

Scaling for Aero-Science Applications

Joseph H. Morrison

Head, Computational AeroSciences Branch

NASA Langley Research Center

13-15 September 2010

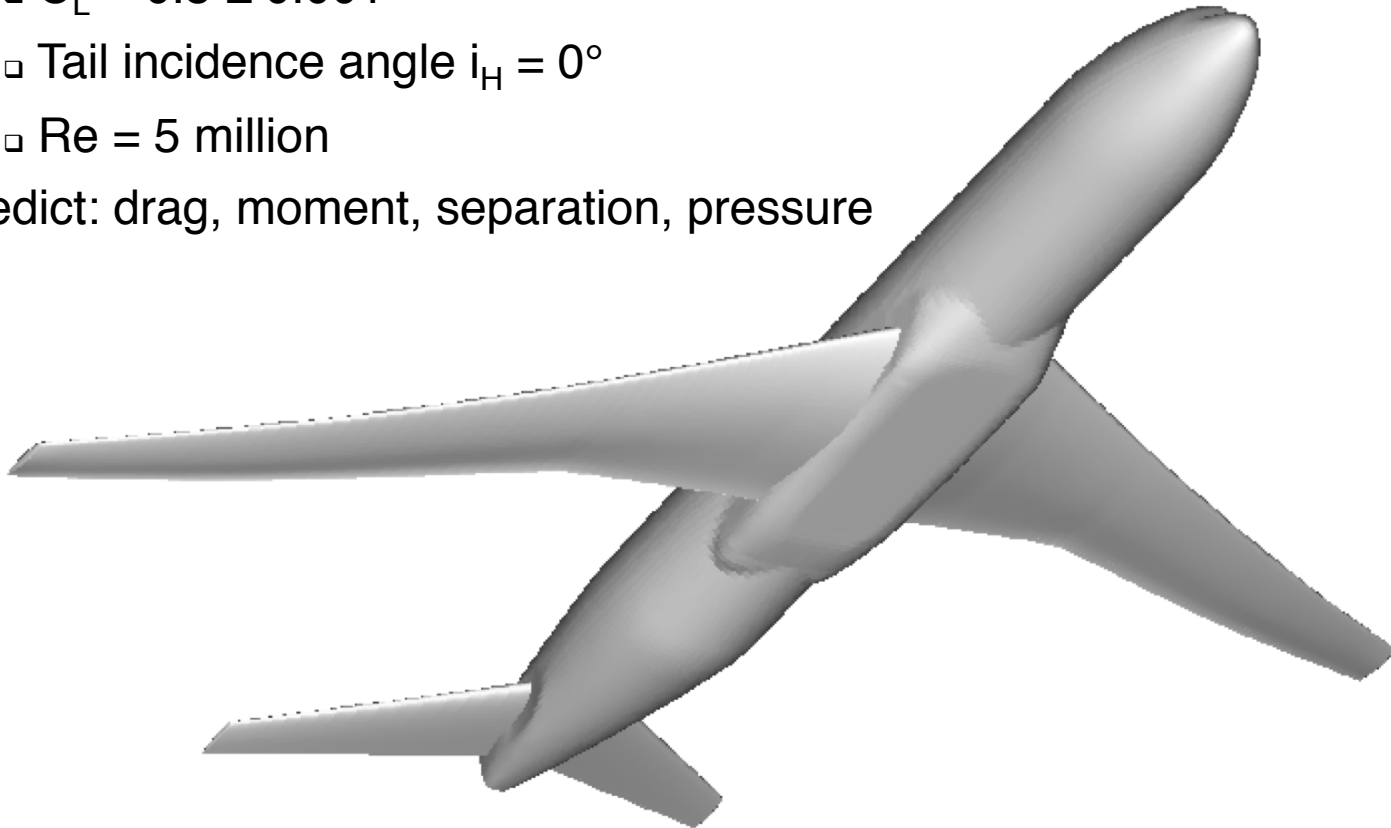
Outline

1. CFD Applications
2. Grid Adaptation
3. Algorithms and Numerics
4. Physical Modeling
5. Multi-Discipline Capabilities
6. Hardware/Software Issues

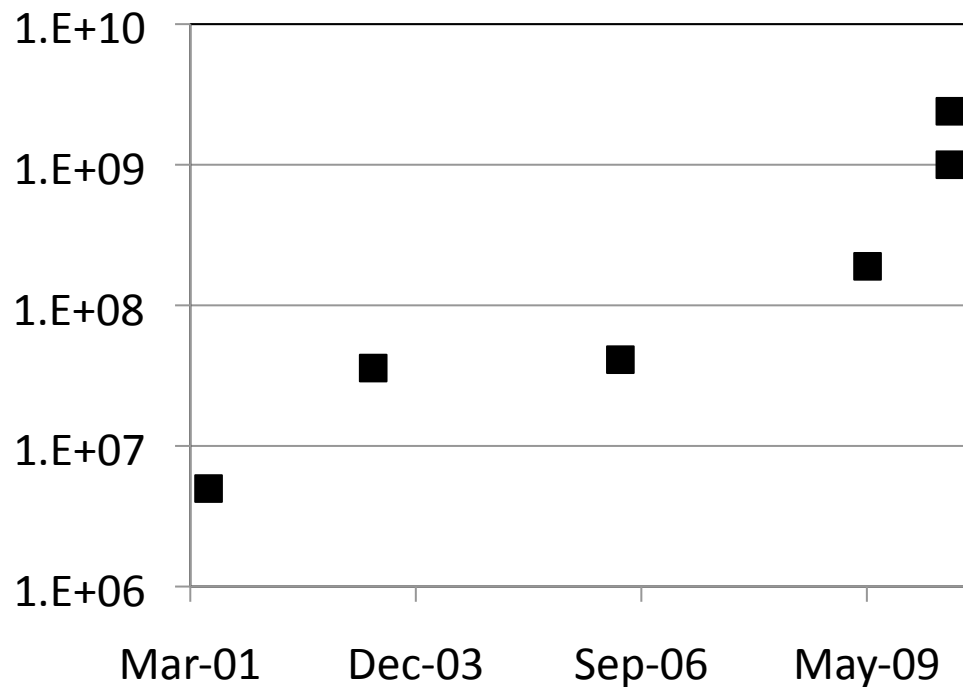
1. CFD Applications

DPW-IV Common Resource Model

- Grid convergence study with 3 levels of grid refinement
 - Optional “Extra Fine” grid level
- Flow conditions
 - Mach = 0.85
 - $C_L = 0.5 \pm 0.001$
 - Tail incidence angle $i_H = 0^\circ$
 - Re = 5 million
- Predict: drag, moment, separation, pressure



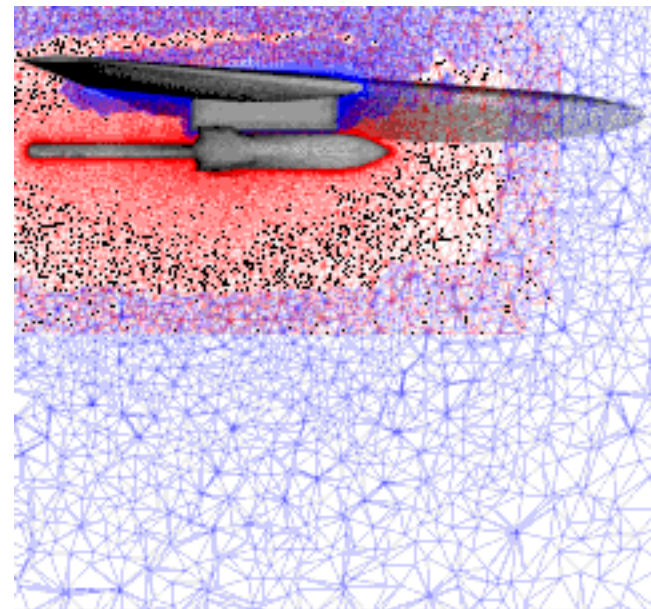
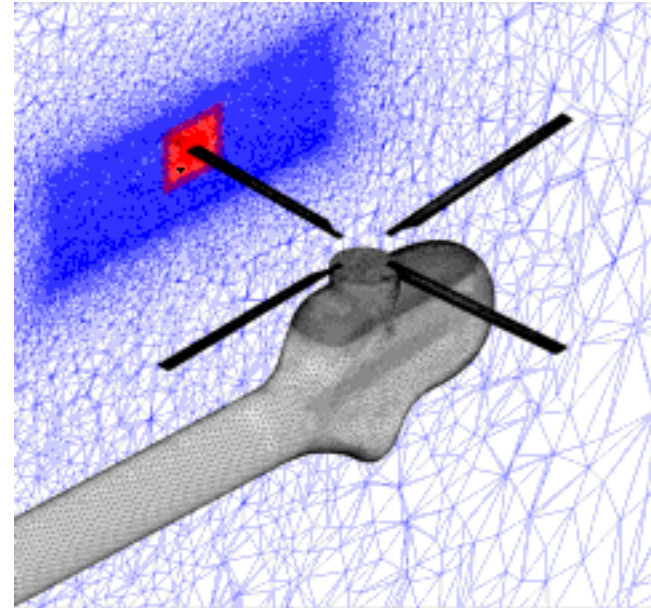
Trend in Grid Size



- *For 100,000 points per processor → 10,000 processors*
- *Must* accommodate distributed-memory, massively parallel computations ***and I/O*** to keep pace
 - Entire operation from grid generation and pre-processing to visualization
 - Unstructured nature of the data presents a challenge
 - Having entire mesh in local memory during any phase is not scalable
- MTBF becomes critical as number of processors grows

