DPW 5 Summary of Participant Data

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Outline:

• Participant Data
• Case 1: Grid Convergence
• Case 2: Buffet Study
• Pressure Data
• Side of Body Separation
• Trailing Edge Separation
• Conclusions
Participant Data:

- 54 Data Total Data Submittals
- 22 Teams/Organizations
  - 10 N. America, 5 Europe, 6 Asia, 1 S. America
  - 8 Government, 5 Industry, 6 Academia, 2 Commercial, 1 Unknown
  - 1 for Case 3 only
- Grid Types:
  - 5 Overset (4 Teams)
  - 7 Structured Multi-block (5 Teams)
  - 25 Unstructured (13 teams)
    (14 Hex, 7 Hybrid, 4 Prism)
  - 16 Custom (all types)
- Turbulence Models:
  - 34 SA (all types), 12 SST, 4 k-e-RT, 1 EARSM, 1 Lag-RST
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<thead>
<tr>
<th>Team</th>
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<th>Name</th>
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Case 1: Grid Convergence Study

- NASA Common Research Model, Wing-Body
- Mach=0.85, $C_L=0.500\pm0.001$
- Grid Resolution Level:
  - 1) Tiny  
  - 2) Coarse  
  - 3) Medium,  
  - 4) Fine  
  - 5) Extra-Fine  
  - 6) Super-Fine  
- Chord Reynolds Number: $5\times10^6$
Case 1: CD_TOT - All Solutions by Grid Type and Turbulence Model
Case 1: CD_PR - All Solutions by Grid Type and Turbulence Model
Case 1: CD_SF - All Solutions by Grid Type and Turbulence Model
Case 1: CM_TOT - All Solutions by Grid Type and Turbulence Model
Case 1: ALPHA - All Solutions by Grid Type
Case 1: CD_TOT – Multi-block and Overset Grids
Case 1: CD_TOT – Unstructured Hexahedral and Prismatic Grids
Case 1: CD_TOT – Unstructured Hybrid and all Custom Grids
Case 1: CD_TOT – Spalart Allmaras and Shear Stress Transport Turb. Models
Case 1: CD_TOT – SA w/ Rotation Correction and SA other Turb. Models
Case 1: CD_TOT – k-ε-RT and EARSM,RST Turbulence Models
## Should we Compare to Wind Tunnel?

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<td>Support System (Sting)</td>
<td>Free Air</td>
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<tr>
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<td>“Fully” Turbulent (usually)</td>
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<td>Rigid 1g Shape</td>
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<td>Numerical Uncertainty &amp; Error</td>
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<td>Corrections for known effects</td>
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- Wind Tunnel and CFD measure/compute different things!
- Data are included for reference only!
Case 1: CD_TOT, ALPHA, and CM_TOT with Wind Tunnel Results

Wind Tunnel Results shown for Reference Only
Richardson Extrapolation:

• Standard 2\textsuperscript{nd} order least squares fit (Excel)
• For 2\textsuperscript{nd} order codes, should be linear vs. \text{Grid\_Factor} = N^{-2/3}
• Y-intercept estimates theoretical infinite resolution (continuum) result
Case 1: Extrapolated CD_TOT by Grid Type
Case 1: Extrapolated CD_TOT by Grid Type (Common Grids Only)
Case 1: Extrapolated CD_TOT by Grid Type (Common Hex Grids Only)
Conclusions from Richardson Extrapolation:

- Most results are monotonically decreasing
- Some are nonlinear
  - Convergence issues
  - Possible flow-feature changes (SOB or TE Separation)
- No clear break-outs with grid type or turbulence model (except for some outliers)
- Scatter is reduced somewhat for Common Grids
  - Scatter still large for coarser grids
  - Best for Hex-based, including Structured, Overset, and Unstructured
Case 1: Extrapolated CD_TOT Statistics
Conclusions from Case 1 Results:

- Still a lot of scatter!
  - Less than DPW4 (was $\sigma=8.1$ for tail on). Are we getting better?
- No clear break-outs with grid type or turbulence model
  - Some Turb. Models are outliers
  - Trends are still hard to isolate due to small sample sizes
- Agreement with experiment on CD_TOT is better than for ALPHA and CM_TOT
  - Wing aeroelastic effects are likely part of this
  - Spread in CD_TOT is similar between wind tunnel and CFD scatter
- Scatter is reduced somewhat for Common Grids
  - Statistics did not change significantly
  - Best for Hex-based, including Structured, Overset, and Unstructured
  - Discretization and Turbulence Modeling is still a major contributor
Case 2 Buffet Study:

