Presented to:

10th Symposium on Overset Grid and Solution Technology
NASA Ames Research Center

RDECOM

Unsteady Adaptive Mesh Refinement in the Helios Code

AMRDEC
STRENGTH THROUGH TECHNOLOGY

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Sept 22, 2010

Presented by:

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Research, Development and Engineering Command
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Acknowledgements

- Helios is a product of the HIARMS institute & CREATE-AV, DoD HPCMP

- **Helios developers**
  - Anubhav Datta
  - Buvana Jayaraman
  - Sean Kamkar
  - Aaron Katz
  - Venke Sankaran
  - Jay Sitaraman
  - Andy Wissink
  - Dimitri Mavriplis
  - Zhi Yang
  - Hossein Saberi

- **Project management**
  - Roger Strawn
  - Chris Atwood
  - Robert Meakin

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Outline

- **Motivation**
- **Approach**
  - Near-body RANS
  - Off-body Euler, high-order adaptive Cartesian
- **Results**
  - NACA 0015 wing
  - AV-8B aircraft at high AOA
  - Model scale V-22 (TRAM) rotor
- **Development plans**
- **Concluding remarks**

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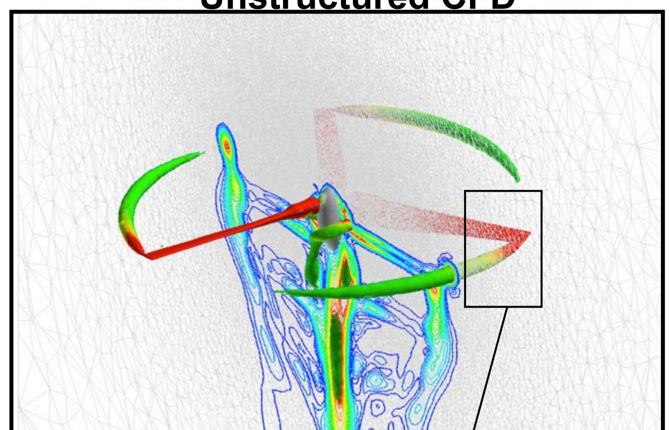
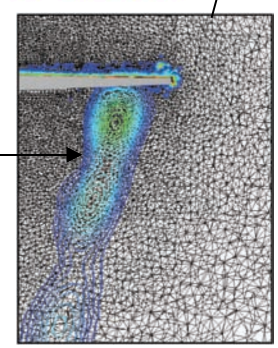
Motivation

- **Computational Fluid Dynamics (CFD) has developed into an effective tool for rotorcraft aeromechanics**
  - Thrust, power, figure of merit (hover) resolution to within 2-3% of experiment
  - Commonly used for aerodynamics in high-fidelity CFD/CSD analysis
- **However, CFD wake predictions remain poor**

Tip vortices

Unstructured CFD





diffused

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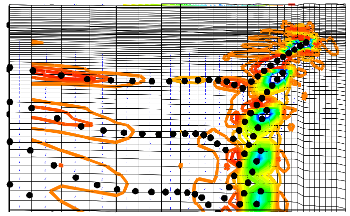
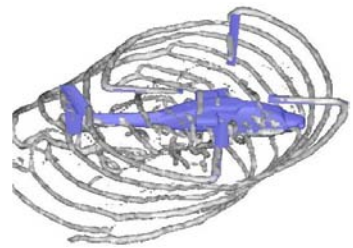
Wake Approaches Used

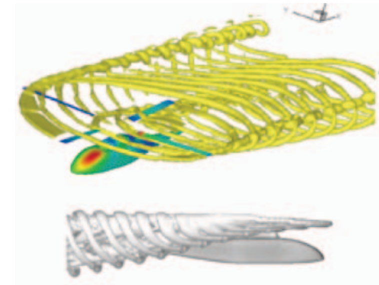
- **Vorticity Embedding**
- **Vorticity Confinement**
- **Vorticity Transport**



Lagrangian/Eulerian Vorticity Embedding
Caradonna



Vorticity Confinement
Steinhoff



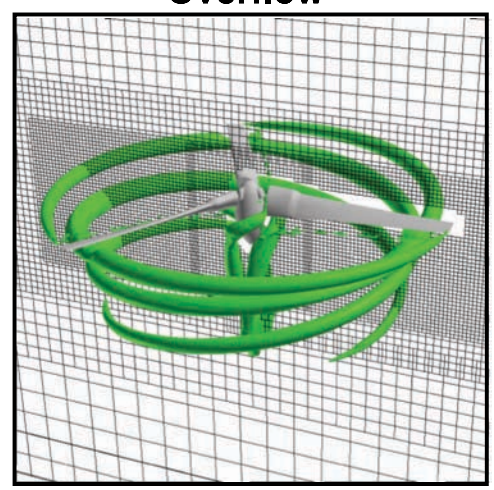
Vorticity Transport Model
CDI - Brown

Useful for fast-turnaround "desktop CFD" or flight simulator applications

- **CFD with very dense background grids**
  - Fine-mesh CFD today - 10% blade chord resolution, 1 point across vortex core
  - 10-20 points across core required
    4 refinements = 16 points across core
  - Problem size grows by 4096X

With computing power growing at a rate of 1000X/ decade (the current trend) it will be 40 years before calculations of this size become routine.

Overflow



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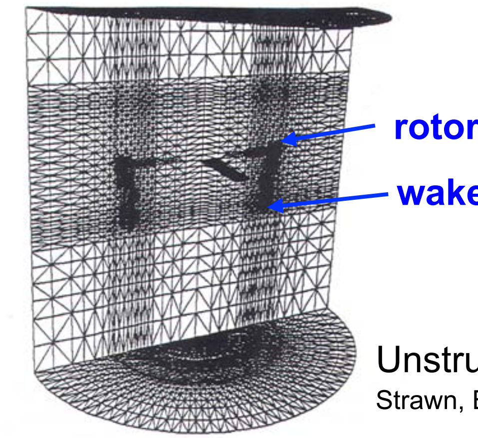
Adaptive Mesh Refinement

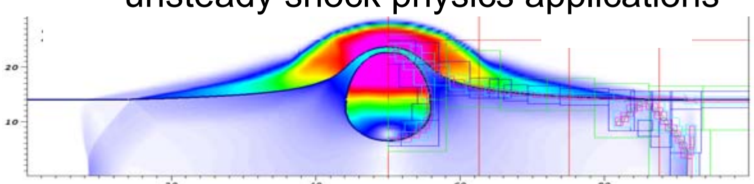
- **A number of researchers have investigated CFD-based adaptive mesh refinement to resolve rotor wakes**
  - Strawn, Barth, AHS J. 1993
  - Meakin, AIAA CFD, 2001
  - Kang, Kwon, AHS J. 2002
  - Park, Kwon, AHS J. 2004
  - Dietz et al, AHS J. 2004
  - Potsdam, Mavriplis, AIAA Aero. 2009
  - Holst, Pulliam, AHS SF Spec. 2010



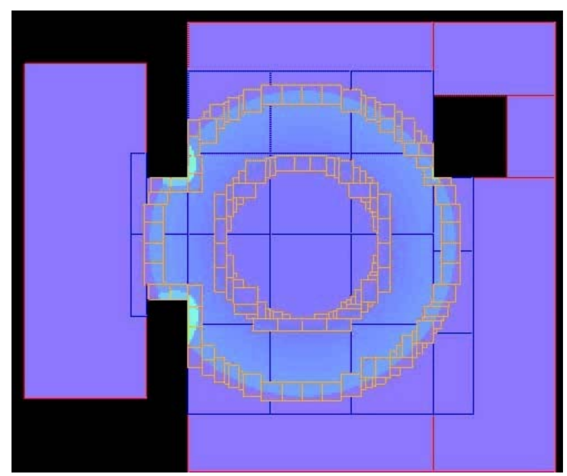
Unstructured AMR
Strawn, Barth, 1993

Techniques drawn mainly from steady fixed-wing applications

- **Dynamic time dependent approach**
  - Block structured AMR - Berger, Colella
  - Technique developed in the 80s-90s for unsteady shock physics applications



R. Nourgaliev - UCSB



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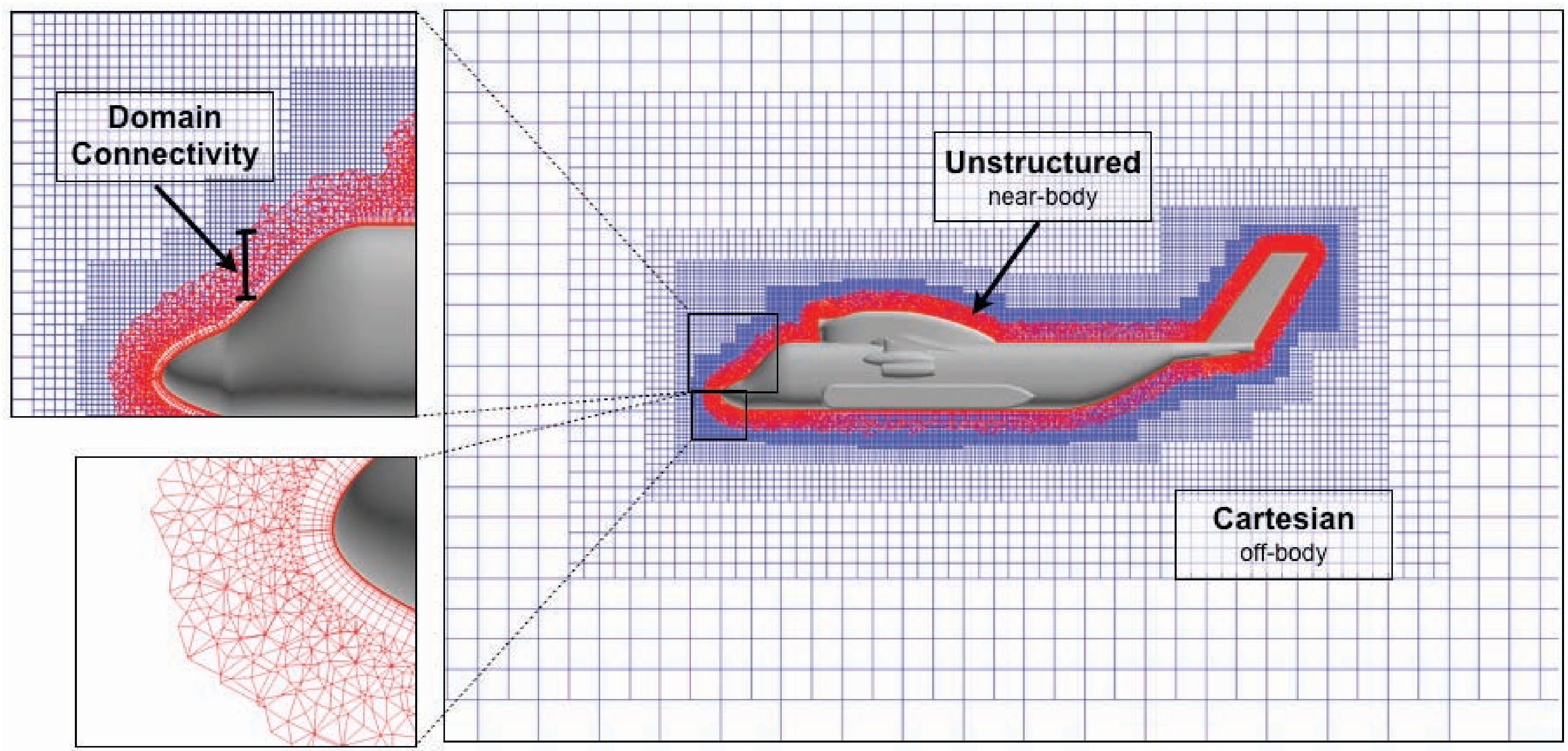
Approach



