# BCFD Analysis of the NASA Common Research Model for the 4th Drag Prediction Workshop

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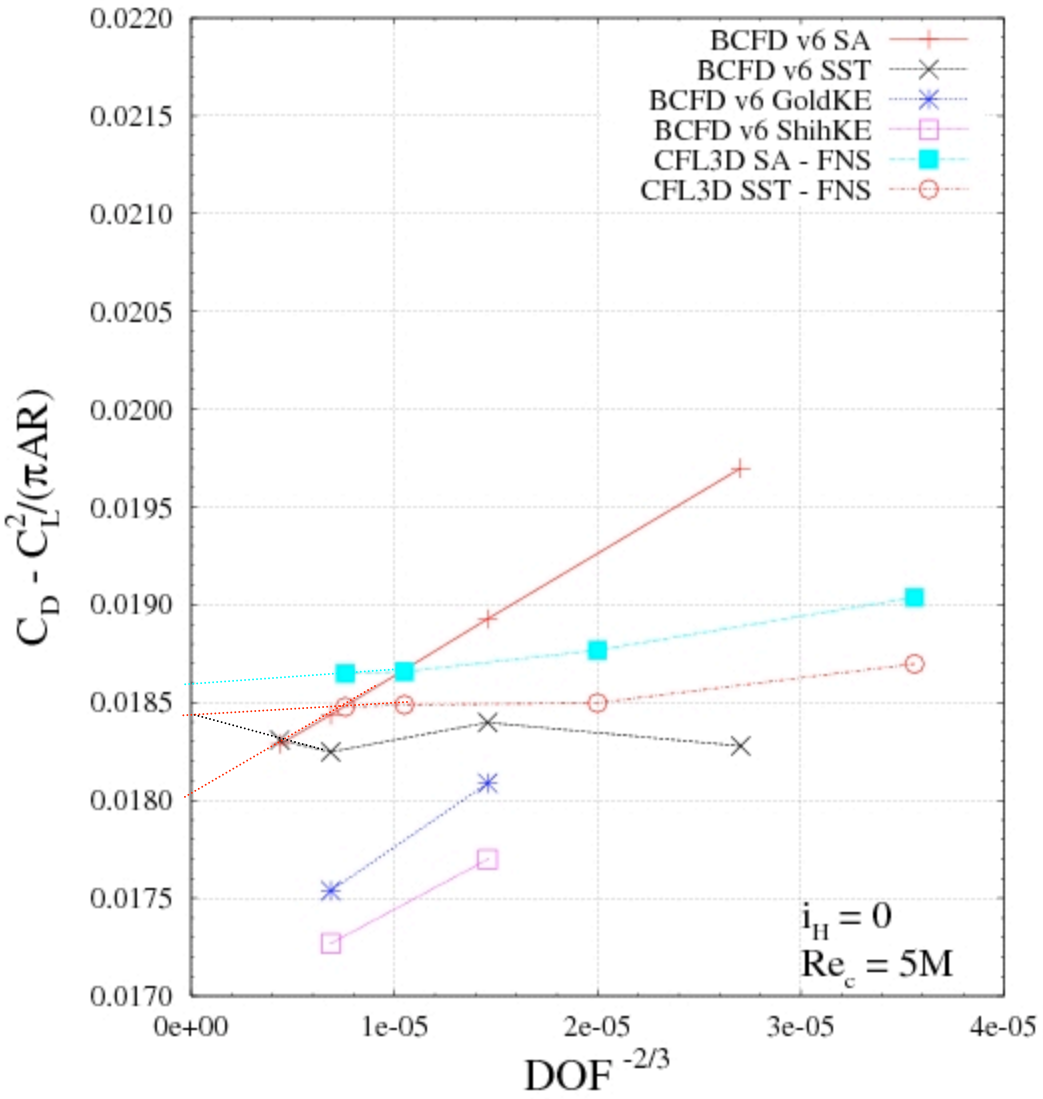
# BCFD Simulations for DPW4

- **Case 1a: Grid Convergence Study (both SA and SST)**
  - Mach = 0.85, CL = 0.500 (±0.001)
  - Tail Incidence angle, $i_H$= 0°
  - Coarse-Fine, Medium-Fine, Fine, Extra-Fine Grids
  - Chord Reynolds Number: Re=5M

- **Typical convergence (fine grid)**
  - Platform: Dual, quad-core AMD Opteron 2354, 2.2 GHZ, 8 cores per node
  - # Cores: 103
  - Run time: 28 hours (wall-clock), 2920 CPU hours
  - Memory: 163 GB (summed across all processors)

# Grid Convergence Study, CL = 0.5




- Significant numerical improvements to BCFD since DPW3 (ref: AIAA 2009-3650)
- BCFD SA solutions exhibit nearly perfect linear convergence with grid refinement
- BCFD SST total drag is less sensitive to grid size than SA, however, $C_{d,p}$ and $C_{d,v}$ are not insensitive to grid
- k-ε models considered with reduced run matrix
  - k-ε models examined in BCFD exhibit significantly less drag than either SA or SST
  - Consistent trend with k-ε predictions by others at DPW4





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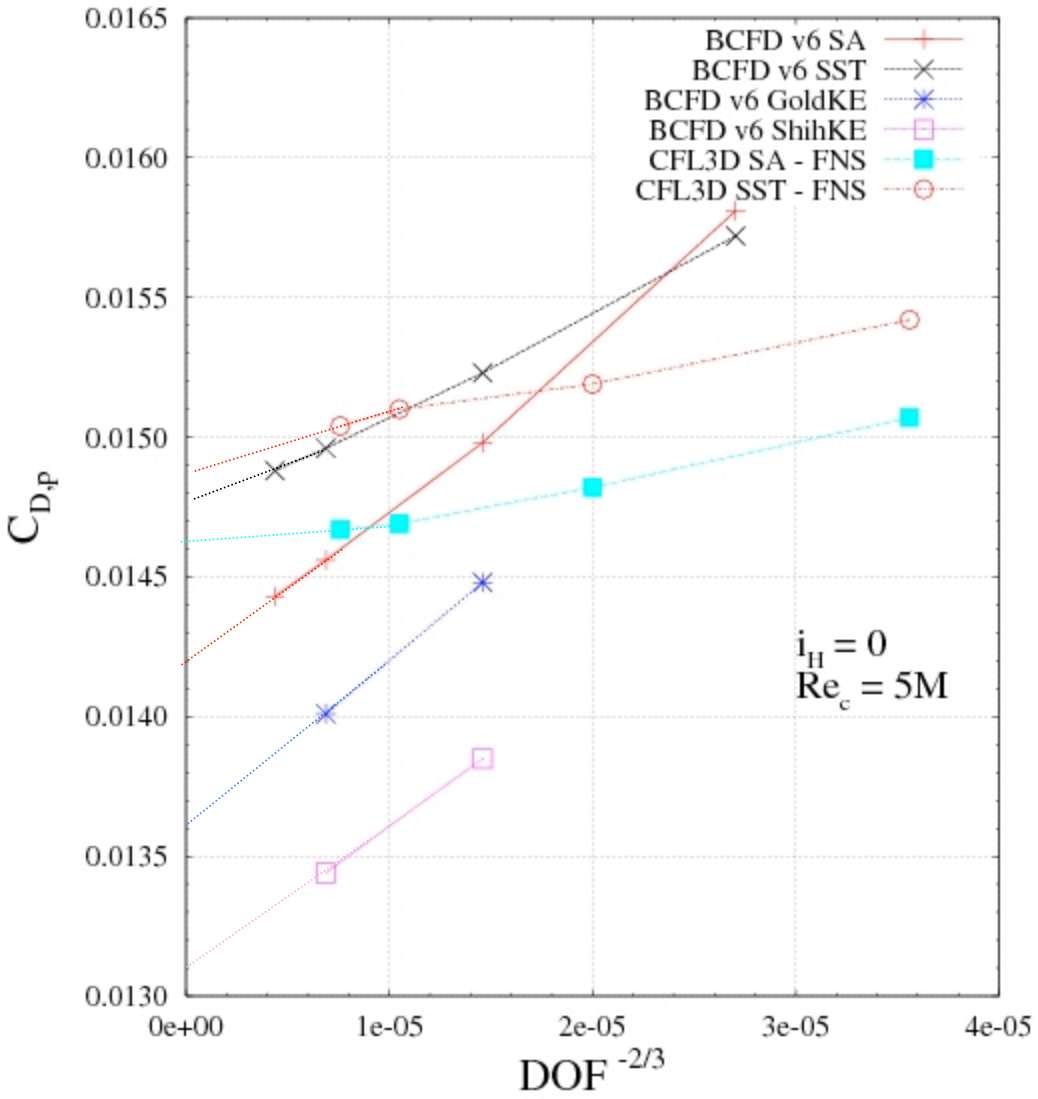
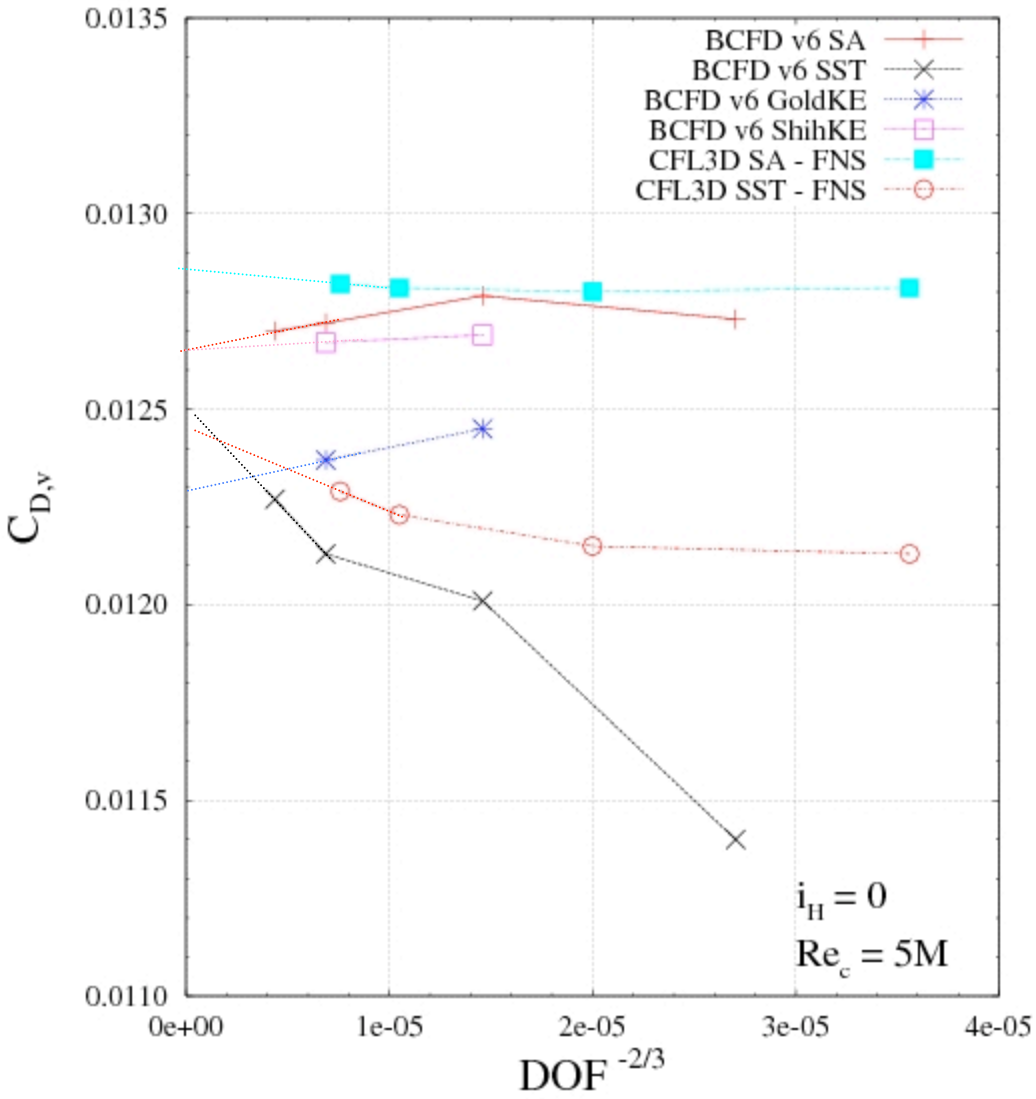
# Grid Convergence Study, CL = 0.5