- NASA Common Research Model, Wing-Body
- Mach=0.85:
  - $\alpha=2.50^\circ, 2.75^\circ, 3.00^\circ, 3.25^\circ, 3.50^\circ, 3.75^\circ, 4.00^\circ$
- Grid Resolution Level:
  - 3) Medium,
- Chord Reynolds Number: $5\times10^6$
Case 2 – All Solutions

Pseudo Test Data

NTF and Ames Test Data

Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209
CREATION OF “PSEUDO TEST DATA”

- The CRM geometry used for DPW5 was that of the wind tunnel model definition.
- AIAA-2012-3209 details recent CFD analyses to account for the wing aeroelastic twist at Mach=0.85, CL=0.50, and for additional wind tunnel mounting system effects.
- “Pseudo Test Data” were created from the NTF data and CFD analyses to reflect what the test data might look like for the wing without the “CL=0.50 aeroelastic” twist.

No corrections were applied to drag data.
Case 2 - All Solutions

NTF and Ames Test Data
Case 2 – All Solutions

NTF and Ames Test Data
Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209
Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209
PRISIM Grids

Custom Unstructured Grids

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Other Turbulence Models

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Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209
Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209
ΔCL = 0.055

ΔCM = 0.043

Outliers defined by CLbreak and/or drag behavior

Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209
Outliers defined by CLbreak and/or drag behavior
CFD spread similar to test data spread!
Case 2 - Concluding Remarks

- No clear break-outs with grid type or turbulence model (except for some outliers)
- In general, the k-e-RT and Lag RST results tend outside the norm of the other solutions.
- For all solutions minus outliers
  - Relatively tight forces and moment at $\alpha=2.5^\circ$
  - Significant force and moment spread at $\alpha=4.0^\circ$, $\Delta CL=0.055$, $\Delta CM=0.043$
- CM predicted too negative – is it CFD, test, geometry, etc.?
- Steady aeroelastic effects are significant
  - Must be included in CFD to better assess accuracy
- Wing section characteristics (section CL, CM) needed to better assess CFD
- High angles of attack characterized by significant shock induced separation
  - How steady is the real flow at these conditions? Need dynamic test data?
  - If there is a significant amount of flow unsteadiness at high angles of attack is RANS adequate or do we need URANS or DES?
Pressure Data

<table>
<thead>
<tr>
<th>WBL</th>
<th>ETA</th>
<th>Chord</th>
</tr>
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<td>0.1306</td>
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<td>232.444</td>
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<tr>
<td>1145.183</td>
<td>0.9900</td>
<td>110.5</td>
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</tbody>
</table>
Case 1: Level 3 Grid, $M=0.85$, $C_L=.50$

Spanwise Variation

NTF Test 197 Run 44:

- $\alpha=2.68^\circ$, $C_L=0.485$
- $\alpha=2.91^\circ$, $C_L=0.519$
Case 1: Grid Refinement Study, $M=0.85$, $C_L=0.50$
Station 10, $\eta=0.502$

NTF Test 197 Run 44:
- $\alpha=2.68^\circ$, $C_L=0.485$
- $\alpha=2.91^\circ$, $C_L=0.519$
Case 2: Buffet Study, Level 3 Grids, M=0.85
Station 10, η=.502

NTF Test 197 Run 44:
- α=2.68°, CL=0.485
- α=2.91°, CL=0.519

NTF Test 197 Run 44:
- α=2.91°, CL=0.519
- α=3.19°, CL=0.557

NTF Test 197 Run 44:
- α=3.42°, CL=0.584
- α=3.70°, CL=0.607

NTF Test 197 Run 44:
- α=3.70°, CL=0.607
- α=3.92°, CL=0.621

NTF Test 197 Run 44:
- α=3.92°, CL=0.621
- α=4.17°, CL=0.638
Conclusions from Pressure Data:

• Agreement with experiment deteriorates at outboard stations, likely due to aeroelastic effects
• Variations with grid level hard to discern due to reduced number of data sets
• Variation at high alphas due to separation effects on shock location
• No clear break-out with grid type (Turbulence model affects not examined yet)
Separation Bubble

Skin Friction Contours

Grayed Area Indicates Region of Negative $C_F$

Saddle points

Dividing Streamlines

$(FS_{EYE}, BL_{EYE}, WL_{EYE})$
Side of Body Separation Bubble

1. Reported some level of SOB Separation:
   I, J, K, L, X, Y, Z, 3, 4, 5, 6, 7, 9,
   b, d, f, g, h, k, t, α, β, δ, γ, λ, π