Overset Meshes For Large Relative Motion

- Mesh for each geometric element generated independently; Interpolate solution from one mesh to another
- Large relative motion well suited to overset grids
- Off-the-shelf software available for unstructured overset meshes: SUGGAR++ cuts holes (similar to PEGSUS) and DiRTlib (add overset capability to existing CFD code)



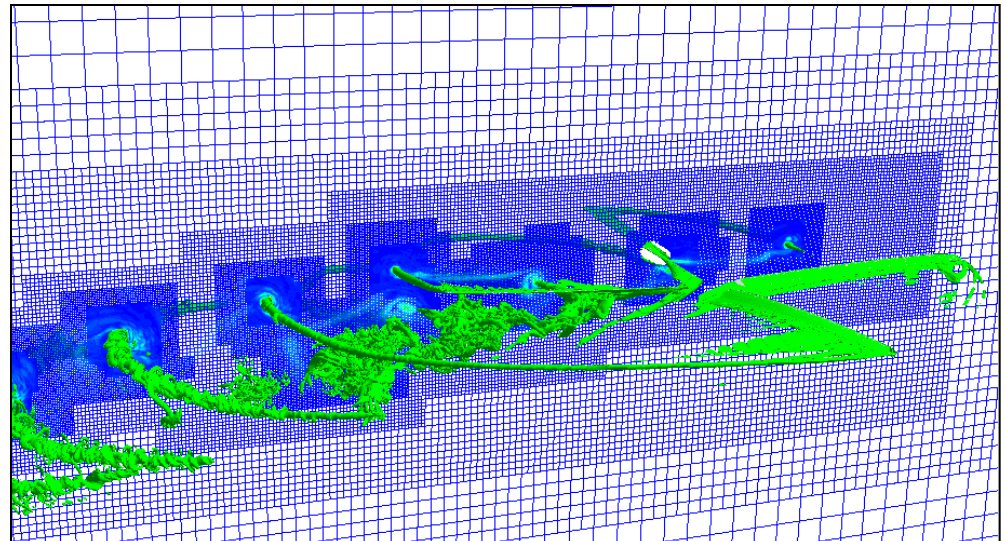
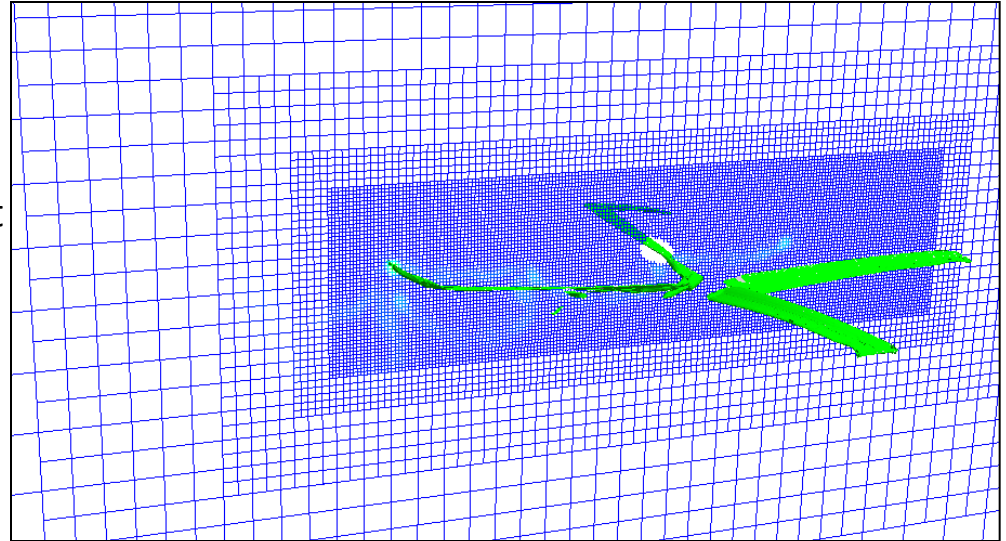
CFD Application Issues

- Scaling
 - Run many cases for design
 - Current approaches based primarily on domain decomposition scale to 10's of thousands of processors
 - Will require new approaches to take advantage of additional parallelism to grow to millions of processors
 - Resilient computing required as number of processors grows
- Everything must be parallel
 - Grid generation
 - Pre-processing
 - Solution
 - I/O
 - Post-processing

2. Grid Adaption

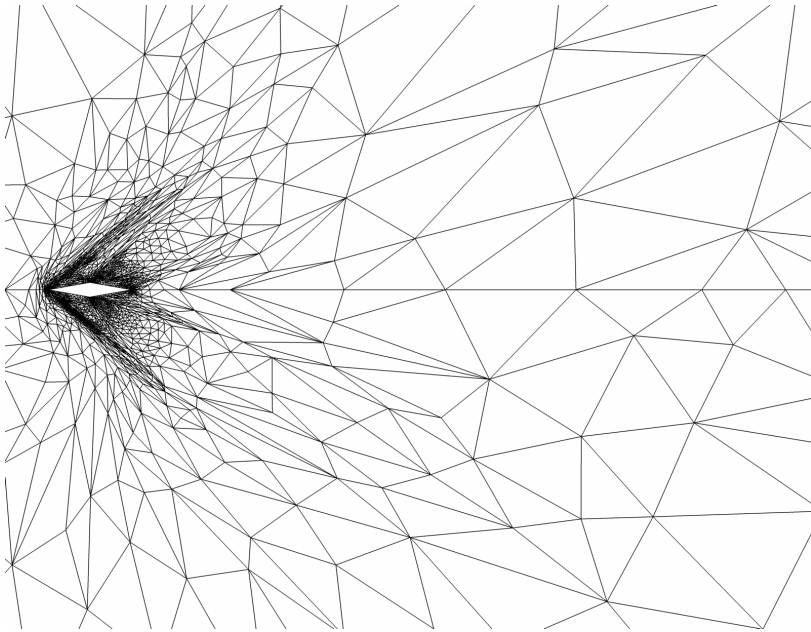
Embedded Structured Grids Applied to UH-60 Case

- Coarse initial grid (4.5Mpts, 43 grids)
- Compute 1 rev in 1440 steps
- Adaption every 10 steps, 2 levels of refinement
- Sensor function is undivided 2nd difference of Q
- Using 5th-order WENOM and SST
- Final adapted grid (53Mpts, 1621 grids)
- Interpolation process is inefficient
 - Uses disk I/O
 - Takes 50% of execution time for 128 cpus
 - In-core interpolation has been coded

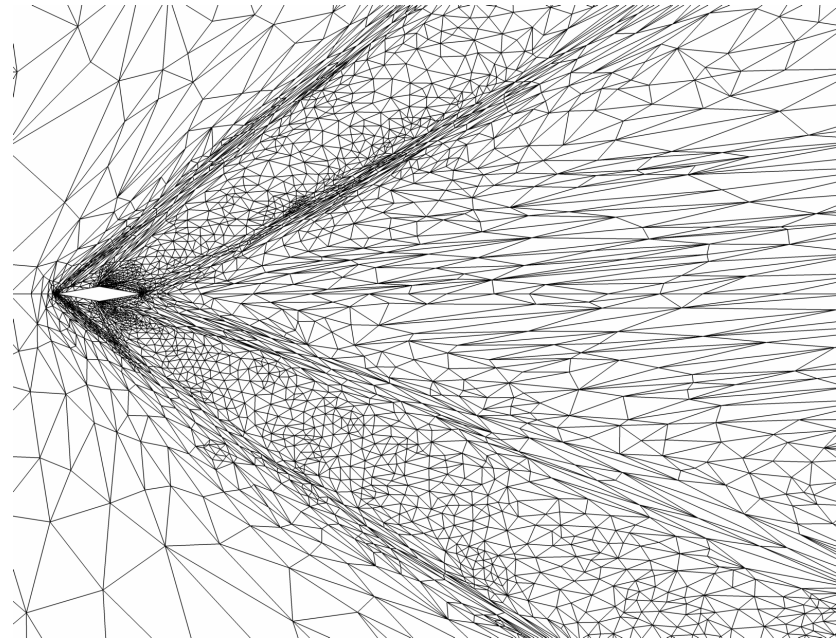


Output-Based Adaptation

- Mathematically rigorous approach involving the adjoint solution that reduces estimated error in an engineering output
- Uniformly reducing discretization error is not ideal from an engineering standpoint – some errors are more important to outputs



