First-Principles Hover Prediction Using CREATE-AV Helios

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Rotorcraft in Hover

- **Rotor wakes are largely dominated by the trailing vortex system**

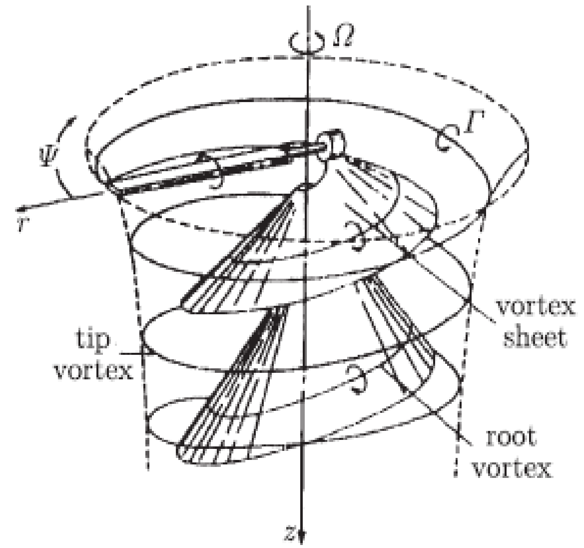
UH-60 Black Hawk in hover

V-22 Osprey in hover

- **The hover condition represents one of the true values of the helicopter**
- **A limiting design point in terms of power requirements**

Why is "First-Principles" Simulation of Hover so Challenging?

- **Rotary-wing vehicle aerodynamic loads are heavily influenced by their own vortical wakes**
- **"First-principles" simulations try to model the entire wake without empirical inputs or vortex-based method inputs**
  - Numerical methods are dissipative
- **Historically, a very challenging task because of the differences in scales (tip vortex from a UH60 rotor is ~1/300* Rotor Radius)**
- **The hover helical vortex system is entirely self-induced:**
  - Feedback between vortex strength and vortex system dynamics – neutrally stable

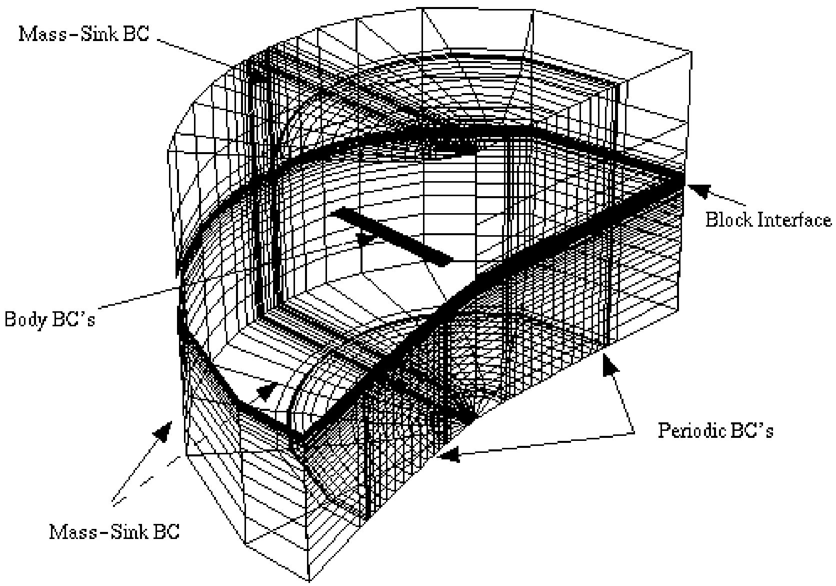


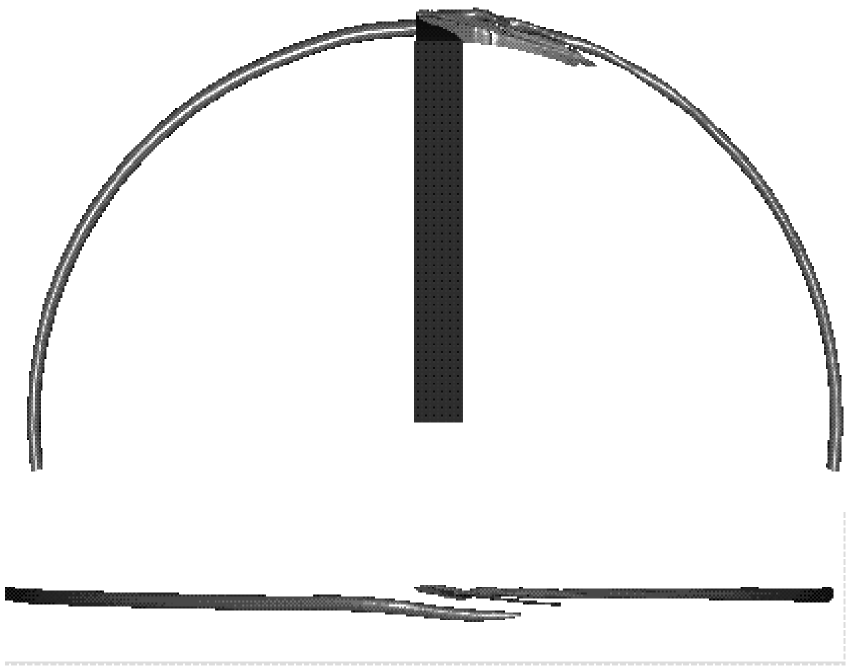
(Gray, 1955)

Scope

- **Several excellent survey articles that summarize rotorcraft flow simulation efforts are available in literature:**
  - McCroskey [1995]
  - Srinivasan and Sankar [1994], Landgrebe [1994]
  - Hariharan and Sankar [2000]
  - Strawn and Caradonna [2005]
- **The present work is not intended to be an all-inclusive survey of rotorcraft wake modeling. In this paper, key technology enablers that make up current-day capabilities are reviewed.**
- **Results from the state-of-art, high-fidelity rotor-wake hover simulations are reviewed and status assessed**

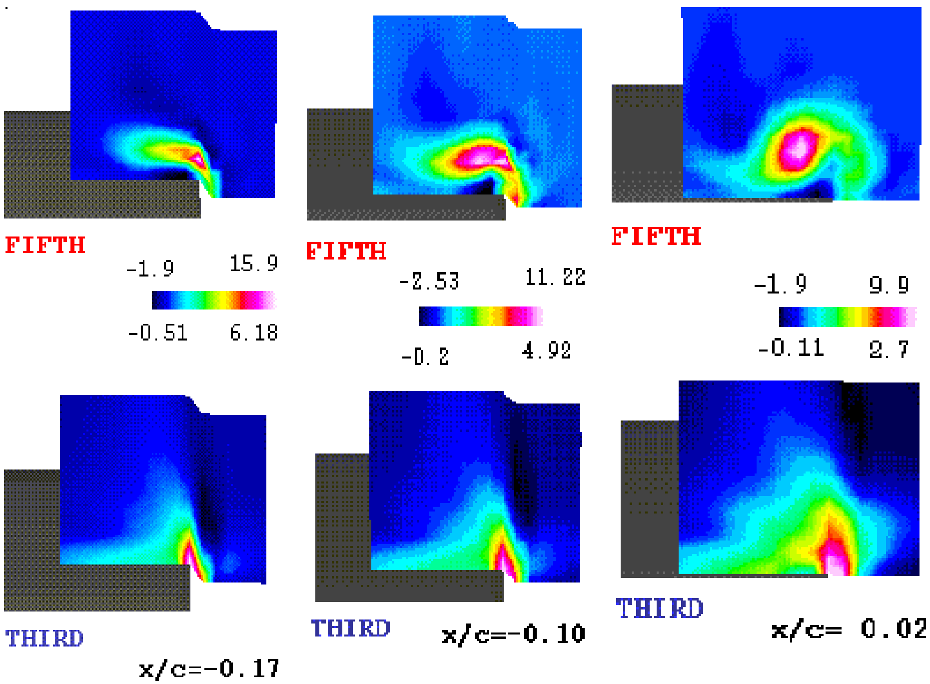
First-Principles Hover: Early/Mid-90s

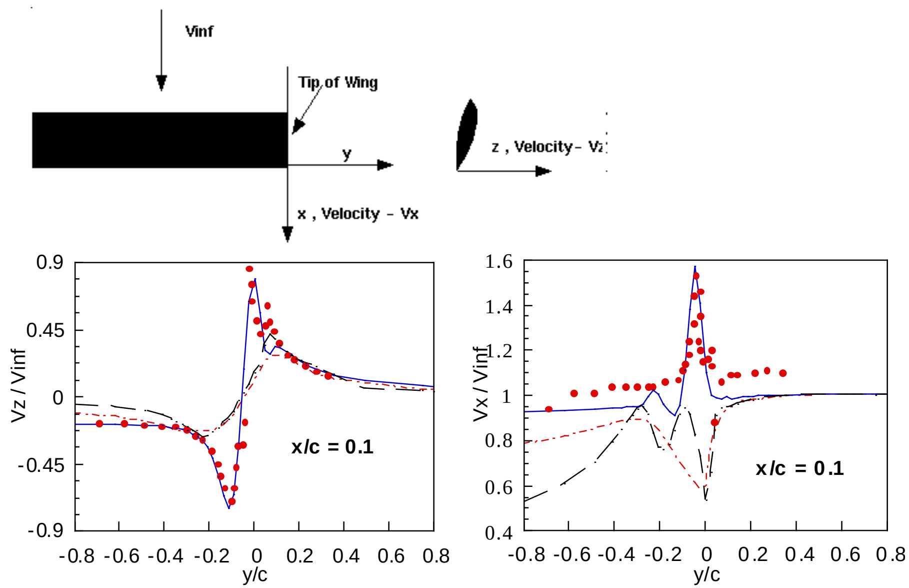


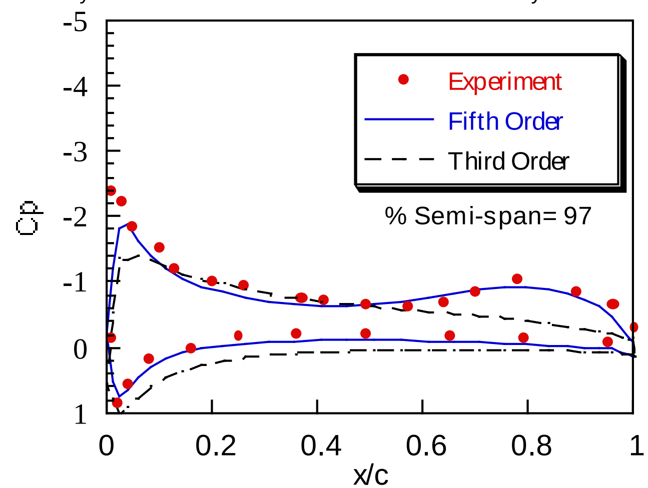


- Structured, cylindrical, periodic (i.e., Srinivasan and Baeder, Duque)
- Unstructured (i.e., Strawn and Barth)
- Second- /Third-order schemes; wake structure dissipated off rapidly

First-Principles Hover Enabler: (i) High-Order Methods



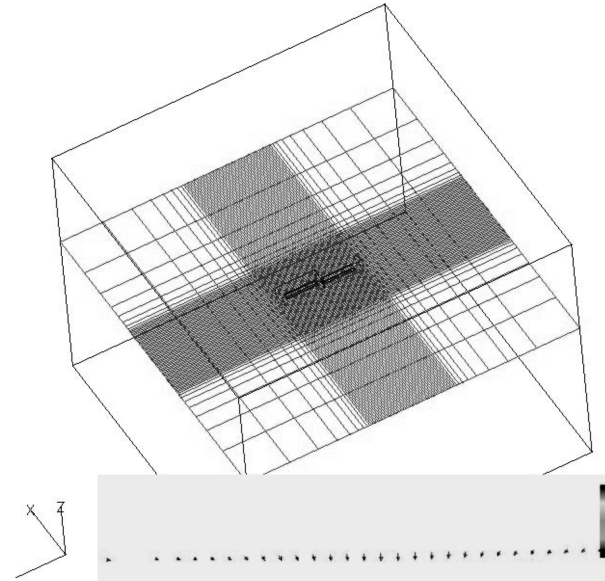


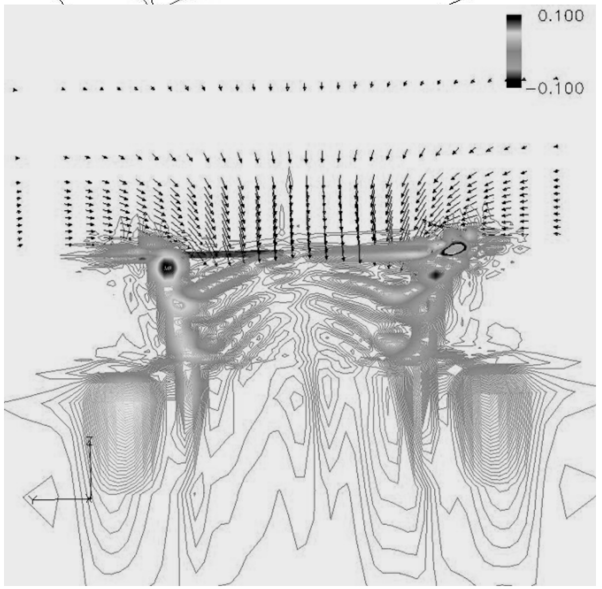


- **Structured grid HO methods (i.e., Hariharan and Sankar)**
- **5th- /7th-order spatially-accurate ENO/WENO schemes; higher efficiency of wake capturing (5th-order 8–10 points, 7th-order 4–6 points)**