Unstructured "near-body"

- near-wall viscous flow
- Complex geometries
- NSU3D

Cartesian "off-body"

- Resolve wake
- High order
- Solution adaptive
- SAMRAI, ARC3D

Implicit Hole Cutting

- Detects overset grid with highest resolution
- Parallel (MPI)
- PUNDIT

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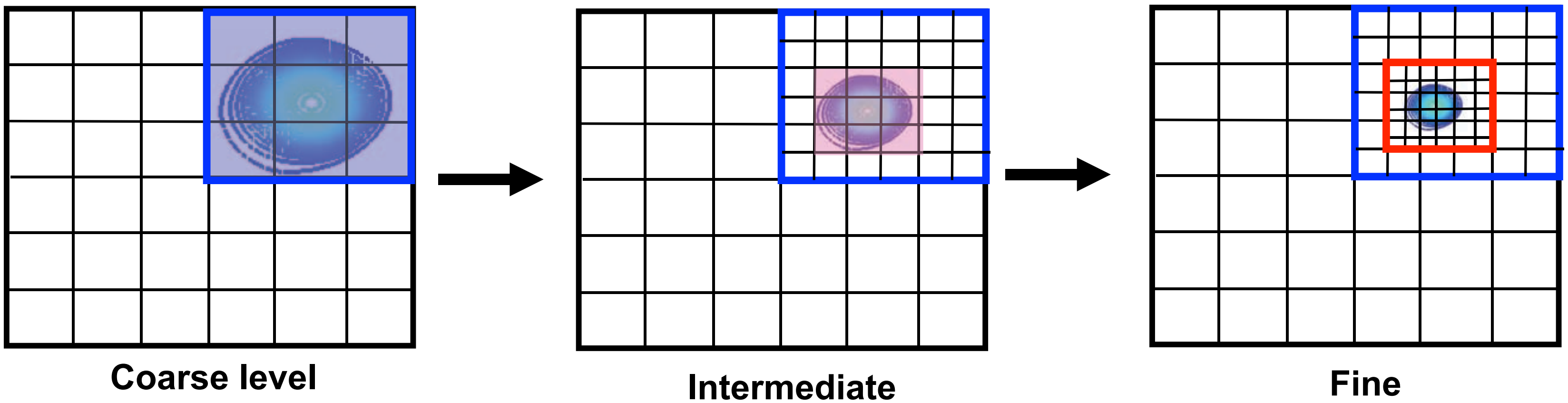
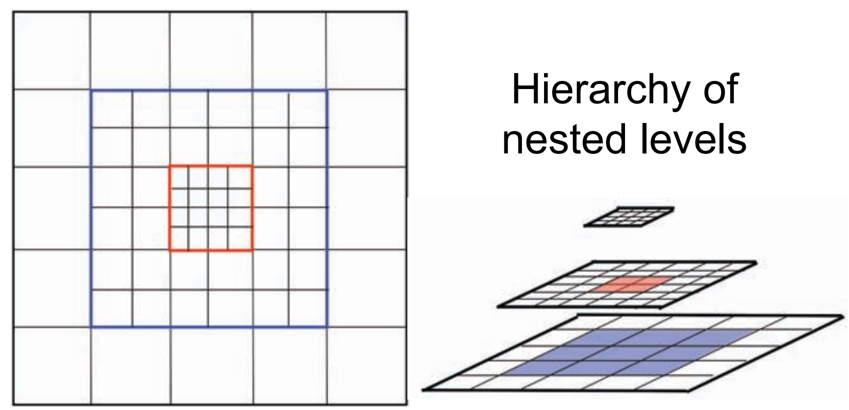
Block Structured AMR
Solution-based Refinement



1. "Tag" cells containing feature
2. Cluster tagged cells into blocks
3. Use blocks to create finer level

→ *Repeat*



ARC3D solver applied on each block

- 3^{rd}-O RK time integration
- High-order spatial ops
  - 6^{th}-O central diff
  - 5^{th}-O diss

- **Minimal overhead**
- **Parallel mesh generation**
- **Load by distributing blocks**

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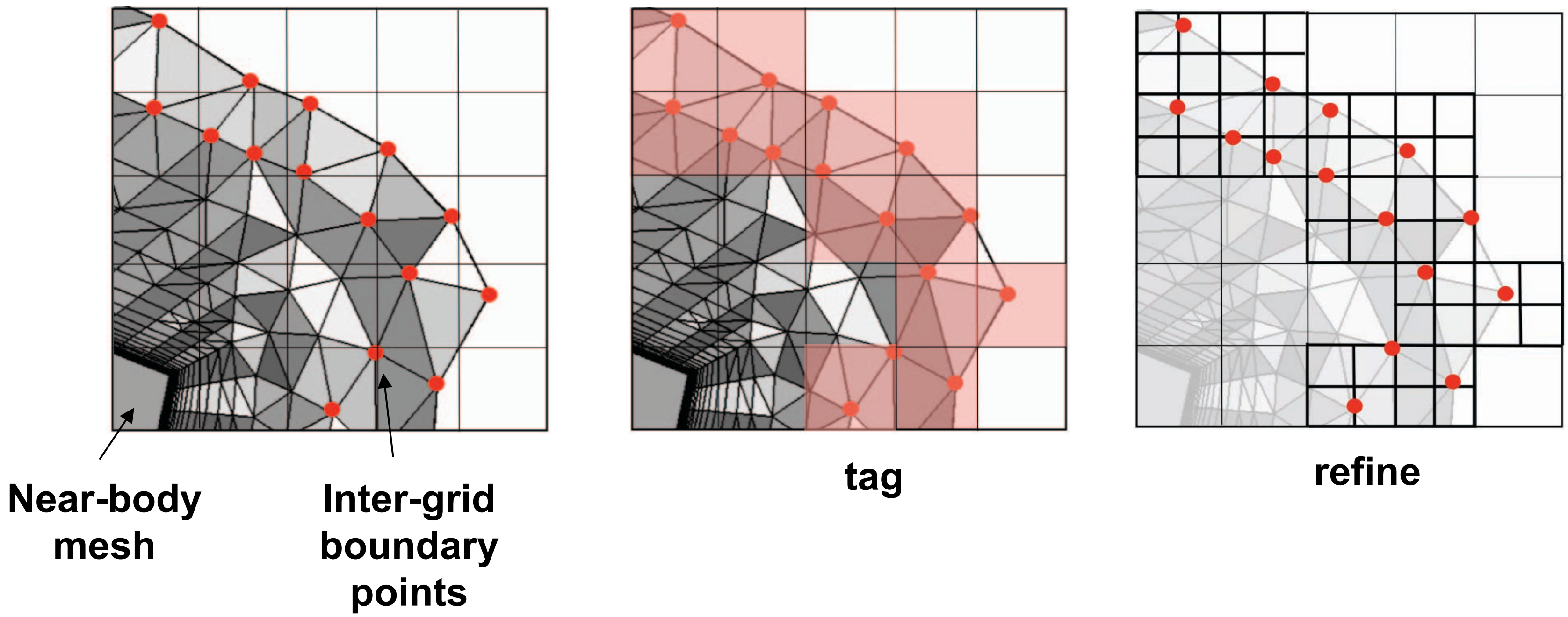
Geometry-based Refinement

Geometry refinement necessary to ensure consistent resolution between near and off-body grids



- Adapt Cartesian grids to match spacing of near-body grid
- Performed at each time step in moving-mesh simulations

