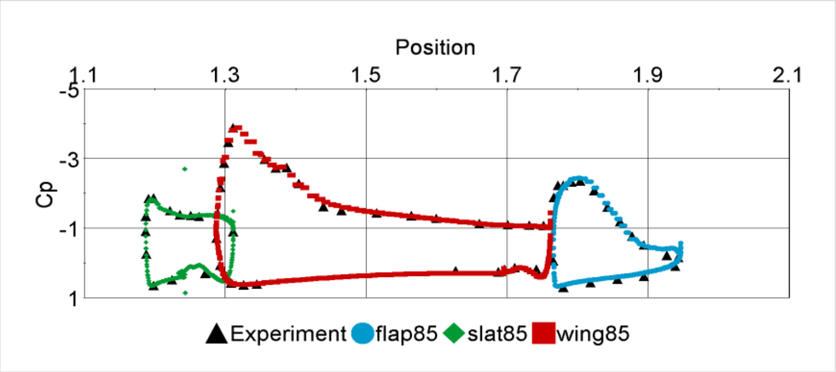
Surface Pressure Coefficients comparison

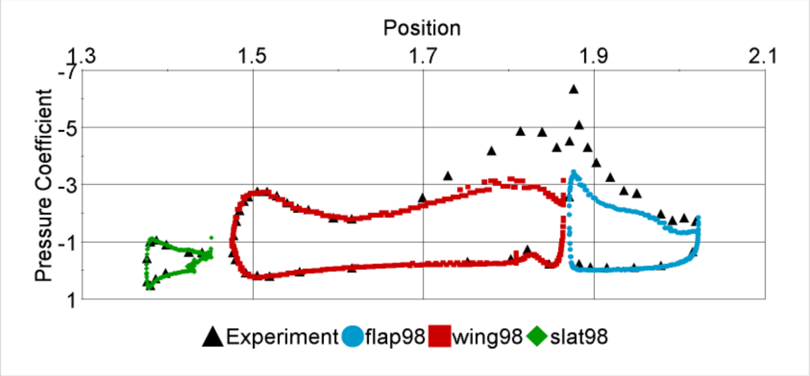




Surface Pressure Coefficients – Medium Mesh $\alpha = 13°$

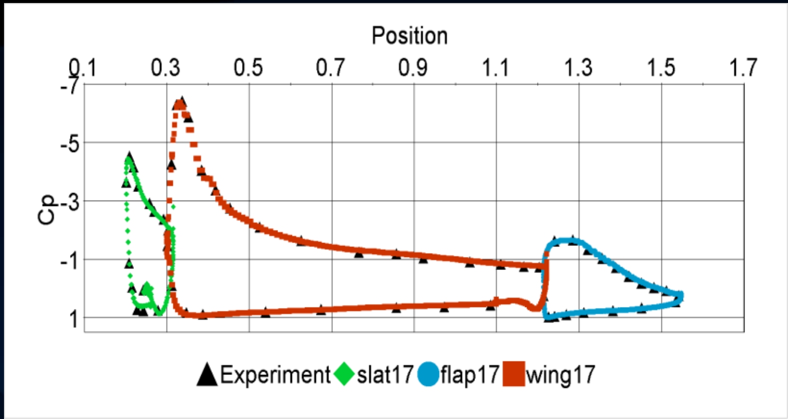


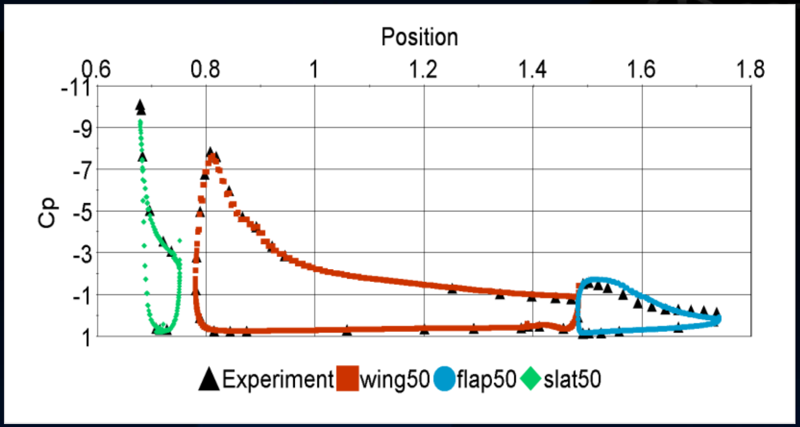


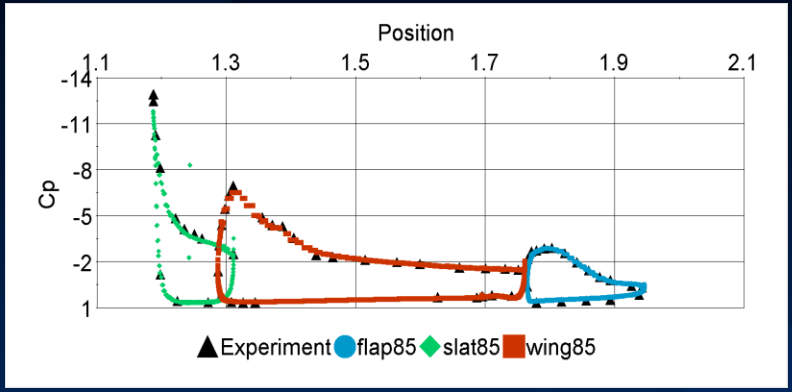


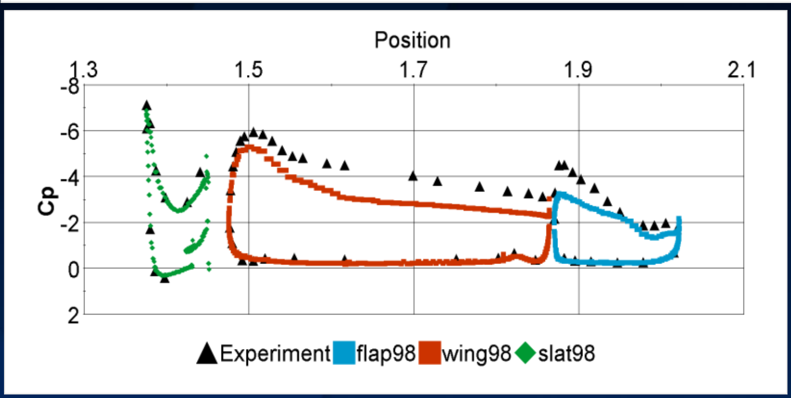
- At η = 17, 50, and 85%
  - Good agreement on slat, main wing, and flap
- At η = 98%, disparity is significant on main wing and flap
  - Challenging to predict flap separation and tip vortex effects

