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Application of 3D Strand Mesh Technology to Rotorcraft Hover

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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Outline

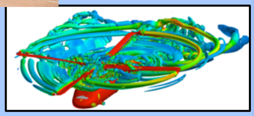
- Background and motivation
- Automatic dual mesh generation
  - Strand near-body
  - Cartesian off-body
- Results
- On-going work
  - Multi-strand meshes
  - High order strand solver
- Conclusions

Helios v5

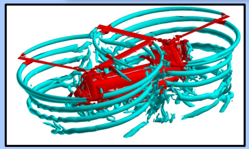
- **Helios is the rotary-wing product of the CREATE™ AV program**
  - **Multi-mesh paradigm**
    - Unstructured and/or structured curvilinear near-body
    - High order Cartesian off-body
    - Adaptive mesh refinement
  - **Fast overset connectivity (PUNDIT)**
  - **Interfaces to RCAS & CAMRAD comprehensive analysis codes**

- **Capabilities recently added**
  - **High-order structured solver (OVERFLOW) for blades to enhance speed and accuracy**
  - **Multi-rotor CFD/CSD support**
  - **CREATE A/V common software infrastructure**

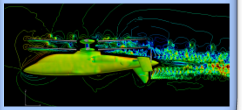
Helios
Version 5
"Haleakala"



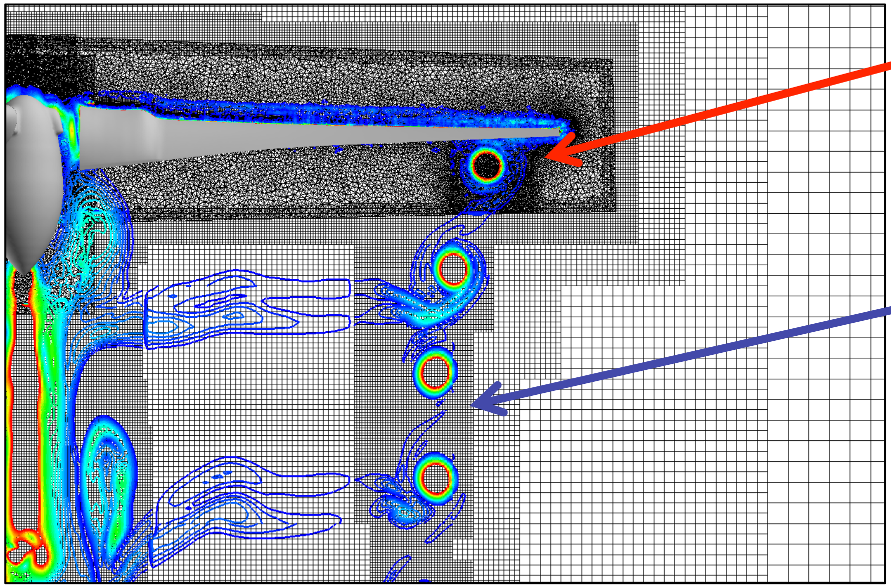
Capabilities
- CFD/CSD coupling
- Full vehicle – rotors & fuselage
- Multiple rotors
- Free flight trim



Key Technologies
- Multi-mesh paradigm
- Adaptive mesh refinement
- High order Cartesian solver
- Python-based common software infrastructure
- Generalized interface to comprehensive codes



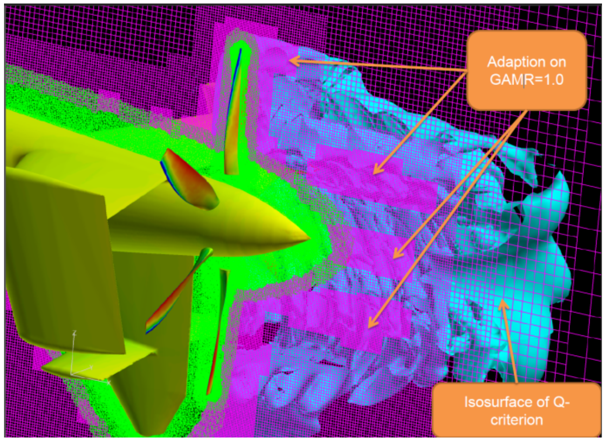
Multi-Mesh CFD Paradigm

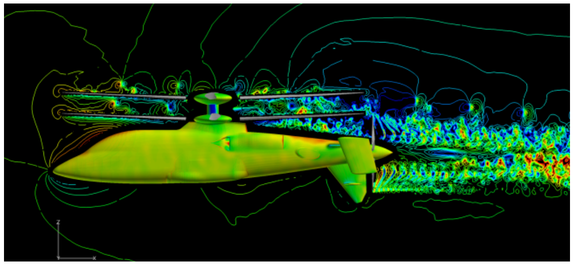


Unstructured and/or Structured Curvilinear "near-body"
- Resolve near-wall viscous flow
- Complex geometries

Cartesian "off-body"
- Computationally efficient
- High order accuracy
- Adaptive mesh refinement

Preserves wake
- Interactional aero
- Noise
- Ground effect

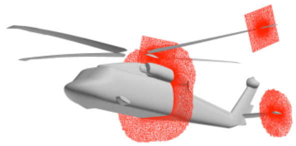


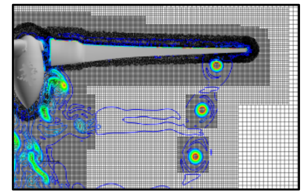


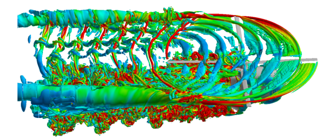
X2, Courtesy Sikorsky Aircraft

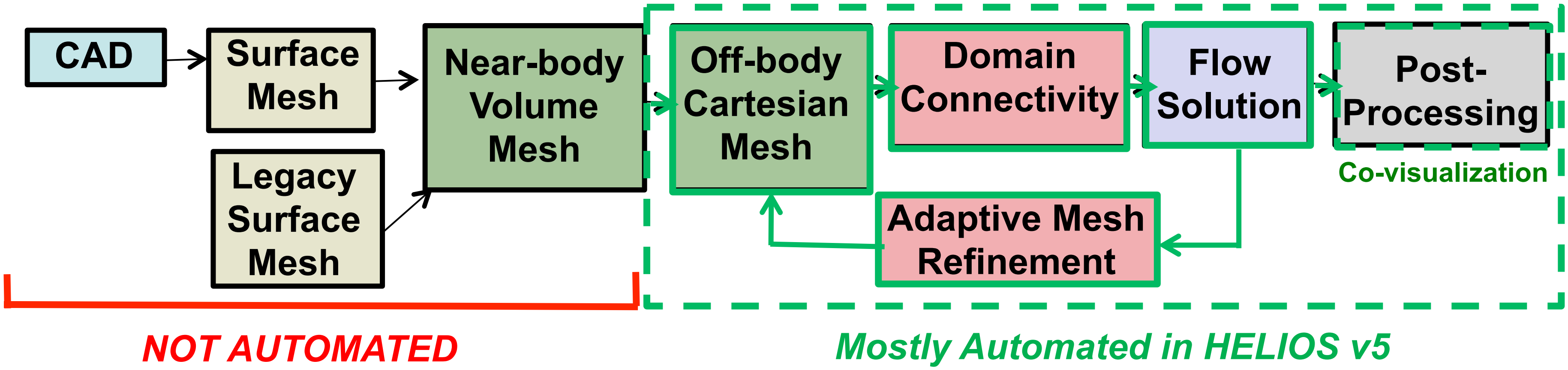
Automation

- **Rotorcraft overset CFD setup is complicated**





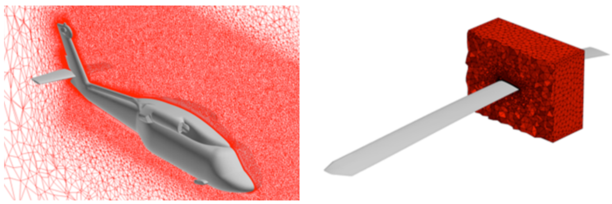




How do we enable skilled rotorcraft engineers to use high-fidelity CFD tools without forcing them to become grid generation experts?

Multi-Mesh Generation

1) Build component meshes

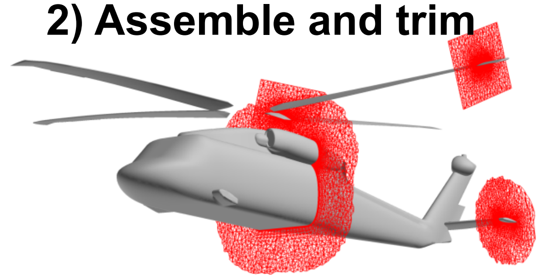


Components

NOT AUTOMATIC

AUTOMATIC

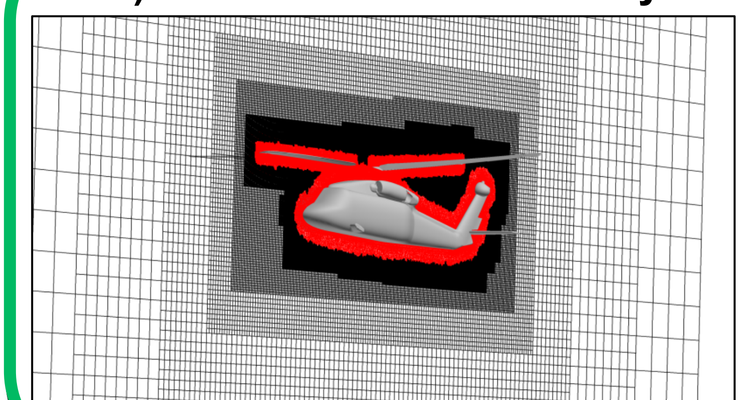
2) Assemble and trim



Subset near-body

AUTOMATIC

3) Build Cartesian Off-body



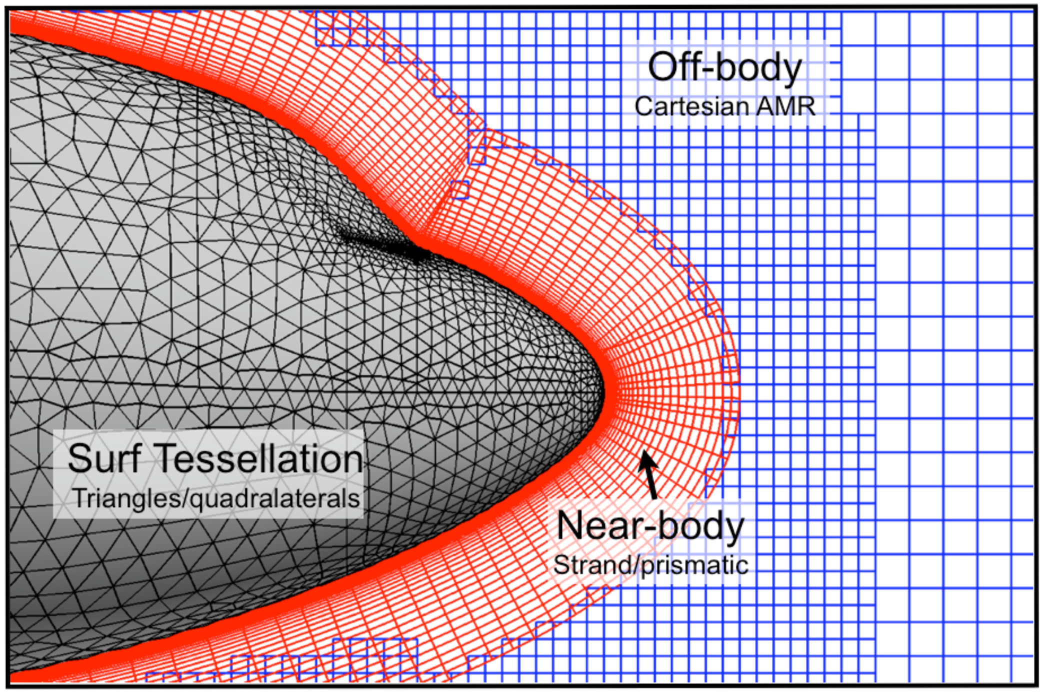
Near-body/off-body

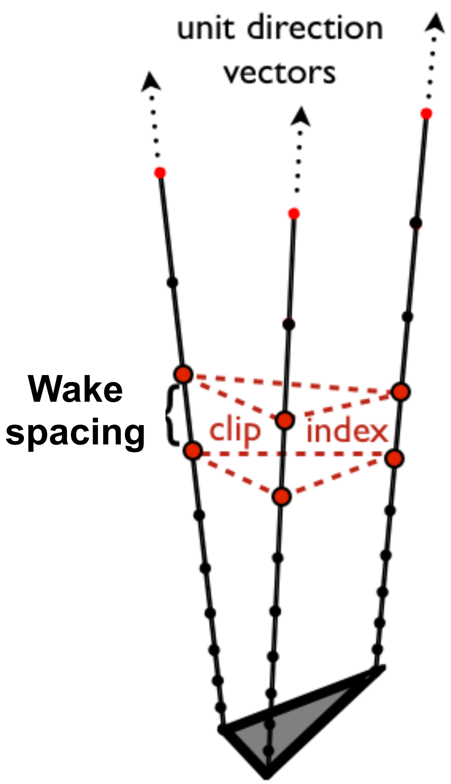
Issues limiting automation

- ✓ **Component meshes require separate mesh generation software/expertise**
- ✓ **Ad hoc user-specified subset distance, based on rules of thumb**
- ✓ **Potential mismatch in near/off-body grid spacing**

