Advanced Modeling & Simulation (AMS) Seminar Series

NASA Ames Research Center, March 8, 2016

Development and Validation of a Multi-Strand Solver for Complex Aerodynamic Flows

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TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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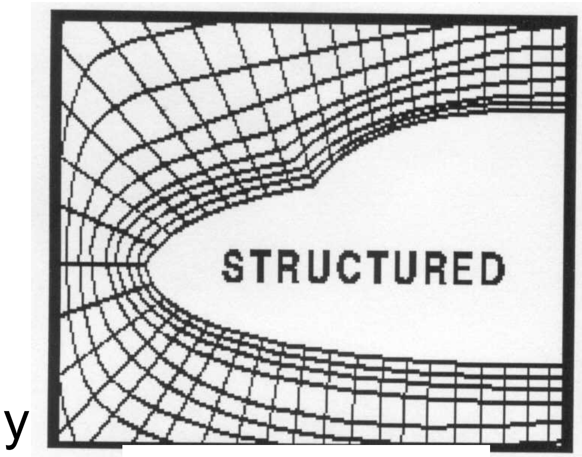
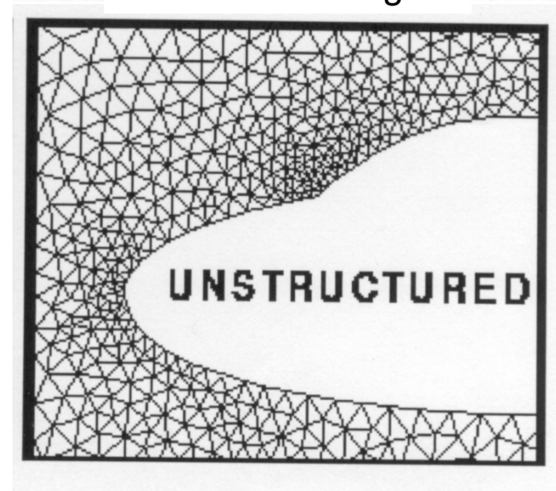
Flow Solver Framework

Structured Grid Framework

- Efficient flow computation
- Low memory requirements
- High accuracy and well-suited to resolve boundary layers
- Generating mesh for complex geometry is extremely challenging



Source: ntl.bts.gov



Unstructured Grid Framework

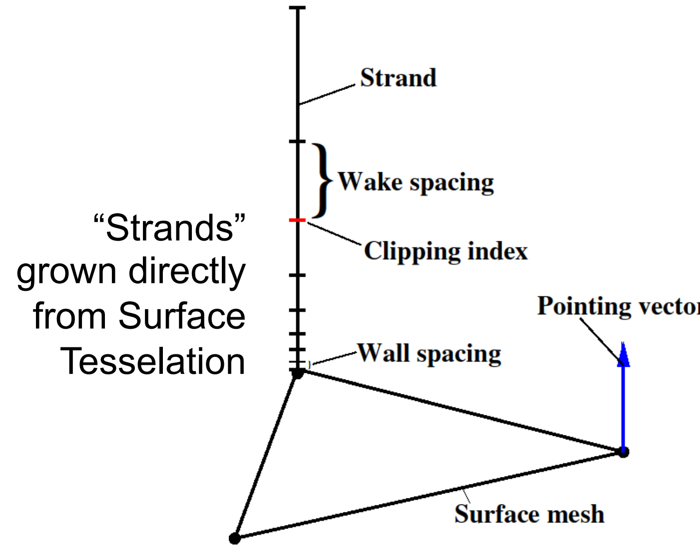
- Relatively easy to generate meshes
- High memory requirements
- Expensive flow computation
- Less accuracy

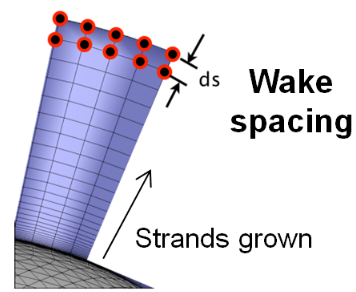
Need for Alternate Framework

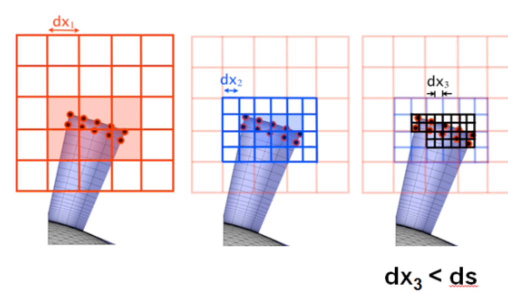
- Automated mesh generation
- Efficient

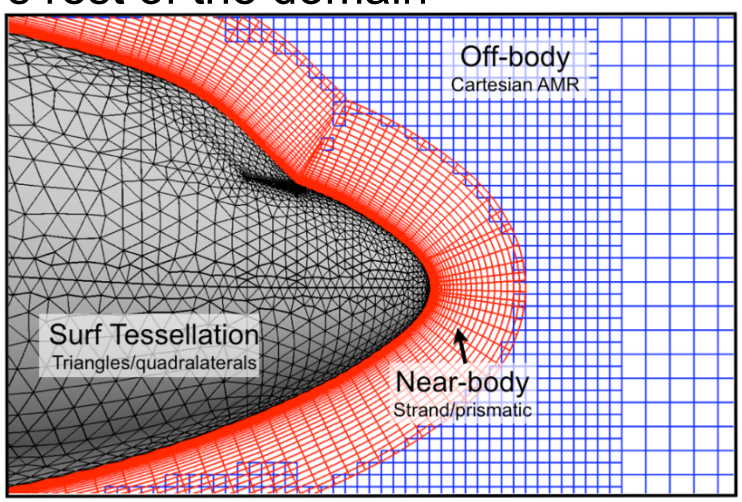
Strand Grid Framework

- **"Strand" near-body grid**
  - Parametric curves (Straight line segments) grown directly from surface tessellation
  - Extrudes a short distance
  - Transitions from viscous spacing at a specified wake spacing
  - Clipped with "Clipping Index"
- **Cartesian AMR off-body grid**
  - Covers rest of the domain









Strand Grid Framework

Advantages

- Nearly automatic viscous mesh generation
- Facilitate efficient flow solvers
- Strands represented with minimal information → Efficient and highly scalable domain connectivity, Sitaraman et al. 2012

Current status from earlier work

- Introduced by Meakin et al, 2007
- Approach validated, Wissink et al, 2009 – 2014 → Unstructured NB solver
- Strand mesh generation, Haimes, 2014 – 2016
- Strand solver, Katz et al, 2011 – 2016 → Development of high order solver

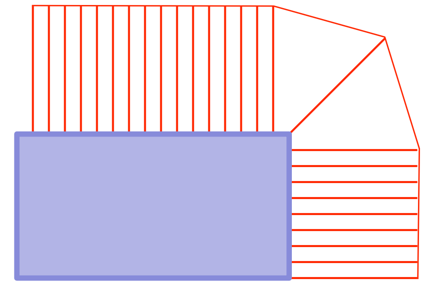
No robust strand solver to handle complex problems

Multi-Strand Approach

Convexity Problem

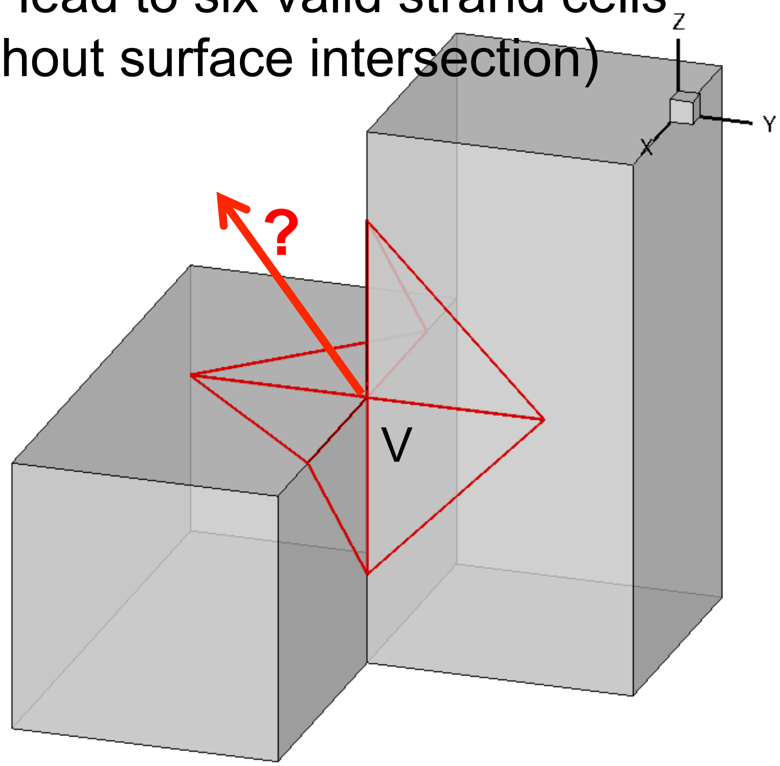
- Strands near convex edges do not provide sufficient resolution

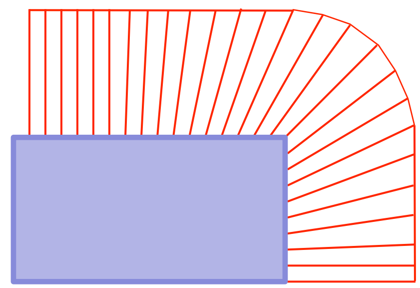
Strands near very convex edges are too large



Visibility Problem

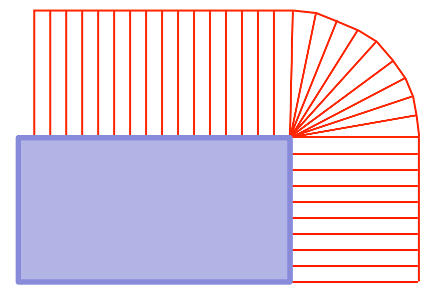
- No single direction from vertex V can lead to six valid strand cells (without surface intersection)