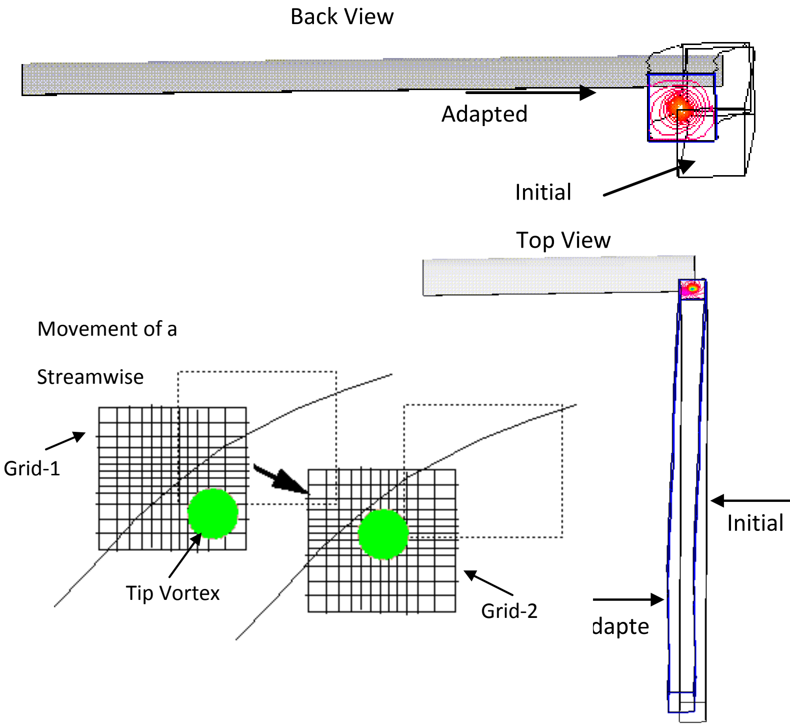
First-Principles Hover Enabler: (ii) Overset Methods

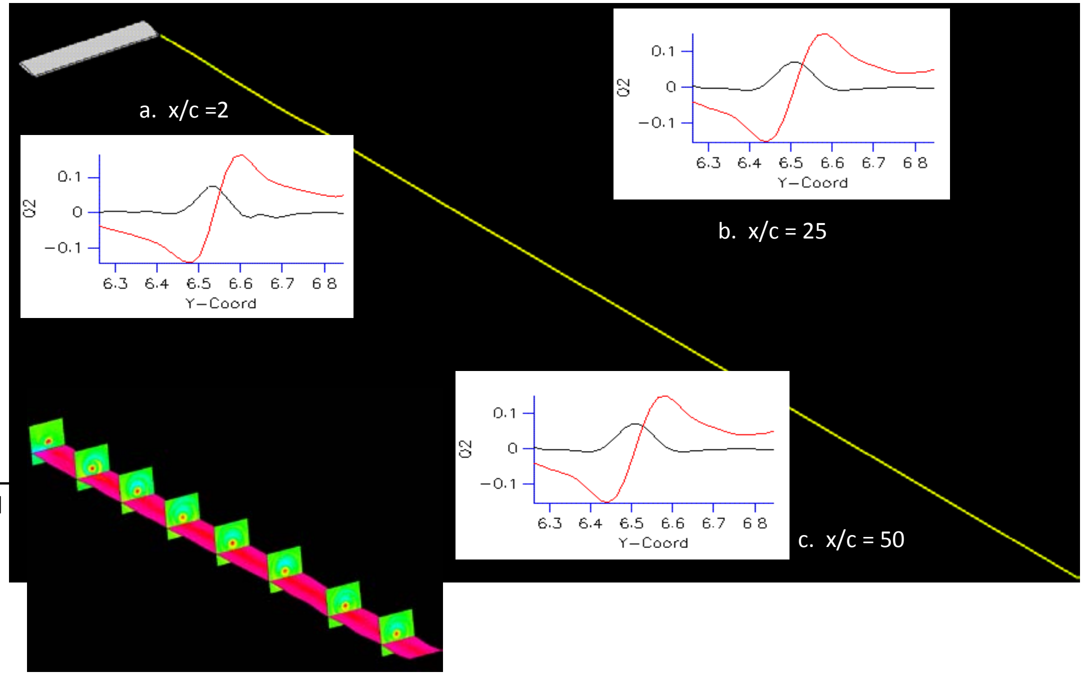
- **Put grid points in the path of wake**
- **Overset methods: For rotor interactional problems (i.e., McCroskey, Duque, et al., Ahmed, et al., Meakin, et al.)**
- **Overset + HO methods (i.e., Hariharan and Sankar) – Cartesian background**





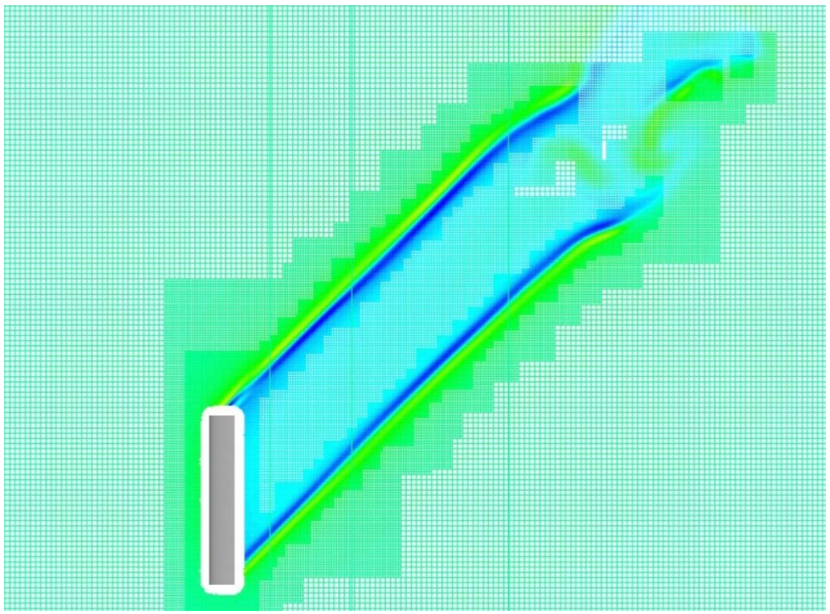
First-Principles Hover Enabler: (iii) Mesh Adaption/Refinement

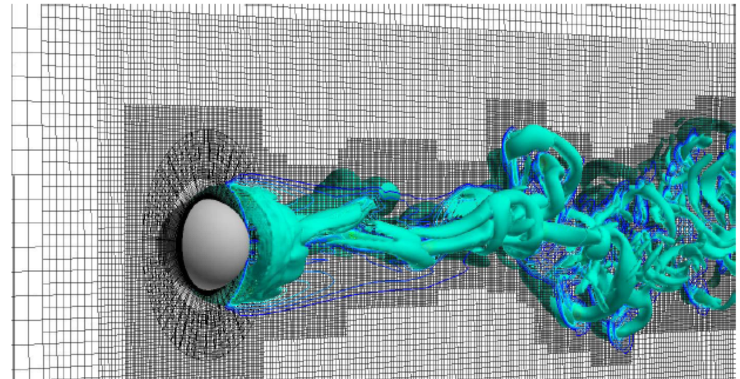


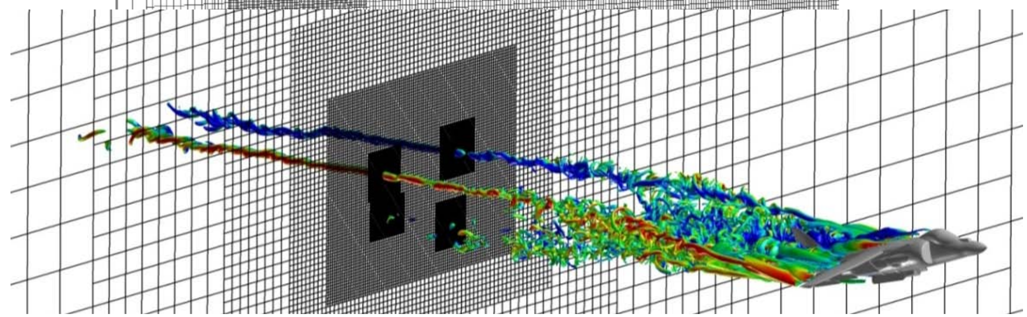


- Unstructured grid adaptive refinement of wake (i.e., Strawn and Barth)
- Structured adaptive mesh refinement (i.e., Vasilescu, et al.)
- Overset vortex grids (i.e., Dietz, Hariharan)

First-Principles Hover Enabler: (iv) Distributed, Scalabe Adaptive Mesh Refinement



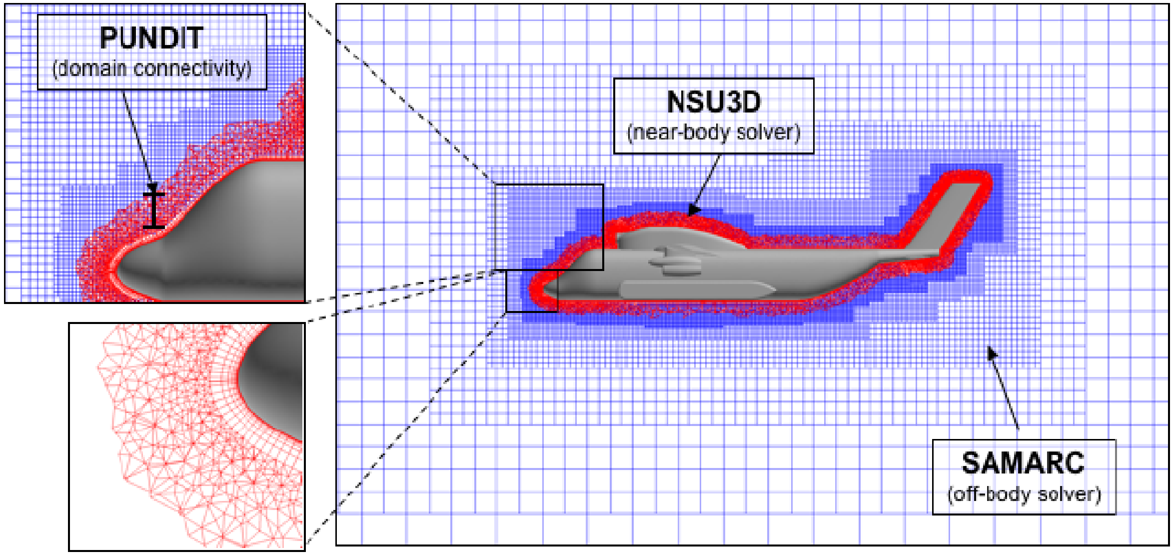




- **Overset adaptive mesh refinement to features (i.e., Meakin, Holst, and Pulliam)**
- **Unsteady parallel AMR (i.e., Wissink, et al.) – refines AND de-refines to provide grid points where required**
- **Parallel automated oversetting (i.e., Sitaraman, et al.)**

CREATE-AV Helios

- **Cartesian off-body grids**
  - No skew, efficient
- **Fifth-order spatial accuracy (off-body)**
- **Flow-based Cartesian grid refinement**
- **Automated overset infrastructure**

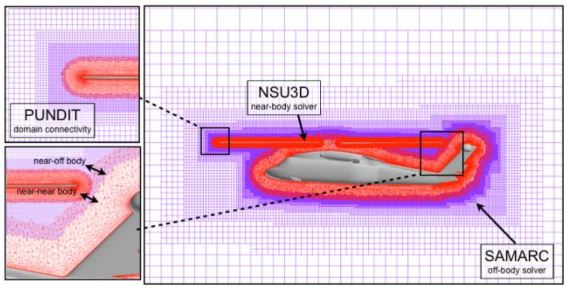


AIAA-2012-0713: Capability Enhancements of the Helios v3.0 High-Fidelity Rotorcraft Simulation Tools

CREATE-AV Helios

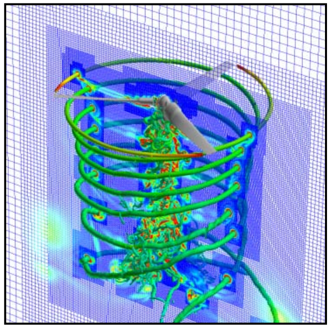
Helios *Helicopter Overset Simulations*

Dual Mesh Paradigm



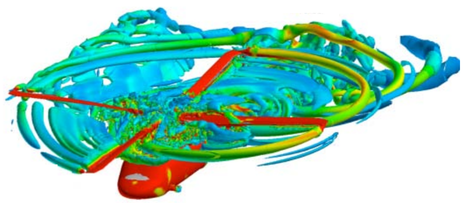
Unstructured near-body cartesian off-body

