Contribution to HiLiftPW-3


EMBRAER

019
3rd High Lift Prediction Workshop
Denver, CO June 3-4, 2017
Outline

Description of codes used
Summary of cases
Overview of grids used
Overview of results
  CRM
  JSM
Summary
Summary of code and numerics used

- Simulations performed using 2 codes:
  - **CFD++**
    - Finite-volume, upwind fluxes and reconstruction algorithms for higher spatial order of accuracy.
    - Time march performed with a point-implicit method and multigrid for convergence acceleration
    - Many turbulence models: used SA with Curvature Correction (CC) and Quadratic Constitutive Relation (QCR)
    - All cases run with restart from previous AOA
  - **SU2**
    - Finite Volume, 2nd order spatial discretization with Venkatakrishnan limiter and ROE convective numerical method.
    - Time march performed with implicit scheme
    - SA and SST turbulence models, used SA
    - All cases run with restart from previous AOA
    - [https://github.com/su2code/SU2/wiki](https://github.com/su2code/SU2/wiki)
<table>
<thead>
<tr>
<th>Case</th>
<th>SOLVER</th>
<th>Turb. Model</th>
<th>Workshop Alpha=8, Fully turb, grid study</th>
<th>Workshop Alpha=16, Fully turb, grid study</th>
<th>Extra Full CL x Alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a (full gap)</td>
<td>CFD++</td>
<td>SA-CC-QCR</td>
<td>B2, B3, M5</td>
<td>B2, B3, M5</td>
<td>B2, B3, M5</td>
</tr>
<tr>
<td></td>
<td>SU2</td>
<td>SA</td>
<td>B3</td>
<td>B3</td>
<td>B3</td>
</tr>
<tr>
<td>1b (full gap w adaption)</td>
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</tr>
<tr>
<td>1c (partial seal)</td>
<td>CFD++</td>
<td>SA-CC-QCR</td>
<td>B2, B3</td>
<td>B2, B3</td>
<td>B2, B3</td>
</tr>
<tr>
<td>1d (partial seal w adaption)</td>
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</tbody>
</table>

Mean aerodynamic chord (MAC) = 275.8 in (7.0053 m)
Wing semi-span = 1156.75 in (29.38 m)
Reference area of the semi-span model = Sref/2 = 297,360.0 in2 (191,8448 m2)
Moment reference center (MRC): x=1325.90 in, y=468.75 in, z=177.95 in
x=33.6779 m, y=11.906 m, z=4.5199 m

Conditions: M=0.20, Rey=3.26E+06
AOAs: 0, 4, 8, 10, 12, 14, 15, 16, 18, 19, 20, 21 and 22°
## Summary of cases completed:

### JSM

<table>
<thead>
<tr>
<th>Case</th>
<th>SOLVER</th>
<th>Turb. Model</th>
<th>Workshop</th>
<th>Extra</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Polar, Fully turb</td>
<td>Polar, w/ transition</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>prediction</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Other (no slat</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>brackets)</td>
</tr>
<tr>
<td>2a (no nacelle)</td>
<td>CFD++</td>
<td>SA-CC-QCR</td>
<td>C2, E</td>
<td>E_mod</td>
</tr>
<tr>
<td></td>
<td>CFD++</td>
<td>SA</td>
<td>C2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SU2</td>
<td>SA</td>
<td>C2</td>
<td></td>
</tr>
<tr>
<td>2b (no nacelle w adaptation)</td>
<td>CFD++</td>
<td>SA-CC-QCR</td>
<td>C2, E</td>
<td>E_mod</td>
</tr>
<tr>
<td>2c (with nacelle)</td>
<td>CFD++</td>
<td>SA-CC-QCR</td>
<td>C2, E</td>
<td>E_mod</td>
</tr>
<tr>
<td></td>
<td>SU2</td>
<td>SA</td>
<td>C2</td>
<td></td>
</tr>
<tr>
<td>2d (with nacelle w adaptation)</td>
<td>SU2</td>
<td>SA</td>
<td>C2</td>
<td></td>
</tr>
</tbody>
</table>

Mean aerodynamic chord (MAC) = 529.2 mm  
Wing semi-span = 2300.0 mm  
Reference area of the semi-span model = $S_{ref}/2 = 1,123,300.0$ mm²  
Moment reference center (MRC): $x=2375.7$ mm, $y=0.0$ mm, $z=0.0$ mm

