Accurate Drag Computation for the DLR-F4 Wing/body Configuration Using Multi-block, Structured-grid CFD Technology

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Contents of Presentation

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- Computational grid
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- Concluding remarks

CFD Method

ENSOLV (part of NLR’s flow simulation system ENFLOW)

- time-dependent Reynolds-averaged Navier-Stokes equations
- cell-centred, central difference, finite volume scheme
- (pseudo) time integration by explicit Runge-Kutta scheme to obtain steady-state solution
- artificial dissipation (scalar and matrix) to prevent odd-even decoupling
- local time stepping, multi-grid and residual averaging to increase convergence

CFD Method (Cont'd)

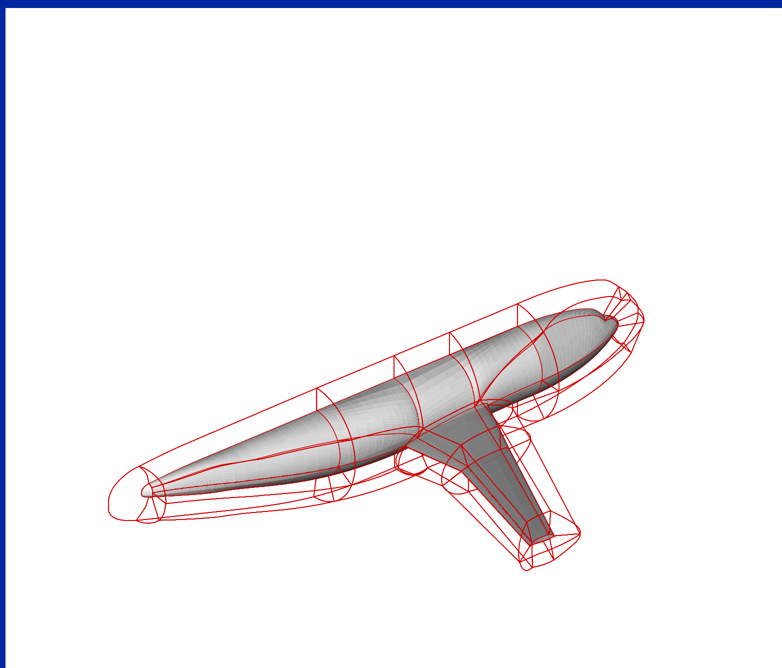
ENSOLV (part of NLR's flow simulation system ENFLOW)

- basically original k-ω turbulence model as proposed by Wilcox
- slight modification by introduction of 'cross diffusion' term to eliminate free-stream dependency of ω
- solve $\tau=1/(\omega+\omega_0)$ instead of ω, to remove singular behaviour of ω at solid walls
- production term in k-equation has been limited to prevent unphysical high values of k near stagnation point

Computational Grid ('NLR' Grid)

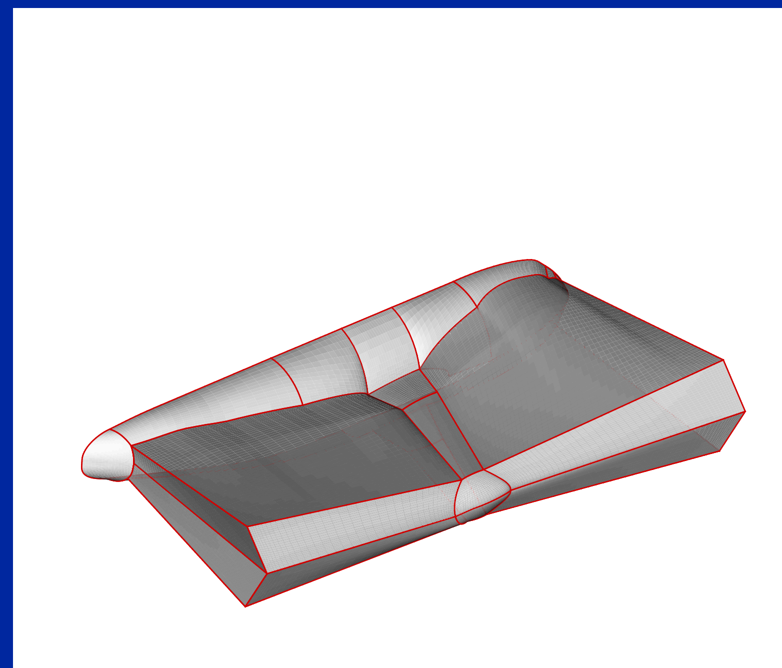
- Structured multi-block grid generated with domain modeller ENDOMO and grid generator ENGRID (part of NLR's flow simulation system ENFLOW)
- Overall topology is O-O-topology (cluster grid points around aerodynamic configuration)
- Three layers of blocks (one created by 'off-set' method, two created by 'potential' method)
- Final grid:
  - 104 blocks,
  - 2,840,576 grid cells,
  - approximately 30 grid points in boundary layer
  - y^+ equal to one

Computational Grid ('NLR'): Topology



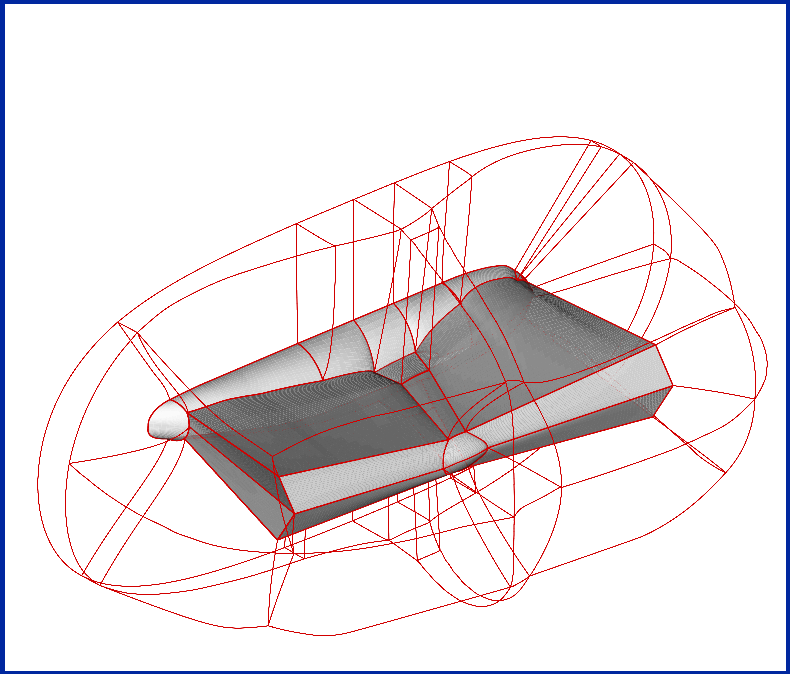
First layer of blocks
(offset method)

