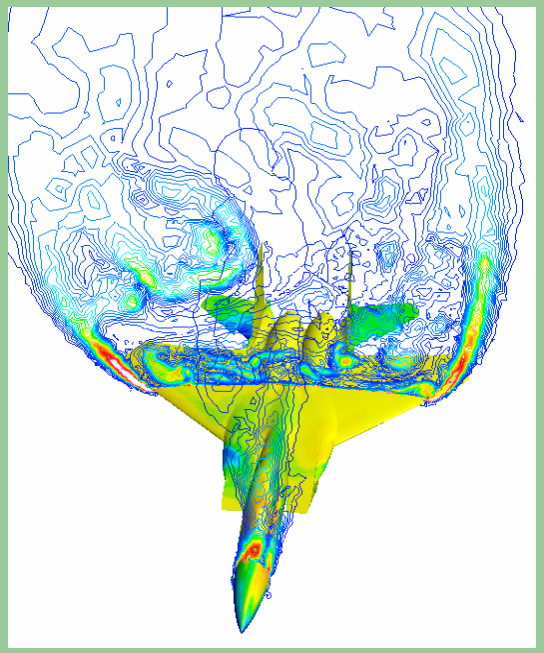
Experiences in Predicting Massively Separated Flows: Taking Advantage of Detached-Eddy Simulation



Russell M. Cummings
U.S. Air Force Academy

UKAA Consortium Conference
5/6 April 2006
Loughborough University

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

increase in cost

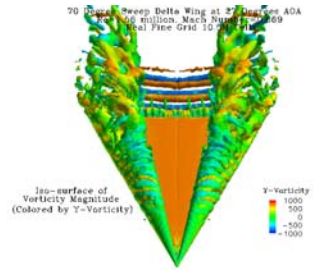
- Direct Numerical Simulation (DNS)
  - solution of the Navier-Stokes equations without use of an explicit turbulence – limited to low Reynolds numbers
  - powerful research tool
  - *ready for full aircraft in ~2080*
- Large Eddy Simulation (LES)
  - direct resolution of the large, energy-containing 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

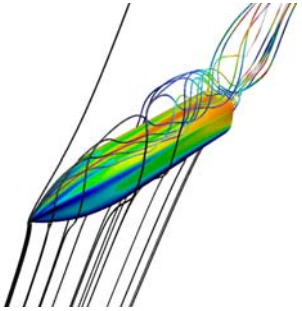
increase in empiricism

Experience with DES

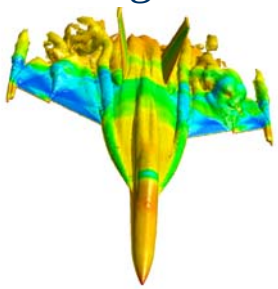
Delta Wing Vortex Breakdown



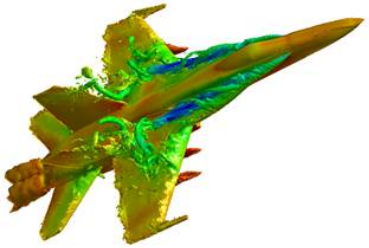
Forebody Crossflow



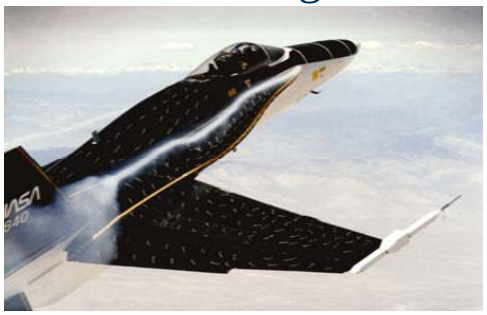
F/A-18E Abrupt Wing Stall



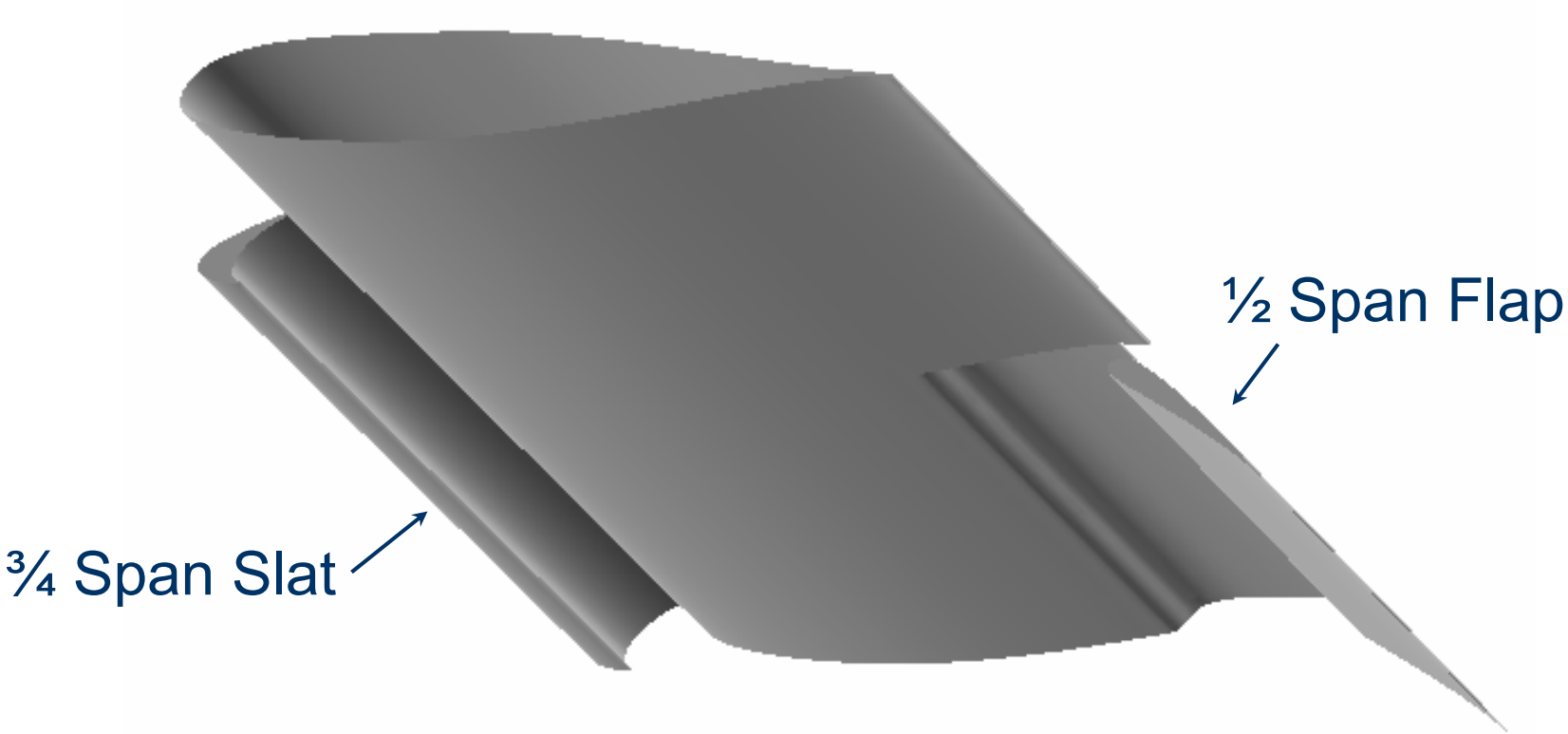
F/A-18C Tail Buffet



F-18 HARV Aeroelastic Flight Tests



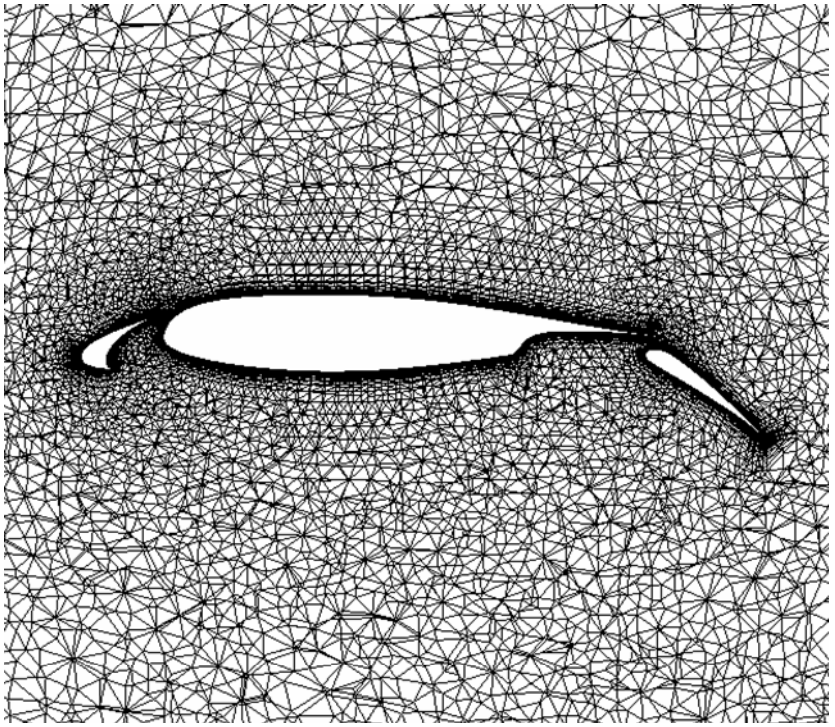
High-Lift Aerodynamics: Part-Span Slat/Part-Span Flap