Strand Mesh Generation

- **Straight line segments grown from surface**
  - All strands have same **point distribution**
  - Each strand has a **direction vector**, normal initially but bent to fill open regions
  - **Wake spacing** defines transition to Cartesian off-body



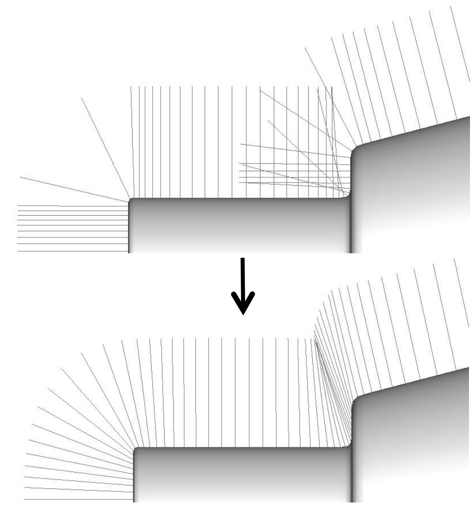


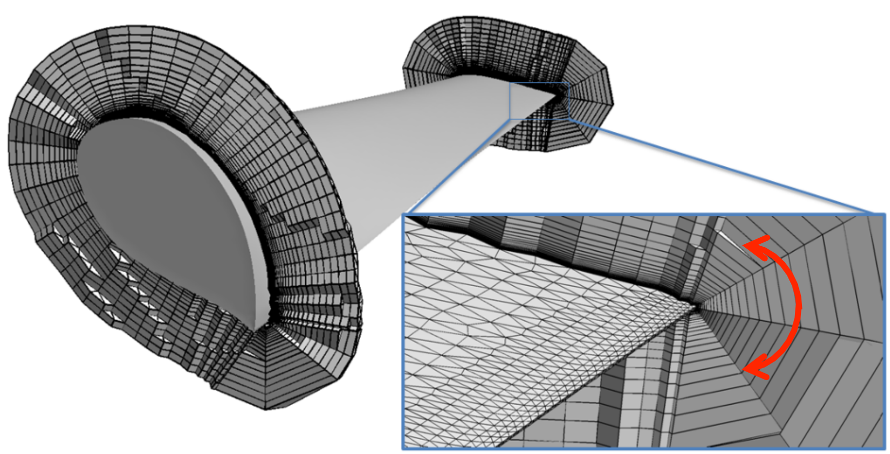
Strands grown directly from surface tesselation

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

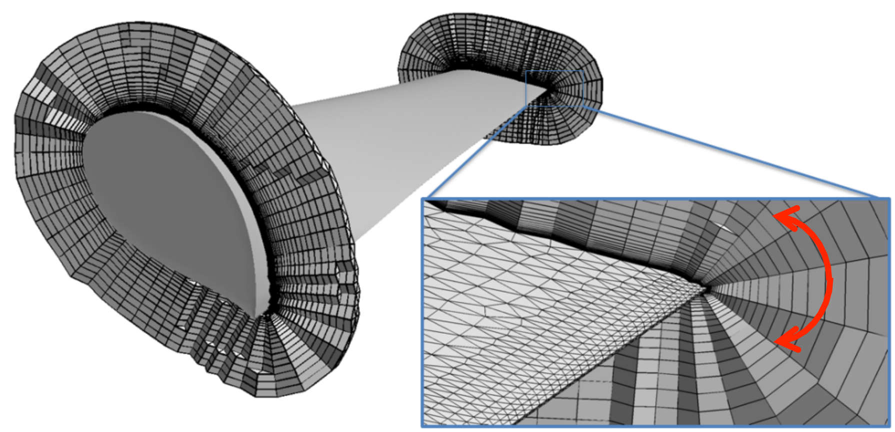
Direction Vector Smoothing

- **Fill in poorly spaced regions**
  - Iterative algorithm seeks uniform distribution at extent, ideal for isotropic Cartesian
  - Excessive smoothing can result in negative volumes





Unsmoothed
(strands normal to surface)



Smoothed
(9 iters)

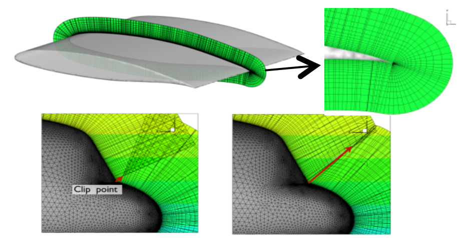
Strand Technology

- **Full automation is the overarching goal**
- **Complex set of inter-related meshing and solver issues addressed in past work**
- **Topics addressed in other work**
  - Multi-strand generation from CAD
    R. Haimes
  - High order strand solver
    O. Tong, A. Katz
  - Fast parallel overset connectivity
    J. Sitaraman

Complex geometries

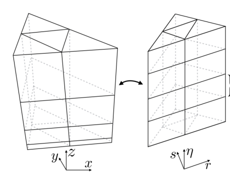
- Legacy surface mesh or CAD

Strand generation



- Single/multi-strand
- Convex & concave corners

Solver

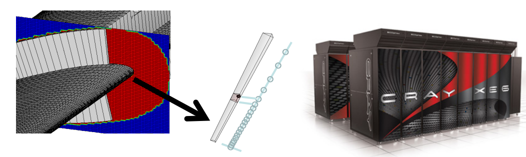


$$\mathcal{F}^L_{0i} = \mathcal{F}^h_0 + \frac{1}{2}\Delta r^T_{0i}\nabla^h \mathcal{F}^h_0$$

$$\mathcal{F}^R_{0i} = \mathcal{F}^h_i - \frac{1}{2}\Delta r^T_{0i}\nabla^h \mathcal{F}^h_i$$

- Legacy 2^{nd}-Order
- New 4^{th}-Order

Performance



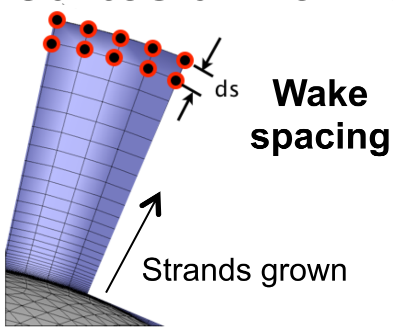
- Structure in normal direction
- Fast parallel overset connectivity

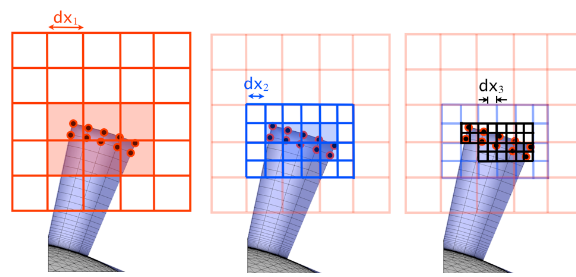
- **Focus of this work**
  - Fully-automated runtime volume mesh generation from discrete surface
  - Production Helios solver - legacy 2^{nd}-Order solver NSU3D for near-body strand grids, 5^{th}-Order Cartesian solver for off-body grids

Strand-Based
Mesh Generation

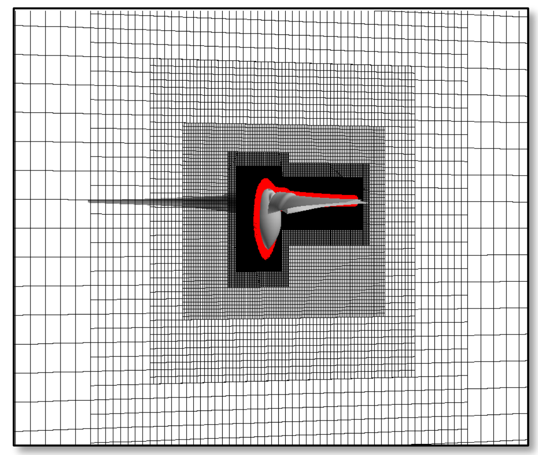
User specifies <u>wake spacing</u>, everything else automated

- **Strand mesh grown until it matches specified wake spacing**
- **Cartesian refines to match specified wake spacing**





Cartesian refines



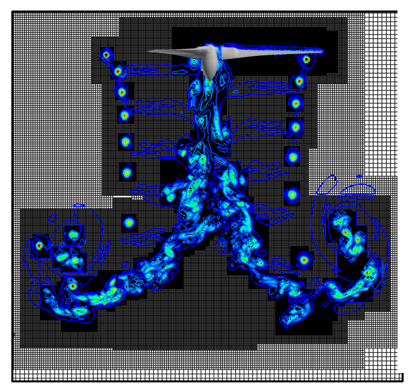
Resulting dual-mesh

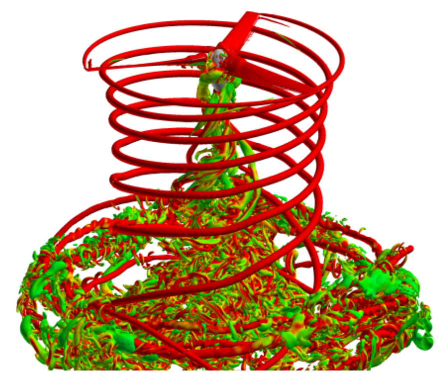
- **AMR refines wake as it evolves**
  - f = Q-criteria normalized by shear strain*
  - Refine wherever f > 1

$$Q = \frac{1}{2}(||\Omega||^2 - ||S||^2), \quad f = Q$$

$$f = \frac{1}{2}\left(\frac{||\Omega||^2}{||S||^2} - 1\right)$$

*Kamkar et al, *JCP, 2011*

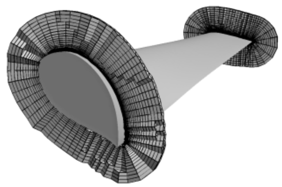




Automatic
Dual-Mesh Generation

AUTOMATIC

1) Strand blade meshes



components

AUTOMATIC

2) Assemble

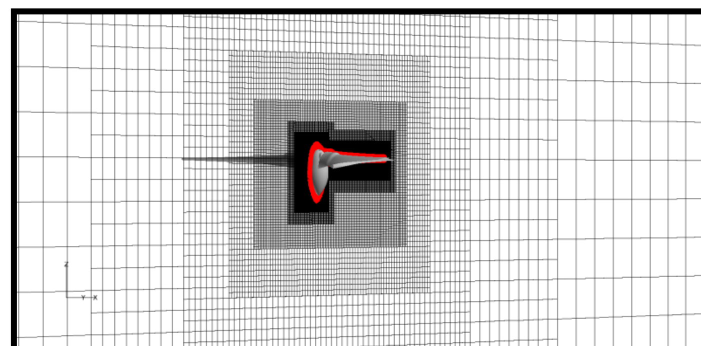
Subset near-body

Inputs

- **Tesselated surface**
- **Wall spacing**
  (satisfies y+ based on Re)
- **Wake spacing**
  (resolve farfield effects)

