DPW 6 Summary of Participant Data
CRM Cases 2-5

Ed Tinoco,
Olaf Brodersen,
and the DPW Organizing Committee
Outline:

• Participant Data
• Case 2: CRM Nacelle-Pylon Drag Increment
• Case 3: CRM WB Static Aero-Elastic Effect
• Case 4: CRM WB Grid Adaptation
• Case 5: CRM WB Coupled Aero-Structural Simulation
• Separation
• Observations/Issues
Participant Data:

- **48 Total Data Submittals**
- **25 Teams/Organizations**
  - 12 N. America, 6 Europe, 6 Asia, 1 S. America
  - 8 Government, 5 Industry, 7 Academia, 5 Commercial
  - 2 for Case 5 only
- **Grid Types:**
  - 17 Common Unstructured (12 teams)
  - 15 Custom Unstructured (11 teams)
  - 6 Overset (3 Teams)
  - 3 Structured Multi-block (3 Teams)
  - 5 Custom Cartesian (2 Teams)
- **Turbulence Models:**
  - 36 SA (all types), 6 SST, 2 k-kLe, 2 k-e Lam, 1 EARSM, 1 LBM-VLES, 1 RSM-ω
<table>
<thead>
<tr>
<th>Team</th>
<th>ID</th>
<th>SYM</th>
<th>Name</th>
<th>Organization</th>
<th>Code</th>
<th>Grid</th>
<th>Turbulence Model</th>
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# CRM Cases 2-5 Participants

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CRM geometry for DPW6 includes the static aeroelastic twist and deformation experienced by the model at different angles of attack.
Should We Compare to Wind Tunnel?

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<th>Wind Tunnel</th>
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<td>Walls</td>
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<td>Support System (Sting)</td>
<td>Free Air</td>
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<td>“Fully” Turbulent (usually)</td>
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<td>Aeroelastic Deformation</td>
<td>Static Measured Deflections</td>
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<td>Measurement Uncertainty</td>
<td>Numerical Uncertainty &amp; Error</td>
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<tr>
<td>Corrections for known effects</td>
<td>No Corrections</td>
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- Wind Tunnel and CFD measure/compute different things!
- Data are included for reference only!
Outline:

• Participant Data

• Case 2: CRM Nacelle-Pylon Drag Increment

• Case 3: CRM WB Static Aero-Elastic Effect

• Case 4: CRM WB Grid Adaptation

• Case 5: CRM WB Coupled Aero-Structural Simulation

• Separation

• Observations/Issues
Case 2: Nacelle-Pylon Drag Increment

- Grid Convergence Study
- NASA Common Research Model, Wing-Body and Wing-Body-Nacelle Pylon
- Mach=0.85, $C_L=0.500\pm0.001$
- Chord Reynolds Number: $5\times10^6$
- Grid Resolution Level:
  - 1) Tiny
  - 2) Coarse
  - 3) Medium,
  - 4) Fine
  - 5) Extra-Fine
  - 6) Super-Fine
- Drag Increment between Wing-Body and Wing-Body-Nacelle-Pylon
Grid Convergence?

Richardson Extrapolation:

- Standard 2\textsuperscript{nd} order least squares fit
- For 2\textsuperscript{nd} order codes, should be linear vs. \texttt{Grid\_Factor} = N\textsuperscript{-2/3}
- Y-intercept estimates theoretical infinite resolution (continuum) result
Case 2: CD_TOT - Wing-Body
All Solutions by Grid Type and Turbulence Model

GRIDFAC = 1/GRIDSIZE^{2/3}
Case 2: CD_PR - Wing-Body Pressure Drag
All Solutions by Grid Type and Turbulence Model
Case 2: CD_SF - Wing-Body
Skin Friction Drag
All Solutions by Grid Type and Turbulence Model
Case 2: CM_TOT - Wing-Body
All Solutions by Grid Type and Turbulence Model
Case 2: CD_TOT - Wing-Body Solutions by Grid Type and Turbulence Model

Common Unstructured Grids

Custom Unstructured Grids

GRIDFAC = 1/GRIDSIZE^{(2/3)}
Case 2: CD_TOT - Wing-Body Solutions by Grid Type and Turbulence Model

Geolab Unstructured Grids

Boeing Unstructured Grids

GRIDFAC = 1/GRIDSIZE^{2/3}
Case 2: CD_TOT - Wing-Body Solutions by Grid Type and Turbulence Model

Overset Grid

Multiblock Structured Grid

GRIDFAC = 1/GRIDSIZE^{(2/3)}
Case 2 & 4: CD_TOT - Wing-Body Solutions by Grid Type and Turbulence Model