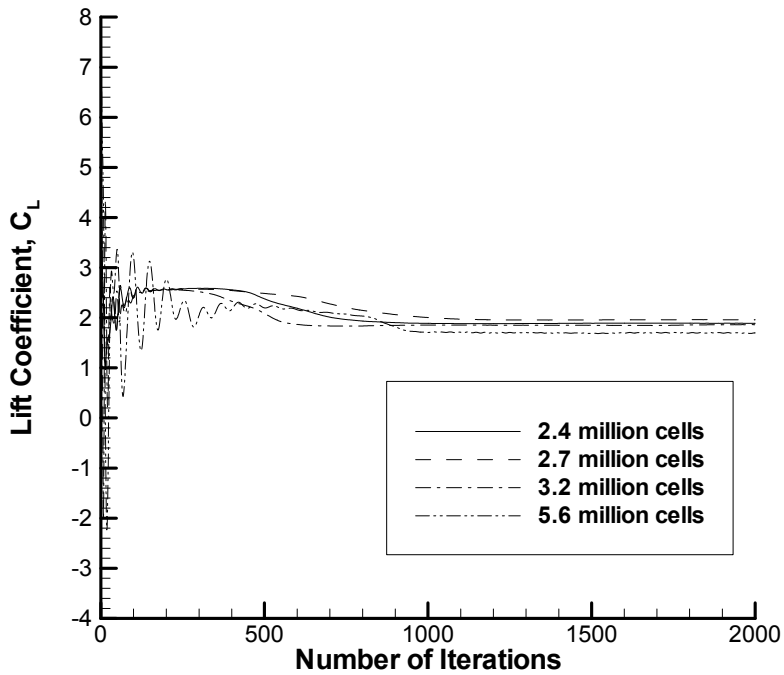
Experiment: NASA TM-1998-112222
Computation: AIAA Paper 2004-1233

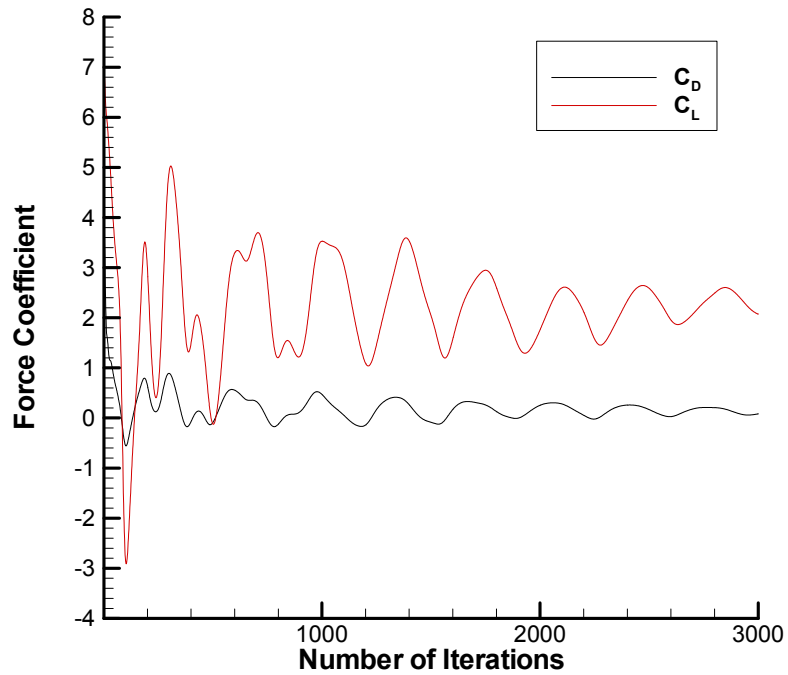
High-Lift Aerodynamics

- 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



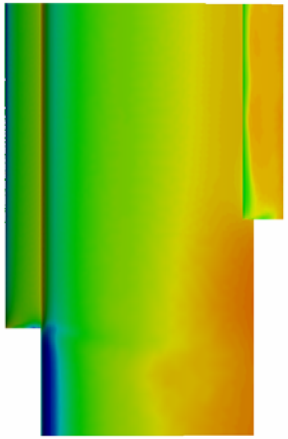


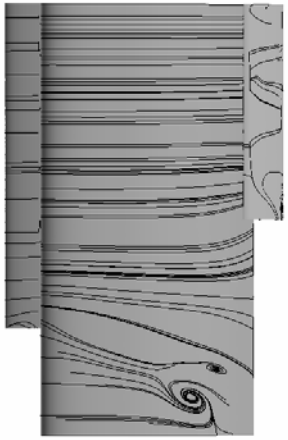
Steady-state initial mesh

Time-accurate adaptive mesh

S-A Computational Results

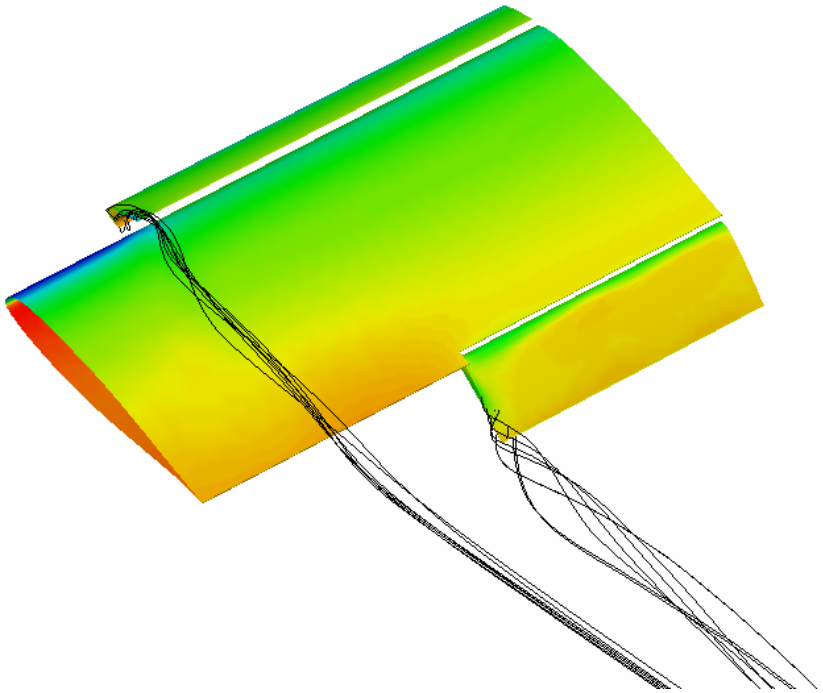
- Slat flow is attached
- Main element flow is attached behind slat
- Flap-tip vortex caused inboard flow on last 30% of main element chord
- Slat-tip vortex causes flow away from flap
- Flow separates on main element near slat-tip vortex
- Flap is stalled at 20% chord





