A Reynolds-Averaged Navier-Stokes Perspective for the High Lift Common Research Model Using the LAVA Framework

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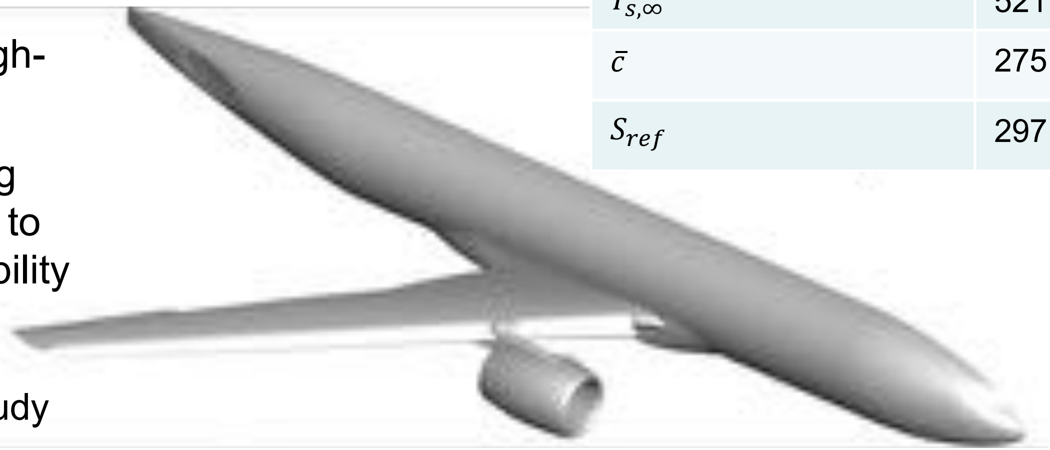
Outline

- Workshop Task Overview
- Computational Methodology
  - Numerical methods and turbulence modeling
  - Structured overset mesh generation
- Results
  - Grid convergence study
  - Flap deflection study
  - c_{Lmax} investigation
    - Turbulence modeling
    - Alternative solution methods
    - Wind tunnel modeling
- Summary

Workshop Tasks and Goals

- Use Reynolds-Averaged Navier-Stokes (RANS) methods to characterize aerodynamic performance for the High Lift- Common Research Model (CRM-HL)
- Utilize workshop-provided test cases to determine RANS capability in accurately predicting complex high-lift configuration flows
- Determine best-practice modeling techniques using various studies to maximize RANS predictive capability
  - Grid sensitivity study
  - Turbulence model sensitivity study
  - Wind tunnel modeling study

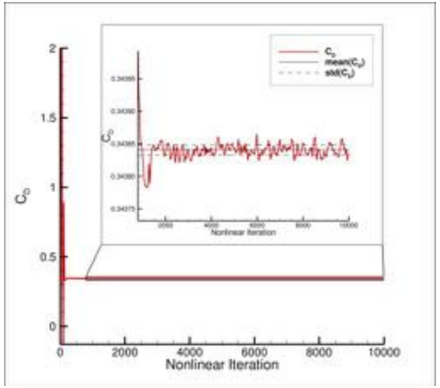
Quantity	Value
$Mach$	0.2
Re_{MAC}	5.49 M
$T_{s,\infty}$	521 °R
$\bar{c}$	275.8 in
S_{ref}	297,360 in^2

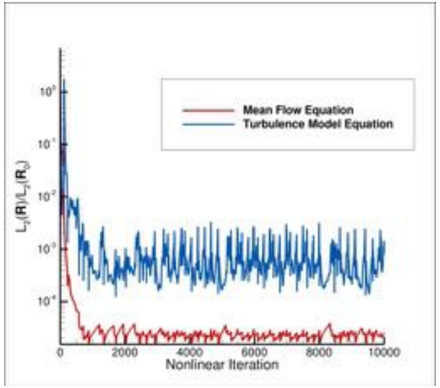


Methodology: Numerical Approach and Convergence

- Flow solver: structured curvilinear solver within the Launch Ascent and Vehicle Aerodynamics (LAVA) solver framework
- All simulations solve the Reynolds-Averaged Navier-Stokes (RANS)
  - Modified Roe convective flux discretization
  - Numerous turbulence models
- Steady-state convergence criteria
  - Standard deviation of c_D in nonlinear iteration space is within 1e-5 and all loads are statistically stationary
  - All cases achieve 4-5 orders of mean flow equation residual convergence

Workshop Task	Turbulence model
Grid Convergence Study	SA, SA-RC-QCR2000
Flap Deflection Study	SA, SA-RC-QCR2000
c_{Lmax} Study	SA, SA-RC, SA-QCR2000, SA-RC-QCR2000, SA-LRe, k-ω BSL
Wind Tunnel Simulations	SA



