NASA ERA Integrated CFD for Wind Tunnel Testing of Hybrid Wing-Body Configuration

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Outline

• Overview
• Efficient Use of Multiple CFD tools
• CFD Quality Assessment
• CFD Wind Tunnel Support
• Lessons Learned and Simulation Guidelines
• Conclusions
Overview

- ERA Project explored various enabling technologies to reduce environmental impact of aviation.
- Wind tunnel tests performed to evaluate propulsion-airframe interference effects.
- Extensive CFD was used to assist these tests in producing high quality data with minimal hardware interference and extrapolation to flight.
- High-level summary of how NASA utilized multiple CFD simulations tools in support of the wind tunnel test.
- CFD simulation guidelines based on post-test aerodynamic data.
CFD Solvers and Methods

- 3 NASA’s CFD Solvers utilized:
  - OVERFLOW
    - Overset grids via the Chimera Grid Tools
    - SA and SST turbulence model
  - USM3D
    - Unstructured tetrahedral meshes via TetrUSS GridTool
    - SA turbulence model
  - FUN3D
    - Unstructured prismatic/tetrahedral meshes via AFLR3
    - SA turbulence model
- 1 Commercial CFD Solver utilized:
  - STAR-CCM+
    - Unstructured prismatic/polyhedral meshes
    - SST turbulence model
Geometry and Mesh Generation

Sample Overflow Mesh

Sample USM3D Mesh

Sample FUN3D Mesh

Sample STAR-CCM+ Mesh

Efficient use of Multiple CFD Tools
CFD Quality Assessment

'Miniwall' Application
CFD Wind Tunnel Support

CFD was used to provide highest quality experimental testing
- Sting selection
- Ejector selection
- Acoustic array selection
- 40’x80’ sting installation
Sting Selection

Long Aft Sting
Long Forward Sting
Short Aft Sting
Short Forward Sting

OVERFLOW: $M_\infty = 0.2$

*Simulations run in free air*
Sting Selection

OVERFLOW: $M_\infty = 0.2 \alpha = 12°$

$\Delta C_p = (C_{p_{Sting\_conf}} - C_{p_{Clean}})$

USM3D: $M_\infty = 0.2 \alpha = 20°$

Long Forward Sting

Short Forward Sting

*Simulations run in free air
Ejector selection

Overflow: \( M_\infty = 0.2 \ \alpha = 20^\circ \)

\[ \Delta C_p = (C_{p\text{Ejector\_conf}} - C_{p\text{Clean}}) \]

\[ \Delta C_p = (C_{p\text{ShortEject}} - C_{p\text{LongEject}}) \]

*Simulations run in free air*
40’x80’ Acoustic array selection

Vertical Placement

Array at 24” below
Array at 48” below
Array at 96” below

STAR-CCM+: $M_\infty = 0.2$

40’x80’ Wind tunnel data

* Simulations run with walls and supports
40’x80’ Acoustic array selection

Horizontal Placement

60° Directivity

90° Directivity

120° Directivity

FUN3D: $M_\infty = 0.2 \alpha = 12°$

Cp comparison with and without Array at ~ 75% Span location

* Simulations run with walls and supports
40’x80’ sting installation

Original step collar

No collar

Faired collar

STAR-CCM+: $M_\infty = 0.2$

Pitching Moment Coefficient

Angle of Attack

* Simulations run with walls and supports
Lessons Learned
&
Simulation Guidelines
Support Post Unsteadiness

**Original Post**

**No Post**

**Modified Post**

**FUN3D:** $M_\infty = 0.2 \alpha = 12^\circ$

- **Orig Post**
- **No Post**
- **Mod Post**

**Time accurate run**

**Lift Coefficient**

**Drag Coefficient**

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* Simulations run with walls
High Alpha CFD flow predictions

Dependency on time integration process

Landing Krueger

Krueger structural bracket

FUN3D: $M_\infty = 0.2 \alpha = 20^\circ$

Non-Time Accurate

Time Accurate

(\(DT=20, 25\) subiterations)

