Detached Eddy Simulation of the UH-60 Rotor Wake Using Adaptive Mesh Refinement

by

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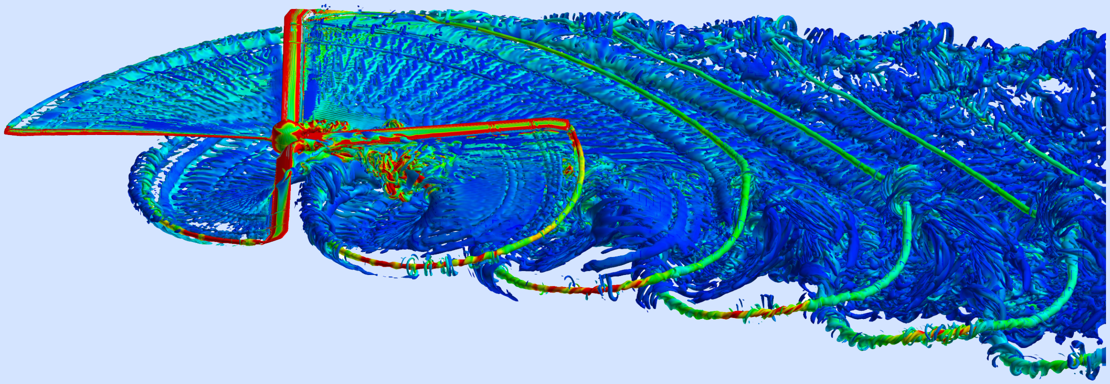

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Fort Worth, TX
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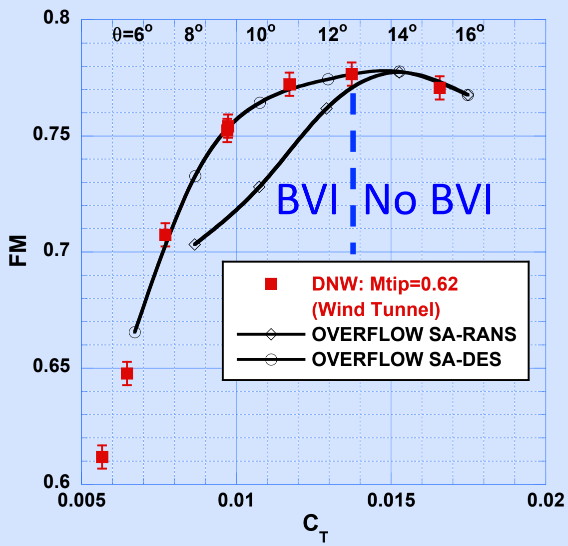
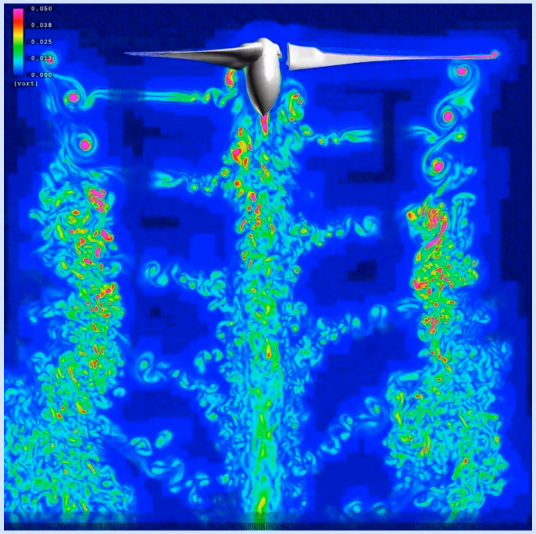
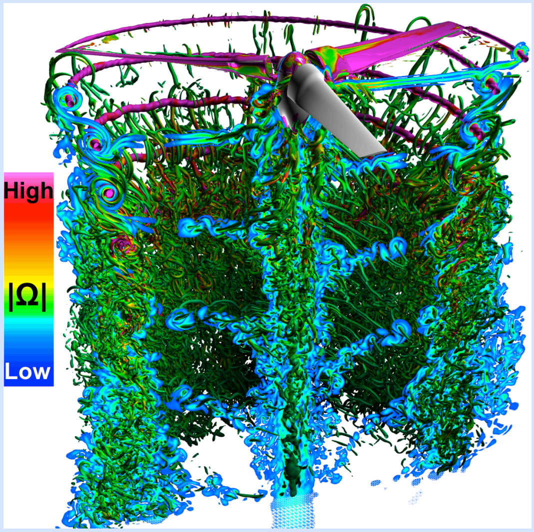
Background