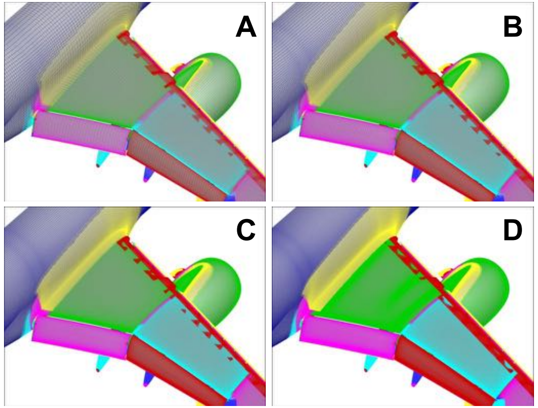


Methodology: Grid Generation

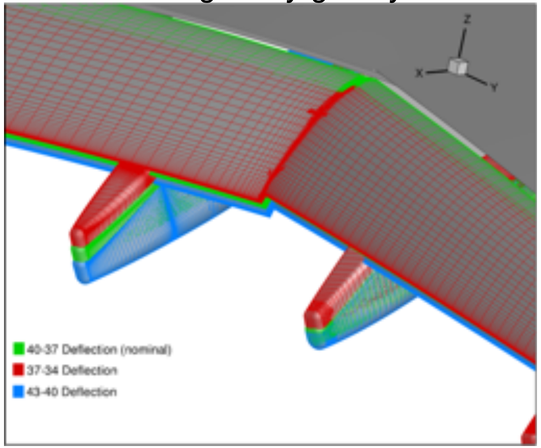
- Very minor updates to the underlying geometry were necessary to allow *structured overset* mesh generation
- Mesh generation completed using Pointwise and Chimera Grid Tools (CGT)
- Meshing strategy based on provided Geometry and Mesh Generation Workshop (GMGW-3) guidelines
- Computational grids would serve as the official committee-provided structured overset mesh family

Wind tunnel modeling study grid system

Mesh Level	Total Solve Points (M)
A	20.15
B	64.71
C	223.5
D	550.2



Free-air nominal configuration grid systems

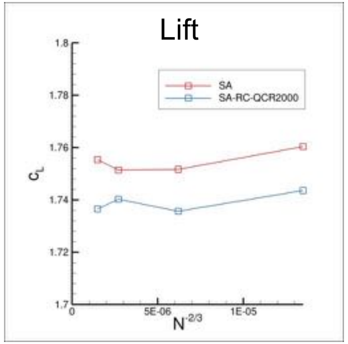


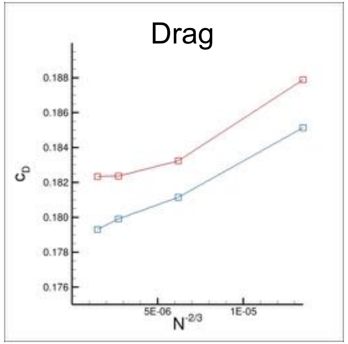
Flap deflection study grid systems

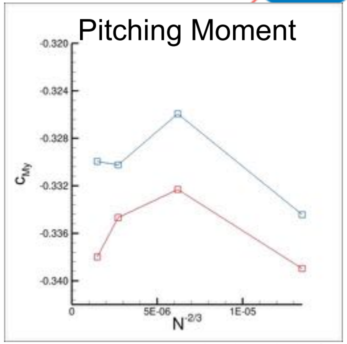
Grid Convergence Study

- Sensitivity of solution to mesh resolution assessed using two variants of the SA turbulence model at α = 7.05º
- Differences in quantities between finest resolutions (C and D) within 0.9%
- Baseline SA demonstrates best agreement with experiment

Mesh Level	c_L (SA)	% Diff. from experiment	c_L (SA-RC-QCR2000)	% Diff. from experiment
A	1.7604	1.03	1.7436	1.97
B	1.7517	1.52	1.7357	2.42
C	1.7514	1.53	1.7402	2.16
D	1.7554	1.31	1.7365	2.37

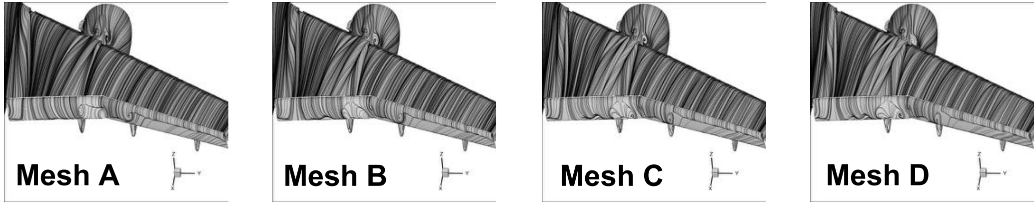




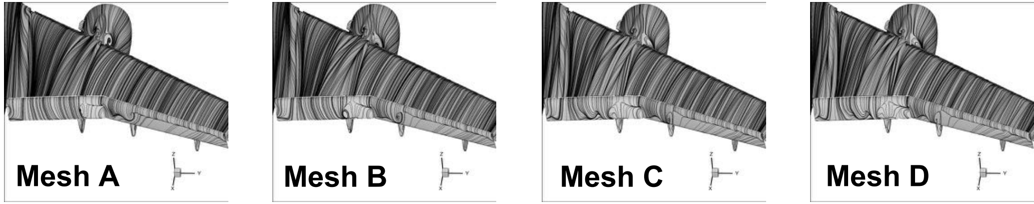


$c_{L,exp}$ = 1.7786 $c_{D,exp}$ = 0.18671 $c_{My,exp}$ = -0.37031

Baseline SA

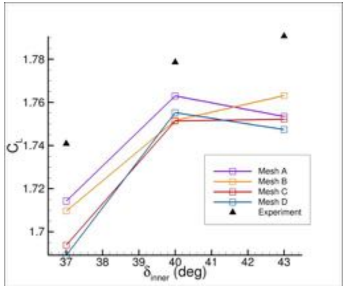


SA-RC-QCR2000

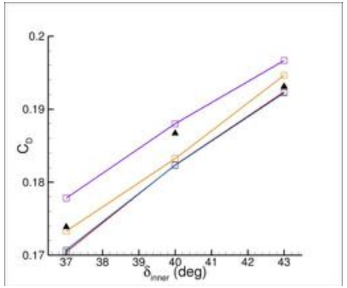


Flap Deflection Study

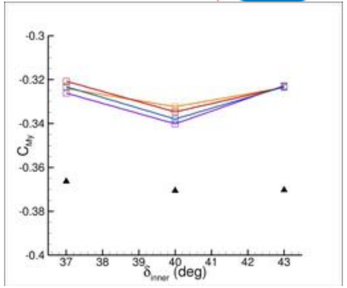
- SA and SA-RC-QCR2000 (not shown) models used to predict flap deflection increments at α = 7.05º
- Mesh levels B and C results using SA do not predict a negative Δc_L between the highest deflections
- Minor differences between resolutions C and D