Adapted for Drag



Adapted for Shock Propagation

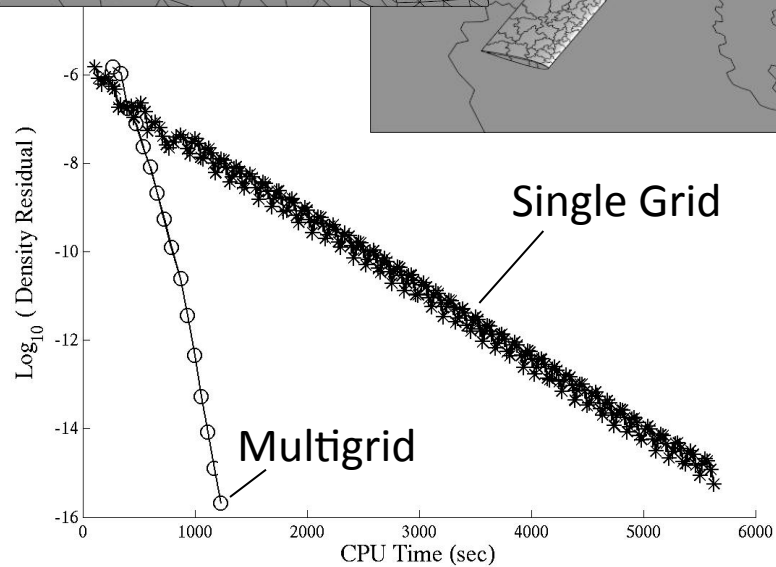
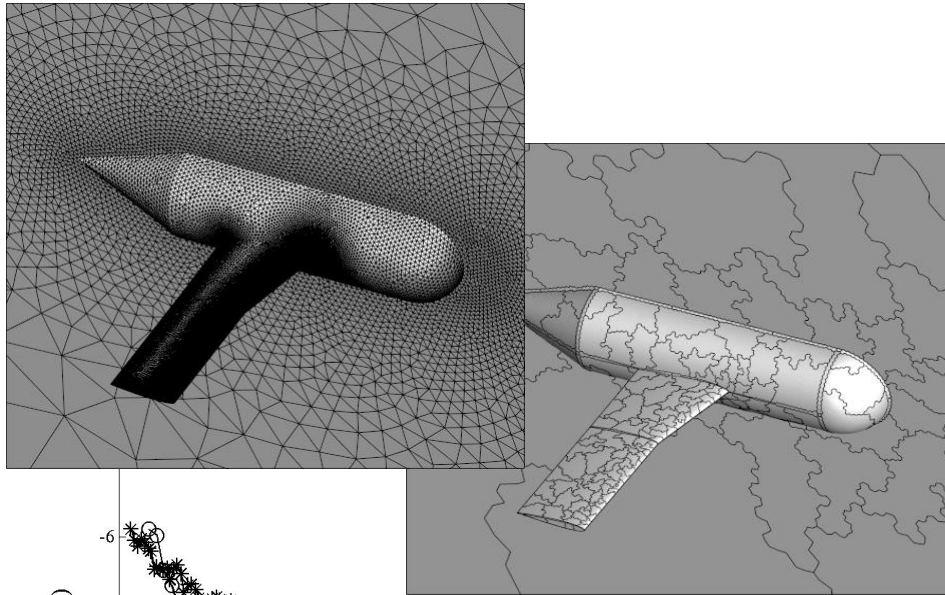
Grid Adaption Issues

- Overhead of grid adaptation
 - Interpolation
 - Data movement
 - Don't know a priori where adaption will be required
- Dynamic load balancing
 - Start with small initial grid and grid grows over an order of magnitude

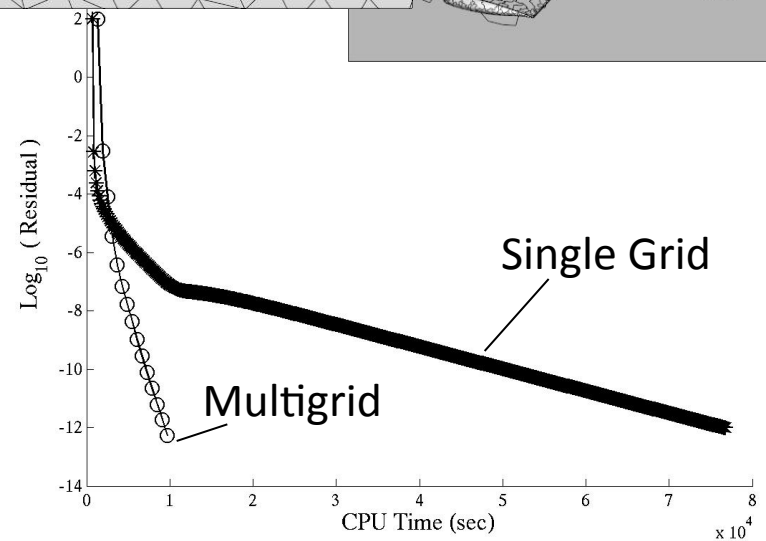
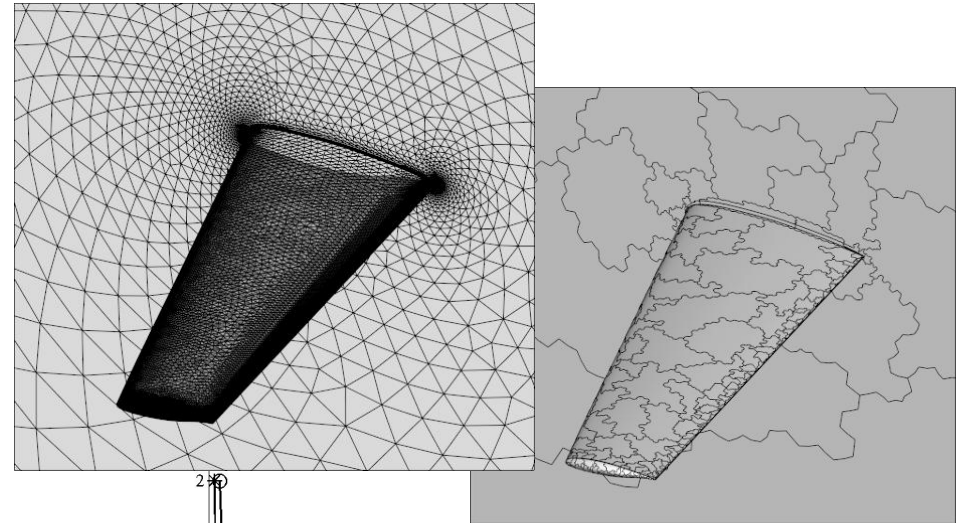
3. Algorithms and Numerics

Agglomeration Multigrid

Towards grid-independent convergence for fully unstructured grids



Inviscid results (1M nodes): ~6 times faster, including the time to generate coarse grids.

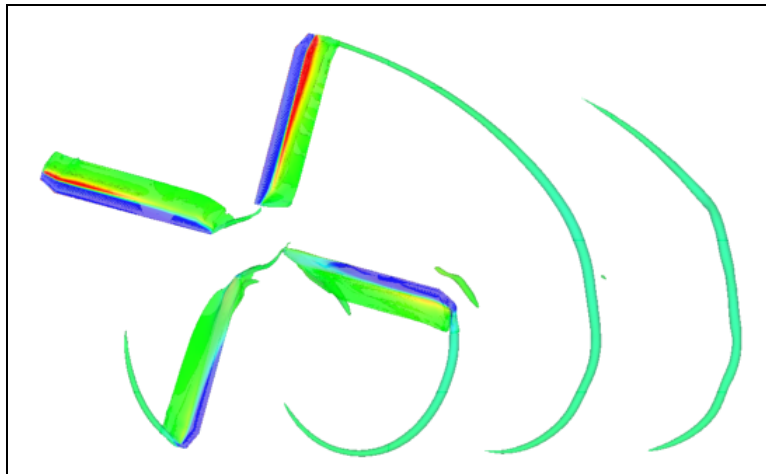


DPW-W2(1.9M nodes); Diffusion equation.

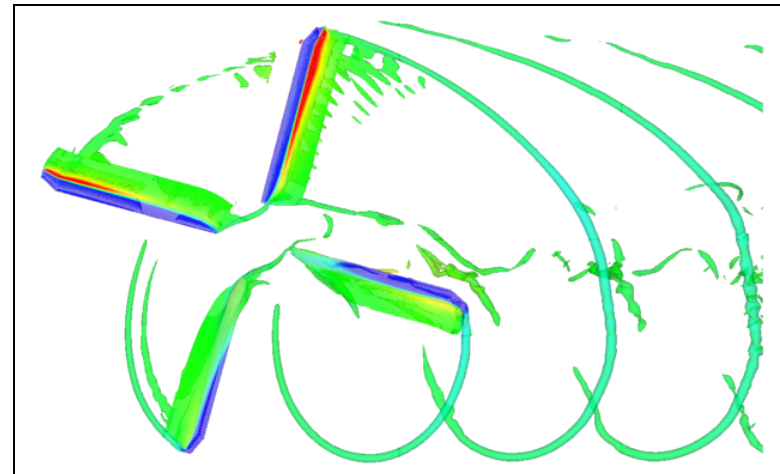
Effect of 5th-Order WENO Scheme

- Provides better propagation of blade tip and root vortices in off-body grids
- Issues with oscillations and vortex breakdown?
- From *Brian Allan et al., "Navier-Stokes Simulation of a Heavy Lift Slowed-Rotor Compound Helicopter Configuration," AHS Annual Forum, May 2009*

4th-order central (with 4th-diff dissipation)



5th-order WENOM upwind



Algorithm and Numerics Issues

- Non-local data
 - Implicit schemes
 - Domain decomposition can break implicit operator
 - Higher order schemes
 - Many higher order methods require data from more neighbors
- Amount of data per processor
 - Multigrid schemes reduce number of unknowns by approximately factor of 8 every grid level