AUTOMATIC

3) Build Cartesian Off-body



Near-body/off-body

Entire dual mesh generated at runtime:

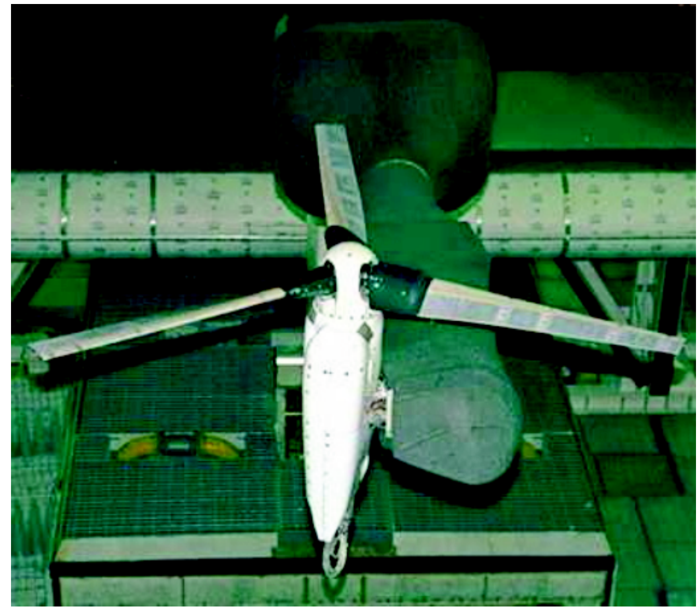
✓ Strand mesh generated automatically from specified wake spacing

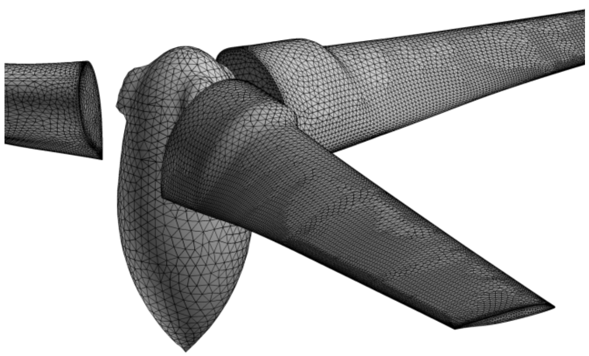
✓ Cartesian mesh generated automatically from strand mesh and wake spacing

✓ Good near/off-body grid spacing ensured

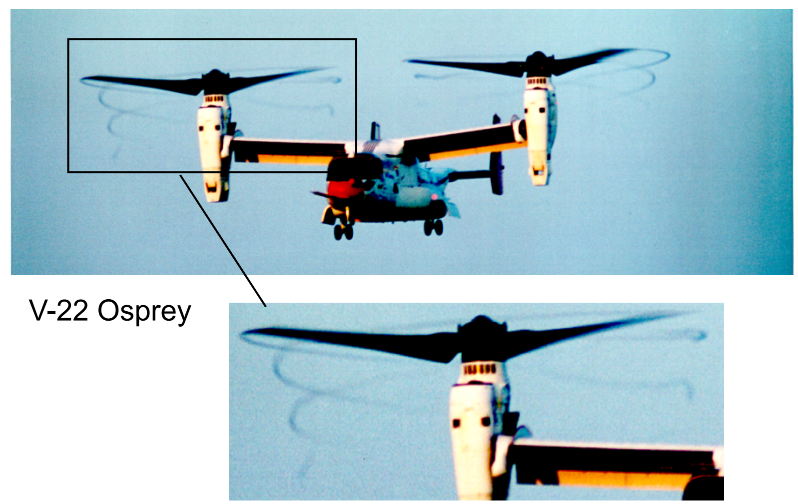
TRAM Test Case

- **Tilt Rotor Aeroacoustics Model (TRAM)**
  - Quarter-scale model V-22 Osprey
  - Tested in DNW-LLF facility
- **Computational conditions**
  - Rigid blade
  - M_{tip}=0.625, Re_{Tip}=2.1M
- **Surface mesh**
  - Blade – 12K nodes, 24.2K triangles
  - Centerbody – 1.4K nodes, 2.2K triangles





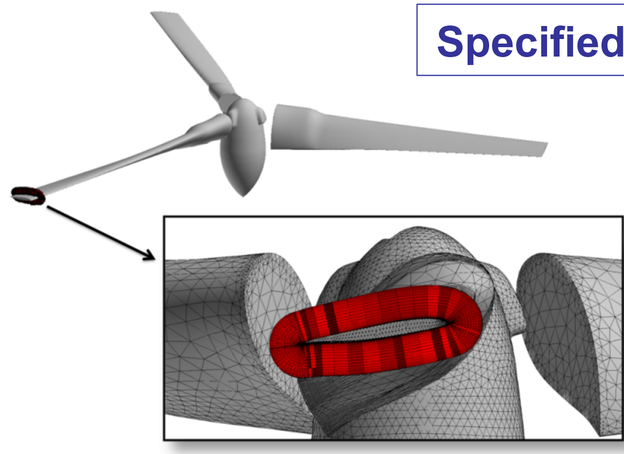
Surface mesh



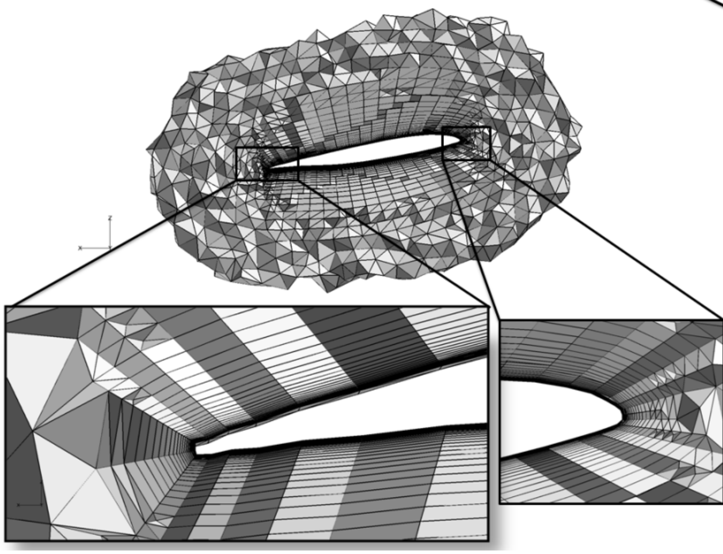
V-22 Osprey

Near-Body meshes

Specified wake spacing Δx = 5% chord

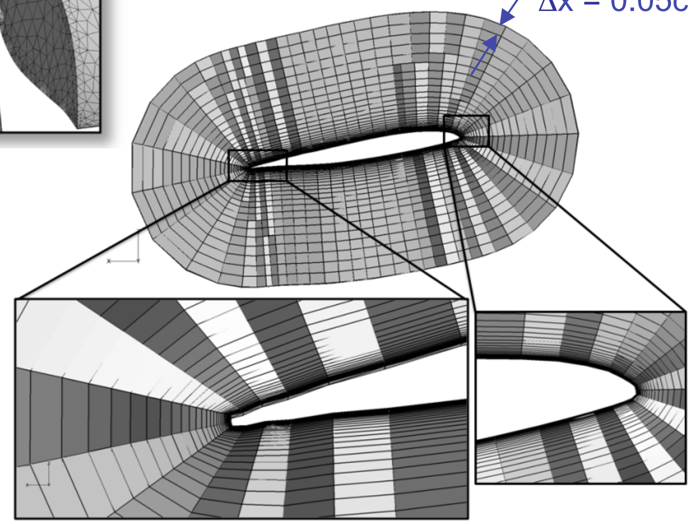


Unstructured



- Blade: prisms + tets
  1.037M prisms, 0.433M tets, **1.48M elems**
  0.615M nodes
- Wall spacing: y+ = 1 at Re_{tip}=2.1M
- Subset distance: 0.5 chords

Strand



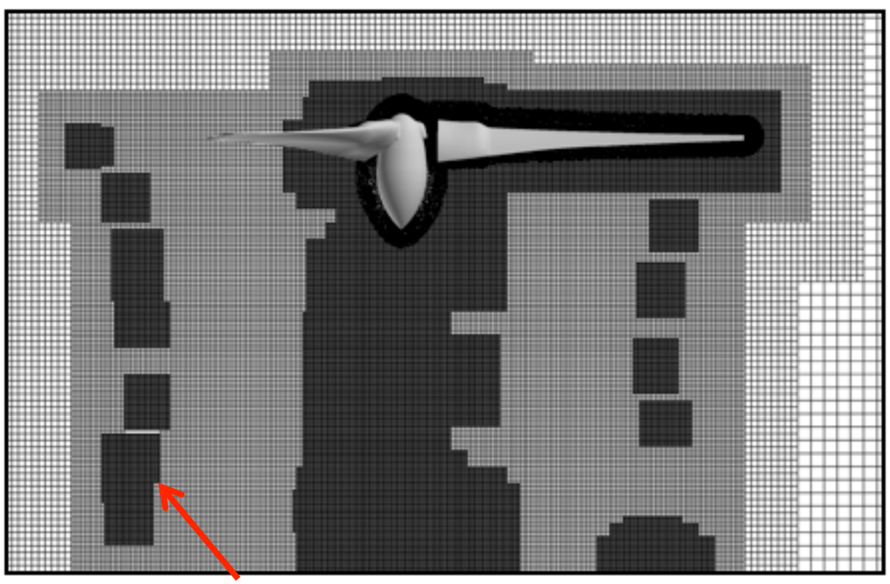
- Blade: prisms only: **1.627M elems**
  0.814M nodes
- Wall spacing: y+ = 1 at Re_{tip}=2.1M
- Strand length: determined from 5%c finest Cartesian spacing (0.5 chords approx)

Unstructured and strand meshes approximately the same size

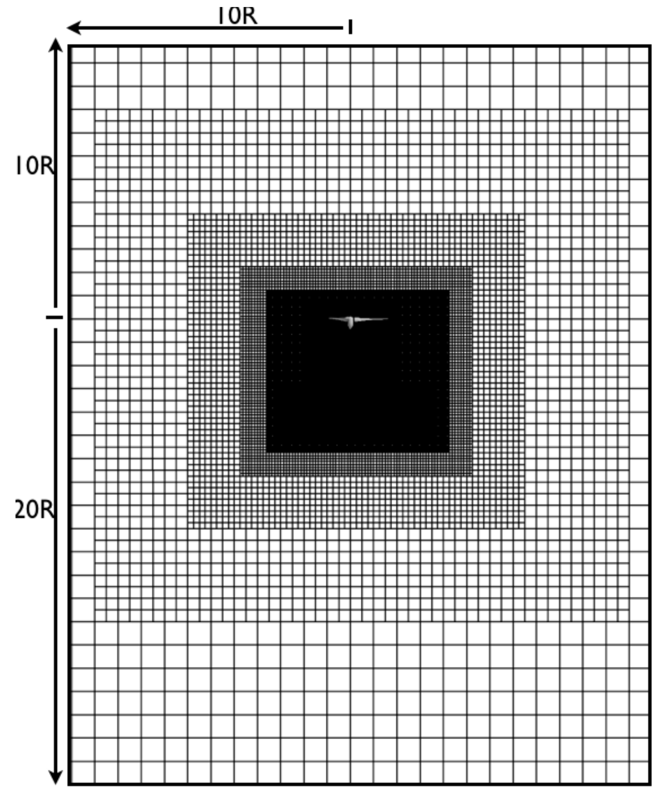
Off-Body Mesh System

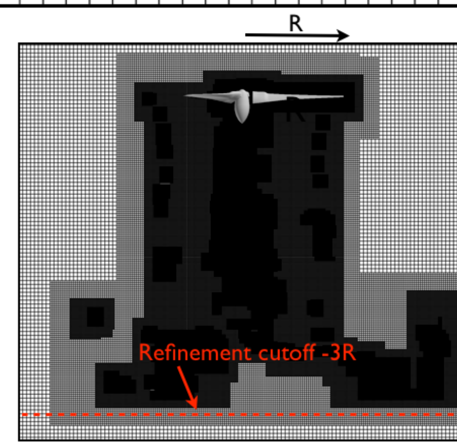
Cartesian grid system

- Extents: 10R streamwise, 20R under rotor
- Finest Δx: 0.05c
- Refinement cutoff: 3R under rotor