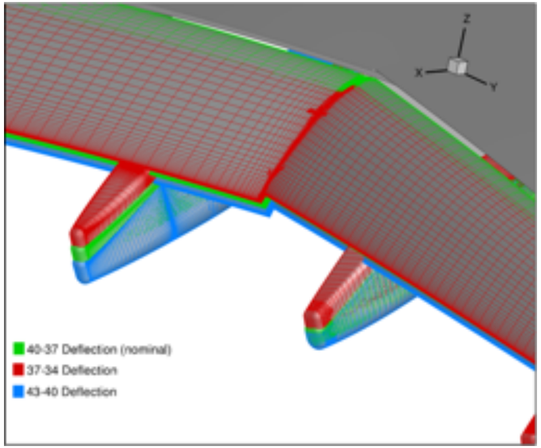
Lift

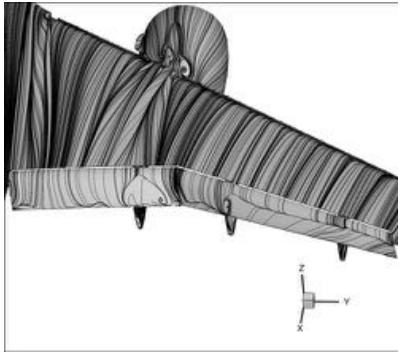


Drag

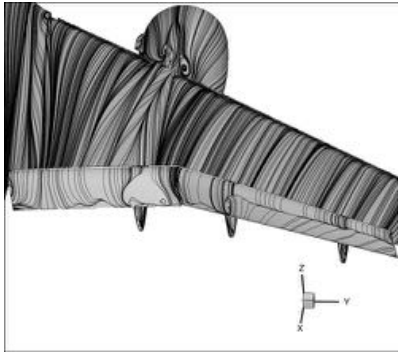


Pitching Moment

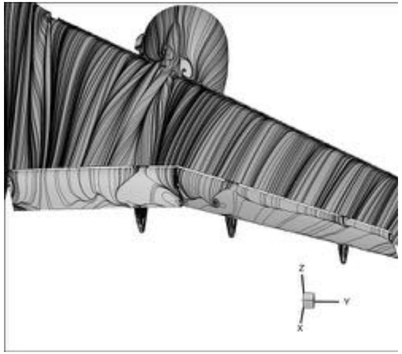




$\delta_f = 37°/34°$



$\delta_f = 40°/37°$



$\delta_f = 43°/40°$

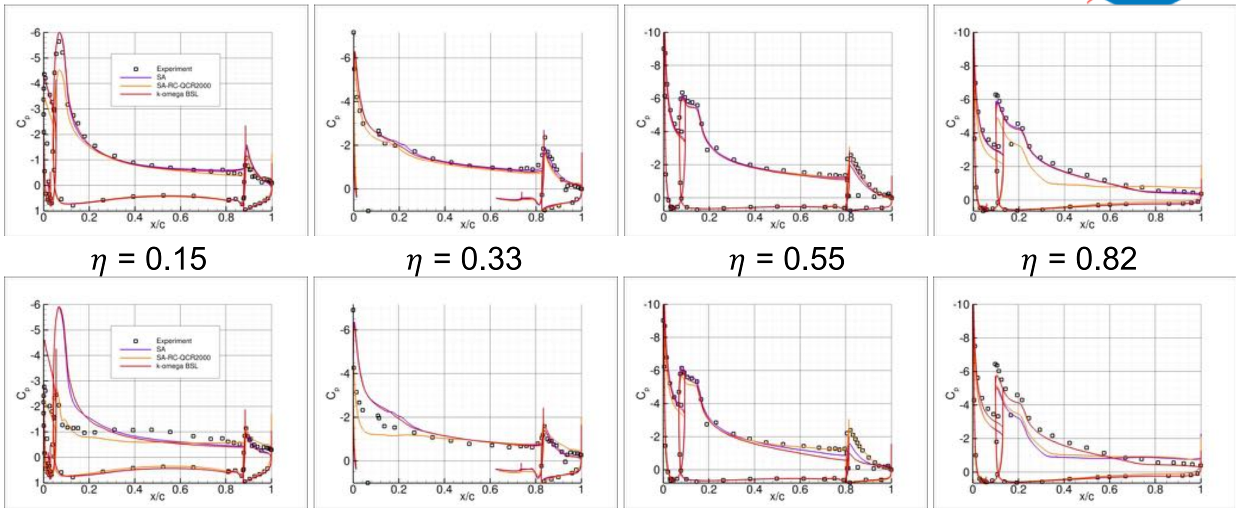
Streamlines shown for each deflection at mesh level C.