- Excellent pressure drag convergence with grid refinement for all turbulence models examined
- Within ~1 drag count of CFL3D for SST
- Within ~4 drag counts of CFL3D for SA
- k-ε models examined in BCFD exhibit significantly less drag than either SA or SST
- Consistent trend with k-ε predictions by others

# Grid Convergence Study, CL = 0.5




- BCFD SA viscous drag predictions exhibit similar convergence as CFL3D
- Within ~2 drag counts of CFL3D SA prediction
- BCFD SST viscous drag predictions much more sensitive to grid spacing
  - Others have documented the SST dependence on near-wall spacing
  - Nearly identical extrapolated value of $C_{D,v}$ as CFL3D

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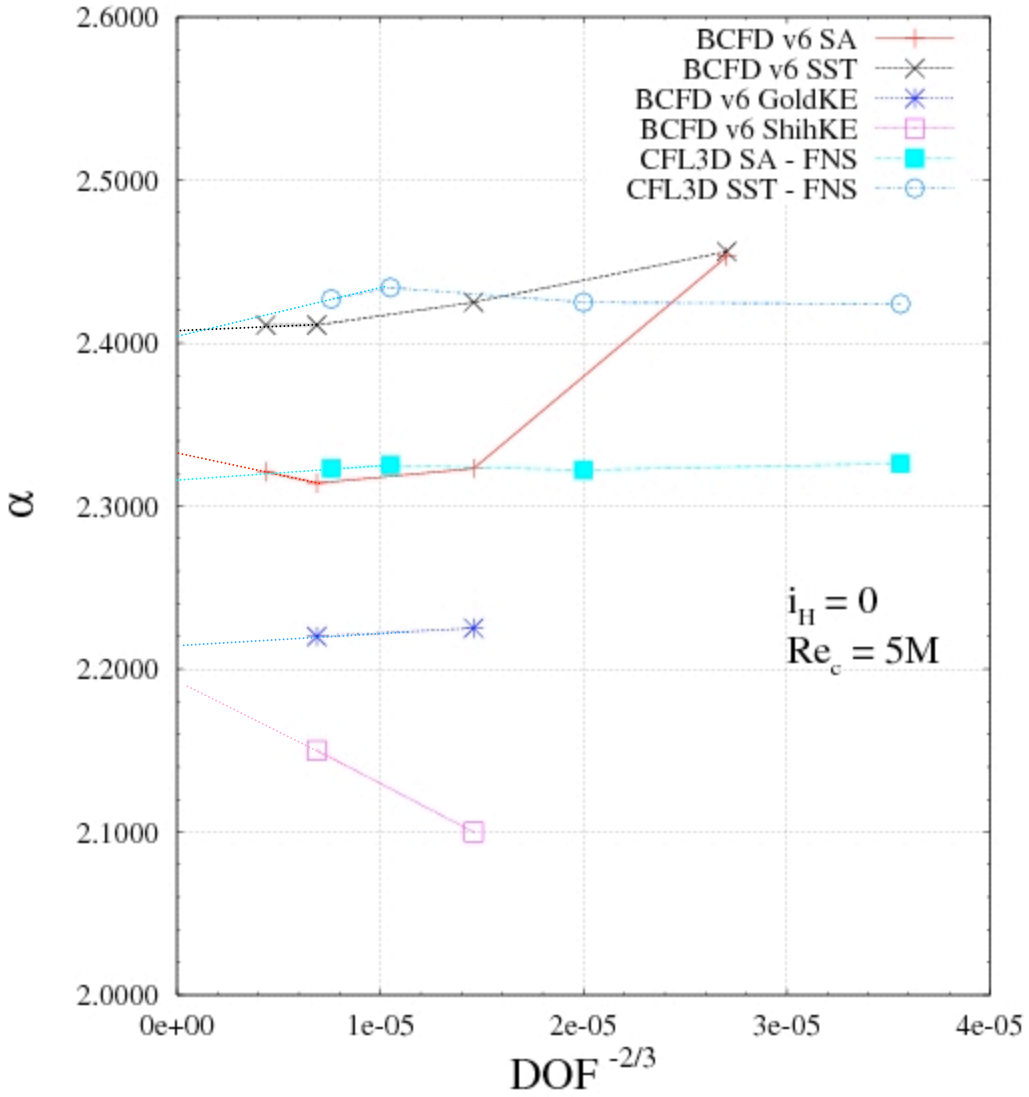
# Grid Convergence – Angle of Attack, CL=0.5




- BCFD and CFL3D extrapolate to nearly the same AoA for SST ($\alpha$ = 2.40°) and SA ($\alpha$ = 2.32°)
- Goldberg's k-ε model seen to predict a lower AoA (~2.21°) consistent with its prediction of lower total drag
- Shih's k-ε model seen to predict an AoA of ~2.20°

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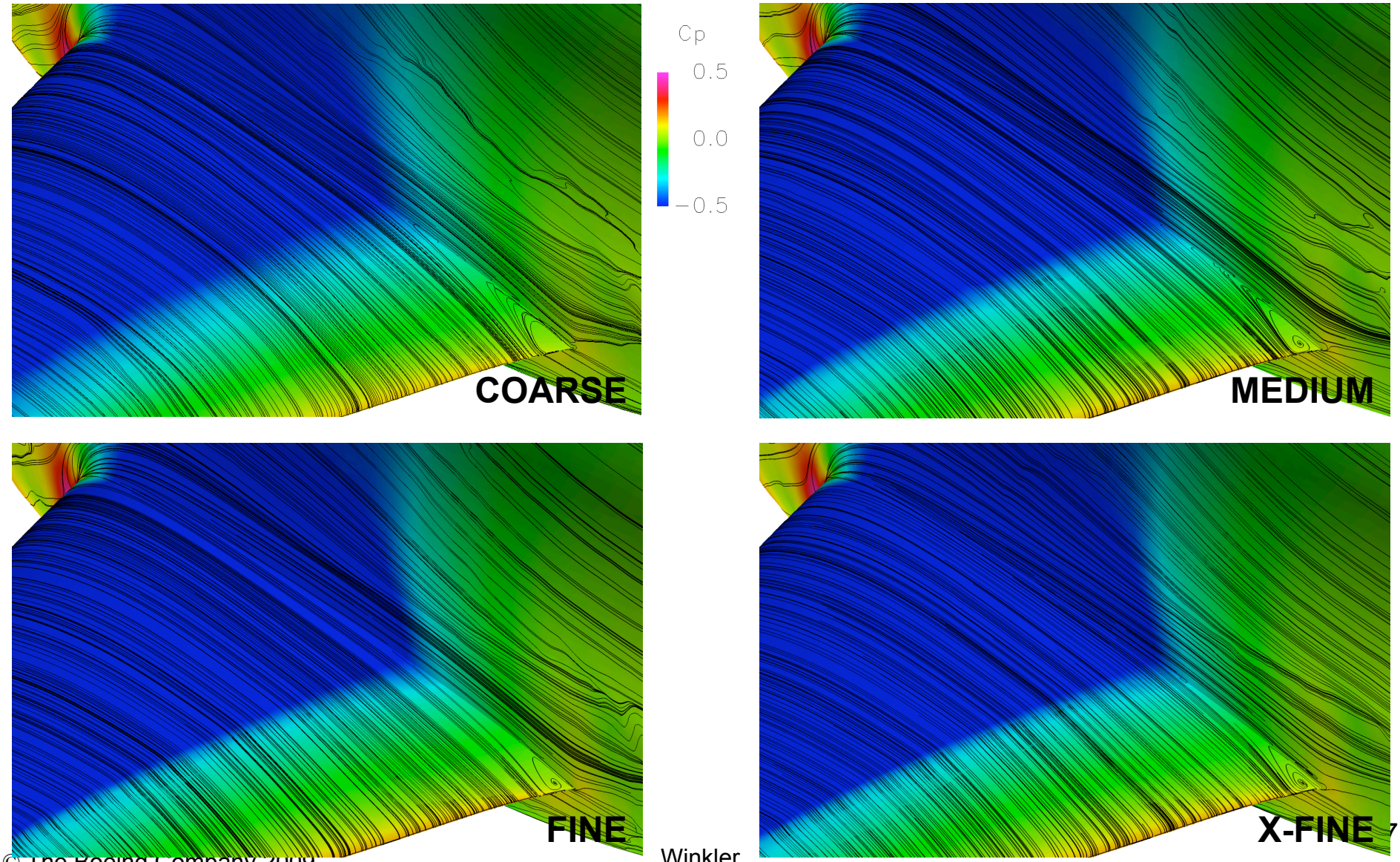
# Side-of-body separation, SA Model, CL=0.5