Smoothing

strands also smoothed where not required



Explicit identification of convex edges and generation of multi-strands

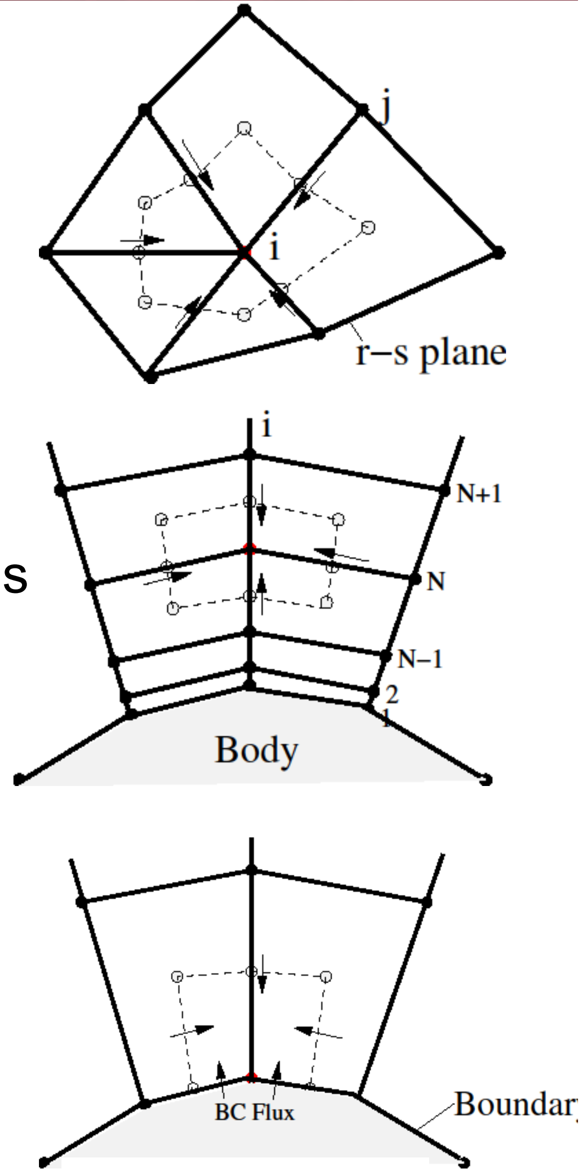
No multi-strand capable solver

Multi-strand solver (mStrand)

Developed from Nov 2014 -

Solver Features

- 2nd order vertex centered compressible FV solver
- Surface grid can be quads or/and triangles
- General prismatic mesh in normal direction
- Support for multi-strand
- MUSCL reconstruction + Riemann solver along strands as well as in the "r-s" plane → Spurious oscillation prevented using gradient-based limiters
- 2nd order full Navier-Stokes term → Gradients computed using Weighted Least-Squares or Green-Gauss method
- 1st order implementation of negative-SA turbulence model
- Boundary conditions implemented in weak form

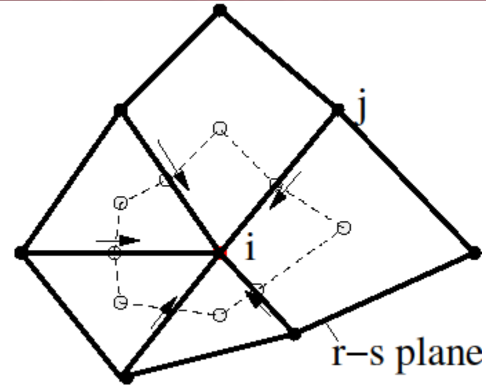


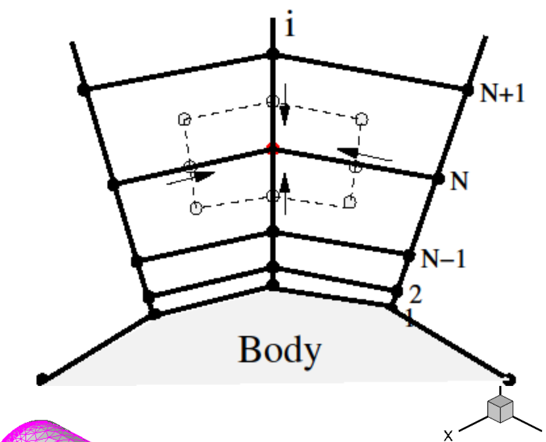
Median-dual CVs

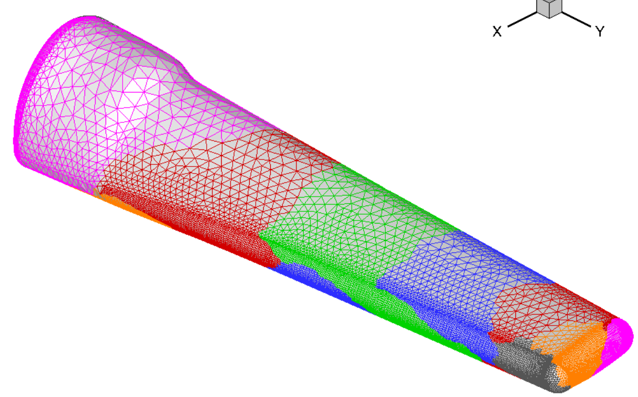
Multi-strand solver (mStrand)

Solver Features

- Preconditioned Jacobian-free GMRES
- Specialized preconditioner
  - Based on first-order Jacobian
  - Fully coupled between mean-flow & turbulence
  - Colored Gauss-Seidel in the “r-s” plane as preconditioner
  - Line-implicit solver in the strand direction
- Fully parallel → Mesh partitioned based on the surface grid using Metis
- Communications on color-basis, residuals are identical in any core-count



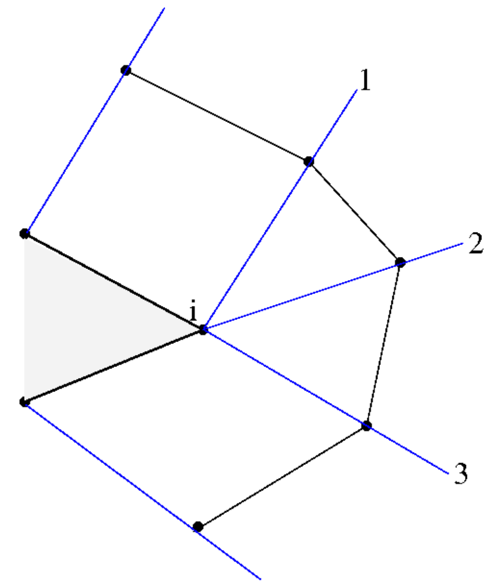




Treatment of Multi-Strands

Challenges with multi-strand

- Structure associated with strand direction is lost in the first layer → complex data structure, degradation in linear solver convergence
- Several volume types such as pyramids, tetrahedras and wedges need to be handled
- Possible stability issues



Solution → Duplicate the multi-strand nodes

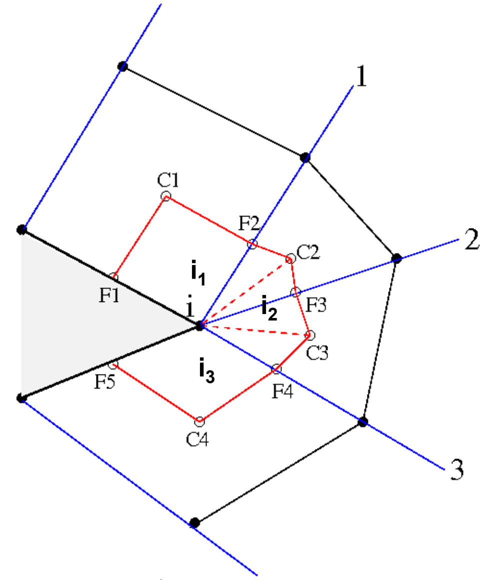
- Recovery of structure
- All volume types can be represented as degenerate prisms or hexahedras

Multi-strand node "i"

Duplicate multi-strand node "i" into i_1, i_2 and i_3

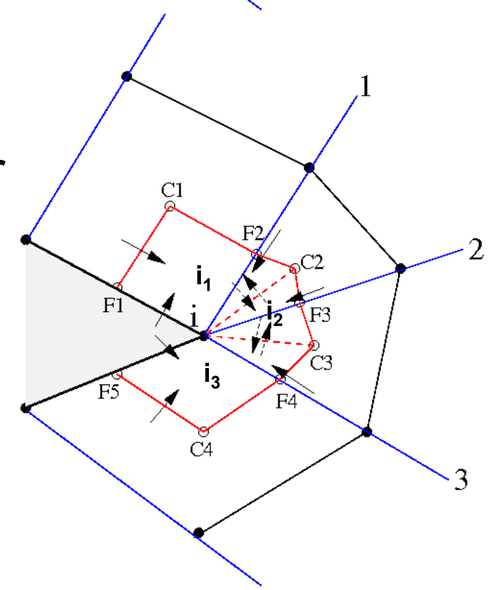
Treatment of Multi-Strands

- Consistent algorithm at node “i”
  - Volume of node “i” 1 2 3
  - Flux at node “i” 1 2 3
  - Gradients at node “i” summing appropriate quantities
- Duplicated nodes represent same physical space as “i”



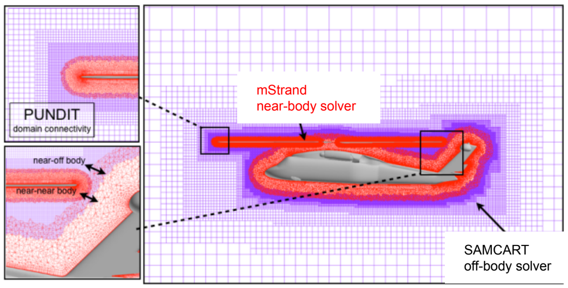
Implementation Strategy

- Assign one duplicated node as multi-strand group master
- Collect and distribute information at appropriate locations
- Preconditioner requires small modification
  - Details in SciTech paper



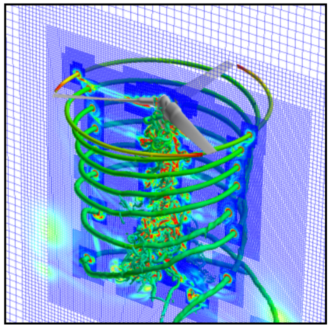
CREATE™ AV Helios Helicopter Overset Simulations