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

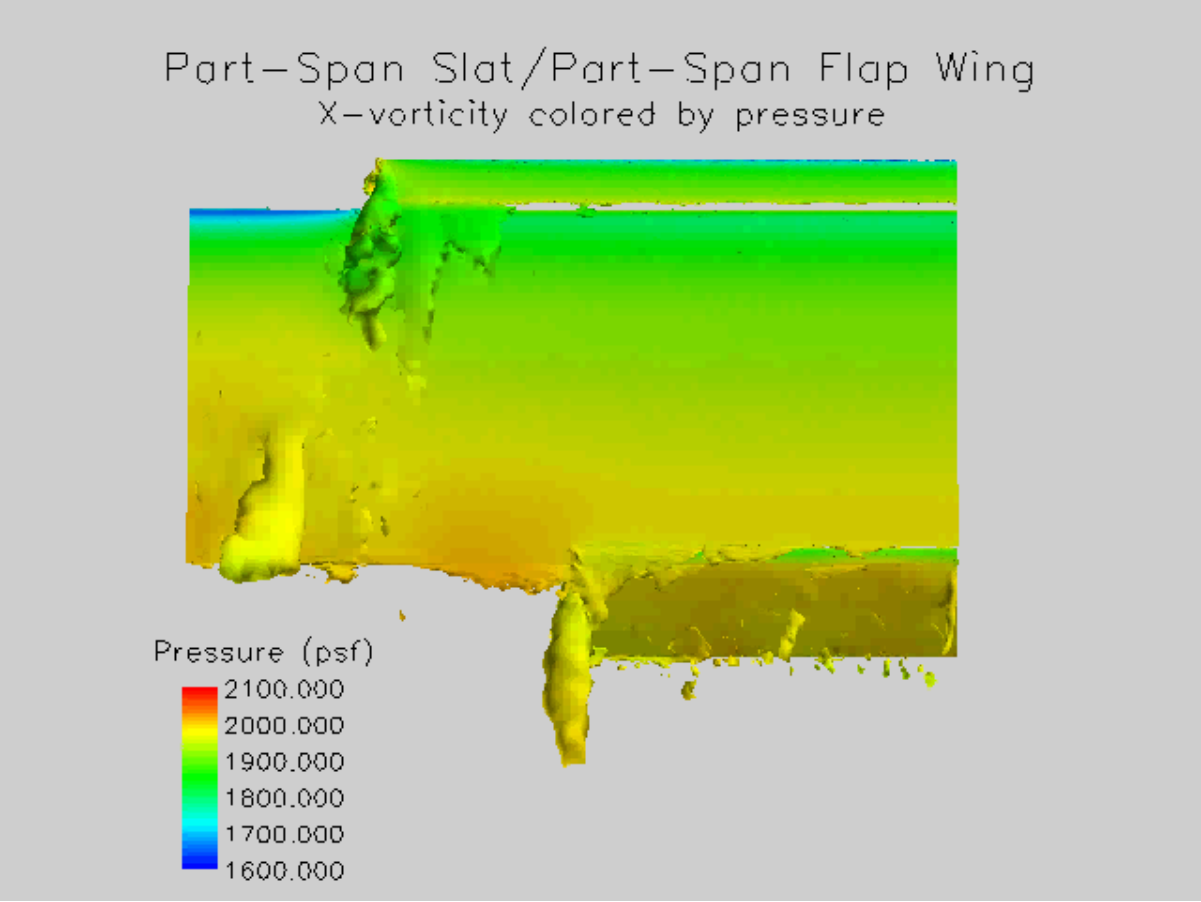


A Troubling Observation

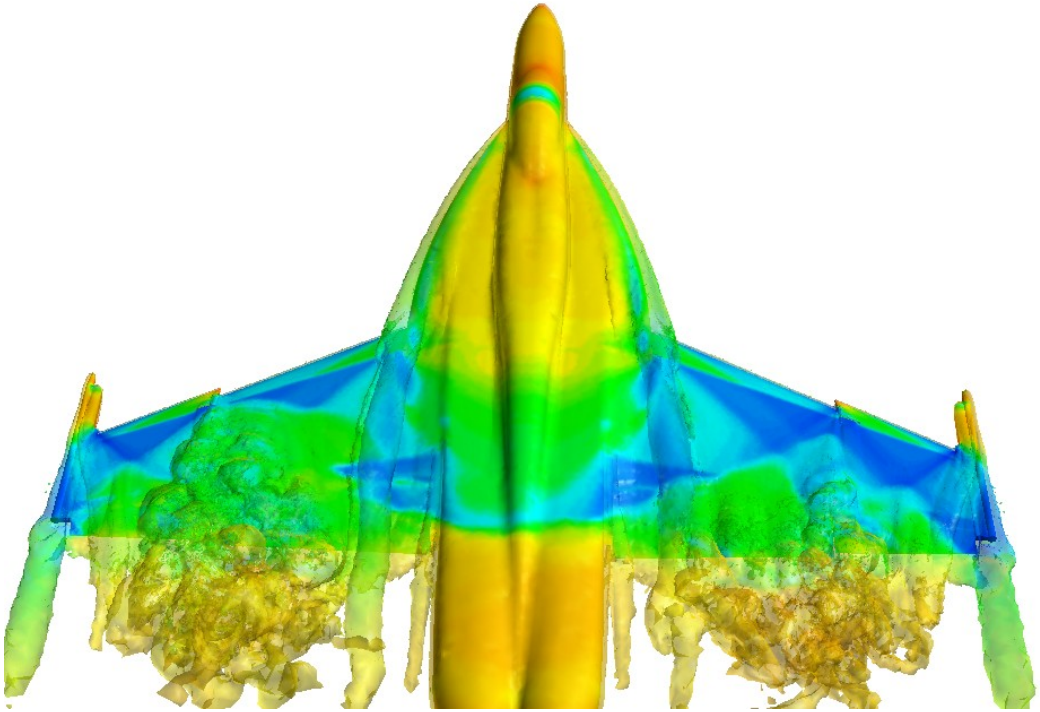
- “As it is convected further downstream, the slat-tip vortex dissipates due to interaction with the main-element boundary layer. At approximately mid-chord of the main element, the slat-tip vortex is no longer discernable using the smoke flow-visualization technique.”

  NASA TM-1998-112222

DES Computational Results



F/A-18E Abrupt Wing Stall (AWS)

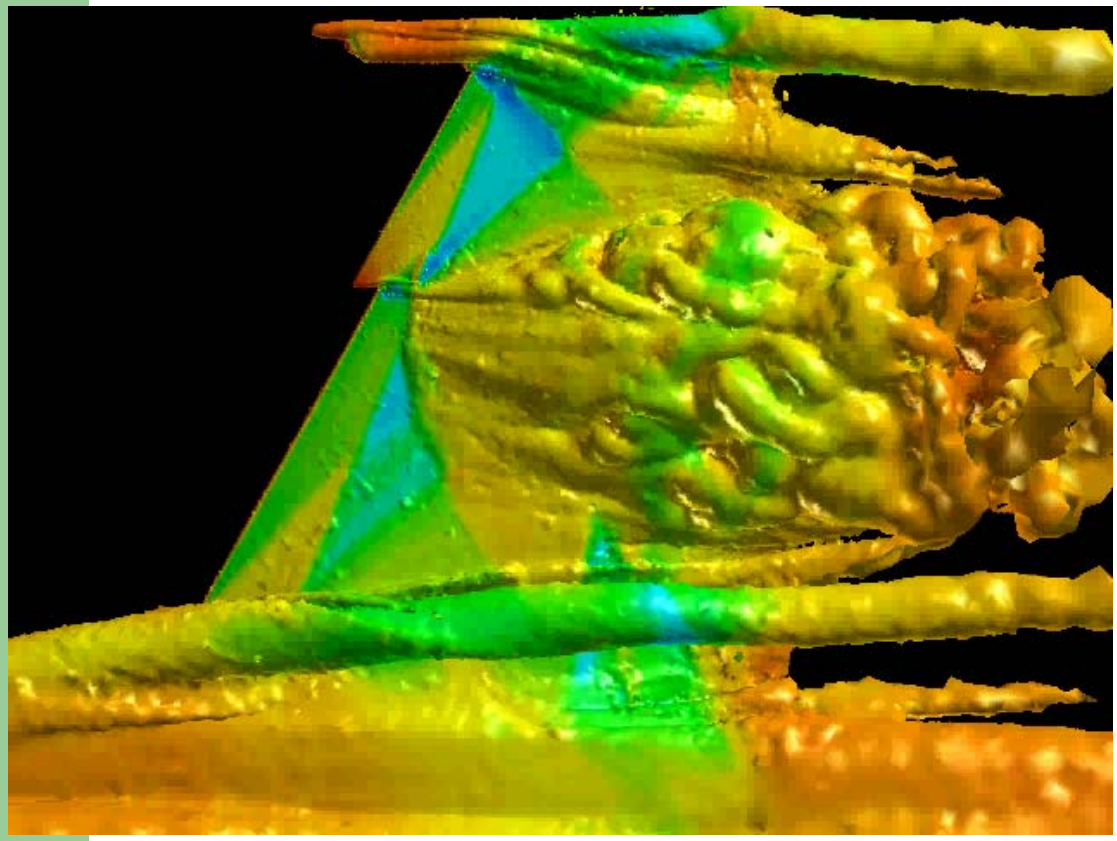


AIAA Papers 2003-0592, 2003-0594, 2003-0923

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

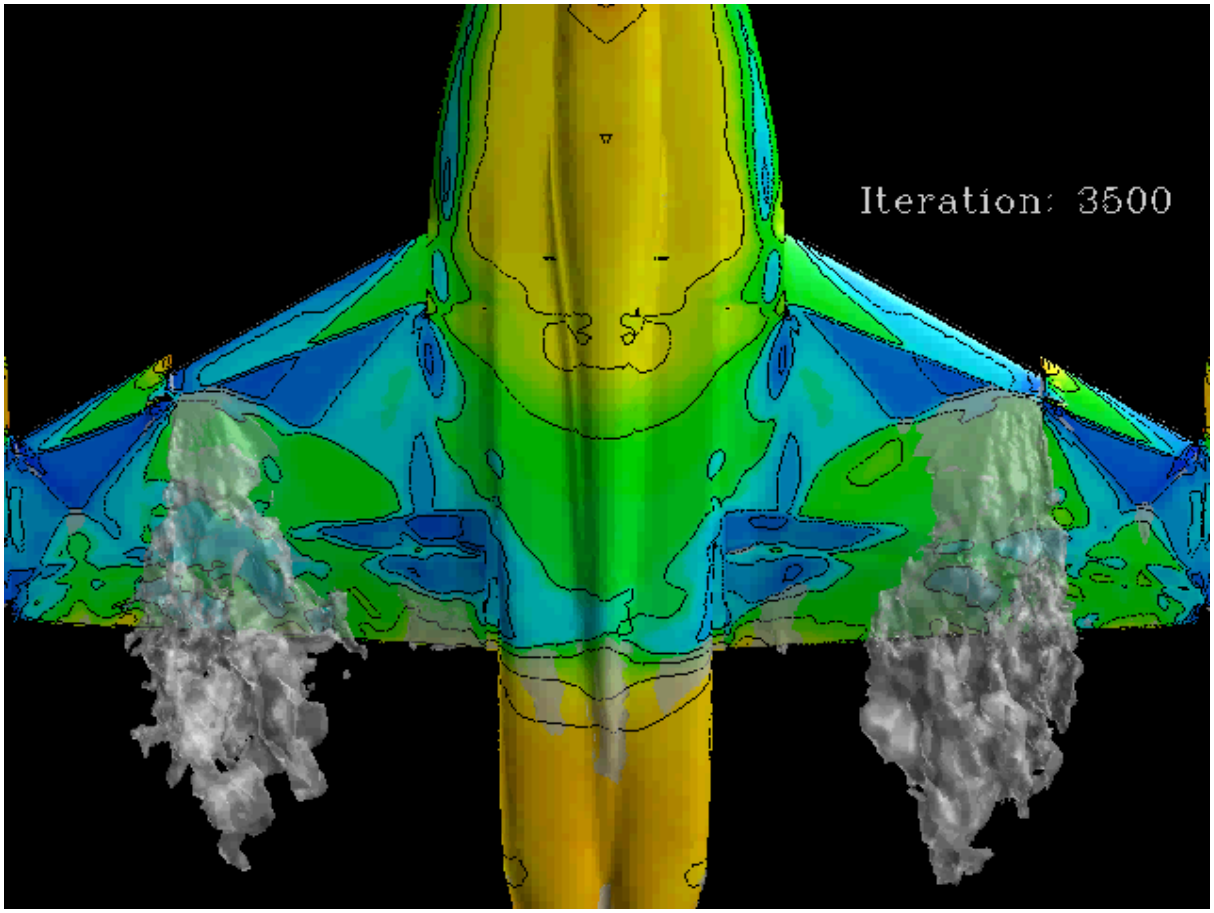


Iso-surface of vorticity, colored by pressure, α=9˚

- Use CFD to predict the unsteady shock oscillations seen in the experiments
- RANS models failed to give unsteady results
- DES solution-based grid adaption

