OVERFLOW Analysis of the DLR F11 Geometry for HiLiftPW-2

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Solution Methods

- Solver: OVERFLOW 2.2e/2.2f
  - RHS: 3rd-order accurate Roe upwind
  - LHS: Scalar pentadiagonal approximate factorization
  - Low-Mach preconditioning
  - Recommended artificial dissipation
  - Grid sequencing and multigrid acceleration
  - Non-time accurate solution
    - Convergence assumed when force/moment limit cycles are reached

- Grids: Committee-provided structured overset grids (series E)
  - Generated by Boeing Huntington Beach

- Hardware
  - DoD HPC machines (AFRL and Navy DSRC Machines)
Solution Methods

• Turbulence Modeling
  – SA (Cases 1, 2a, and 2b)
  – SA-RC (Case 1 – Medium, 2a, and 2b)
  – SA-\( \tilde{\eta} \) (Transition – 2c)
  – SA-QCR2000-\( \tilde{\eta} \) (Transition – 2c)

• Turbulence model studies limited by time and available computing resources
  – Originally planned for full studies of SA, SA-RC, SST, and SST-RC for Cases 1, 2a, and 2b
  – Also planned to compare behavior of Langtry-Menter model (both original and applied to the Spalart-Allmaras model) with the Penn State amplification factor transport model
Grid Convergence Study
(Case 1)
Force/Moment Convergence Behavior

![Graph showing convergence behavior for different mesh resolutions (Coarse, Medium, Fine) with iteration count and lift coefficient (CL) on the y-axis and iteration on the x-axis.](image-url)
**Grid Convergence, R = 15.1 Million : Lift Curve**

Good grid convergence, but $C_{L_{\text{max}}}$ significantly over-predicted (Case 1 AoA sweep does not reach stall)
Grid Convergence, $R = 15.1$ Million: Drag Polar

Little discernible difference between grid levels, but this scale is very large in terms of aerodynamics.
Grid Convergence, $R = 15.1$ Million: Profile Drag Polar

“Profile” drag calculated as the difference between actual drag and idealized induced drag

$$C_{D,\text{profile}} = C_D - \frac{C_L^2}{\pi AR}$$
Grid Convergence, $R = 15.1$ Million: Pitching Moment

Good convergence, but converging away from experimental data

- Coarse
- Medium
- Fine
- ETW Experiment
High Re Grid Convergence Study

**Coarse**

**Medium**

**Fine**

$C_p$ contours

$R = 15.1e6$, $\alpha = 7^\circ$

$\eta = 0.150$

$\eta = 0.449$

$\eta = 0.751$

$\eta = 0.964$
High Re Grid Convergence Study

- Coarse
- Medium
- Fine

**C_p contours**

- $R = 15.1 \times 10^6$, $\alpha = 18.5^\circ$

- $\eta = 0.150$
- $\eta = 0.449$
- $\eta = 0.751$
- $\eta = 0.964$
High Re Grid Convergence Study

Coarse

Medium

Fine

$C_p$ contours

$R = 15.1e6, \alpha = 18.5^\circ$

$\eta = 0.150$

$\eta = 0.449$

$\eta = 0.751$

$\eta = 0.964$
RC Correction, No Tracks, R = 15.1 Million

\( \gamma = 0.150 \)

\( \gamma = 0.449 \)

\( \gamma = 0.751 \)

\( \gamma = 0.964 \)

R = 15.1e6, \( \alpha = 7^\circ \)

C_p contours
Effect of Slat Tracks and Flap Track Fairings (Cases 1 and 2b)
Tracks/Fairings Effects, $R = 15.1$ Million: Lift Curve

Modeling the tracks reduces overall lift and $C_{L,max}$
Tracks/Fairings Effects, R = 15.1 Million: Drag Polar

Modeling the tracks increases predicted drag, but does not change character of the polar