4. Physical Modeling

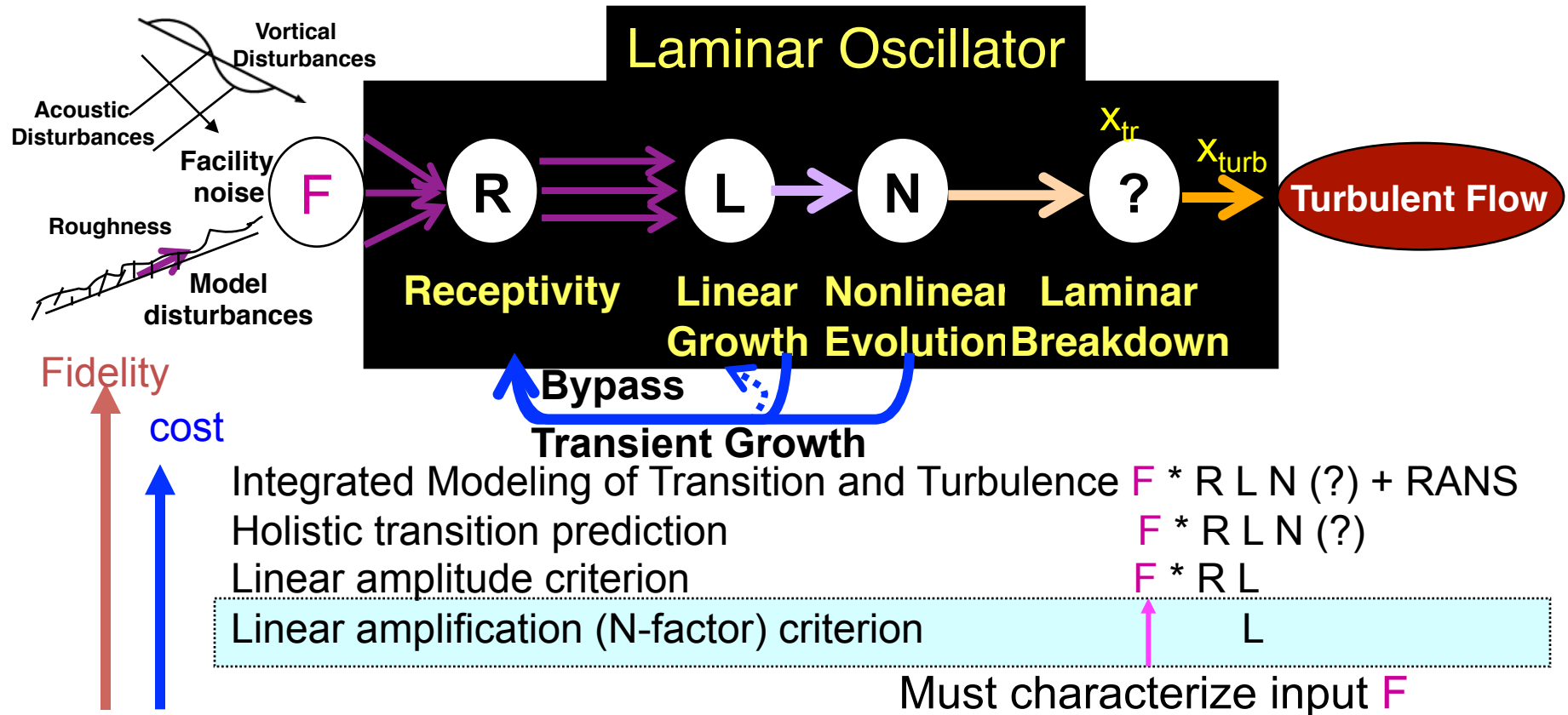
CFD Challenge: Turbulence and Transition

- P. Spalart, 1999 (*J. Heat Fluid Flow* – reiterated in 2003)
 - Date for which approach will become viable for flow over a wing at useful Reynolds number (grand challenge problem):

RANS	1995
DES	2000
LES	2045
DNS	2080

- P. Spalart and D. Bogue, 2003 (*The Aeronautical Journal*)
 - “...transition and turbulence will be permanent pacing items.”
- Challenges:
 - Improved turbulence models for RANS and DES
 - Improved transition prediction
 - Improved algorithms for LES
 - Accurate predictions for separated flows and unsteady, massively separated flows

Hierarchy of Transition Prediction



- **Technical Challenge:** multiple paths + differential sensitivity to stochastic disturbance environment
- **Goal:** Enable validated set of hierarchical prediction tools with known strengths/limitations, so as to enable “sufficiently” accurate transition predictions and practical transition control for future vehicle concepts (understand→predict→control)

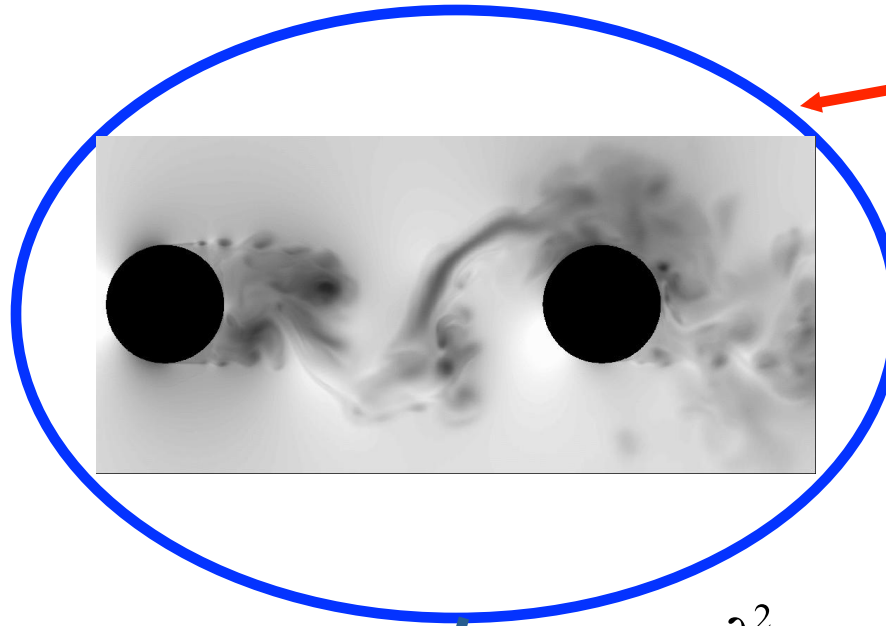
Physical Modeling Issues

- Unsteady simulations → Long run times
 - Need to increase parallelization to achieve results in time to impact decisions
 - Resilient computing
- Large data sets
 - Parallel I/O
 - Visualize and process while computing

5. Multi-Discipline Capabilities

How Do We Compute the Noise?

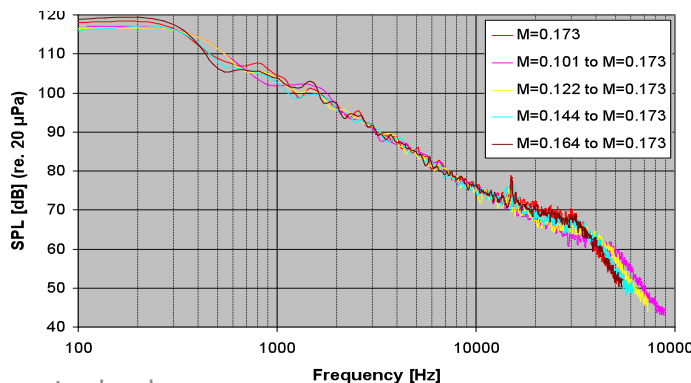
Unsteady
Numerical
Simulation



Accurately determine the unsteady noise source characteristics and account for near-field scattering.

$$\frac{\partial^2 p}{\partial t^2} - c_o^2 \frac{\partial^2 p}{\partial x_i \partial x_i} = \square^2 p = S(x_i)$$