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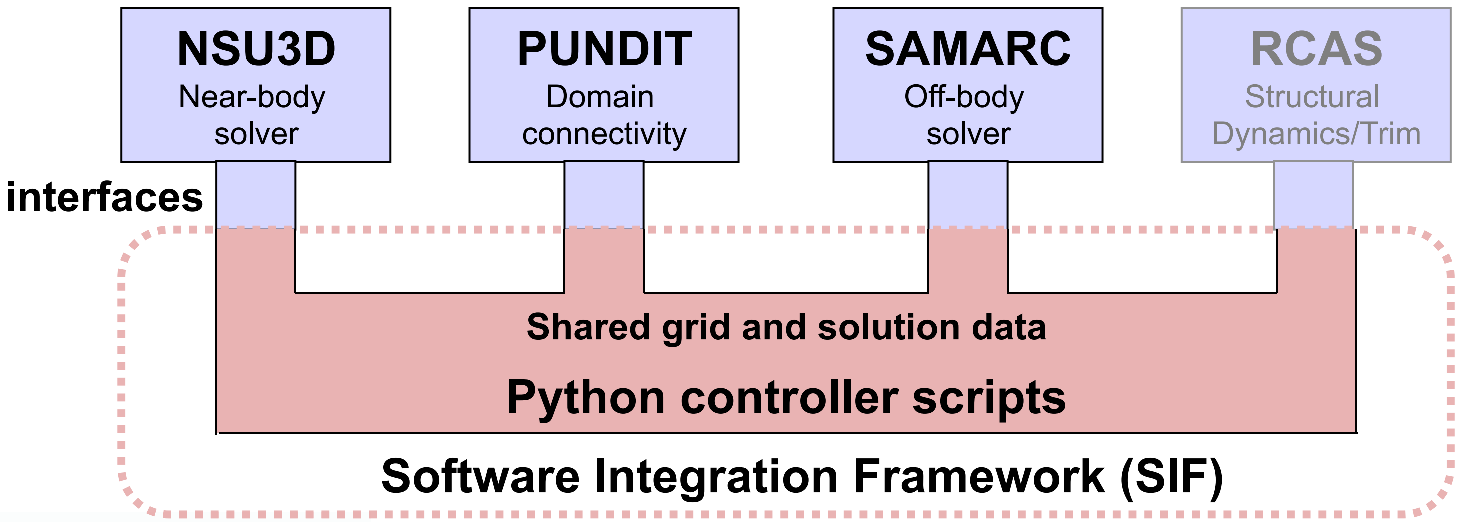
Helios Code

- **Aero CFD components**
  - Near-body unstructured: **NSU3D**
  - Off-body Cartesian: **SAMARC**
  - Domain connectivity: **PUNDIT**
- **Structural dynamics components**
  - Structures & trim: RCAS
  - Fluid structure interface: FSI
  - Mesh motion: MMM



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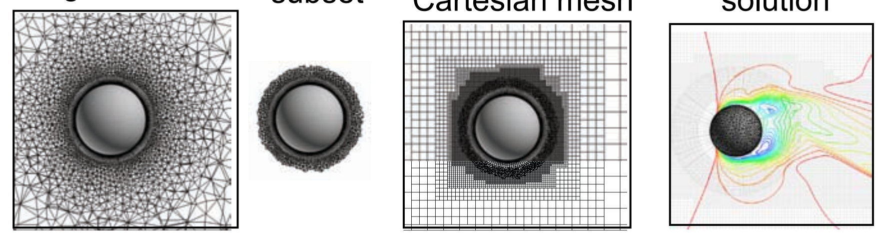
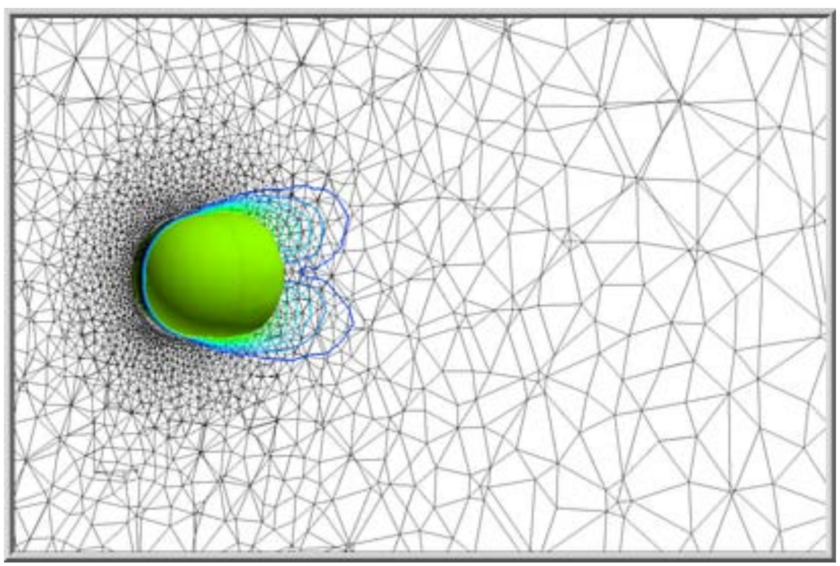
Example Application
Flow Over Sphere

- **Flow conditions**
  - Re=1000
  - Laminar (no turb model)
  - Expect unsteady shedding

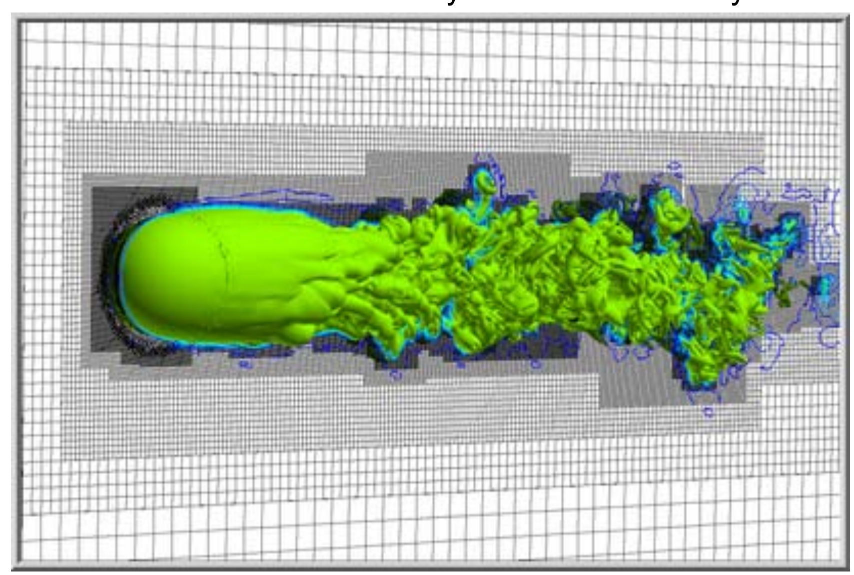


Fully unstructured



No shedding

Dual-mesh adaptive
Unstructured near-body / Cartesian off-body



Expected shedding behavior

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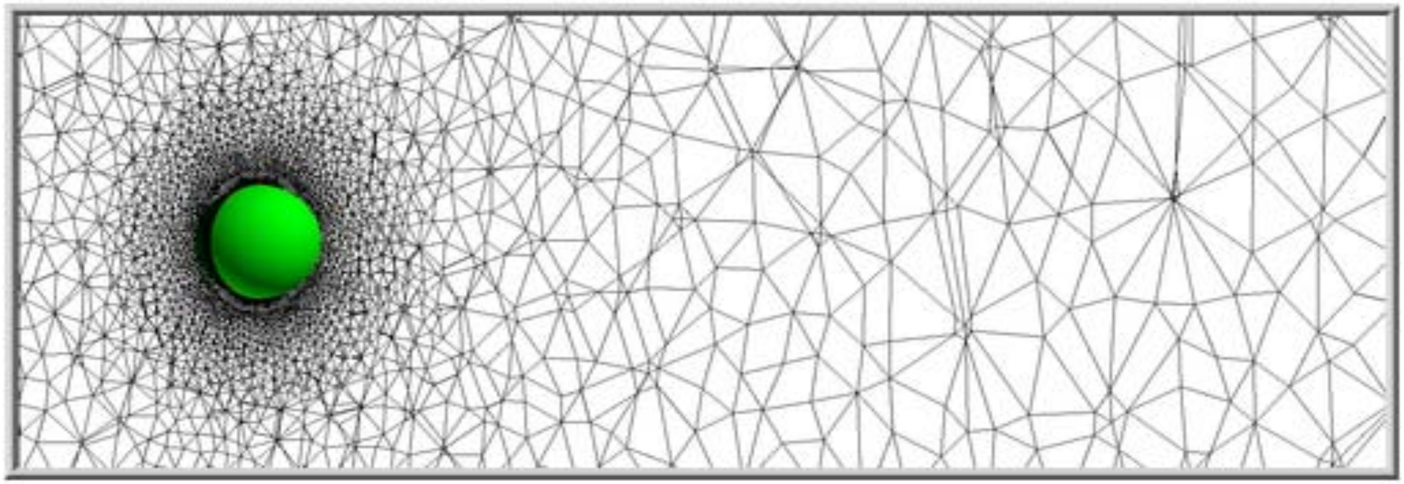
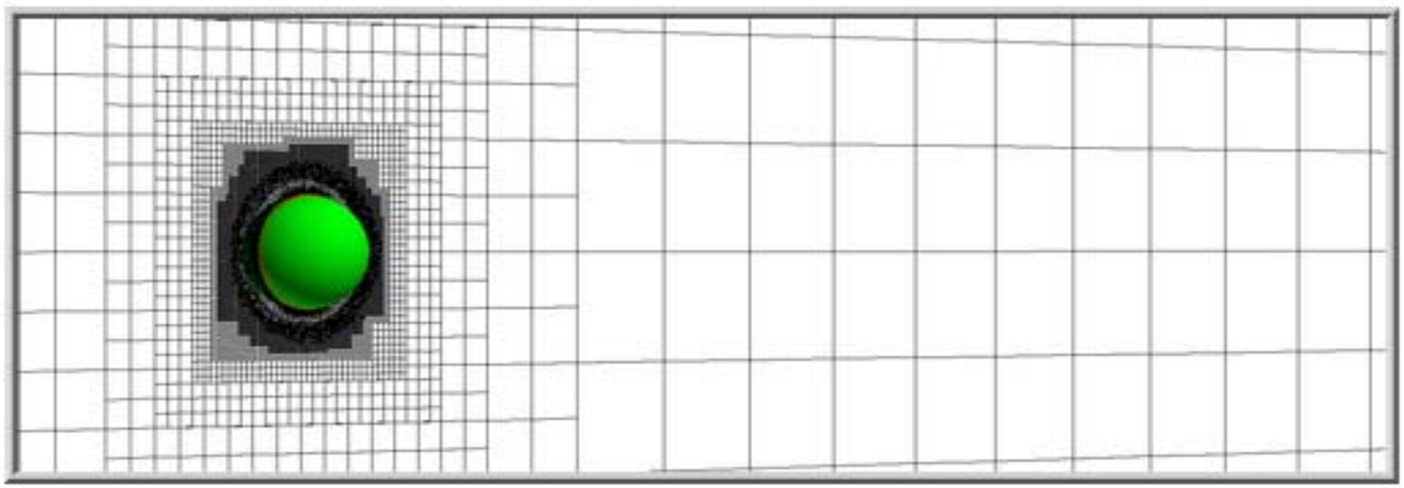
Example Application
Flow Over Sphere (cont)