Dual Mesh Paradigm



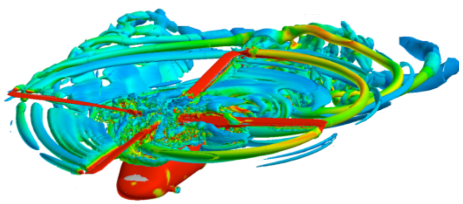
Near-body
Cartesian off-body

Adaptive Mesh Refinement



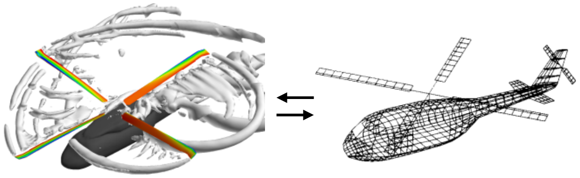
To resolve wake

Moving Body Overset



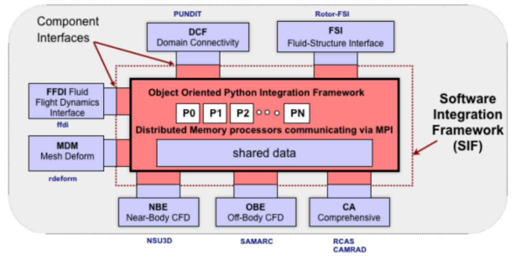
Rotor-Fuselage and Multi-rotor moving mesh support

CFD/CSD Coupling



RCAS and CAMRAD Structural Dynamics and Trim coupling

Advanced Software Infrastructure



Python-based infrastructure readily supports addition of new software

High Performance Computing

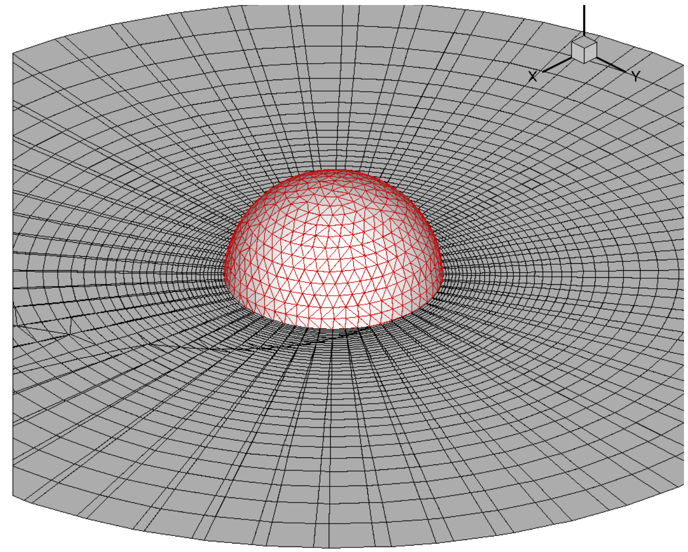
Runs on HPC hardware with focus on parallel scalability

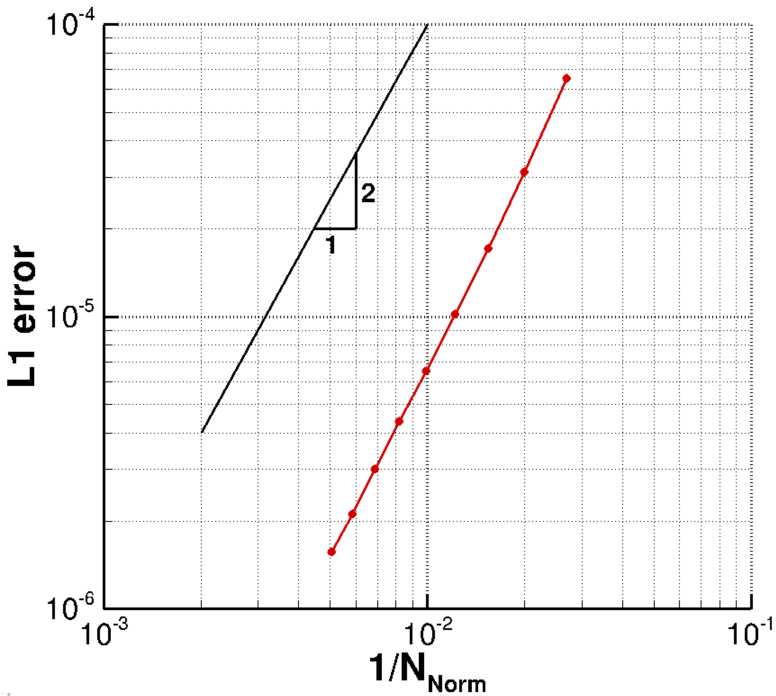
Supports high-fidelity rotary-wing simulation by government and industry
Developed & maintained by a team at Army AFDD.

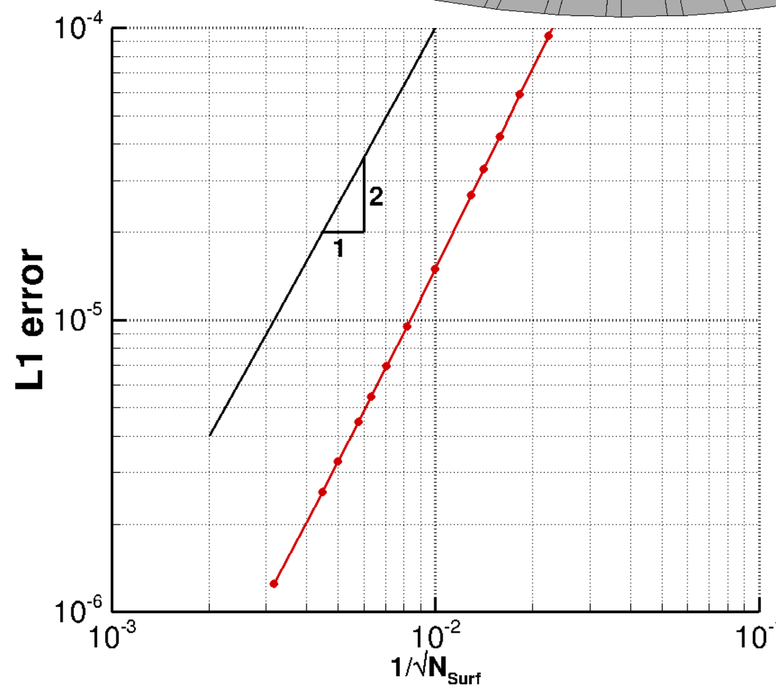
Accuracy Analysis

Method of Manufactured Solution (MMS)

- Accuracy analysis performed on spherical grids
- Independent surface and normal refinements
- Surface Refinements → 1000 to 100,000 nodes, 400 normal layers
- Normal Refinements → 36 to 200 layers, 200,000 surface nodes







Validation Cases

1. Turbulent flow past NACA0012 airfoil (standalone)
2. Transonic flow past Onera M6 wing (standalone and Helios)
3. Rotor wake validation with single bladed rotor in hover (Helios)
4. TRAM rotor in hover (Helios)

Meshes generated using mStrandGen
code developed by Beatrice Roget

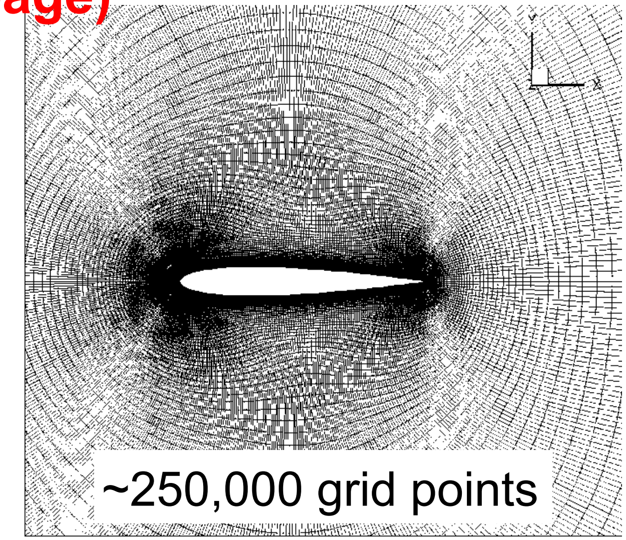
Turbulence Flow Past NACA0012 Airfoil

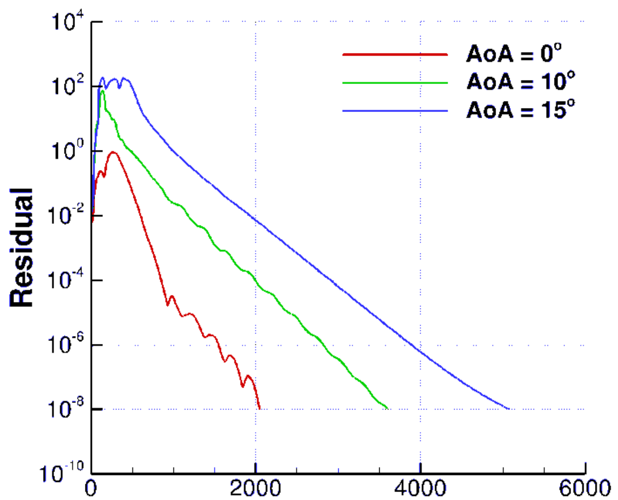
NACA0012 Airfoil (from NASA Turbulence webpage)