Experiment



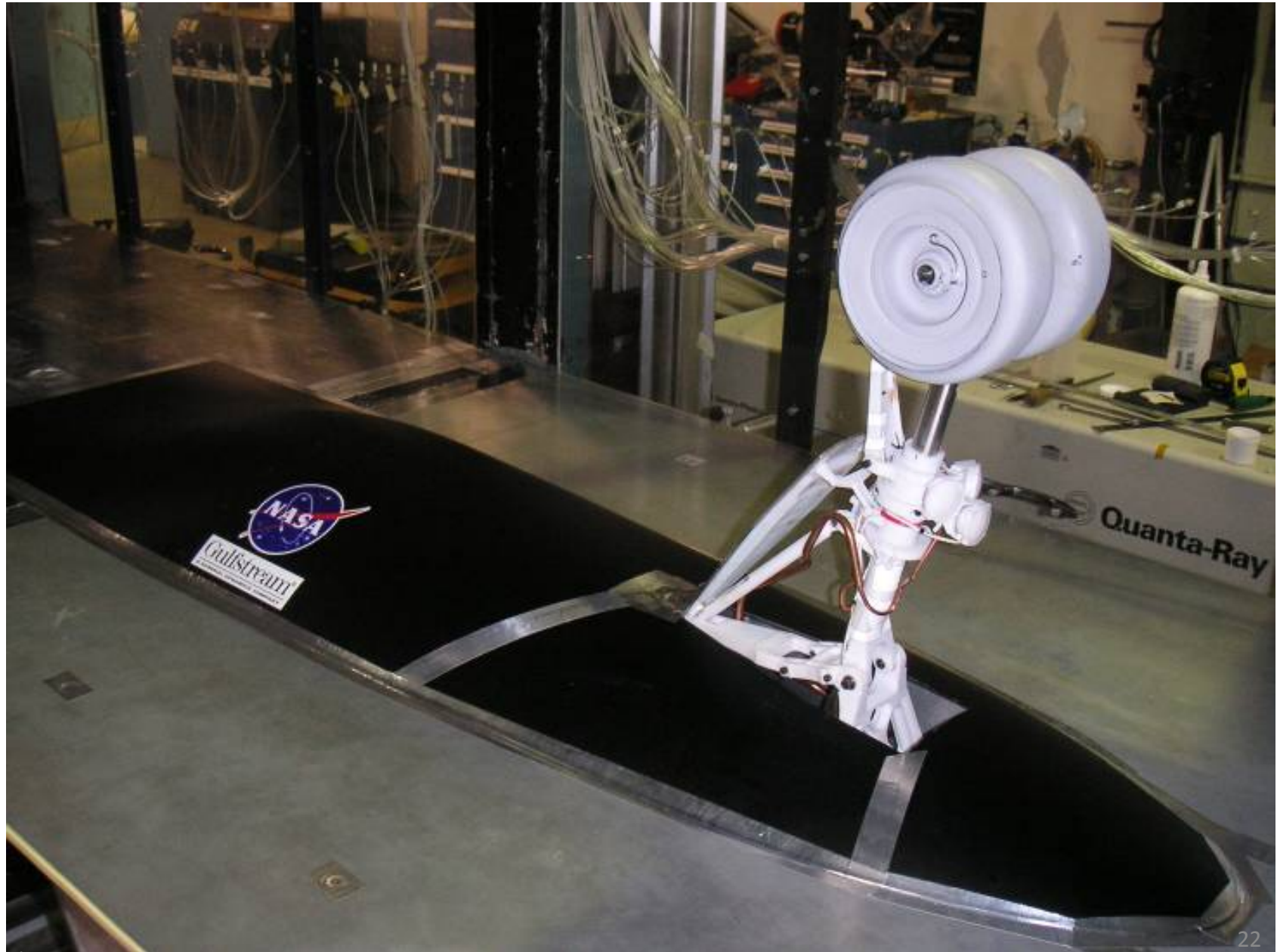
Lockard



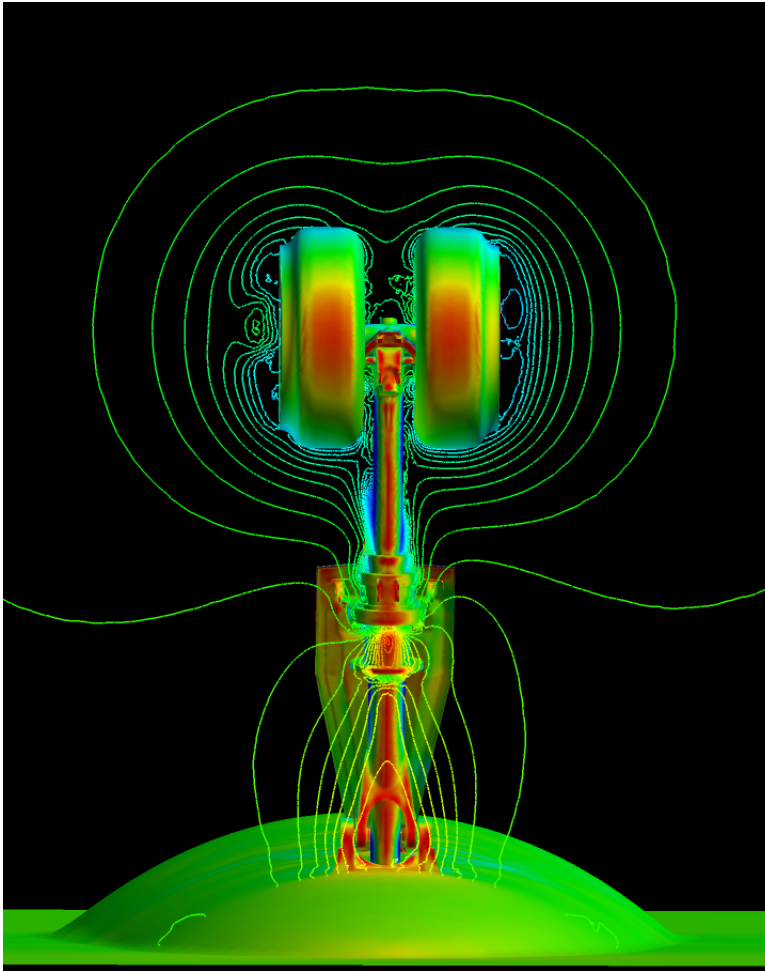
Obtain the noise at far-field listener positions

- Physical insight
- Cause & effect relationships
- Detailed source description

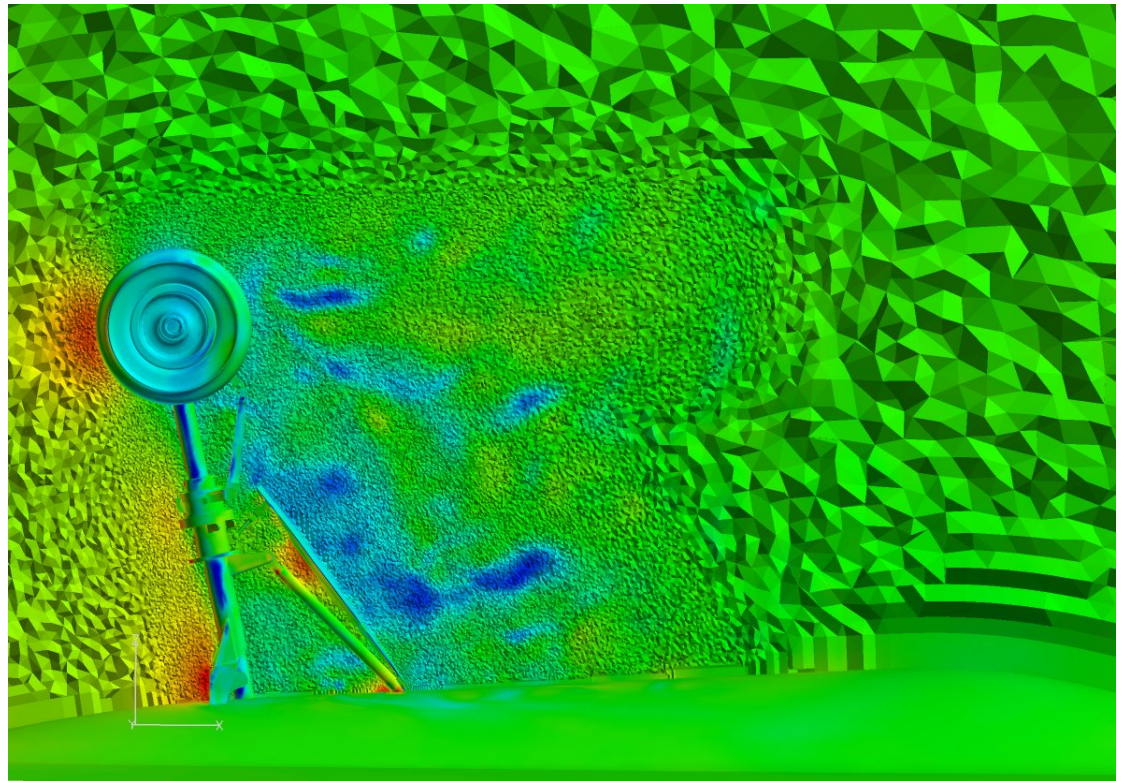
Complex Configurations with Multiple Scales



Nose Landing-Gear Configuration



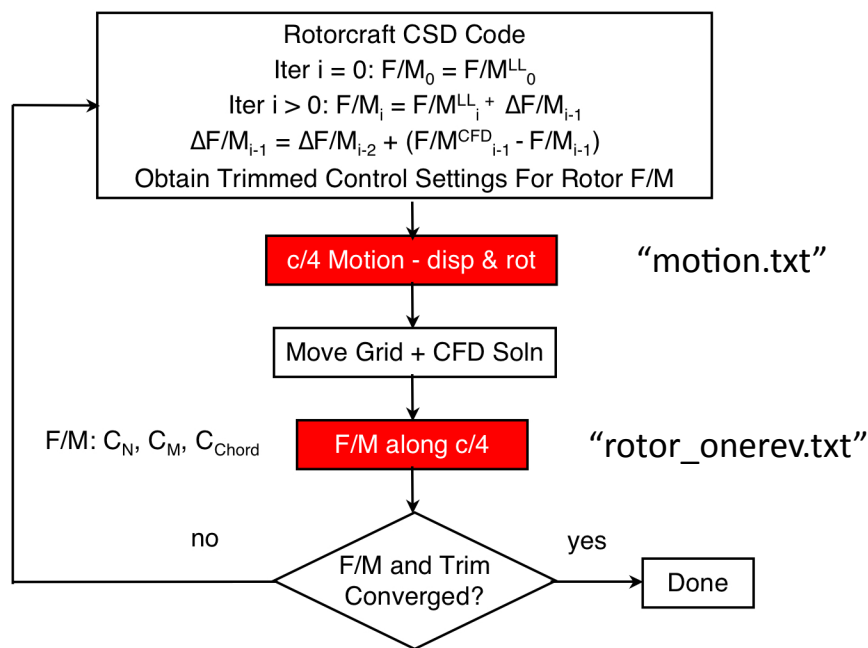
Instantaneous pressure from FUN3D simulation



- Family of 3 meshes – 9, 25, 71 million nodes
 - Manually refined 48 million node mesh
- Two turbulence models