Re=1000

Fully unstructured



Dual Mesh
Unstructured with adaptive Cartesian



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- **Results**
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  - AV-8B aircraft at high AOA
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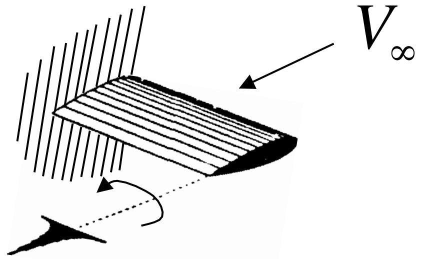
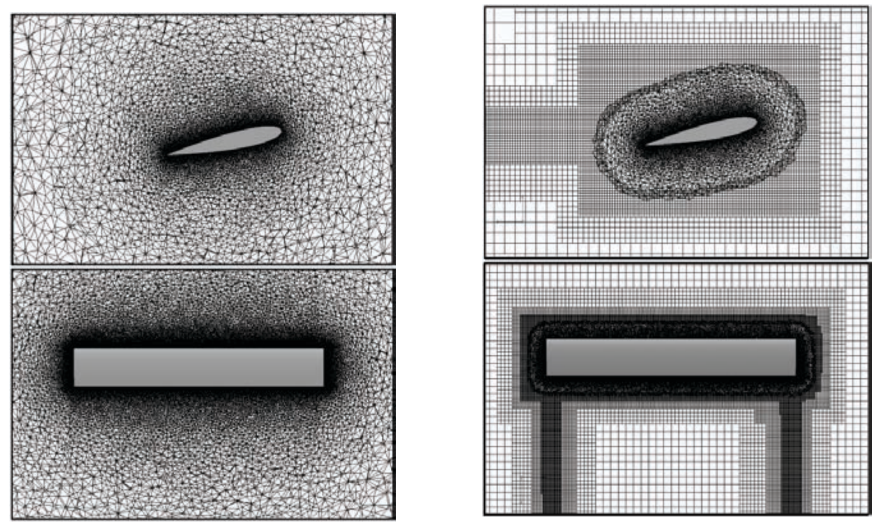
Results
3D NACA0015 Wing



$M_\infty = 0.1235$, $\alpha = 12^o$

- **Experimental results**
  - McAlister et al
  - Tip vortex measurements
- **Computational model**
  - Re = 1.5 million
  - Spalart-Allmaras turb model

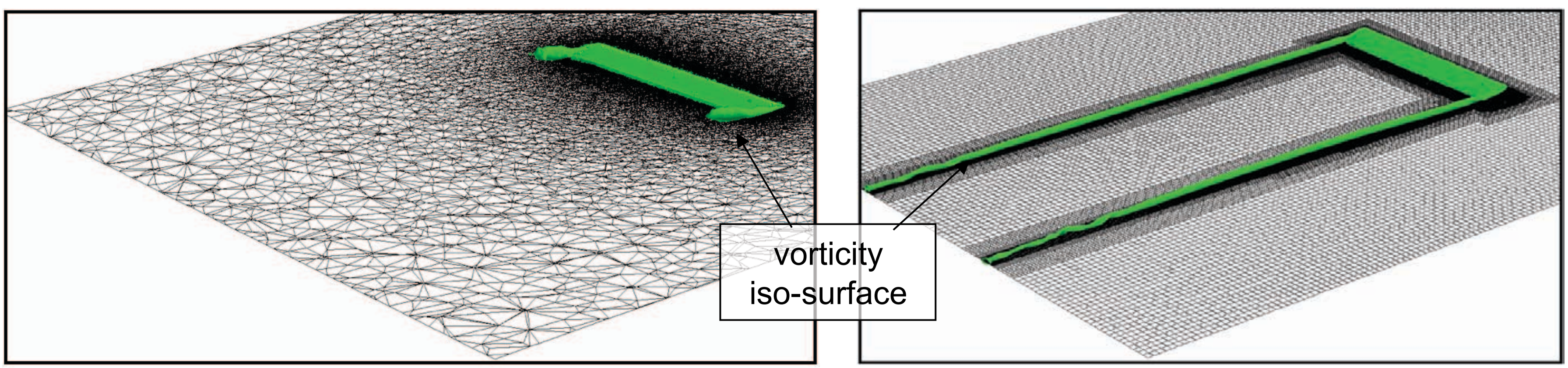
Meshes



Fully unstructured

Dual mesh adaptive
Unstructured-Cartesian

Wake



Fully unstructured

Dual mesh adaptive

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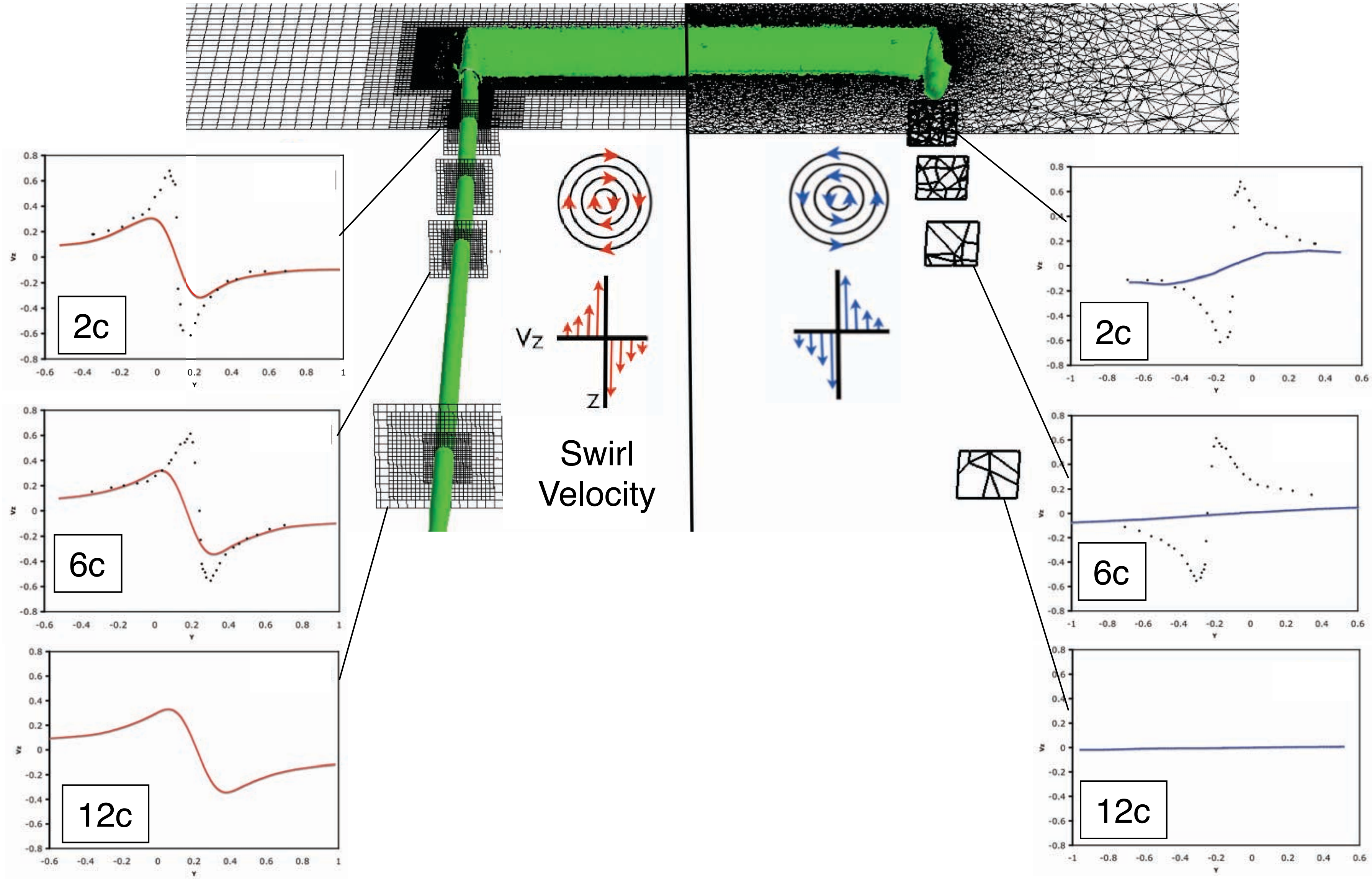
Results

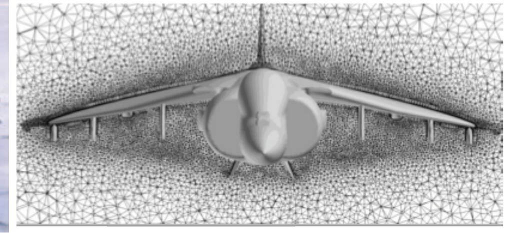
NACA0015 Comparison with Experiment



Results

AV-8B Aircraft

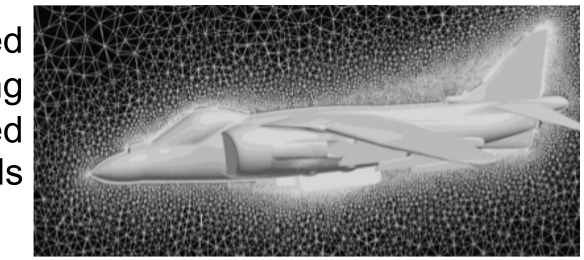
- **Aft fuselage/tail fatigue cracks**
  - Tail buffet from shed vortices
  - Experienced in high AOA flight