Conditions: $M=0.17$, $Rey=1.93E+06$  
AOAs: 0, 4.36, 8, 10.47, 13, 14.54, 17, 18.58, 19.59, 20.59 and 21.57°
## Summary of cases completed:
### 2D Verification study

<table>
<thead>
<tr>
<th>Case</th>
<th>SOLVER</th>
<th>Turb. Model</th>
<th>Workshop</th>
<th>Extra</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td>2D Verification study</td>
<td>Other</td>
</tr>
<tr>
<td>Case 3</td>
<td>CFD++</td>
<td>SA-CC-QCR</td>
<td>Committee 1, 2, 3, 4, 5</td>
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<tr>
<td></td>
<td>CFD++</td>
<td>SA</td>
<td>Committee 1, 2, 3, 4, 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SU2</td>
<td>SA</td>
<td>Committee 1, 2, 3, 4, 5</td>
<td></td>
</tr>
</tbody>
</table>

Mean aerodynamic chord (MAC) = 1.0 m

Conditions: \( M=0.09 \), \( \text{Rey}=1.2E+06 \)
Brief overview of grid system(s)

- We used several grid systems
  - CRM B2, B3
  - JSM C2, E
- EMBRAER created its own grid for the CRM geometry
  - More uniform increase in refinement throughout the geometry
  - More refined at the leading edge region
- EMBRAER removed brackets from slat and created a new grid based on mesh family ‘E’ for the JSM geometry

<table>
<thead>
<tr>
<th>Grid Source</th>
<th>Grid System</th>
<th>Case(s)</th>
<th>Refinement</th>
<th>Problems/Issues/Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Committee</td>
<td>B2</td>
<td>1A</td>
<td>Coarse, Medium, Fine, Extrafine</td>
<td>Extra-fine grid is very large</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>1C</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>1A</td>
<td>Coarse, Medium, Fine</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>1C</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>2A,2C</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>2A,2C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMBRAER</td>
<td>M5</td>
<td>1A</td>
<td>Coarse, Medium, Fine</td>
<td>Fine grid is very large</td>
</tr>
<tr>
<td>EMBRAER</td>
<td>E_mod (*)</td>
<td>2A, 2C</td>
<td>Medium</td>
<td>Similar to mesh_family_E, but without slat brackets</td>
</tr>
</tbody>
</table>

(*) Thanks to ANSA, which provided the E grid for modifications
Grid comparison (coarse): B2, B3, M5
Grid comparison (medium): B2, B3, M5

<table>
<thead>
<tr>
<th>B2</th>
<th>B3</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Grid comparison (fine): B2, B3, M5
Grid comparison: extrafine B2, fine M5
Grid comparison (PyNa Off): C2, E
Grid comparison (PyNa On): C2, E
HL-CRM results

M=0.20

Rey=3.26E+06
HL-CRM results – grid convergence – CFD++

Grids B2, B3, M5

Mesh convergence for AOA=8deg and AOA=16deg
Comparison between curves of CL vs h=1/N^2/3
HL-CRM results – grid convergence – CFD++

Grids B2, B3, M5

Mesh convergence for AOA=8deg and AOA=16deg
Comparison between curves of CD vs h=1/N^{2/3}
HL-CRM results – grid convergence – CFD++

Grids B2, B3, M5

Flow separation position and extent strongly affect CM
HL-CRM results – grid convergence – CFD++ x SU2

Grid B3

Mesh convergence for AOAs 8deg and 16deg for solvers CFD++ and SU2
Comparison between curves of CL vs h=1/N^{2/3}
HL-CRM results – grid convergence – CFD++ x SU2

Grid B3

Mesh convergence for AOAs 8deg and 16deg for solvers CFD++ and SU2

Comparison between curves of CD vs h = 1/N²/³

- CFD++
- SU2
HL-CRM results – grid convergence – CFD++ x SU2

Grid B3

Flow separation position and extent strongly affect CM
HL-CRM results – coefficients – CFD++

Grids B2, B3, M5

Results for CRM configuration with mesh families B2, B3 and M5
Comparison between curves of CL vs AOA
Grid comparison: B2, B3, M5