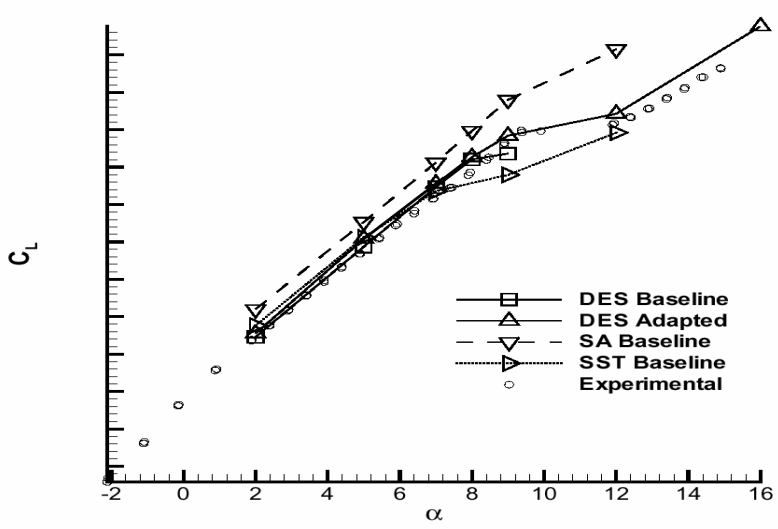
F/A-18E Abrupt Wing Stall

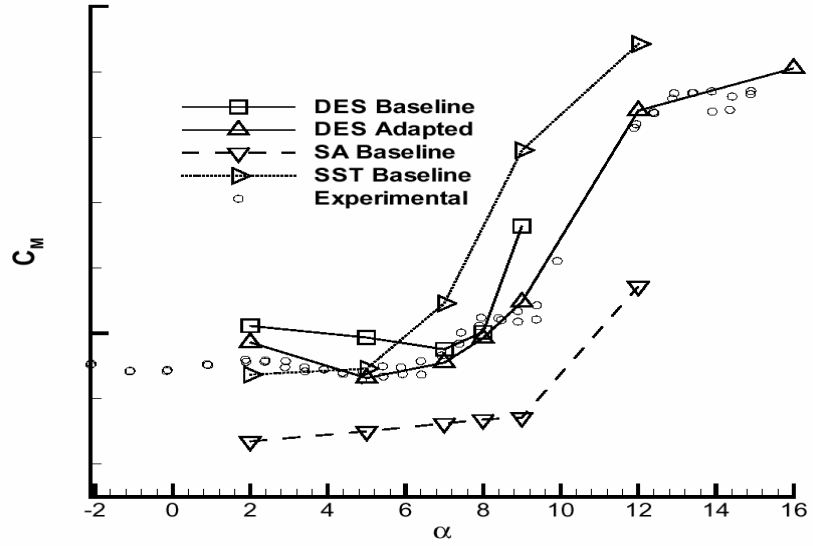
Full span F/A-18E without tails: Surface colored by pressure with vorticity iso-surfaces



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

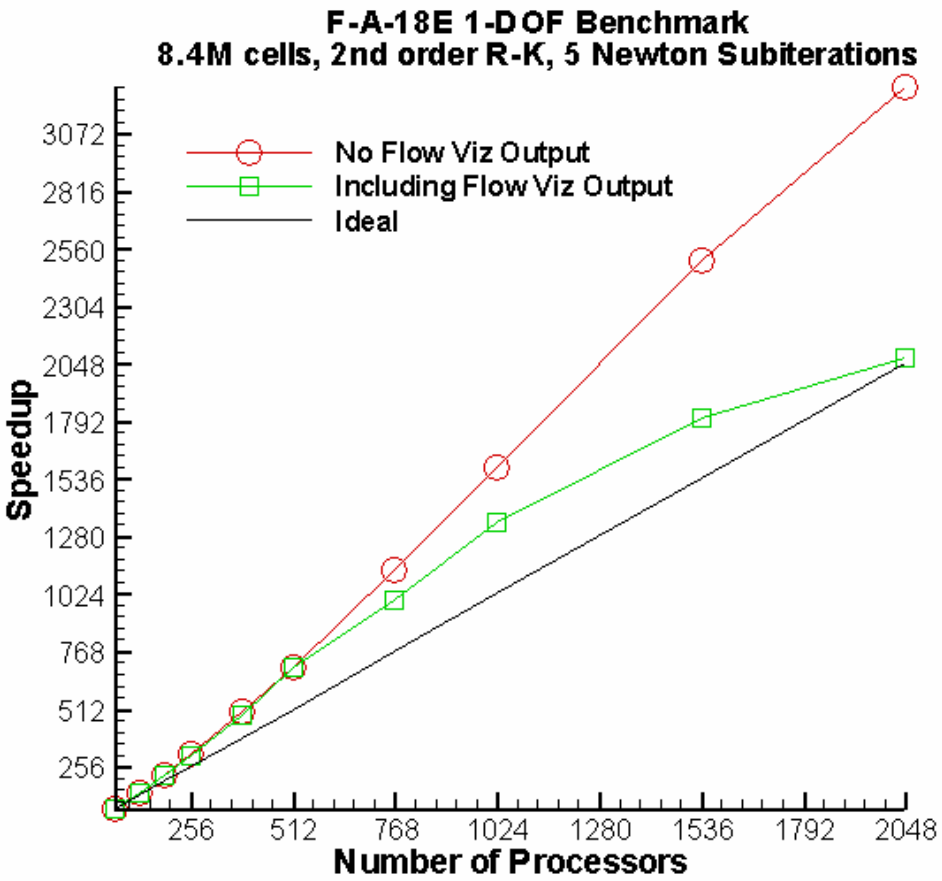
- 1-DOF grid mirrored about symmetry plane
- 6/8/4 flap set
- 8.4 million cells for both sides of aircraft
- Adaption performed on a α=9° time-averaged DES solution under previous work
- Prisms in boundary layer
- Average $y^+ < 0.7$

F/A-18E Abrupt Wing Stall

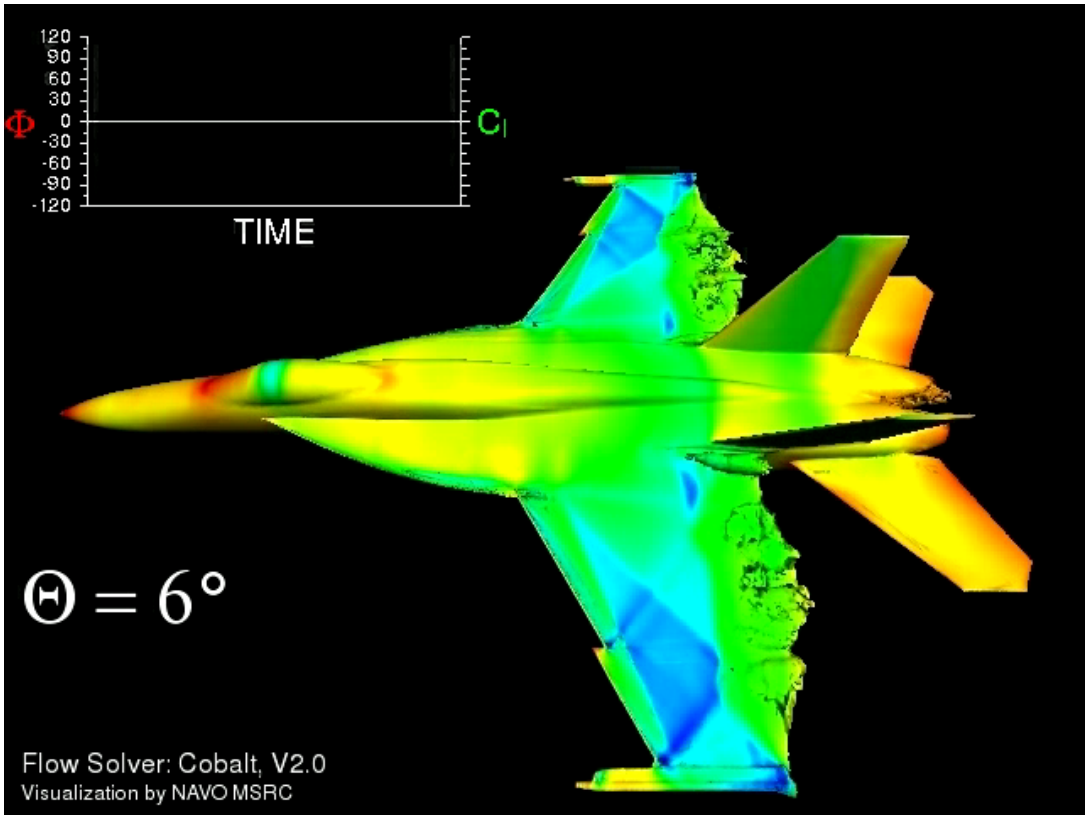
- Aircraft released from a 60 degree bank to match wind tunnel tests
- Initial aircraft response examined for damping or amplification
- Mach=0.9, 8% model
- Wing drop range in experiments was roughly α=7-10 degrees
- Wing drop events in wind tunnel were highly sporadic – model would be quiet for long 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