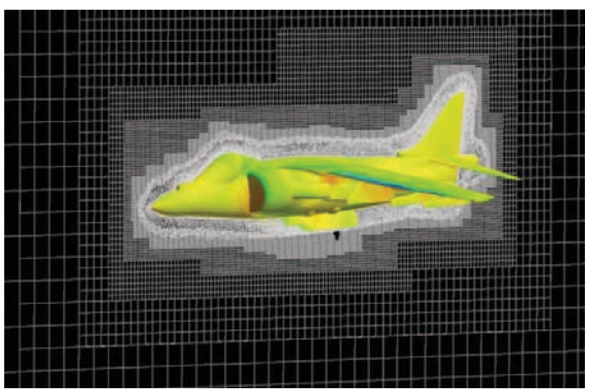


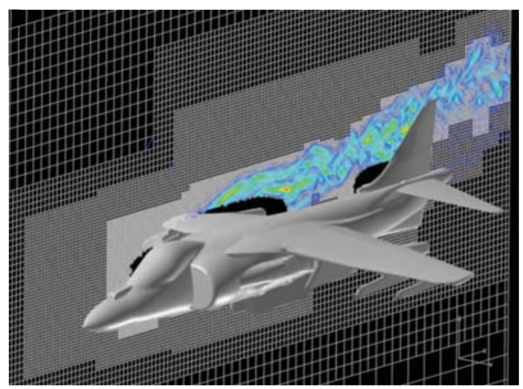
NAVAIR

N. Hariharan

Configuration analyzed extensively using traditional unstructured grid methods







Investigating application of dual mesh adaptive approach

- **Further details in Hariharan et al (AIAA-2010-1234)**

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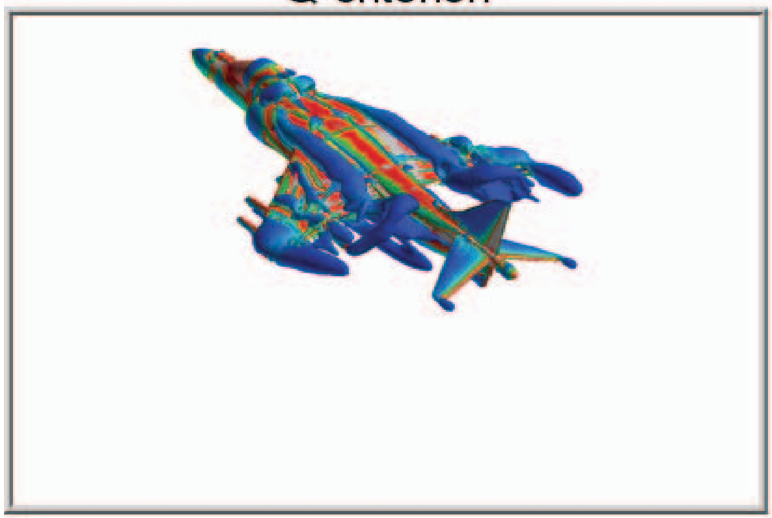
Results
AV-8B trailing vortices

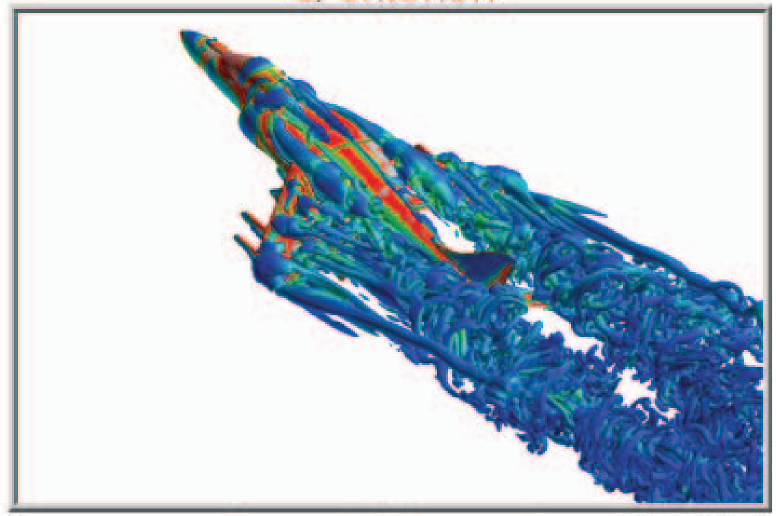
α =20º

Q-criterion

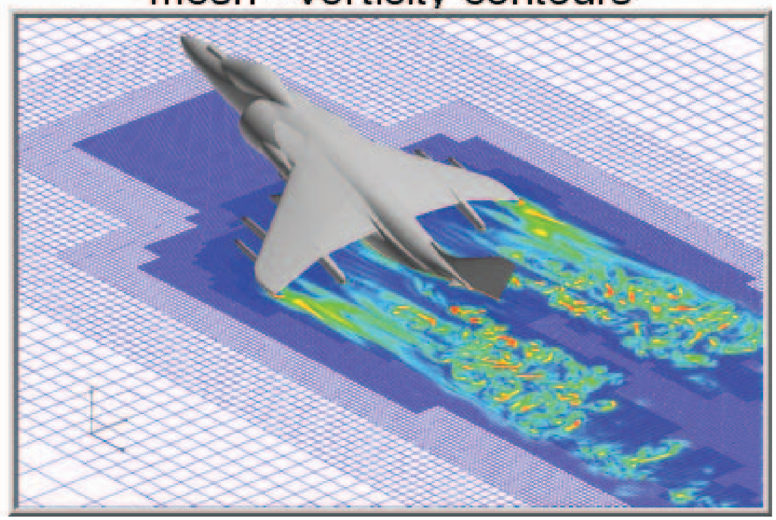


NSU3D

Q-criterion



mesh - vorticity contours



Helios

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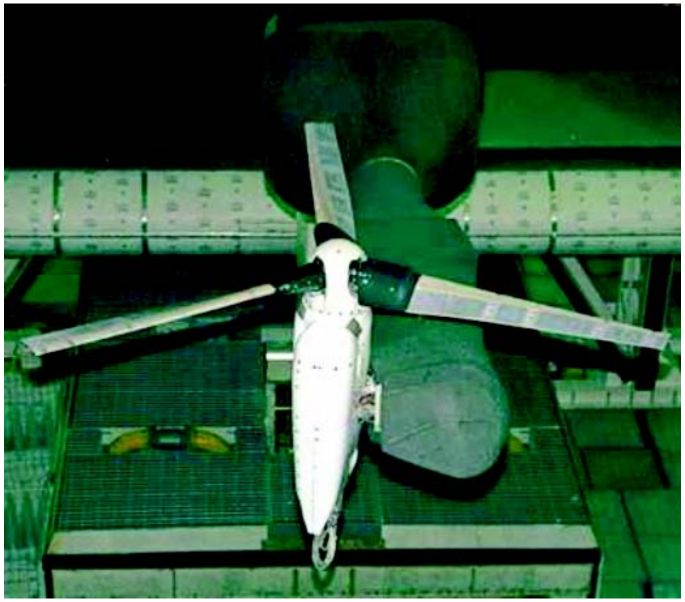
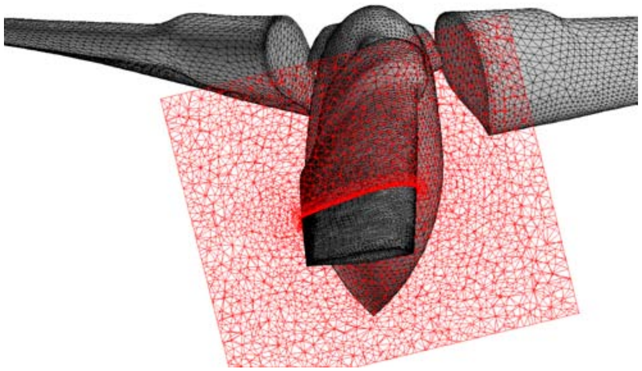
Results
TRAM Rotor

- **Tilt Rotor Aeroacoustics Model (TRAM)**
  - Quarter-scale model V-22 Osprey rotor/ nacelle
  - Tested in DNW-LLF facility



- **Computational conditions:**
  - Rigid blade, 14 deg collective
  - M_{tip}=0.625, Re_{Tip}=2.1M
  - Spalart-Allmaras turbulence model



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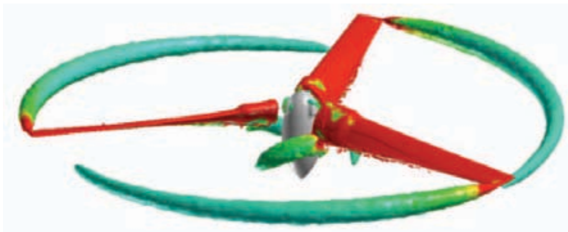
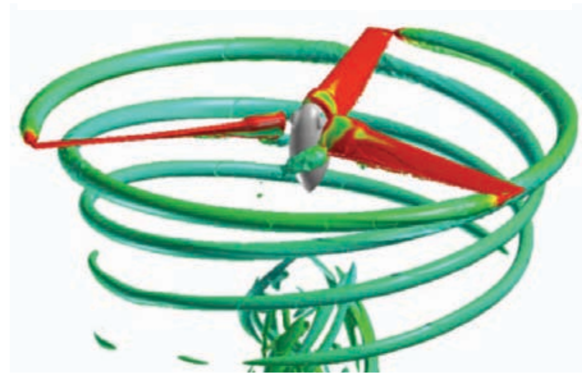
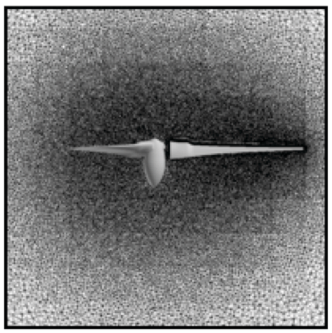
Results
TRAM Baseline