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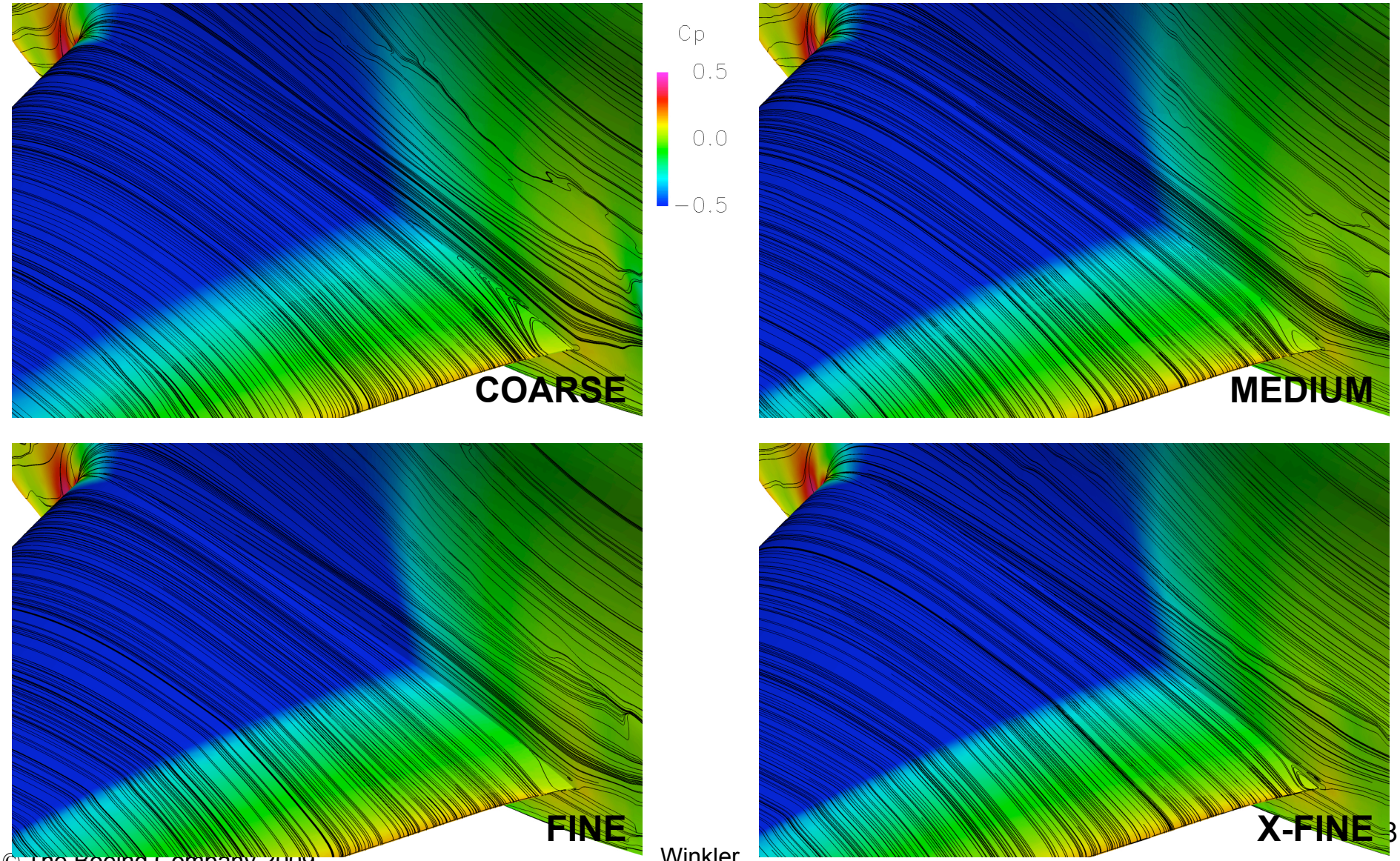
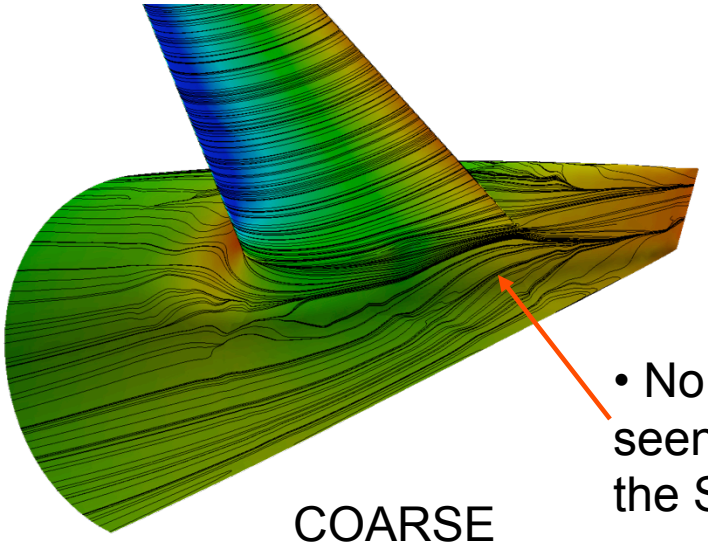
# Side-of-body separation, SST Model, CL=0.5

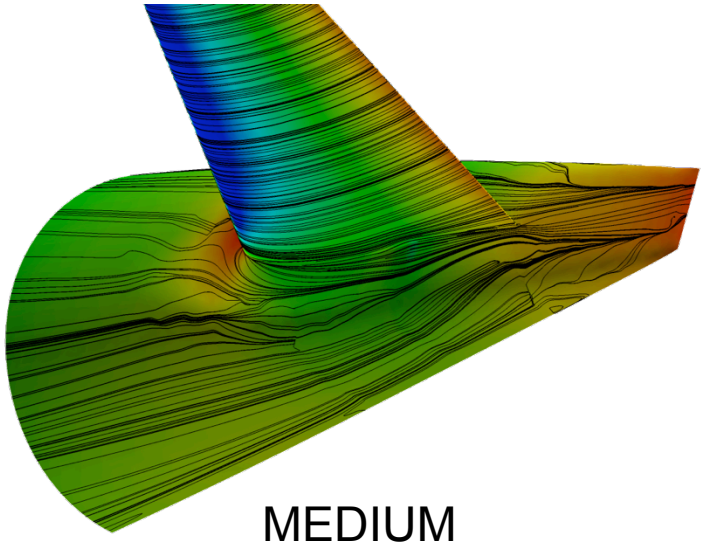


# Tail oil flow, SA Model, CL=0.5

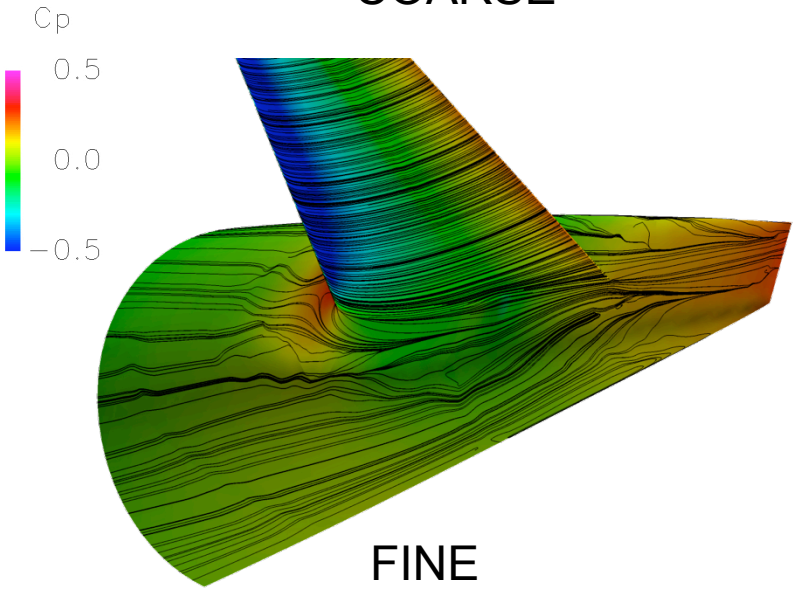


COARSE

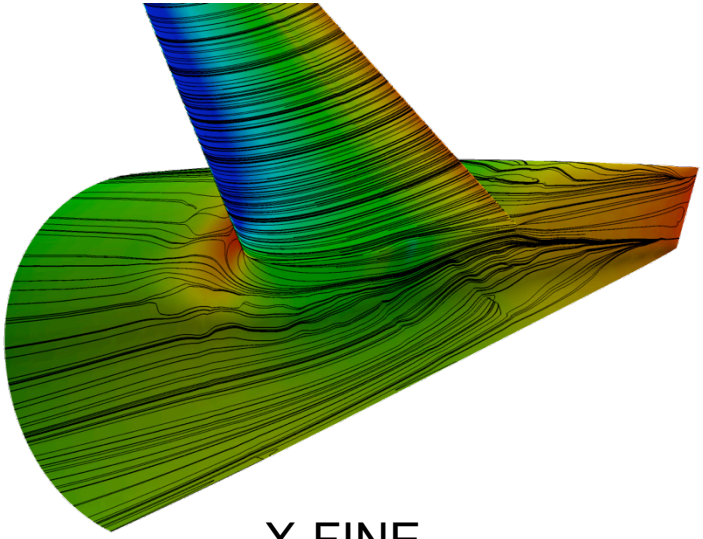
- No separation pocket seen near tail root for the SA results