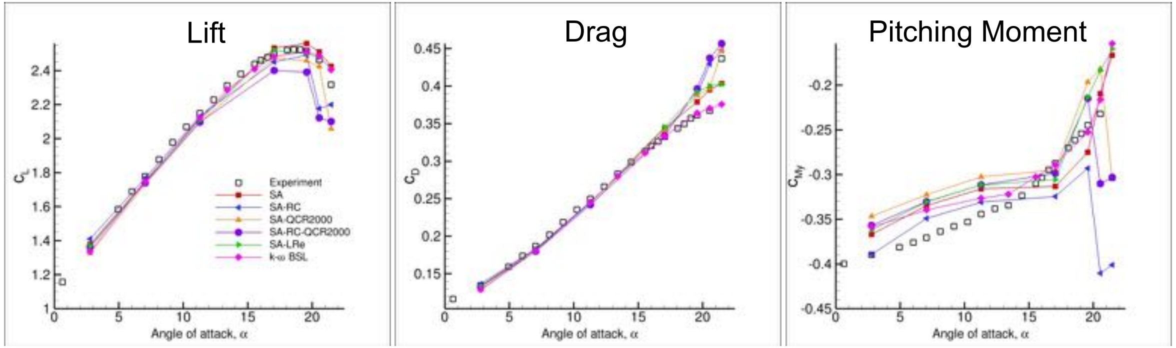
c_{Lmax} Study: Turbulence Model Sensitivity

- Six turbulence models were assessed using mesh level C (5 SA variants and k-ω BSL)
- Simulations demonstrate unique characteristics at high-α conditions
- Corrections to SA model generally lead to mispredictions in these regions
- Pressure distributions analyzed for perceived “best” and “worst” performing models with respect to c_{Lmax} prediction

α = 19.57°

α = 21.47°

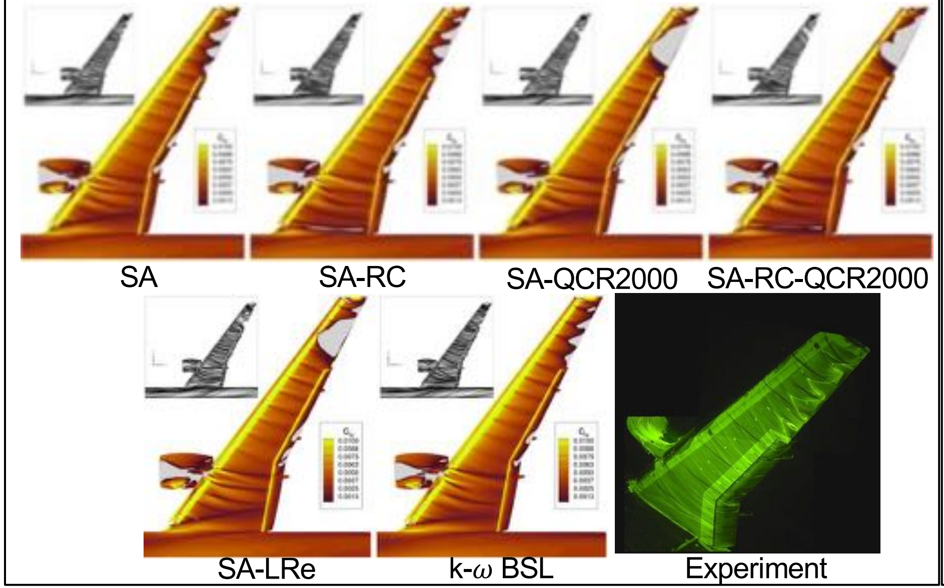




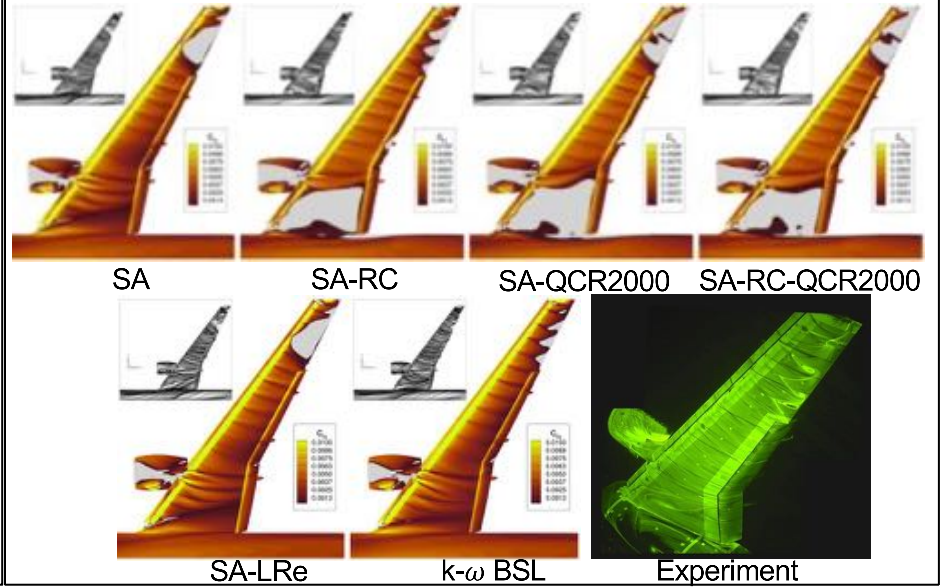
c_{Lmax} Study: Turbulence Model Sensitivity

- Six turbulence models were assessed using mesh level C (5 SA variants and k-ω BSL)
- Simulations demonstrate unique characteristics at high-α conditions, driven by flow topology predictions on the outboard wing and inboard corner flow regions
- Corrections to SA model generally lead to mispredictions in these regions