Last Year's AHS Forum (V22 TRAM Rotor)*

- Demonstrated improved prediction of figure of merit (FM)
  - ❖ Improved blade grid resolution with high-order spatial differences
  - ❖ Spalart-Allmaras turbulence mode with the DES length scale
- Demonstrated Cartesian off-body (OB) adaptive mesh refinement (AMR)
  - ❖ No affect on FM and blade loads
  - ❖ Resolved vortex wake rich in turbulent flow physics
  - ❖ Vortex worms: Entrainment of shear layers by vortices







*Chaderjian, N. M. and Buning, P. G., "High Resolution Navier-Stokes Simulation of Rotor Wakes, AHS 67th Annual Forum, Virginia Beach, VA, May 3-5, 2011.

Objectives

•Demonstrate on the UH-60 flexible rotor in forward flight and hover

- OVERFLOW's high-order spatial differencing, AMR process, and SA-DES turbulence model
- Convergence of the dual-time algorithm
- Convergence of loose coupling process with CAMRAD-II and AMR
- Explore details of the rotor wake in forward flight and hover

Numerical Approach For This Study

OVERFLOW Version 2.2

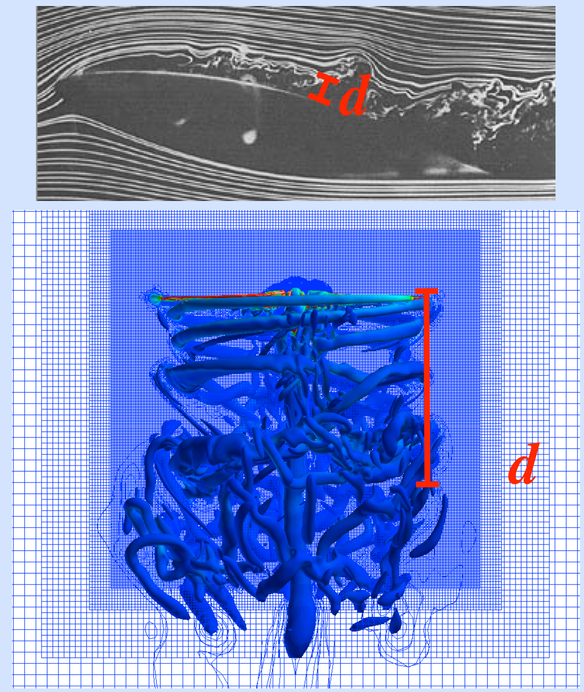
- Time-dependent Navier-Stokes equations solved everywhere (body & off-body)
- Overset body-fitted curvilinear grids rotate through fixed off-body Cartesian grids
- 2nd-order time accuracy using dual time-stepping (pseudo-time with sub-iterations)
    - ❖ Approximately factored Pulliam-Chaussee diagonal algorithm
- 5th-order convective differences, 2nd-order grid metrics/viscous terms
- Dynamic adaptive mesh refinement (AMR) for the off-body (OB) Cartesian grids
- OVERFLOW is loosely coupled with CAMRAD-II every ¼ revolution (4-bladed rotor)
    - ❖ CFD delta-loads replace CAMRAD-II's simplified aerodynamics model
    - ❖ CAMRAD-II provides OVERFLOW with blade deflections and trim conditions
- Many other options and features

Spalart-Allmaras Turbulence Model

$$\frac{D\tilde{\nu}}{Dt} = \underbrace{C_{b1}\tilde{\nu}\left(\Omega + \frac{\tilde{\nu}}{k^2 d^2} f_{v2}\right)}_{\text{Production}} - \underbrace{C_{w1} f_w \left(\frac{\tilde{\nu}}{d}\right)^2}_{\text{Dissipation}} + \underbrace{\frac{1}{\sigma}\left[\nabla \bullet \left(\left(\nu + \tilde{\nu}\right)\nabla\tilde{\nu}\right) + C_{b2}\left(\nabla\tilde{\nu}\right)^2\right]}_{\text{Diffusion}}$$

***"d "* is the distance to the nearest wall**

- It should represent the largest turbulent eddy size
- It's too large in the wake, so TEV is too large
  - ❖ **Production**, but **no dissipation** **(out of balance)**
- In the wake it has simply become a geometric parameter