Surface Pressure Coefficients – Medium Mesh
$\alpha = 28°$



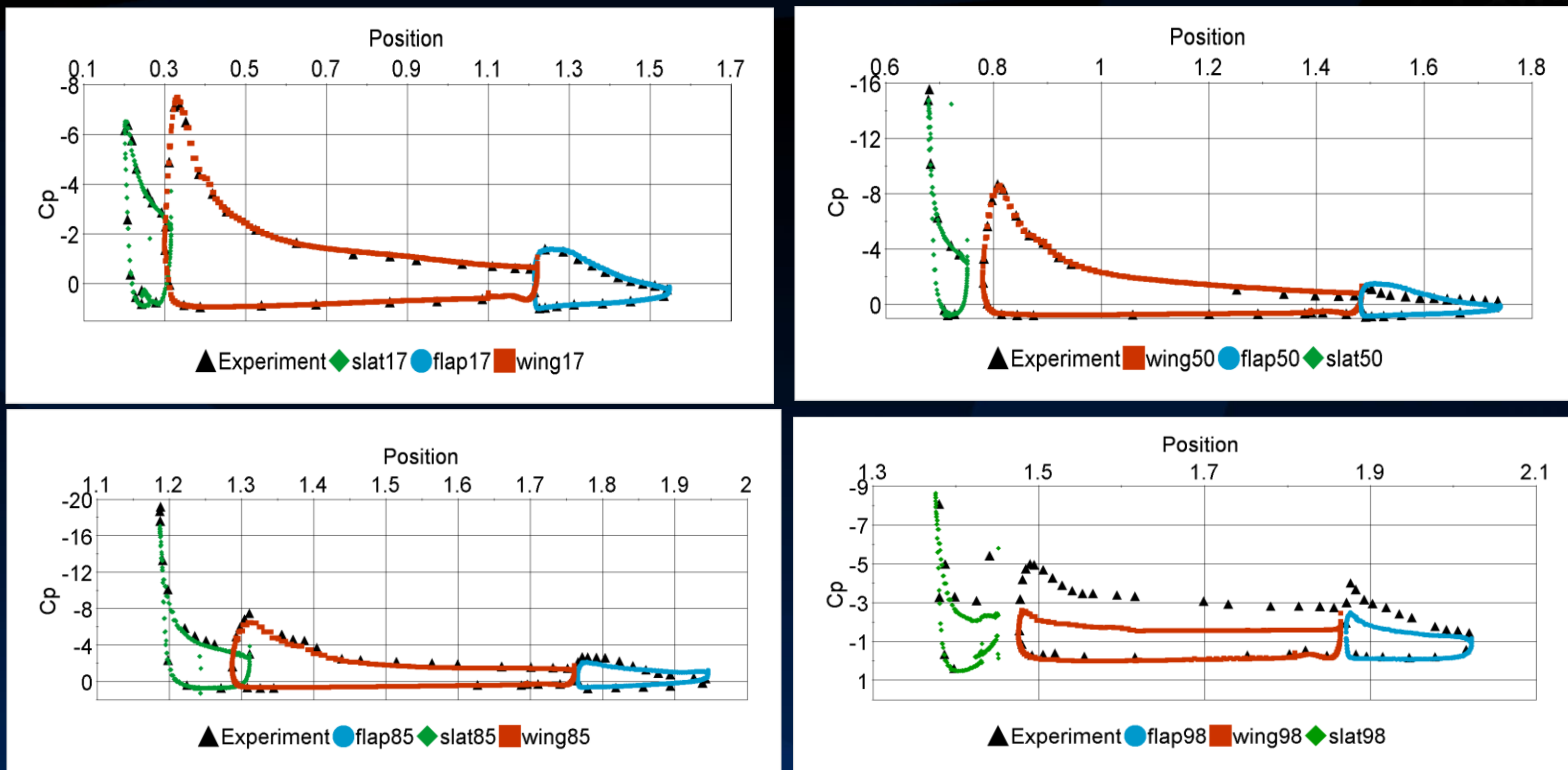






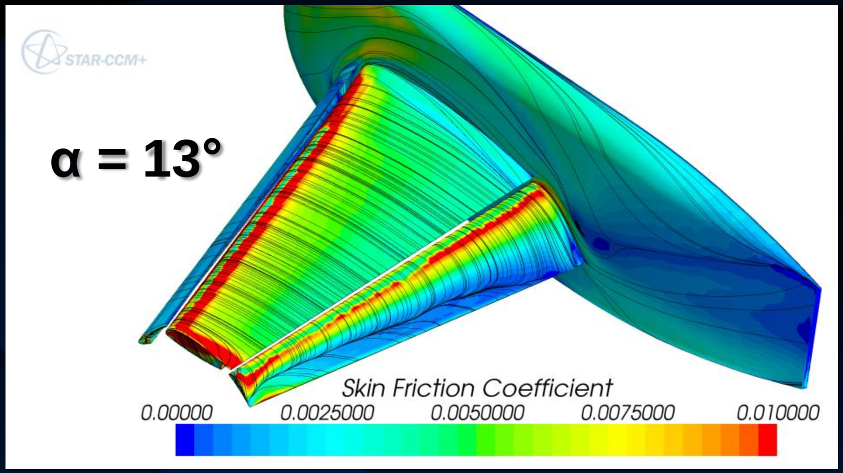
- At η = 17, 50, and 85%
  - Good agreement on slat, main wing, and flap
  - Some discrepancy on flap suction surface noted at η = 50%
- At η = 98%, disparity is significant on main wing and flap
  - Challenging to predict flap separation and tip vortex effects

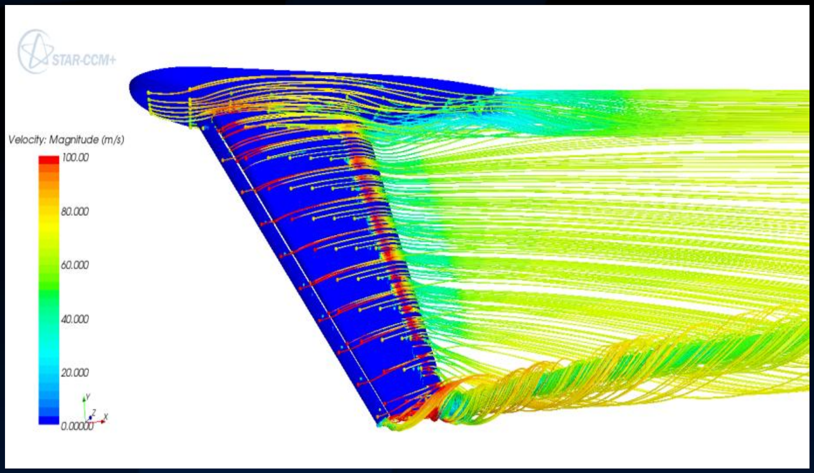
Surface Pressure Coefficients – Medium Mesh
α = 34°



