CFL3D and FUN3D Analysis of HiLiftPW-2 Workshop Cases

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2nd AIAA CFD High Lift Prediction Workshop (HiLiftPW-2)
Sponsored by the Applied Aerodynamics TC
San Diego, CA
June 22-23, 2013
CFD Code Descriptions

- **CFL3D Structured-Grid Code**
  - Parallel 3D compressible cell-centered finite-volume RANS
  - Full Navier-Stokes equations
  - Upwind Roe flux-difference splitting for inviscid fluxes
  - Spalart-Allmaras and SST turbulence models, fully-turbulent
  - SST-Gamma-Re-Theta (GRET), transition
  - Implicit local time-stepping using AF relaxation for linear system
  - Restart computations from lower angles of attack

- **FUN3D Unstructured-Grid Code**
  - Parallel 3D compressible finite-volume RANS for mixed-element meshes
  - Full Navier-Stokes equations-node centered
  - UMUSCL 0.5 scheme (Averaging + Upwind) for inviscid fluxes
  - Spalart-Allmaras turbulence model, fully-turbulent
  - Implicit local time-stepping using multi-color point Gauss-Seidel relaxation for linear system
  - Restart computations from lower angles of attack
Cases and Grids

- Required Case 1 and Case 2
- Optional Case 3 not done

<table>
<thead>
<tr>
<th></th>
<th>Struct. 1 to 1 – A (Boeing)</th>
<th>Unst. Nodal - D (UWYO/Cessna)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FUN3D</td>
<td></td>
<td>SA (Mixed)</td>
</tr>
<tr>
<td>CFL3D (Case 1 only)</td>
<td>SA SST (incomplete)</td>
<td>GRET (incomplete)</td>
</tr>
</tbody>
</table>

http://fun3d.larc.nasa.gov
## Comparison of Grid Sizes

<table>
<thead>
<tr>
<th></th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Struct. 1-to-1 A Boeing</td>
<td>11M</td>
<td>34M</td>
<td>105M</td>
</tr>
<tr>
<td>Mixed ver. Unst. D UWYO/Cessna</td>
<td>10M</td>
<td>31M</td>
<td>76M</td>
</tr>
</tbody>
</table>
Case 1 – FUN3D Grid Convergence, SA

Lift

Drag

Pitching Moment

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Case 1 – CFL3D Grid Convergence, SA

Lift

Drag

Pitching Moment

002.2 case1 FT coarse no tracks
002.2 case1 FT medium no tracks
002.2 case1 FT fine no tracks
Exp. ETW

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Case 1 – CFL3D results, other models

Medium Grids

Lift
Drag
Pitching Moment

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Case 1 – Grid Convergence, SA

Lift

Drag

Pitching Moment

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Case 1 – Grid Convergence, AoA=7

Lift

Drag

Pitching Moment

Note: Grid D (fine) was discovered to have incorrect min spacing – so not of similar family to C and M.
Case 1 – Grid Convergence, AoA=16

Lift

Drag

Pitching Moment

Note: Grid D (fine) was discovered to have incorrect min spacing – so not of similar family to C and M.
Case2 – Reynolds Number Study

Lift

Drag

Pitching Moment

002.1 case2a (low Re) FT medium w tracks
002.1 case2b (hi Re) FT medium w tracks
Exp. LSTW low Re
Exp. ETW hi Re

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Case 1 Surface Restricted Streamlines

AOA 16deg
Medium Grids

FUN3D

CFL3D

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FUN3D Surface Restricted Streamlines

AOA 16deg
Medium Grid

Case 1

Case 2b

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Case 1 Surface Restricted Streamlines

AOA 20deg
Medium Grids

FUN3D

CFL3D

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FUN3D Surface Restricted Streamlines

AOA 20deg
Medium Grid

Case 1
Case 2b
FUN3D Surface Restricted Streamlines

AOA 18.5deg
Medium Grid

Exp. Oil Flow

Case 2a
FUN3D Pressure Distributions

Case 1 Medium Grid
Eta = 0.45

Red - 7deg
Blue - 16deg
Green - 18.5deg
Black - 21 deg

Slat
Main
Flap

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FUN3D Pressure Distributions

Case 2b
Eta = 0.45

Red - 7deg
Blue - 16deg
Green - 18.5deg
Black - 21 deg

Slat      Main      Flap

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FUN3D Pressure Distributions

Case 1 Medium Grid
Eta = 0.75

Red - 7deg
Blue - 16deg
Green - 18.5deg
Black - 21 deg

Slat  Main  Flap

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FUN3D Pressure Distributions

Case 2b
Eta = 0.75

Slat
Main
Flap

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Velocity contours over flap, AoA=7

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Velocity profiles over flap, AoA=7

Plane 2
Case 1 Medium/Fine Grids

Note: exp data at low Re, shown for reference only
Effect of Re on velocity profiles, AoA=7

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Summary (1)