Adaptive Mesh Refinement



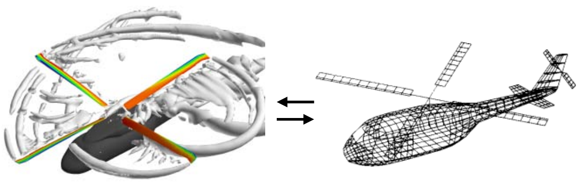
To resolve wake

Moving Body Overset



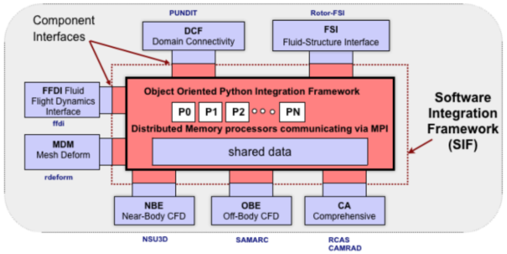
Rotor-fuselage and multi-rotor moving mesh support

CFD/CSD Coupling



RCAS and CAMRAD structural dynamics and trim coupling

Advanced Software Infrastructure



Python-based infrastructure readily supports addition of new software

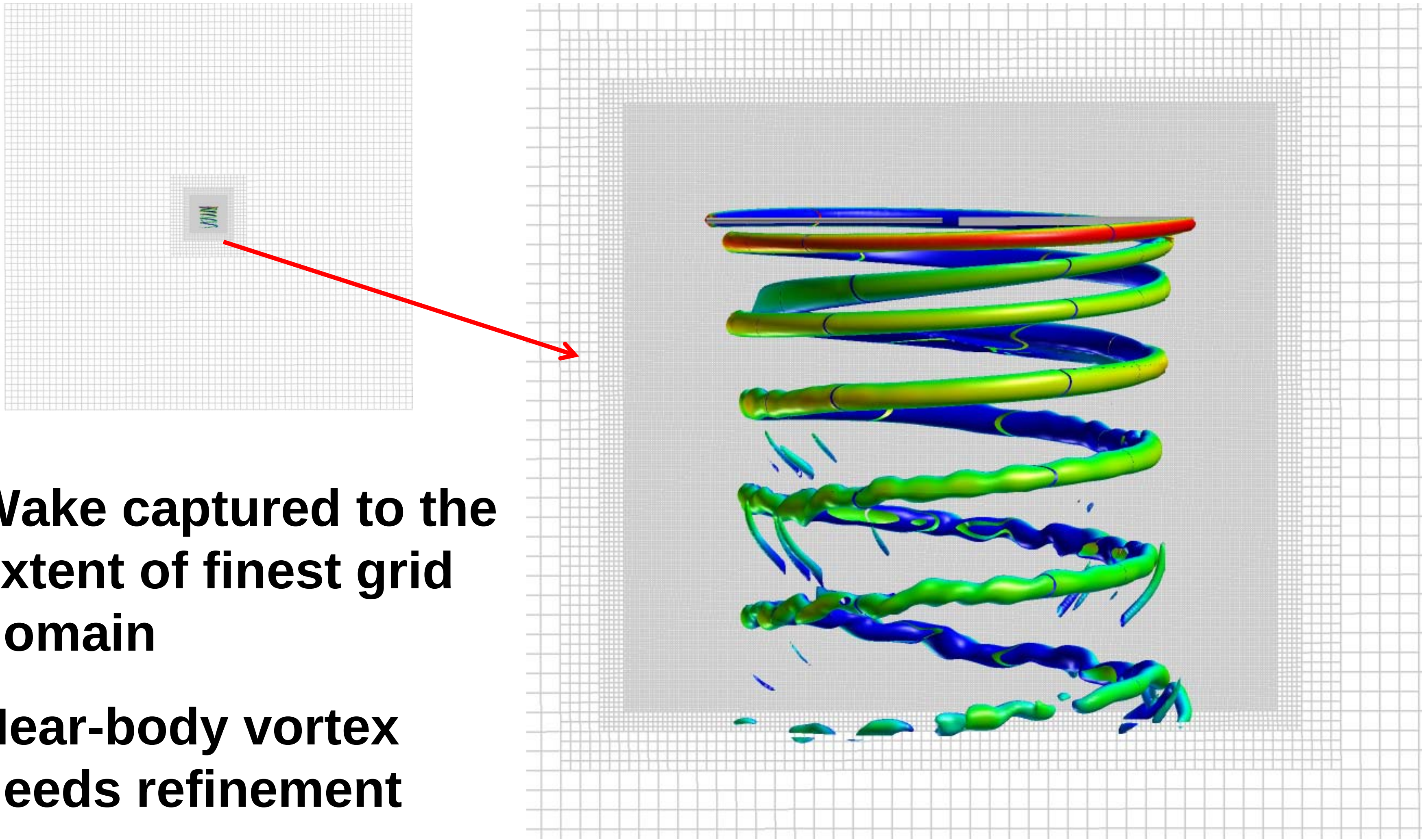
High Performance Computing

Runs on HPC hardware with focus on parallel scalability

Helios Results from Rotor in Hover

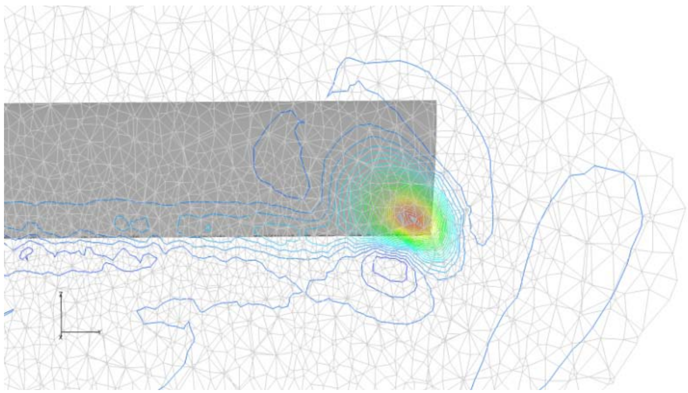
- Two-bladed Rotor, Caradonna and Tung
- Three-bladed Rotor, TRAM
- Six-bladed Rotor, RAH66
- Ducted Rotor

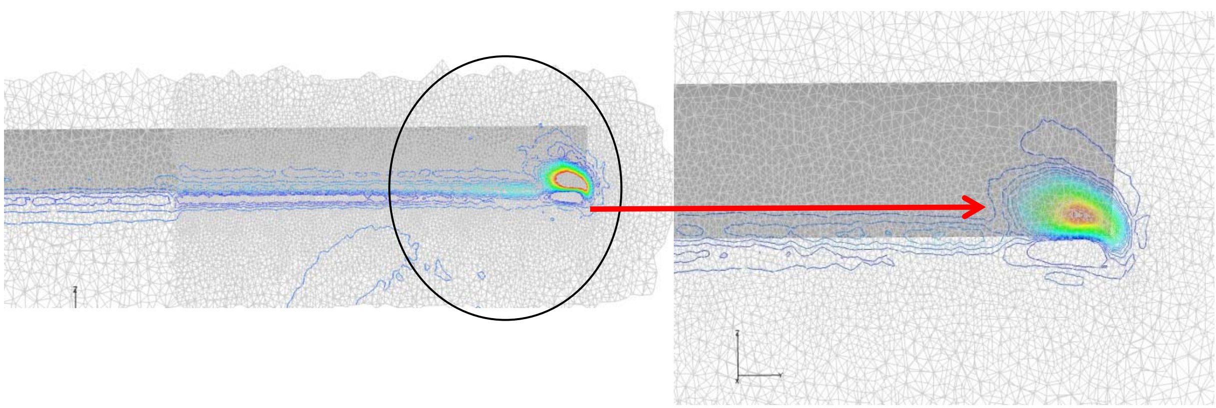
Non-Adaptive Mesh Refinement (AMR) Solution



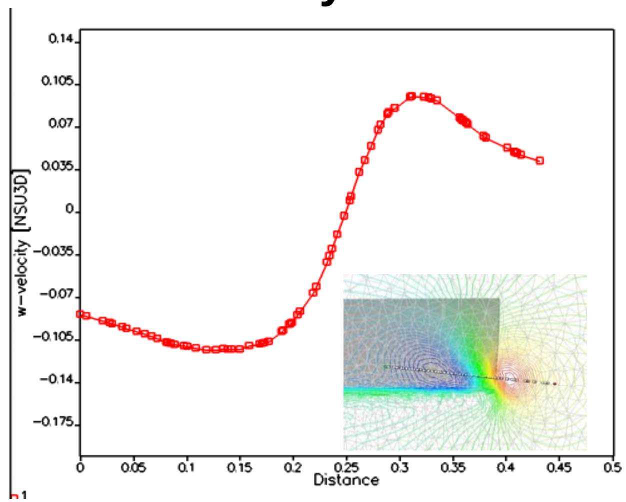
- **Wake captured to the extent of finest grid domain**
- **Near-body vortex needs refinement**

Near-Body Grid Refinement

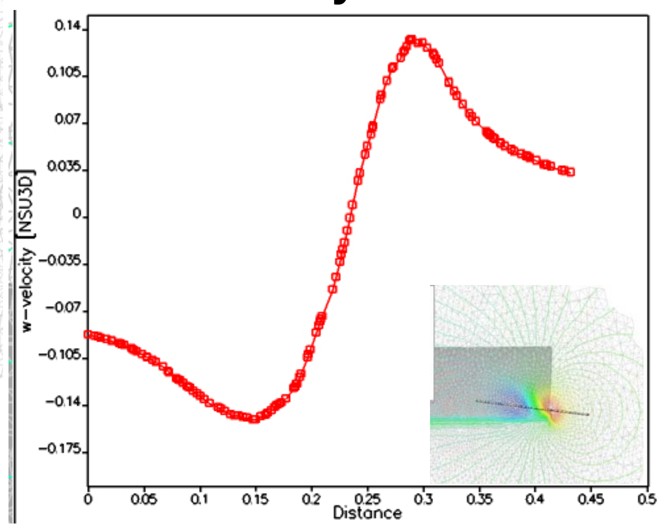




Near-Body Grid – R0



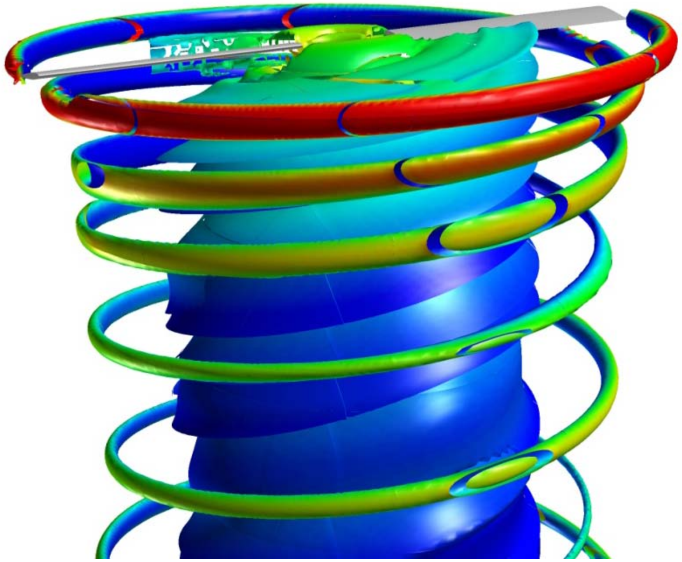
Near-Body Grid – R1



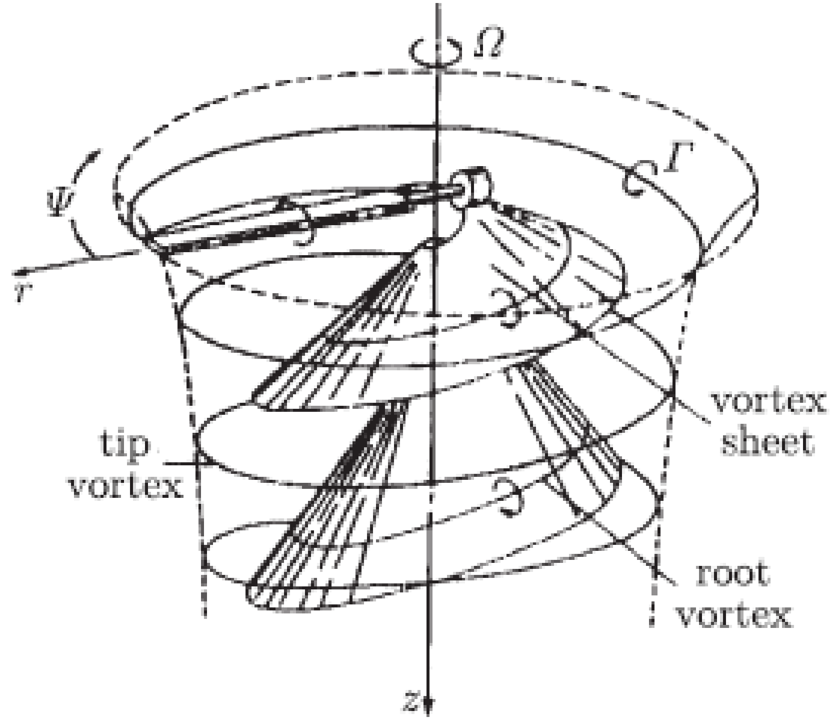
- **Near-body tip refinement improves load predictions**