- Even at post CLmax angle of 34°, surface pressure predictions are quite good until through 85% section for slat and main element
- Significant over-prediction of flow separation near wing-tip at 98% section
- Concentrated mesh refinement based on tip vortex structure will likely help here

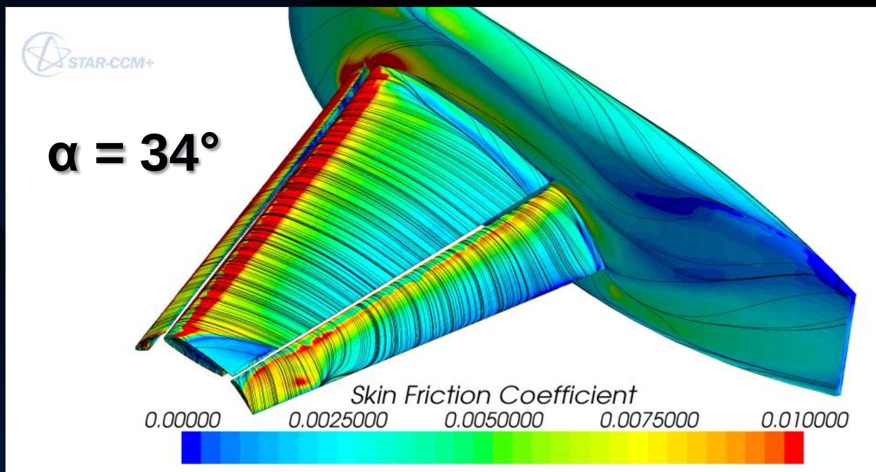
Surface Streamlines Comparison

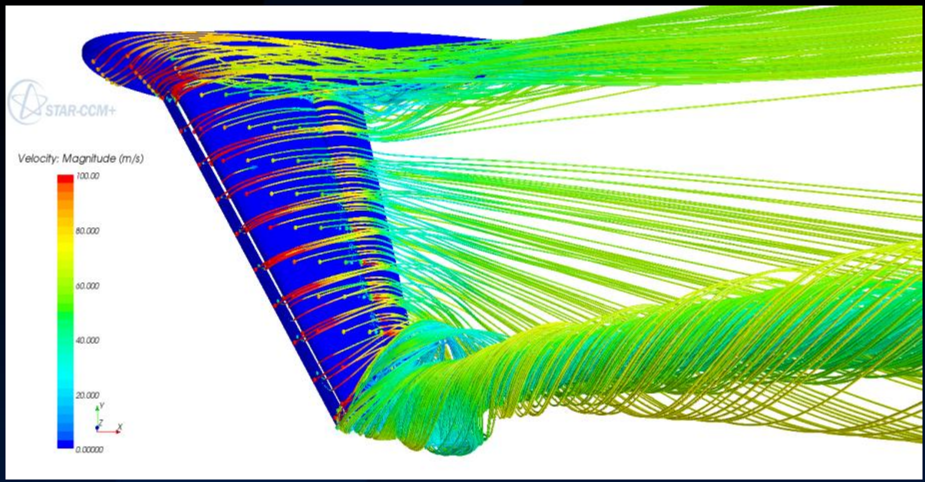




- At 13°, flap separation aft of mid-way nearly along entire span
- Flap Side-of-body (SOB) separation bubble visible
- Effective tip vortex is seen in the skin friction contours