MEDIUM

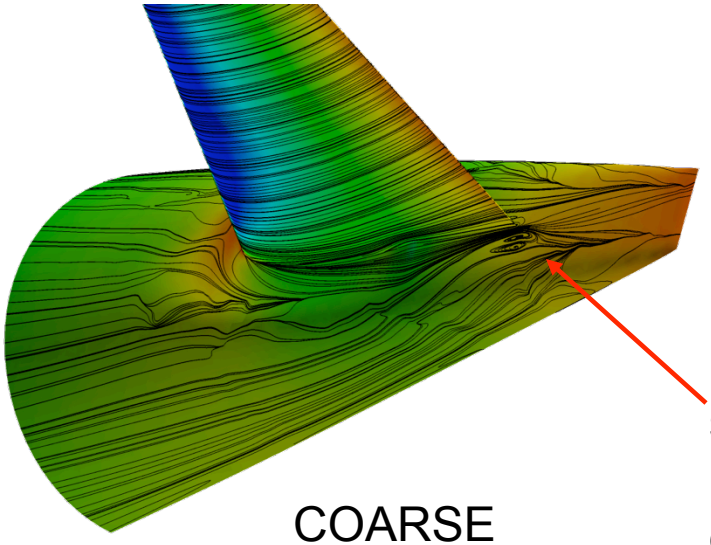



FINE



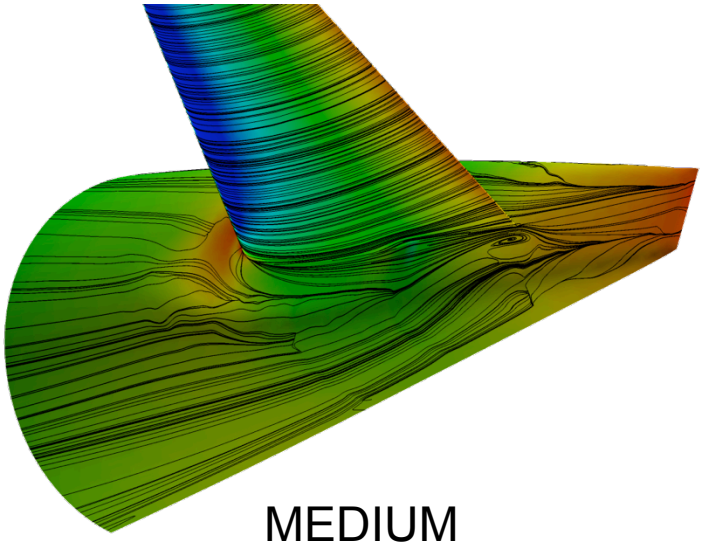
X-FINE

# Tail oil flow, SST Model, CL=0.5

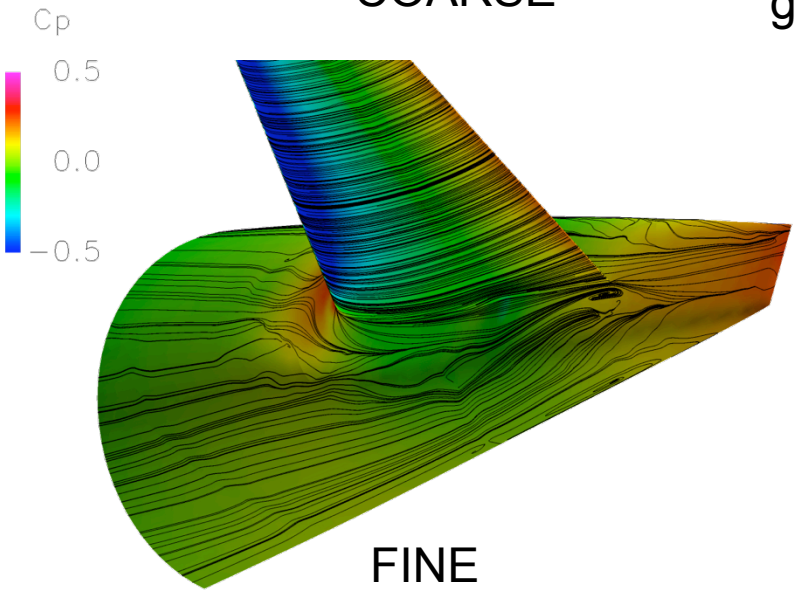


COARSE

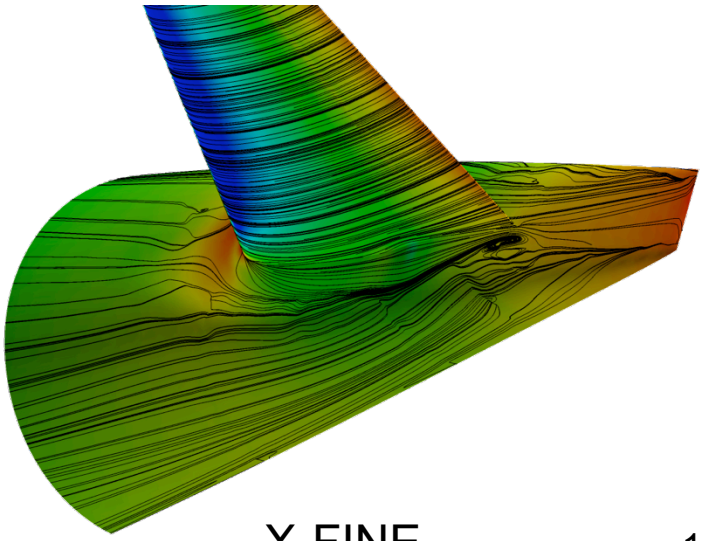
- Tail separation seen with SST model on all grids



MEDIUM




FINE



X-FINE

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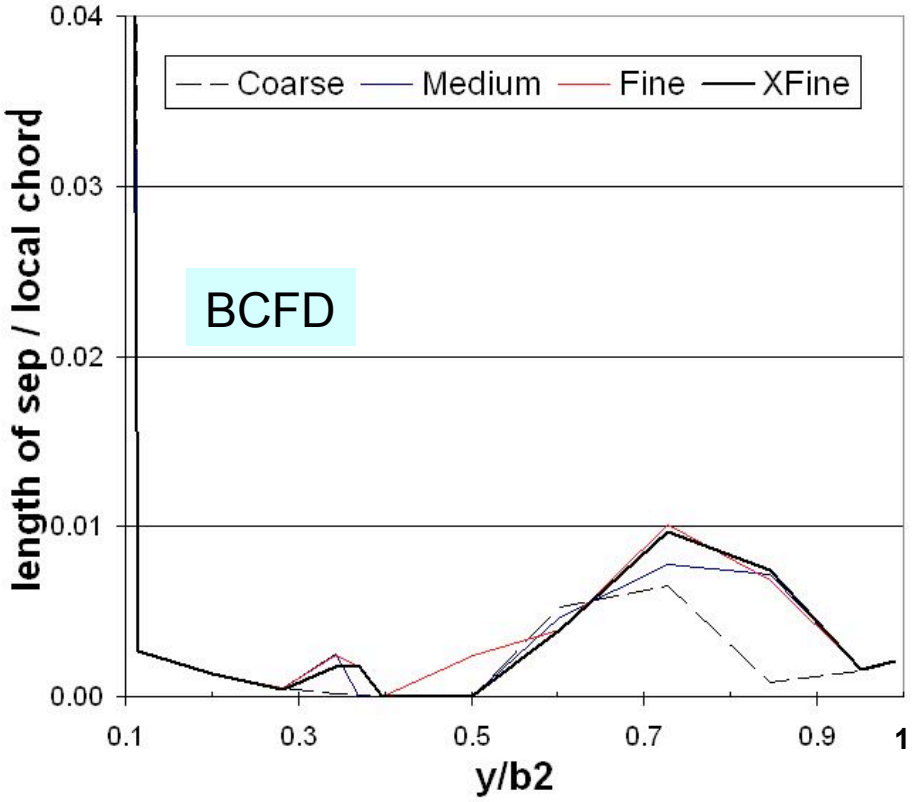
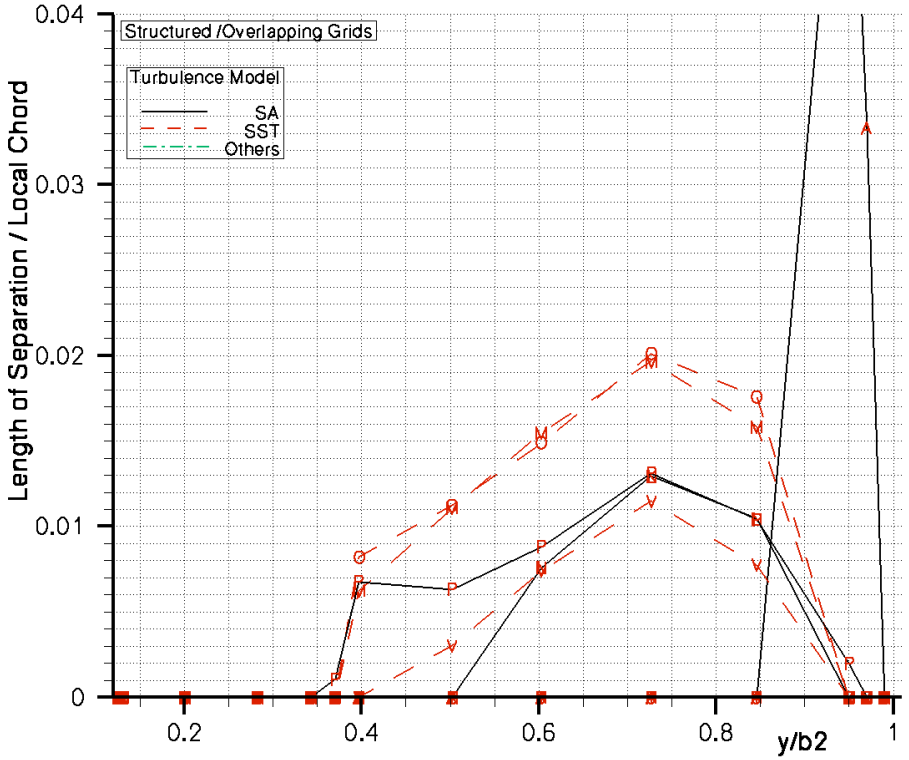
# Trailing edge separation, CL = 0.5

## BCFD SA Results




- BCFD seen to give similar TE separation for the medium through x-fine grids
- Shape/magnitude of BCFD TE separation curve very similar to that predicted by the structured codes.

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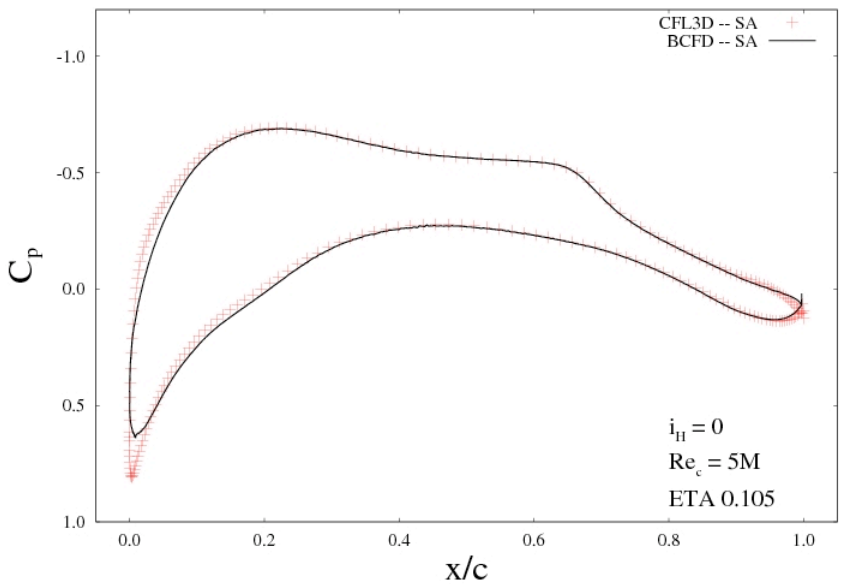
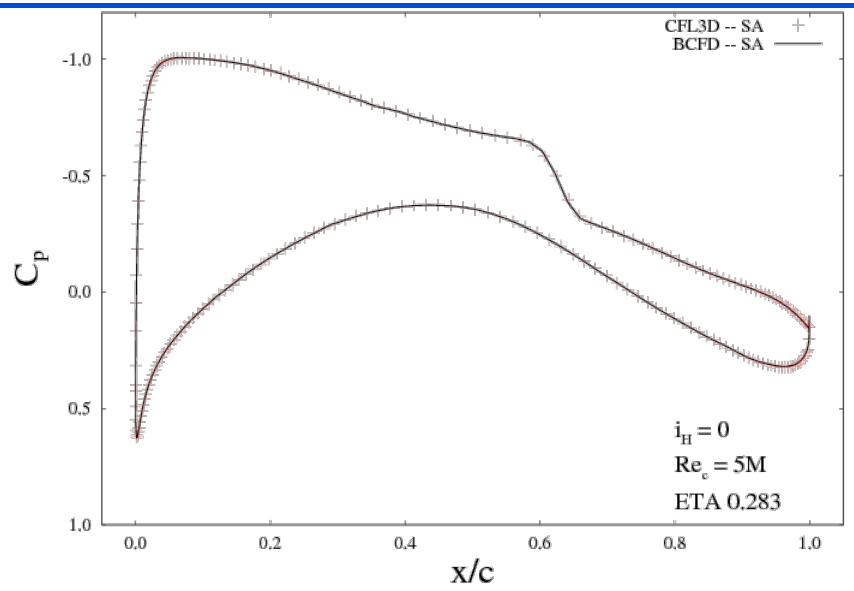
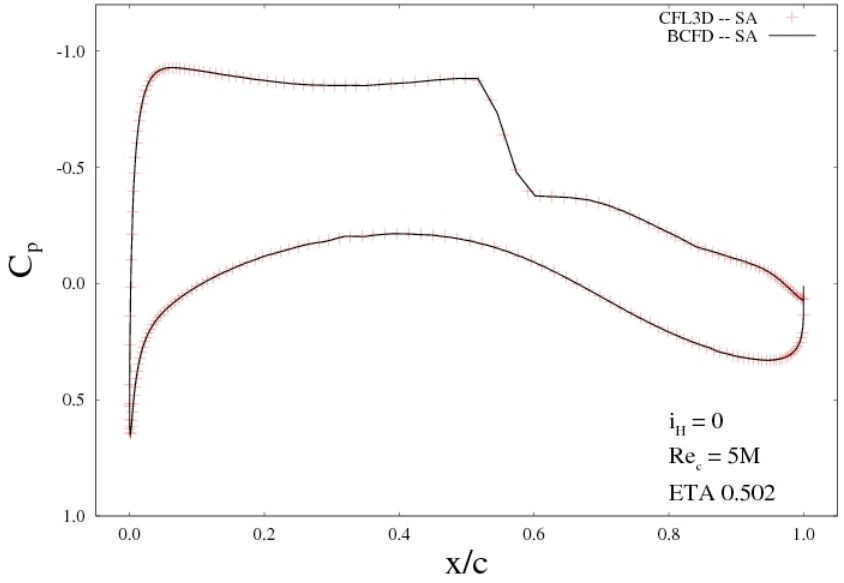
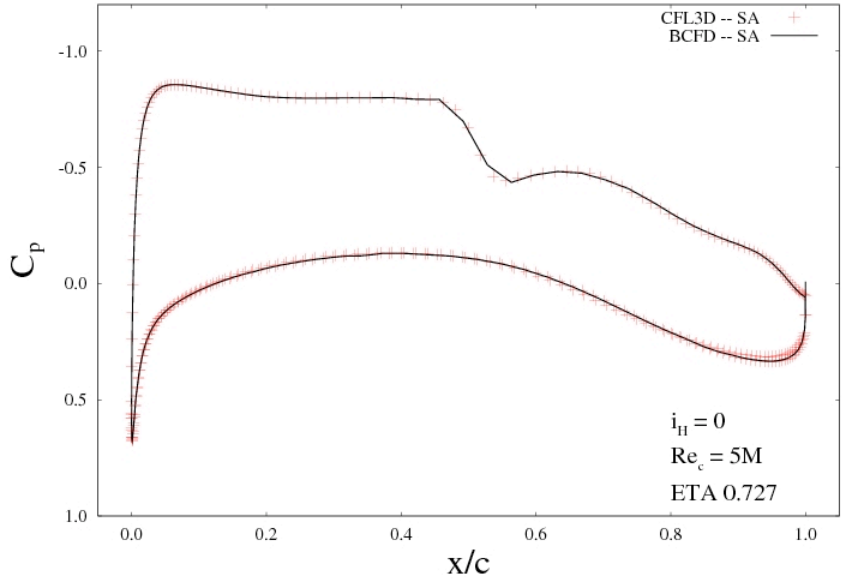
# Cp plots: Comparison with CFL3D