Loose (Periodic) CFD/CSD Coupling

Coupling Process (Common to FUN3D and OVERFLOW)

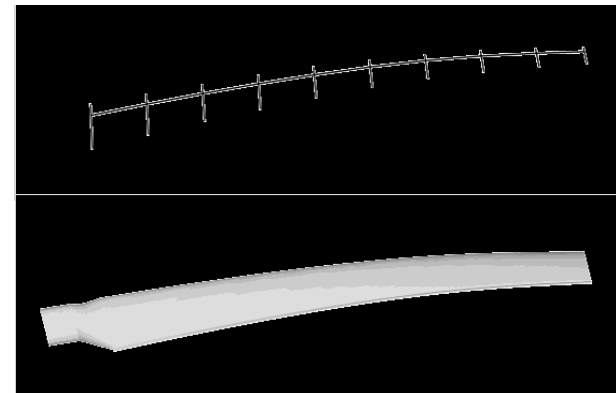


motion.txt and rotor_onerev.txt files common to FUN3D and OVERFLOW

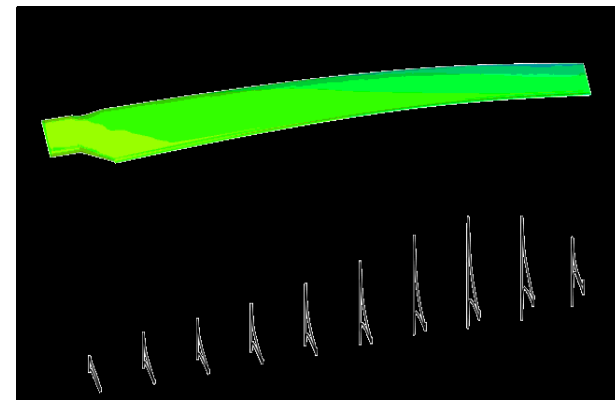
Loose Coupling: appropriate for steady forward flight or hover where solution is time periodic

Biedron

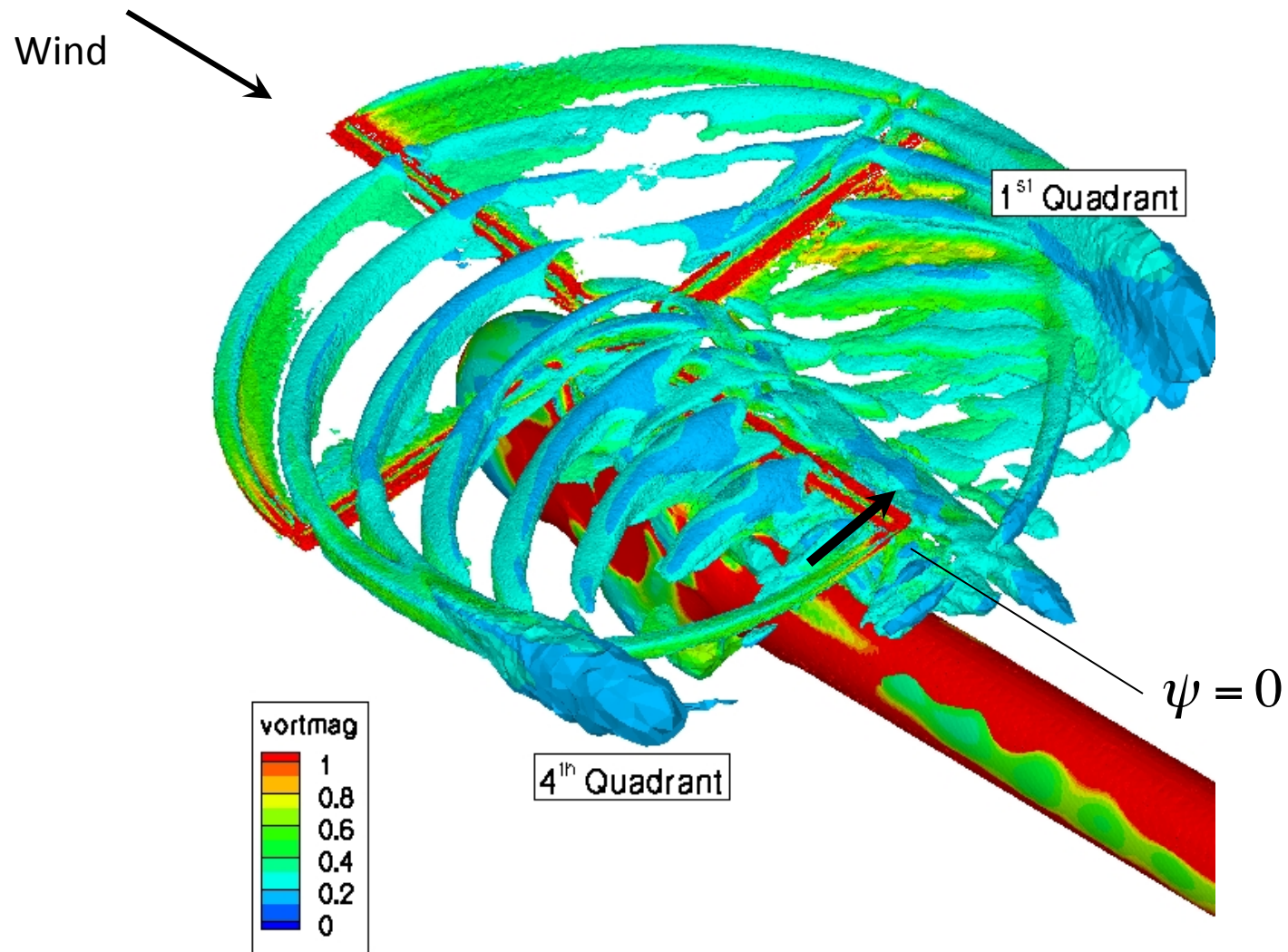
CSD -> CFD



CFD -> CSD



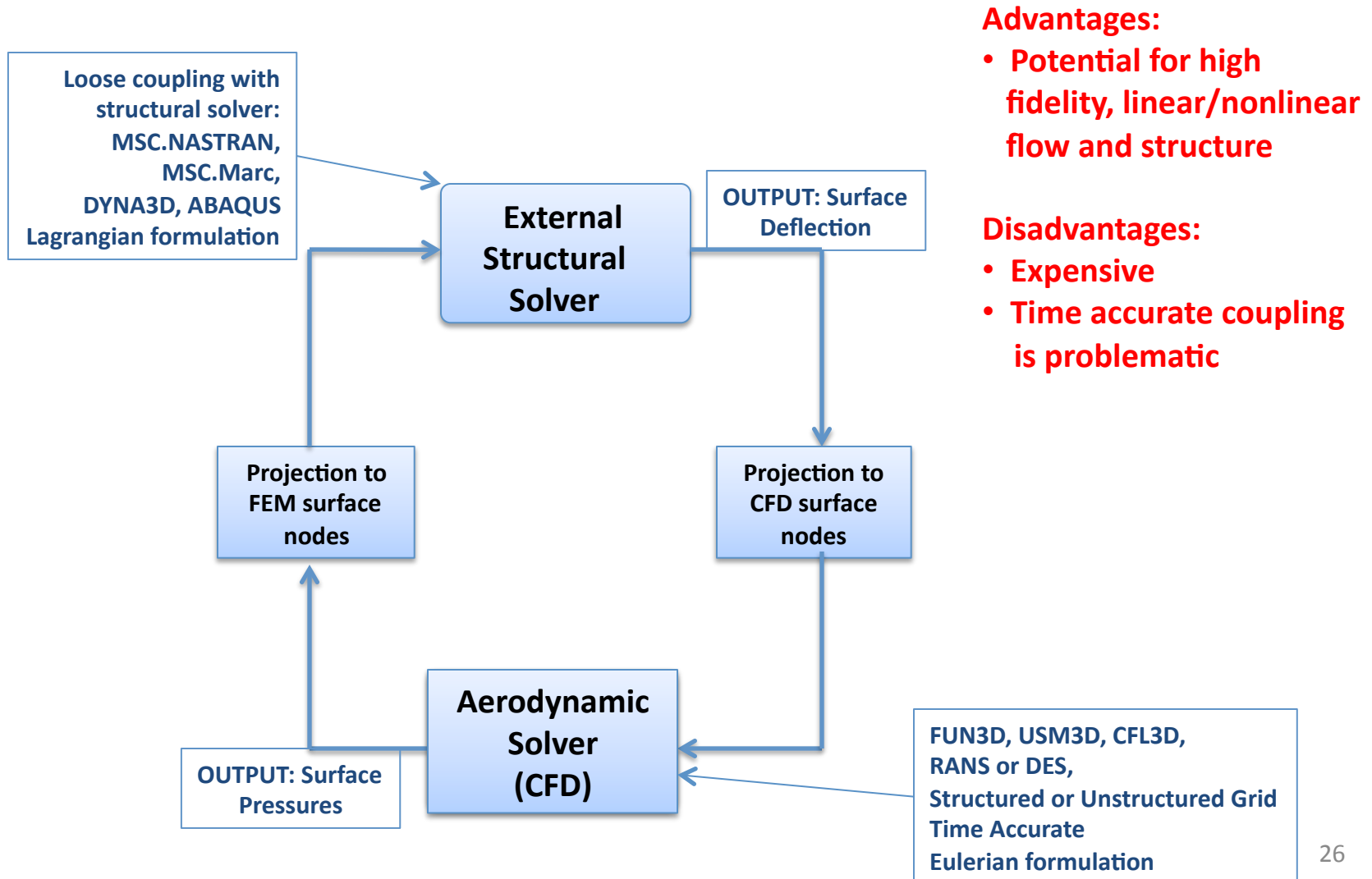
HART-II BL Wake Structure (Computed)