off-set: 0.354 amc

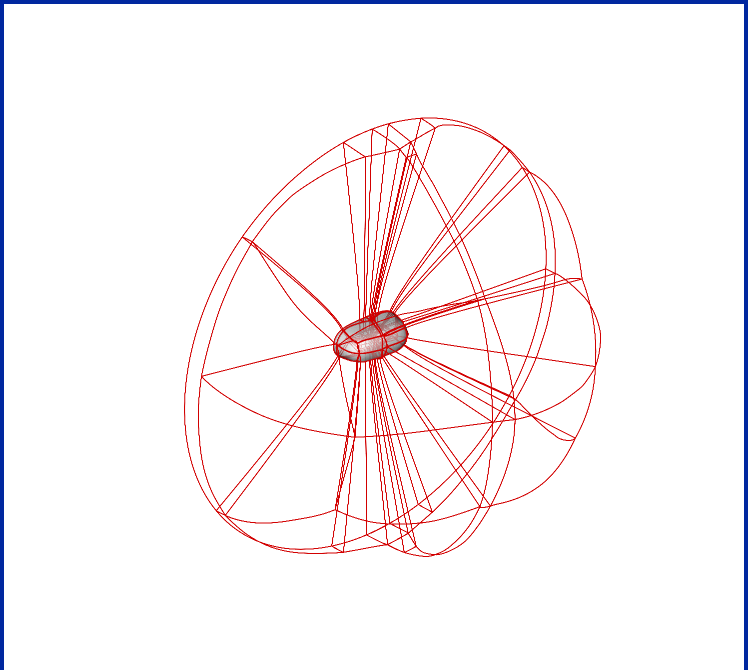


More convex first layer

Computational Grid ('NLR'): Topology (Cont'd)



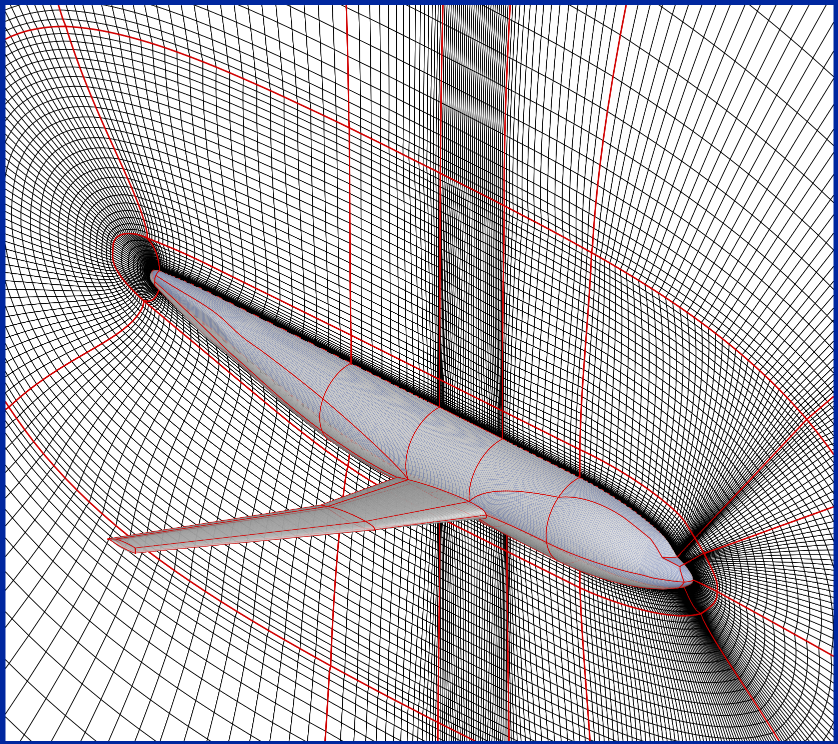
Second layer of blocks (potential method)



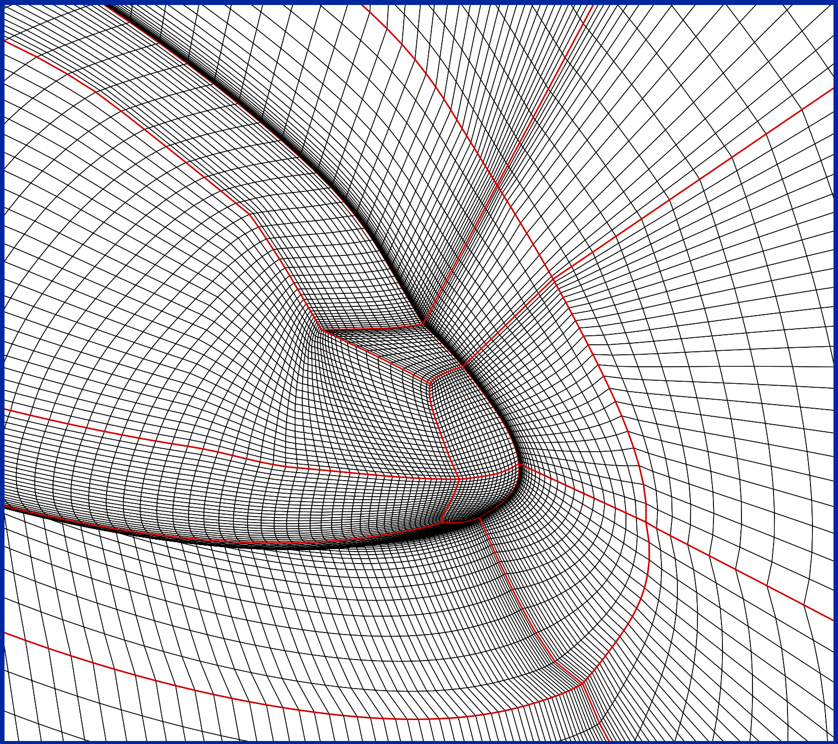
Third layer of blocks (potential method)

far-field: 38 amc

Computational Grid ('NLR')



Grid in symmetry plane



Grid around nose

Red lines indicate block boundaries

Test Cases

All test cases of AIAA Drag Prediction Workshop have been calculated using ‘NLR’ grid (test case one and three also using ‘DPW’ grid)

- Results are presented in paper
- Drag polar simulations (test case two) have been compared with NLR-HST experiment
- Data point α=0° and M_∞=0.75 (test case two) used for further study:
  - Grid convergence study
  - Drag breakdown analysis