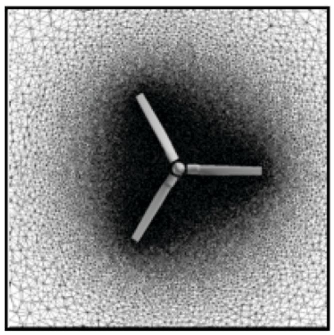
Fully unstructured

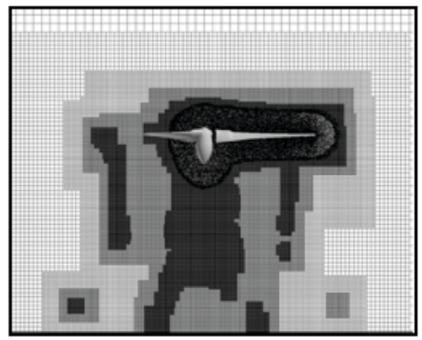


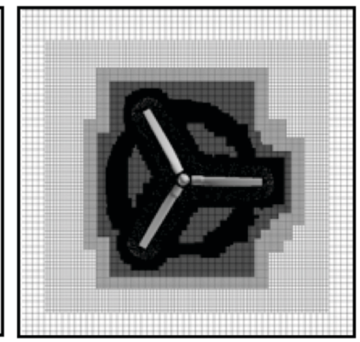
Dual mesh adaptive











	# Points	Solution time	Figure of merit
Experiment	-	-	0.779
Fully unstructured	5M	*11.1 hrs	0.694 (-11%)
Dual mesh adaptive	56M	*29.8 hrs	0.739 (-5%)

*64 core Linux cluster

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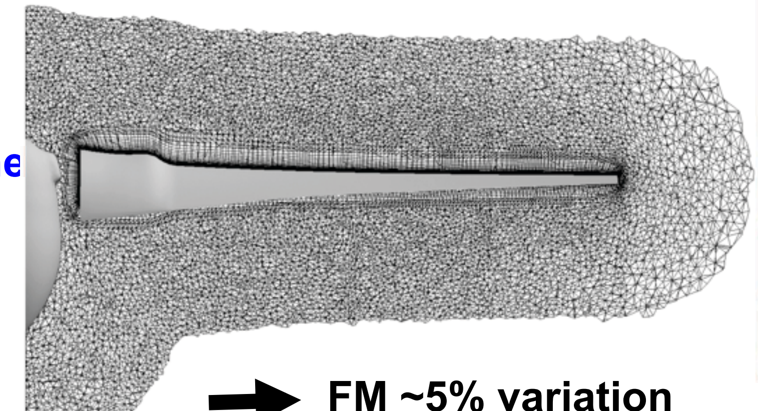
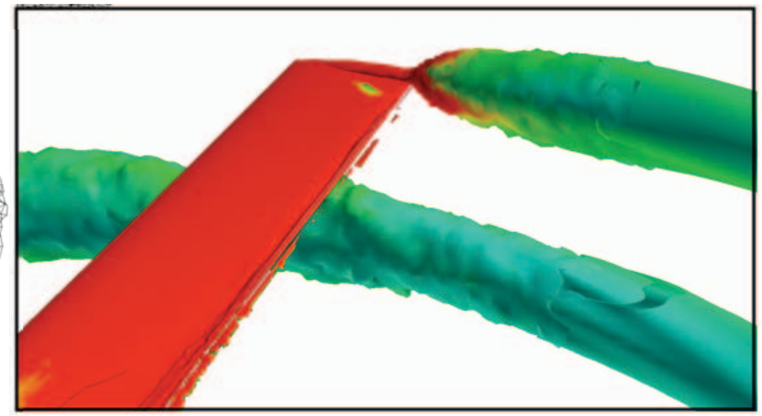
Near-body Refinement Important

Baseline
2.8M

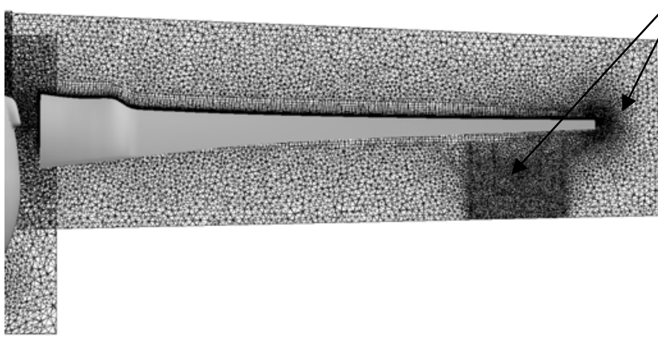


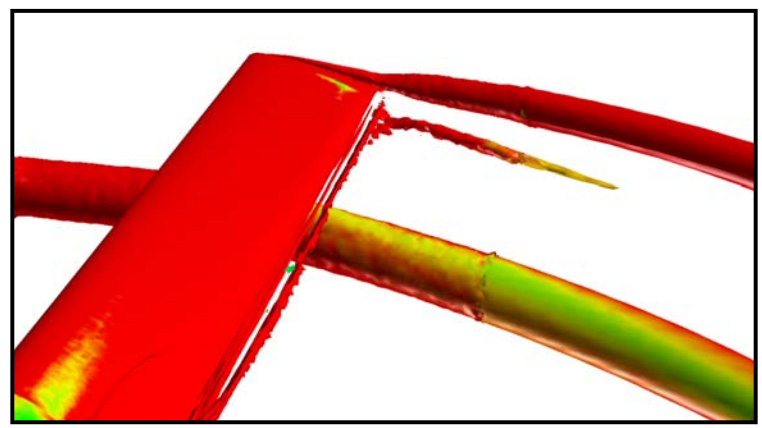


➡ **FM ~5% variation**

Refinement applied around tip and in the vicinity of first tip vortex

Refined
9.4M





➡ **FM ~1% variation**

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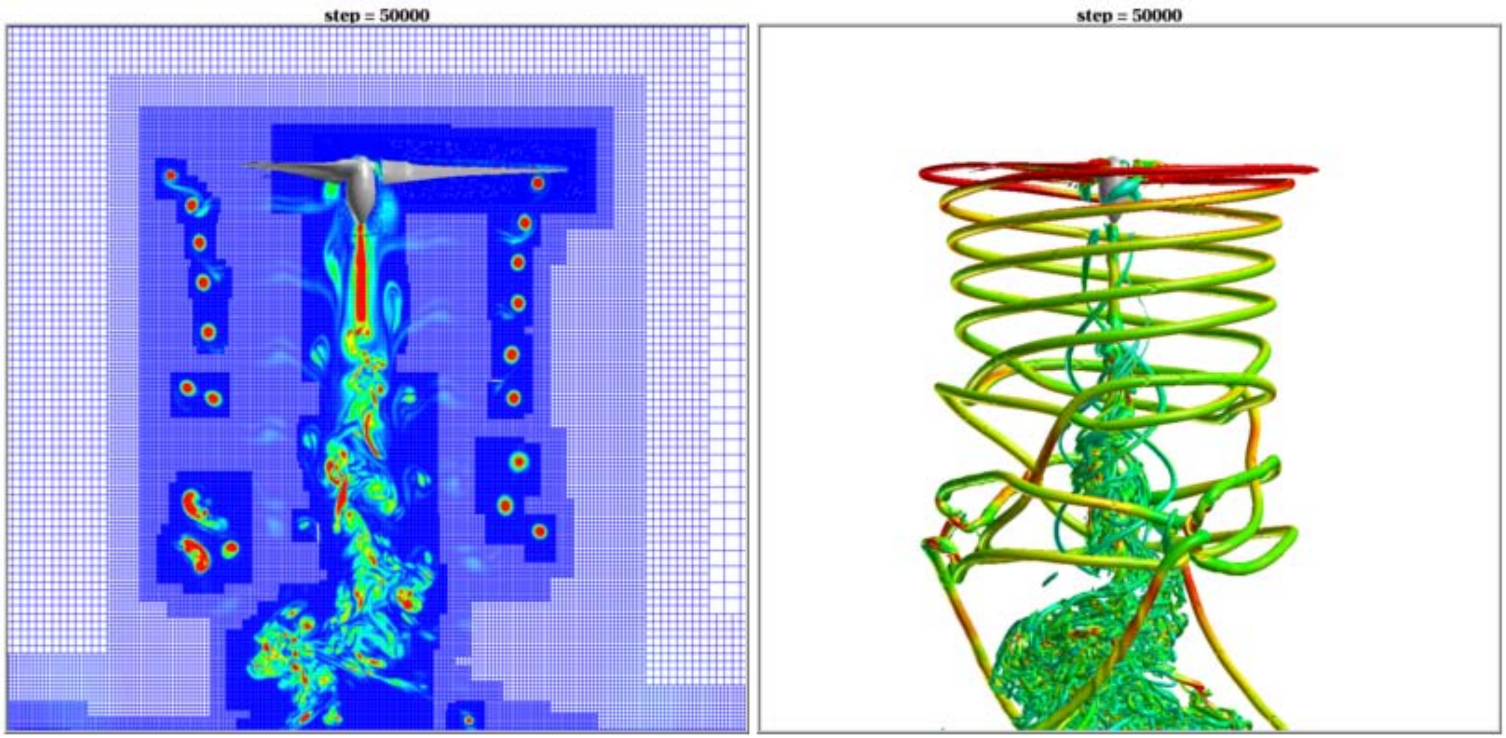
Results:
TRAM Refined



- **50,000 total steps**
- **Steady near-body/Time Accurate off-body**
- **Adapt every 100 steps**
- **128 core linux cluster**

	Time (hours)	# points
Near-body solver	18.23 **(43%)**	9.4M
Off-body solver	23.46 **(55%)**	110.2M
Adaptive overhead	1.02 **(2%)**	--
Total	**42.71 hours**	**119.6M**

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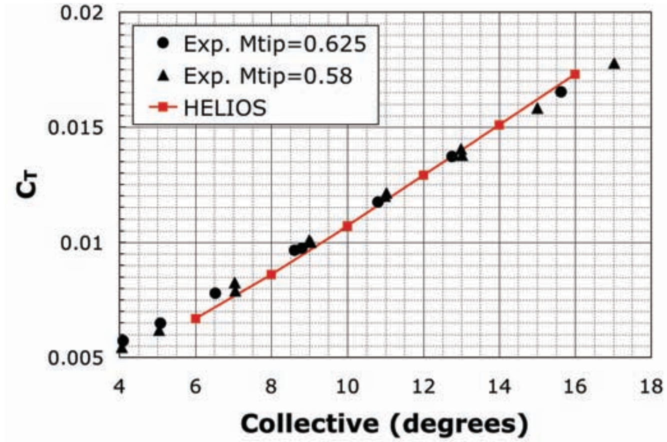
Results
TRAM Collective Sweep