Custom Cartesian Grid

Turbulence Model
- SA
- SA QCR
- SST
- k-e, k-kl
- LBM-VLES

Note: Change in Scale

GRIDFAC = 1/GRIDSIZE^{(2/3)}

Case 4: Solution Adaptive Grid

Turbulence Model
- SA
- SA QCR
- SST
- k-e, k-kl
- LBM-VLES

Note: Change in Scale

GRIDFAC = 1/GRIDSIZE^{(2/3)}
Case 2: CD_TOT - Wing-Body-Nacelle-Pylon
All Solutions by Grid Type and Turbulence Model

GRIDFAC = 1/GRIDSIZE\(^{(2/3)}\)
Case 2: CD\_TOT - Wing-Body-Nacelle-Pylon minus Wing-Body Solutions by Grid Type and Turbulence Model

Geolab Unstructured Grids

Boeing Unstructured Grids

GRIDFAC = 1/GRIDSIZE^{(2/3)}
Case 2: CD_TOT - Wing-Body-Nacelle-Pylon minus Wing-Body
Solutions by Grid Type and Turbulence Model

Overset Grids

Multiblock Structured Grids

\[ \text{GRIDFAC} = \frac{1}{\text{GRIDSIZE}^{(2/3)}} \]
Case 2: CD_TOT - Wing-Body-Nacelle-Pylon minus Wing-Body Solutions by Grid Type and Turbulence Model

Custom Cartesian Grids

Grid Fac = 1/Grid Size^{2/3}
Case 2: Wing-Body
Finest Grid - Most Solutions
M=0.85, CL=0.50

Symbols - Test Data
- Unstructured
- Custom Unst
- Overset
- Multiblock
- Custom Cart

Cp vs X/C for different Eta values.
Case 2: Wing-Body
Finest Grid - Most Solutions
M=0.85, CL=0.50

Symbols - Test Data
- Unstructured
- Custom Unst
- Overset
- Multiblock
- Custom Cart

\[ C_p \text{ vs. } X/C \]

- \( \text{Eta}=0.727 \)
  - \( \text{Eta}=0.727, \alpha=2.60, \text{CL}=0.4818 \)
  - \( \text{Eta}=0.727, \alpha=2.86, \text{CL}=0.5182 \)

- \( \text{Eta}=0.846 \)

- \( \text{Eta}=0.950 \)
Case 2: Wing-Body Pressure Distributions
Grid Convergence History
M=0.85, CL=0.50
Case 2: Wing-Body Pressure Distributions
Grid Convergence History
M=0.85, CL=0.50

Custom Cartesian Grid

Solution Adaptive Grid

**Note:**
- G1 Grid Level L1
- G1 Grid Level L3
- G1 Grid Level L5
- Test a=2.60, CL=0.4818
- Test a=2.86, CL=0.5182
Case 2: Wing-Body-Nacelle-Pylon
Finest Grid - Most Solutions
M=0.85, CL=0.50

Symbols - Test Data
Unstructured
Custom Unst
Overset
Multiblock
Custom Cart

[Graphs showing Cp vs X/C for different Eta values]

Eta=0.131
Eta=0.201
Eta=0.286
Eta=0.397
Eta=0.502
Eta=0.603
Case 2: Wing-Body-Nacelle-Pylon
Finest Grid - Most Solutions
M=0.85, CL=0.50

Symbols - Test Data
Unstructured
Custom Unst
Overset
Multiblock
Custom Cart
Case 2: Wing-Body-Nacelle-Pylon - Nacelle Pressures
Finest Grid
M=0.85, CL=0.50
Case 2: Wing-Body Wing Section Lift and Moment
Finest Grid
Mach = 0.85, CL=0.5

Symbols - Test Data

Section Lift Coefficient
Section Pitching Moment Coefficient

Cp's OK, error in calculating section characteristics
Case 2: Wing-Body Wing and Wing-Body-Nacelle-Pylon

Section Lift and Moment

Finest Grid

Mach = 0.85, CL=0.5

Wing-Body
Black Symbol - Test Data
Solid Lines

Wing-Body-Nacelle-Pylon
Red Symbol - Test Data
Dashed Lines

Section Lift Coefficient

Section Pitching Moment Coefficient

Span fraction - eta
Observations from Case 2 Results:

- We are getting better!
- Nacelle-Pylon drag increment prediction within experimental variation.
- Scatter for k-e Lam-Bremhorst and LBM-VLES models cannot be separated from grid type.
- With the exception of one set of Cartesian grid results very little differences seen in wing or nacelle pressure distributions, or in wing section lift and pitching moment due to grid type, turbulence model, or convergence level.
Outline:

• Participant Data
• Case 2: CRM Nacelle-Pylon Drag Increment
• **Case 3: CRM WB Static Aero-Elastic Effect**
• Case 4: CRM WB Grid Adaptation
• Case 5: CRM WB Coupled Aero-Structural Simulation
• Separation
• Observations/Issues
Case 3: CRM WB Static Aero-Elastic Effect:

- 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: $5\times10^6$
- Measured Static Aero-Elastic Wing Deformation at each angle of attack
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
All Solutions
Turbulence Model

Turbulence Model
- SA
- SA QRC
- SST
- k-e, k-kl
- EARSM
- LBM-VLES

CL - Lift Coefficient

Angle-of-Attack

CM - Pitching Moment

Test NTF Test Ames

04 -0.06 -0.08 -0.1 -0.12
Case 3: Wing-Body Drag w/Static Aeroelastics
All Solutions - Grid Type
Case 3: Drag minus Idealized Induced Drag
Wing-Body w/Static Aeroelastics
All Solutions
Grid Type

Grid Type
- Unstructured
- Custom Unst
- Overset
- Multiblock
- Custom Cart

\[ CD_p = CD - CL^2/(\pi*AR) \]
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Grid Type & Turbulence Model

Geolab and Boeing Unstructured Grids

Custom Unstructured Grids

Turbulence Model
- SA
- SA QRC
- SST
- k-ε, k-KL
- EARSM
- LBM-VLES
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Grid Type & Turbulence Model
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Grid Type & Turbulence Model
Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85, AOA=3.0
Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85, AOA=3.0
Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85, AOA=3.25

Symbols - Test Data
Unstructured
Custom Unst
Overset
Multiblock
Custom Cart
Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85, AOA=3.25
Case 3: Wing-Body Wing Pressue Distributions
All Solutions
M=0.85, AOA=3.5

Symbols - Test Data
Unstructured
Custom Unst
Overset
Multiblock
Custom Cart

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$\eta = 0.201$
$\eta = 0.286$
$\eta = 0.397$
$\eta = 0.502$
$\eta = 0.603$
Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85, AOA=3.5

Symbols - Test Data
- Unstructured
- Custom Unst
- Overset
- Multiblock
- Custom Cart
Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85, AOA=3.75

Symbols - Test Data
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Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85, AOA=3.75

Symbols - Test Data
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ETA=0.727

ETA=0.846

ETA=0.950
Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85, AOA=4.00

Symbols - Test Data
- Unstructured
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- Overset
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Case 3: Wing-Body Wing Pressure Distributions
All Solutions
M=0.85, AOA=4.00

Symbols - Test Data
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Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Outliers - CL Break at AOA=3.50 or Below
Turbulence Model

![Graph showing CL vs. Angle-of-Attack and CL vs. CM for different Turbulence Models and Cases]
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Outliers - CL Break between AOA=3.50 and 3.75
Turbulence Model

**Turbulence Model**
- SA
- SA QRC
- SST
- k-e, k-kl
- EARSM
- LBM-VLES

**Graphs**
1. **CL - Lift Coefficient vs. Angle-of-Attack**
2. **CM - Pitching Moment**
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Outliers - CL Break between AOA=3.75 and 4.00

Turbulence Model

![Turbulence Model Graph](image)

![CM - Pitching Moment Graph](image)
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Solutions minus All Outliers
Turbulence Model Type

ΔCL=0.043

ΔCM=0.044
Case 3: Drag minus Idealized Induced Drag
Wing-Body w/Static Aeroelastics
Solutions minus All Outliers
Turbulence Model Type

\[ C_{Dp} = C_D - \frac{C_{L}^2}{\pi \cdot AR} \]
Case 3: Wing-Body Section Lift Coefficient
M=0.85

[Turbulence Model Graphs with Eta values and premature flow separation noted]
Case 3: Wing-Body Section Lift Coefficient
M = 0.85

Excessive aft loading in CFD contributes to excessive lift and pitching moment outboard
Case 3: Wing-Body Section Pitching Moment Coefficient

M = 0.85

Cp's OK probable calculation error

Symbols - Test Data
- Unstructured
- Custom Unst
- Overset
- Multiblock
- Custom Cart
Case 3: Wing-Body Section Pitching Moment Coefficient
\( \text{M} = 0.85 \)
Case 3: Lift and Pitching Moment
Wing-Body w/Static Aeroelastics
Solutions minus All Outliers* - Extremes
Turbulence Model Type

*G is considered an outlier
Case 3: Wing-Body Wing Pressure Distributions
Solutions at Force & Moment Extremes
M=0.85, AOA=3.5