AMR targets local regions with swirling flow





Moving Grid Calculation

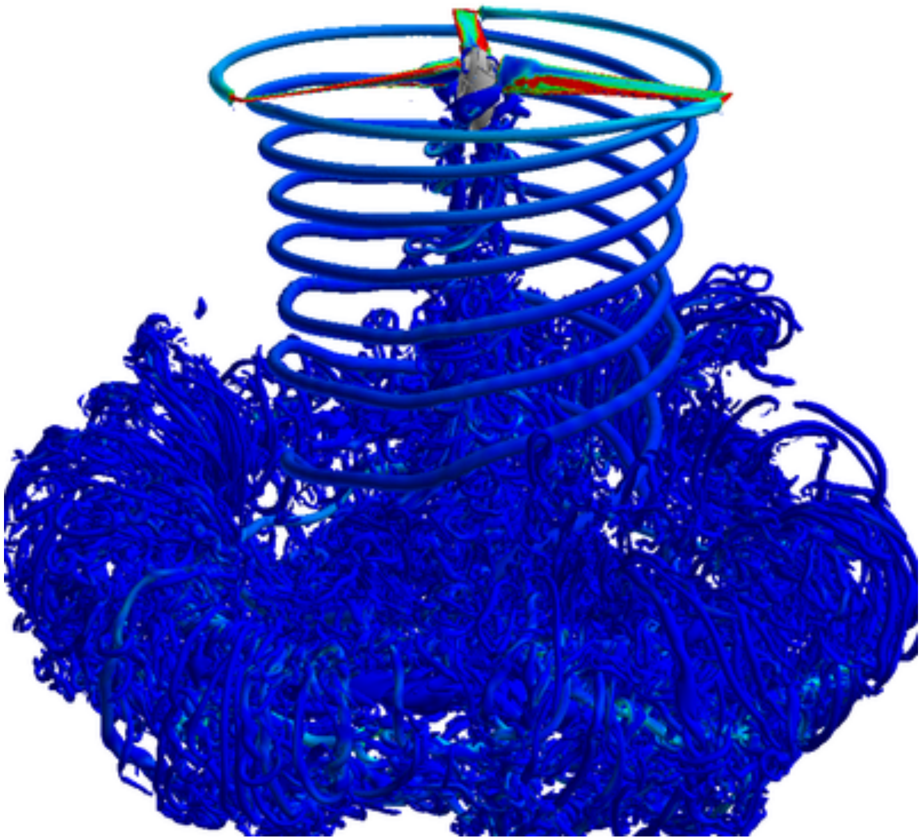
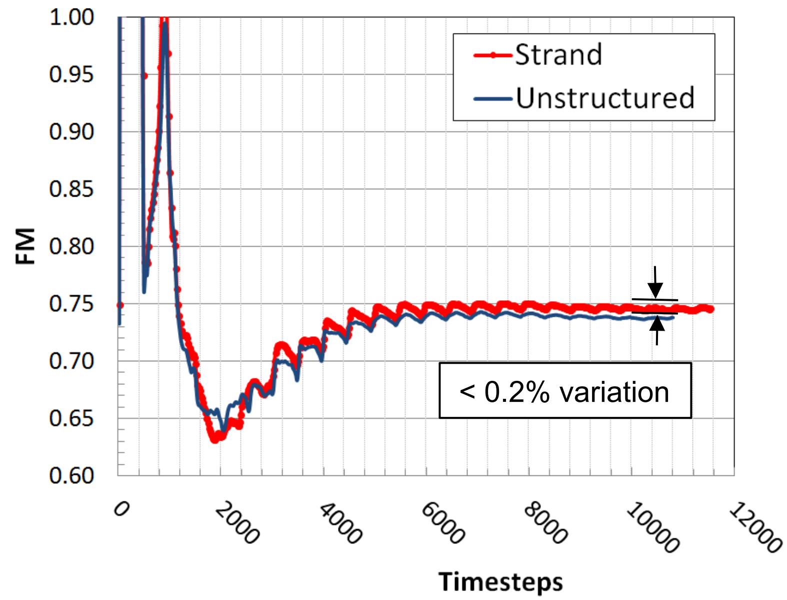
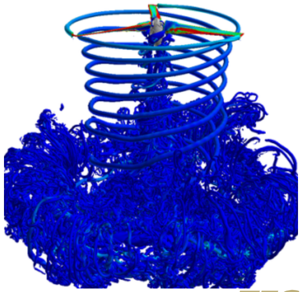


Figure of Merit convergence



– Assumed convergence when FM variation < 0.2%

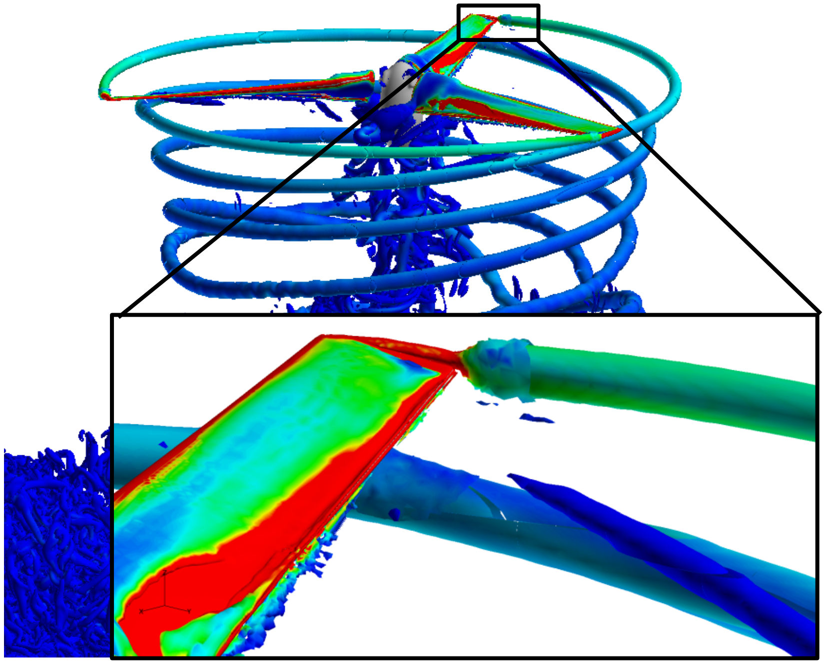
- **8 revs total**
- **Refinement started after 2 revs**



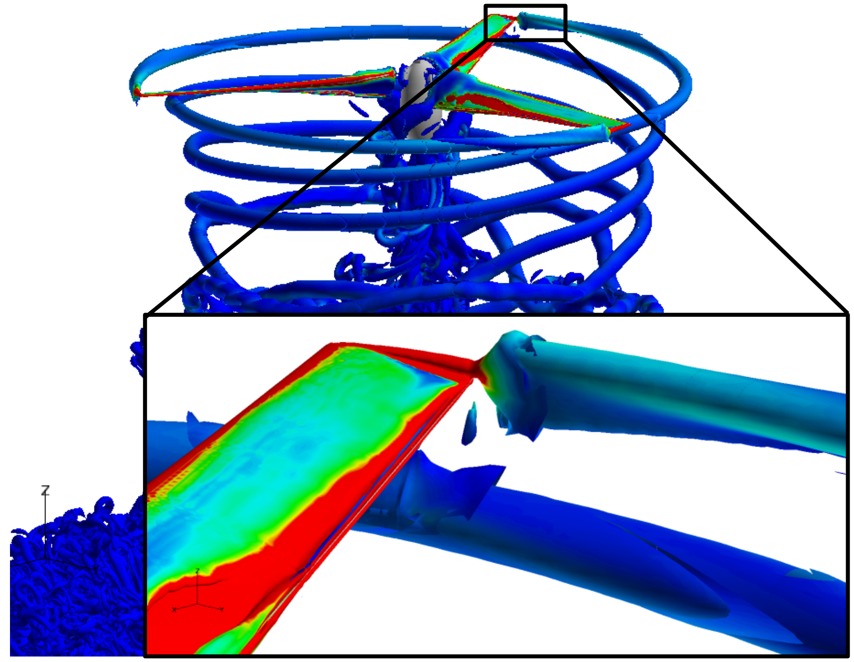
NSU3D convergence comparable on strand and unstructured meshes

Results
Unstructured vs Strand

Unstructured



Strand

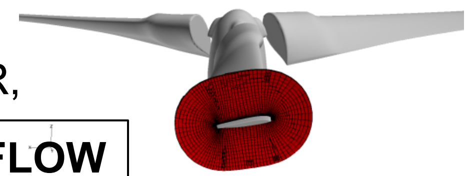


	Thrust C_T/σ	Power C_Q/σ	Figure of Merit	% Diff from Experiment
Experiment	0.1495	0.01596	**0.774**	**--**
Unstructured	0.1453	0.01640	**0.738**	**- 4.6%**
Strand	0.1422	0.01650	**0.745**	**- 3.7%**

Comparable

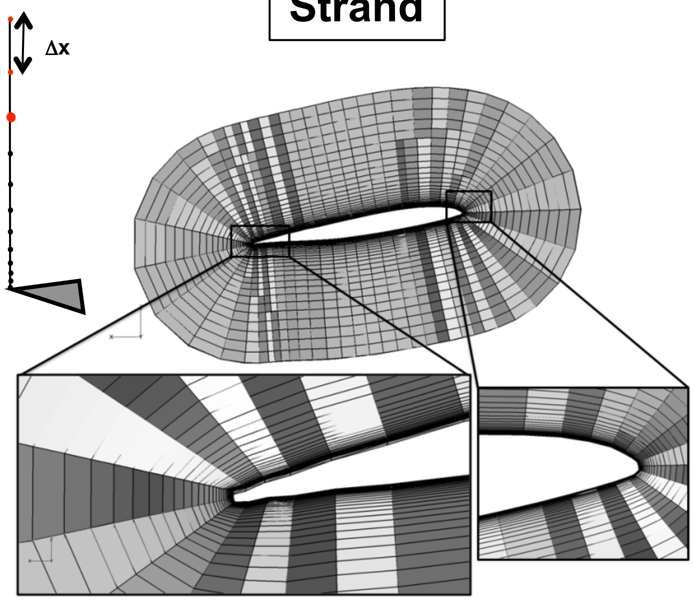
OVERFLOW near-body

- **OVERFLOW added as near-body solver option in Helios v5**
  - Better accuracy for simple geometries like rotor blades
  - Computationally faster, higher order algorithms, near-body AMR, alternate turb models, etc.