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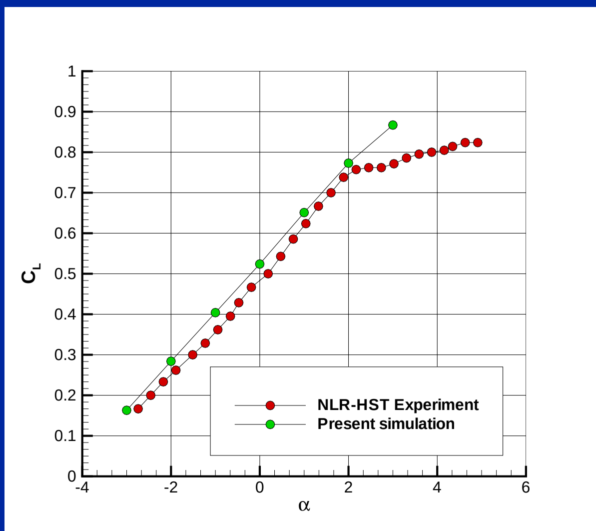
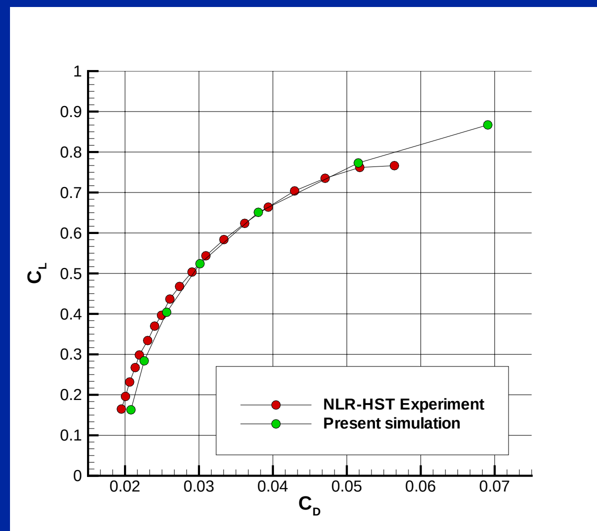
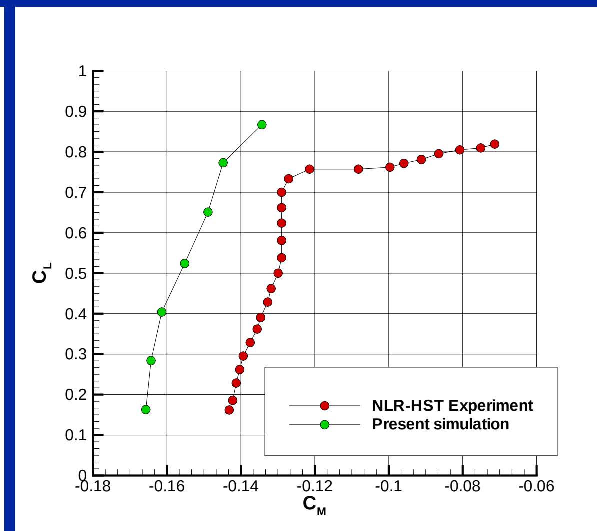
Drag Polar Simulations (Test Case 2)



C_L-α-curve



C_L-C_D-curve



C_L-C_M-curve

- Experimental data: NLR-HST wind tunnel (AGARD-AR-303)
- Data point α=0° and M_∞=0.75 used for grid convergence study and drag breakdown analysis

Grid Convergence Study

Basic assumption for this ‘near-field’ extrapolation method

- Global accuracy of CFD solution on family of successively refined grid depends on relative mesh size h

Total drag coefficient on sequence of nested grids can be represented by:

- $C_D(h)=C_D(h=0)+c_1h+c_2h^2$, or
- $C_D(h)=C_D(h=0)+c_3h^{3/2}$

$C_D(h=0)$ is the grid-converged drag coefficient, i.e drag coefficient for vanishing mesh width

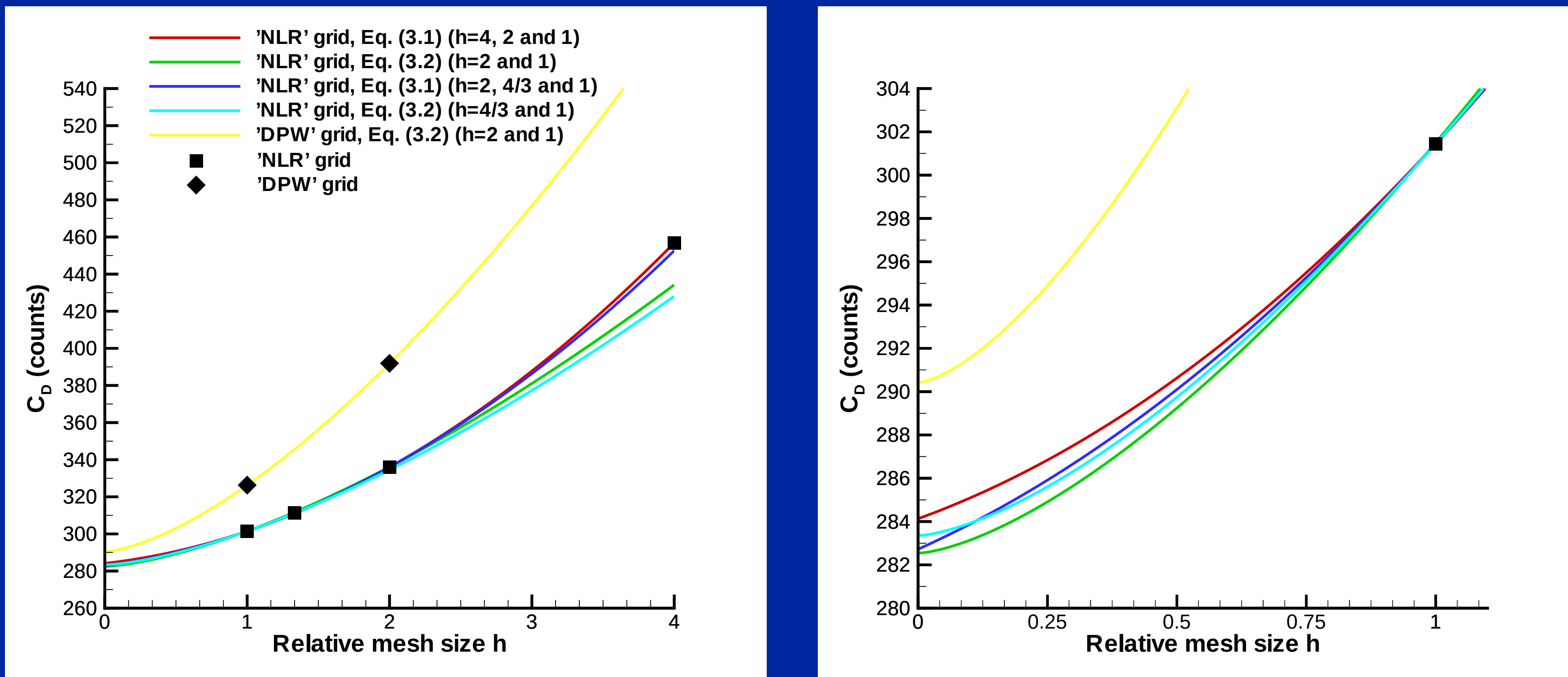
Grid Convergence Study (Cont'd)