Thrust vs. Collective



Power vs. Thrust^3/2

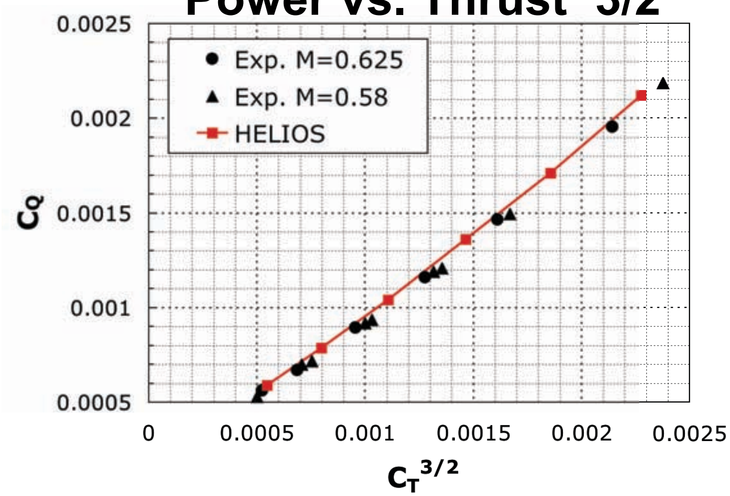
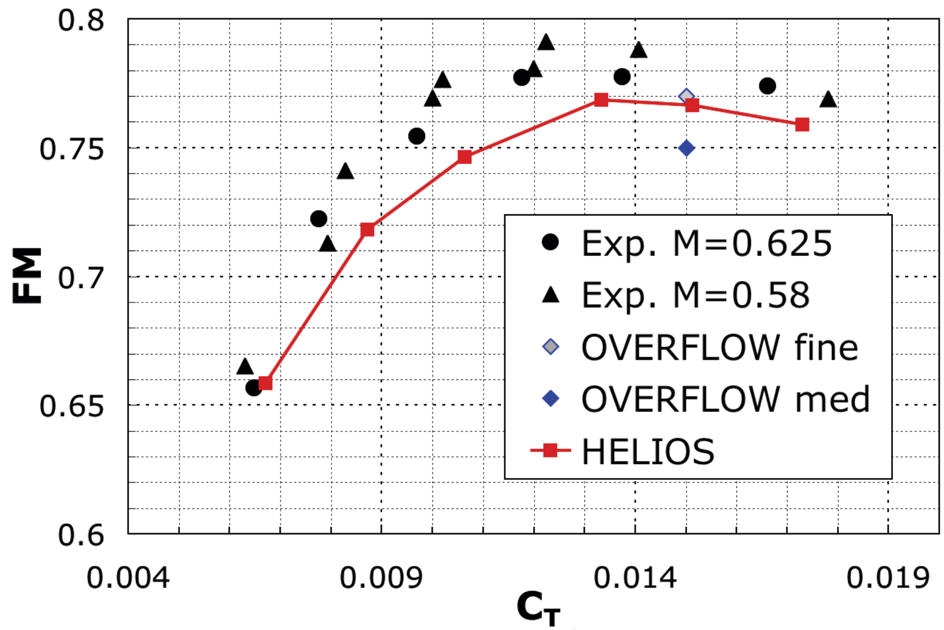


Figure of Merit vs. Thrust



- CQ over-predicted by 1-2%
- FM under-predicted by 2-3%

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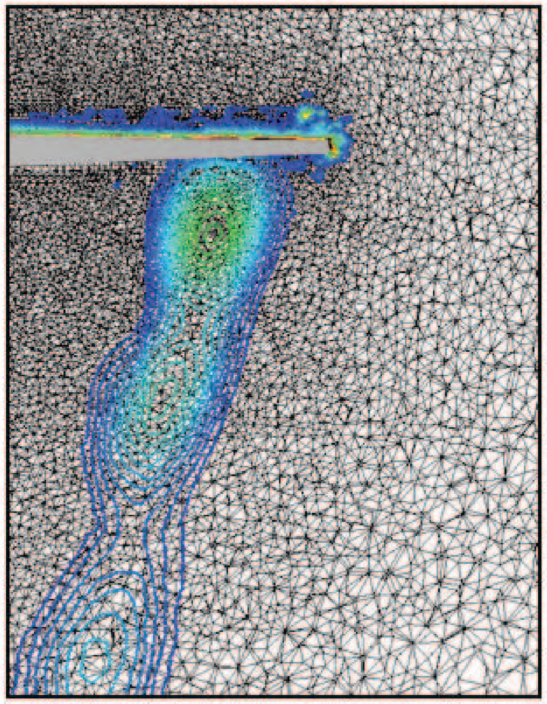
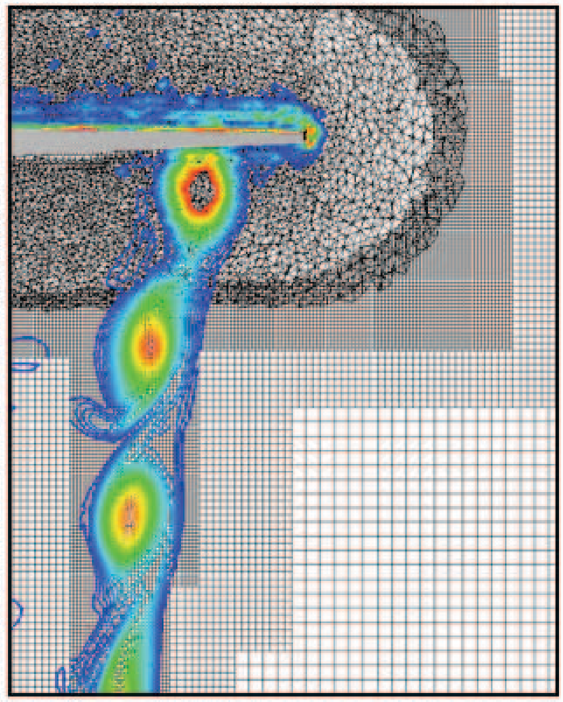
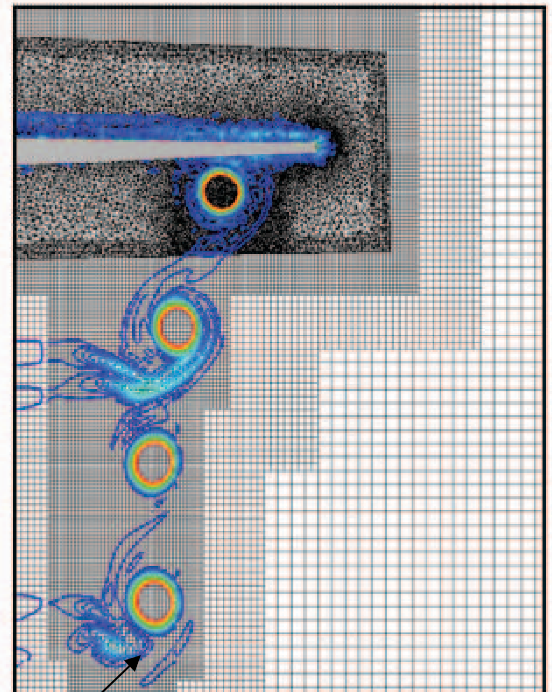
TRAM
Wake Summary



Standalone unstructured



Baseline dual mesh



Refined dual mesh

Computed CFD wake approaching observed…

further validation needed

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Helios Status & Plans

- **Helios 1.0 (Whitney) released Feb 2010 to selected beta testers in government and industry**
  - Army AFDD, AED, ARL
  - Navy NAVAIR
  - Bell Helicopter
  - Boeing Philadelphia, Mesa
  - Sikorsky/UTRC

- **Helios 2.0 (Shasta) scheduled release Jan 2011**
  - Off-body AMR with feature detection and error estimation
  - Rotor + fuselage
  - Generalized CSD interfaces – support both CAMRAD & RCAS

- **Helios 3.0 (Rainier) scheduled release Jan 2012**
  - Strand solver
  - Scalable dynamics and trim module

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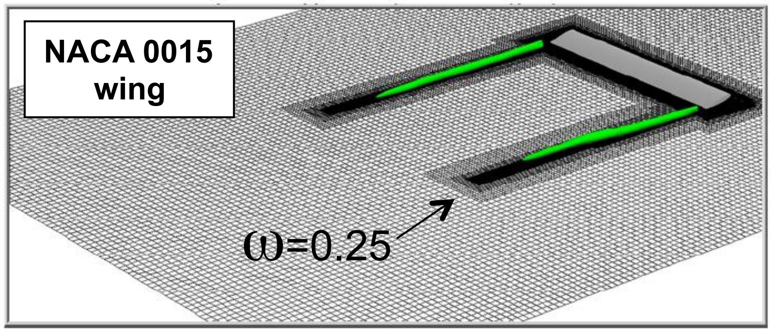
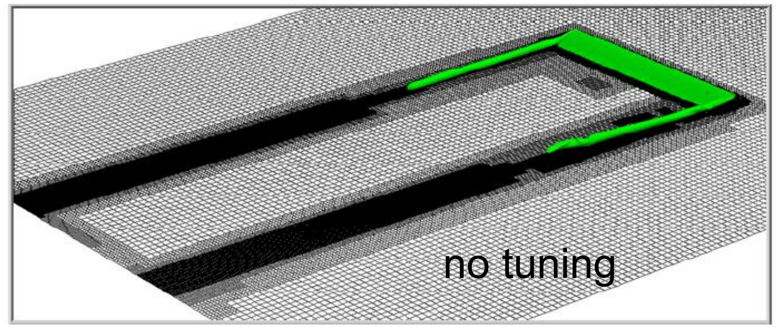
Automated Wake-based Refinement

v2.0 Capability

- **Non-dimensional feature detection algorithms**
  - Detects vortical flow regions without tuning
  - Finds features of differing magnitude