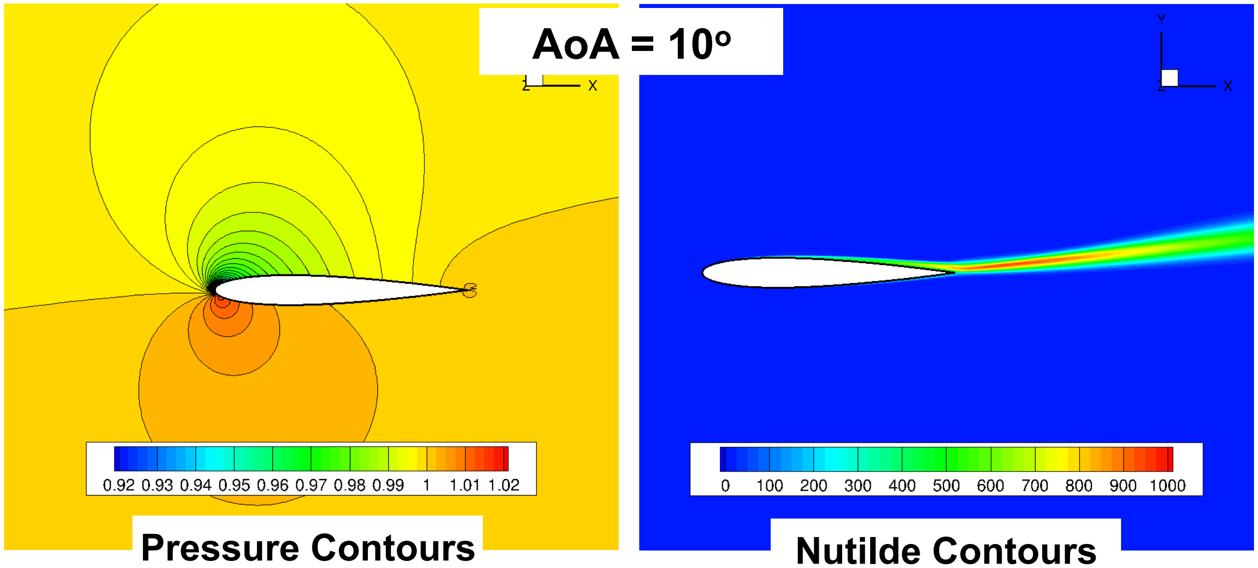
- Mach ➔ 0.15
- Reynolds number ➔ 6 million
- Angles of attack ➔ 0°, 10°, 15°

Grid

- O-mesh with 2-planes
- Not same as the grid provided at NASA webpage





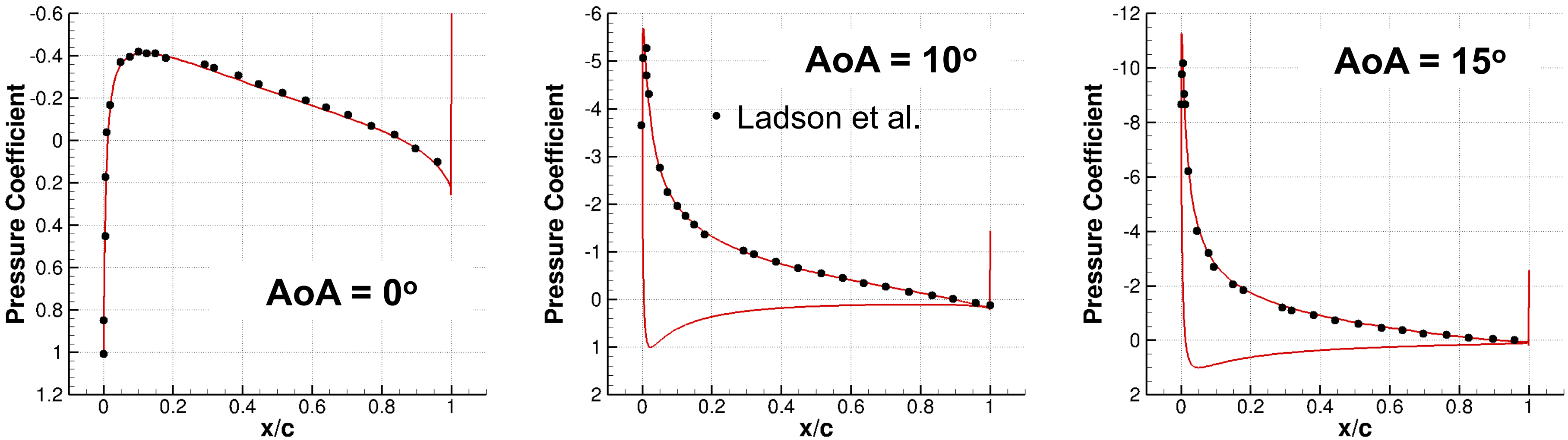


Pressure Contours

Nutilde Contours

Turbulence Flow Past NACA0012 Airfoil

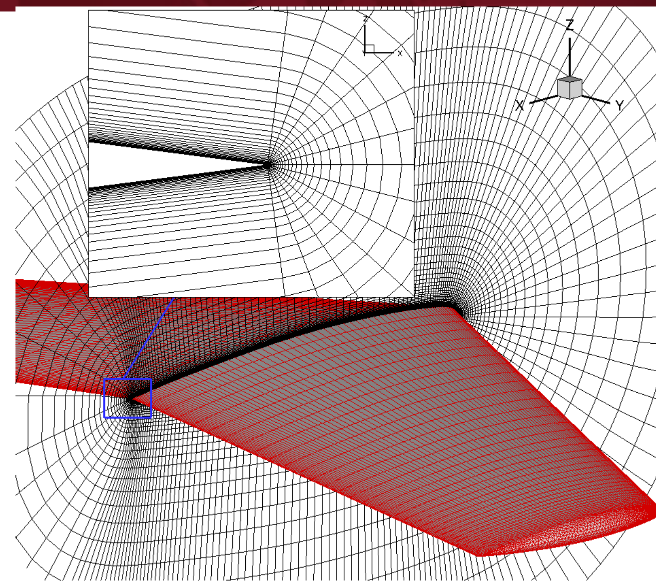
NACA0012 Airfoil (from NASA Turbulence webpage)



CODE	CL (AoA = 0°)	CL (AoA = 10°)	CL (AoA = 15°)	CD (AoA = 0°)	CD (AoA = 10°)	CD (AoA = 5°)
CFL3D	approx 0	1.0909	1.5461	0.00819	0.01231	0.02124
FUN3D	approx 0	1.0983	1.5547	0.00812	0.01242	0.02159
NTS	approx 0	1.0891	1.5461	0.00813	0.01243	0.02105
JOE	approx 0	1.0918	1.5490	0.00812	0.01245	0.02148
SUMB	approx 0	1.0904	1.5446	0.00813	0.01233	0.02141
TURNS	approx 0	1.1000	1.5642	0.00830	0.01230	0.02140
GGNS	approx 0	1.0941	1.5576	0.00817	0.01225	0.02073
mStrand	**approx 0**	**1.0967**	**1.5621**	**0.00804**	**0.01251**	**0.02195**

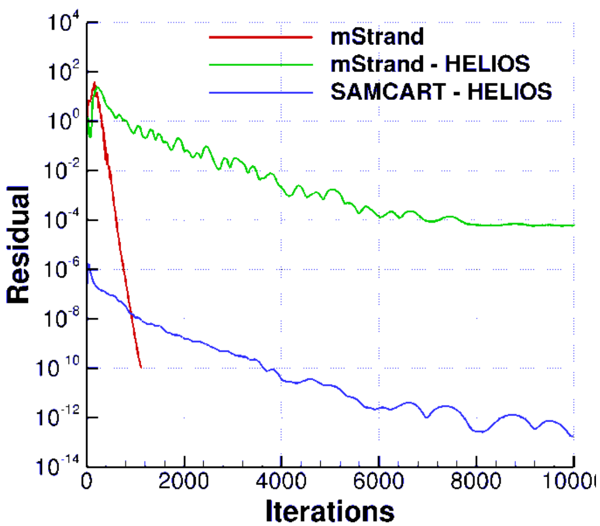
Onera M6 Wing Validation

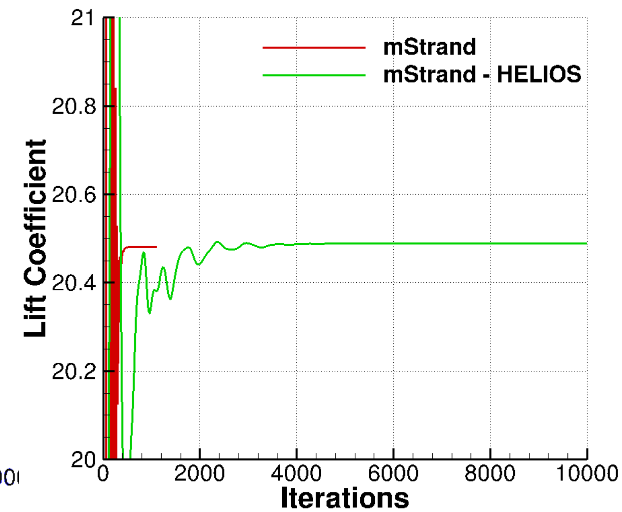
- Mach ➔ 0.8395
- Reynolds number ➔ 11.72 million
- Angles of attack ➔ 3.06º

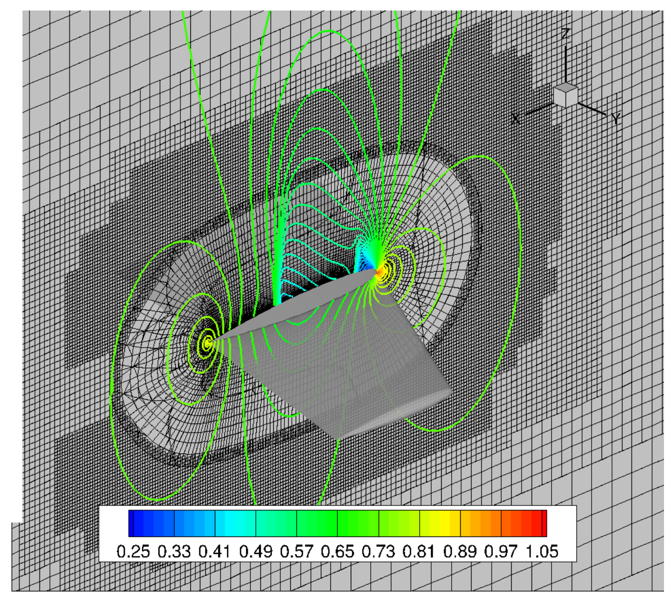


Grid

- Multi stranded mesh
- Two mesh systems:
  - Standalone → ~1.8 million grid points
  - Helios → ~1.3 million NB + 2.6 million OB