Grids used in present study:

- h=1-grid,
- h=2-grid (deleting alternately grid points from h=1-grid),
- h=4-grid (deleting alternately grid points from h=2-grid), and
- h=4/3-grid (3/4 of number of grid points in each direction compared to h=1-grid)

Grids belong to same family, i.e. in terms of cell angle, cell aspect ratio and cell stretching

Grid Convergence Study (Cont'd)



Aerodynamic drag extrapolation for α=0° and M_∞=0.75

Grid Convergence Study: Conclusions

'NLR' grid

- Difference between lowest (282.5 drag counts) and highest (284.1 drag counts) extrapolated value only 1.6 drag counts

'DPW' grid

- Extrapolated value using h=2-grid and h=1-grid 290.4 drag counts, i.e. approximately 7 drag counts higher than on 'NLR' grid

O-O-topology ('NLR' grid) well suited for 'near-field' extrapolation method, due to clustering of grid points around configuration

Drag Breakdown Analysis

Decompose aerodynamic drag into its ‘physical’ components (‘far-field’ approach), i.e.

- Vortex drag: due to trailing, streamwise vorticity
- Viscous drag: due to turbulent dissipation in boundary layers and wakes
- Wave drag: due to shock waves

In addition also spurious drag present (neither vortex drag, viscous drag or wave drag)

Combination of viscous drag, wave drag and spurious drag is referred to as entropy drag

Drag Breakdown Analysis (Cont'd)

Calculation procedure is as follows:

1 Calculate vortex drag on 'Trefftz plane' downstream of aerodynamic configuration using vorticity-streamfunction formulation

2 Calculate entropy drag for all cells in box surrounding aerodynamic configuration

3 Assign entropy drag to either wave drag, viscous drag or spurious drag using automated zonal detection algorithm

Drag Breakdown Analysis (Cont'd)

Automated zonal detection algorithm:

- Entropy drag is assigned to wave drag, if value of shock sensor (based on local velocity and pressure gradients) exceeds threshold
- Entropy drag is assigned to viscous drag, if value of viscous sensor (based on dissipation function associated with fluid viscosity) exceeds threshold
- Otherwise entropy drag is assigned to spurious drag

Spurious drag is not added to total drag balance

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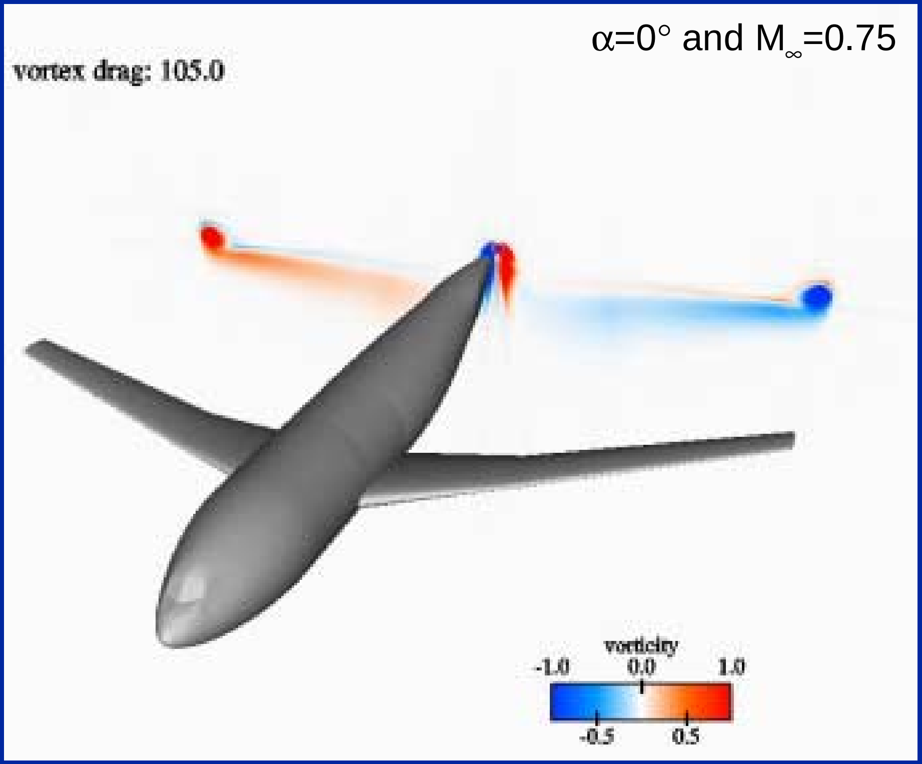
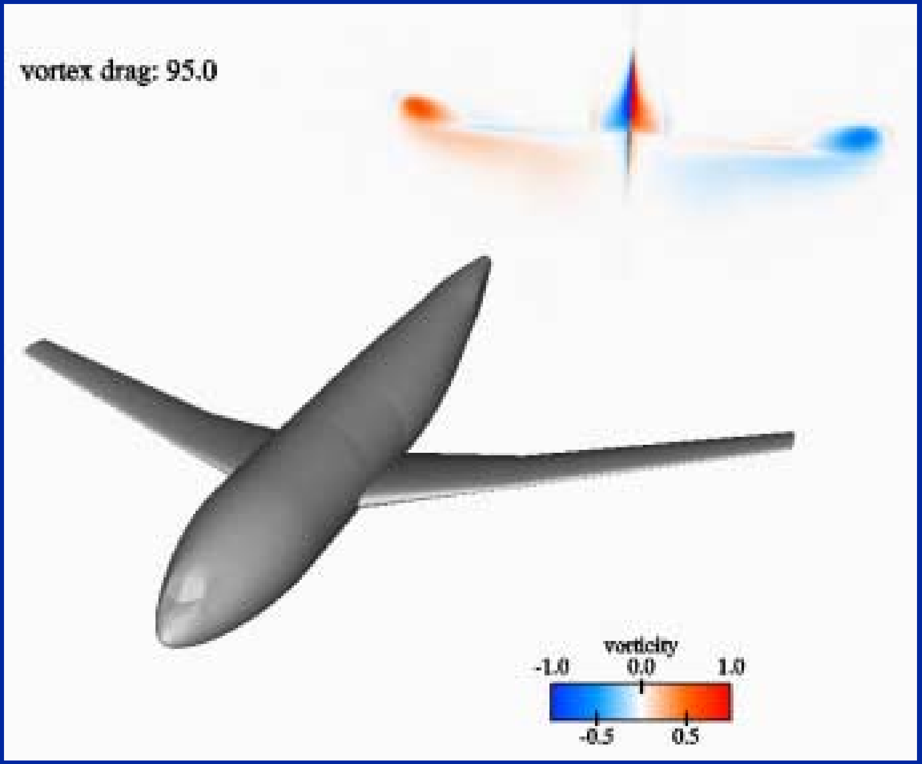
Drag Breakdown Analysis: Vortex Drag