α = 19.57º

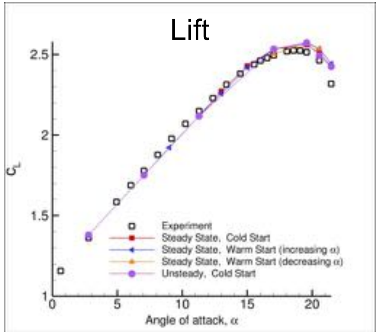


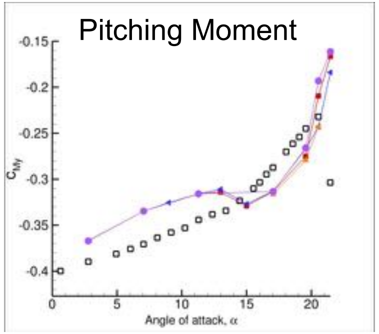
α = 21.47º

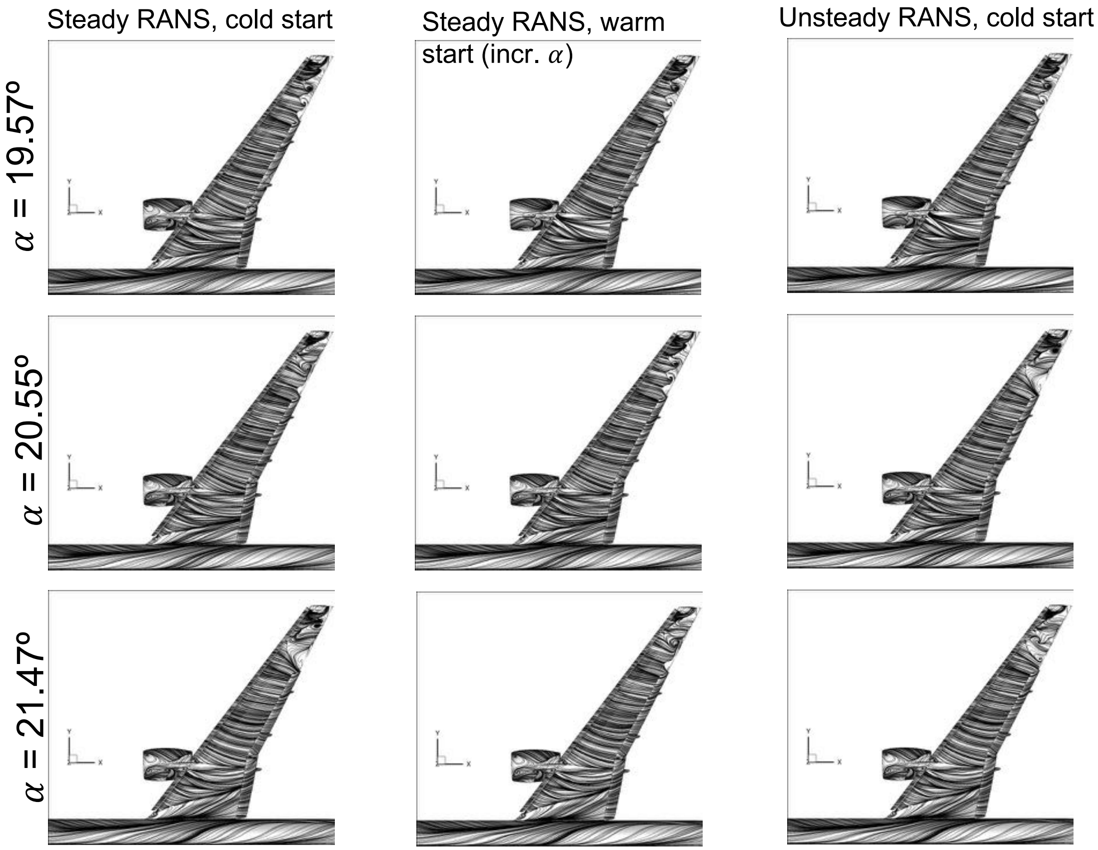


c_{Lmax} Study: Alternative Solution Methods

- Additional simulation methods utilized in attempt to improve baseline SA predictions at high-α
  - Unsteady RANS, cold start
  - Steady RANS, warm start (increasing α)
  - Steady RANS, warm start (decreasing α)
- Benefit observed with steady RANS, warm start (increasing α), which delays spurious outboard separation