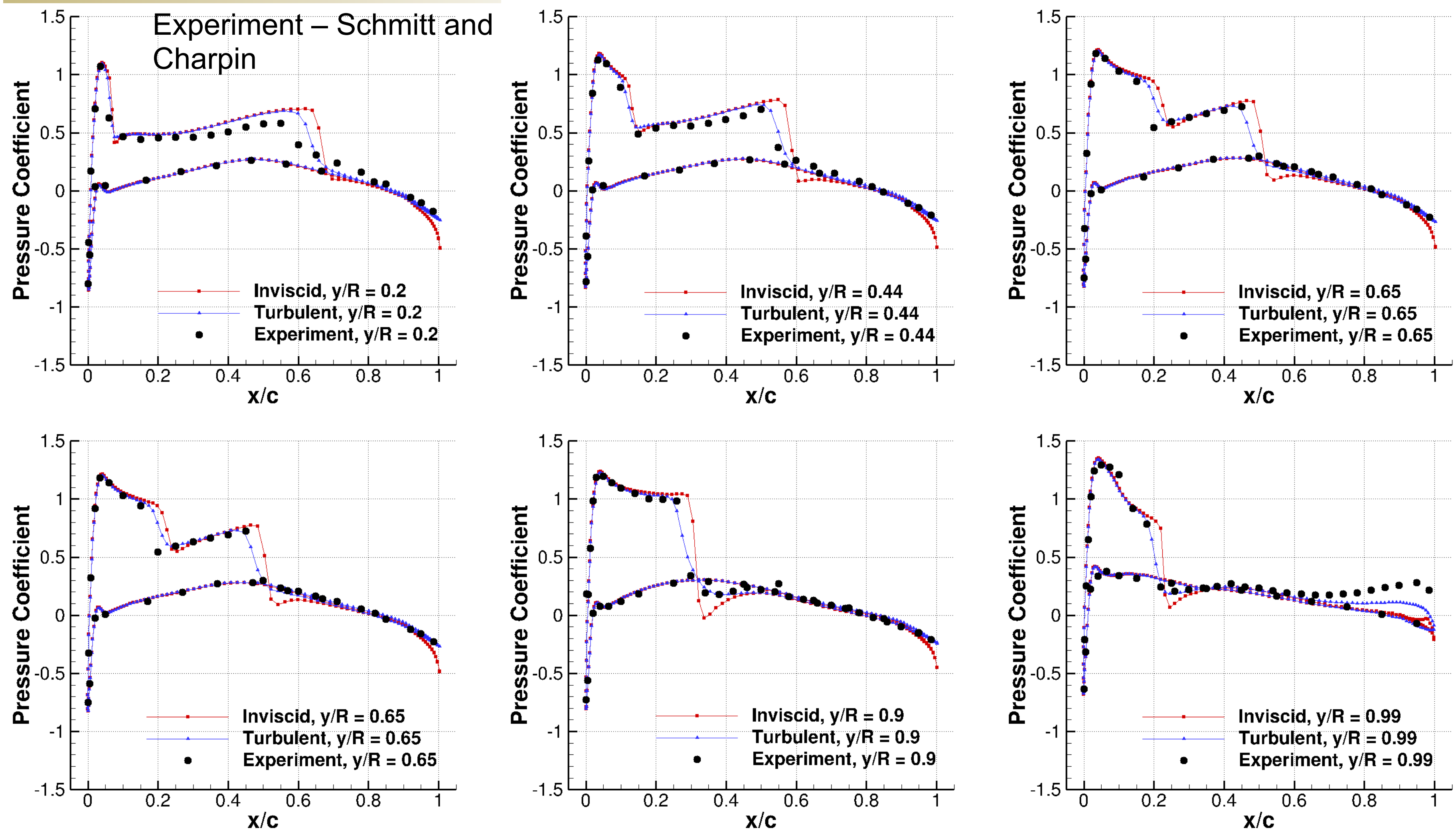






- Helios convergence typical for overset calculation for this problem

Onera M6 Wing Validation



- Excellent agreement with experiment
- Improvements with the use of turbulence model clearly evident

Hovering Rotor Wake Validation

One bladed rotor tested by Martin et al.

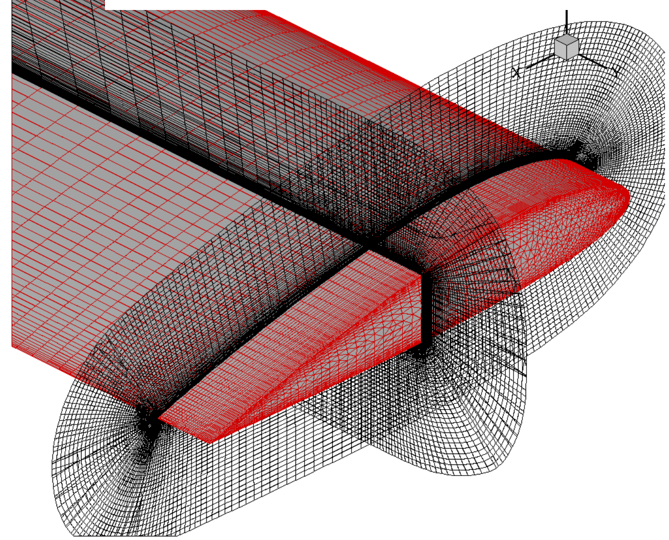
- Aspect ratio ➔ 9.12
- Tip Mach ➔ 0.26
- Tip Re number ➔ 272,000
- Collective ➔ 4.5°

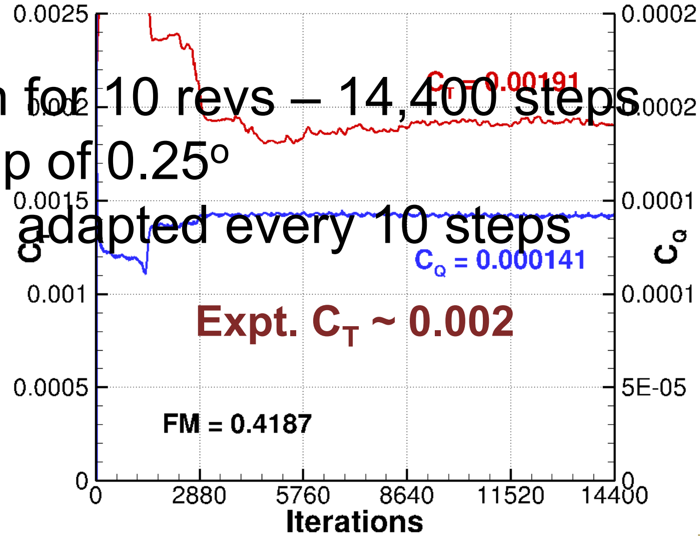
Grid

- Simulated in Helios framework
- Multi stranded mesh
- Quad + Tri surface mesh
- ~2.7 million NB (81 strand layers)

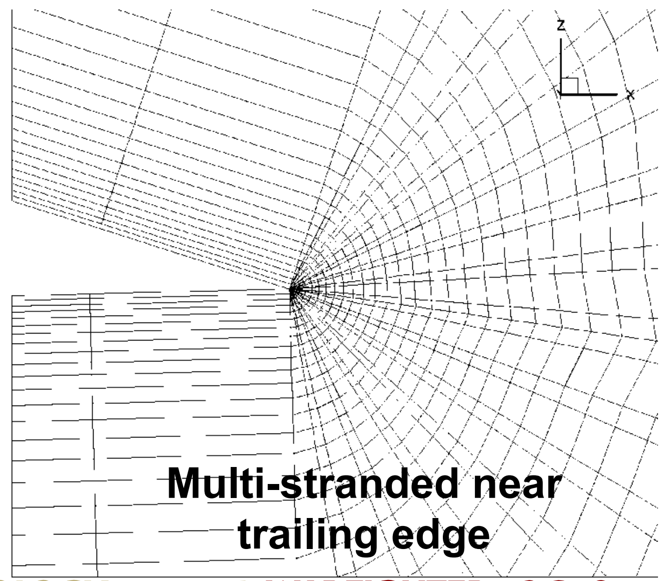
- Calculation run for 10 revs – 14,400 steps with a rotor step of 0.25°
- Off-body mesh adapted every 10 steps