These 3 meshes are about the same size.
HL-CRM results – coefficients – CFD++

Grids B2, B3, M5

Results for CRM configuration with mesh families B2, B3 and M5
Comparison between curves of CL vs AOA

AOA (deg)
HL-CRM results – coefficients – CFD++

Grids B2, B3, M5

Results for CRM configuration with mesh families B2, B3 and M5
Comparison between curves of L/D vs CL
Results for CRM configuration with mesh families B2, B3 and M5
Comparison between curves of CM vs AOA
HL-CRM results – 20° – CFD++

Grids B2 fine x M5 medium
HL-CRM results – 21° – CFD++

Grids B2 fine x M5 medium
HL-CRM results – partial sealed x full gap

Sealing effect for CRM configuration with mesh family B2
Comparison between curves of CL vs AOA

Partial sealed
Full gap

AOA (deg)
HL-CRM results – sealed gap x non-sealed – $c_l$ x span

- Inboard more loaded (unexpected)
- Outboard reattaches
HL-CRM results – partial sealed x full gap – flow visualization

AOA=16°
HL-CRM results – sealed gap x non-sealed – flow visualization

AOA=17°
Brief overview of HL-CRM results

- Grid convergence
  - Grid M5 seems to converge to a lower value of CD and more negative CM (due to a smaller flow separation on flap)
    - Uniform surface grid distribution
  - Results are reasonably converged for CL and CD but not for CM

- Coefficients
  - Grids B2 and B3 (Fine mesh) yield virtually the same results for CL and CD, with grid B3 having less elements
  - Grid M5 captured an inboard stall at 20°, while grids B2 and B3 captured outboard stall

- Partial seal
  - The partial seal caused an increase in loading in the inboard panel but increased flow separation in the outboard panel for alphas smaller than 16°
  - After 16°, the seal increased loading over the full span, with increase in CLMax
  - Overall, the seal increases CL, CM (more negative) and L/D ratio
JSM results
M=0.17
Rey=1.93E+06
JSM results – CFD++ x SU2 (mesh family C2)

SU2: SA
CFD++: SA

Exp.

CFD++
SU2

Comparison between curves of CL vs AOA
JSM results – PyNaOn x PyNaOff

Non-monotone behavior of CL near stall region for grid E

Exaggerated PyNa effect on CLmax for grid C2
JSM results – DPyNaOn - PyNaOff

- Captured small DCLmax
  - AIAA 2007-4298, Low Speed High Lift Validation Tests within the European Project EUROLIFT II, Quix H, Schulz M, Quest J, Rudnik R, Schröder A
  - The pylon-nacelle can have much larger effects depending on the geometry
JSM results – PyNaOn x PyNaOff

JSM configuration - CFD++ results - All meshes
Comparison between curves of CM vs AOA

Jun/03/2017
JSM results – PyNaOn x PyNaOff

PyNa effect - all meshes
Comparison between curves of delta_CM vs AOA

- PyNa effect - EXP
- PyNa effect - C2
- PyNa effect - E

delta_CM

AOA (deg)
JSM results – PyNaOn x PyNaOff – 8°
JSM results – PyNaOn x PyNaOff – 10°
JSM results – PyNaOn x PyNaOff

Captured the change in L/D ratio
Overall poor comparison
JSM results – PyNaOn x PyNaOff

PyNa effect - all meshes
Comparison between curves of delta_CD vs AOA

- Exp
- C2
- E
JSM results – C2 – PyNaOn x PyNaOff – 4.36°
JSM results – C2 – PyNaOn x PyNaOff – 10.47°
JSM results – C2 – PyNaOn x PyNaOff – 18.58°
JSM results – C2 – PyNaOn x PyNaOff – 21.57°
JSM results – PyNaOff – 4.36°

INBOARD SECTIONS

SLAT | WING | FLAP
--- | --- | ---
A-A | B-B | D-D

OUTBOARD SECTIONS

SLAT | WING | FLAP
--- | --- | ---
E-E | G-G | H-H
JSM results – PyNaOff – 10.47°
JSM results –PyNaOff – 18.58°