Surface Streamlines Comparison

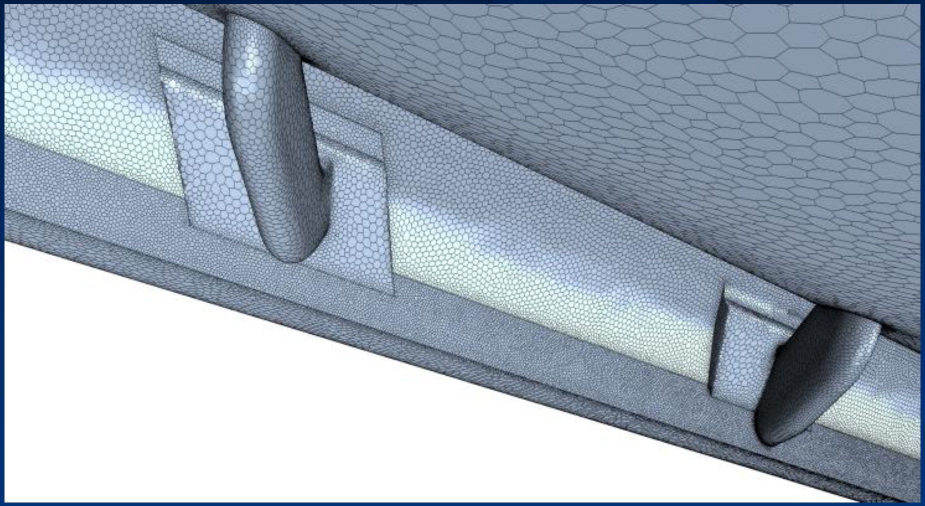


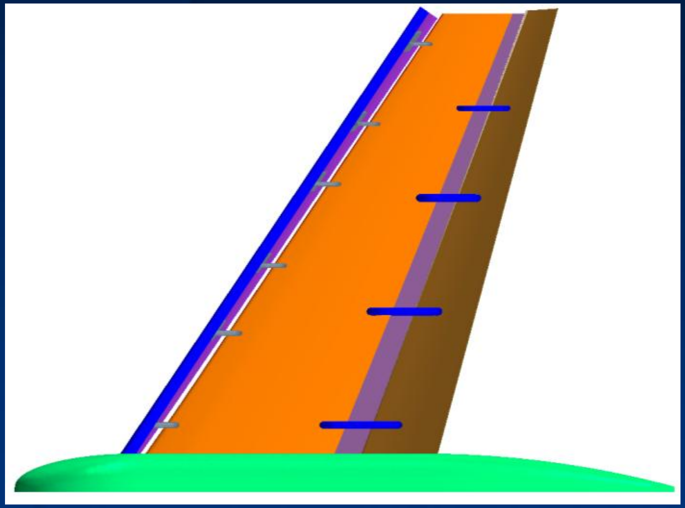


- Flap separation delayed to TE
- Large separation near the wing tip on the main element
- Flap SOB separation disappears