Quad + Tri surface mesh





Convergence of thrust and power

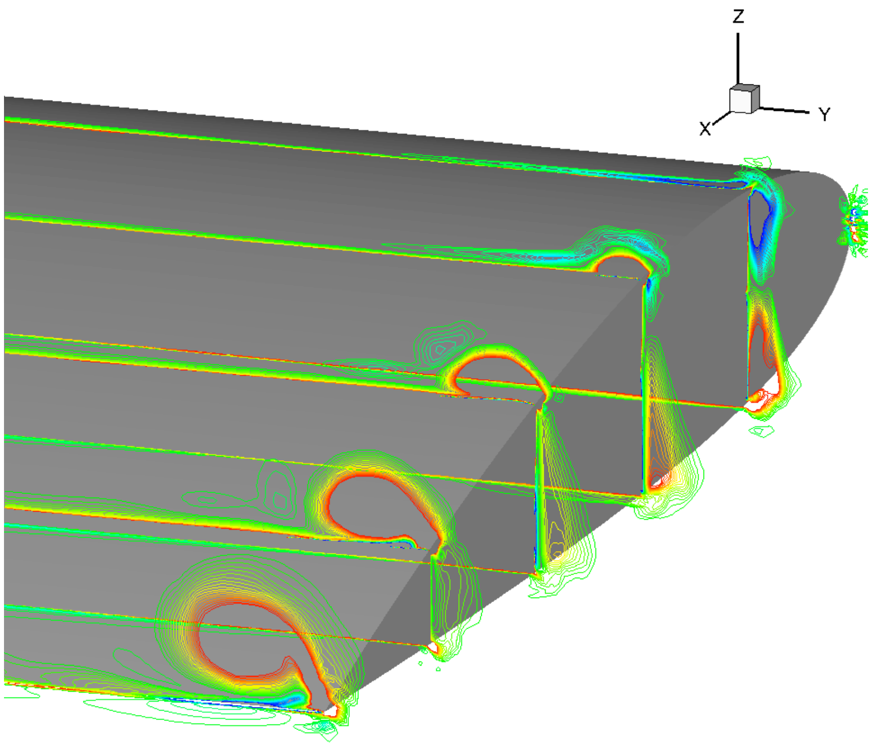


Multi-stranded near trailing edge

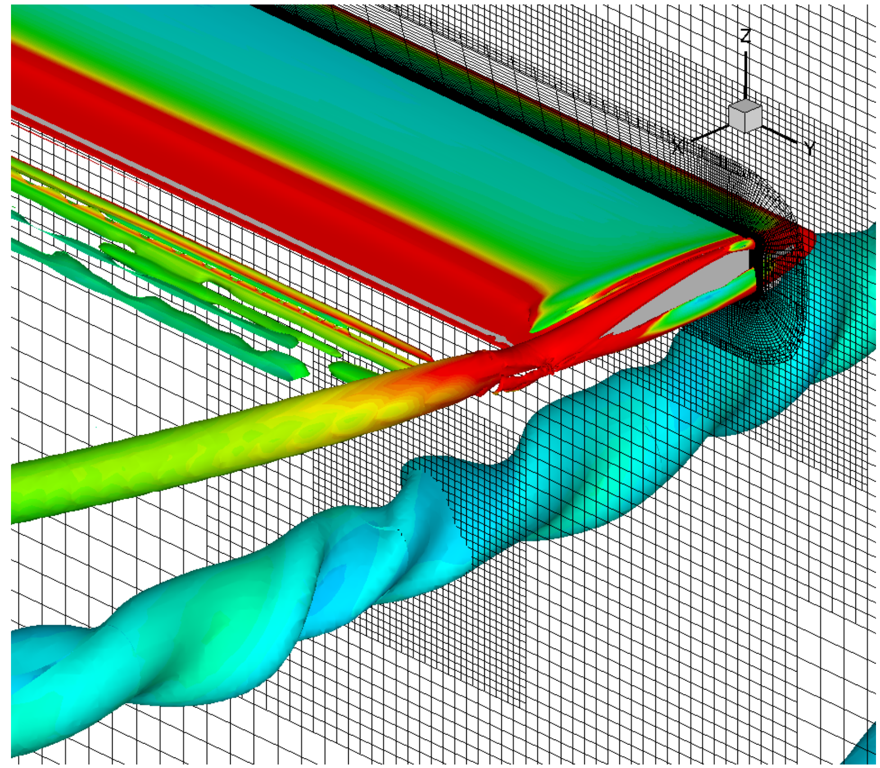
TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Hovering Rotor Wake Validation

One bladed rotor tested by Martin et al.



Voricity Magnitude



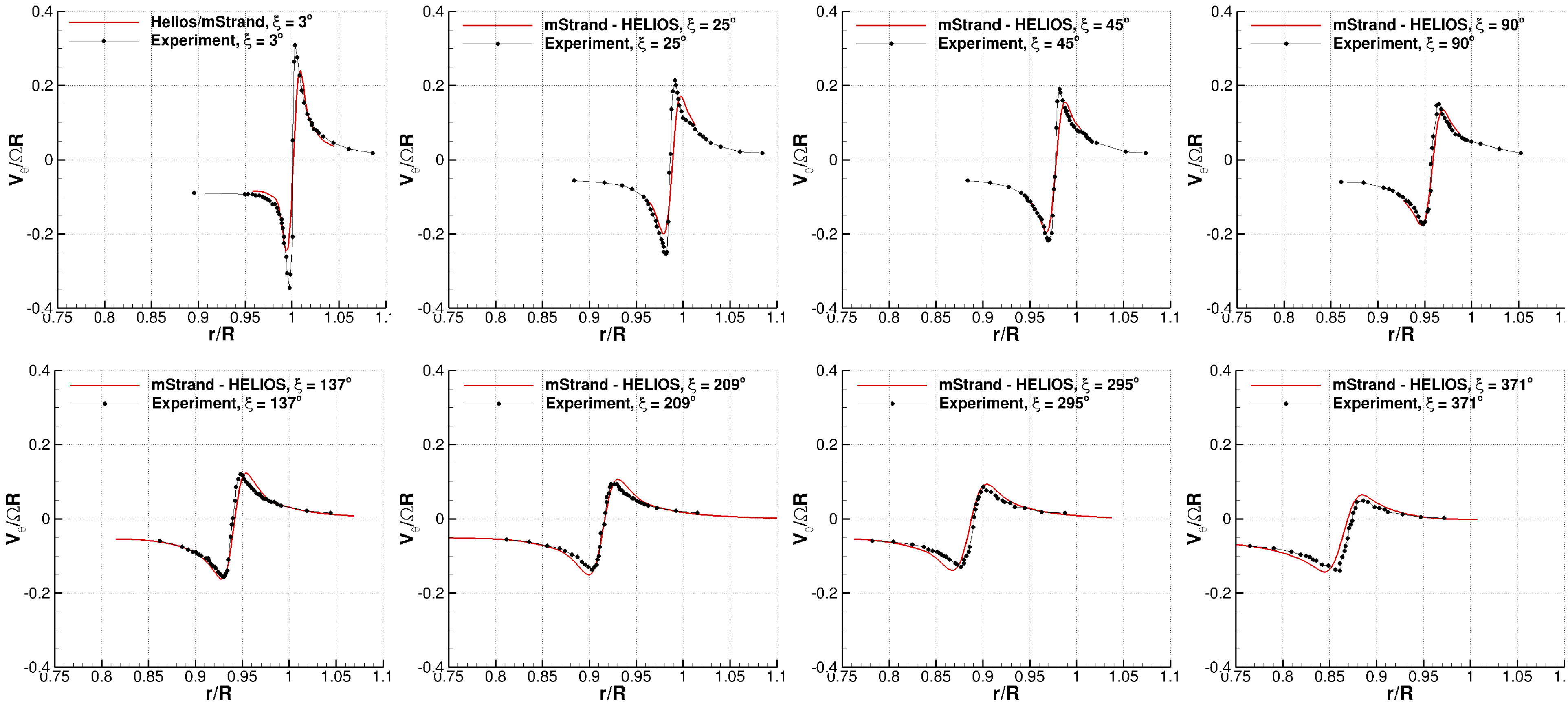
Iso-surface of Q-criterion colored by vorticity magnitude

- Formation of tip vortex very well resolved
- Vortex transferred smoothly from near-body to off-body mesh
- Prominent twisting of returning vortex

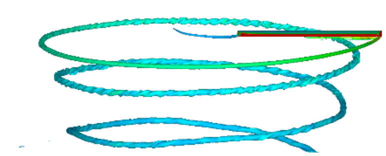
Hovering Rotor Wake Validation

One bladed rotor tested by Martin et al.

Swirl Velocity profile across the center of vortex



- Vortex strength preserved well for long time
- Wake contraction predicted accurately



Tram Rotor in Hover

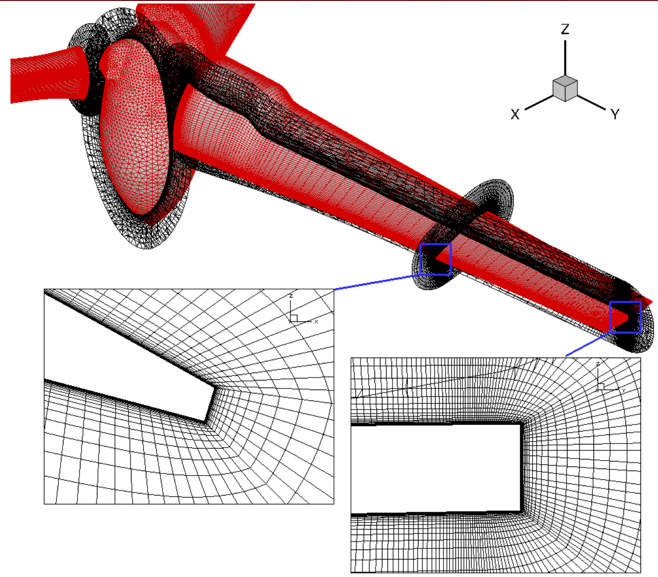
Test developed by NASA and U.S. Army

- Aspect ratio ➔ 10.36
- Tip Mach ➔ 0.62
- Tip Re number ➔ 2.1 million
- Collective ➔ 6º - 16º

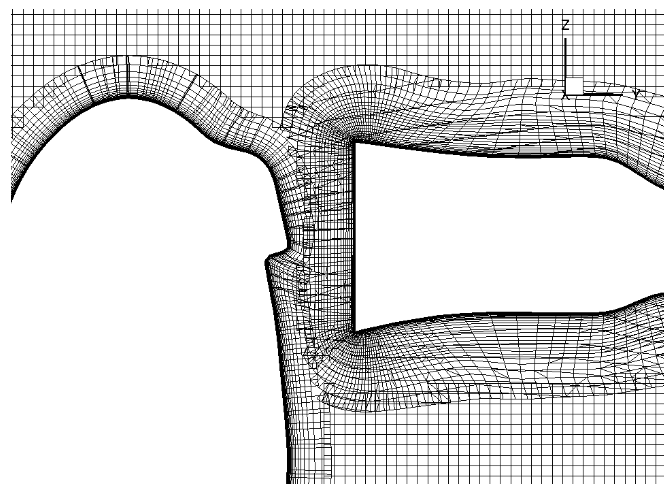
Grid

- Simulated in Helios framework
- Single stranded mesh
- Quad + Tri surface mesh
- Each body meshed separately
- ~6.7 million NB (51 strand layers)

- Calculations run for 8 revs – 11,520 steps with a rotor step of 0.25º.
- Off-body mesh adapted every 10 steps
- 2 days on 1024 procs