2. Reported no SOB Separation (SOB File Provided):
   U, V, W, 2, e, m, n, q, r

3. No Report (No SOB File Provided):
   A, B, C, D, E, F, G, H, M, N, O, P, Q, R, S, T, 8, a
Example Grid Refinement: with Dataset “f” only
Grid Refinement: All Data
Bubble Width (Wing): Case 1 By Grid Type and Turbulence Model
Bubble Leading Edge: Case 1 By Grid Type and Turbulence Model
Bubble Height (Fuselage): Case 1 By Grid Type and Turbulence Model
Example Alpha Sweep: with Dataset “f” only
Alpha Sweep: All Data
Bubble Width (Wing): Case 2 By Grid Type and Turbulence Model
Bubble Leading Edge: Case 2 By Grid Type and Turbulence Model
Bubble Height (Fuselage): Case 2 By Grid Type and Turbulence Model
Conclusions from Separation Bubble:

• Variation with grid level fairly consistent (note that coarse level grids do not have proper resolution)

• Some data sets show dramatic increase in bubble size at higher alpha
  – Mostly for Spalart-Allmaras results
Trailing Edge Separation:

- DPW-4: $C_f$ normal to TE $< 0$ as criteria
- For higher $\alpha$ more difficult to define & detect
Case 1: Trailing Edge Separation, Level 1
Case 1: Trailing Edge Separation, Level 2
Case 1: Trailing Edge Separation, Level 3
Case 1: Trailing Edge Separation, Level 4
Case 1: Trailing Edge Separation, Level 5
Trailing Edge Separation, Alpha = 2.5°

- Overset, MB, Hyb., Cust.
- Hex
- Prism

- k-ε-\(R_t\)
- SST
- SA
- EARSM, RST
Trailing Edge Separation, Alpha = 3.0°

- Overset, MB, Hyb., Cust.
- Hex
- Prism

Legend:
- $k$-$\varepsilon$-$R_t$
- SST
- SA
- EARSM, RST
Trailing Edge Separation, Alpha = 3.5°

- Overset, MB, Hyb., Cust.
- Hex
- Prism

k-ε-R_t
SST
SA
EARSM, RST
Trailing Edge Separation, Alpha = 4.0°

- Overset, MB, Hyb., Cust.
- Hex
- Prism
Conclusions from Trailing Edge Separation:

• Case 1:
  – SA, SST show similar small TE sep ≤ 2% between sections 8, ..., 14
  – Slightly larger for SST on coarse, medium grids

• Case 2:
  – Trend to extend towards sections 5 & 16 for $\alpha \geq 2.5^\circ$
  – No clear conclusion

• Overall check necessary whether same TE sep identification procedure has been applied
General Conclusions:

• Very successful workshop. Thank You!
  – 54 data submittals, many with parametric variations in grid type and/or turbulence model

• Still more variation than desired
  – Some improvement from DPW4: We are getting better
  – Mixed results from common grid study. Discretization and turbulence modeling are still a factor

• Drag comparisons to wind tunnel generally favorable
  – Variations similar between WT and CFD
  – ALPHA and CM_TOT offsets
  – Aeroelasticity
General Conclusions (Cont’d):

• Force/Moment predictions better at $\alpha=2.5^\circ$
  – Less separation
  – Bigger spread at $\alpha=4.0^\circ$

• Pressures consistent with Force/Moments
  – Correlation outboard supports aeroelastic effects
  – Wide variation in $\alpha$ for shock separation

• Large variations in separation prediction
  – SOB Separation
  – TE Separation and Buffet onset alpha
  – Is RANS good enough? Is flow steady?
Further Study:

- Check SOB/TE separation with wind tunnel data
  - Is flow visualization data available?
- Include static aeroelastics in CFD
  - Needed to match wind tunnel data
- Include boundary layer transition model
  - Forced/Free
- Unsteady RANS?
  - Will only help if flow is unsteady
- LES/DES?
  - DES only helps for off-body separation
  - LES (beyond current SOA?)
Case 2 - SA Turbulence Model
No CL Break below AoA=4.0

Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209
Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209
Case 2 - SST and Other
No CL Break below AoA=4.0

- SST HYBRID
- SST HYBRID
- EARSIM HEX
- SST HEX
- SST HEX
- SST HEX
- SST HEX
- SST HEX
- Lag RST Overset
- Pseudo Test

Angle of Attack
CL\_TOT
CM\_TOT
Pseudo Test data based on NTF test data modified by results from AIAA-2012-3209