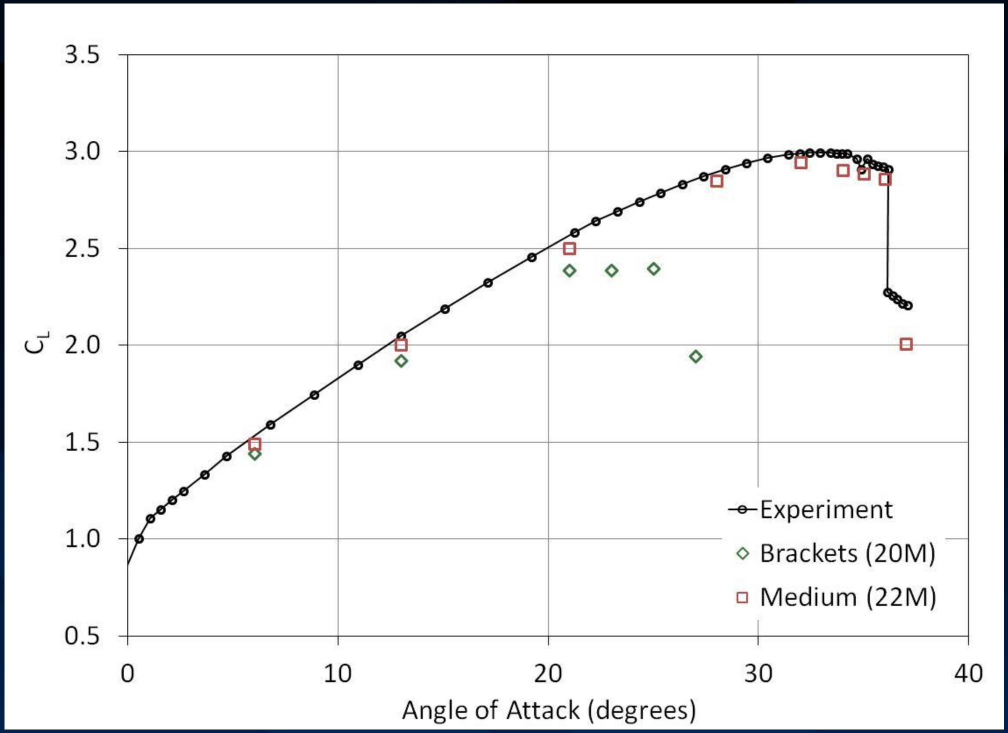
Brackets Analysis

- Config 1 with brackets at α = 6°, 13°, 21°, 23°, 25°, 27°, 28°
  - Effect of flap and support brackets studied
  - 6 slat brackets and 4 flap brackets
  - Local flow separation
- 22M medium mesh used as baseline mesh
- No grid convergence study
- Initial study to identify flow features and areas for focused refinement
- All cases after 21° restarted from previous solution