'DPW'grid (H-H)



$x_{Trefftz}$=1250 mm



$x_{Trefftz}$=2400 mm

Decrease of vortex drag: 10 drag counts

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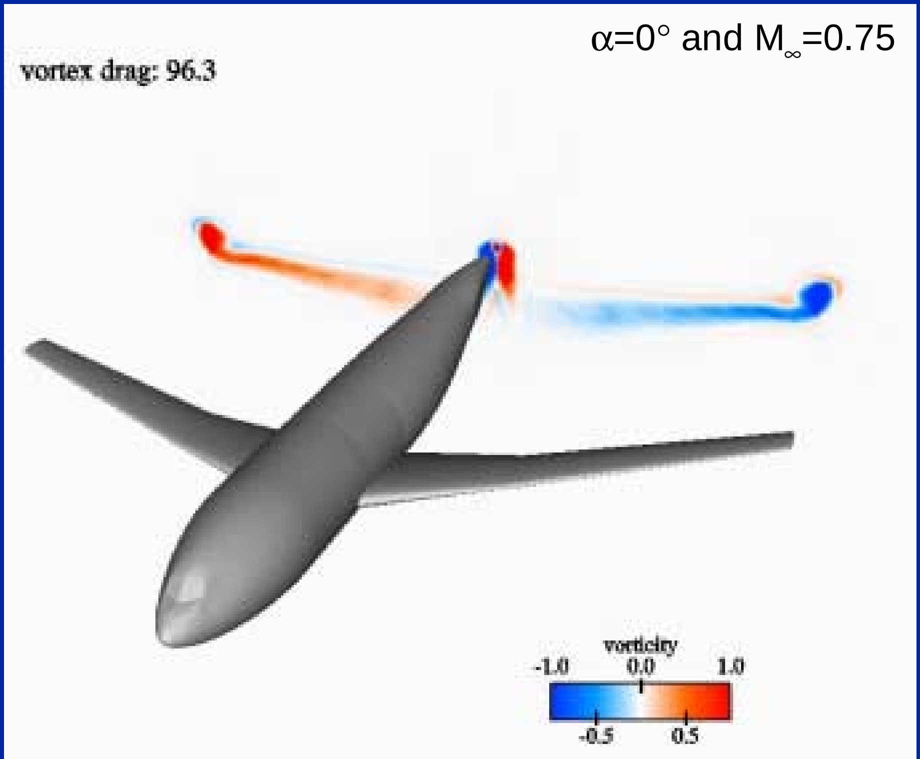
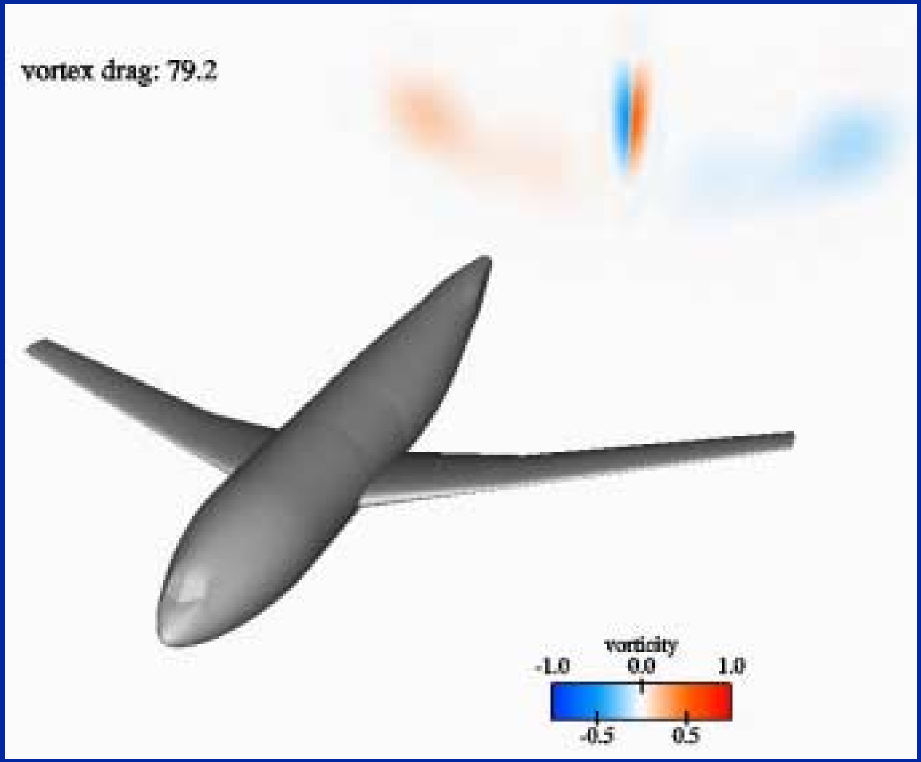
Drag Breakdown Analysis: Vortex Drag (Cont'd)

'NLR'grid (O-O)