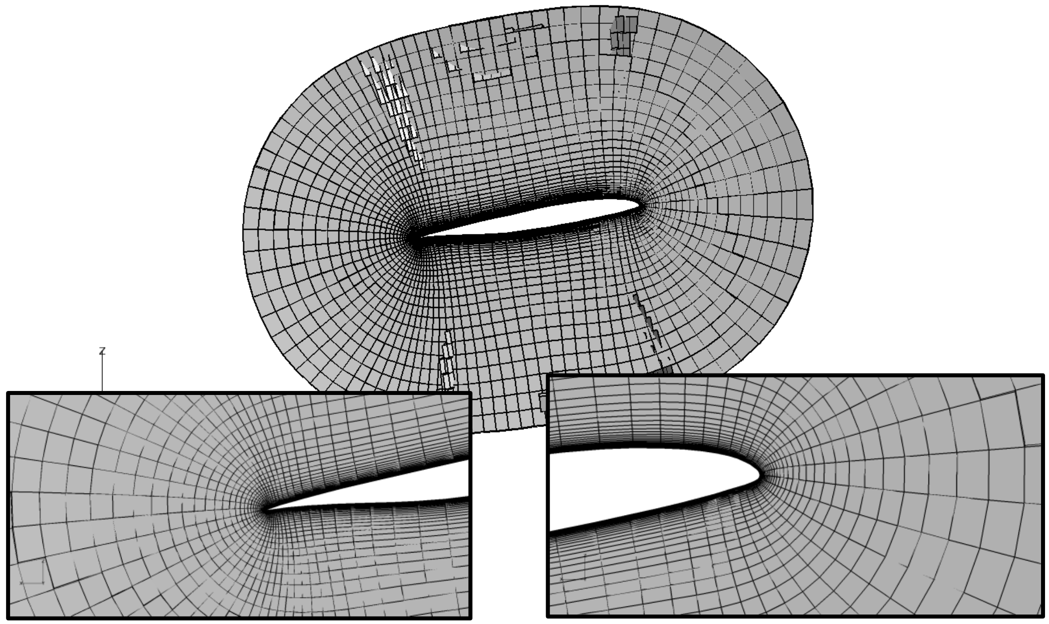


OVERFLOW

Strand



- Surf nodes blade: 12.1K
- Normal points (strand dir): 67
- Volume nodes blade **0.81M**



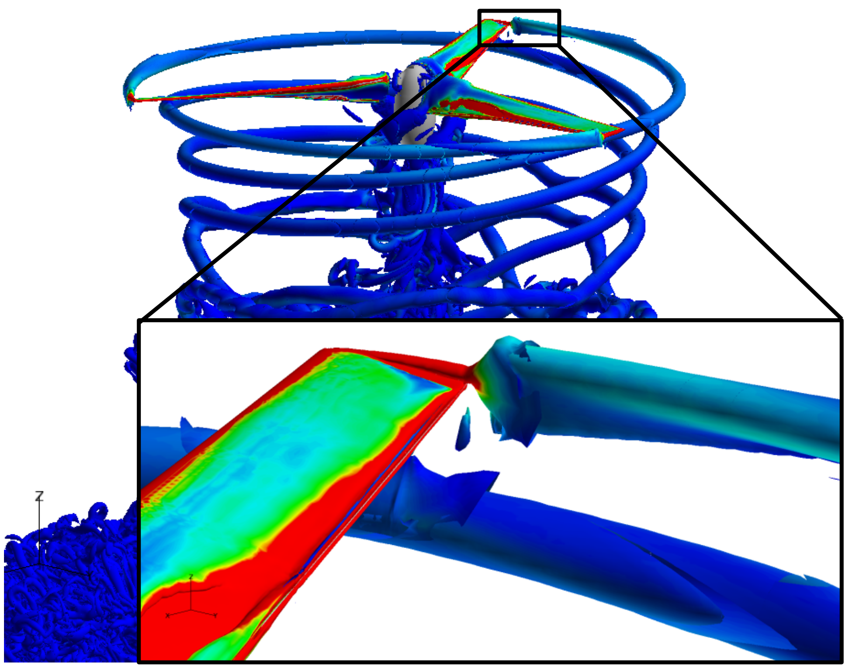
- Surf nodes blade: 14.5K
- Normal points (strand dir): 66
- Volume nodes blade **0.96M**

Strand & Overflow meshes approximately the same size

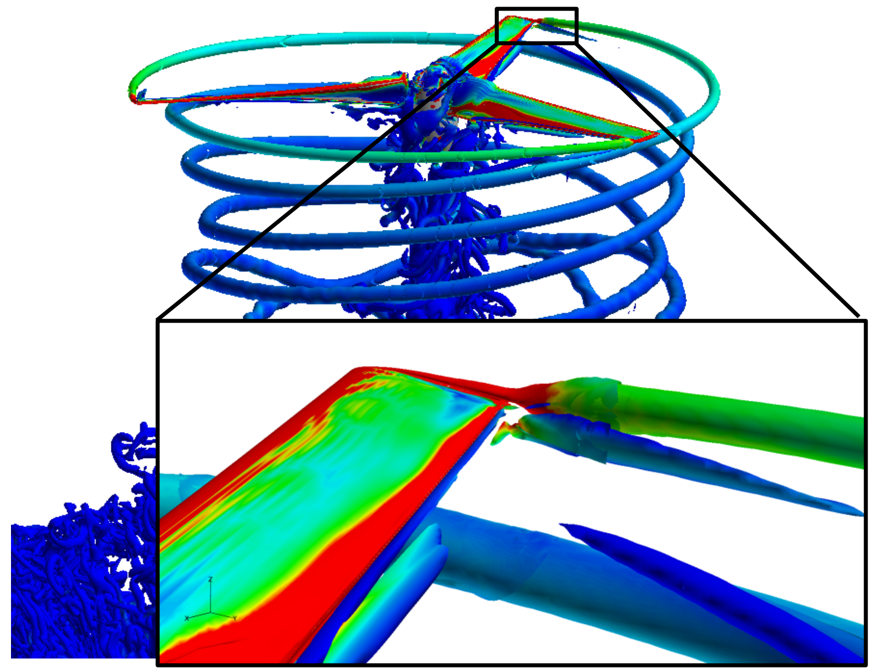
Results

Strand vs OVERFLOW

Strand 0.81M nodes/blade



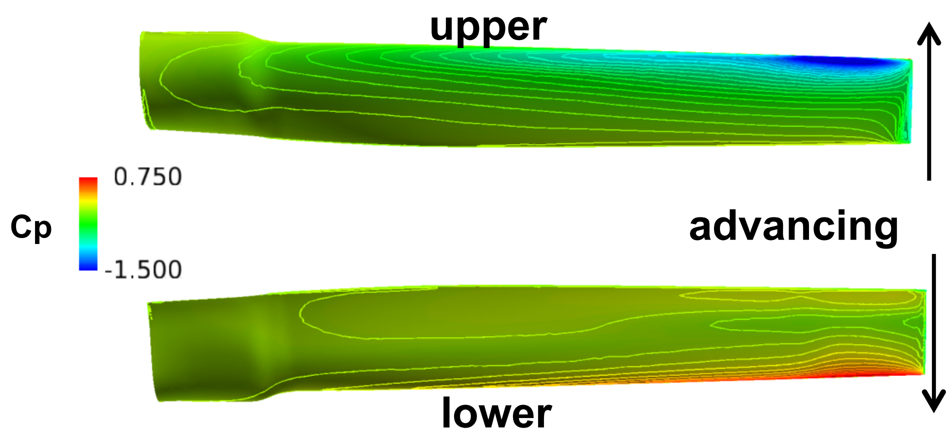
OVERFLOW 0.96M nodes/blade

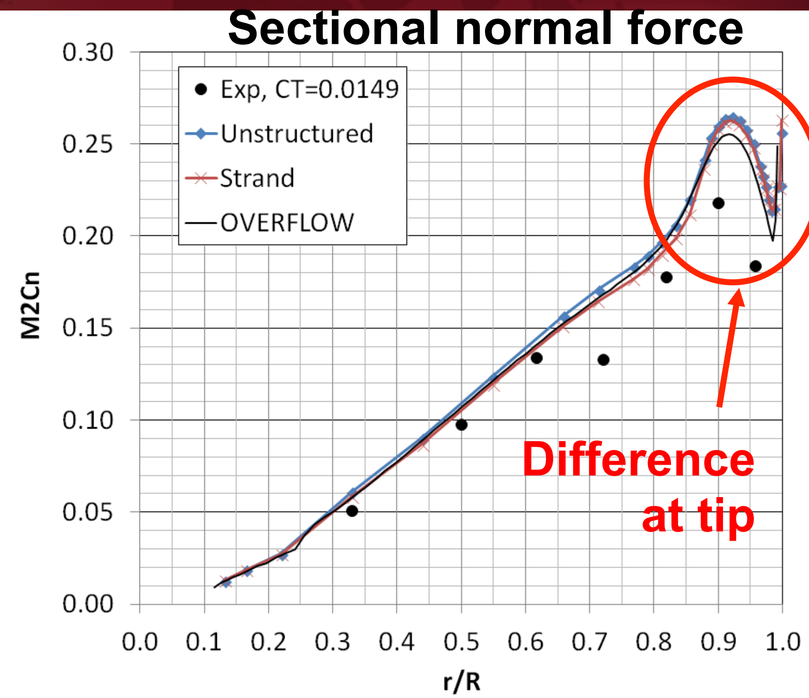


	Thrust C_T/σ	Power C_Q/σ	Figure of Merit	% Diff from Experiment
Experiment	0.1461	0.01736	**0.774**	**--**
Strand	0.1422	0.01650	**0.745**	**- 3.7%**
OVERFLOW	0.1446	0.01655	**0.761**	**- 1.7%**

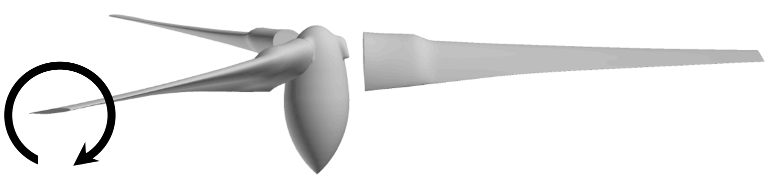
Significant improvement

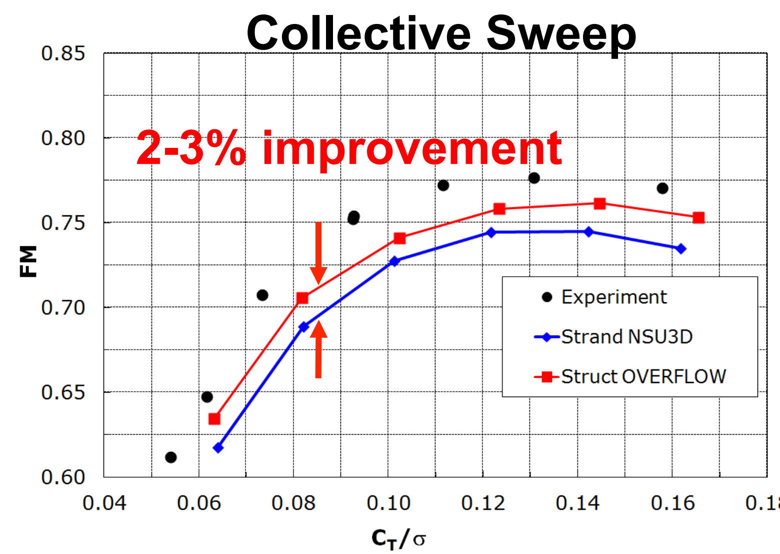
Results
(cont)