## SA model

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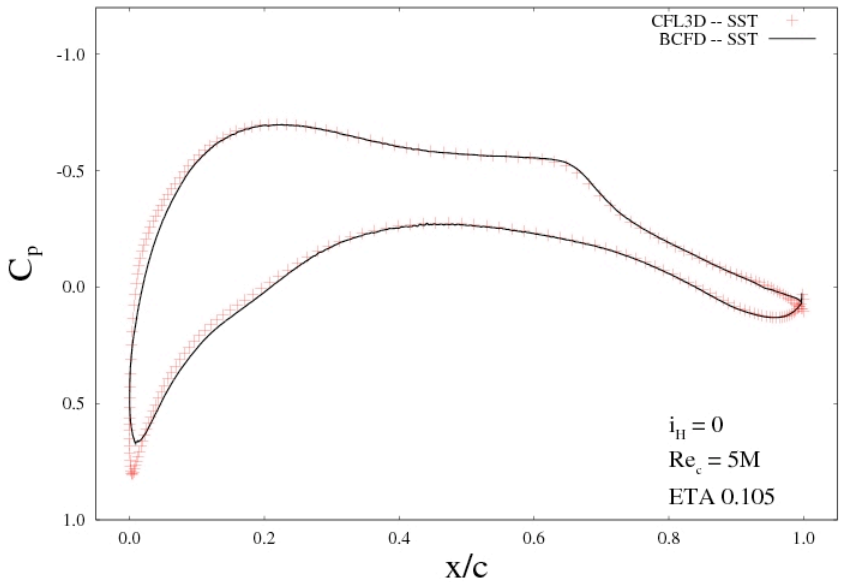
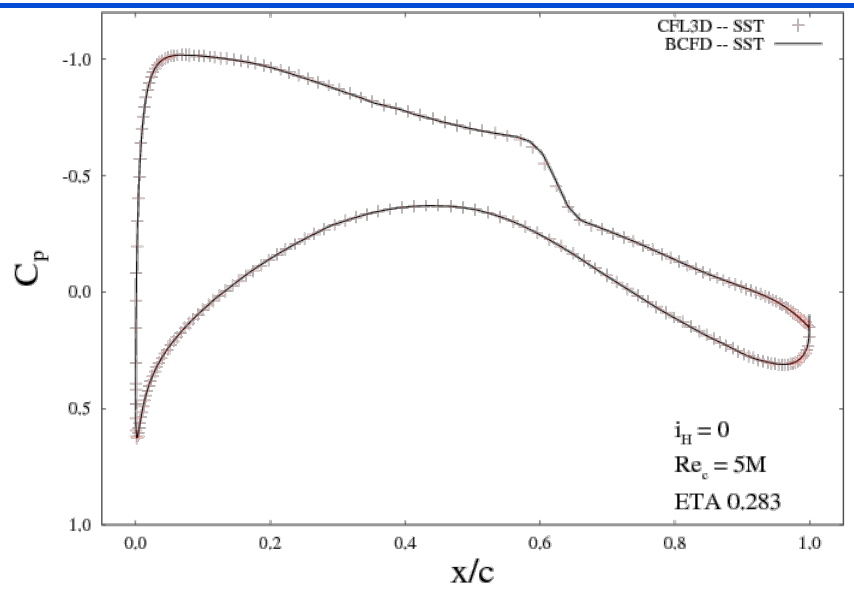
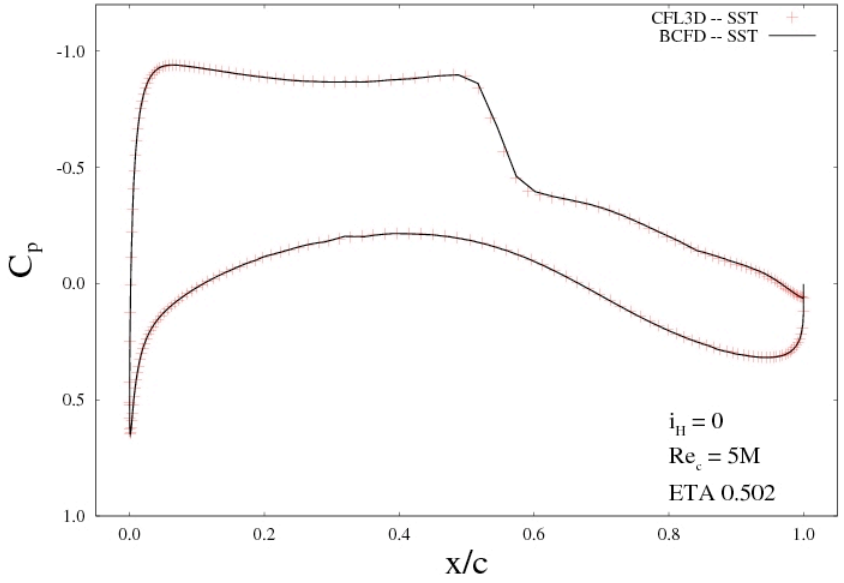
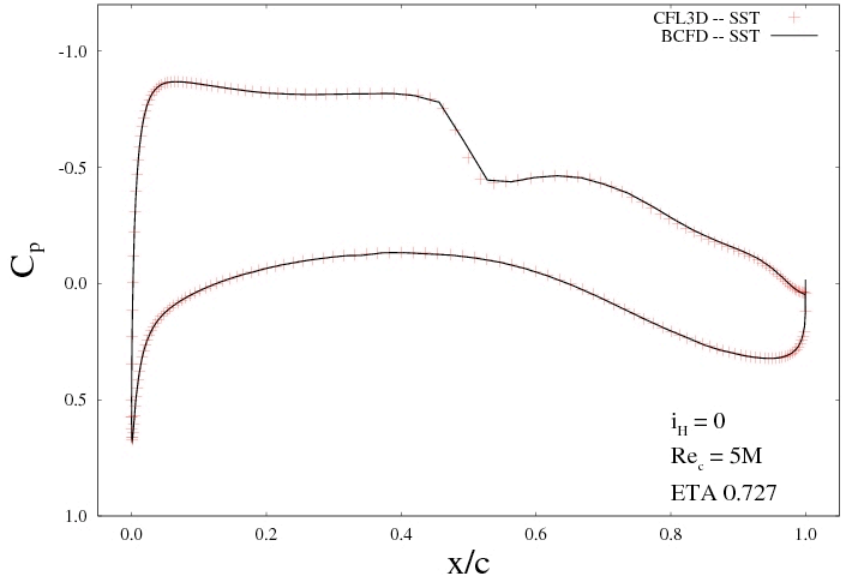
# Cp plots: Comparison with CFL3D SST model

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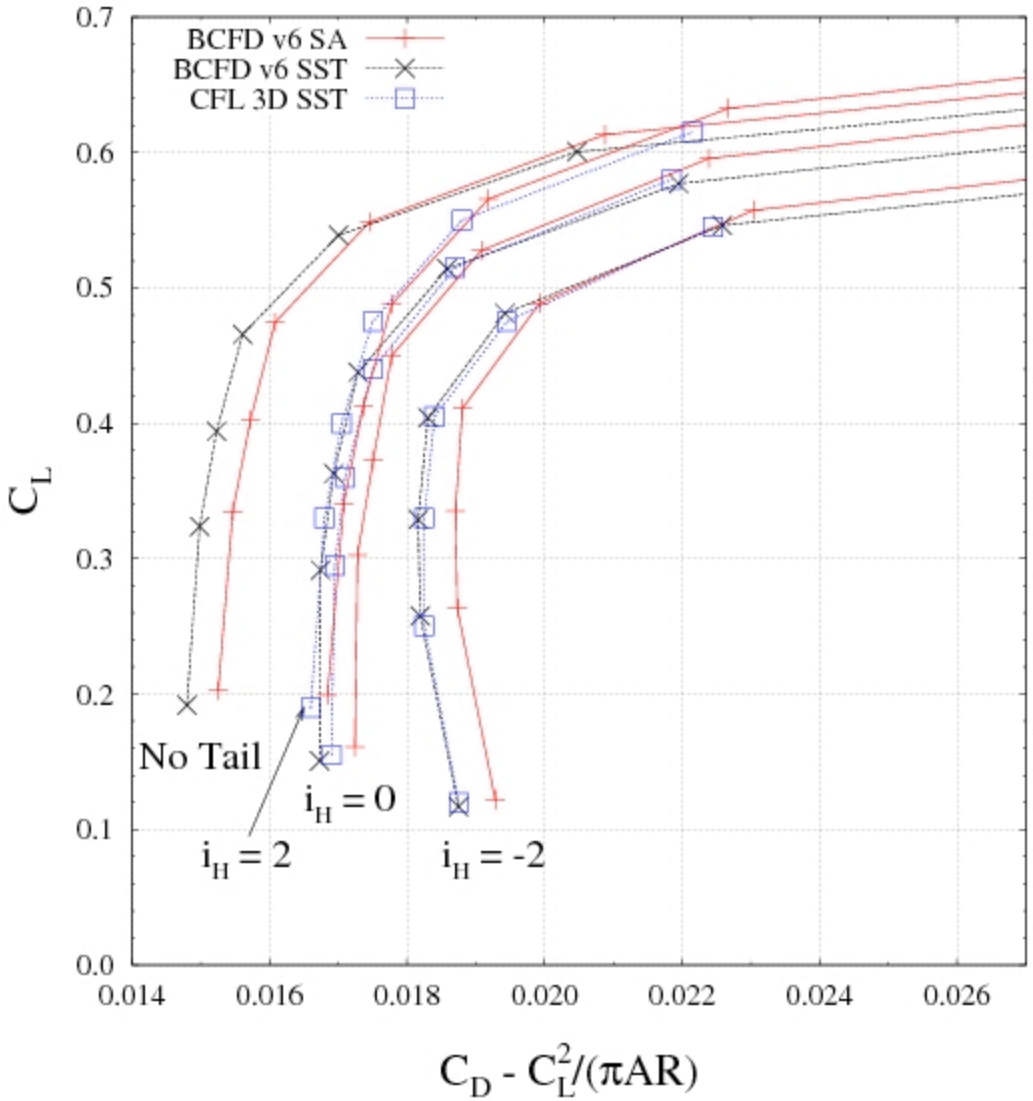
# BCFD Simulations for DPW4