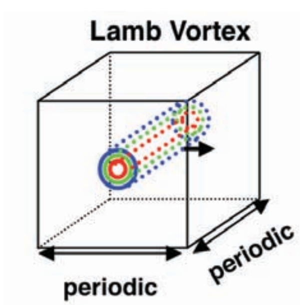


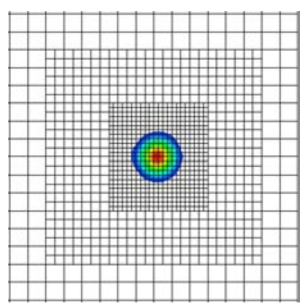
Refine to vorticity magnitude

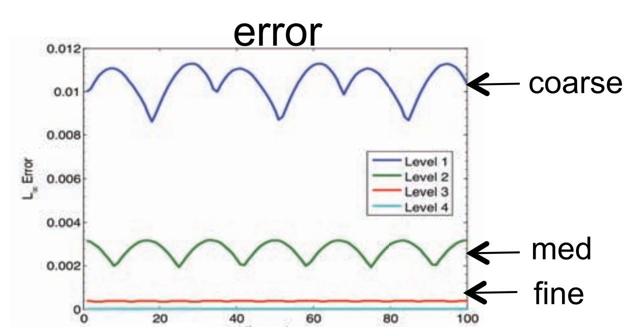


Non-dimensional algorithms

- **Error-based refinement termination**
  - Error computed between coarse/fine grid levels (Richardson extrapolation)
  - Refinement terminated when local error drops below threshold



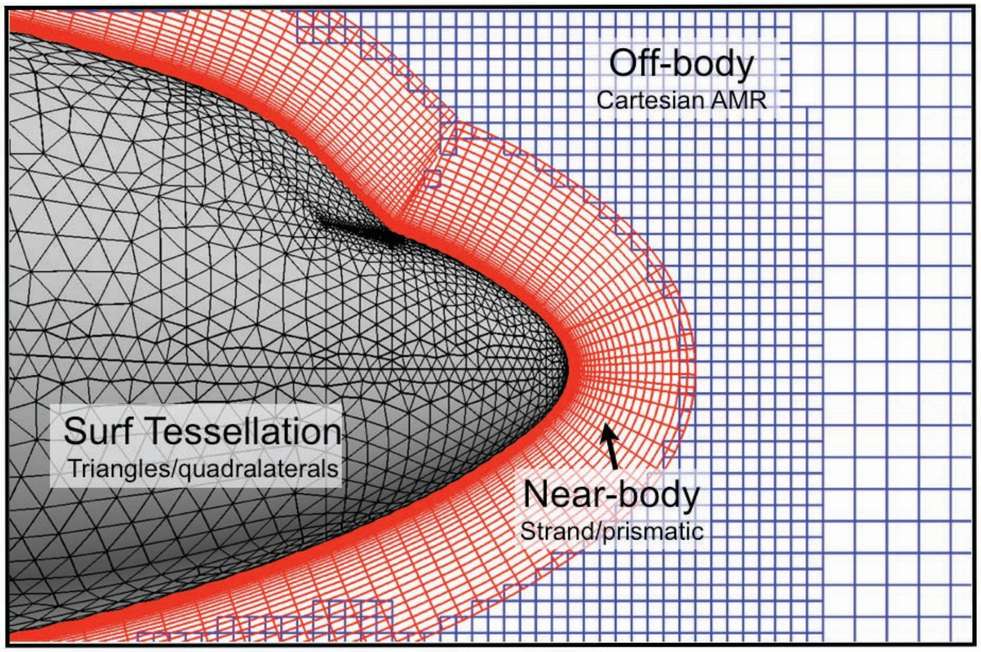




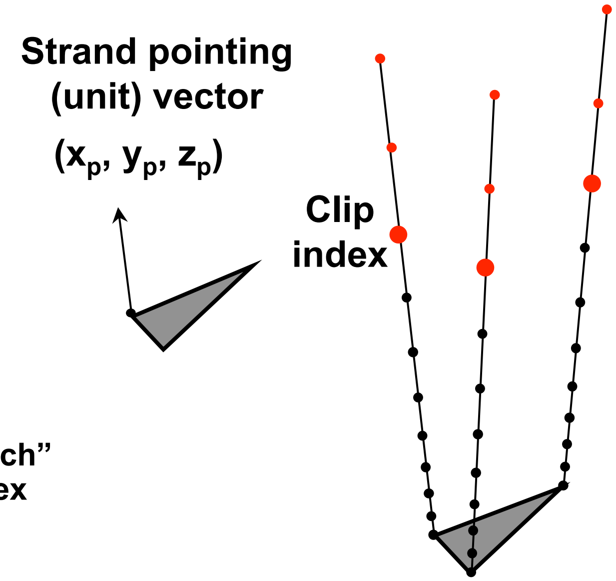
Kamkar

Near-body "Strand" solver

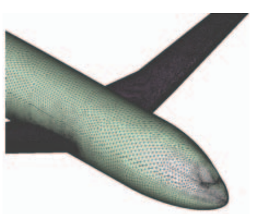
v3.0 Capability

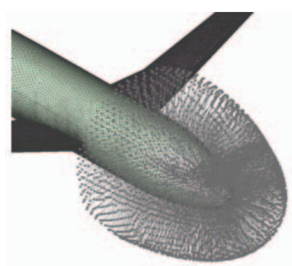


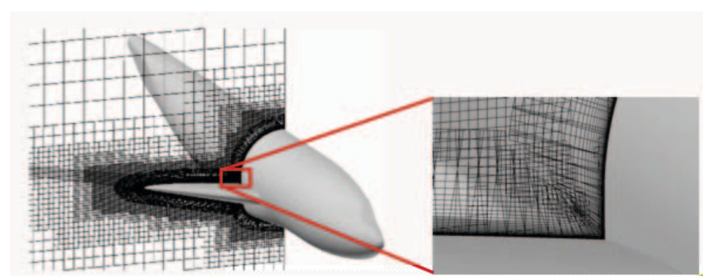
- Automatic volume grid generation from surface tessellation
- Fits well in Helios near-off body grid paradigm



Meakin et al - AIAA-2007-3834 "On Strand Grids for Complex Flows"
Wissink et al – AIAA-2009-3792 "Validation of the Strand Grid Approach"
Katz et al – AIAA-2010-4934 "Application of Strand Meshes to Complex Aerodynamic flowfields"





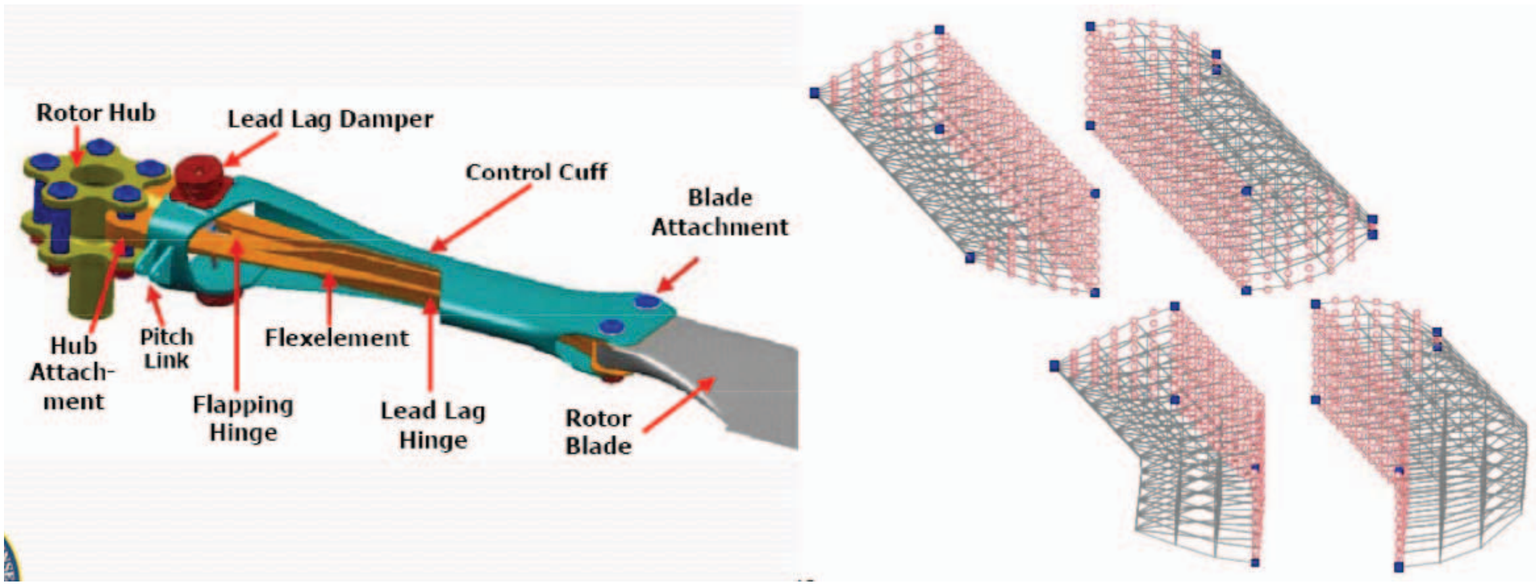


Katz

Parallel Dynamics & Trim

v3.0 Capability

- **Structural dynamics & trim conditions greatly impact accuracy in rotary-wing simulations**
- **Aerodynamics calculation much higher fidelity than structural dynamics**
  - Navier-Stokes CFD on parallel HPC computer systems
  - Beam-model CSD on single processor
- **Pursuing three-dimensional rotor dynamics modeling**
  - Scalable multi-body dynamics
  - Internal structural discretization and dynamics solution



Datta

Concluding Remarks

- **Dual-mesh overset approach in Helios appears effective and efficient for computation of aerodynamic loads and wake**
  - Loads (figure of merit) within 2% of experiment
  - Wake vortices maintained well downstream with little dissipation
  - AMR overhead ~2% total cost
  - High-fidelity simulations on “working class” HPC systems (128 processors or less)

- **Refinement needed for near-body, as well as off-body**

- **New capabilities currently under development by Helios team**
  - Automated wake refinement through feature detection/error estimation
  - Automated near-body grid generation through strands
  - Three-dimensional parallel structural dynamics & trim

Look forward to presenting results of these capabilities at the 2012 Overset Symposium!

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