Experiences in Predicting Massively Separated Flows: Taking Advantage of Detached-Eddy Simulation

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Overview

- Brief description of DES
- Overview of DES experience
- Some recent applications of DES:
  - High-lift aerodynamics
  - F-18E Abrupt Wing Stall
  - F-15 Spin
  - F-18C High Angle of Attack
- Current and future applications:
  - Aeroelasticity
  - Computational stability and control
- Delayed DES
- Conclusions
Flow Solver

- Unstructured finite volume Navier-Stokes solver from Cobalt Solutions, LLC
- Grid decomposition using Parmetis
- Information passing using MPI
- Movies using Fieldview (both PC and Linux versions)
Detached-Eddy Simulation

- **Direct Numerical Simulation (DNS)**
  - solution of the Navier-Stokes equations without use of an explicit turbulence
  - limited to low Reynolds numbers
  - powerful research tool
  - ready for full aircraft in ~2080

- **Large Eddy Simulation (LES)**
  - direct resolution of the large, energy-containing scales of the turbulent flow
  - model only the small eddies
  - high computational cost in boundary layers
  - ready for full aircraft in ~2045

- **Reynolds-average Navier-Stokes (RANS)**
  - model the entire spectrum of turbulent motions
  - Highly unreliable performance in separated flows
  - ready for full aircraft today

DES method combines RANS and LES

increase in cost

increase in empiricism
Experience with DES

Delta Wing Vortex Breakdown

F/A-18E Abrupt Wing Stall

F/A-18C Tail Buffet

Forebody Crossflow

F-18 HARV Aeroelastic Flight Tests
High-Lift Aerodynamics: Part-Span Slat/Part-Span Flap

Experiment: NASA TM-1998-112222
Computation: AIAA Paper 2004-1233
High-Lift Aerodynamics

- Spalart-Allmaras one equation turbulence model initially used
- Four initial meshes: 2.4 to 5.6 million cells
- Unsteadiness apparent with 5.6 million cell mesh
- Mesh adapted in regions of high vorticity
High-Lift Aerodynamics

Steady-state initial mesh

Time-accurate adaptive mesh
S-A Computational Results

- Slat flow is attached
- Main element flow is attached behind slat
- Flap-tip vortex caused inboard flow on last 30% of main element chord
- Slat-tip vortex causes flow away from flap
- Flow separates on main element near slat-tip vortex
- Flap is stalled at 20% chord
S-A Computational Results

- Both slat-tip and flap-tip vortices appear steady
- Both vortices convect downstream without evidence of breakdown or dispersion
- Evidence of double vortex system on flap tip as seen in experiments
A Troubling Observation

“As it is convected further downstream, the slat-tip vortex dissipates due to interaction with the main-element boundary layer. At approximately mid-chord of the main element, the slat-tip vortex is no longer discernable using the smoke flow-visualization technique.”

NASA TM-1998-112222
DES Computational Results

Part-Span Slat/Part-Span Flap Wing
X-vorticity colored by pressure

Pressure (psf)
- 2100.000
- 2000.000
- 1900.000
- 1800.000
- 1700.000
- 1600.000
F/A-18E Abrupt Wing Stall (AWS)

F/A-18E AWS

- 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
  - Steady and unsteady (non-moving) CFD
  - 6-DOF CFD
F/A-18E Abrupt Wing Stall

- Use CFD to predict the unsteady shock oscillations seen in the experiments
- RANS models failed to give unsteady results
- DES solution-based grid adaption
F/A-18E Abrupt Wing Stall

Full span F/A-18E without tails: Surface colored by pressure with vorticity isosurfaces
F/A-18E Abrupt Wing Stall

- SST predicted early lift curve break
- DES showed an improved lift curve break (required a finer grid)
F/A-18E Abrupt Wing Stall

- 1-DOF grid mirrored about symmetry plane
- 6/8/4 flap set
- 8.4 million cells for both sides of aircraft
- Adaption performed on a $\alpha=9^\circ$ time-averaged DES solution under previous work
- Prisms in boundary layer
- Average $y^+ < 0.7$
F/A-18E Abrupt Wing Stall

- Aircraft released from a 60 degree bank to match wind tunnel tests
- Initial aircraft response examined for damping or amplification
- Mach=0.9, 8% model
- Wing drop range in experiments was roughly $\alpha=7$-$10$ degrees
- Wing drop events in wind tunnel were highly sporadic – model would be quiet for long stretches of time, then bank rapidly past 20 degrees.
- Timestep set by need to resolve high-frequency shedding.
  - $\Delta t=0.02c/U_\infty$
- Low frequency of oscillation required 25-50,000 iterations per cycle
  - Large # of new/fast processors used (1024) made turn around time for simulation 1 week, rather than several months
F/A-18E Abrupt Wing Stall