Collective pitch variation

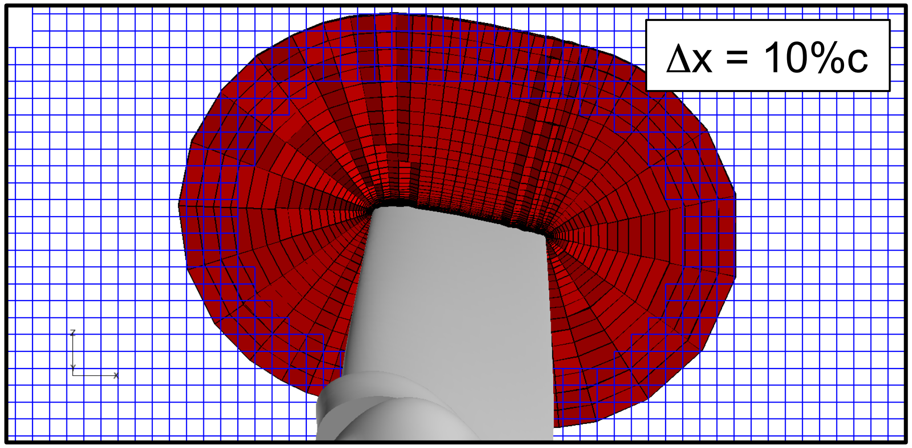


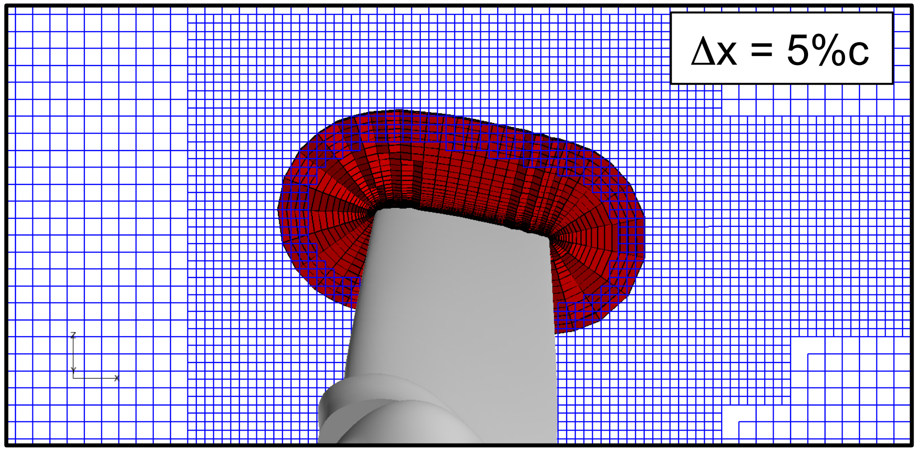


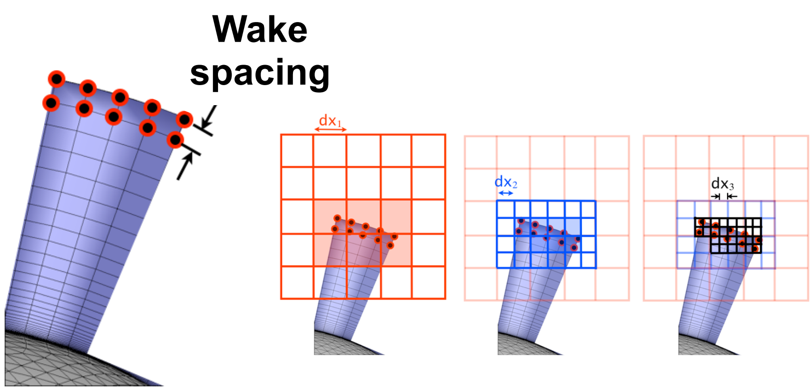
- **OVERFLOW FM prediction consistently more accurate**

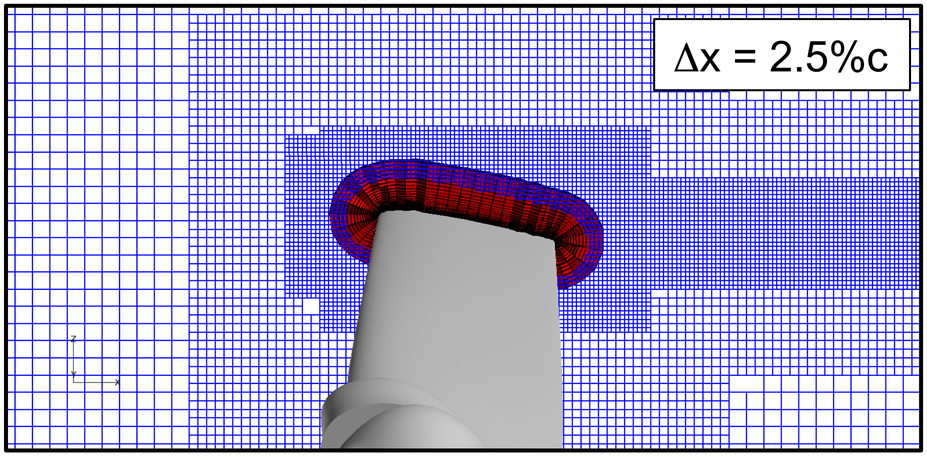
Wake Spacing

- Varying the user-specified wake spacing changes both the near-body strand length and the Cartesian off-body mesh



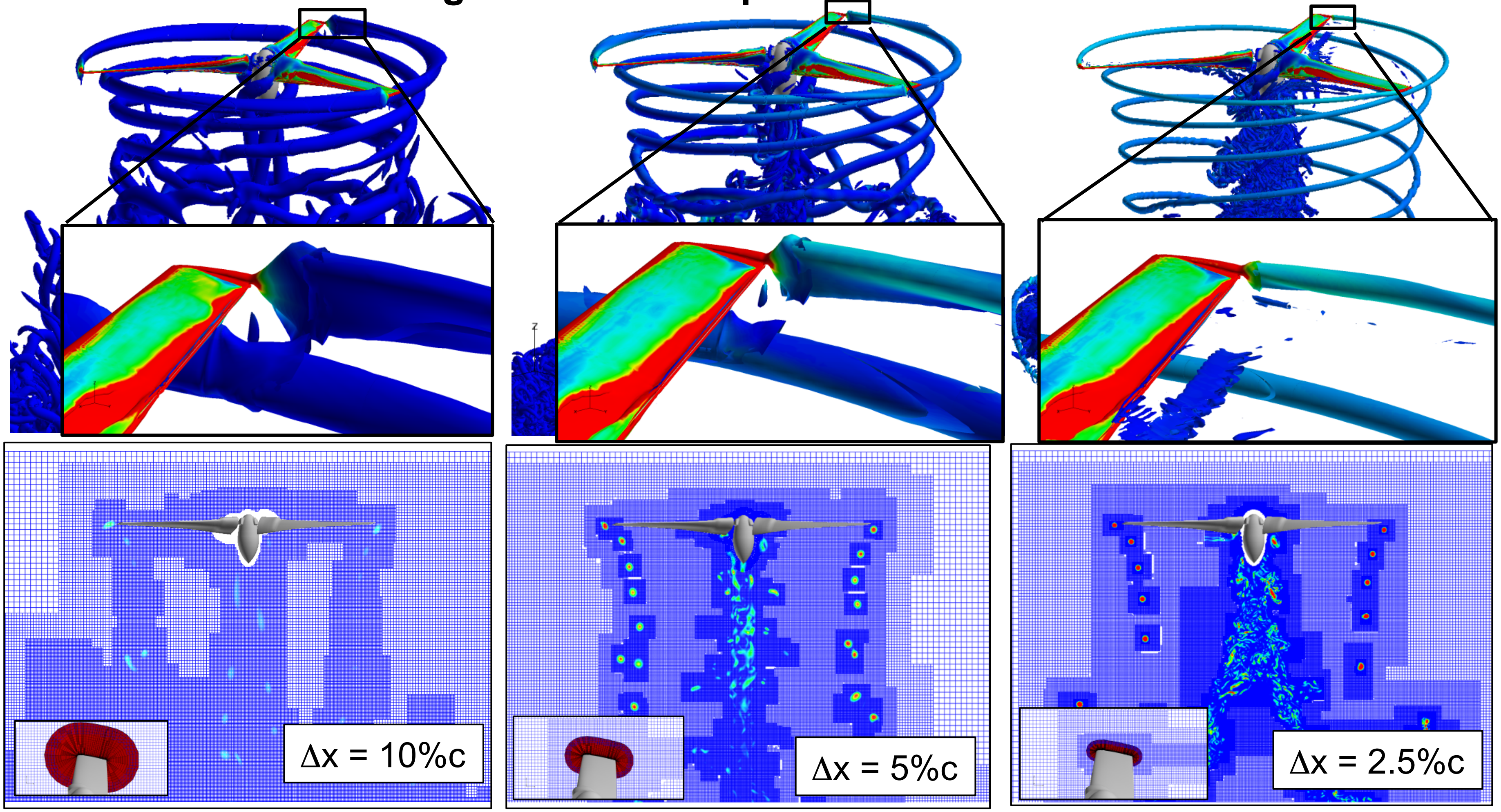






Wake Spacing (cont)

- **Refined wake spacing leads to better tip vortex and wake resolution, but also leads to large variations in problem size**



2.64M NB/21.1M OB
23.7M nodes

2.53M NB/89.4M OB
91.9M nodes

2.39M NB/210.0M OB
10X increase! **212.4M nodes**

Outline

- Background and motivation
- Automatic dual mesh generation
  - Strand near-body
  - Cartesian off-body
- Results
- **On-going work**
  - **Multi-strand meshes**
  - **High order strand solver**
- Conclusions

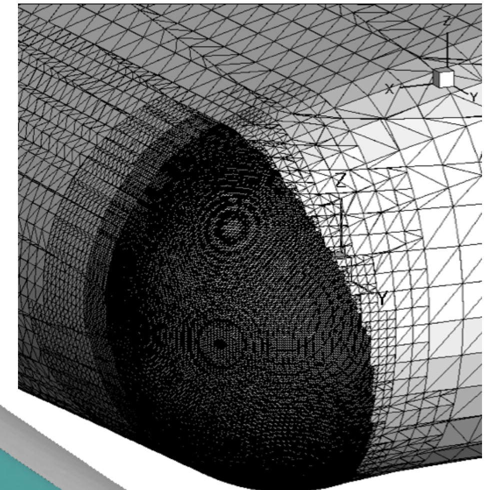
Multi-Strand Mesh

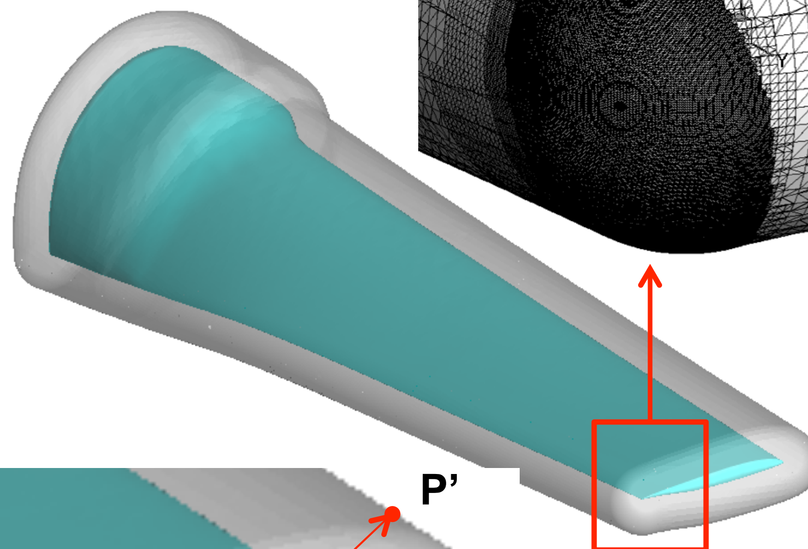
B. Roget

Steps

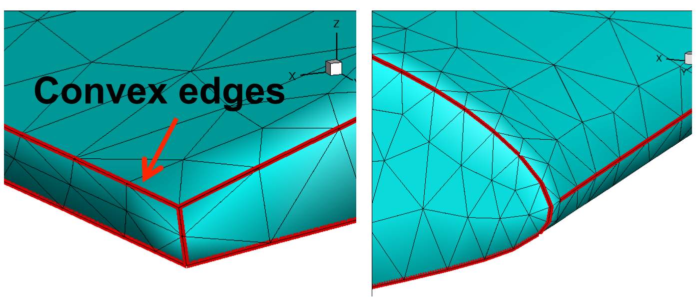
1. Build adaptively tesselated iso-surface of minimum distance field P' using min-wall distance algorithm + adaptive marching cubes.
2. Identify convex edges (CE) with face angle > X°, X is set to 40 deg now.
3. For all surface vertices P not part of CE, find the point of minimum distance on the min-dist iso-surface P'. The line connecting P->P' is the strand direction