$x_{Trefftz}$=1250 mm



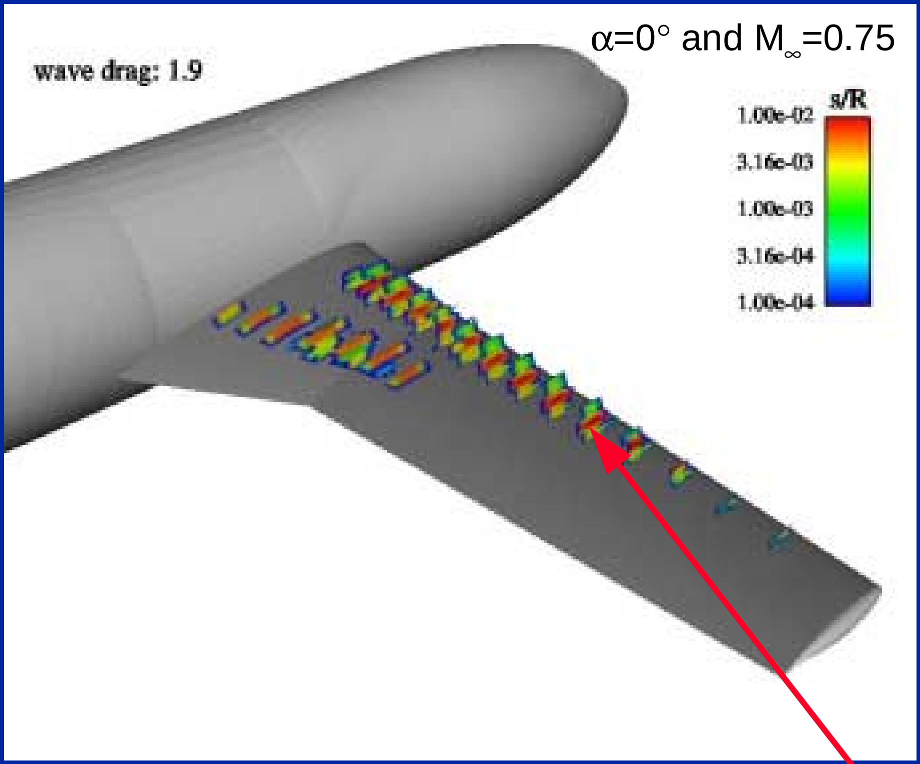
$x_{Trefftz}$=2400 mm

Decrease of vortex drag: 17.1 drag counts

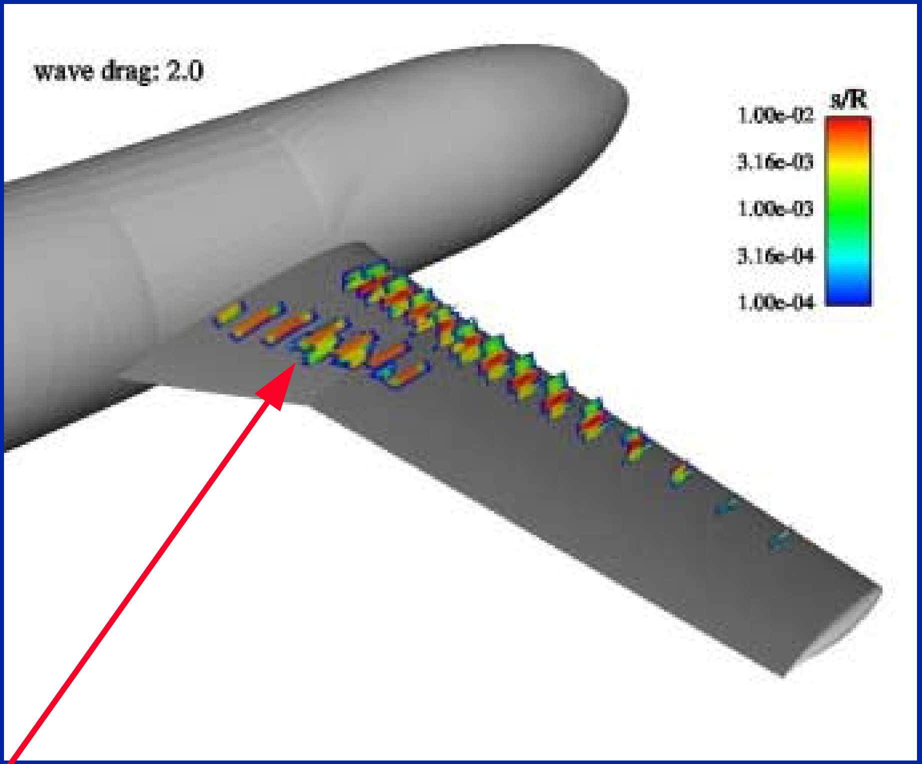
O-O-topology in wake ⇨ faster vorticity dissipation

Drag Breakdown Analysis: Wave Drag

'DPW'grid (H-H)