Spalart-Allmaras Detached Eddy Simulation

$$\frac{D\tilde{\nu}}{Dt} = \underbrace{C_{bl}\tilde{\nu}\left(\Omega + \frac{\tilde{\nu}}{k^2 d^2} f_{v2}\right)}_{\text{Production}} - \underbrace{C_{w1} f_w \left(\frac{\tilde{\nu}}{d}\right)^2}_{\text{Dissipation}} + \underbrace{\frac{1}{\sigma}\left[\nabla \bullet \left((\nu + \tilde{\nu})\nabla\tilde{\nu}\right) + C_{b2}(\nabla\tilde{\nu})^2\right]}_{\text{Diffusion}}$$

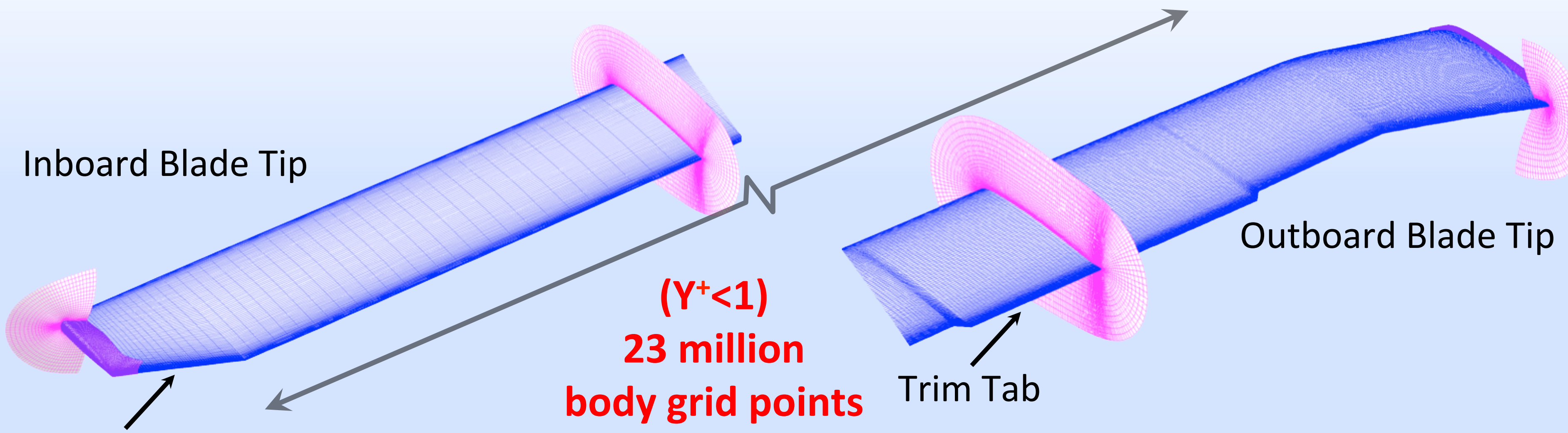
DES provides a more realistic turbulent length scale

$$\bar{d} = \min\left(d, C_{DES}\Delta\right)$$

$$\Delta = \max\left(\Delta x, \Delta y, \Delta z\right)$$

- Rational way to reduce the TEV, even when using RANS grid spacing
- Viewed as a hybrid model
  - RANS in boundary layer
  - LES outside of boundary layer
- Turbulent structures are resolved if the mesh is refined
  - Unique application of DES to rotorcraft wakes
  - Vortices are not diffused
  - Blade flow separation still determined by RANS model
- Use delayed detached eddy simulation (DDES) as a precaution