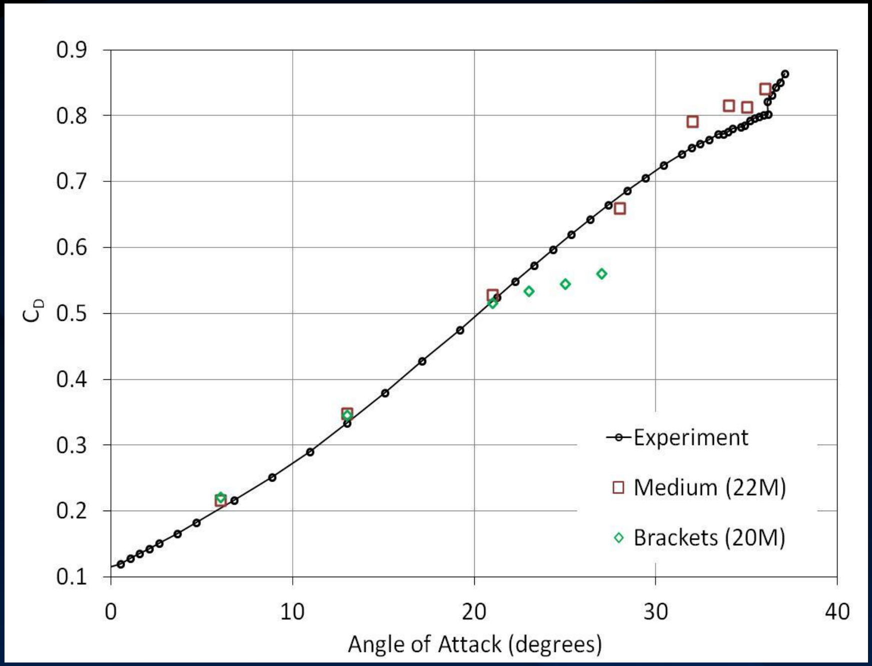


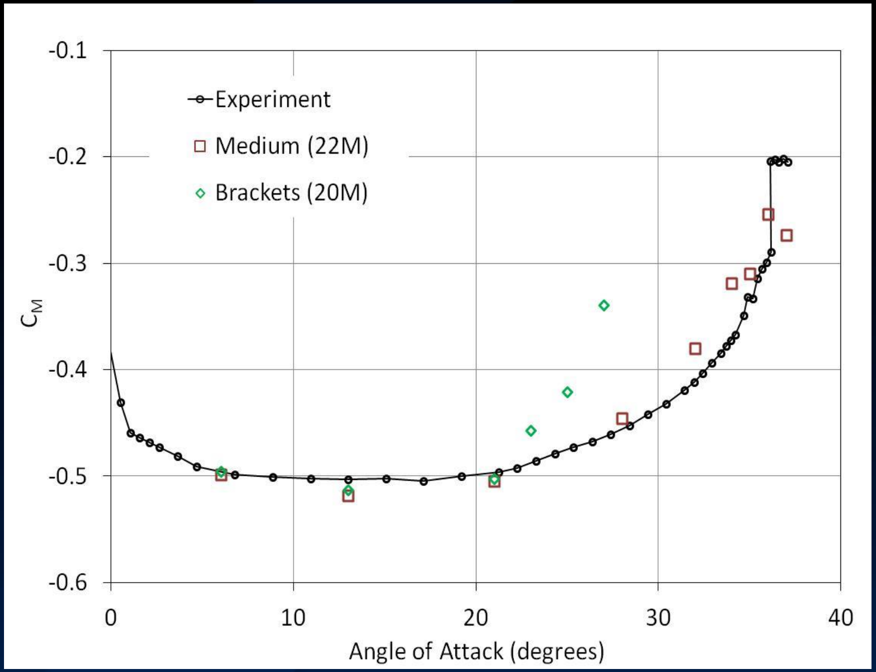
Brackets Analysis – Lift Coefficient



- CL is predicted lower compared to case without brackets at all angles of attack
  - Similar results from other participants
- Early stall predicted after 21° resulting in loss of lift

Brackets Analysis – Drag & Moment Coefficient





- **Brackets have little effect on drag and pitching moment**
  - Until premature stall

Brackets Analysis – Flow Visualization (Top view)

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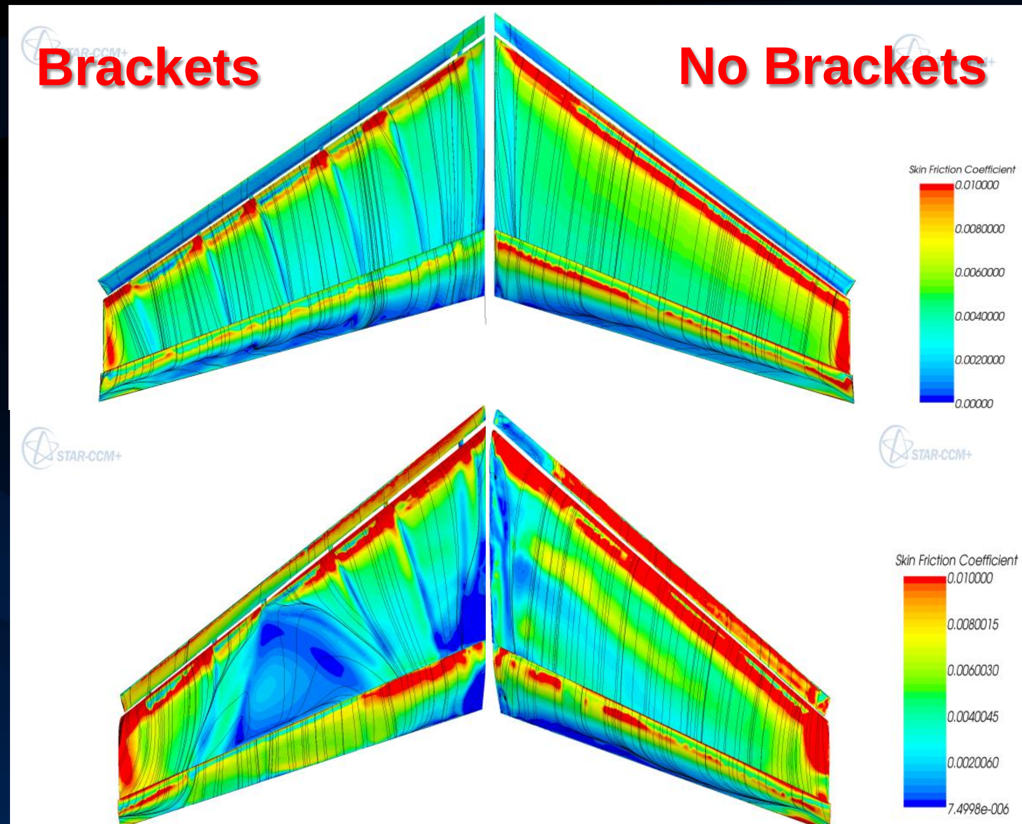
α = 13°

α = 28°



- $\alpha = 13$
  - Bracket wake affects transition on main element suction side
  - Flap separation is delayed in local regions with brackets
- $\alpha = 28$
  - Massive flow separation occurs along bracket wake
  - Early separation leading to stall – focused mesh refinement behind and around the brackets needed

Conclusion

- **General polyhedral mesh with predictive transition model yields good results**
  - Lift, drag & pitching moment
- **Feasible methodology for production environment**
  - Mesh set-up time of 4 hrs (CAD to volume mesh)
- **Brackets predict early stall**
  - Further investigation needed
  - Likely requires additional focused mesh refinement