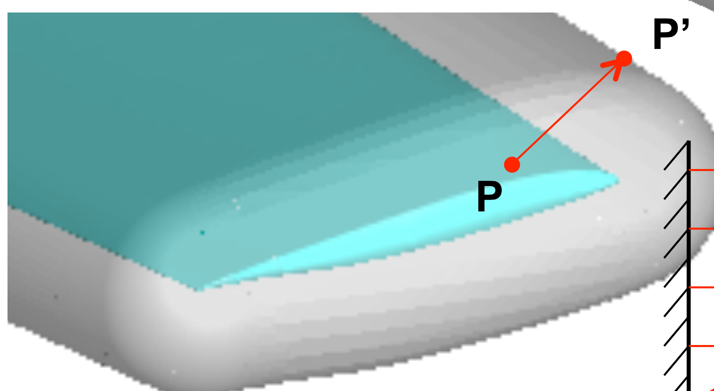
Step 1

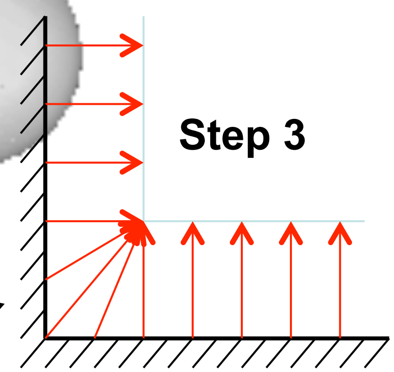




Step 2







Algorithm automatically bends strands at concave corners

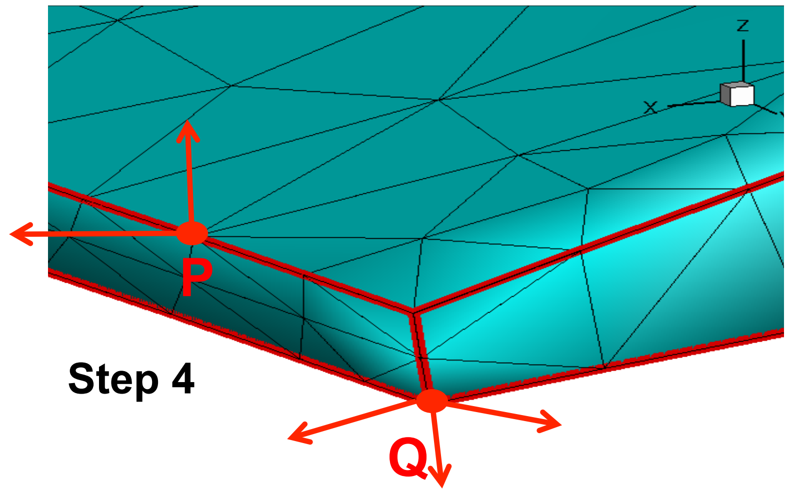
Multi-Strand Mesh (cont)

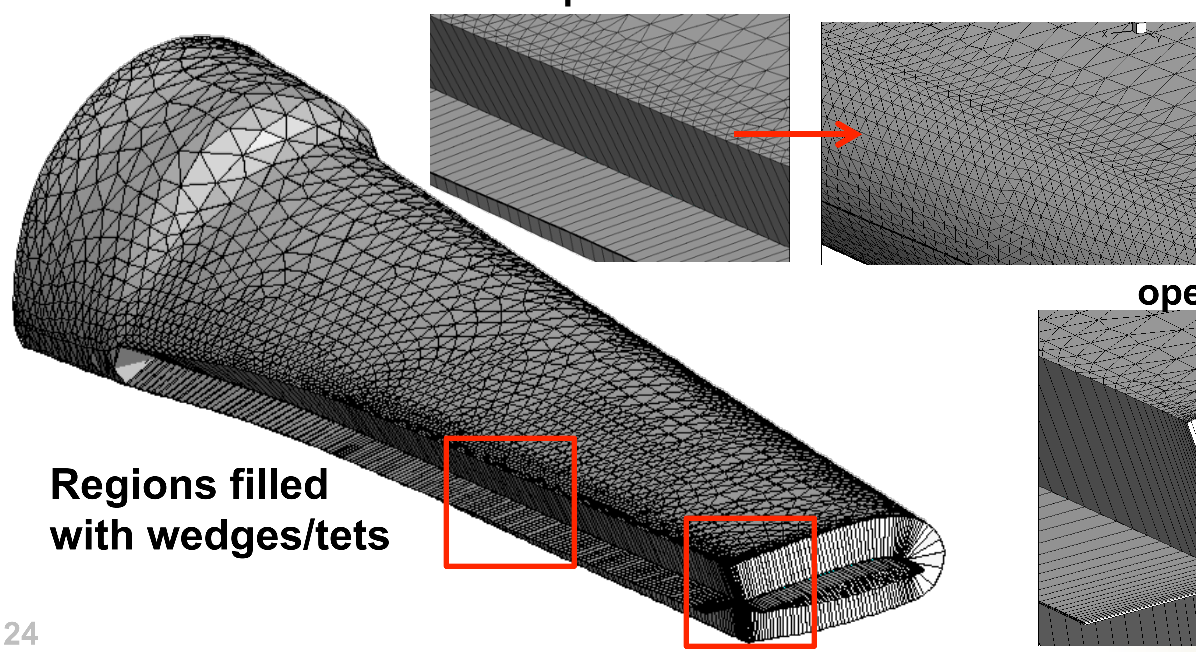
<u>**Steps**</u>

4. **Construct multiple strand directions on vertices that reside on convex edges, based on face normal.**

   e.g. Point P -> two strand directions
   Point Q -> three strand directions

5. **Fill open areas with wedges and tetrahedra.**



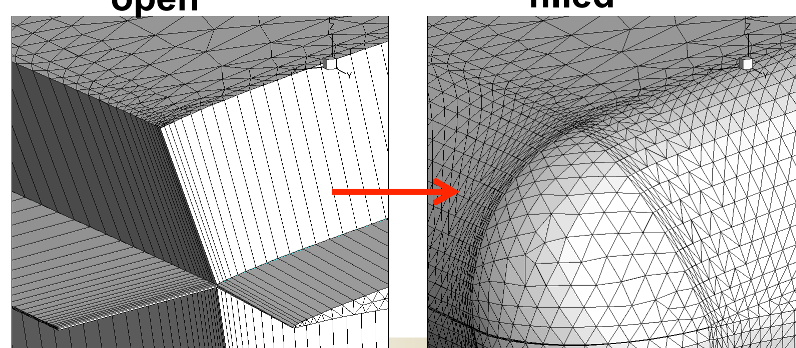


Regions filled with wedges/tets

open **filled**

Apply a few smoothing sweeps to the final iso-surface triangulation

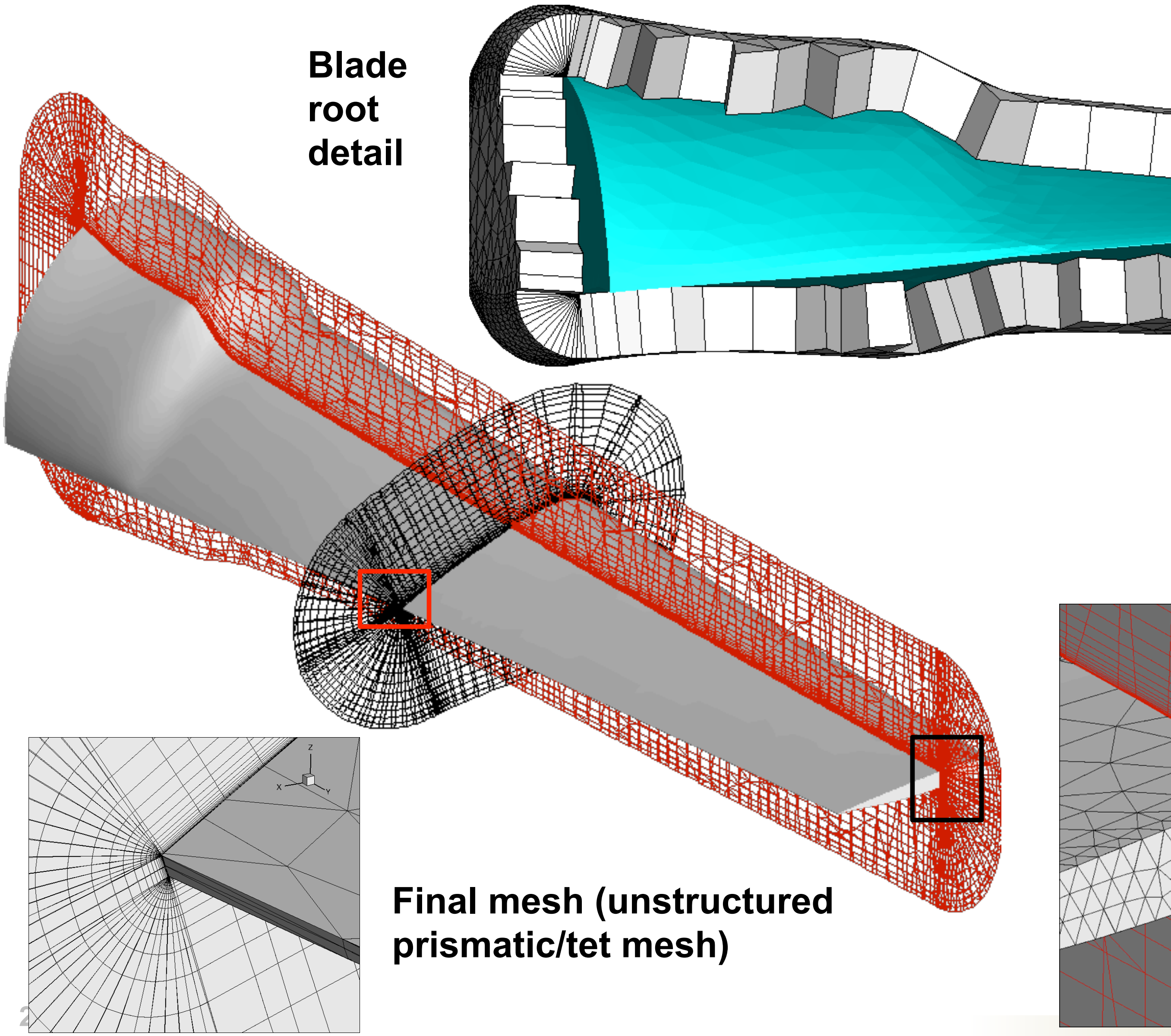
open **filled**



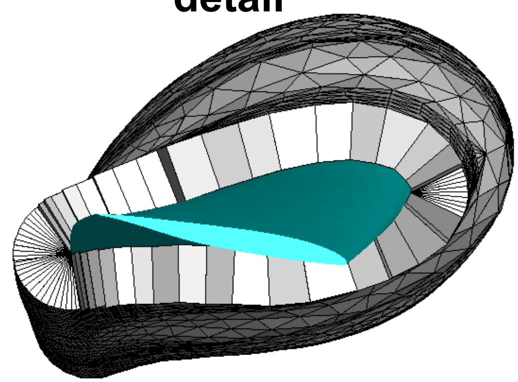
Multi-Strand Mesh

Final Helios mesh

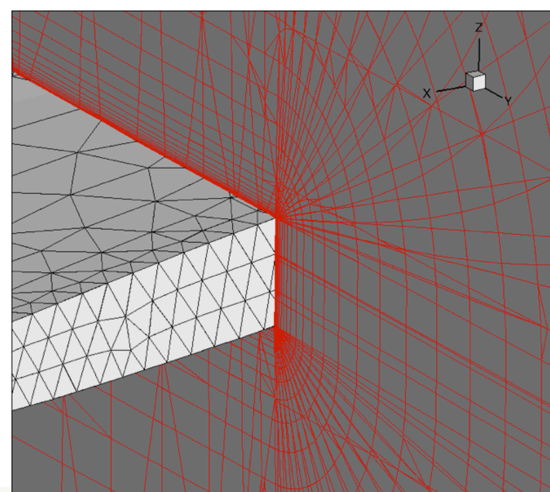
Blade root detail



Section detail



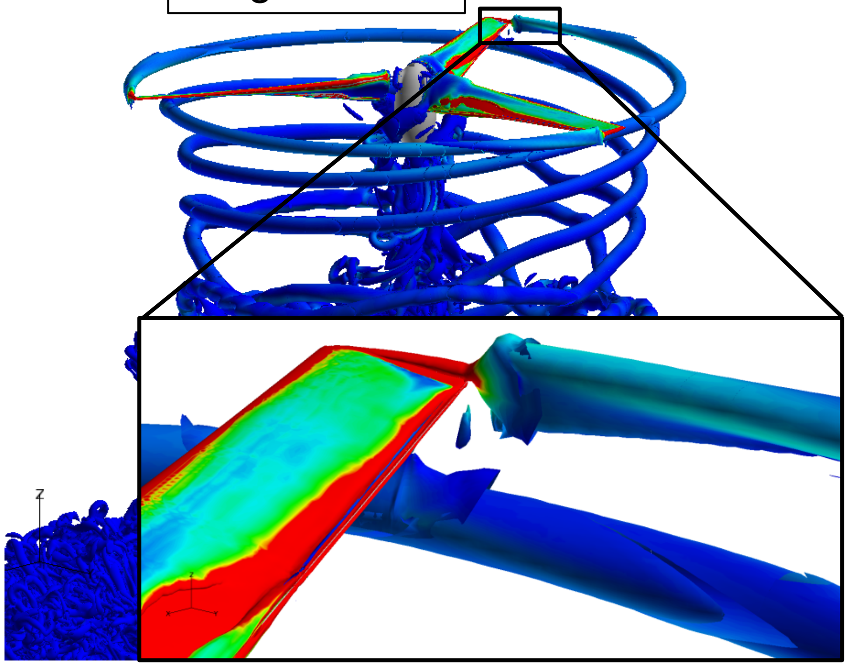
Final mesh (unstructured prismatic/tet mesh)