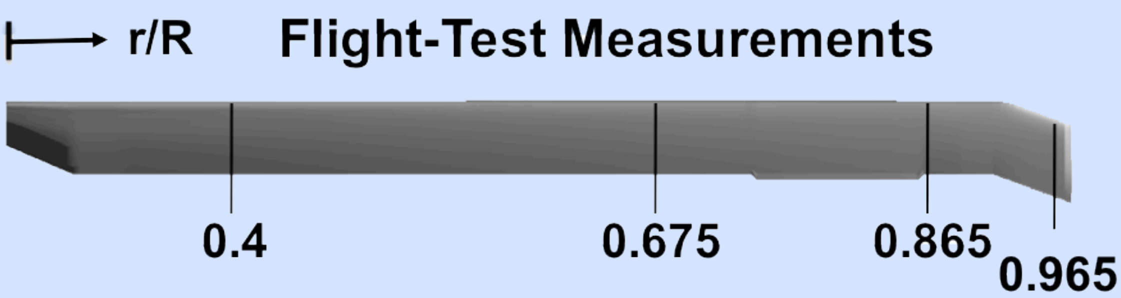
Overset Grid System - UH-60 Rotor

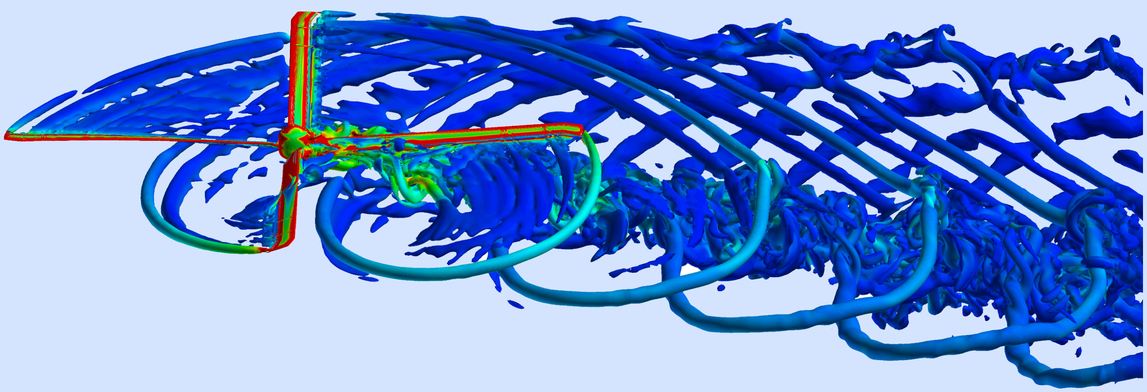


Component	Dimensions	Grid Points
Rotor Blade	241x291x63	4,418,253
Inboard Tip	137x69x63	595,539
Outboard Tip	122x49x63	376,614
	One Blade Total	**5,390,406**
Hub Body	93x301x54	1,511,622
Hub Top	21x21x54	23,814
Hub Top	21x21x54	23,814
	Hub Total	**1,559,250**

High-Speed Level Flight

Low BVI



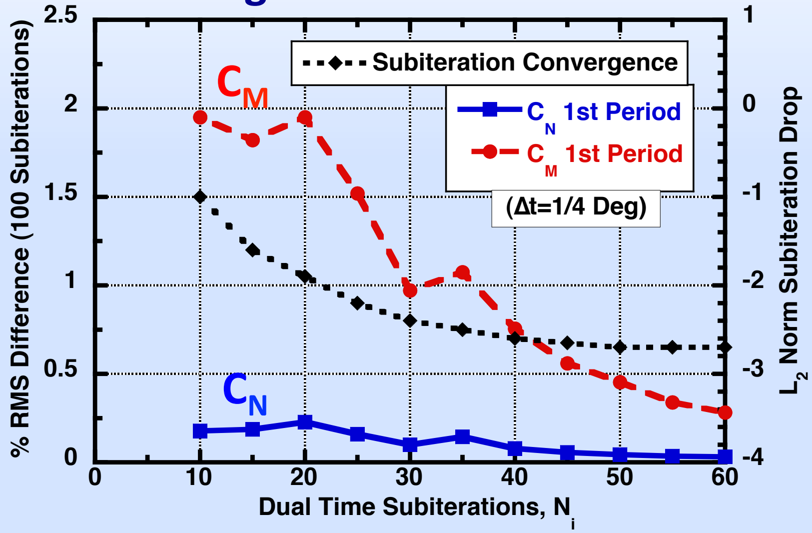


Flight Parameters: C8534	
M_∞	0.236
M_{tip}	0.64
$\mu = M_\infty / M_{tip}$	0.37
Shaft Angle	-7.31°
Sideslip Angle	1.28°
$Re_{tip/inch}$	3.3×10^5