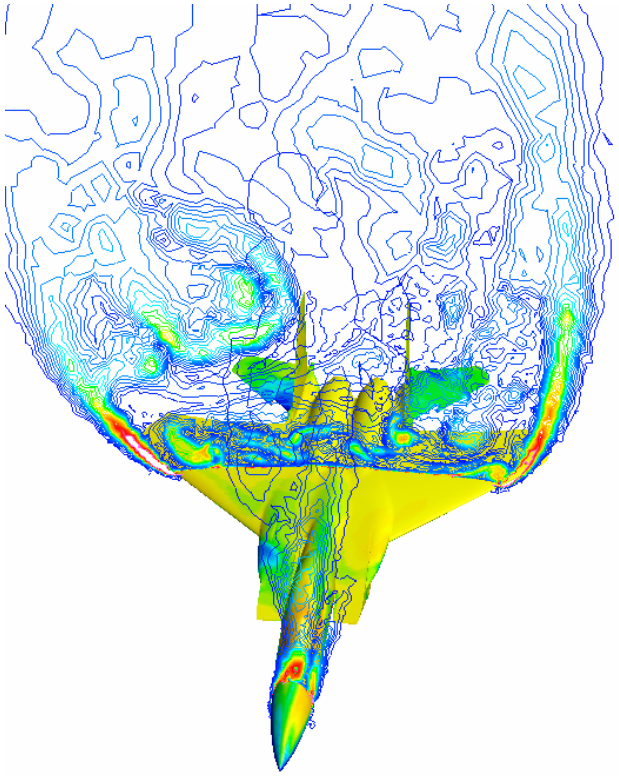


F/A-18E Abrupt Wing Stall



α=6 degree pitch angle case

F-15E Aircraft Spin



AIAA Papers 2002-0591, 2003-0839, 2006-0858

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

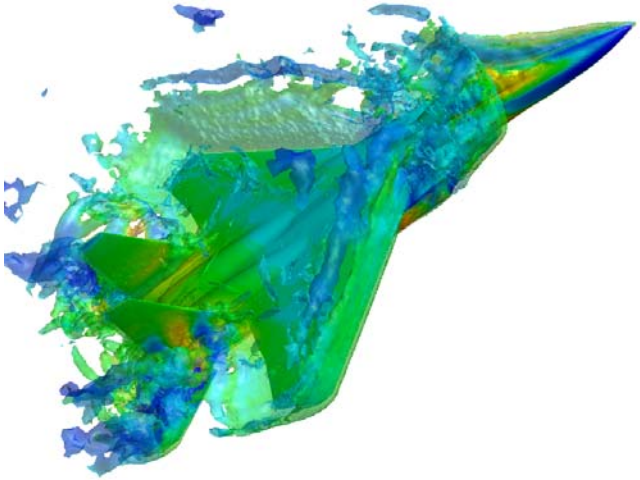
F-15E Aircraft Spin

- 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 → To accurately predict separated flow
  - 6 Degree-of-freedom → 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

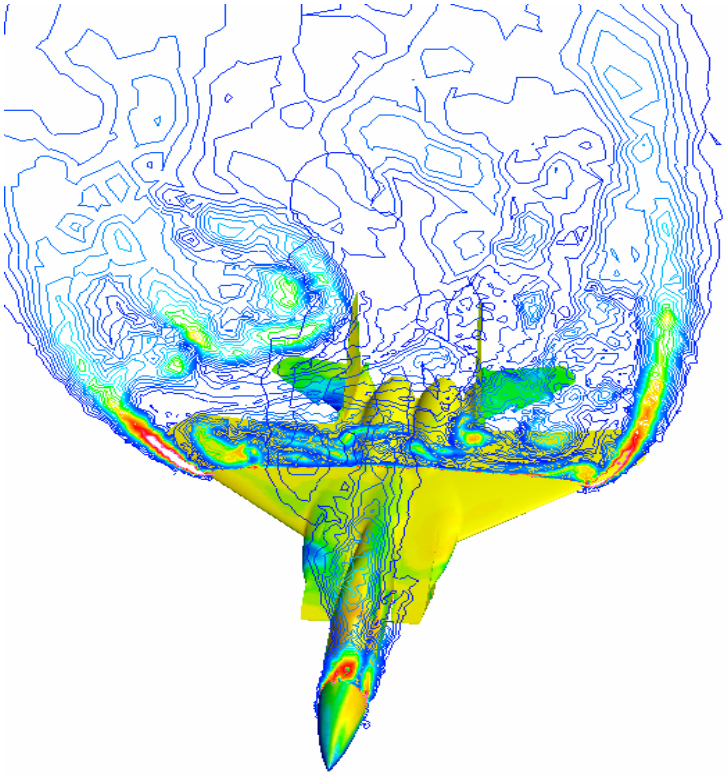
- Unsteady, non-moving calculations – α=65º, zero sideslip
- Timestep and grid refinement study
- Comparison between DES and RANS
- Key Findings
  - Fine grid (10×10^6 per side) could get results within 5% of database
  - Differences between grids mainly on nose and tail (wings grid converged)
  - Steered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

		C_L	C_D	C_M	$\%C_L$	$\%C_D$	$\%C_M$
	Exp	0.781	1.744	-0.466			
	Coarse	0.747	1.677	-0.431	-4.25%	3.86%	-7.62%
DES	Baseline	0.736	1.616	-0.495	-5.70%	-7.35%	6.10%
	Fine	0.759	1.648	-0.457	-2.81%	-5.52%	-2.00%
	Coarse	0.855	1.879	-0.504	9.49%	7.73%	8.17%
S-A	Baseline	0.852	1.867	-0.523	9.09%	7.05%	12.22%
	Fine	0.860	1.880	-0.507	10.22%	7.78%	8.72%



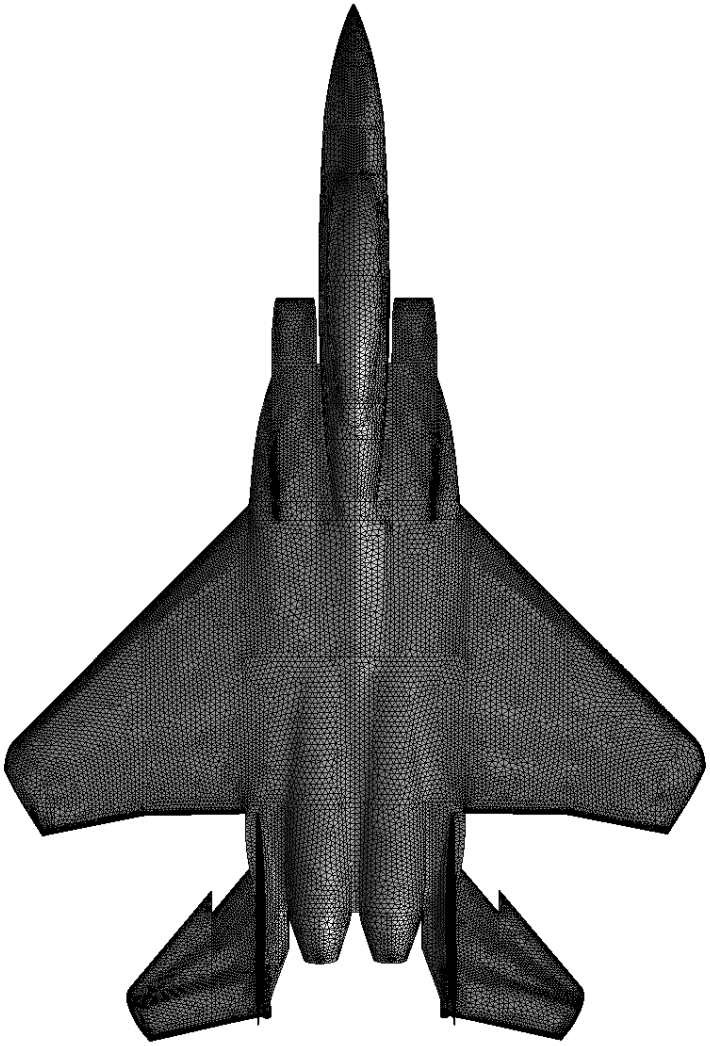
F-15E Aircraft Spin

- Prescribed spin based on expected spin conditions of α=65˚, β=-2.5˚, 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
- 6.5×10^6 cells for entire aircraft
- Average first y^+ was 0.2
- Geometric progression of 1.25
- M=0.3, 30,000 ft
- $Re=13.6 \times 10^6$