Coupling NASA CFD with Commercial Finite Element Codes



LaRC Aeroelasticity Branch



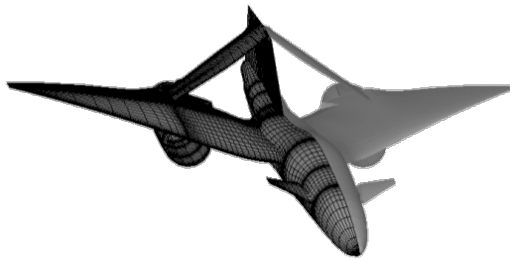
Predicting Body-Freedom Flutter of Flexible Lockheed-Martin QSST Vehicle - Using Hybrid Mesh Deformation



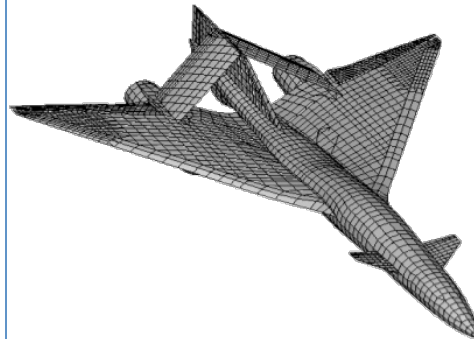
LaRC Aeroelasticity Branch

- Body-Freedom Flutter (BFF) - Coupling of rigid body and flexible modes
- Modeled with CFL3D and MSC.Nastran

CFD mesh/surface



Finite Element Model

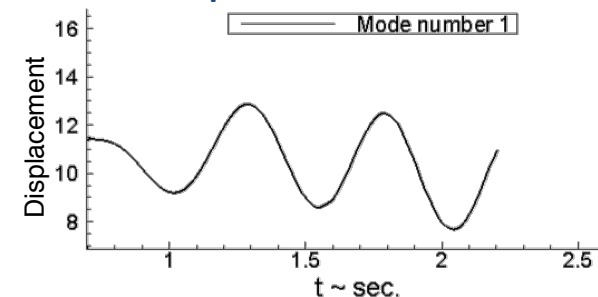


Flutter frequencies

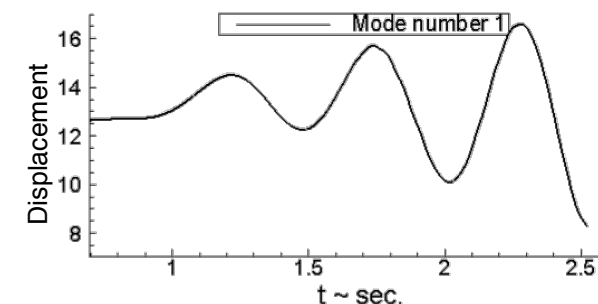
Mach	RANS Flutter Freq (Hz)	NASTRAN Flutter Freq (Hz)
0.80	2.18	2.00
1.20	2.39	2.10

Bartels, R. E., "Development of Advanced Computational Aeroelasticity Tools at NASA Langley Research Center," NATO RTO Specialists Meeting on Advanced Aeroelasticity AVT-154, paper 003, May 3-6, 2008.

1st mode response below onset



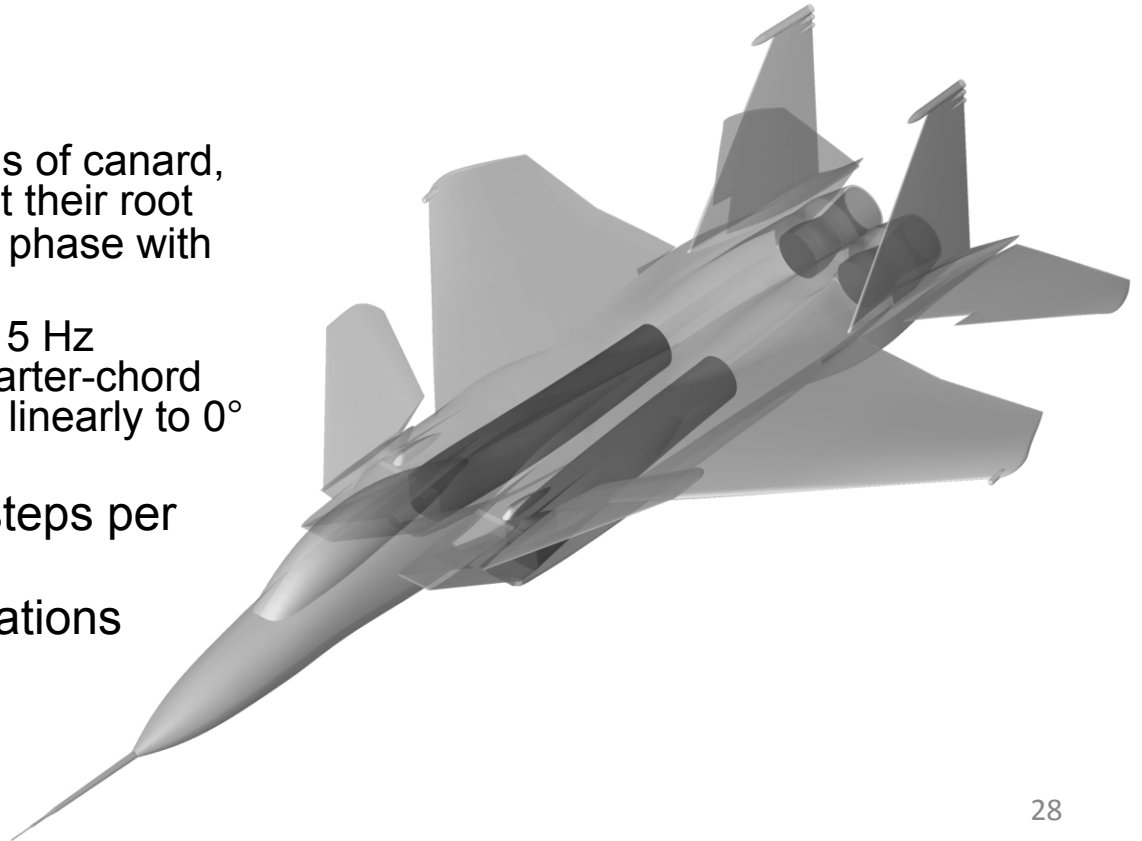
1st mode response beyond onset



Optimization with Unsteady Adjoint

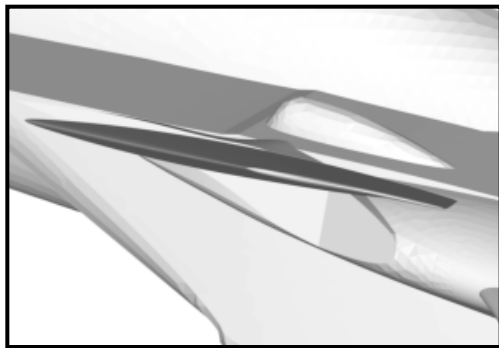
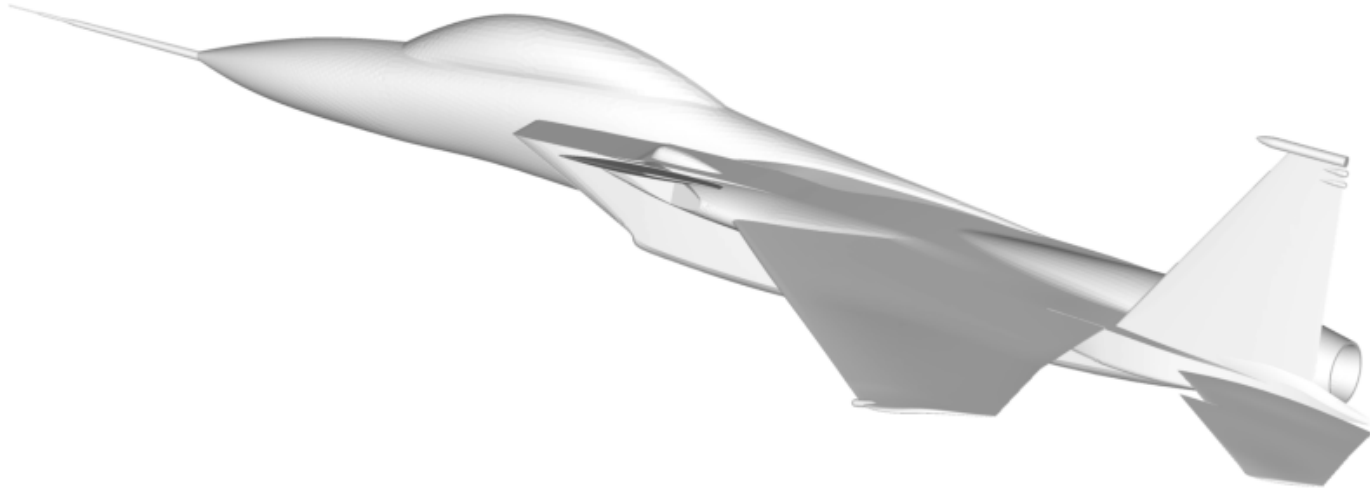
Modified F-15 Example