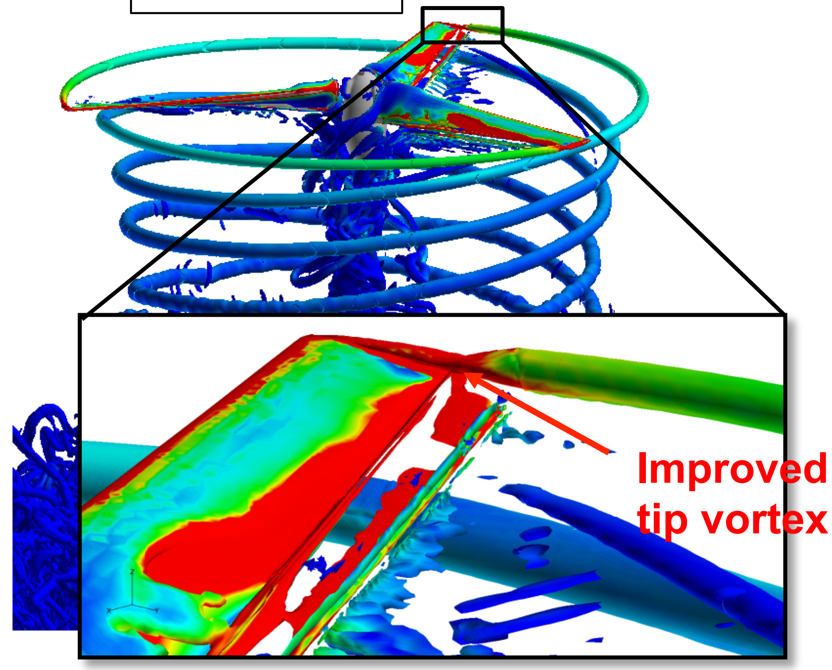
Multi-Strand Mesh

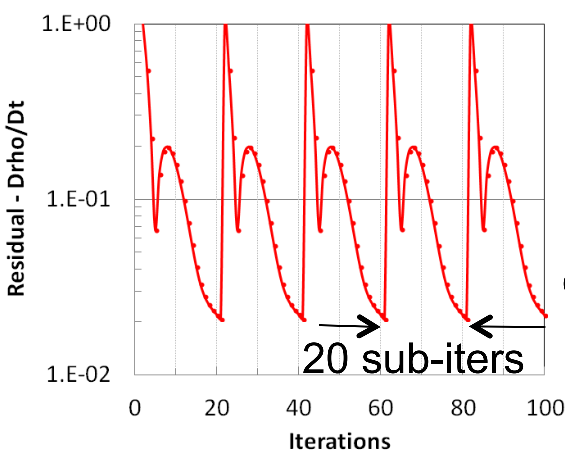
Helios results

Single Strand

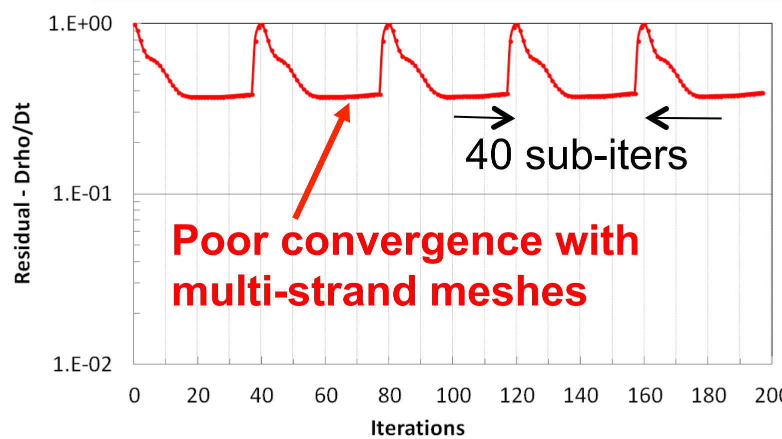


Multi-Strand





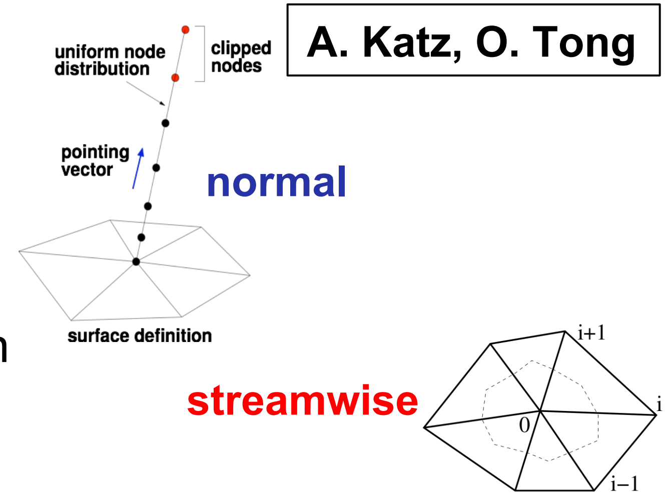
NSU3D
Unsteady
sub-iteration
convergence

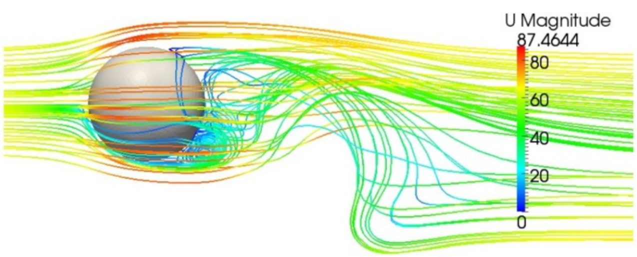


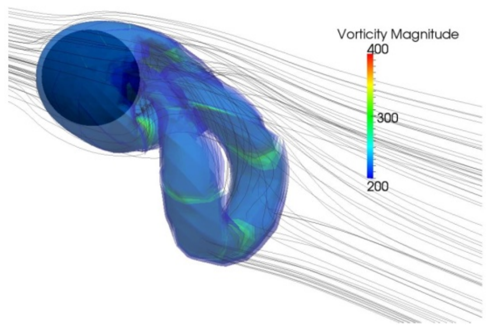
High Order Strand Solver

A. Katz, O. Tong

- **Strand normal direction:**
  High Order Finite Differences
- **Unstructured streamwise direction:**
  High Order Flux corrections
  - High order through truncation error cancellation of finite volume scheme
- **Layers coupled via source term containing derivatives in strand direction**

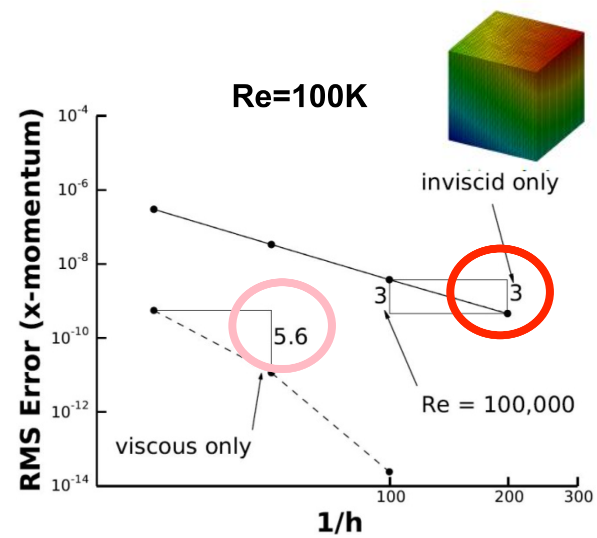






Shedding Sphere
- M=0.2, Re=600
- Surface with quartic elements

AIAA-2015-0835



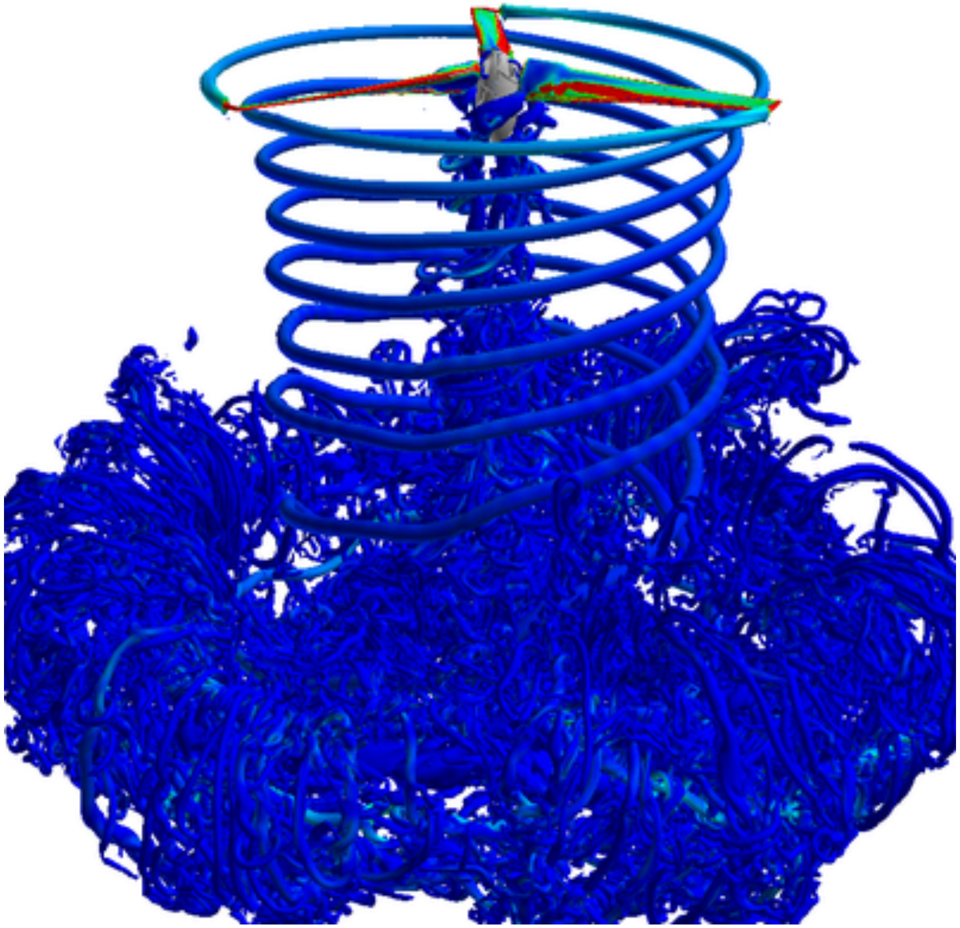
Method of Manufactured Solutions

3rd Order inviscid
5th Order viscous

Summary & Conclusions

- **Demonstrated for the first time automatic strand-based volume mesh construction from a discrete surface**
  - ✓ Minimal inputs: tessellated surface, wall spacing, wake spacing
  - ✓ Support for both single and multi-strand from discrete surface
  - ✓ Meshes constructed with automated approach produce comparable solutions to general unstructured meshes
- **Issues identified that need further development**
  - ✓ Poor tip vortex resolution with single-strand meshes
  - ✓ Poor solver convergence on multi-strand meshes
  - ✓ Prediction of compute resources required can be difficult with runtime strand mesh generation and off-body AMR
- **Future work**
  - ✓ High-order strand solver
  - ✓ Geometrically complex problems
  - ✓ Scalability on many processors – exascale systems

Questions?



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