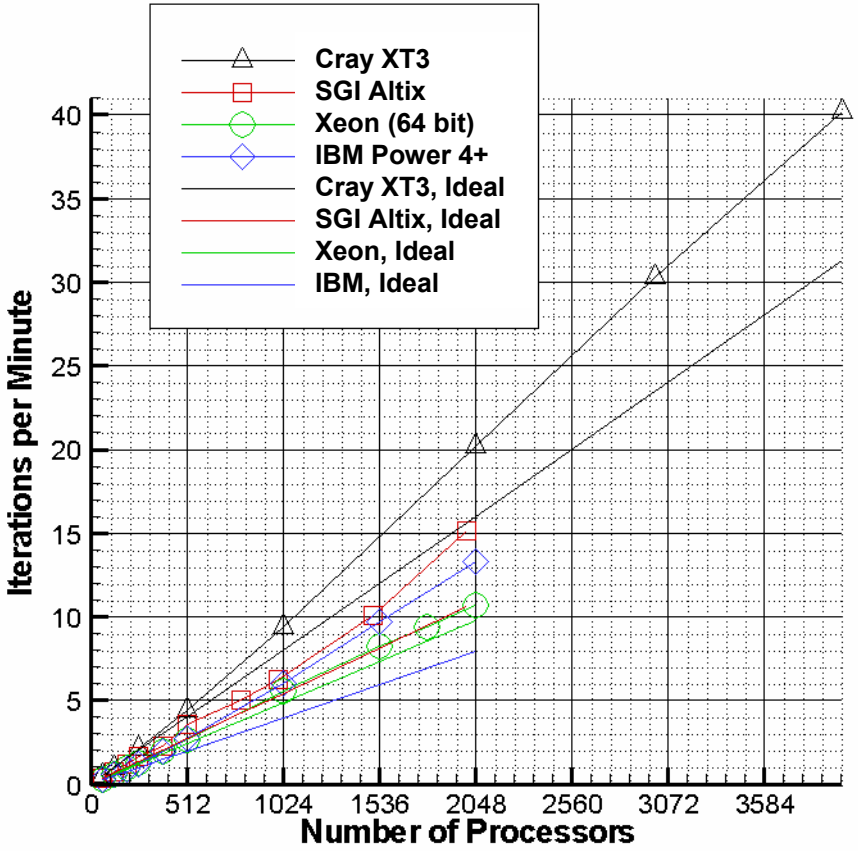


F-15E Aircraft Spin

- 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°/sec
  - α=65°, β=-2.5°
  - M=0.302
  - H=30,000ft
- Three attempts to get into the spin
  - Drop aircraft from rest in a horizontal position
  - Start in a left prescribed spin at 100°/sec, α=90°, M=0.3 (vertical)
  - Start in a right prescribed spin at 100°/sec, α=90°, M=0.3 (vertical)