- Geometry based on a modified F-15 configuration with canards
- Grid consists of 4,715,852 nodes and 27,344,343 tetrahedral elements; half-plane symmetry assumed
- Model includes details of the external airframe as well as internal ducting upstream of engine fan face and plenum/nozzle downstream of turbine
- $M_\infty=0.90$, $\alpha=0^\circ$, $Re_{MAC}=1$ million; $p/p_\infty=0.9$ at fan face; $p_t/p_{t,\infty}=5.0$ at plenum
- Deforming grid motion:
 - 5 Hz 0.3° oscillatory rotations of canard, wing, and tail surfaces about their root chordlines; wing 180° out of phase with canard and tail
 - Main wing also subjected to 5 Hz oscillatory twisting about quarter-chord line: 0.5° at the tip decaying linearly to 0° at the root
- Δt chosen according to 100 steps per cycle of grid motion
- BDF2_{opt} used with 10 subiterations

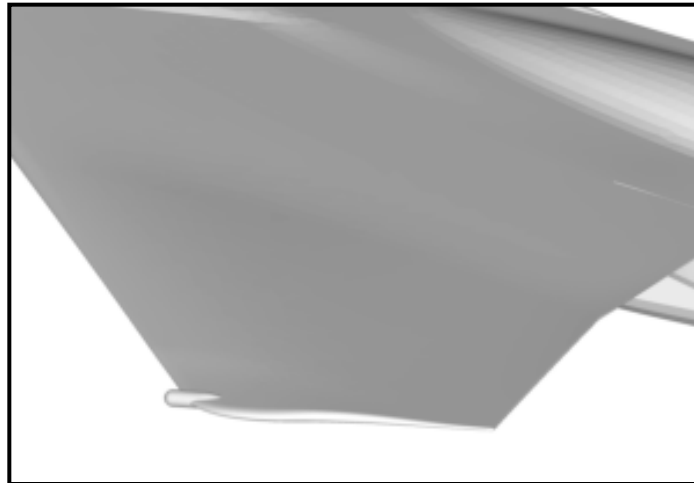


Modified F-15 Example

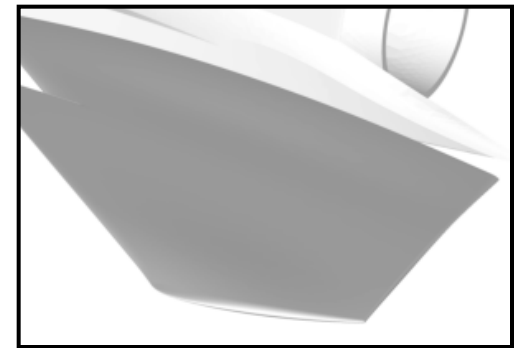
Prescribed Surface Deformations



Canard Surface



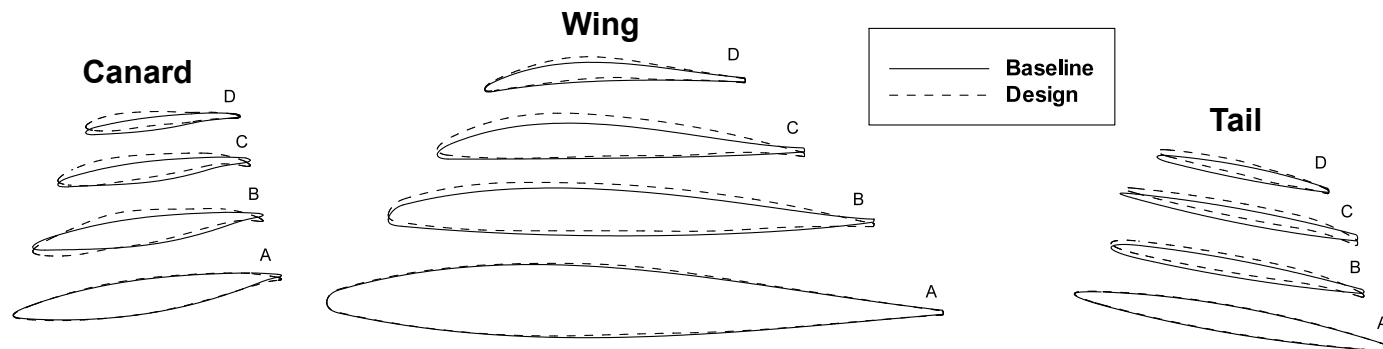
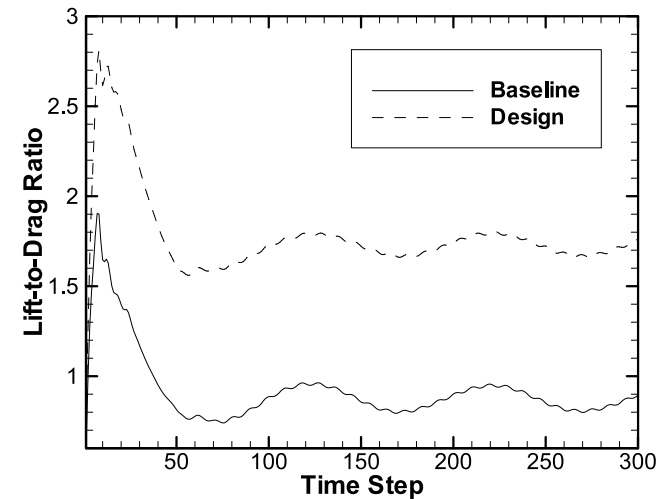
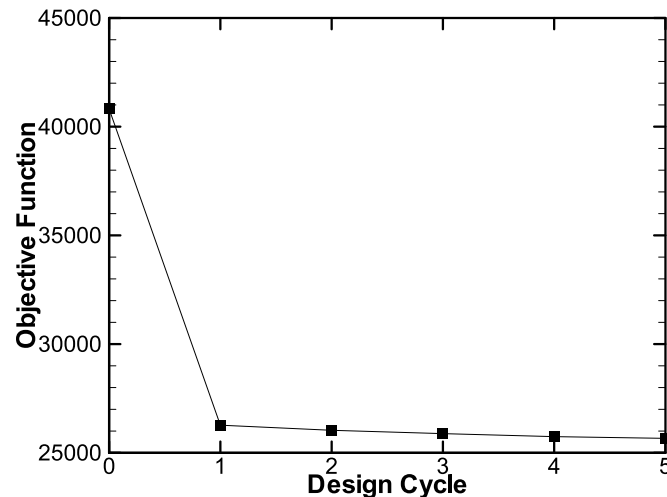
Main Wing



Tail Surface

Modified F-15 Example

- Large initial reduction in cost function; many variables quickly reach their bounds
- Wing and canard thickness increased, camber increased on all three surfaces
- Downward deflection of all trailing edges
- Single flow solution takes 1 hr; single adjoint solution takes 1.5 hrs
- Optimizer requires 10 flow and 5 adjoint solutions: 18 hrs or 18,400 CPU hrs
- Single unsteady flow solution requires 136 GB of disk space



Multi-Discipline Issues

- Coupling multiple simulations codes
 - Codes have different parallelization needs
 - CFD needs 1-2 GB RAM per core; many cores
 - CSM needs 8-64 GB RAM per core; fewer cores
 - Transfer data between codes
 - Synchronization
- Parallel I/O; Visualization; Post-processing

6. Concluding Remarks

The Aero-Sciences Problem

- Applications are growing larger and more complex
 - Modeling more complex problems - e.g. from wing alone to wing/body/fuselage/tail/nacelles
 - Increasing grid resolution – reducing uncertainty, looking for grid independent solutions
 - Increasing physical complexity – aeroacoustics, aeroelasticity, rotating and translating bodies, etc.
 - Increasing modeling complexity – DES, LES, etc.
 - Design and Optimization
 - Uncertainty quantification

The Computing Problem

- Hardware Challenges:
 - The new reality:
 - Single thread performance will not increase dramatically in the future as it did in the recent past
 - “Many”-core appears to be the near term future
 - We have *tens of thousands* of cores now
 - Will see *millions* of cores soon and *tens of millions* of cores in about a decade
 - Will these cores be homogeneous or heterogeneous?
 - New hardware architectures
 - FPGA, GPGPU, Cell, ASICs, Larrabee, Fusion, ...
 - All have different characteristics
 - But all have better floating point performance than memory bandwidth

The Computing Problem

- Software Challenges:
 - What algorithms will work best on these architectures?
 - How do we program for these new architectures?
 - We can't afford to write code specific to each architecture
 - Will need to use multiple levels of parallelism
 - What APIs and languages will we use? Will it take multiple APIs/languages?
 - FORTRAN still common for scientific applications
 - C/C++ is where development first occurs to support new hardware
 - MPI, OpenMP predominate today
 - Pthreads, OpenCL, TBB, CUDA, UPC, Co-array Fortran, HPF, ZPL, Fortress, Chapel, X10, etc.
 - How will we debug on tens of millions of cores?

Aero-Science Application Approach

- Fully parallel process
- Automation will be required
- Hands-off operation will require robust schemes
- Design and uncertainty quantification will require fast system
 - Grid generation automatically from CAD
 - Automatic grid adaption
 - Robust, high-accuracy flow solvers
 - Accurate physical models
 - Turbulence and transition models
 - Multi-discipline models
 - Solutions provided with quantified uncertainty
 - Automatic modification of CAD models for design
- Multiple physical models coupled together