- Superlinear speedup due to increased cache efficiency as problem size per processor decreased with more processors.
- Scalability impacted by file I/O since outputting flow viz files at a high frequency.
- 1024p used for production runs since that gave the best speedup/processor.
F/A-18E Abrupt Wing Stall

$\alpha = 6$ degree pitch angle case
F-15E Aircraft Spin

F-15 Aircraft Spin

- post-stall, self-propelled rotary motion
- advanced aircraft operate increasingly in regimes characterized by high angle of attack under dynamic conditions
- over-arching objective: develop a computational tool for spin study
Spin testing is a key step in any aircraft evaluation. Current analytical methods for spin prediction are inadequate (non-linear aero and inertial effects). Experimental methods have Re and dynamic scaling issues. Flight test is expensive (difficult for design phase). Motivates development of CFD methods of spin prediction.

**Approach**
- Detached-Eddy Simulation $\rightarrow$ To accurately predict separated flow
- 6 Degree-of-freedom $\rightarrow$ To predict non-linear inertial effects

F-15E chosen for study due to the comprehensive spin tests performed, and the availability of the stability and control database (courtesy of Boeing).
F-15E Aircraft Spin

- Unsteady, non-moving calculations – $\alpha=65^\circ$, zero sideslip
- Timestep and grid refinement study
- Comparison between DES and RANS
- Key Findings
  - Fine grid (10x10^6 per side) could get results within 5% of database
  - Differences between grids mainly on nose and tail (wings grid converged)
  - Steered subsequent grid for current study
  - RANS not as far off as expected

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<th>$C_D$</th>
<th>$C_M$</th>
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<th>$%C_D$</th>
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<td>1.744</td>
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<td>Coarse</td>
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<td>7.78%</td>
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F-15E Aircraft Spin

- Prescribed spin based on expected spin conditions of $\alpha=65^\circ$, $\beta=-2.5^\circ$, 100°/sec
- Rotating around velocity vector
- Spin axis determined by balancing lift with centripetal acceleration
- Spun in direction of zero beta yaw moment (nose right)
F-15E Aircraft Spin

- Grid clustering and density driven by previous DES grid refinement study
- Timestep determined from previous timestep study
- $6.5 \times 10^6$ cells for entire aircraft
- Average first $y^+$ was 0.2
- Geometric progression of 1.25
- $M=0.3$, 30,000 ft
- $Re=13.6 \times 10^6$
F-15E Aircraft Spin

- Attempted 6-DOF spin of a clean configuration
  - More difficult than a pro-spin controls case, since the stabilized spin is very touchy.
  - In the spin tunnel, only about 3 of 10 tosses resulted in a stabilized spin (Fremaux, C.M, NASA Langley)
- The stable spin parameters from the S&C Database provided:
  - $100^\circ$/sec
  - $\alpha=65^\circ$, $\beta=-2.5^\circ$
  - $M=0.302$
  - $H=30,000$ft
- Three attempts to get into the spin
  - Drop aircraft from rest in a horizontal position
  - Start in a left prescribed spin at $100^\circ$/sec, $\alpha=90^\circ$, $M=0.3$ (vertical)
  - Start in a right prescribed spin at $100^\circ$/sec, $\alpha=90^\circ$, $M=0.3$ (vertical)
F-15E Aircraft Spin Benchmarks

- Large cpu time required due to small required timestep for resolving turbulence/motion, and need to do many revolutions (many iterations)
- 4 stage Runge-Kutta for benchmark (4x cost of a normal iteration)
- Production runs were done with 2 stage (2x cost of normal iteration)
- $\Delta t=0.013* c/U_\infty$
  - Leads to about 4000 iterations per revolution
F-15E With Prescribed Right Spin
F-15E With Prescribed Right Spin
Future Applications of DES

- Delta Wing Vortex Breakdown
- Forebody Crossflow
- F/A-18E Abrupt Wing Stall
- F/A-18C Tail Buffet
- F-18 HARV Aeroelastic Flight Tests
Moving Mesh Strategies

- To further extend the CFD capabilities for DES we are currently investigating two additional applications that require moving meshes:
  - Aeroelasticity
  - Computational stability and control
Aeroelasticity