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Case 3: Wing-Body Wing Pressure Distributions
Solutions at Force & Moment Extremes
M=0.85, AOA=3.5

Turbulence Model
- SA
- SA QCR
- k-L
- EARSM
- LBM-VLES

\[ \frac{\Delta C_p}{C_p_0} \times \frac{12}{10} \]

\[ \frac{\Delta C_l}{C_l_0} \times \frac{12}{10} \]

\[ \frac{\Delta C_m}{C_m_0} \times \frac{12}{10} \]
Case 3: Wing-Body Wing Pressue Distributions
Solutions at Force & Moment Extremes
M=0.85, AOA=4.00
Case 3: Wing-Body Wing Pressure Distributions
Solutions at Force & Moment Extremes
M=0.85, AOA=4.00
Section Lift Coefficient

\[ \alpha = 3.50 \]

\[ \alpha = 4.00 \]

Low experimental lift level due to “bad” pressures
Case 3 - Observations

- No clear break-outs with grid type or turbulence model (except for some outliers)
- In general, the k-e Lam-Bremhorst and LBM-VLES results tend outside the norm of the other solutions but this could have been due to grid/solution type.
- For all solutions minus outliers
  - Tighter forces and moment at $\alpha=2.5^\circ$
  - Significant force and moment spread at $\alpha=4.0^\circ$ $\Delta CL=0.043$, $\Delta CM=0.044$
- Excessive aft-loading on outboard wing sections contributes to too negative section pitching moments and excessive section lift.
- Steady aeroelastic effects are significant
  - Inclusion greatly improved agreement with wind tunnel
- 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?
Outline:

- Participant Data
- Case 2: CRM Nacelle-Pylon Drag Increment
- Case 3: CRM WB Static Aero-Elastic Effect
- **Case 4: CRM WB Grid Adaptation**
- Case 5: CRM WB Coupled Aero-Structural Simulation
- Separation
- Observations/Issues
Case 4: CRM WB Grid Adaptation:

- NASA Common Research Model, Wing-Body
- Mach=0.85, $C_L=0.500\pm0.001$
- Chord Reynolds Number: $5\times10^6$
- Solution Adapted Grid
Case 4: CD_TOT - WB Grid Adaption
All Solutions by Grid Type and Turbulence Model
Case 4: CD_TOT - Wing-Body Grid Adaption
All Solutions by Grid Type and Turbulence Model
Case 4: Wing-Body Grid Adaption
Finest Grid
M=0.85, CL=0.50
Case 4: Wing-Body Grid Adaption
Finest Grid
M=0.85, CL=0.50
Outline:

- Participant Data
- Case 2: CRM Nacelle-Pylon Drag Increment
- Case 3: CRM WB Static Aero-Elastic Effect
- Case 4: CRM WB Grid Adaptation
- Case 5: CRM WB Coupled Aero-Structural Simulation
- Separation
- Observations/Issues
Case 5: CRM WB Coupled Aero-Structural Simulation:

- NASA Common Research Model, Wing-Body
- Mach=0.85, $C_L=0.500\pm0.001$
- Chord Reynolds Number: $5\times10^6$
- Fixed lift condition for the CRM Wing-Body coupled with computational structural analysis
- Medium Grid
- Structural FEM from the CRM Website
Outline:

- Participant Data
- Case 2: CRM Nacelle-Pylon Drag Increment
- Case 3: CRM WB Static Aero-Elastic Effect
- Case 4: CRM WB Grid Adaptation
- Case 5: CRM WB Coupled Aero-Structural Simulation
- Separation
- Observations/Issues
General Observations:

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

• Still more variation than desired
  – Some improvement from DPW5: We are getting better

• Drag comparisons to wind tunnel generally favorable
  – Variations similar between WT and CFD
  – Very good on increment for nacelle-pylon
  – Aeroelastic effects essential to decent agreement with test data
General Observations (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  
  – Wide variation in $\alpha$ for shock separation for many cases

• Large variations in separation prediction  
  – Premature flow separation is still an issue for many solutions  
  – SOB Separation  
  – TE Separation and Buffet onset alpha  
  – Is RANS good enough? Is flow steady?
Issues: Excessive Aft Loading
Wing-Body
Mach=0.85, CL=0.50

Results in too negative pitching moment
Issues: Premature Flow Separation

Case 3: Wing-Body
Mach=0.85, AOA=3.50

Many solutions showed premature flow separation

Solutions without premature flow separation
Issues: Aft Shock Location

Case 3: Wing-Body
Mach=0.85,

AOA=3.50

AOA=4.00

We also need better experimental data that shows just how much the shock is moving at these flow conditions.

Shock location too far aft for most solutions.
Further Study:

- 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?)