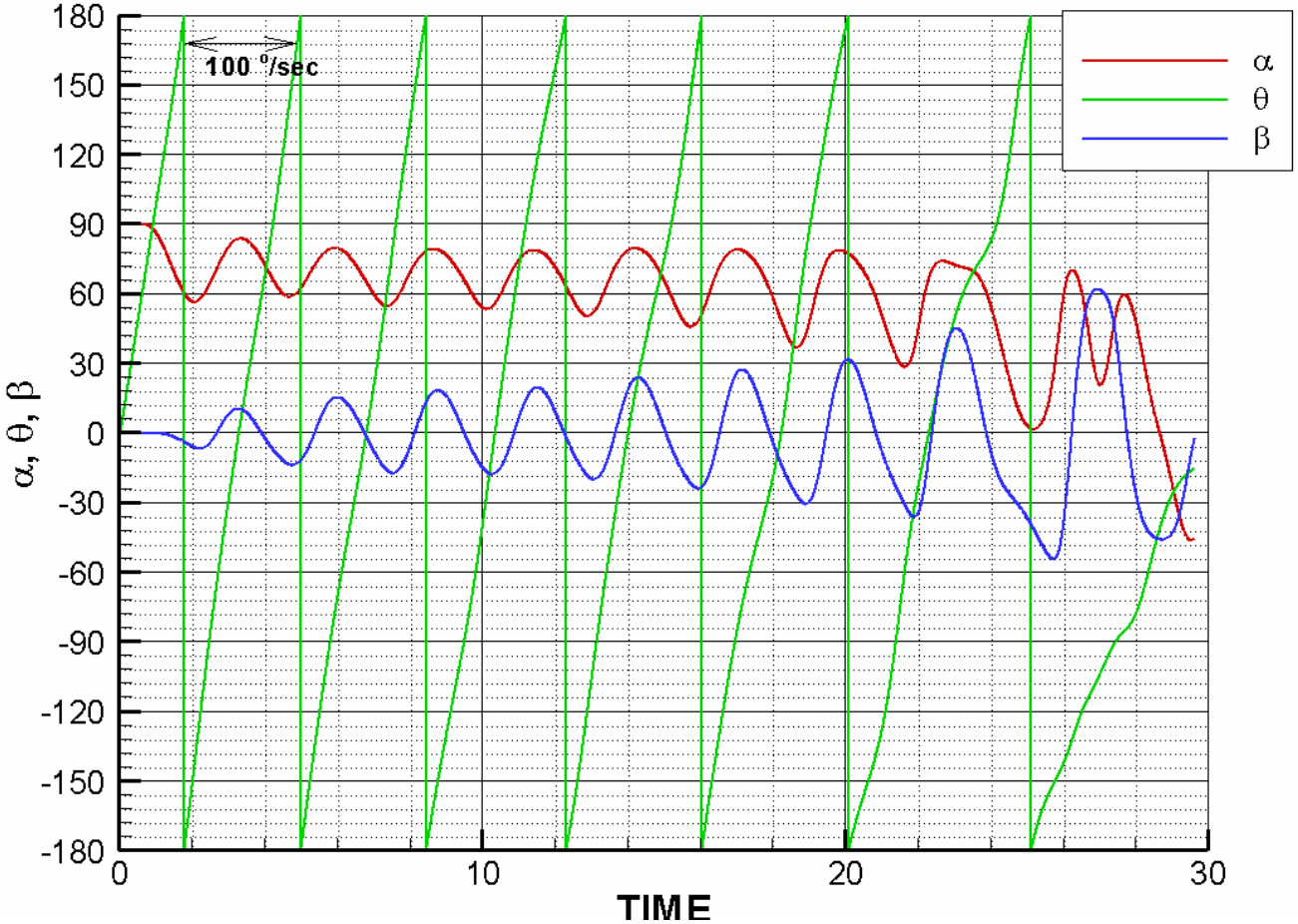
F-15E Aircraft Spin Benchmarks

- 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



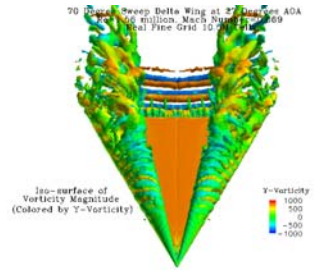
F-15E With Prescribed Right Spin

F-15E With Prescribed Right Spin

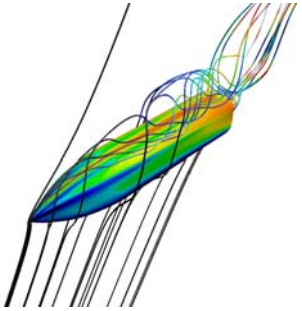


Future Applications of DES

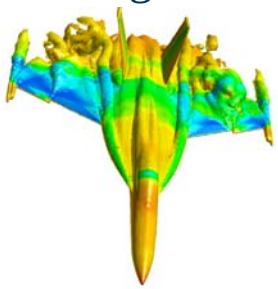
Delta Wing Vortex Breakdown



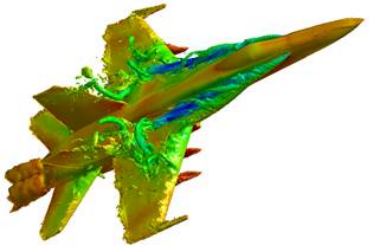
Forebody Crossflow



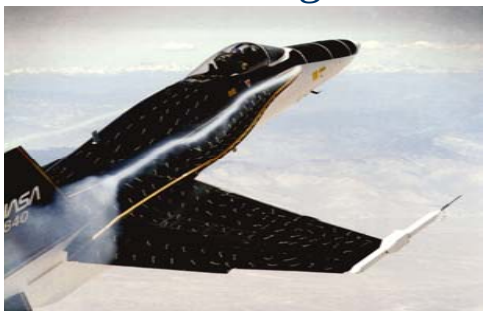
F/A-18E Abrupt Wing Stall



F/A-18C Tail Buffet



F-18 HARV Aeroelastic Flight Tests

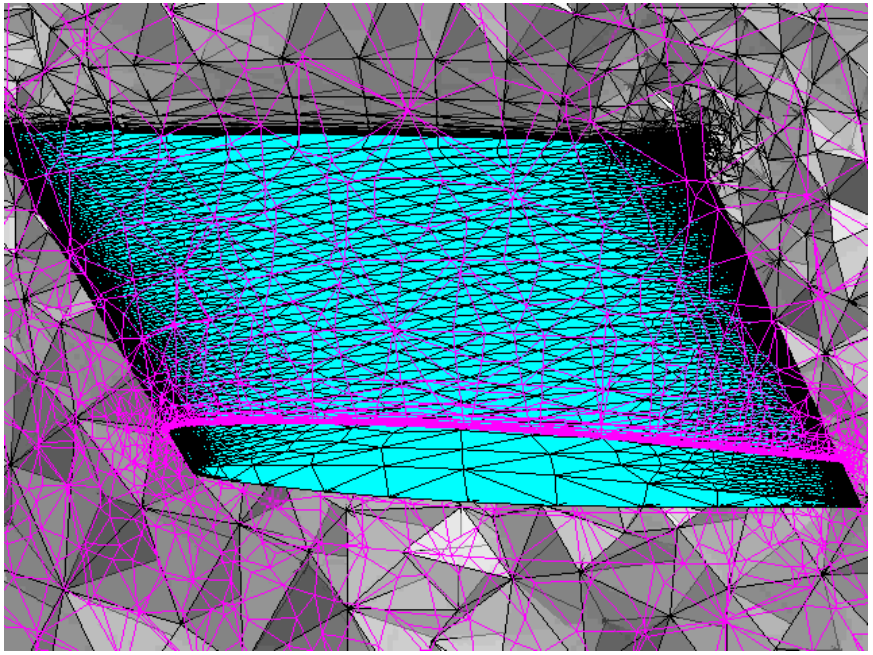


Moving Mesh Strategies

- 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

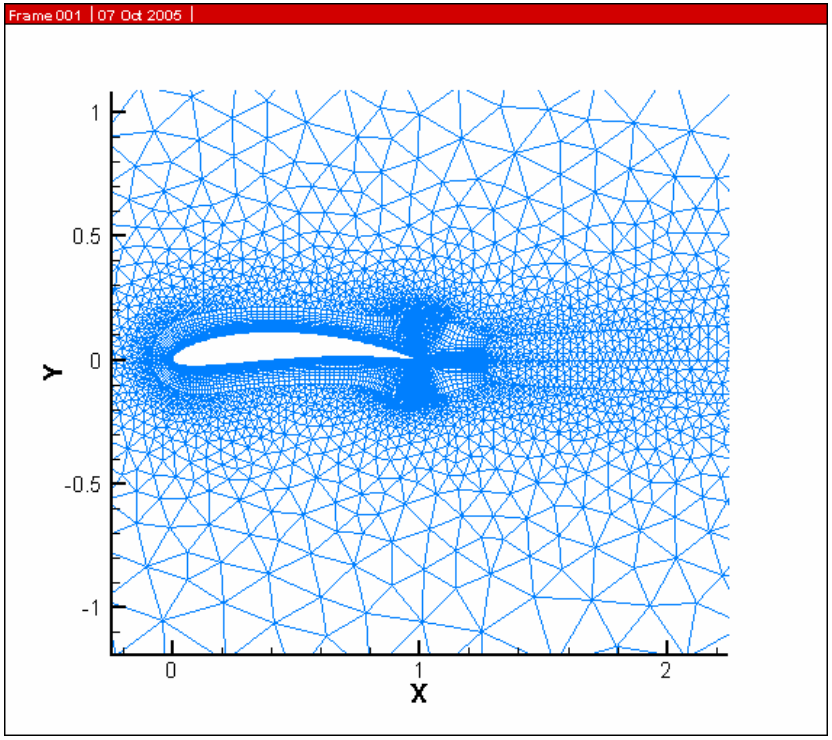
- Based on the torsional spring analogy of Farhat for inviscid cells
- Redistribution of points for viscous cells
- Allows for large amplitude deformation
- Eventually couple CFD solution with structural model



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



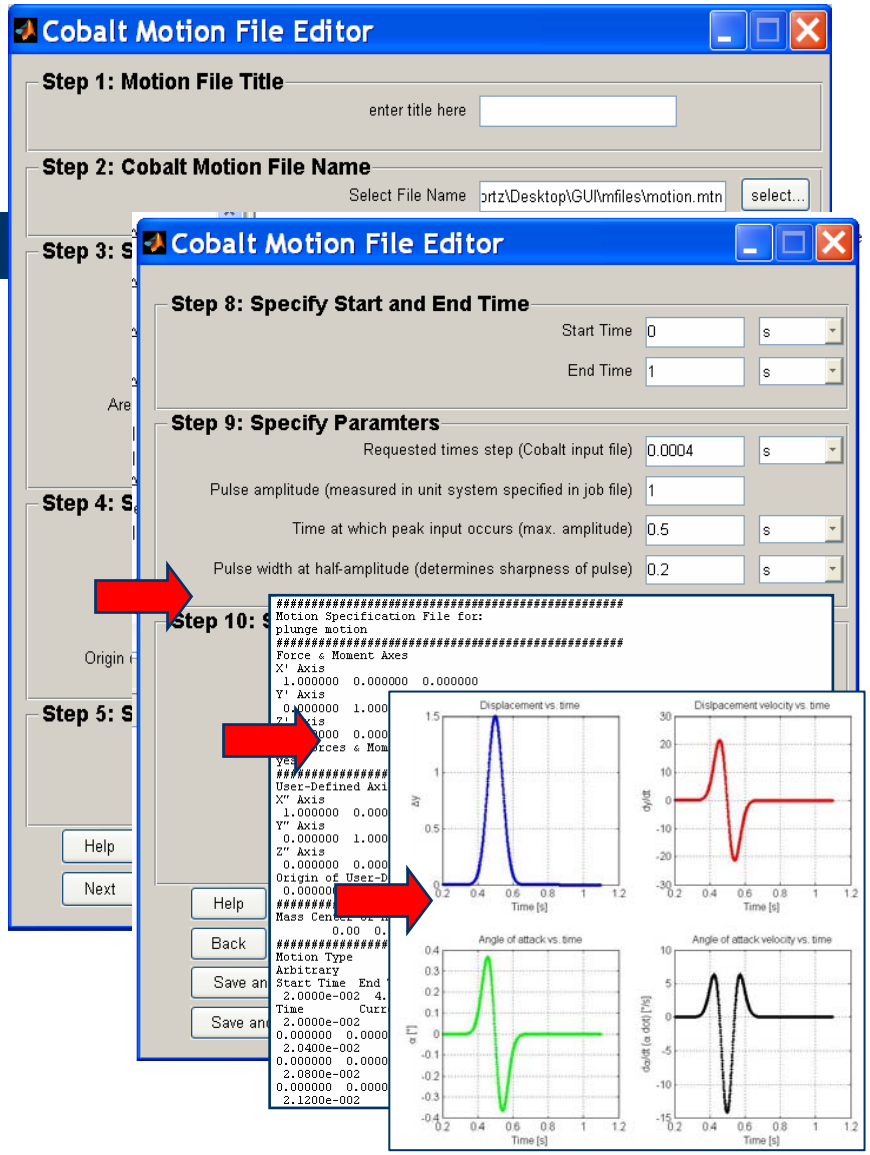
Computational Stability & Control

- 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

$$C_{m_q} + C_{m_{\dot{\alpha}}}$$

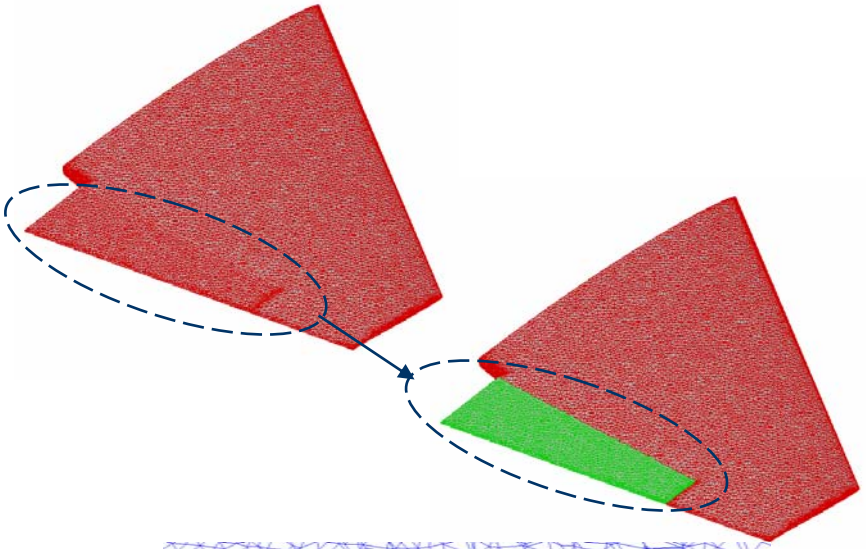
Maneuver Module

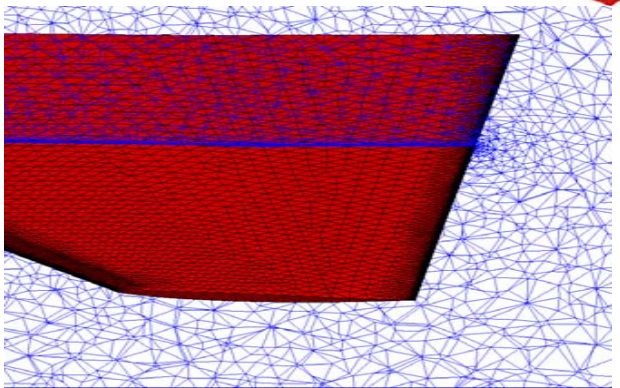
- Easily define maneuvers for S&C analysis using stand-alone, interactive Matlab GUI
- Takes inputs from user of what motion category and type, and key parameters
- Converts inputs into rigid-body motion file in Cobalt format
  - Arbitrary motions
  - Predefined S&C maneuvers
  - 6 DOF