$x_{Trefftz}$=1250 mm



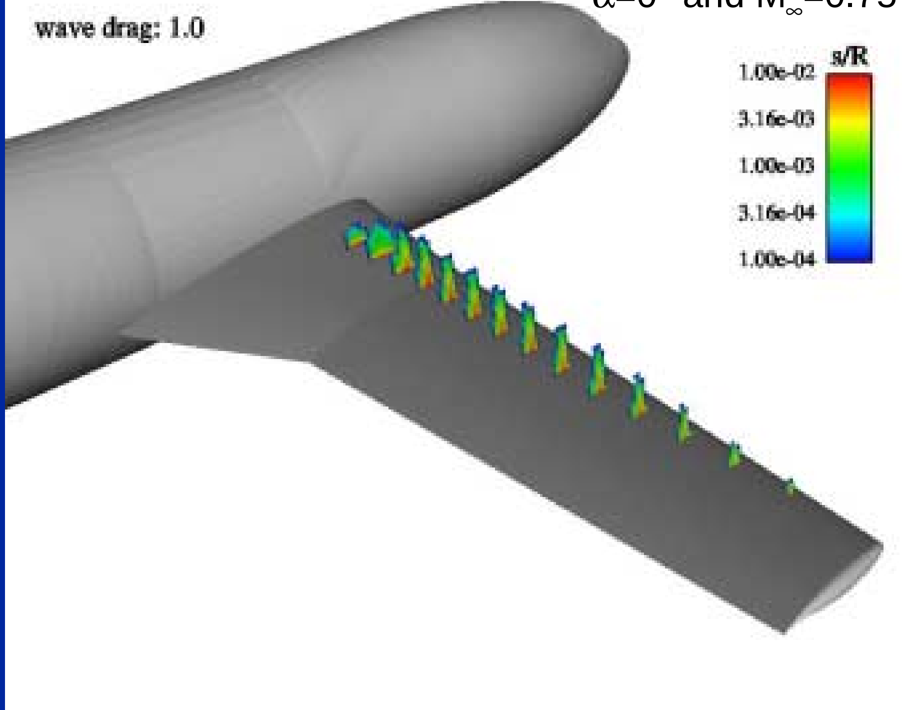
$x_{Trefftz}$=2400 mm

Spurious wave drag contributions (1 drag count) on block boundaries

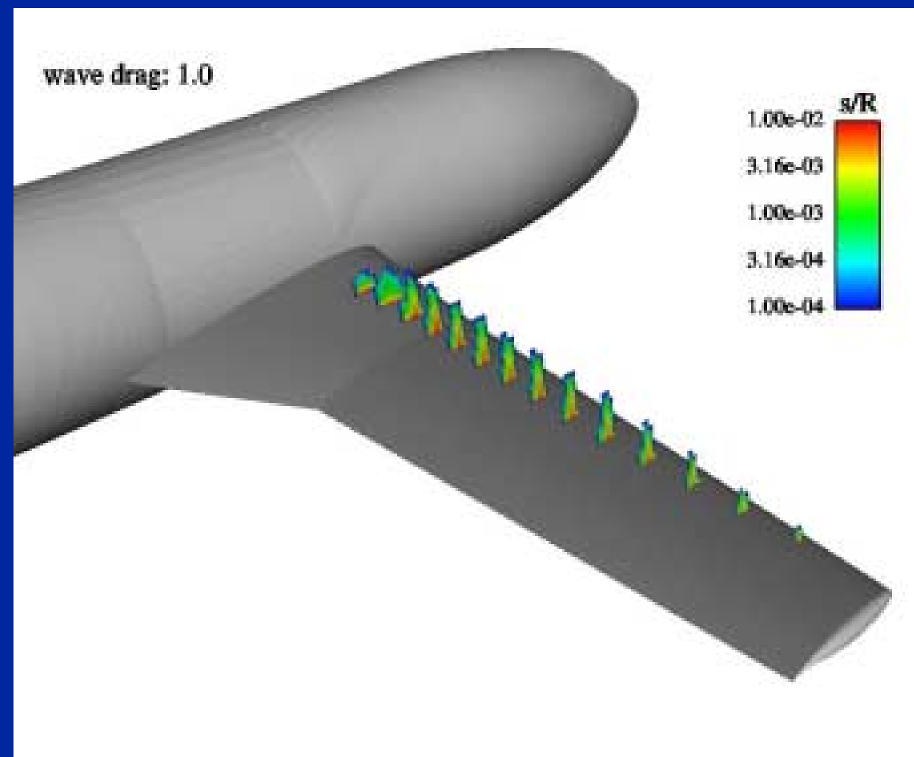
Drag Breakdown Analysis: Wave Drag (Cont'd)

'NLR'grid (O-O)

α=0° and M_∞=0.75



$x_{Trefftz}$=1250 mm



$x_{Trefftz}$=2400 mm

O-O-topology ⇨ no spurious wave drag contributions

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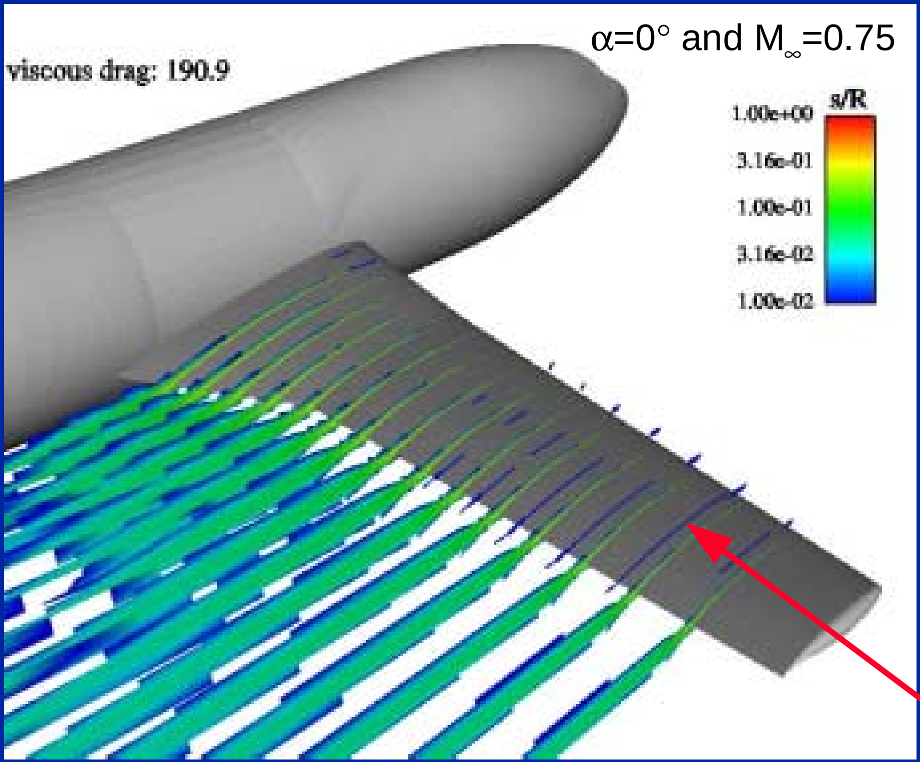
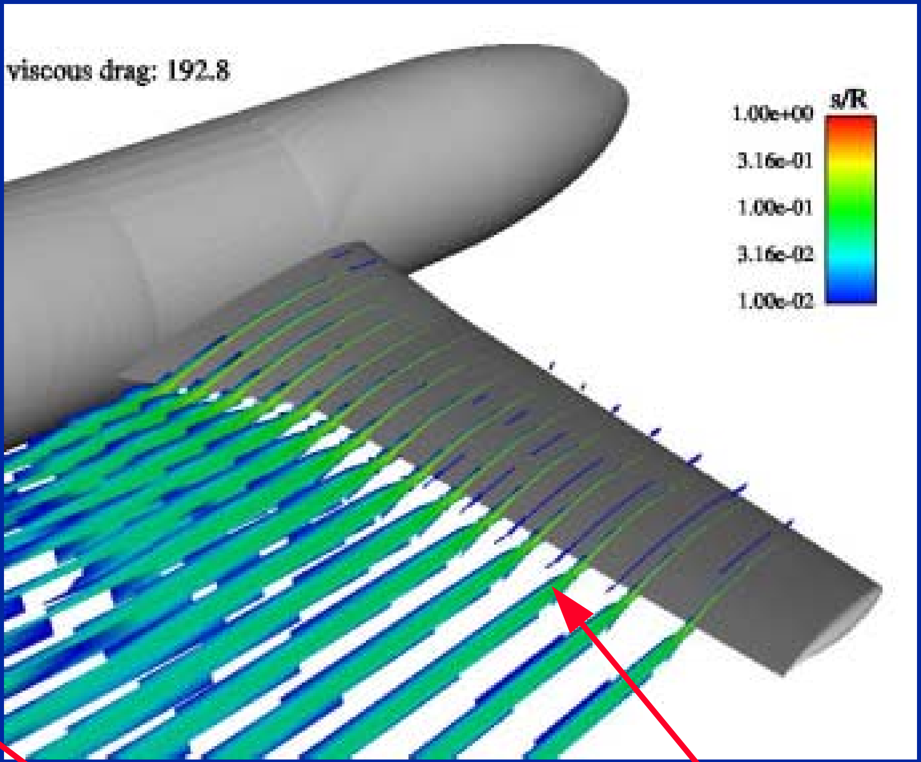
Drag Breakdown Analysis: Viscous Drag