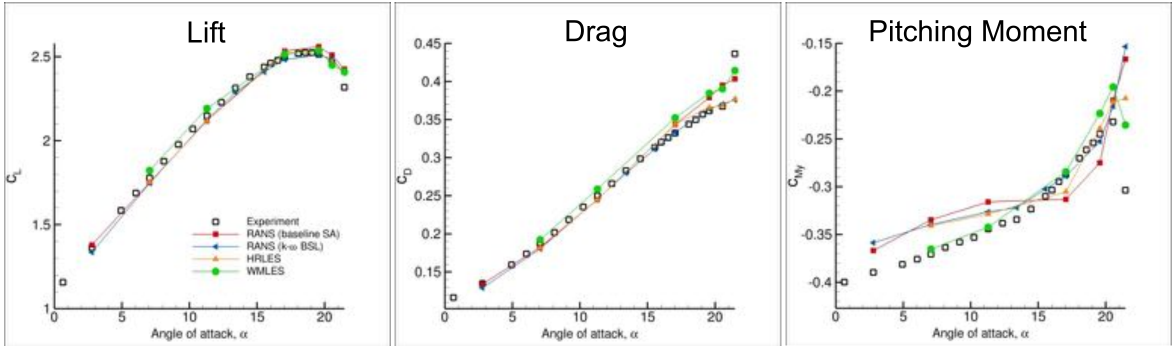


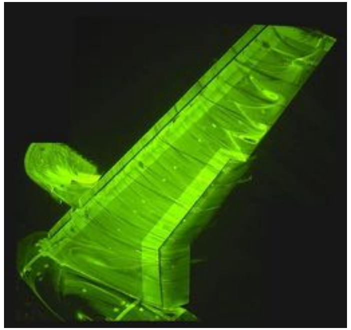


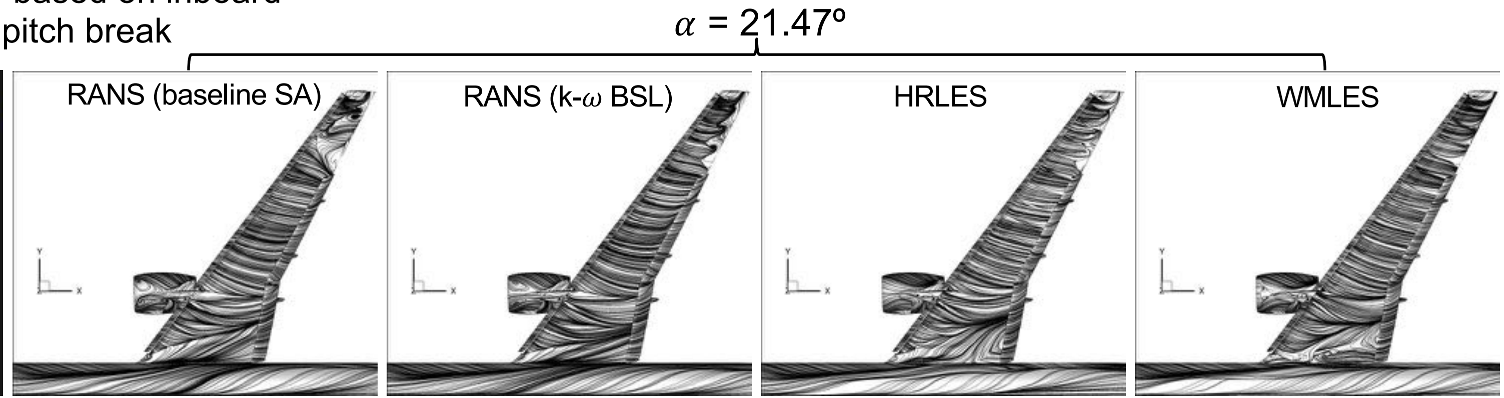


c_{Lmax} Study: Comparison with Scale-Resolving Methods

- RANS solutions compared with results from scale-resolving simulations in LAVA
  - Hybrid RANS/LES (HRLES)[1]
  - Wall-Modeled LES (WMLES)[2]
- Scale-resolving simulations also struggle to predict accurate pitch break in free air
- Validity of RANS methods in free air should not be solely based on inboard separation-induced pitch break