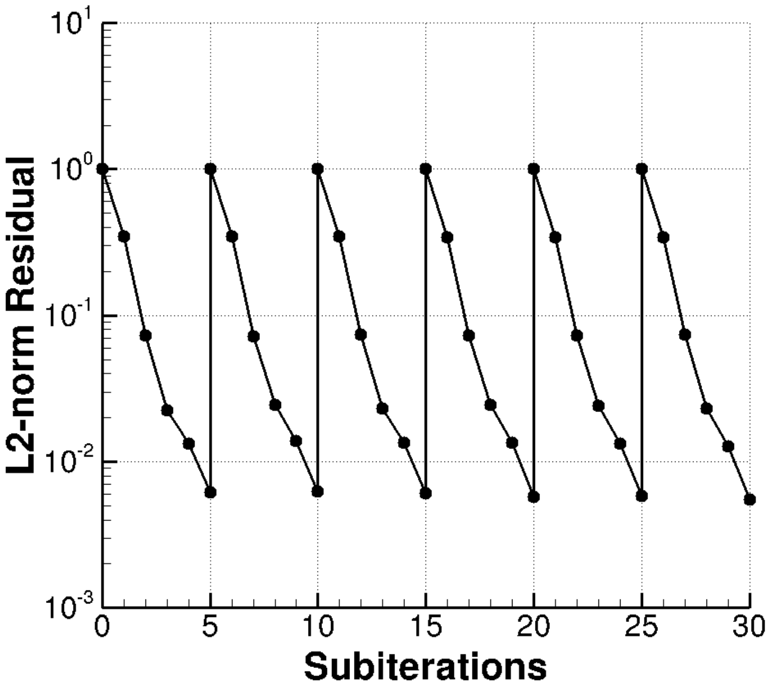


Quarter-scale V22

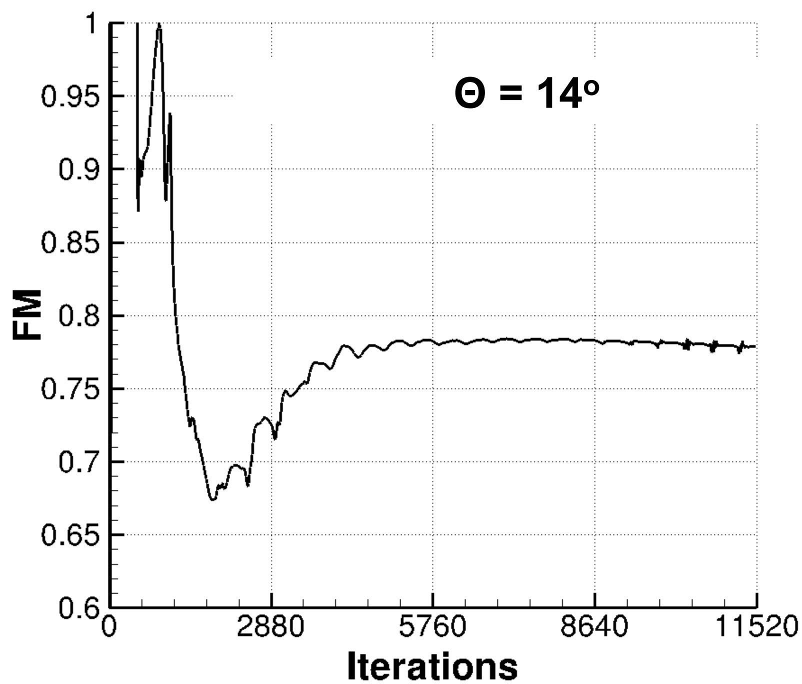


Interface between blade, hub and Cartesian mesh

Tram Rotor in Hover



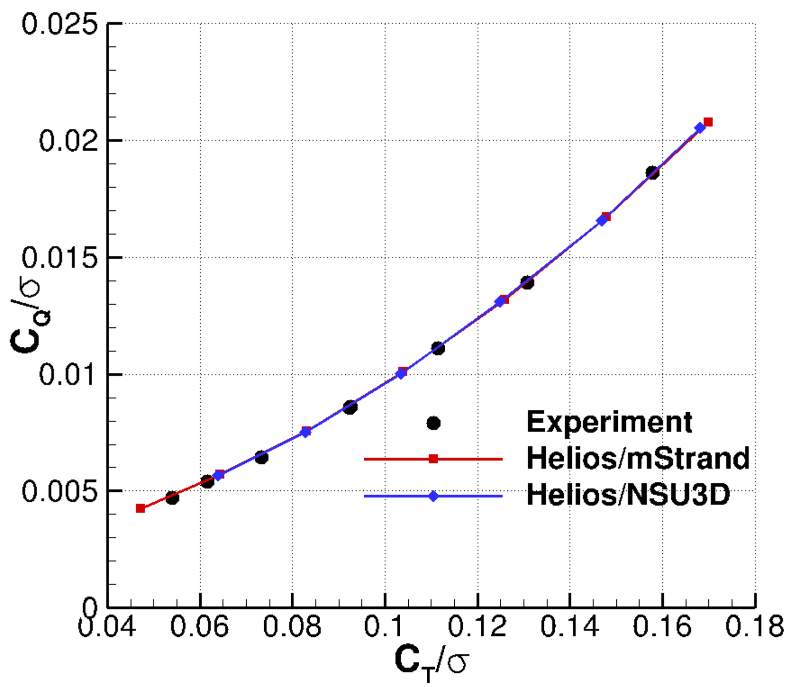
Subiteration Convergence



Force Convergence

- Two order convergence within 5 subiterations
- Forces converge fairly well in 5 - 6 revs (7200 – 8640 steps)

Tram Rotor in Hover



Power vs Thrust

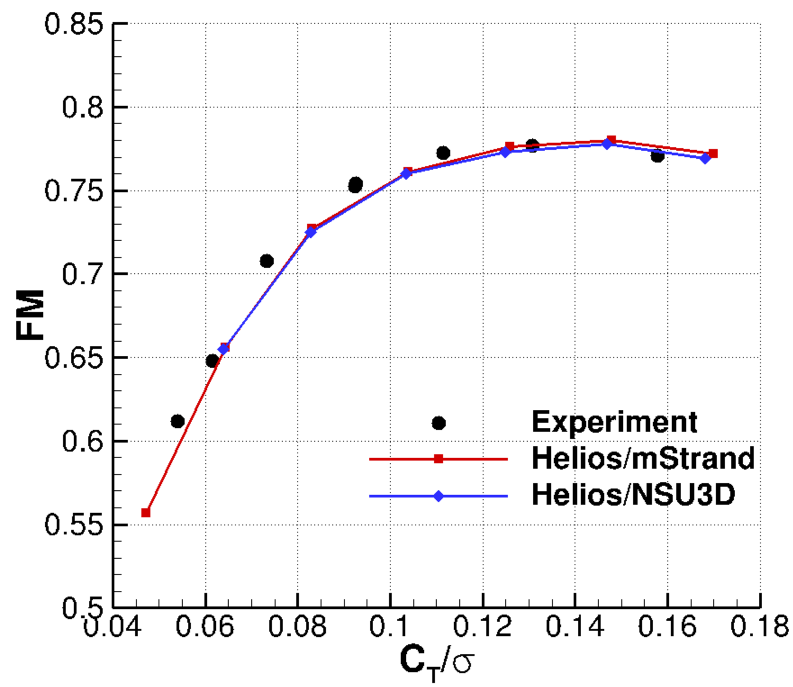
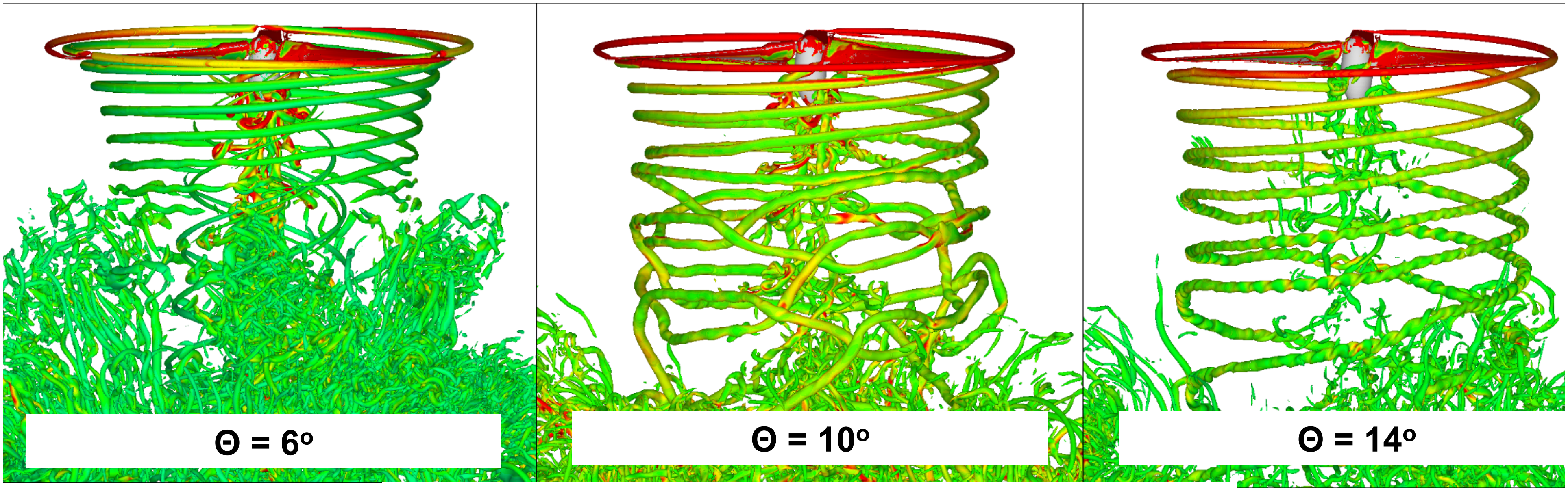


Figure of Merit vs Thrust

- Helios/NSU3D provides benchmark best available results from Helios
- Excellent performance prediction