~10% drop in Lift coefficient

*similar results obtained with Star-CCM+ using the SST turbulence model and with OVERFLOW using SA model.
High Alpha CFD flow predictions

Time accuracy study effect on HWB landing configuration

FUN3D: $M_\infty = 0.2 \, \alpha = 20^\circ$

Experimental Value

~10% drop in Lift coefficient

Lift Coefficient vs Physical Time (sec)

- $DT=0.02$, subit=6
- $DT=5.0$, subit=60
- $DT=10.0$, subit=100
- $DT=10.0$, subit=10
- $DT=50.0$, subit=250
High Alpha CFD flow predictions

**FUN3D: $M_\infty = 0.2 \ \alpha = 20^\circ$**

DT=10, 10 subiterations

DT=10, 100 subiterations

Lift coefficient subiteration

Residual subiteration Convergence

Turbulence

Flow variables
Conclusions

- CFD was an integral part of NASA’s ERA project.
  - Supported experimentalists in evaluating interference
  - Provided alternate support options to reduce unwanted effects

- Efficient use of multiple CFD solvers successfully used to provide timely insight.
  - NASA’s CFD solvers: OVERFLOW, USM3D, and FUN3D
  - Commercial CFD solver STAR-CCM+

- CFD analyst worked side-by-side with wind tunnel experimentalists throughout entire project.
  - Enabled direct knowledge on specific testing setup
  - Provided key insight to how test data was measured and post-processed for later CFD analysis.

- Lessons Learned and CFD simulation guideline development possible due to available test data.
Acknowledgements

- The NASA ARMD Environmentally Responsible Aviation Project provided multi-year funding for both the wind tunnel testing and CFD analysis.
- Boeing support staff played an integral part in the success of the tests
The rationale used to select these CFD time steps was to express them in terms of a physical vortex shedding Strouhal number \((\text{St})\) of 0.25. This was done since the nominal Strouhal number of many unsteady separated wake flows tends to fall into a small range between 0.15 and 0.25. Further, the Strouhal number is defined as: \(\text{St} = fL/U\). Where, \(f\) is the frequency, \(L\) is the relevant length scale, and \(U\) is the relevant velocity. In order to express \(\text{St}\) in terms of a CFD time step \((\text{DT})\), the Strouhal number equation is rewritten such that the frequency \(f = 1/\text{DT}\), and the velocity \(U\) is set to freestream \((U_\infty)\). In FUN3D, the time step is normalized by the sound speed. This will then yield what is referred to as the time step based Strouhal number \((\text{StDT})\) as follows: \(\text{StDT} = L/(\text{DT} \times M_\infty)\) in terms of the FUN3D grid units. Next, the ratio of the time step Strouhal number \((\text{StDT})\) to the physical Strouhal number \((\text{St})\) is used as a coarse measure of time integration accuracy. For good time accuracy, this Strouhal ratio, \(\text{StDT}/\text{St}\) must be at least 20, as the second-order backwards-difference time-integration scheme requires roughly that many points per period assuming a simple sinusoidal oscillation for high accuracy. An even higher ratio is needed if any part of the unsteady flow changes more rapidly than the gross features like integrated loads, and this is very common. Thus, the ratio of Strouhal numbers, \(\text{StDT}/\text{St}\) should be 20 or greater, by an unknown amount, to achieve good time accuracy.
14’x22’ Wind Tunnel Corrections

CFD Wind Tunnel Support

Uncorrected

Classic Corrections

CFD Based Corrections

ΔC_l

ΔC_D

ΔC_m

α°

α°

α°

Run 10 Closed
Run 11 Closed
Run 12 Closed
Run 18 Open
Trip dot selection

Upper Surface Thermal Imaging **With Trip Dots**

Key:
- Lighter patch = transition due to presence of Krueger bracket

Upper Surface Thermal Imaging **Without Trip Dots**

Key:
- Lighter patch = transition due to bug
- Darker areas on model = laminar

Additional Notes:
- Trip strip marks
- CFD Wind Tunnel Support

Image 104x36 to 108x756