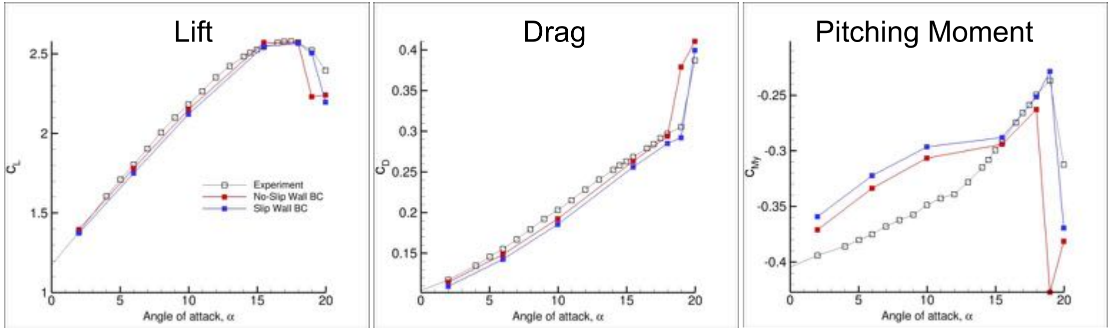


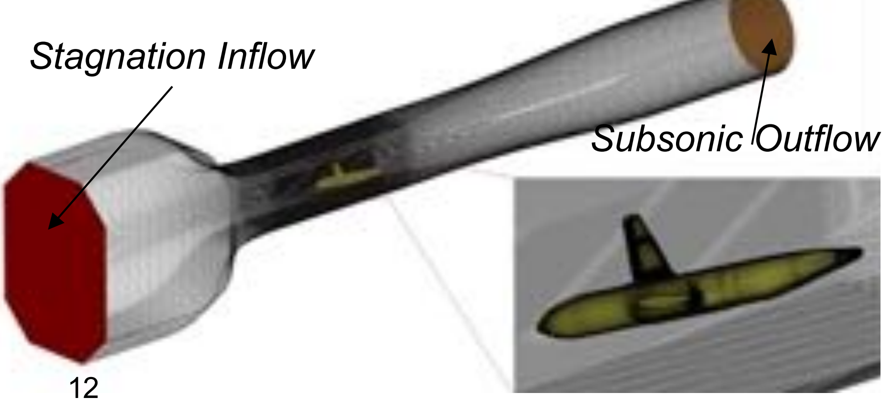


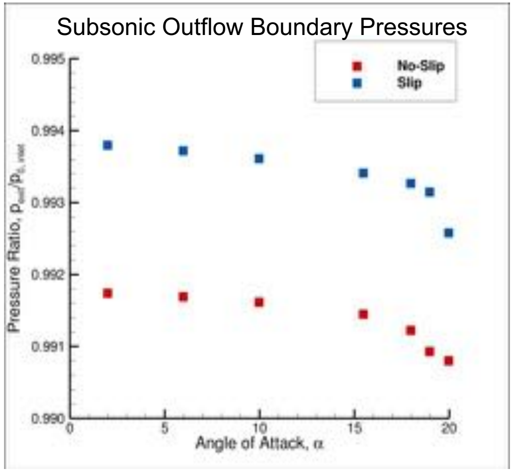
[1]Browne, O. M., Housman, J. A., Kenway, G., Ghate, A. S., and Kiris, C. C., “A Hybrid RANS-LES Perspective for the High Lift Common Research Model Using LAVA,” AIAA Aviation Paper to appear , 2022.
[2]Ghate, A. S., Stich, G.-D., Kenway, G., Housman, J. A., and Kiris, C. C., “A Wall-Modeled LES Perspective for the High Lift Common Research Model Using LAVA,” AIAA Aviation Paper to appear , 2022.

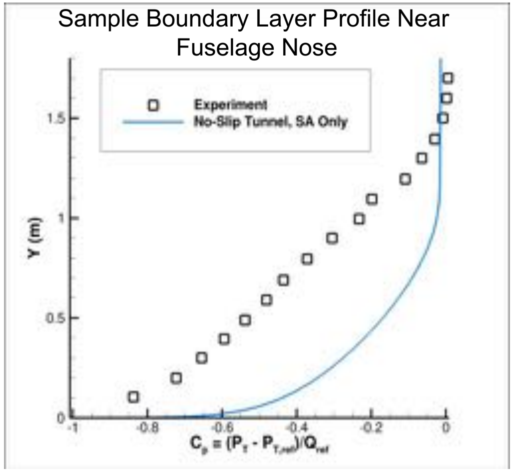
c_{Lmax} Study: Wind Tunnel Modeling

- QinetiQ tunnel wall interference effects studied by incorporating the CRM-HL test article into test section
- Inviscid (slip) wall and viscous (no-slip) wall treatments tested
- Total conditions prescribed at tunnel inflow and static pressure prescribed at outflow to set test section Mach number



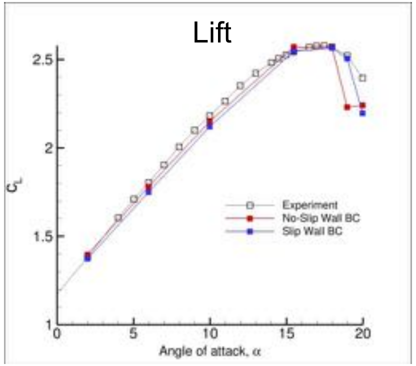


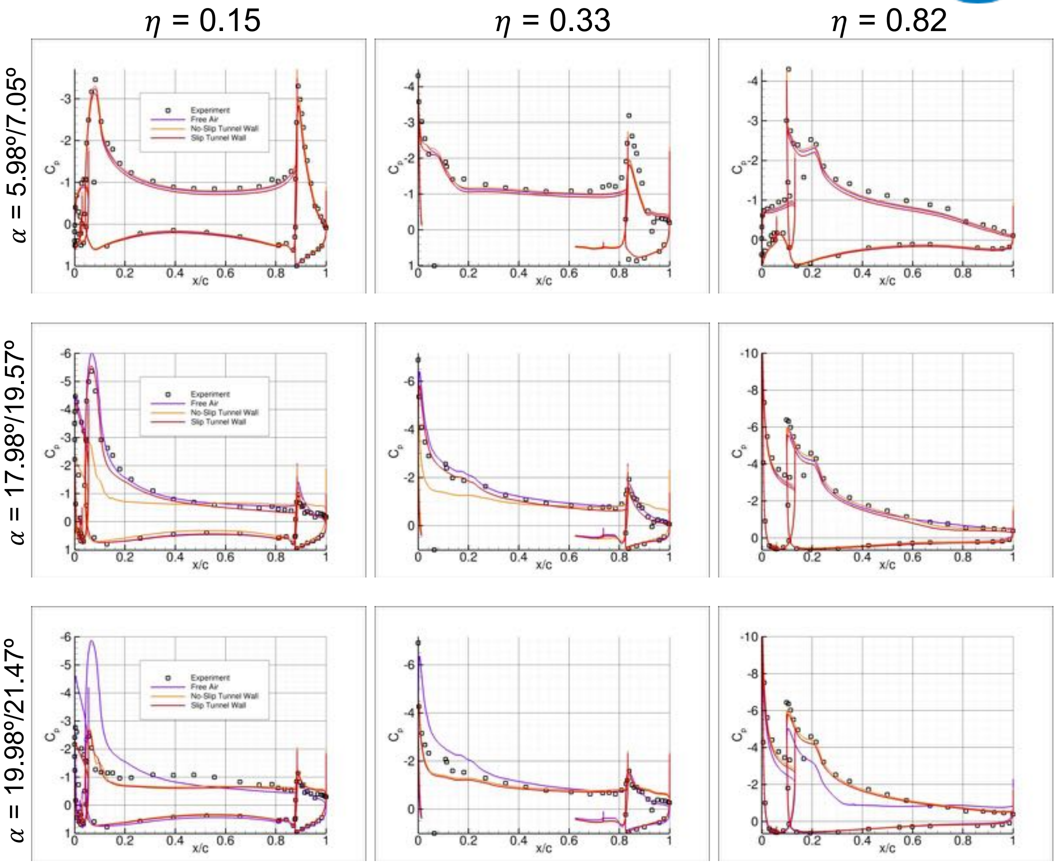




c_{Lmax} Study: Wind Tunnel Modeling

- Pressure distributions at selected angles of attack compared
  - α = 5.98º/7.05º: pressure differences on suction side related to tunnel impacts on effective angle of attack
  - α = 17.98º/19.57º: Inboard suction side pressure rise noted for no-slip tunnel treatment only
  - α = 19.98º/21.47º: Both tunnel treatments exhibit better agreement with experiment