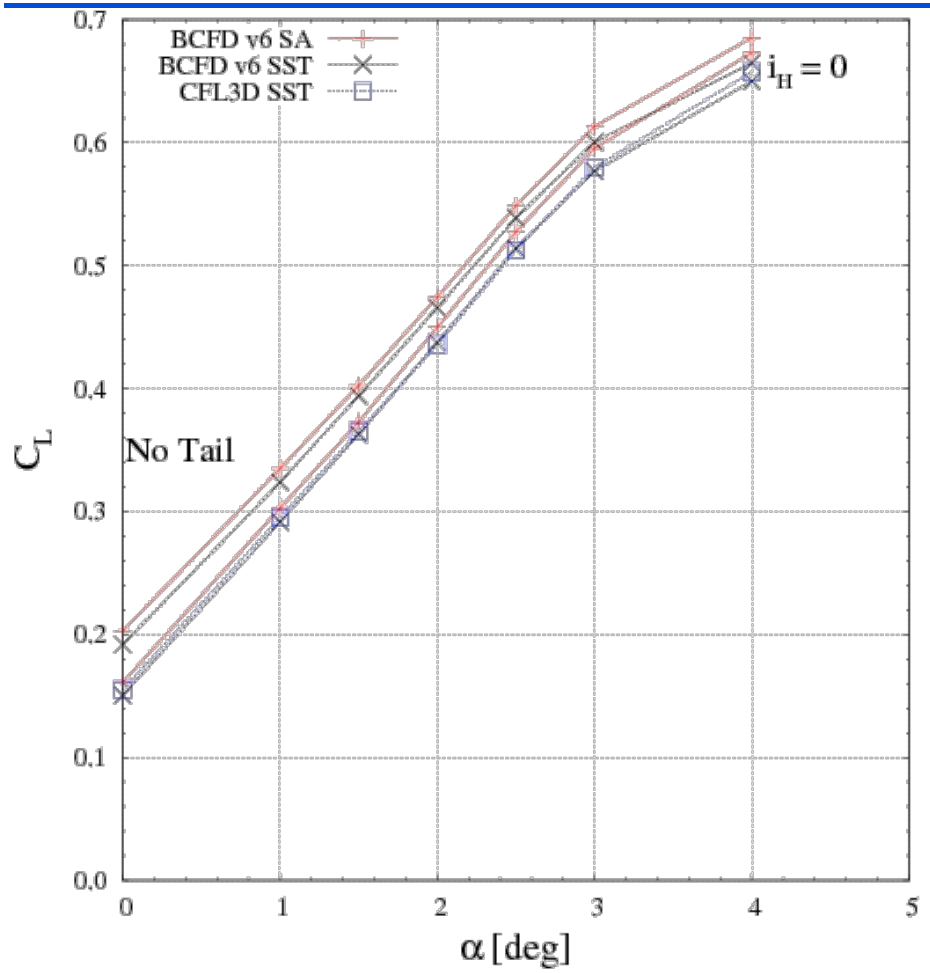
- **Case 1b: Downwash Study (both SA and SST (except SST at $i_H$ = 2))**
  - Mach = 0.85
  - Drag Polars for alpha = 0.0°, 1.0°, 1.5°, 2.0°, 2.5°, 3.0°, 4.0°
  - Tail Incidence angles, $i_H$ = -2°, 0°, +2°, and Tail off
  - Fine grid (AFLR Medium grid was seen to not be adequate for our purpose)
  - Chord Reynolds Number: Re=5M
  - Trimmed Drag Polar (CG at reference center)
    - Derived from polars at $i_H$ = -2°, 0°, +2°
  - Delta Drag Polar of tail off vs. tail on
    - i.e. WB vs. WBH trimmed

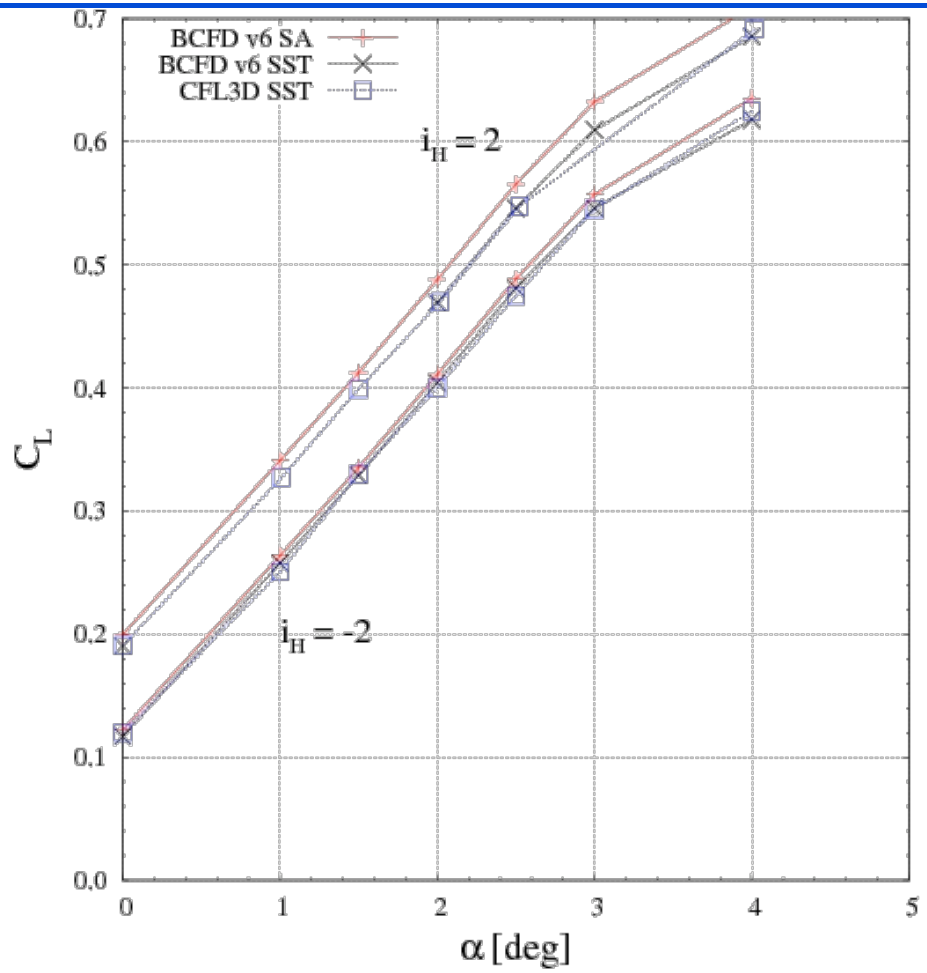
# Drag Polars – Comparison with CFL3D




- Excellent agreement between BCFD SST and CFL3D SST
- BCFD SA is seen to give slightly more drag for a given CL compared to SST