'DPW'grid (H-H)

α=0° and M_∞=0.75



$x_{Trefftz}$=1250 mm



$x_{Trefftz}$=2400 mm

Spurious viscous drag contributions on block boundaries and in wake

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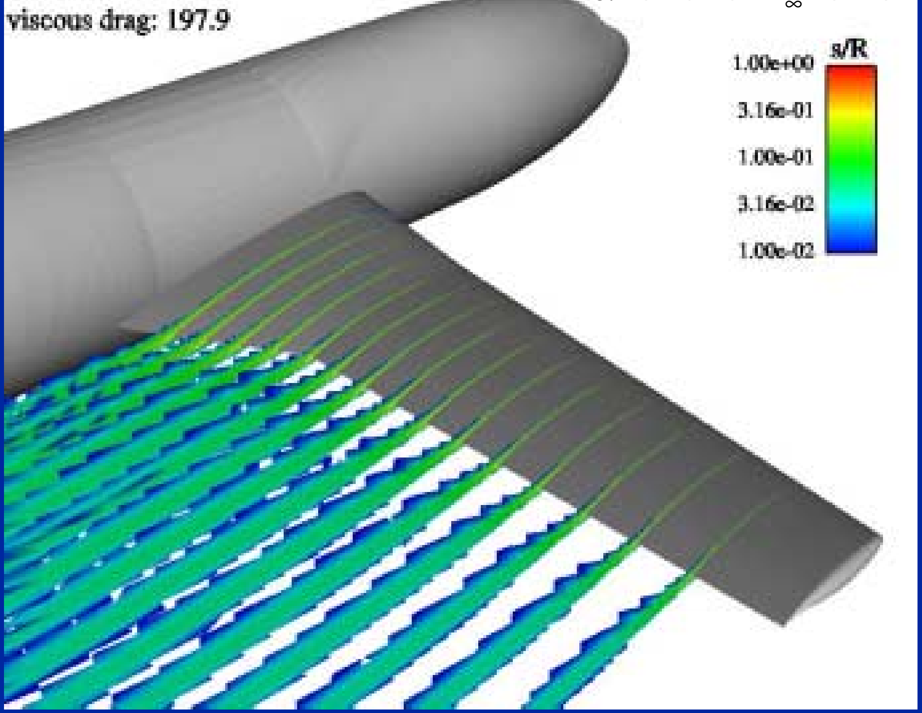
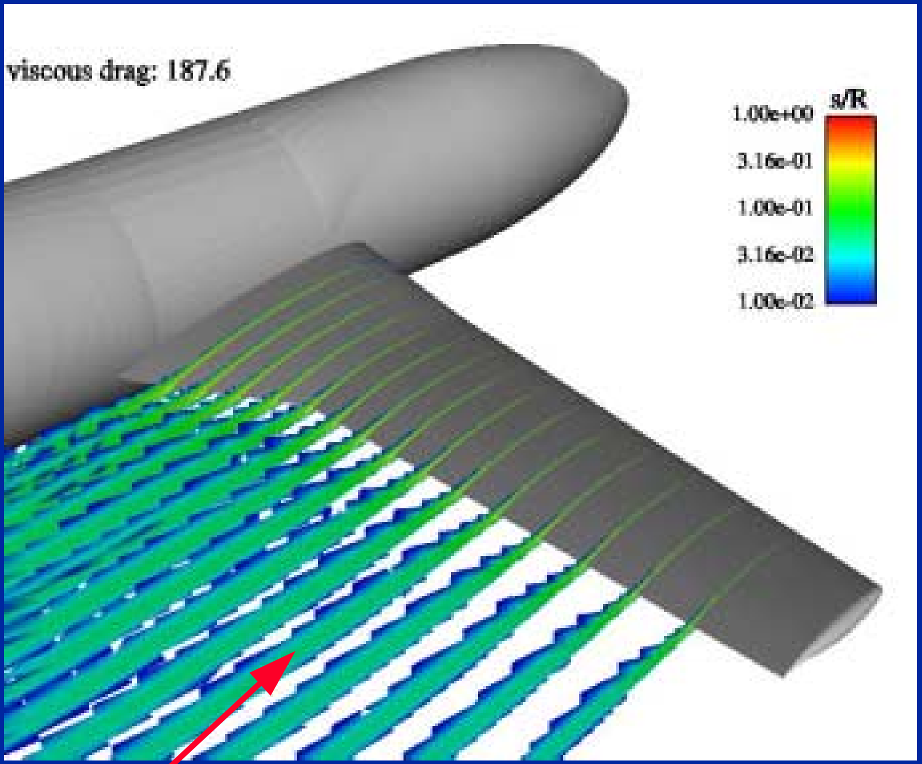
Drag Breakdown Analysis: Viscous Drag (Cont'd)

'NLR'grid (O-O)

$\alpha=0°$ and $M_\infty=0.75$



$x_{Trefftz}$=1250 mm



$x_{Trefftz}$=2400 mm

Spurious viscous drag contributions in wake

Total Drag Breakdown Analysis: Conclusions

- Total drag coefficients for $x_{Trefftz}$=1250 mm (least amount of vorticity dissipation)
  - On ‘DPW’ grid: C_D=297.8 drag counts
  - On ‘NLR’ grid: C_D=295.2 drag counts
- Good grid quality (e.g. in terms of vorticity convection) required to obtain accurate results
- Method helpful to aerodynamic designers, due to diagnostic potential

Grid Convergence Study Vs. Total Drag Breakdown

- 'Far-field' drag breakdown approach results in higher total drag values than 'near-field' extrapolation method
  - 7.4 drag counts on 'DPW' grid
  - 11.1-12.7 drag counts on 'NLR' grid
- Note that 'NLR' grid (O-O-topology) is more suited for 'near-field' extrapolation method, due to clustering of grid points around configuration. However, on coarsest grid flow features should still be captured!
- If applied to sequence of grids, 'far-field' method yields same grid-converged drag result

Concluding Remarks

Two methods to obtain accurate drag values have been presented:

- ‘near-field’ extrapolation method
- ‘far-field’ drag breakdown method

Both methods require good grid quality to obtain accurate results:

- ‘near-field’ extrapolation method on coarsest grids
- ‘far-field’ drag breakdown method in wake region

‘Far-field’ drag breakdown method is helpful to aerodynamic designers, because its diagnostic potential