Wake of Rotor in Hover

5th-Order Cartesian, 18 cells/chord off-body



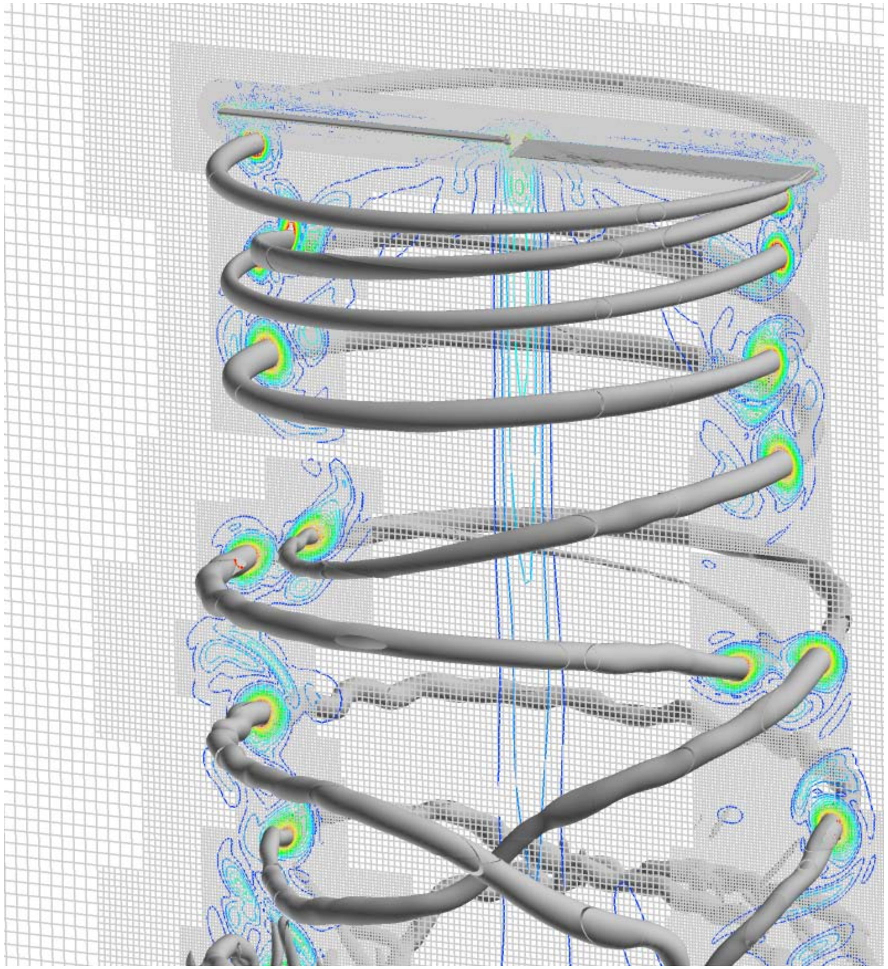
Classical Schematic



- **Captures the tip vortex and wake sheet structure**
- **Predicted blade load of C_T =0.0048 (experimental C_T =0.0046)**

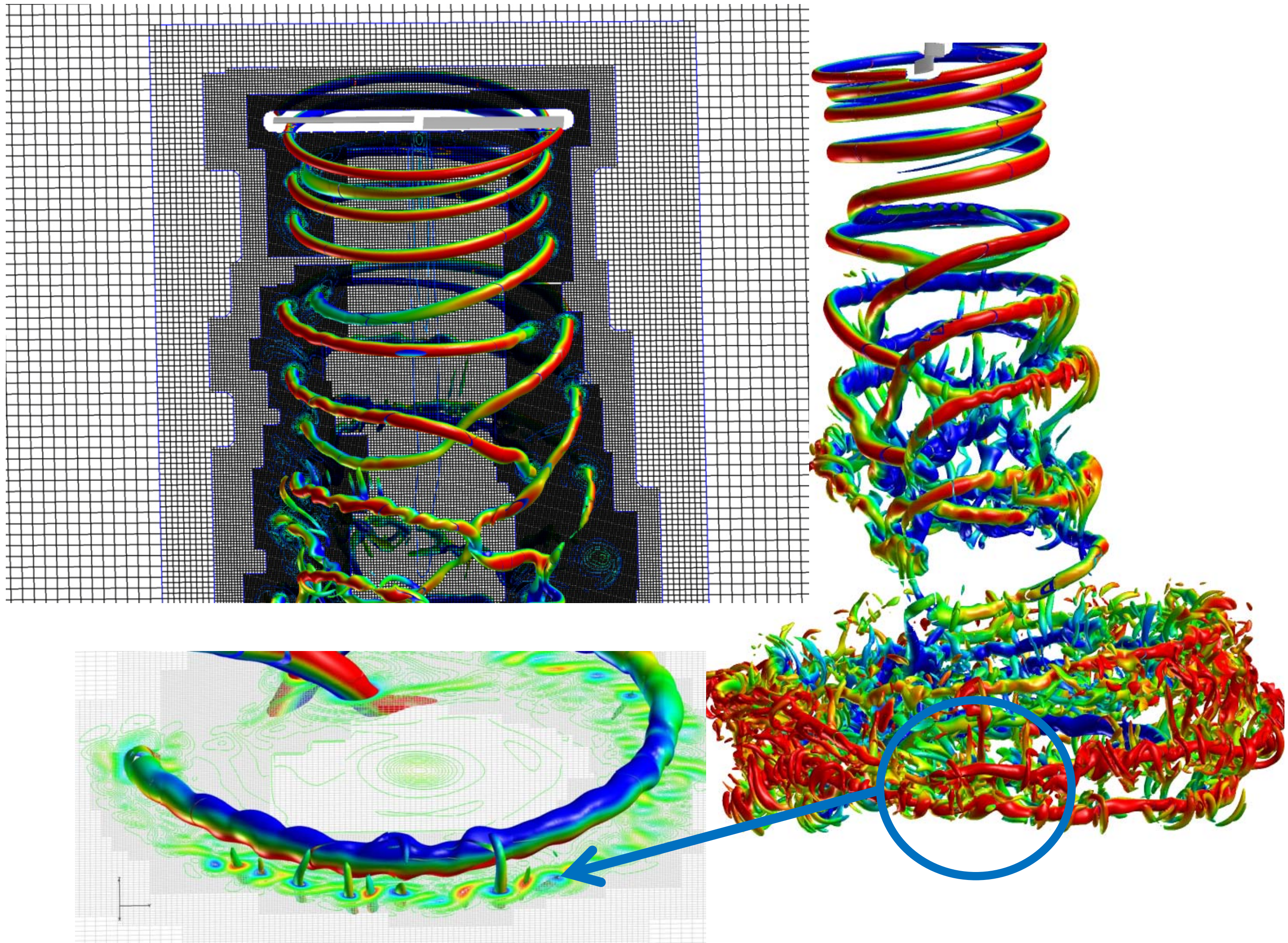
Wake of Rotor in Hover (AMR)

- **Cartesian AMR resolves the wake more efficiently targeting the tip vortex (fewer finest-grid cells)**
- **No further change in blade loading**



Secondary Vortex Braids (AMR Solution)

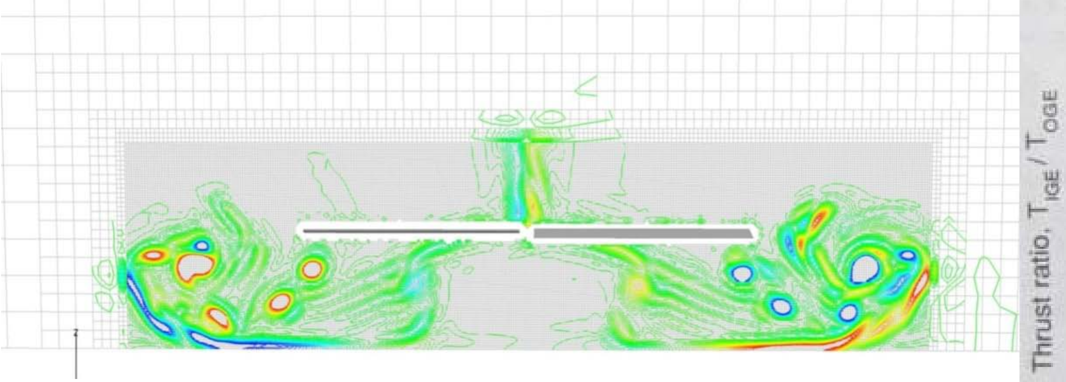
- Secondary vortex braids appear in the far-wake
- No bearing on the load convergence
- Secondary braid vorticity associated with instability patterns when far-wake helical braids come together