- Grid convergence study (no brackets)
  - Structured grid and unstructured grid results with same turbulence model (SA) compare reasonably well in forces/moments
  - There is flap separation at all AoAs
    - FUN3D on unstructured D grid shows more separation than CFL3D on structured A grid
  - Maximum lift coefficient is over-predicted
  - At higher alphas, there are larger differences between codes (esp. in the moment coefficient)
  - CFL3D on structured A grid series captures wake profiles better than FUN3D on unstructured D grid series
Summary (2)

- Bracket study
  - Including brackets improves results (forces, moments, surface pressures)
  - General trends captured
  - \(C_{L,\text{max}}\) not predicted well due to early main wing separation
  - Slat wakes not resolved on D grids

- Reynolds number study
  - General trends captured, but \(C_{L,\text{max}}\) not predicted well
  - Velocity profiles compare with experiment only qualitatively
Next Steps

- Adjoint-based adaption: output functional L/D
  - Off-body adaption
  - C1 coarse and medium grids (SA model)
  - AOA 16deg
  - Four adaption cycles (4 additional adjoint and flow solutions)
C1 Medium Grid Adaption $\eta=70\%$

Original Grid – 31M nodes

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C1 Medium Grid Adaption $\eta=70\%$

Adapted 4 – 62M nodes

C1 Medium Grid Adaption Flap Cp

η=72%

η=82%

η=89%

Orig. Grid – 31M nodes : Adapted 4 – 62M nodes

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Effect of Turb. Model on Flap Cp

$\eta = 89\%$

SADM – SA model with Dacles-Mariani correction

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Backup Slides
CFL3D Residual Convergence

C1 Medium Grid Polar

RESIDM-1 vs ITER

- 7deg
- 16deg
- 18.5deg
- 20deg
- 21deg
- 22.4deg

CD
CL

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HiLiftPW-2 - Rehearsal Background

Objectives

- Assess the numerical prediction capability (meshing, numerics, turbulence modeling, high-performance computing requirements, etc.) of current-generation CFD technology/codes for swept, medium-to-high-aspect ratio wings for landing/take-off (high-lift) configurations.
- Develop practical modeling guidelines for CFD prediction of high-lift flow fields.
- Determine the elements of high-lift flow physics that are critical for modeling to enable the development of more accurate prediction methods and tools.
- Enhance CFD prediction capability for practical high-lift aerodynamic design and optimization.

Focus

- The HiLiftPW-2 test cases are based on the European High Lift Programme (EUROLIFT) DLR F11 high-lift configuration.
  - Representative of a commercial wide-body twin-jet high-lift configuration
  - 3 elements: full-span slat, main and full-span flap
  - Landing configuration: slat 26.5 degs and flap 32 degs
- A significant amount of high-quality surface and flow field data are available, including data for an assessment of Reynolds number scale effects.
  - Force and moment (ETW and B-LSWT)
  - Surface pressures (ETW and B-LSWT)
  - PIV and oil flow (B-LSWT)
HiLiftPW-2 – DLR F11

Pressure Tap Stations

η = 75.1%

η = 44.9%

PIV Planes

η = 87.4%

η = 70%

η = 17.6%

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HiLiftPW-2 - Rehearsal Background

- Case 1: Grid convergence study (required)
  - Mach = 0.175, free-air
  - Angles-of-attack to be computed (deg) = 7 and 16 (18.5, 20, 21 and 22.4)
  - Re_{MAC} = 15.1 M, fully turbulent
  - DLR F11 "Config 2" - Slat 26.5 deg, Flap 32 deg (Wing/Body/HL system + SOB Flap Seal)
  - Coarse, medium, fine and extra-fine
- Case 2a and 2b: Reynolds number study (required)
  - Mach = 0.175, free-air
  - Angles-of-attack to be computed (deg) = 0, 7, 12, 16, 18.5, 19, 20 and 21
  - Re_{MAC} = 1.35M (Case2a) and 15.1 M(Case2b), fully turbulent
  - Medium density mesh from Grid Convergence Study
  - DLR F11 "Config 4" - Slat 26.5 deg, Flap 32 deg (Config 2 + Slat Tracks and Flap Track Fairings)
- Case 2c (OPTIONAL) - Low Reynolds Number Condition with Transition
- Case 3 (OPTIONAL) - Full Configuration Study
- Case 4 (OPTIONAL) - Turbulence Model Grid-Convergence Verification Study
Case 1 Surface Restricted Streamlines

AOA 7deg
Medium Grids

FUN3D

CFL3D

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FUN3D Surface Restricted Streamlines

AOA 7deg
Medium Grid

Case 1

Case 2b
Case 1 – Grid Convergence, AoA=20

Lift

Drag

Pitching Moment

Note: Grid D (fine) was discovered to have incorrect min spacing – so not of similar family to C and M.
C1 Medium Grid Adaption $\eta=70\%$

Adapted 1 – 37M nodes

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C1 Medium Grid Adaption $\eta=70\%$

Adapted 2 – 42M nodes

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