c_{Lmax} Study: Wind Tunnel Modeling

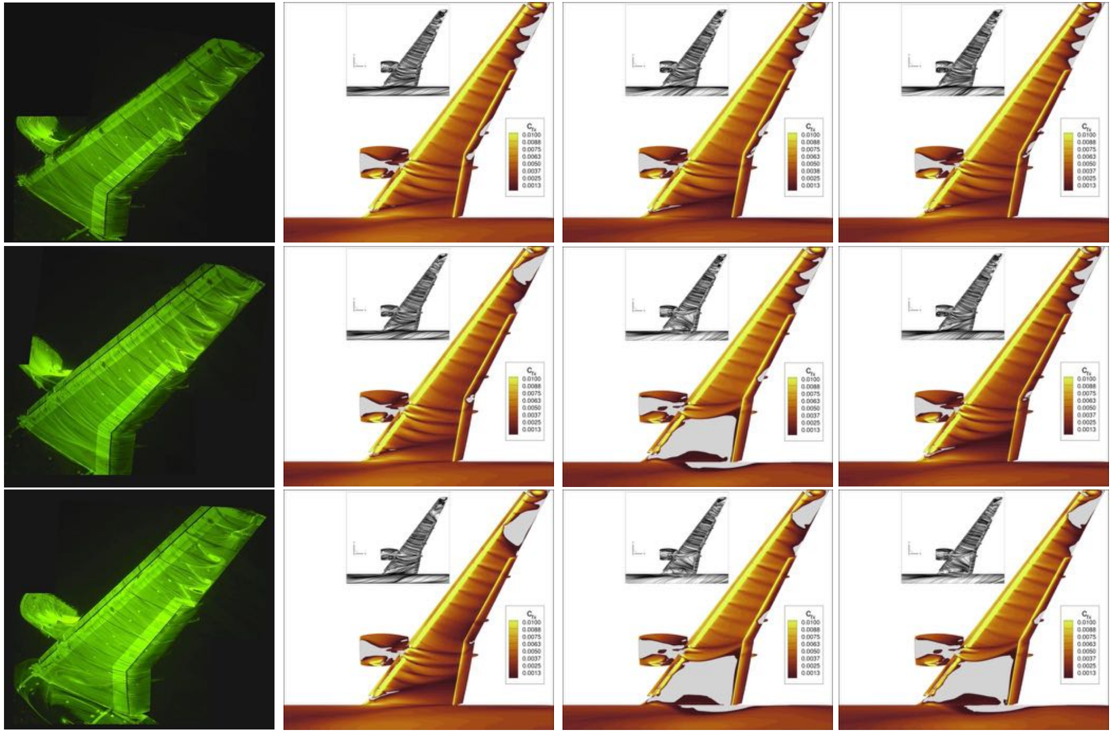
- Skin friction distributions at the highest three angles of attack used to assess separation tendencies for each simulation method
  - α = 17.98º/19.57º: All methods exhibit qualitatively similar flow topologies
  - α = 18.97º/20.55º: No-slip tunnel case exhibits premature inboard separation, free-air exhibits spurious outboard separation
  - α = 19.98º/21.47º: Both tunnel treatments experience inboard and outboard separation, inboard section in free air still attached

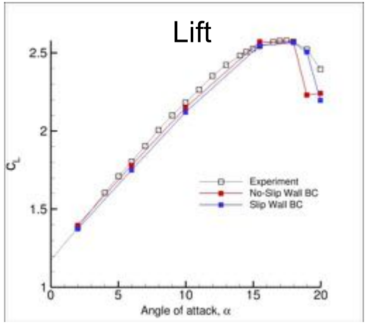
Experiment | Free Air | No-Slip Tunnel Boundaries | Slip Tunnel Boundaries

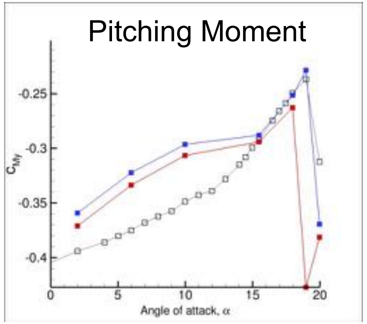
α = 17.98º/19.57º

α = 18.97º/20.55º

α = 19.98º/21.47º







Summary of LAVA RANS Contributions to Workshop

- Hundreds of RANS simulations conducted in pursuit of identifying RANS prediction capabilities and shortcomings for high-lift configurations
- Preliminary simulations used to reduce modeling errors where possible and determine best-practices (grid resolution, numerical methods, etc.) for additional workshop studies
- Six turbulence models (SA variants and k-ω BSL) were used in c_{Lmax} study in free air
    - SA corrections generally lack accuracy in c_{Lmax} prediction, but do exhibit varying degrees of pitching moment break
    - Baseline SA exhibits excellent c_{Lmax} prediction, but spurious outboard separation present in post- c_{Lmax} conditions
    - k-ω BSL provides best agreement with experiment, but is very computationally expensive using current simulation methods and convergence criteria
- Wind tunnel modeling improves various shortcomings of the baseline SA model in free air, with other erroneous features persisting
- While all experimental flow phenomena could be predicted qualitatively using at least one method, no one RANS methodology can capture all flow topologies across entire α-range with exceptional accuracy

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