- SA (No Tracks, Medium)
- SA-RC (No Tracks, Medium)
- SA (Tracks)
- SA-RC (Tracks)
- ETW Experiment
Tracks/Fairings Effects, $R = 15.1$ Million: Pitching Moment

Much better agreement and even predicts a pitch break
**Effect of Slat and Flap Tracks, R = 15.1 Million**

*No Tracks (Case 1)*

*Tracks (Case 2b)*

*\(C_p\) contours*

\(R = 15.1e6, \alpha = 7^\circ\)
Effect of Slat and Flap Tracks, $R = 15.1$ Million

No Tracks (Case 1)

Tracks (Case 2b)

$C_p$ contours
$R = 15.1 \times 10^6$, $\alpha = 21^\circ$
Reynolds Number Study
(Cases 2a and 2b)
Lower Reynolds number predictions show increasing lift after initial stall

Distinct shift in zero-lift angle of attack implies strong influence of TE separation
Reynolds Number Study: Drag Polar

Some difference just before stall between SA and SA-RC predictions at $R = 1.35$ Million

C vestibule

$C_D$ profile

SA (High Re)
SA-RC (High Re)
SA (Low Re)
SA-RC (Low Re)
ETW Experiment (High Re)
B-LSWT Experiment (Low Re)
Reynolds Number Study: Pitching Moment

Good agreement at low lift coefficients for both Reynolds numbers

- SA (High Re)
- SA-RC (High Re)
- SA (Low Re)
- SA-RC (Low Re)
- ETW Experiment (High Re)
- B-LSWT Experiment (Low Re)
Effect of RC Correction, Tracks/Fairings On, $R = 1.35$ Million

SA

SA-RC
Effect of RC Correction, Tracks/Fairings On, R = 1.35 Million

\( R = 1.35 \times 10^6, \, \alpha = 21^\circ \)

\( \gamma = 0.150 \)

\( \gamma = 0.449 \)

\( \gamma = 0.751 \)

\( \gamma = 0.964 \)

\( C_p \) contours
Transitional Flow Effects

(Case 2c)
• Amplification Factor Transport Equation (AIAA 2013-0253)

\[
\frac{\partial (\rho \tilde{n})}{\partial t} + \frac{\partial (\rho u_j \tilde{n})}{\partial x_j} = \rho \Omega F_{\text{crit}} F_{\text{growth}} + \frac{\partial}{\partial x_j} \left[ \sigma_n (\mu + \mu_t) \frac{\partial \tilde{n}}{\partial x_j} \right]
\]

- Predictive model based on the approximate envelope method of Drela and Giles
  - Models Tollmien-Schlichting transition
  - Uses local flow variables and wall distance to estimate the boundary-layer shape factor
    - Parallelizable (no integration paths)
    - Requires free-stream conditions to be available at every grid point
-Insensitive to domain size
  - Transition criterion set critical amplification factor
- Shows improvement over local-correlation methods for predicting flow around airfoils (including multi-element airfoils)
• Applied to the Spalart-Allmaras eddy-viscosity model

\[
\frac{D\tilde{\nu}}{Dt} = c_{b1} \left(1 - f_{t2,\text{mod}}\right) \tilde{S}\tilde{\nu} - \left[c_{w1} f_w - \frac{c_{b1}}{K^2} f_{t2,\text{mod}}\right] \left(\frac{\tilde{\nu}}{d}\right)^2 + \frac{1}{\sigma} \left[\frac{\partial}{\partial x_j} \left((\nu + \tilde{\nu}) \frac{\partial \tilde{\nu}}{\partial x_j}\right) + c_{b2} \frac{\partial \tilde{\nu}}{\partial x_j} \frac{\partial \tilde{\nu}}{\partial x_j}\right]
\]

where the \( f_{t2} \) function is modified to

\[
f_{t2,\text{mod}} = c_{t3} \left[1 - \exp(2(\tilde{n} - N_{\text{crit}}))\right] \exp\left(-c_{t4} \left(\frac{\tilde{\nu}}{\nu}\right)^2\right)
\]

with \( c_{t3} = 1.2 \) and \( c_{t4} = 0.05 \)