Control Surface Module

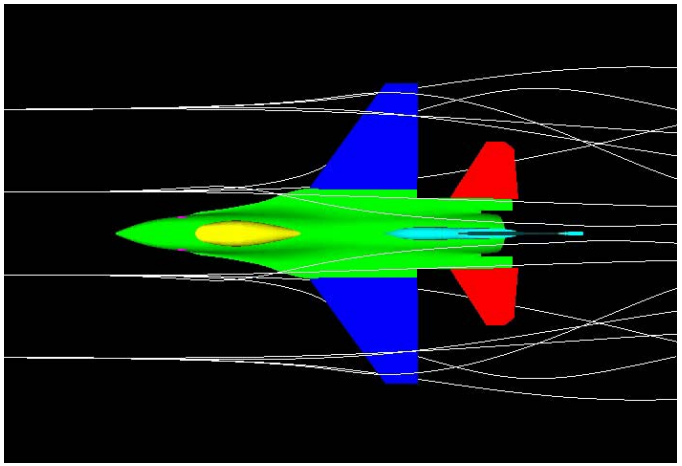
- Automatically creates control surfaces in grid and deforms grid due to control surface movement
- Generates control surface within subset of existing good-quality grid using local remeshing
- Quick and efficient algebraic deformation of surface and volume grid
- A-priori determination of grid quality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

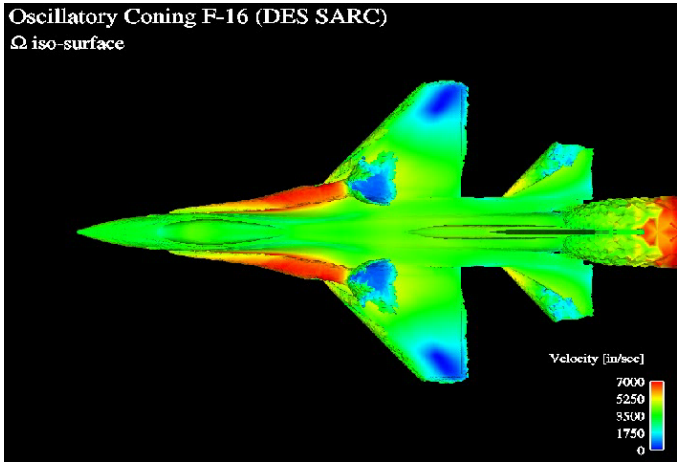




Coning Motion

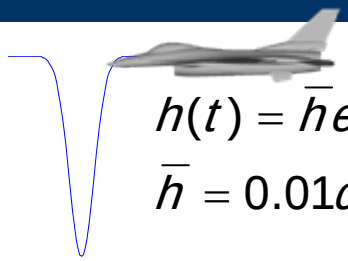
- Conventional coning:
  - Axis of rotation is coincident with wind direction
  - Used in rotary balance testing to estimate dynamic S&C derivatives
  - α=30°, Ω=180°/s, t_{sim}=1.68s, 2,978 CPU h
- Inclined axis oscillatory coning:
  - Axis of rotation not aligned with wind direction (inclined by 60°),
  - Oscillating α and β
  - Estimate unsteady terms, separate combined derivatives determined in conventional forced oscillation exp.
  - α_{init}=30°, α=+30°…-90°, Ω=180°/s, t_{sim}=3.12s





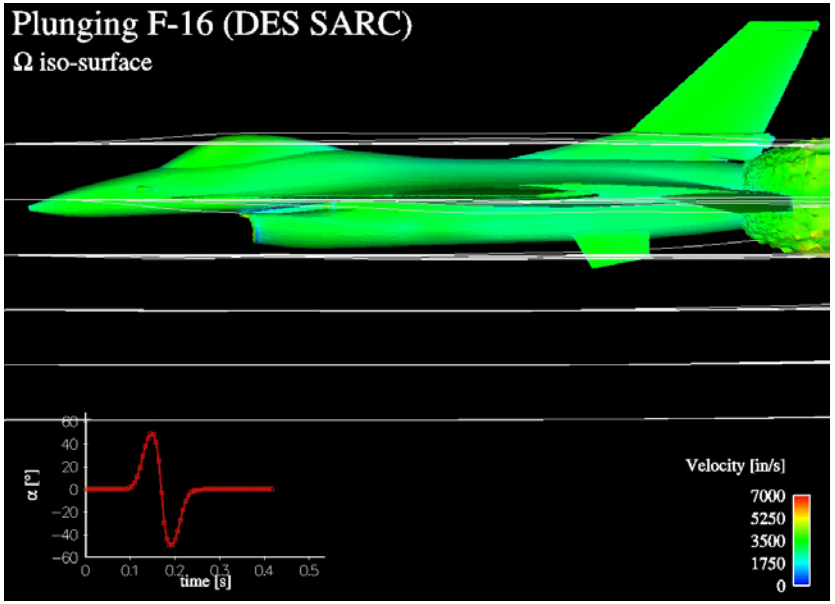
Configuration Plunge Pulse

- 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_{sim}=0.42 s, 356 CPU h



$$h(t) = \bar{h} e^{-\ln(0.5)(2\cdot(t-t_0)/t_{12})^2}$$

$$\bar{h} = 0.01c, 0.1c, 1.0c$$



$\bar{h} = 1.0c$

Delayed Detached-Eddy Simulation

- DES switches from RANS to LES based on the local grid density
- Can cause problems for shallow separation flowfields
- An improved version has been proposed called DDES (Spalart, P., Deck, S., Shur, M., Squires, K., Strelets, M. K., and Travin, A., "A New Version of Detached-Eddy Simulation, Resistant to Ambiguous Grid Densities," *Theoretical and Computational Fluid Dynamics*, to appear)
- 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

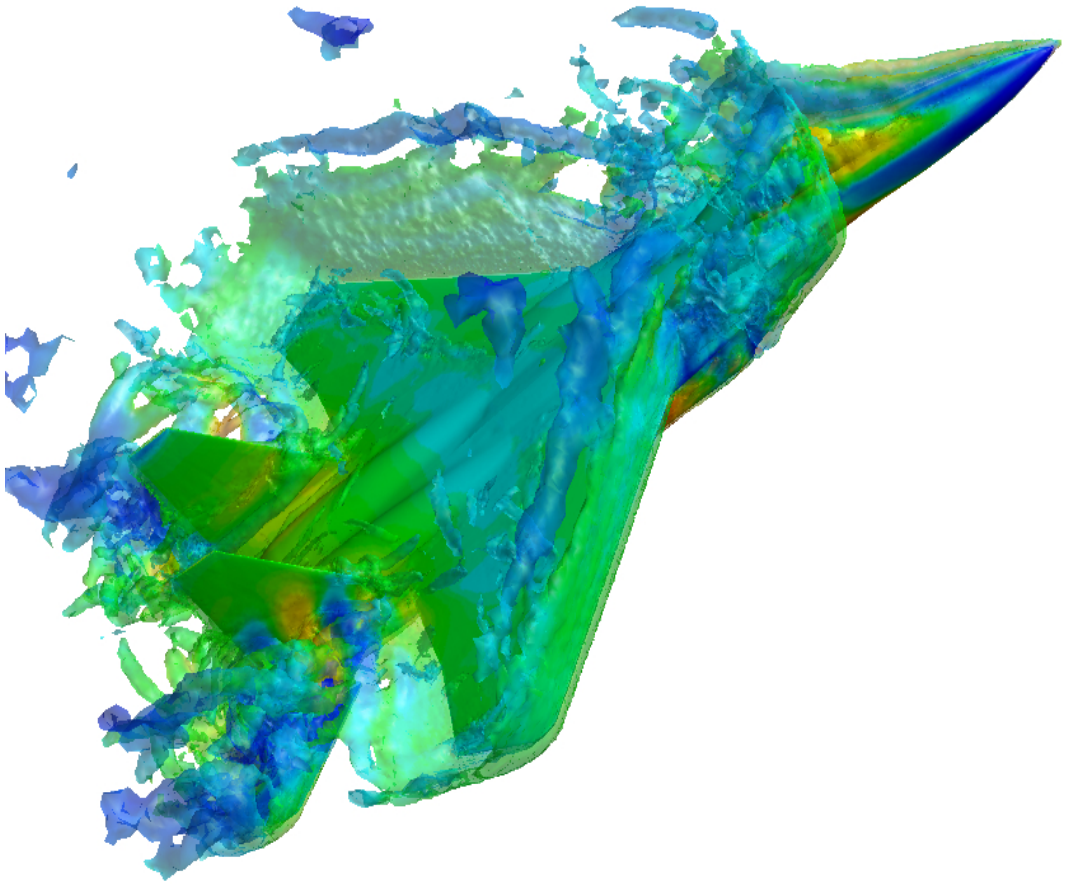
Conclusions

- 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?



Detached-Eddy Simulation

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

X-29 at high angle of attack

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)