Near-Ground Hover

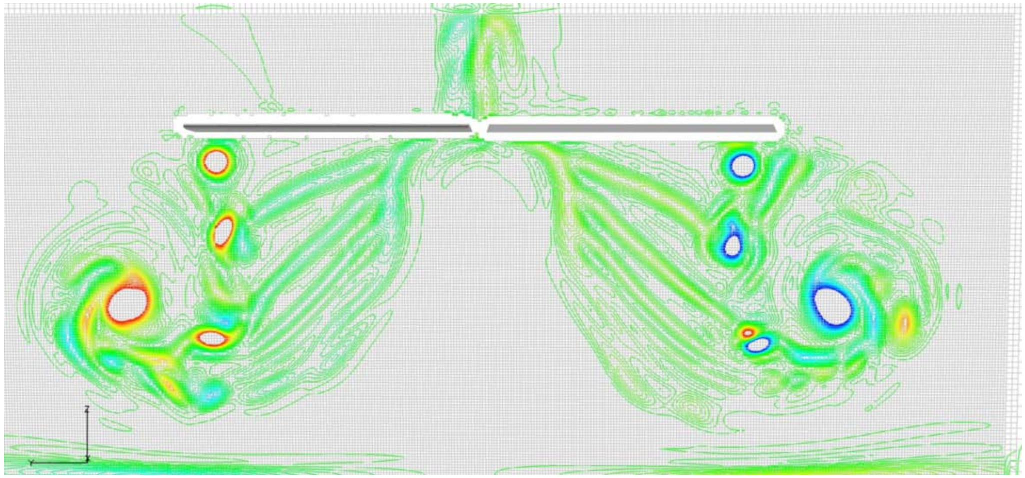
Rotor at z=0.5R

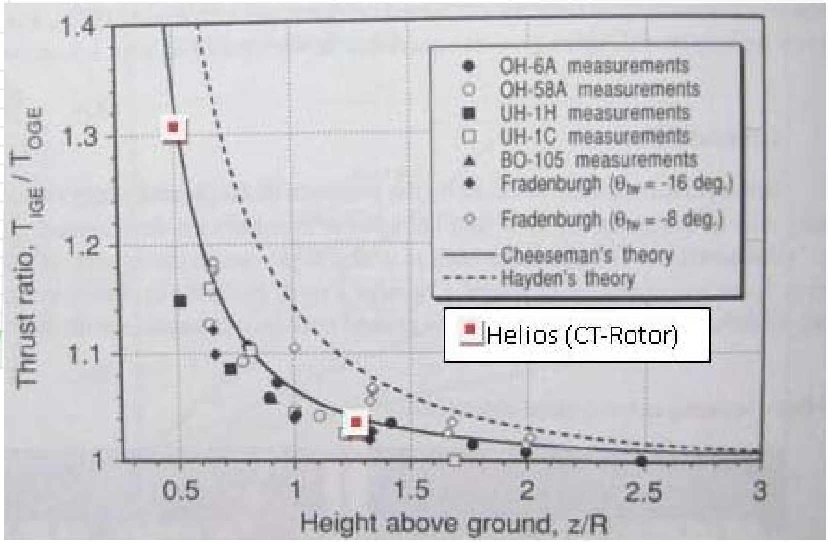
- Flared-out vortex wake structure



Rotor at z=1.25R

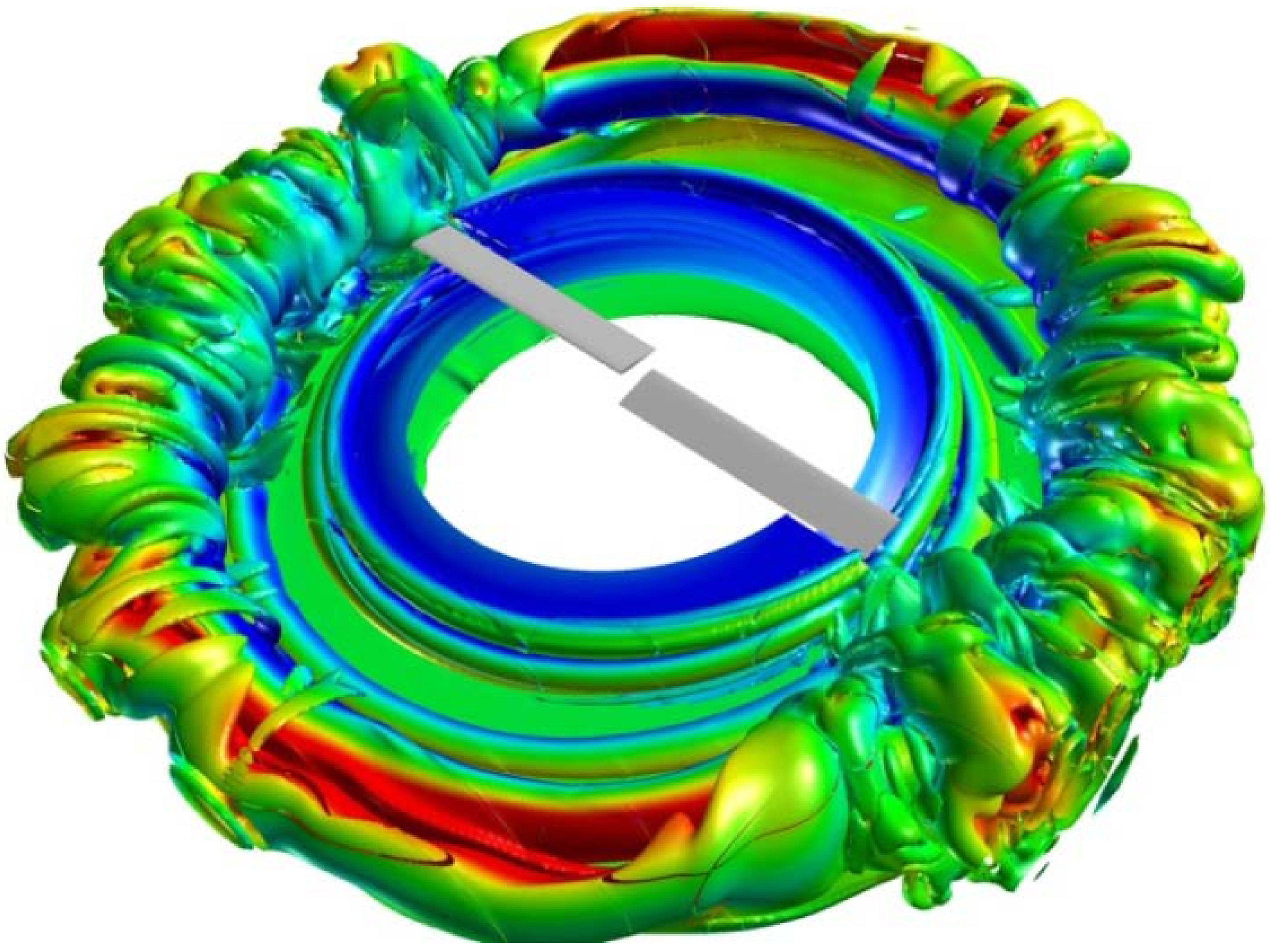
- Flow-field tending towards OGE solenoidal pattern





(From Leishman, Helicopter Aerodynamics)

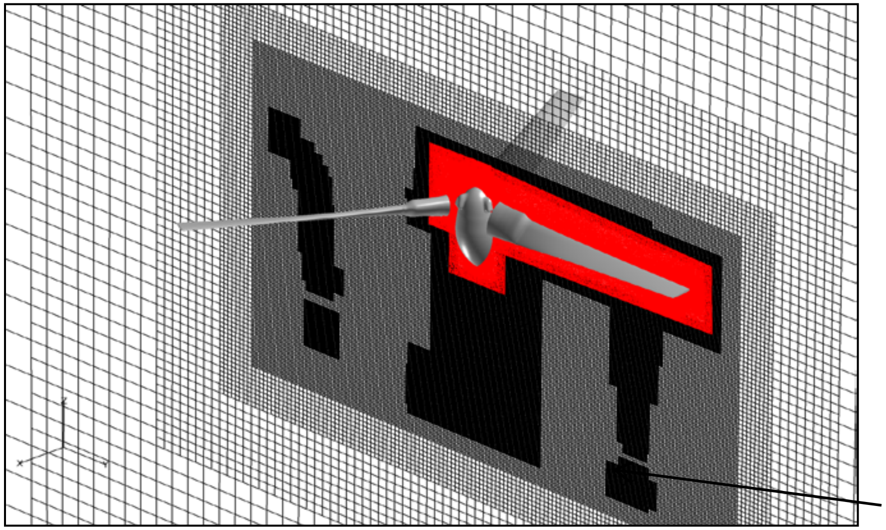
Near-Ground Hover Vortex Pattern

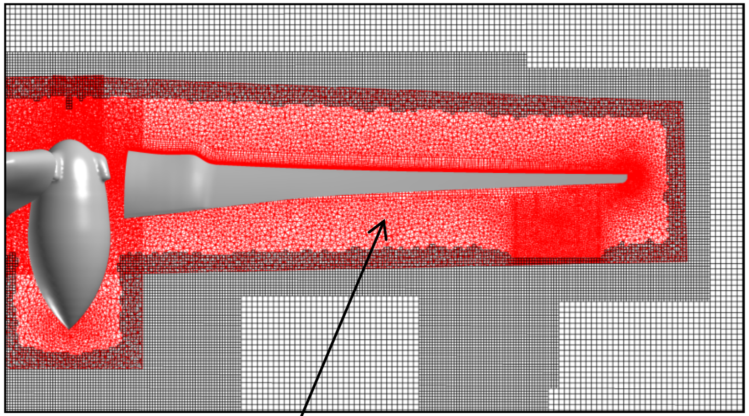


- **Toroidal vortex ring structure with secondary braided circumferential structures**

TRAM Isolated Rotor

- **Tilt Rotor Aeroacoustics Model (TRAM)**
  - Quarter-scale model V-22 Osprey
  - Experiments at DNW (1998) and NASA Ames (2000)
- **Computational conditions:**
  - Rigid blade
  - $q=14°$ collective, $M_{tip}=0.625$, $Re_{Tip}=2.1M$

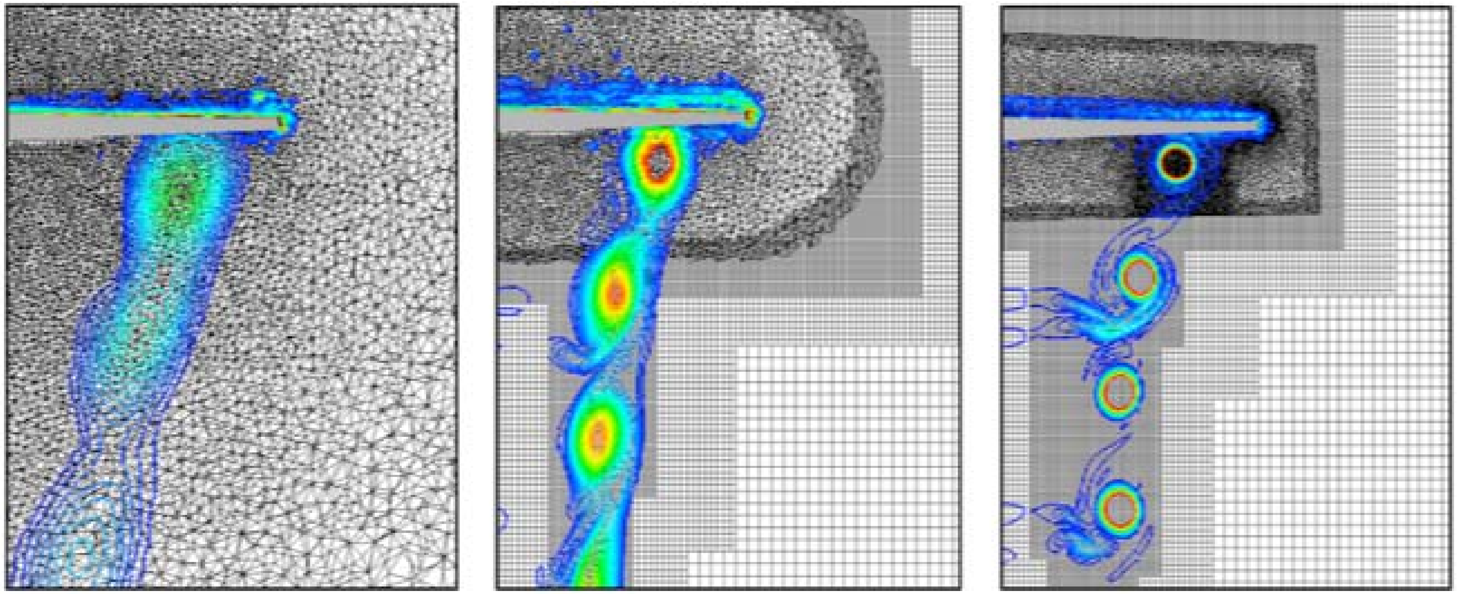




Near-body rotor mesh: 9.3M nodes

Off-body finest-grid resolution: $\Delta x = 0.05c$

Wake of Rotor in Hover (AMR)



Standalone
unstructured

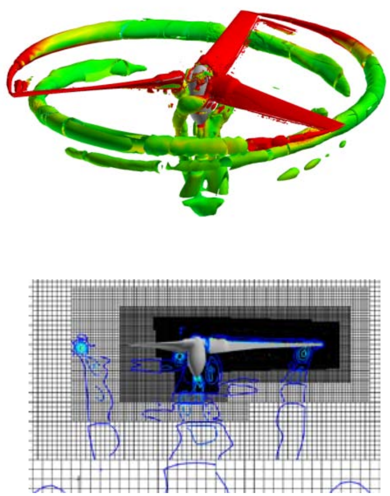
Med NB mesh
8L AMR OB mesh

Fine-a NB mesh
8L AMR OB mesh

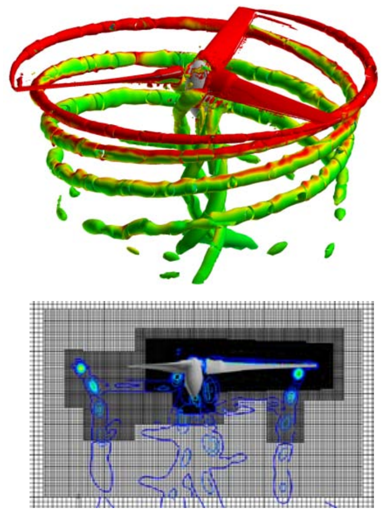
- **Near-body and off-body refinement to get the wake right**

Feature Detection Augmented with Richardson Error

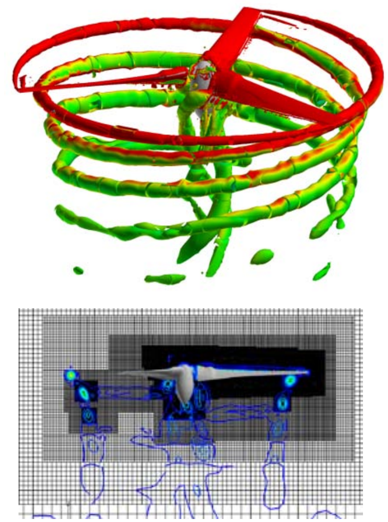
err = 10e-3



err = 10e-4



err = 10e-5



err = 10e-6

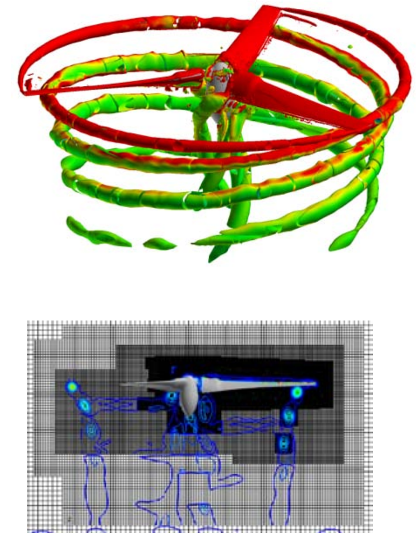
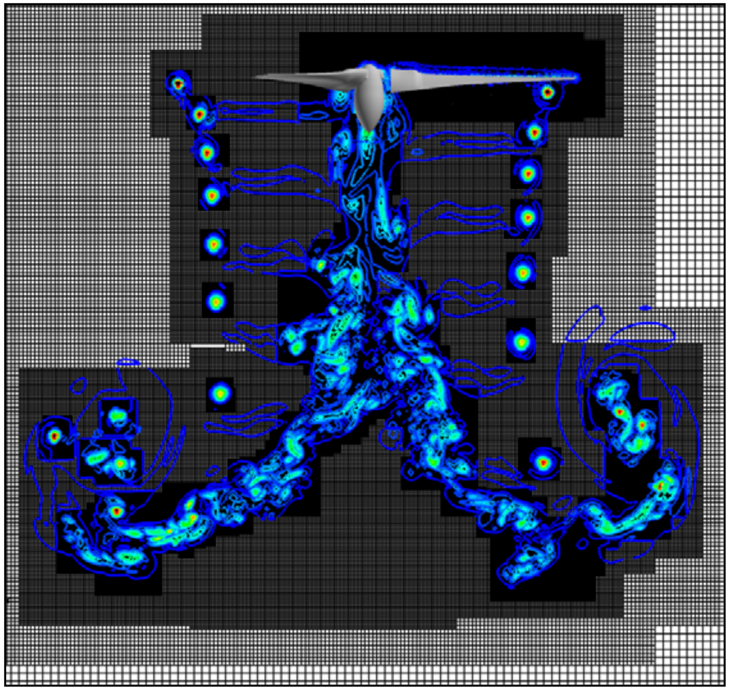