RDECOM AMRDEC

Tram Rotor in Hover

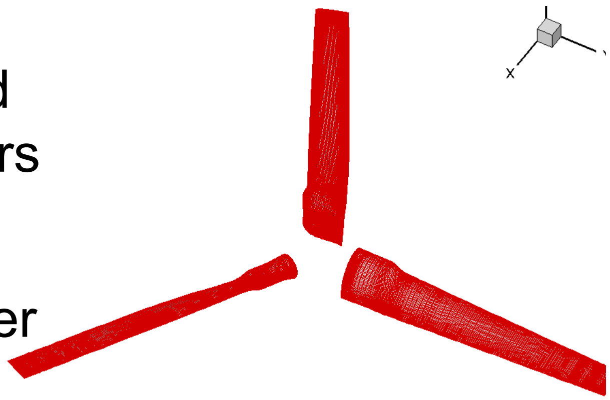


Iso-surface of q-criterion with vorticity magnitude

- Tip vortices very well resolved ➔ Vortex formation captured well
- Twisting of vortices evident
- Vortex interactions

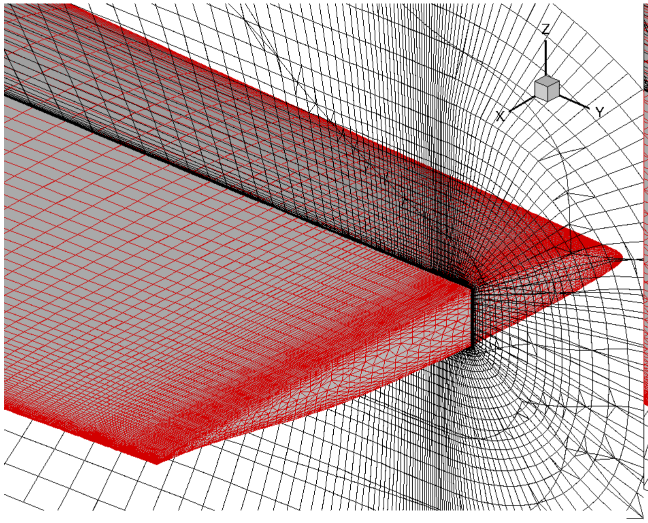
Code Performance

- Performance for TRAM blade simulation compared with established structured and unstructured solvers
- **OVERFLOW** – NASA structured grid solver
- **NSU3D** – Univ. of Wyoming unstructured grid solver

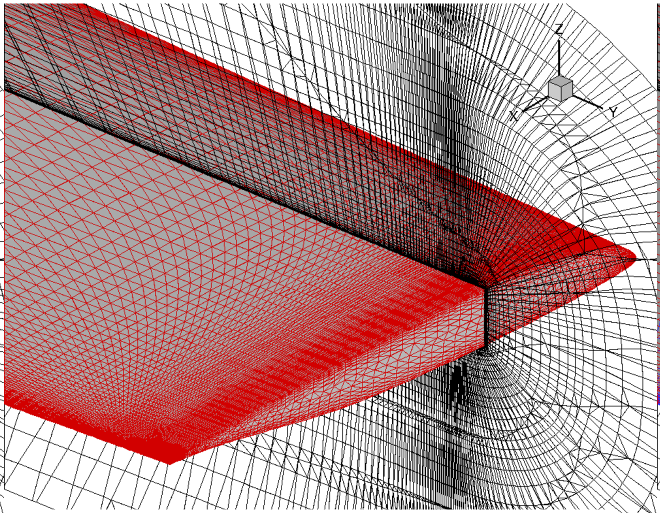


TRAM case without hub

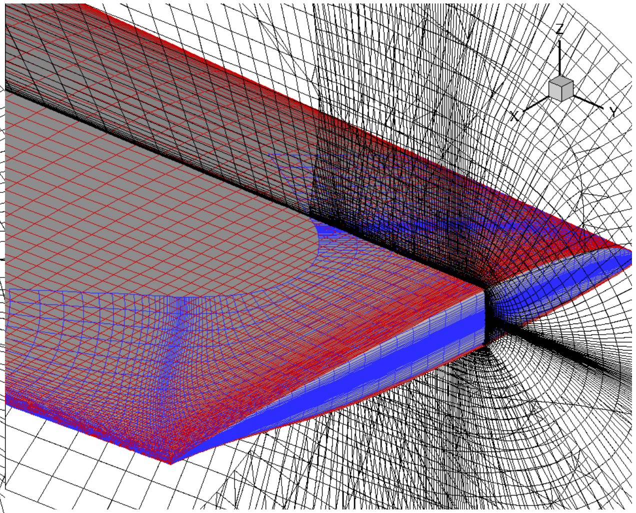
~6.4 million grid points



mStrand grid



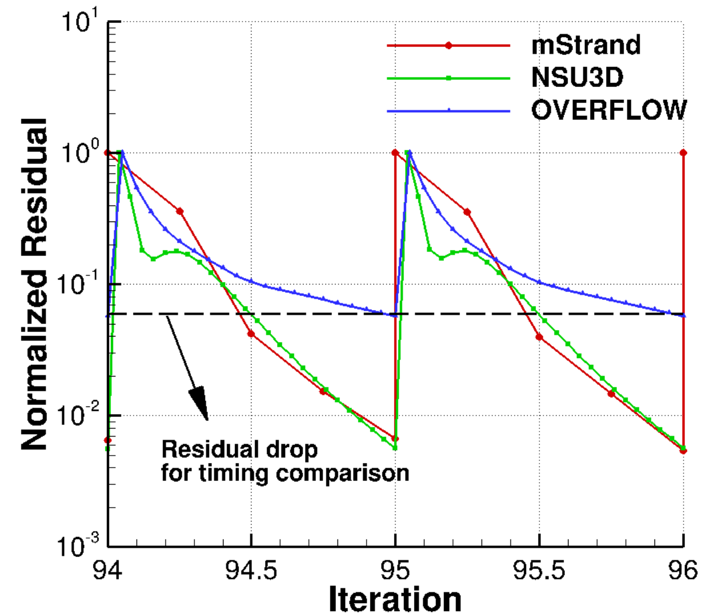
NSU3D grid

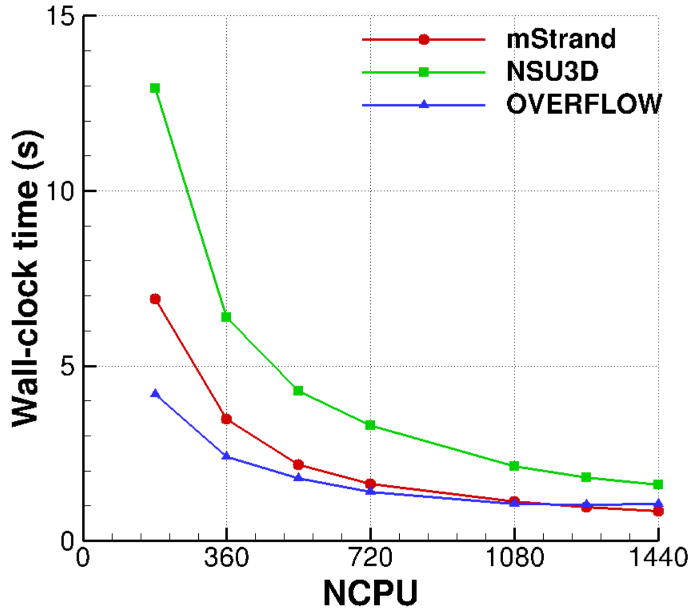


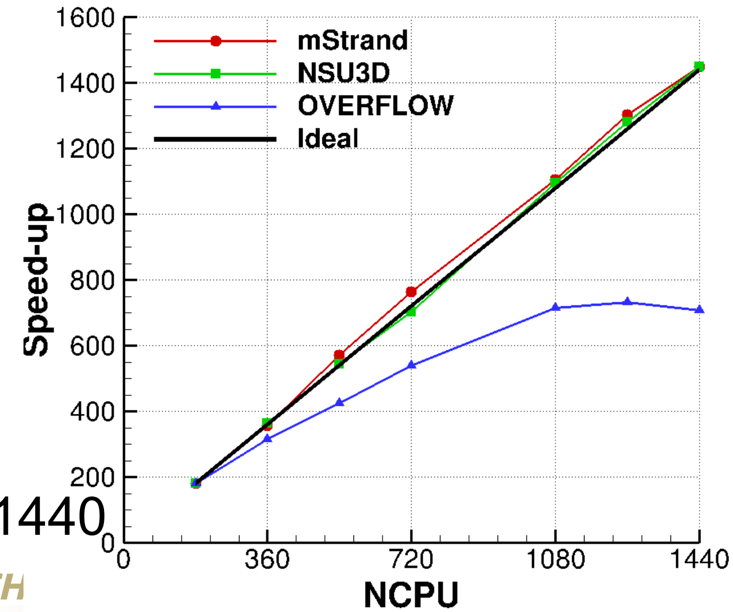
OVERFLOW grid

Code Performance

- **OVERFLOW** – Structured grid solver
- **NSU3D** – Unstructured grid solver
- Two orders sub-iteration convergence sought
- Set max number of sub-iterations
- Codes tested on different number of procs







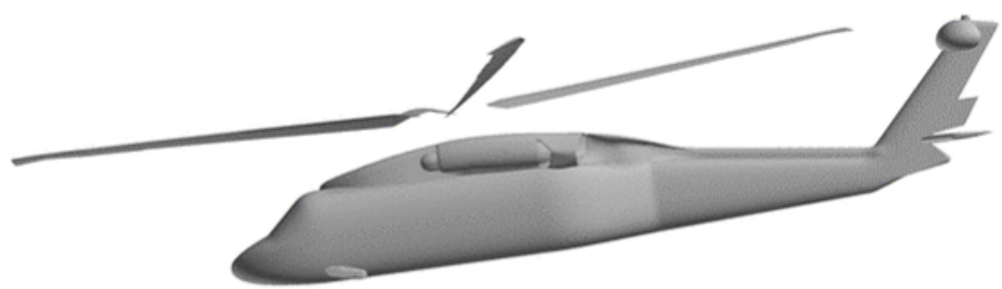
- mStrand → best turn-around time at NCPU = 1440

Concluding Remarks

- **mStrand** - fully parallel, highly efficient multi-strand solver
- Multiple strands handled robustly using simple and elegant approach
- Accuracy and stability of mStrand demonstrated for complex aerodynamic flows by coupling with Helios
- Strand technology is promising with the ability to automate mesh generation; at the same time provide good solver efficiency

Future Work

- High-order solver
- Address meshing challenges
- Simulate complete helicopter



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