- Based on the torsional spring analogy of Farhat for inviscid cells
- Redistribution of points for viscous cells
- Allows for large amplitude deformation
- Eventually couple CFD solution with structural model

AIAA Paper AIAA 2005-0926
Control Surface Modeling

- Based on Delaunay mapping technique of Liu et al developed for aeroelastic applications
  - Tetrahedralization of surface nodes with fixed boundary nodes generated
  - Location of volume nodes within cells of tetrahedralization stored for initial configuration
  - As surface deforms, graph cells deform naturally, and volume nodes are repositioned based on original location

- Also allows for large deformations
- Currently being applied to 3D control surfaces
Computational Stability & Control

- Takes advantage of mesh deformation and/or unsteady CFD capabilities
- Models aircraft stability derivative definitions to more precisely determine aircraft capabilities—example: pitch and plunge damping

\[ C_{m_q} + C_{m_{\ddot{\alpha}}} \]
Maneuver Module

- Easily define maneuvers for S&C analysis using stand-alone, interactive Matlab GUI
- Takes inputs from user of what motion category and type, and key parameters
- Converts inputs into rigid-body motion file in Cobalt format
  - Arbitrary motions
  - Predefined S&C maneuvers
  - 6 DOF
Control Surface Module

- Automatically creates control surfaces in grid and deforms grid due to control surface movement
- Generates control surface within subset of existing good-quality grid using local remeshing
- Quick and efficient algebraic deformation of surface and volume grid
- A-priori determination of grid quality throughout control surface range of motion
Coning Motion

- **Conventional coning:**
  - Axis of rotation is coincident with wind direction
  - Used in rotary balance testing to estimate dynamic S&C derivatives
  - $\alpha=30^\circ$, $\Omega=180^\circ/s$, $t_{\text{sim}}=1.68\text{s}$, 2,978 CPU h

- **Inclined axis oscillatory coning:**
  - Axis of rotation not aligned with wind direction (inclined by $60^\circ$),
  - Oscillating $\alpha$ and $\beta$
  - Estimate unsteady terms, separate combined derivatives determined in conventional forced oscillation exp.
  - $\alpha_{\text{init}}=30^\circ$, $\alpha=+30^\circ$...$-90^\circ$, $\Omega=180^\circ/s$, $t_{\text{sim}}=3.12\text{s}$
Configuration Plunge Pulse

- Gives static lift curve slope and dynamic derivatives due to angle-of-attack rate
- Provides detail in frequency domain at significant cost reduction over multiple oscillatory response method
- Can be used to extract pitch rate derivative when combined with pitch pulse
- Similar benefits exist for lateral derivatives
- $t_{\text{sim}} = 0.42 \text{ s}, 356 \text{ CPU h}$

\[
h(t) = \bar{h}e^{-\ln(0.5)(2(t-t_0)/t_{12})^2}
\]
\[
\bar{h} = 0.01c, 0.1c, 1.0c
\]
Delayed Detached-Eddy Simulation

- DES switches from RANS to LES based on the local grid density
- Can cause problems for shallow separation flowfields
- The new version would maintain RANS in the boundary layer regardless of the grid spacing
- Uses a blending function to transition from RANS to LES
- DDES has been tested with good results: AIAA Paper 2006-0901
Conclusions

- Aircraft flying at conditions with massive flow separation can be modeled accurately using DES
- High lift and high alpha flows are good candidates for this hybrid model
- New applications (such as aeroelasticity and computational stability & control) are currently being investigated
- DDES may extend these results to cases with shallow separation
Acknowledgements

- Scott Morton, Jim Forsythe, Stefan Görtz, Dave McDaniel of USAFA
- DOD High Performance Computing
Questions?
External flows around vehicles of technological interest usually occur at high Reynolds numbers for which the underlying fluid motion is usually turbulent

- main challenge: flows with massive separation
- wind tunnel test problematic
  » important Reynolds number effects
- flight tests costly, time-consuming

computational modeling important for advancing fundamental understanding and engineering prediction
Detached-Eddy Simulation

- Turbulence modeling approach proposed by Spalart et al. (1997)
  - Combines Large Eddy Simulation and Reynolds-Averaged approaches
  - Designed to provide accurate solutions for massively separated flows
  - Can resolve unsteady flow features (aero-acoustics, aero-elasticity)
  - RANS model responsible for predicting boundary layer growth and separation (NUMERICALLY FEASIBLE)
  - LES model responsible for prediction of unsteady flow in separated region (ACCURATE)