	Figure of Merit	Difference	Mesh Points
Experiment	0.774	-	--
err = 10e-3	0.760	-1.8% (+/- 0.4%)	9.6M
err = 10e-4	0.767	-0.9% (+/- 0.4%)	13.2M
err = 10e-5	0.768	-0.8% (+/- 0.2%)	14.2M
err = 10e-6	0.769	-0.6% (+/- 0.2%)	14.3M
no error	**0.773**	**-0.1% (+/- 0.2%)**	**86M**

Tightening error tolerance improves the computed FM

6X fewer gridpoints

Finest TRAM Wake



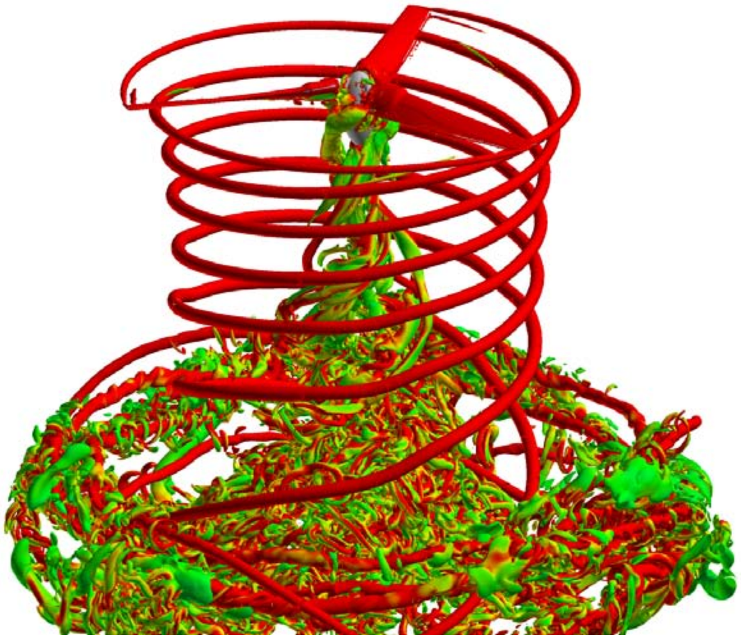


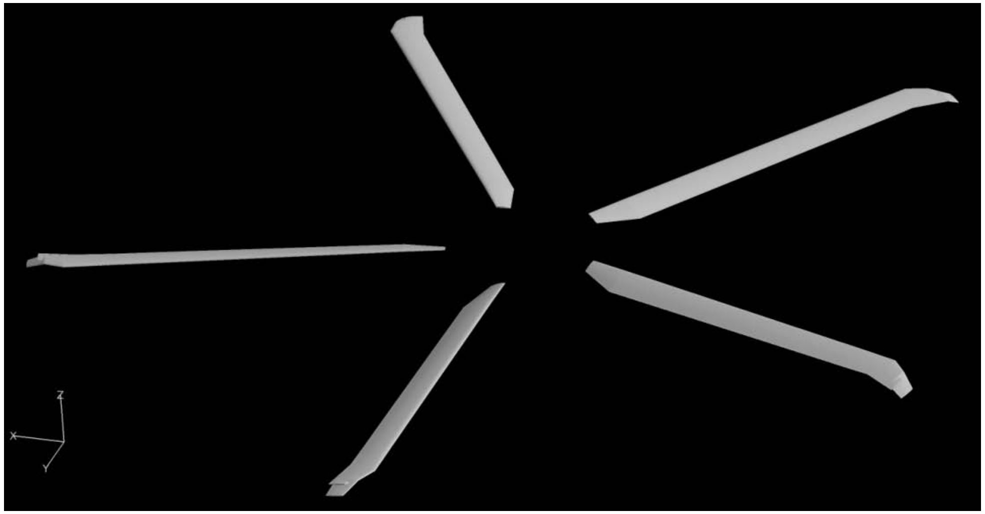
	Figure of Merit	Difference	Mesh Points
Experiment	0.774	-	--
Computation	0.773	-0.1% (+/- 0.2%)	86M

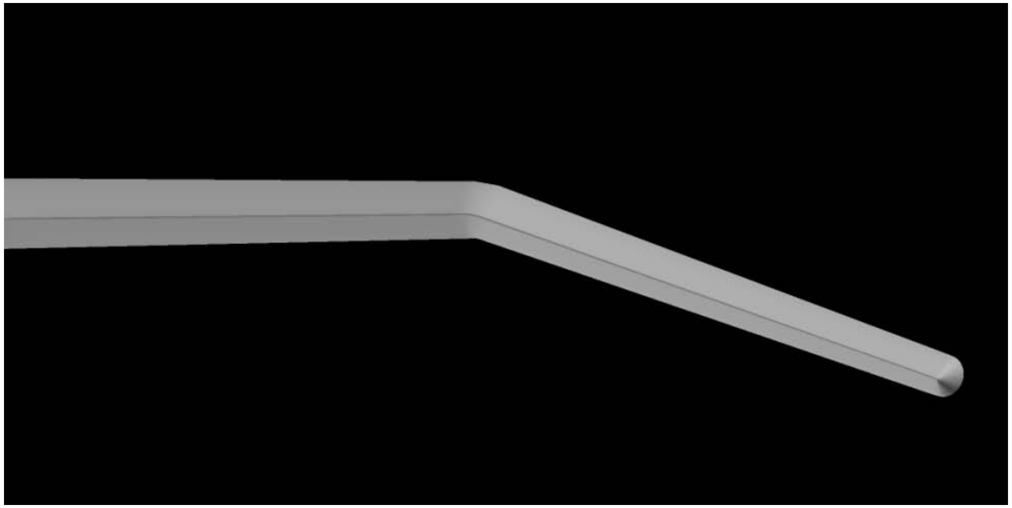
- **Finest mesh resolution applied to all regions of swirling flow**

Capability: Anhedral Blade in Hover

RAH Comanche Hover

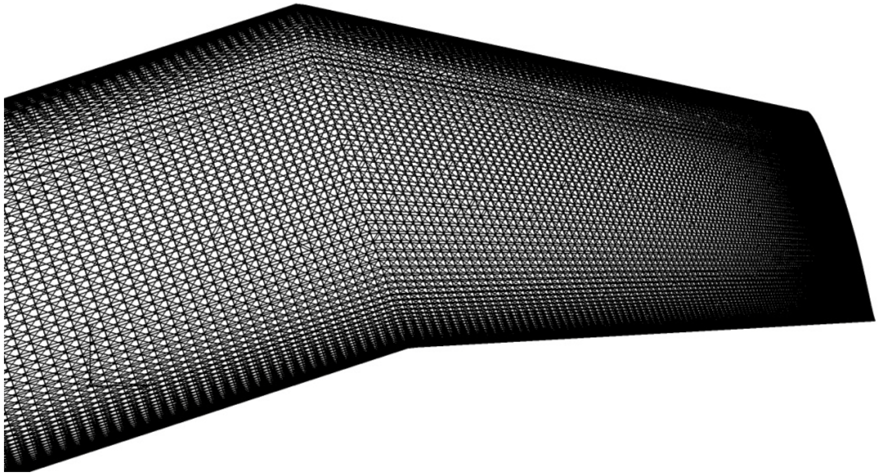
- **Five- (5) bladed rotor: Straight and improved anhedral tip**
- **AED (Huntsville, AL) ACRB blade solution issues inspired this case**
- **Approximate RAH anhedral**

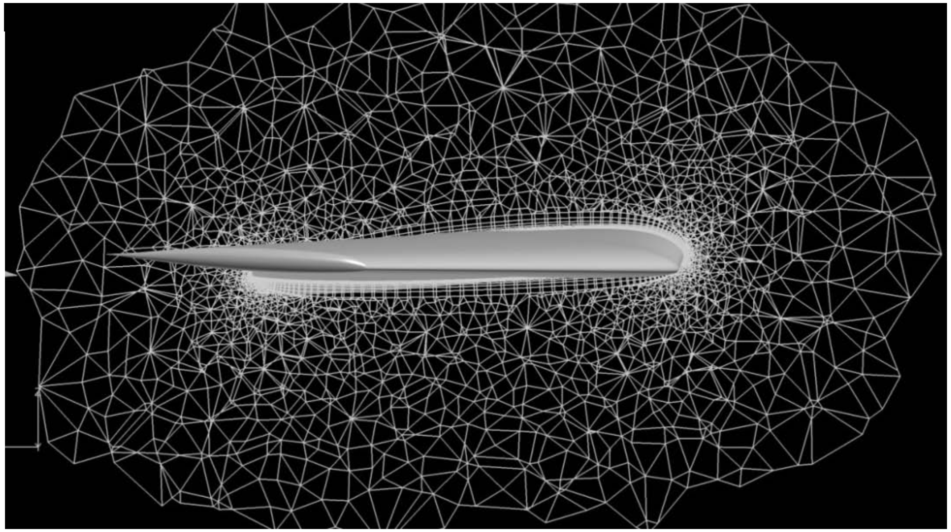




Grids

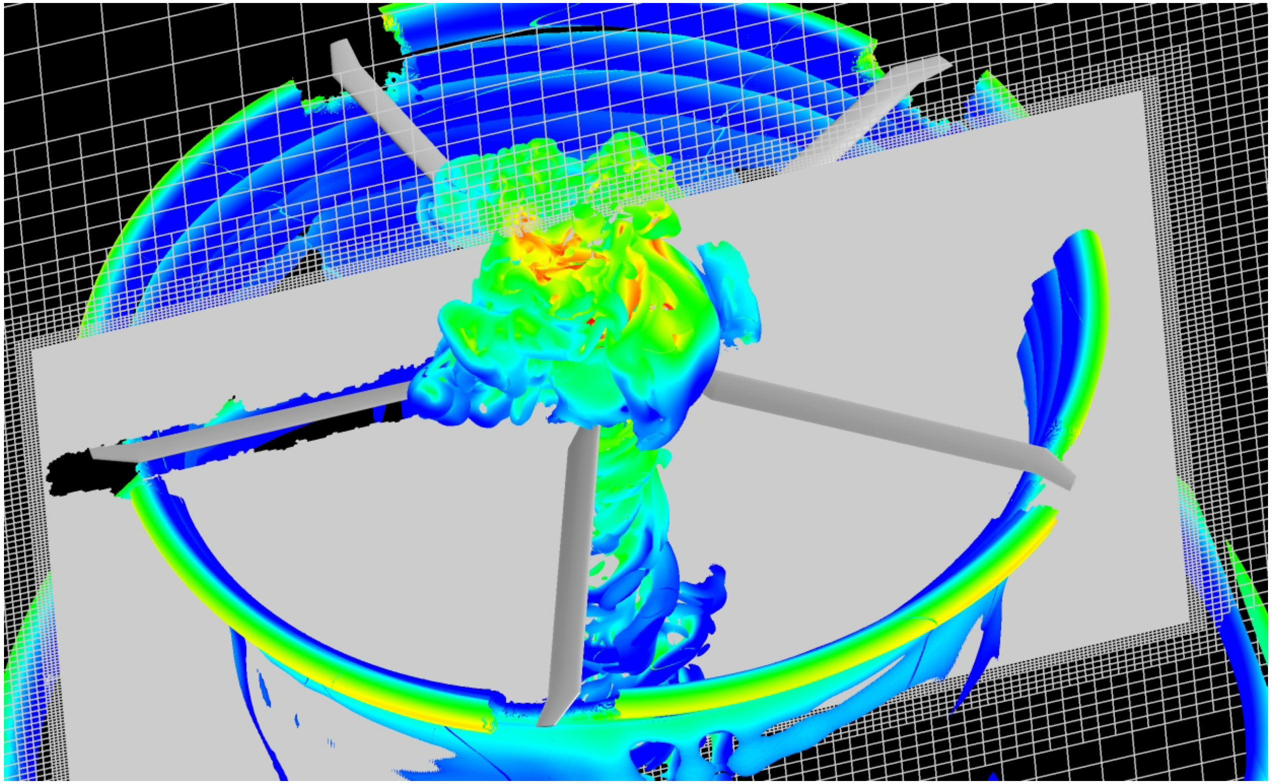
RAH Comanche Hover





- **Point-wise surface grids and AFLR volume grids**
- **Five (5) blades, ~6 million/blade**

Fixed Off-Body Grid Solution
RAH Comanche Hover



- Straight and anhedral blade solutions ran well with default settings
- Weak vortex system feeding the off-body

Aerodynamic Loads

RAH Comanche Hover

Collective Pitch = 0			
	CT	CQ	FM
Baseline	0.0002627	0.000125	0.024
Anhedral	0.00020181	0.000145	0.014

