Application of CFD to Abrupt Wing Stall Using RANS and DES

Jim Forsythe
Cobalt Solutions, LLC

NASA LaRC SAMS Contract NAS1-00135
Charles Fremaux, Robert Hall

Acknowledgements: Joe Chambers, Paresh Parikh, Scott Morton (USAFA), ASC MSRC
Outline

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Previous work published at AIAA meeting in Reno 2003, and to be published in AIAA Journal of aircraft (FOM=Figure of Merit).

Motivation?

- Pre-production F/A-18E
  - Exhibited “wing drop” in flight test
    - “wing drop” is an uncommanded lateral motion
    - “abrupt wing stall” is an aerodynamic characteristic, and can cause wing drop
  - Numerous flight tests resulting in a production fix
    - Revised flight control laws and porous wing fold fairing
  - A comprehensive program was created to be able to predict these phenomenon with wind tunnels and CFD
    - Free-to-roll wind tunnel test method
    - FOM’s for steady and unsteady (non-moving) CFD

- Current work: Progress CFD to calculations of damping derivatives and free-to-roll for this flow by application to pre-production F/A-18E
For DES, RANS is responsible for predicting boundary layer growth and separation. LES is responsible for predicting the geometry dependant turbulent flow features. Grid adaptation done using NASA Langley’s RefineMesh program. Adaptation on time average of vorticity.
DES results are time-averaged coefficients. Left axis removed to protect proprietary data.

- 10/10/5 flap set with no tails
- SST predicted early lift curve break
- DES showed an improved lift curve break (but on a grid finer than the current grid)
- Motivates inclusion of DES in the current project, along with RANS
These DES projects represent a cross section of those done over the past few years using Cobalt.

Delta wing vortex breakdown on a delta wing and the F-18C done by Major Scott Morton of the USAF Academy (Scott.morton@usafa.af.mil).

2-D forebody geometry by Kyle Squires (squires@asu.edu).

Prescribed spin of the F-15E by James Forsythe.
Prisms created using “Blacksmith” to recombine the tets in the boundary layer into prisms. Blacksmith is a Cobalt grid utility.

- Grid mirrored about symmetry plane
- Grid provided by Paresh Parikh
- 6/8/4 flap set
- 8.4x10⁶ cells for both sides of aircraft
- Adaption performed on a 9° time-averaged DES solution under previous work
- Prisms in boundary layer
- Average y⁺ < 0.7
The following are non-moving cases – but can be unsteady (for DES)
CPU hours based on a Compaq ES45. Timestep for DES non-dimensionalized by chord and freestream velocity.

- **Menter’s SST RANS model**
  - Convergence monitored by observing forces and moments. Rolling moment was generally the most sensitive and last to converge.
    - 4000 iterations
    - 1 Newton sub-iteration
    - CFL of $1 \times 10^6$
    - 2000 cpu hours per run.

- **Spalart-Allmaras based DES model**
  - Unsteady flow simulation
    - 16000 iterations
    - 3 Newton sub-iterations
    - $\Delta t^*=0.01$
    - 8x the cost of the steady RANS simulations
Model was set to a given pitch angle (theta), then rolled about the longitudinal axis (phi). This resulted in a decrease of alpha, and an increase in beta as phi increased. The CFD was performed at the given alphas and betas, which were corrected in the wind tunnel data for wall effects.

- Conditions chosen to match NASA Langley wind tunnel test 565
- Mach=0.9
- Reₖ=3.9x10⁶
- Flow through engines
- Sting not included in grid
Normal force for near-zero sideslip

Normal force vs. angle of attack for zero roll

Left axis not labeled to protect proprietary data.
Pitching moment for near-zero sideslip
Note reversal of rolling moment for phi=30 using SST.
Yawing moment well predicted – as with all cases.
Side force well predicted – as with all cases.
Shock retreating off trailing edge of leading edge flap.
DES isosurface looks like separation is at trailing of leading edge flap. But it moves back from there unsteadily. This leads to the blue low pressure in the separation bubble (since it is not always separated).
Run 247 ($\theta \approx 7^\circ$, $\phi \approx 10^\circ$)

SST

DES

Isosurface of $u=0$, surface colored by pressure
The separation moving forward on the right wing is the cause for the roll moment reversal.
At this high phi, the alpha is reduced so much that the flow remains attached until the trailing edge of the wing.
Note asymmetries in wind tunnel data. Decrease in lateral stability derivative picked up with DES.
Good agreement for yawing moment, as with all cases – this is likely due to the attached flow at the tail, which is easily predicted.
Good agreement for side force, as with all cases – this is likely due to the attached flow at the tail, which is easily predicted.
Separation is making it onto the leading edge of the leading edge flap.
Run 240 ($\theta \approx 8.5^\circ$), $\phi \approx 4^\circ$

SST

DES
Run 240 (θ≈8.5°), φ≈10°
SST  DES

Isosurface of u=0, surface colored by pressure
Run 240 ($\theta \approx 8.5^\circ$), $\phi \approx 30^\circ$

SST

Isosurface of $u=0$, surface colored by pressure
Large asymmetries in wind tunnel data. Around this angle there was difficulty in testing, since model dynamics became significant.
Good agreement for yawing moment, as with all cases.
Good agreement for side force, as with all cases.
Run 242 (θ≈9°), φ≈10°
SST

Isosurface of u=0, surface colored by pressure
Run 242 (θ≈9°), φ≈30°
SST
Rolling moment offset predicted by DES – is the sample size large enough?
Looks like enough samples have been taken to well define rolling moment. However more might change the time-averaged rolling moment some.
Run 244 ($\theta \approx 10^\circ$)
Run 244 ($\theta \approx 10^\circ$)
Unsteadiness now is due to separation moving from leading to trailing edge of the leading edge flap.
Run 244 ($\theta \approx 10^\circ$), $\phi \approx 0^\circ$

SST

DES
Run 244 (θ≈10°), φ≈10°

SST  DES
Run 244 ($\theta \approx 10^\circ$), $\phi \approx 30^\circ$

SST
Run 244 ($\theta \approx 10^\circ$), $\phi \approx 60^\circ$

SST
Oscillating Cases
ALE = Arbitrary Eulerian/Lagrangian.
Linear and well behaved. Stable roll damping.
Separation at trailing edge – flow well behaved.
Large rolling moment offset. Several cycles run with varied timestep, but offset remained.
Offset due to differences in separation location. Hysteresis?
Slightly chaotic behavior, but linear and stable roll damping.
\( \alpha \approx 7^\circ \)
Positive roll damping. Note lowered slope – due to lower lift curve slope once shock moves forward on the wing.
$\alpha \approx 8^\circ$
Rolling moment vs. Roll rate
Rolling moment vs. Roll rate

\[ \frac{d\phi}{dt} \times b/2U_\infty \]
Study still underway – not enough samples. Looking at dependence of roll damping on roll rate.
Conclusions

- RANS and DES applied to predict static stability derivatives in roll in AWS regime
  - DES showed better lift and moment predictions
  - Yawing moments and side force well predicted by both methods
  - Rolling moment more sensitive (both for CFD and wind tunnel)
- Prescribed rolls used to look at roll damping (RANS only)
  - All cases were stable in roll, but in AWS regime had more chaotic behavior. For one angle there was a significant rolling moment offset
  - Comparison to experiments still ongoing
- Continuing work
  - DES of prescribed rolls
  - More iterations on varying roll rate