Statistical Analysis of CFD Solutions from the 3rd AIAA Drag Prediction Workshop

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Outline of the talk

- Method for analyzing the collective

- Case 1 DLR-F6 and FX2B Fairing
  - Individual Solution Analysis
  - Grid Convergence Study
  - Comparison with DPW-2

- Case 2 Grid Convergence Study for DPW-W1

- Summary

- Concluding Remarks
Analysis Method

• Grid Convergence for nested solutions
  – Reduction in spread?
  – Reduction in scatter of “core” solutions?
  – Significant changes in medians?
  – Compare DPW-2 and DPW-3 spread and scatter
The median gives a robust estimate of the population mean.
Case 1: DLR-F6 Wing Body and DLR-F6 with FX2B Fairing
## Case 1 Solution Statistics

<table>
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<tr>
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<th>DPW-2</th>
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<th>DPW-3</th>
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<tr>
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Solution Analysis

CD_TOT F6 Fine Grid

- Multiblock
- Overset
- Unstructured
- Median
- Limits
Solution Analysis (2)  DPW-3

CD_PR

CD_SF
Solution Analysis (3)

ALPHA

CM_TOT
Solution Analysis (4)  DPW-3

CD_TOT F6 Fine Grid

- Same Code
- Same Grid
- Different Turbulence Models

- Same Grid Nodes; Different Cells
- Same Turbulence Model
- Different Code
What does convergence look like?

Scatter in solutions is due to:
- Numerical error
- Modeling error (e.g. physics models, computational models)
- User errors
- Code errors

For grid convergence, numerical error asymptotically approaches zero leaving the other three contributors.

For the collective to show convergence, the following would have to happen:
- The ranges for the configurations would approach a constant as the grid “improved”.
- The scatter (standard deviation) of the “core” solutions would approach a constant as the grid improved.
- The medians of the core solutions would change asymptotically.
Grid Sizes

DPW-3

![Graph showing grid sizes for different categories C, M, and F with data points for DPW3 F6, DPW3 FX2B, and DPW2 WB.]
Nested CD_TOT

**DPW-3**

- **F6**
  - Graph showing CD_TOT vs. NPTS^{-2/3}
  - Various data points are plotted.

- **FX2B**
  - Graph showing CD_TOT vs. NPTS^{-2/3}
  - Various data points are plotted.
Nested CD_TOT minus Outliers
Convergence of CD\_TOT

DPW-3

![Graph showing the convergence of CD\_TOT with NPTS\(^{-2/3}\)]
Convergence CD_PR, CD_SF  DPW-3

**CD_PR**

**CD_SF**

![Graphs showing convergence of CD_PR and CD_SF](image)
Convergence of ALPHA & CM_TOT

**ALPHA**

**CM_TOT**

- **DPW3 F6**
- **DPW3 FX2B**
- **DPW2 WB**
Convergence of Spread

CD_TOT

- DPW3 F6
- DPW3 FX2B
- DPW2 WB

C  M  F
Convergence of Spread (2)  DPW-3

**CD_PR**

- DPW3 F6
- DPW3 FX2B
- DPW2 WB

**CD_SF**

- DPW3 F6
- DPW3 FX2B
- DPW2 WB
Convergence of Spread (3)  DPW-3

**ALPHA**

- C
- M
- F

**CM_TOT**

- C
- M
- F

Legend:
- DPW3 F6
- DPW3 FX2B
- DPW2 WB
Convergence of Core Interval

CD_TOT

- DPW3 F6
- DPW3 FX2B
- DPW2 WB

C  M  F
Convergence of Core Interval (2) DPW-3
Convergence of Core Interval (3) \( \text{DPW-3} \)
Case 2: DPW-W1 Wing Alone

N.B. DPW-W2 has not been analyzed
## Case 2 Solution Statistics

<table>
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<tr>
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Convergence of CD_TOT, CL_TOT

CD_TOT

CL_TOT

NPTS^{-2/3}

NPTS^{-2/3}
Convergence of CM_TOT

![Graph of CM_TOT vs NPTS^{2/3}](image)
Spread of CD\_TOT, CL\_TOT

Spread of CD\_TOT

Spread of CL\_TOT
CD_TOT, CL_TOT Core Interval

CD_TOT Core Interval

CL_TOT Core Interval

NPTS$^{-2/3}$ vs. Value

NPTS$^{-2/3}$ vs. Value
Summary
Spread (of nested data) for Finest Grid

![Bar chart showing spread for nested data]

- **ALPHA**
- **CD_TOT**
- **CD_PR**
- **CD_SF**
- **CM_TOT**

Legend:
- DPW2 WB
- DPW3 F6
- DPW3 FX2B
- DPW3 W1
Core Interval for Finest Grid

DPW-3

![Bar chart showing data for different intervals and categories.](image-url)
Concluding Remarks

• The Good News:
  – **DPW-3** was a “blind test”, i.e. no experimental data existed to “guide” solutions. The results were about as good for the blind test as for **DPW-2**.
  – **DPW-W1** might be showing evidence that it is in the asymptotic range

• The Less Good News:
  – Have not demonstrated convergence of medians, spread or core interval for F6/FX2B despite increased grid sizes
  – F6 spread and core interval have not improved from **DPW-2**
  – FX2B spread and core interval are not substantially better than F6
  – **DPW-W1** spread and core interval are not showing convergence
  – After 3 drag prediction workshops, grids remain a leading order issue
Concluding Remarks (2)

Hemsch’s remarks from DPW-2 still apply:

- Regarding grid convergence for the collective:
  - There is no reduction in spread;
  - There is no reduction in core scatter;
  - The medians MAY be converging, although it can’t be proven with the present results.
Some Recommendations

- We must make a concerted effort to understand the differences in the codes and models

- We must make a concerted effort to understand the effects of grid quality and grid resolution

- We must analyze and improve our processes
Fini?
Grid Convergence – All Solutions

F6 Wing-Body w/wo FX2, MACH = 0.75
Re = 5 Million, Fixed CL=0.50

GRIDFAC = 1/(GRIDSIZE)^2/3