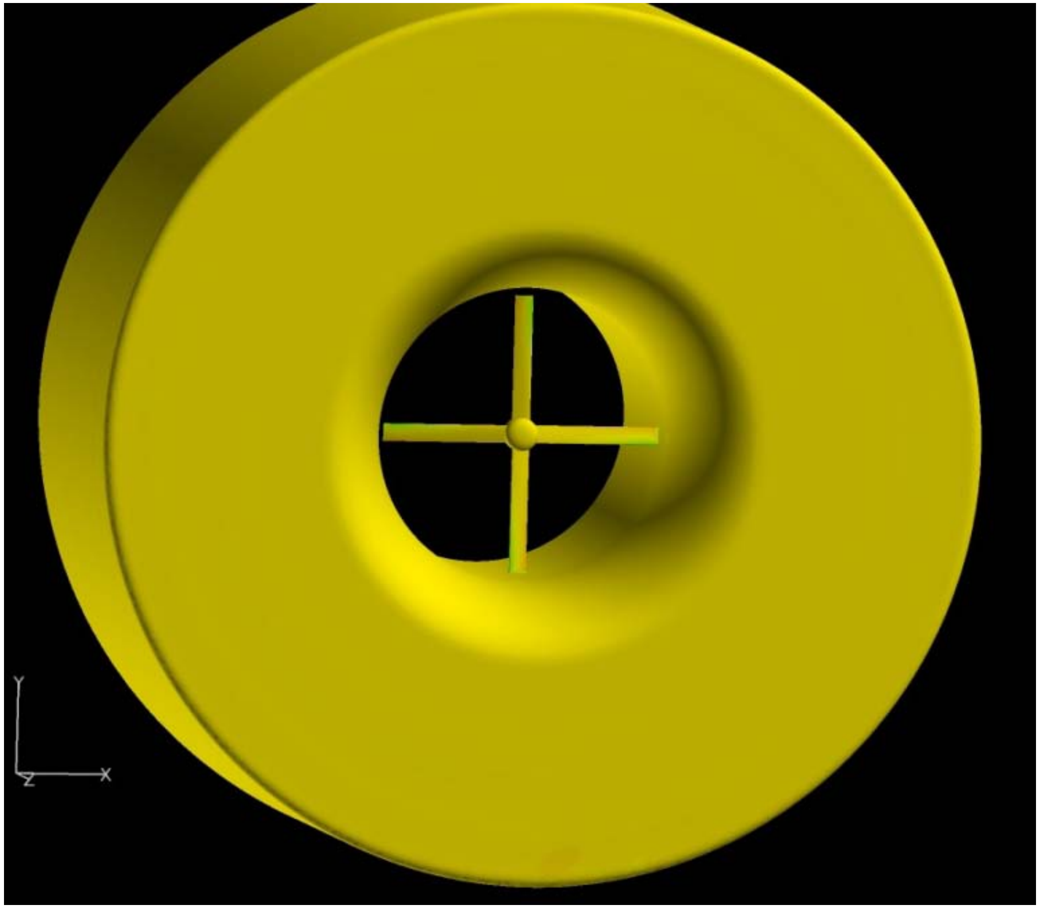
Collective Pitch =10			
	CT	CQ	FM
Baseline	0.008365	0.0008873	0.609
Anhedral	0.009079	0.000979	0.624
Anhedral (Adaptive)	0.009281	0.000988	0.6397

- **Correct trending – Anhedral improves hover efficiency at operating collectives**

Capability: Ducted Fan

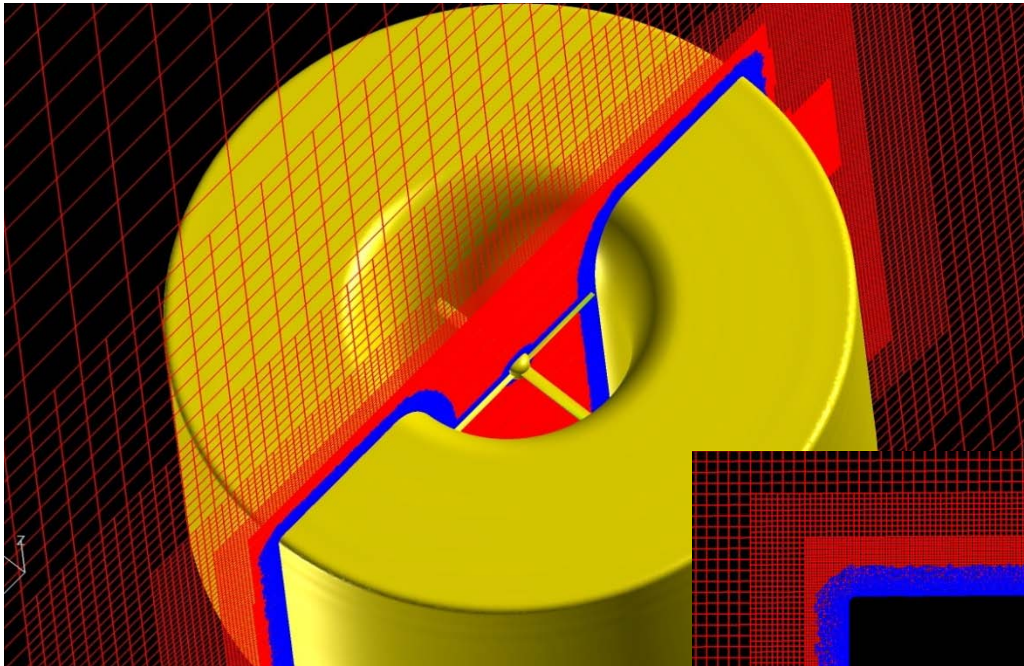
ARL Ducted Fan

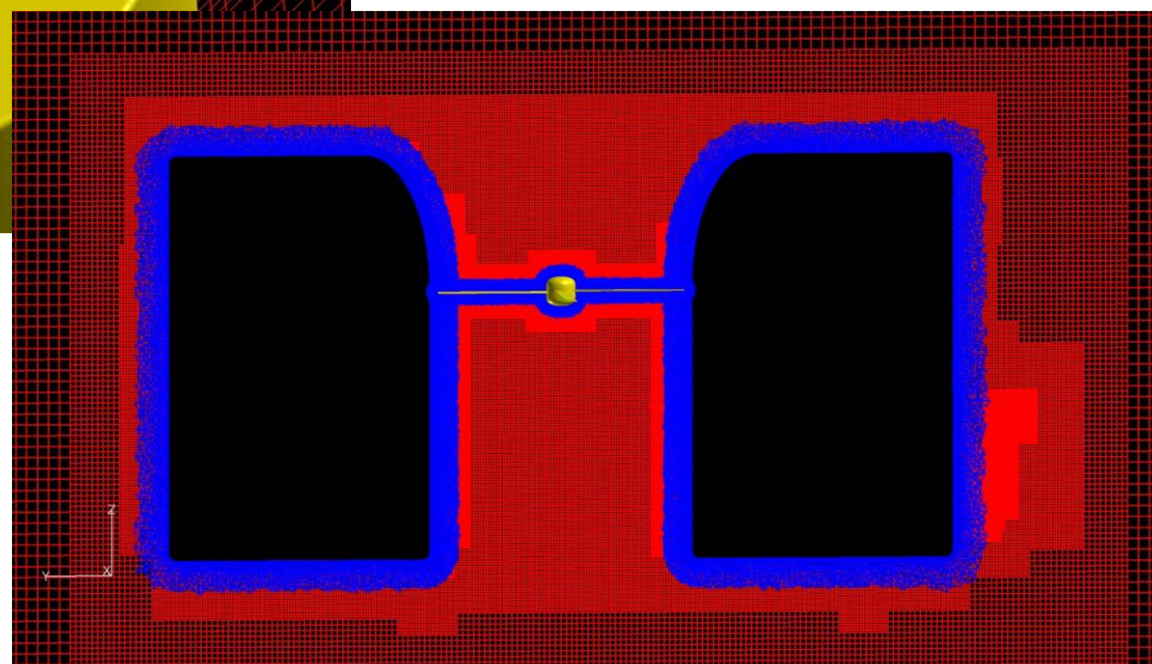
- ARL (Aberdeen, MD) conceptual design case
- Multi-component, close proximity
- External/Internal flow
- Point-wise/AFLR grids for duct and rotor+hub