INBOARD SECTIONS

SLAT  WING  FLAP

OUTBOARD SECTIONS

SLAT  WING  FLAP

A-A

B-B

D-D

E-E

G-G

H-H
JSM results – PyNaOff – 21.57°

INBOARD SECTIONS

SLAT | WING | FLAP

OUTBOARD SECTIONS

SLAT | WING | FLAP

A-A | B-B | D-D | E-E | G-G | H-H
JSM results – Slat brackets effect

JSM configuration - Brackets effect - All meshes
Comparison between curves of CL vs AOA

No brackets

With brackets

Exp.
Brief overview of JSM results

- CFD++ x SU2
  - Embraer needs to improve its setup for using SU2 for high-lift simulations
- Coefficients & surface streamlines
  - Both grids employed, C2 and E, yielded good results for DCL, DCD and DCM
  - CL/CD ratio did not compare well to experiment
    - Peniche effect on aspect ratio?
  - Behavior of CL near stall could be improved
    - Stall starts on the inboard panel for experiment while CFD predicts stall starting on the outboard panel
      - Slat brackets effect seems a little exaggerated at high AOA
      - However, results without slat brackets were not representative of experiment
Summary

• Although a lot of improvements have happened in the past, high-lift flow prediction is still difficult

• Processing capabilities and enhancements in mesh generation allowed an increase in geometry fidelity, such as including slat and flap brackets as well as wind tunnel walls
  • Where to refine, how much to refine, how to circumvent grid generator crashes still exist

• Another challenge seems to remain the accurate prediction of flow separation in terms of position and extent
  • Flow physics (transition, unsteady vs steady etc.)
  • Turbulence modeling
THANK YOU!

QUESTIONS?
CRM – APPENDIX
Grid comparison: B2, B3, M5

B2 (fine)  B3 (fine)  M5 (Medium)
HL-CRM results – coefficients – CFD++

Grids B2, B3, M5

Results for CRM configuration with mesh families B2, B3 and M5
Comparison between curves of CL vs AOA
HL-CRM results – coefficients – CFD++

Grids B2, B3, M5

Results for CRM configuration with mesh families B2, B3 and M5
Comparison between curves of L/D vs CL
HL-CRM results – coefficients – CFD++

Grids B2, B3, M5
HL-CRM results – 20° – CFD++

Grids B2 fine x M5 medium
HL-CRM results – 20° – CFD++

Grids B2 fine x M5 medium
HL-CRM results – 21° – CFD++

Grids B2 fine x M5 medium
HL-CRM results – 21° – CFD++

Grids B2 fine x M5 medium
HL-CRM results – 21° – CFD++

Grids B2 fine x M5 medium

20°

21°
HL-CRM results – sealed gap x non-sealed

Sealing effect for CRM configuration with mesh family B2
Comparison between curves of CL vs AOA

- **Full gap**
- **Partial sealed**
HL-CRM results – sealed gap x non-sealed

Sealing effect for CRM configuration with mesh family B2
Comparison between curves of CM vs AOA

- Full gap
- Partial sealed
HL-CRM results – sealed gap x non-sealed

Sealing effect for CRM configuration with mesh family B2
Comparison between curves of L/D vs CL

Partial sealed
Full gap
JSM – APPENDIX
JSM results – CFD++ x SU2

SU2: SA

CFD++: SA-CC-QCR

Comparison between curves of CL vs AOA

JSM EXP PyNa-Off
JSM EXP PyNa-On
JSM C2 CFD++ PyNa-Off
JSM C2 CFD++ PyNa-On
JSM C2 SU2 PyNa-Off
JSM C2 SU2 PyNa-On
JSM results – PyNaOn x PyNaOff – 8°
JSM results – PyNaOn x PyNaOff – 10°
JSM results – PyNaOn x PyNaOff – 8°
JSM results – PyNaOn x PyNaOff – 10°
JSM results – C2 – PyNaOn x PyNaOff – 4°
JSM results – C2 – PyNaOn x PyNaOff – 10°
JSM results – C2 – PyNaOn x PyNaOff – 18°
JSM results – C2 – PyNaOn x PyNaOff – 21°
Case 3 – APPENDIX
Turbulence model verification study results

- Observed differences in coefficients between
  - SA
  - SA-CC-QCR
- Small differences in CL and CDviscous
  - 0.0015 in CL
  - 0.0003 in CD