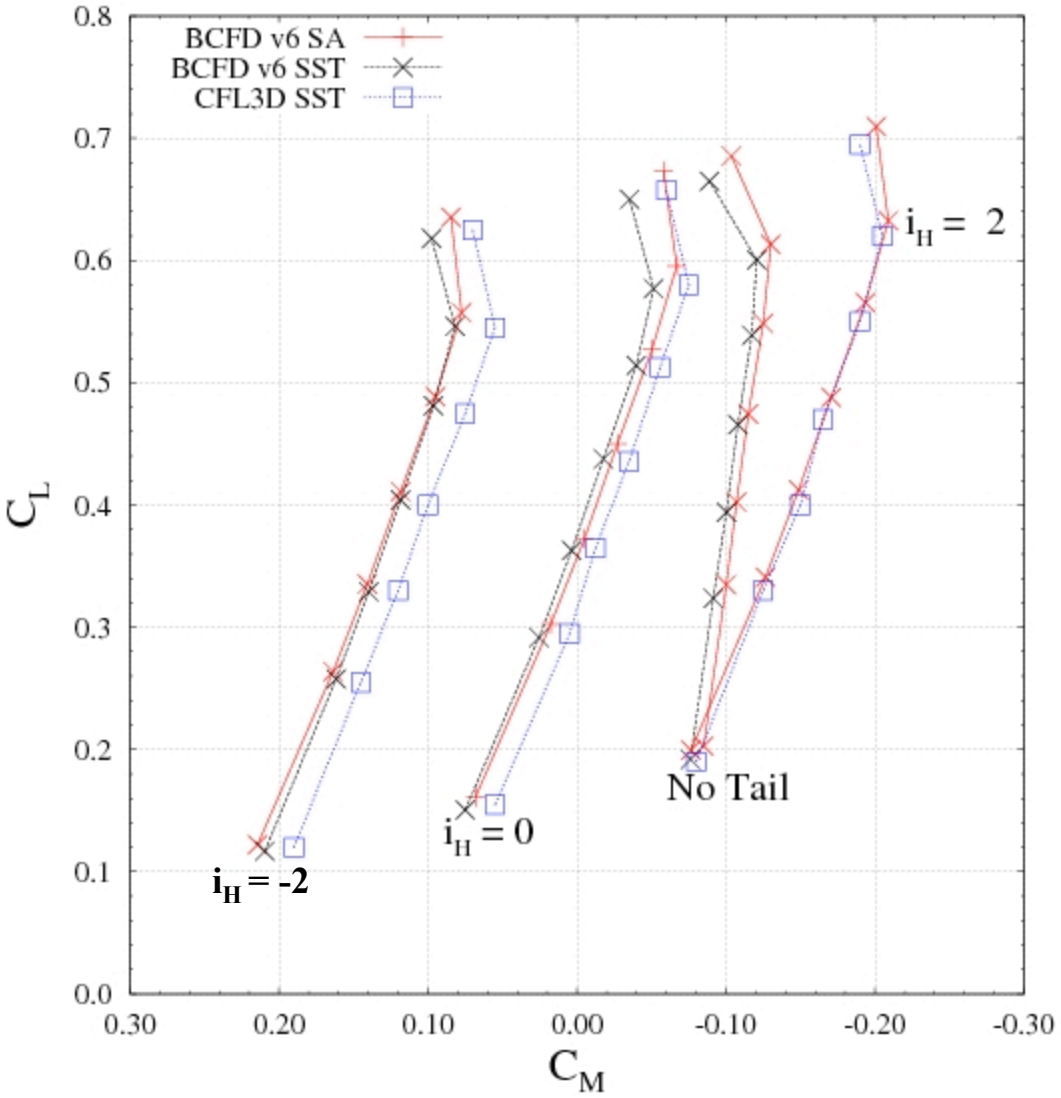
# Lift Curves – Comparison with CFL3D



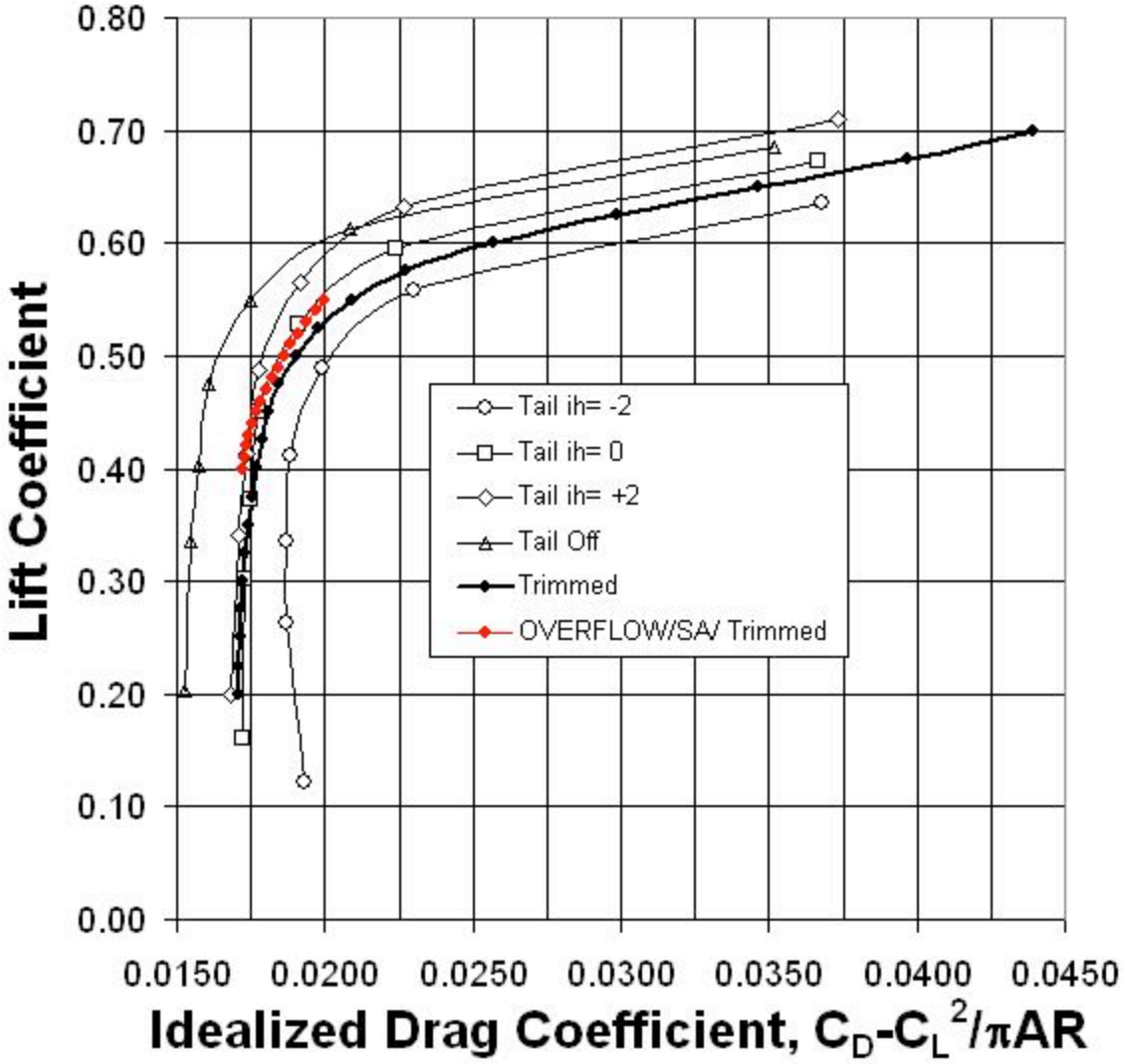

- BCFD SST predictions are seen to nearly match CFL3D SST predictions
- SA model predicts a nearly constant higher lift offset for a given AoA for any given tail setting

# Pitching Moment Results – Comparison with CFL3D



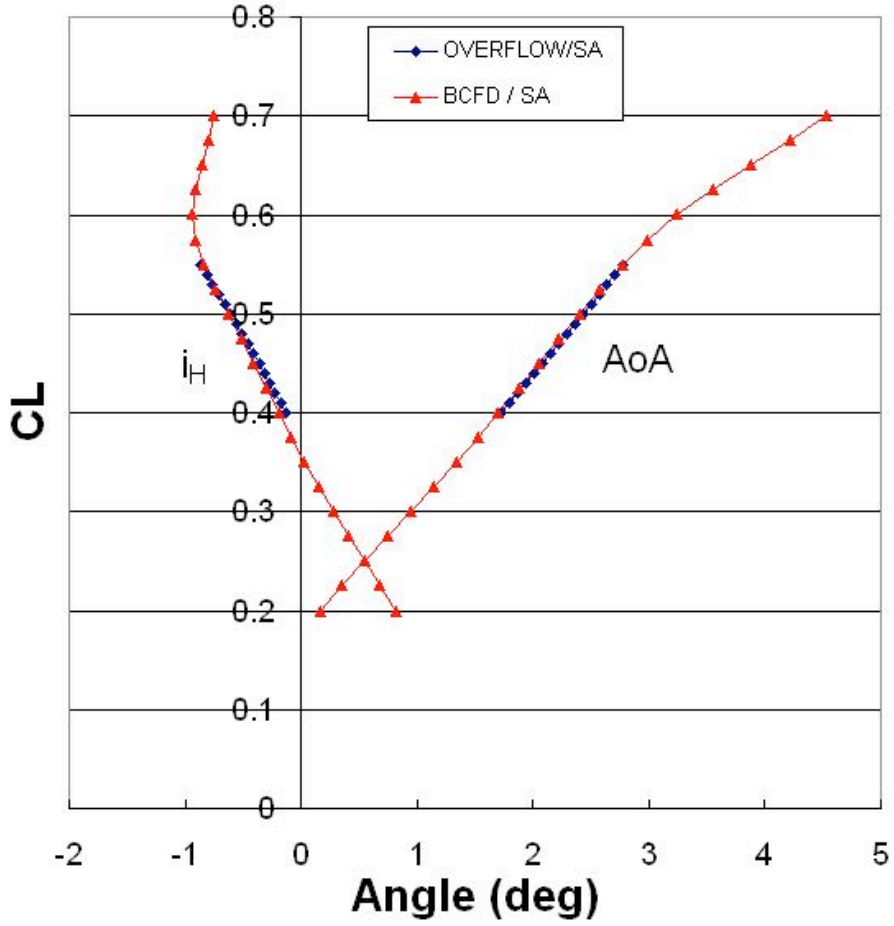

- Overall good agreement with CFL3D
- At $i_H$ = -2, BCFD SA and SST show similar $C_M$ behavior
- Pitch break similar to that observed by CFL3D
- SST seen to have a slightly more severe pitch break than SA solutions

# Trimmed Polar




- Trimmed polar defined by more points than suggested in DPW4 spreadsheet to capture “knee” in curve
- BCFD trimmed polar shifted slightly from OVERFLOW result
- OVERFLOW extrapolated to a lower drag than BCFD