• \( N_{\text{crit}} \) set to 8.15 for Case 2c
  – Based on reported B-LSWT turbulence levels and Mack’s relationship
Quadratic Constitutive Relation (QCR)

- Non-linear extension to the Boussinesq eddy-viscosity hypothesis proposed by Spalart
  - Original (QCR2000) version implemented into OVERFLOW 2.2f
    \[ \tau_{ij,\text{QCR}} = 2\mu_t \left[ S_{ij} - c_{nl1} \left( O_{ik} S_{jk} + O_{jk} S_{ik} \right) \right] \]
  - where \( c_{nl1} = 0.3 \) and
    \[ O_{ik} = \frac{\frac{\partial u_i}{\partial x_k} - \frac{\partial u_k}{\partial x_i}}{\sqrt{\frac{\partial u_m}{\partial x_n} \frac{\partial u_m}{\partial x_n}}} \]
- Higher-order terms demonstrated to improve predictions for corner flows
Quadratic Constitutive Relation (QCR)

- SA-QCR predicts significantly reduced SOB separation on the CRM wing used for DPW-V

From Sclafani, et al. (AIAA 2013-0048)

- Of great interest for HiLiftPW-2 simulations, but only applied to transitional data due to time constraints
Including T-S transition does not reconcile lift curve at lower lift coefficients!
Transition Study, $R = 1.35$ Million : Drag Polar

“Profile” drag calculated as the difference between actual drag and idealized induced drag.
Pitching moment agrees at lower lift coefficients, but not through the pitch break.
Surface Streamlines vs. QCR/Transition: $\alpha = 18.5^\circ$

Experiment shows separation onset on the main element at ~50% and ~75% semispan locations.

OVERFLOW predicts onset of separation at 75%, but not at 50%.

Separation on flap appears to be more prominent.
Surface Streamlines vs. QCR/Transition : $\alpha = 18.5^\circ$

Good agreement for laminar-separation bubble patterns

$C_f$ contours
Surface Streamlines vs. QCR/Transition: $\alpha = 18.5^\circ$

OVERFLOW solution shows contamination on the slat and main element near the root.

This behavior for the slat seems to agree with experiment.

Laminar-separation patterns are well-predicted outboard of the contaminated region.

$L_f$ contours
Surface Streamlines vs. QCR/Transition : $\alpha = 21^\circ$

Experiment shows large separated region mid-span causing wing stall

OVERFLOW predicts stall-causing separation farther outboard

$C_f$ contours
Root contamination on the main element is more prominent, but still contained on slat.

Seems to be the result of slat wake contamination (essentially bypass transition) rather than leading-edge contamination.
Surface Streamlines vs. QCR/Transition: $\alpha = 21^\circ$

Contamination occurs on the flap as well near the root.

Preliminary studies indicate it being a result of excessive eddy-viscosity production.

More investigation required into this behavior.
Some Conclusions and Future Work

- Behavior dominated by trailing-edge separation
  - Shift in zero-lift angle of attack
  - Relatively soft stall behavior
  - Choice of turbulence model has strong influence

- OVERFLOW failed to predict spanwise location of upper-surface separation wedge
  - Experiment showed $\eta \approx 50\%$
  - OVERFLOW predicted $\eta \approx 75\%$

- Transition modeling had little effect on the predictions
  - Slight reduction in profile drag
  - Not enough to reconcile CFD predictions with experiment
  - More transition models need to be explored!
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Thank you for your time

Questions?
Without multigrid acceleration, solution locally destabilized on the medium grid but produced reasonable forces/moments.

Multigrid stabilized the solution, but barely affected the lift, drag, and pitching moment in comparison.

Density contours, $R = 15.1\times10^6$, $\alpha = 18.5^\circ$