Near-Body and Adapted Off-Body Grids

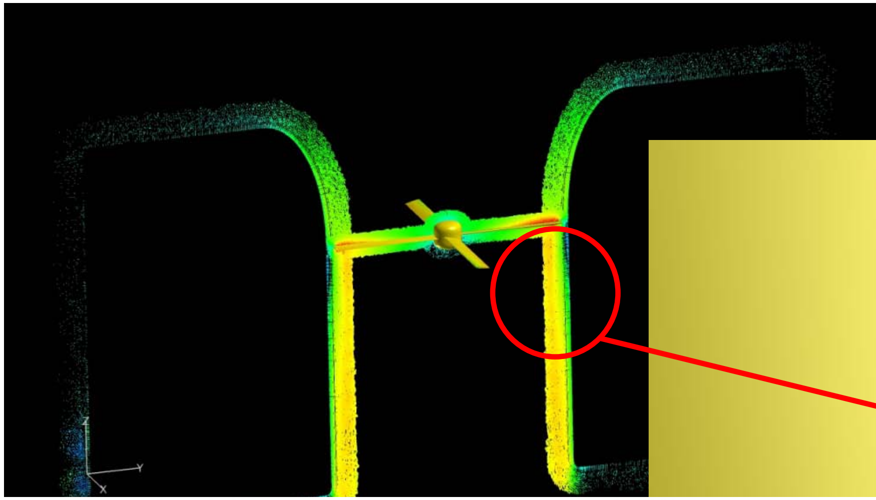
ARL Ducted Fan

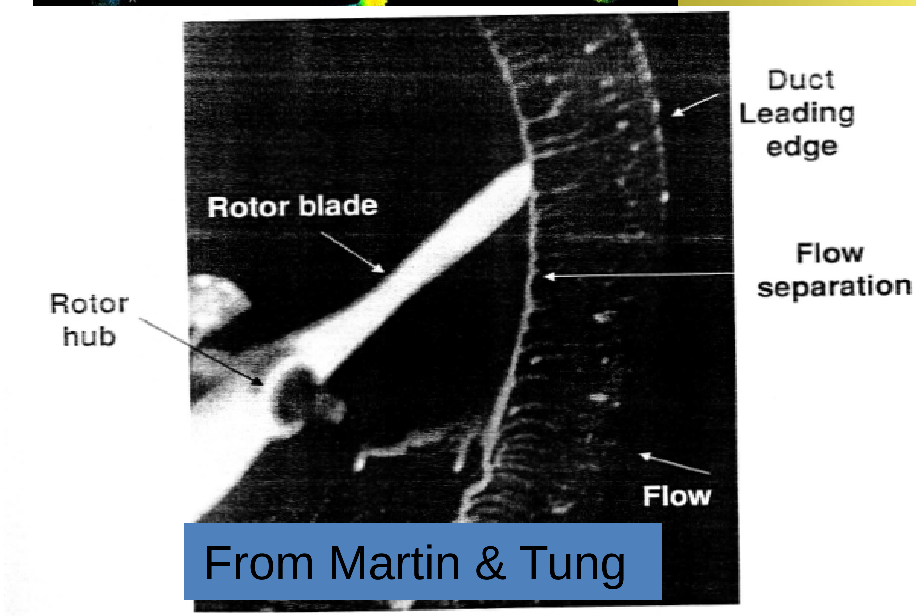




QAT 2012 – Helios v3

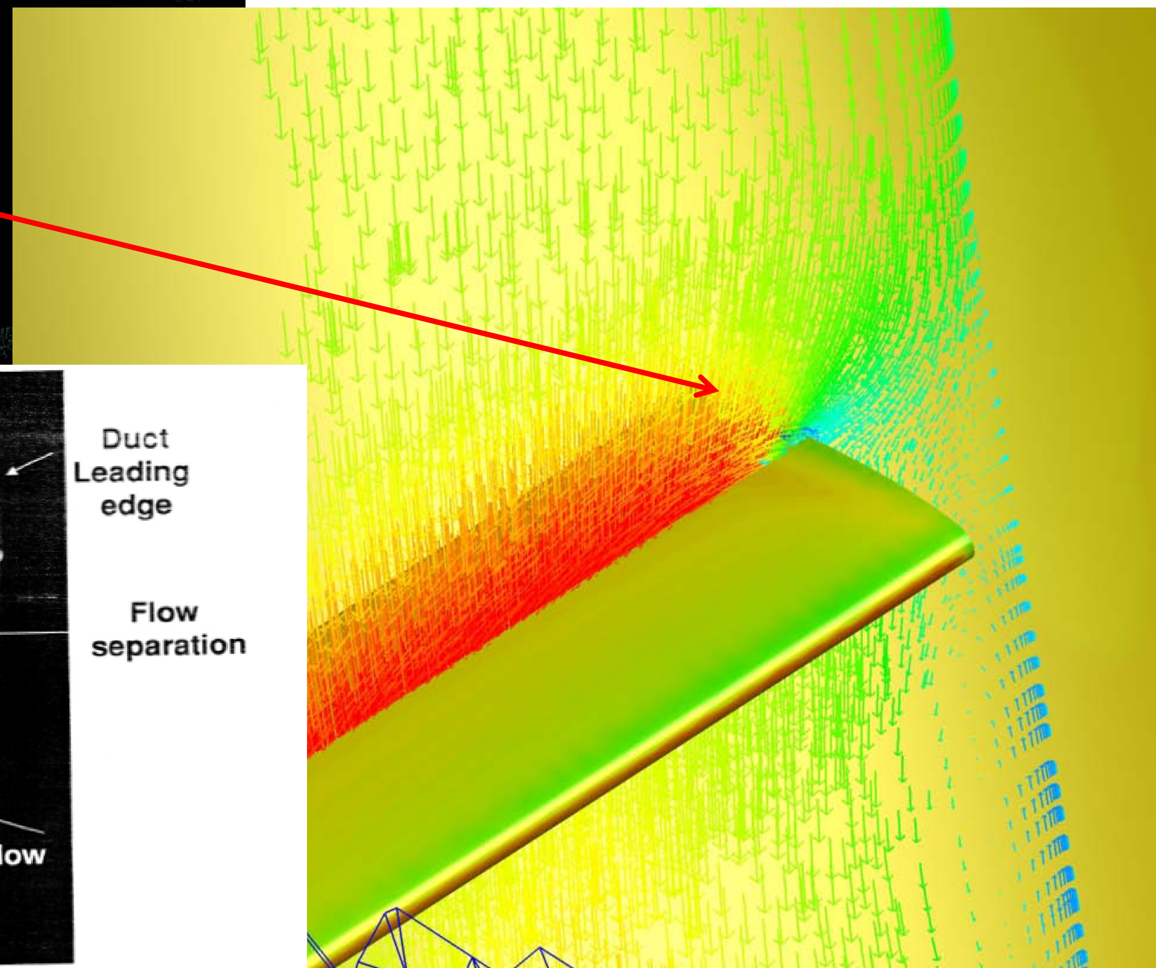
ARL Ducted Fan





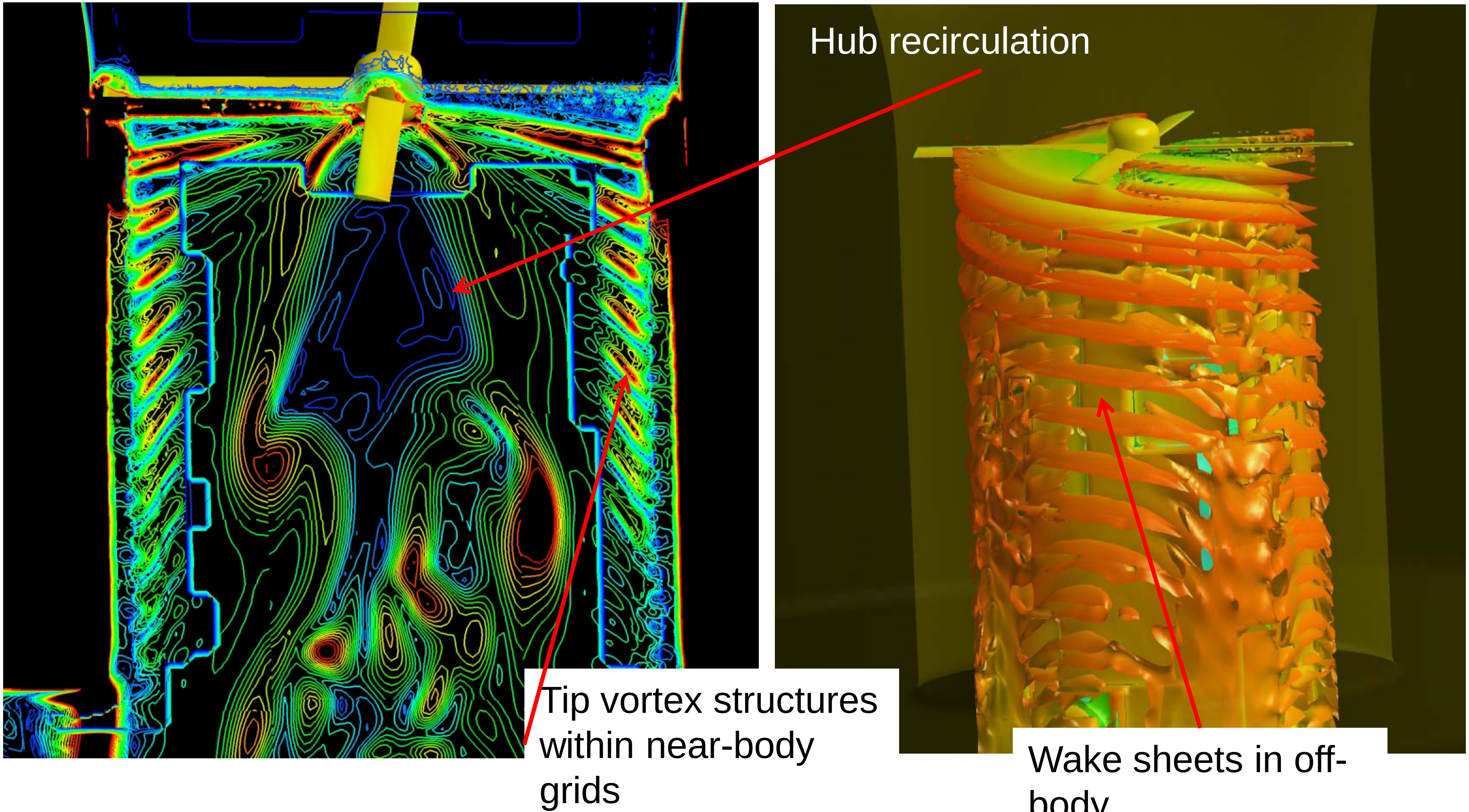
From Martin & Tung

Tip path plane Separation



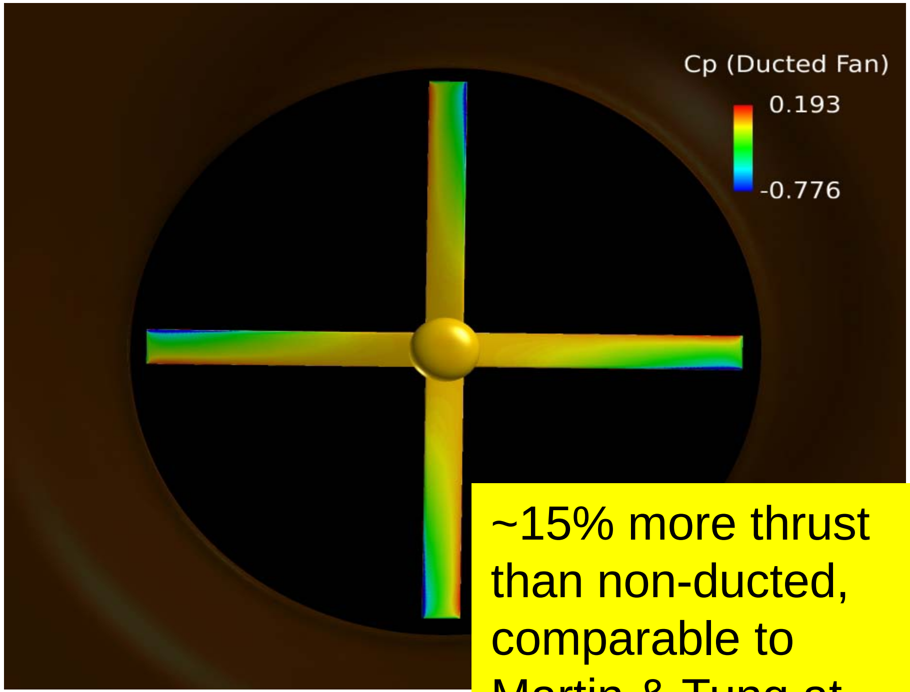
Duct Vorticity Contours

ARL Ducted Fan

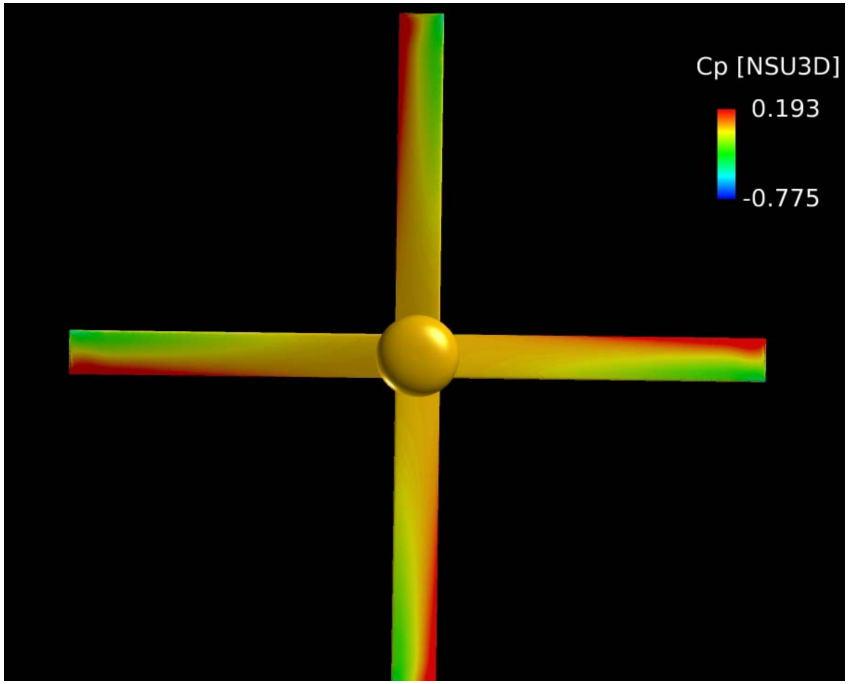


Ducted Rotor Tip Efficiency

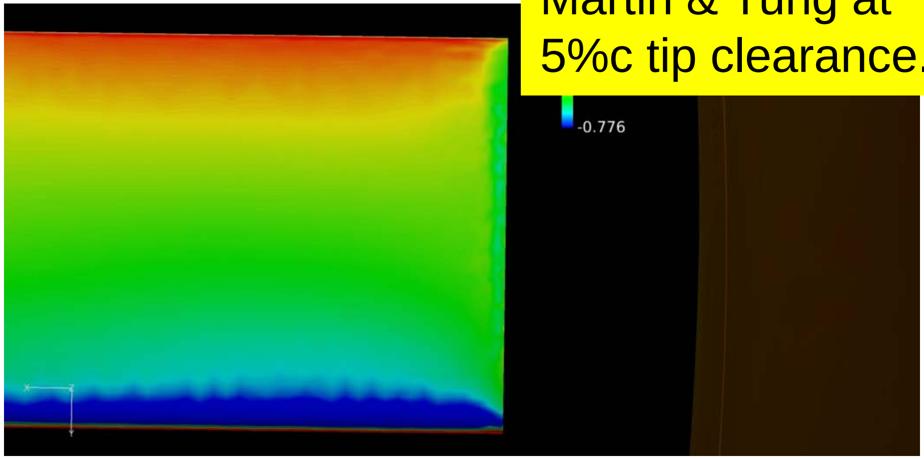
ARL Ducted Fan

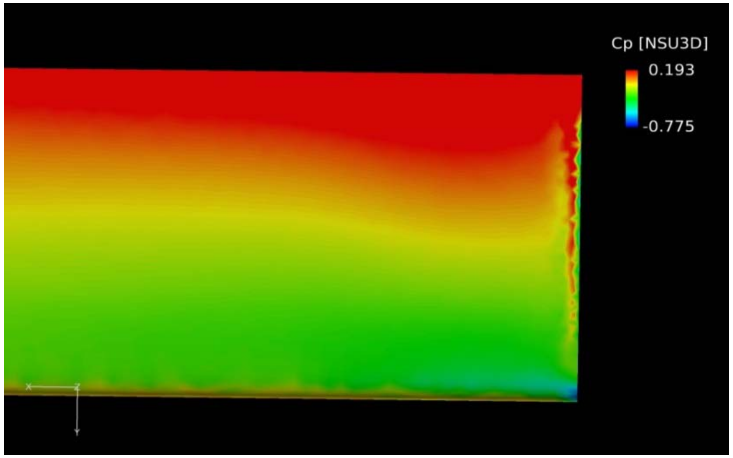


Ducted Wake



~15% more thrust than non-ducted, comparable to Martin & Tung at 5%c tip clearance.





Concluding Thoughts

- **First-principles hover simulations without external inputs or vortex methods have become a practical reality**
- **A combination of (i) High-order methods; (ii) Oversetting; (iii) Cartesian framework in parallel; and (iv) Scalable adaptive mesh refinement, such as in Helios enables routine first-principles hover computations**
- **For certain rotor-blades in hover, challenges remain in form of being able to resolve helical wake instability physics correctly. Some future things to looks at:**
  - Resolve tip vortex core further accurately
  - Explore mechanisms to damp-out braid instabilities while still resolving the necessary part of the wake

Thanks!....Questions?