# $i_H$ to Trim

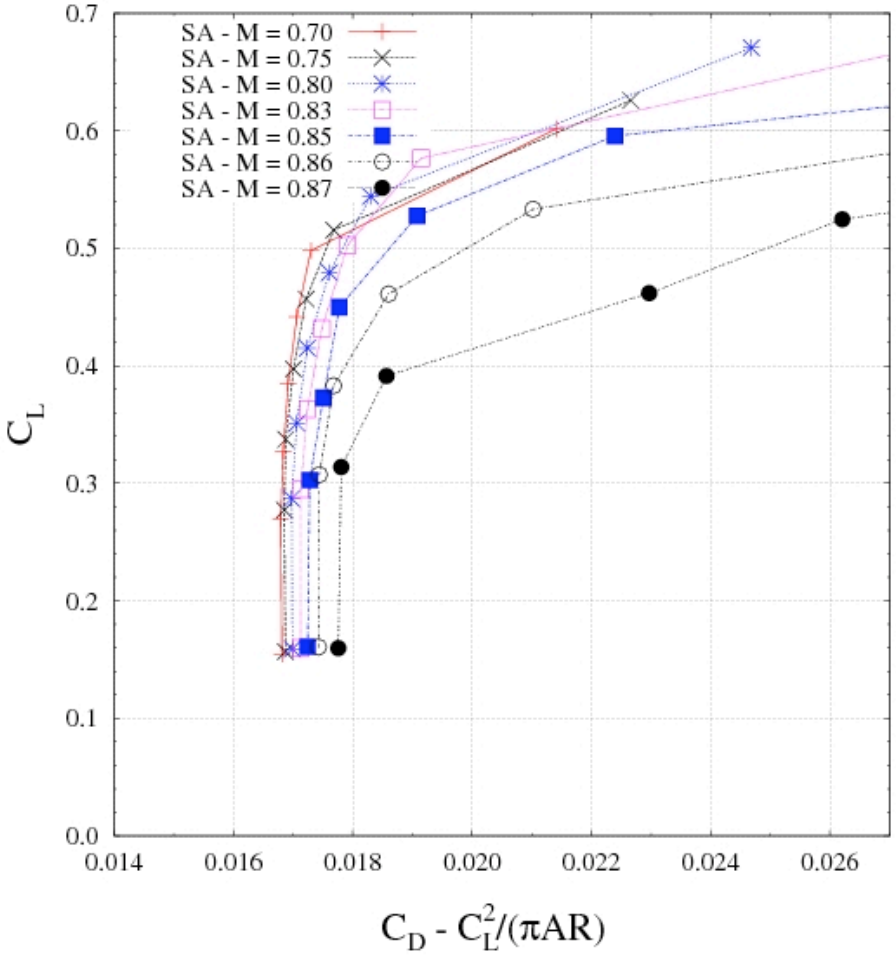


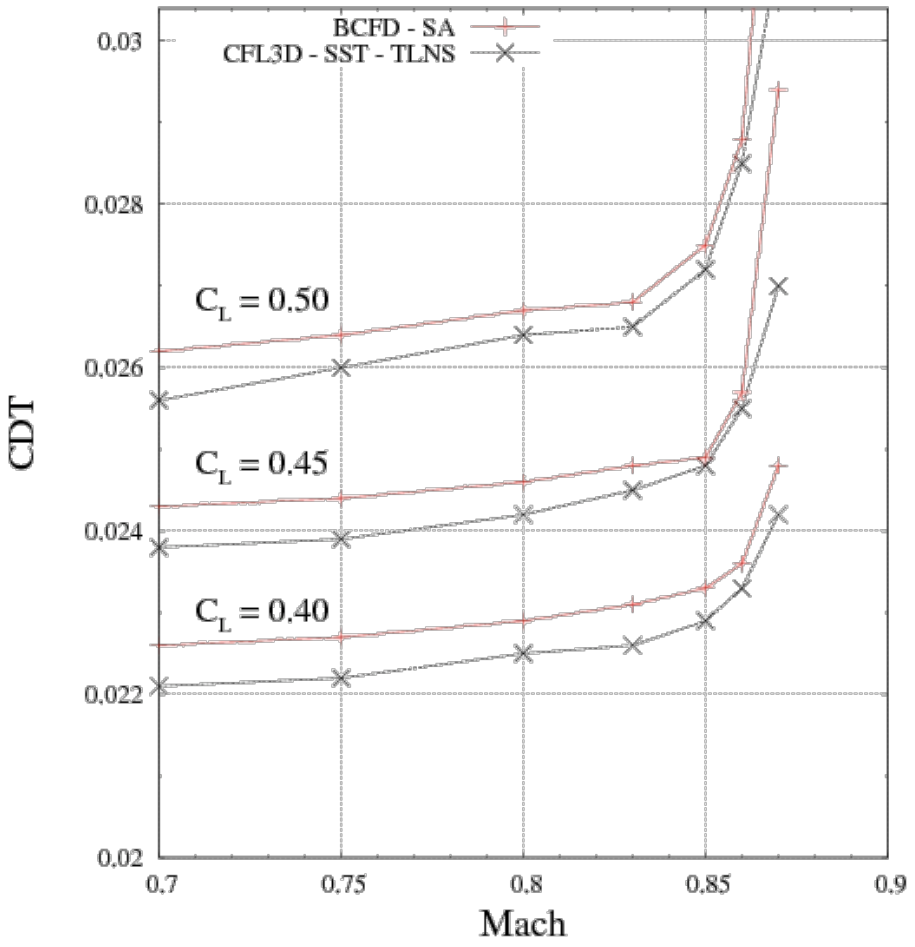

- Interpolated BCFD SA and OVERFLOW SA solutions are remarkably similar
- At CL = 0.5, trim requires $i_H$ ~ -0.6°
- Trimmed curves defined by more points than suggested in DPW4 spreadsheet

# BCFD Simulations for DPW4

- **Case 2 (Optional) : Mach Sweep Study (SA model only)**
  - Drag Polars at: Mach = 0.70, 0.75, 0.80, 0.83, 0.85, 0.86, 0.87
  - Drag Rise curves at CL = 0.400, 0.450, 0.500
    - ±0.001 or extracted from polars
  - Untrimmed, Tail Incidence angle, iH = 0°
  - Fine grid
  - Chord Reynolds Number: Re=5M

# Effect of Mach number



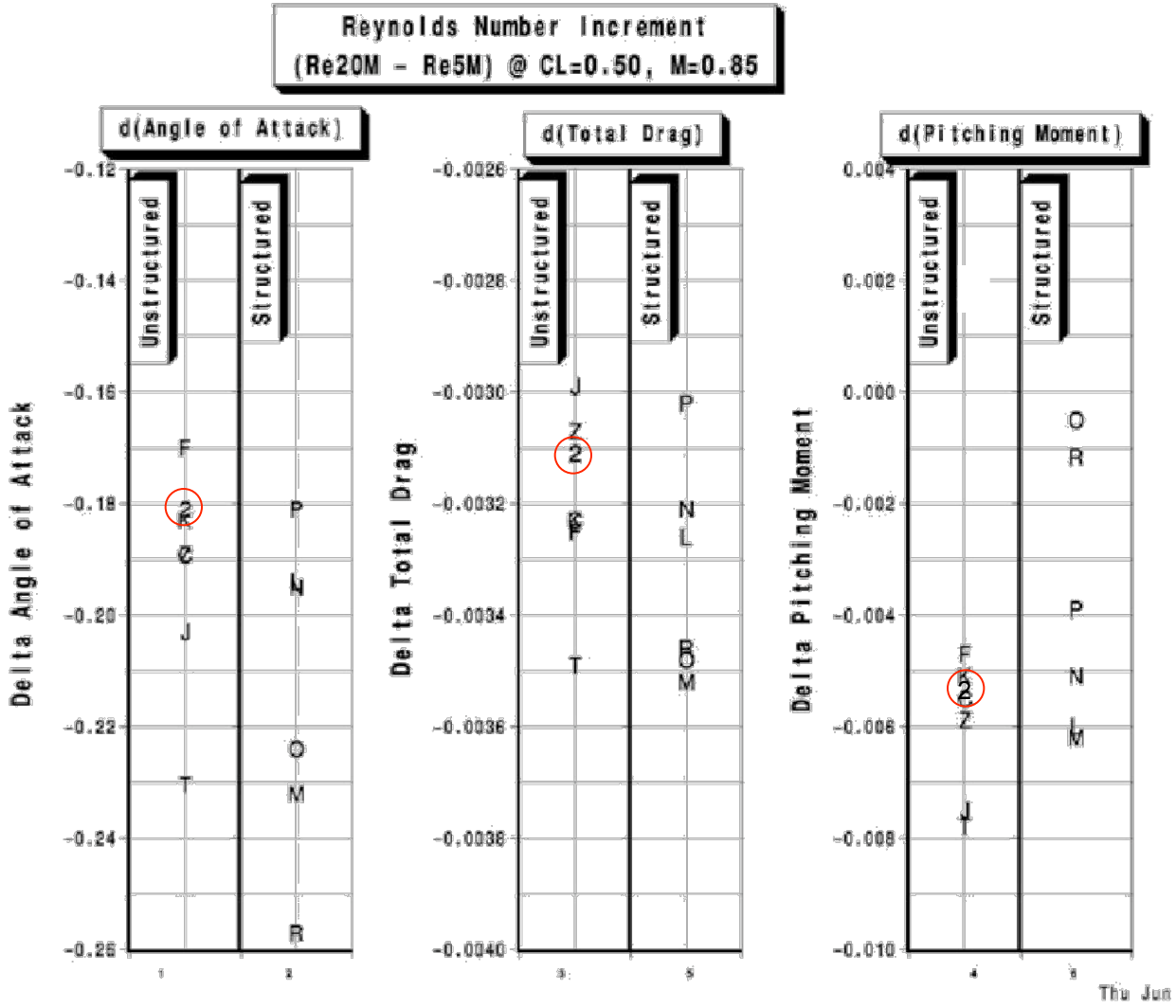




- Drag rise effects apparent in the polars
- Similar trends between BCFD SA and CFL3D SST

# BCFD Simulations for DPW4

- **Case 3 (Optional) : Reynolds Number Study (SA model only)**
  - Mach = 0.85, CL = 0.500 (±0.001)
  - Tail Incidence angle, iH = 0°
  - Fine grid
  - Chord Reynolds Numbers: Re=5M and Re=20M

# Re = 20M BCFD Results



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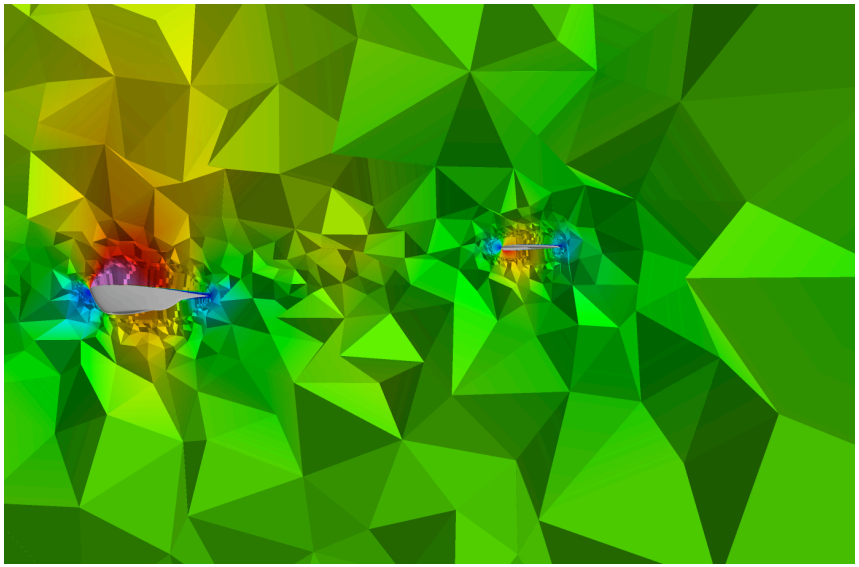
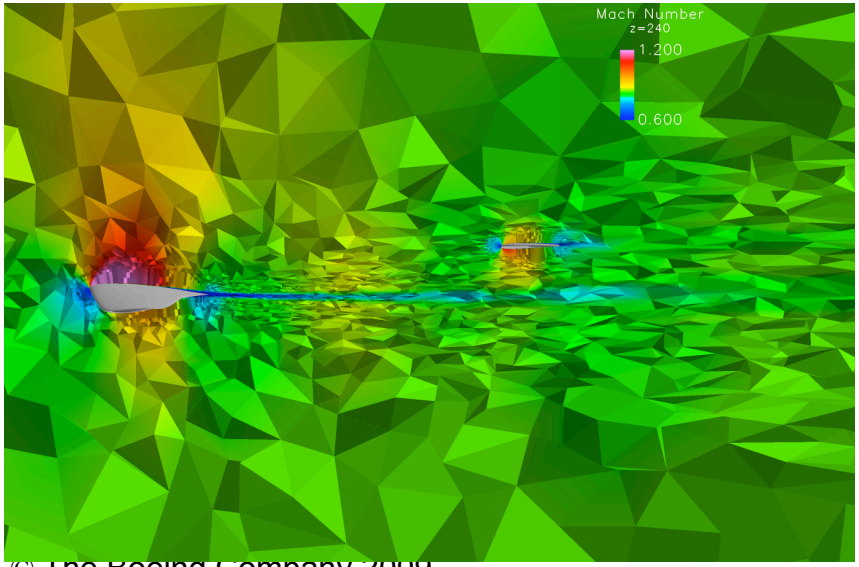
# Mach contours at BL = 240”

# Effect of anisotropic grid refinement






- Created additional grids using the medium-fine surface grid, but added an anisotropic wake sheet behind the wing and consistent AFLR options for each
- New medium-fine grid : 26.3M cells
- Medium-fine grid with anisotropic (AR = 10) sheet: 32.6M cells
- Ran at CL = 0.5 with minimal convergence differences
- Slight (5 count) drag increase with anisotropic cells (compared to medium-fine)
- Additional grids being created (AR = 100 and Fine grid with wake)

# SUMMARY

- **BCFD unstructured solutions in agreement with multiple structured codes (CFL3D, OVERFLOW) for SA and SST**
- **Completed Case 1a, 1b, 2, and 3 for DPW4 for SA and nearly completed with SST**
- **Negligible difference seen between Cp profiles predicted by BCFD and CFL3D using both SA and SST models**
- **Trim study agrees well with OVERFLOW results**
- **Drag rise similar to that seen in CFL3D**
- **Side of body separation present for all grids/turbulence models at CL = 0.5**
  - Typically less separation when the grid is refined
  - SST had a smaller SOB separation than SA

# SUMMARY

- **Tail separation**
  - Not present for SA model at CL = 0.5
  - SST model showed separation for all grids at CL = 0.5 and separation bubble size rather independent of grid size
- **For BCFD numerics: AIAA 2009-3650 (Monday)**
- **CFL3D solutions courtesy of Ed Tinoco and Ben Rider**
- **OVERFLOW solutions courtesy of John Vassberg and Tony Sclafani**