Establishing Dual Time-Step Asymptotic Range

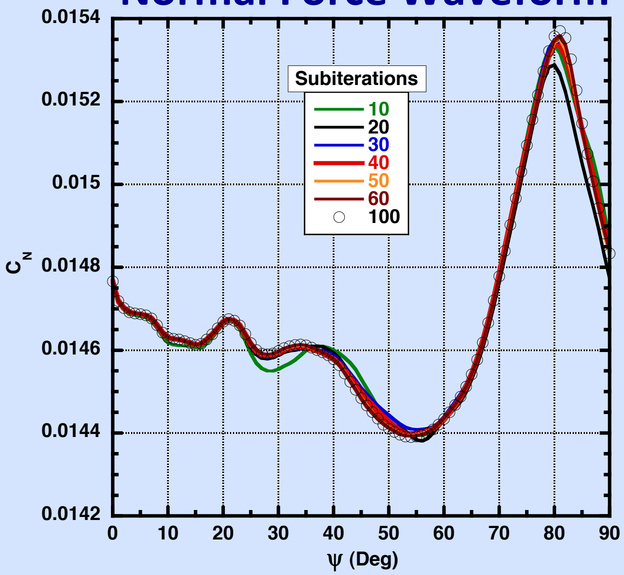
2nd-Order Accuracy: C8534

Convergence with Subiteration

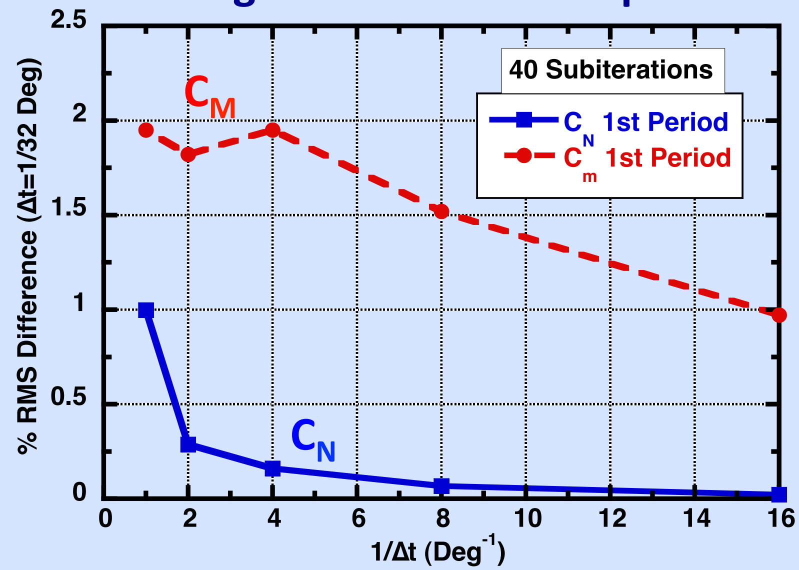


- RMS difference formed from highly converged result
- Asymptotic range begins at N_i=35, Δt=¼˚
  - ❖ Typical choice: N_i=15, Δt=¼˚
- Differences are quantitatively larger than they appear
- Chose N_i=40, Δt=¼˚
  - ❖ 2.6-order sub-iteration drop is larger than the 2-order rule-of-thumb

Normal Force Waveform



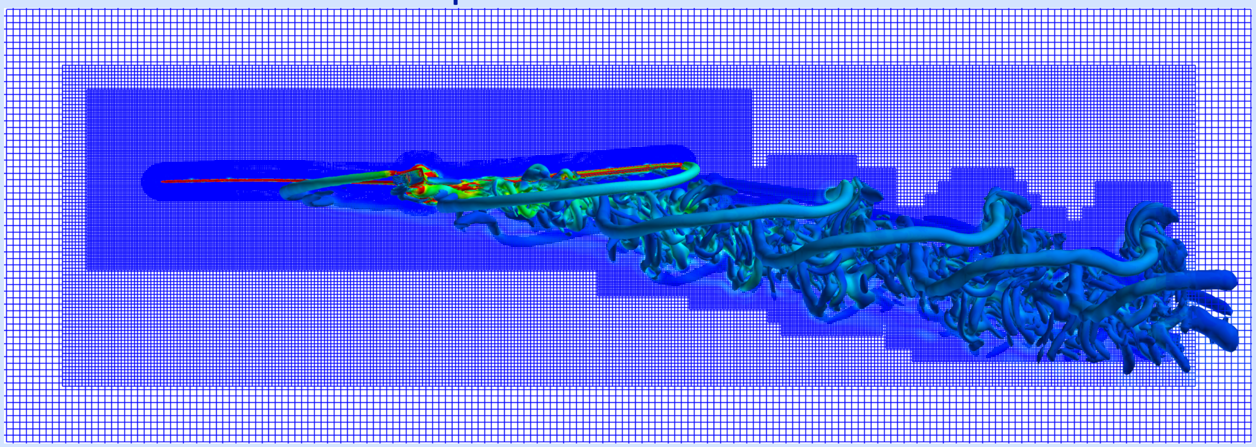
Convergence with Timestep



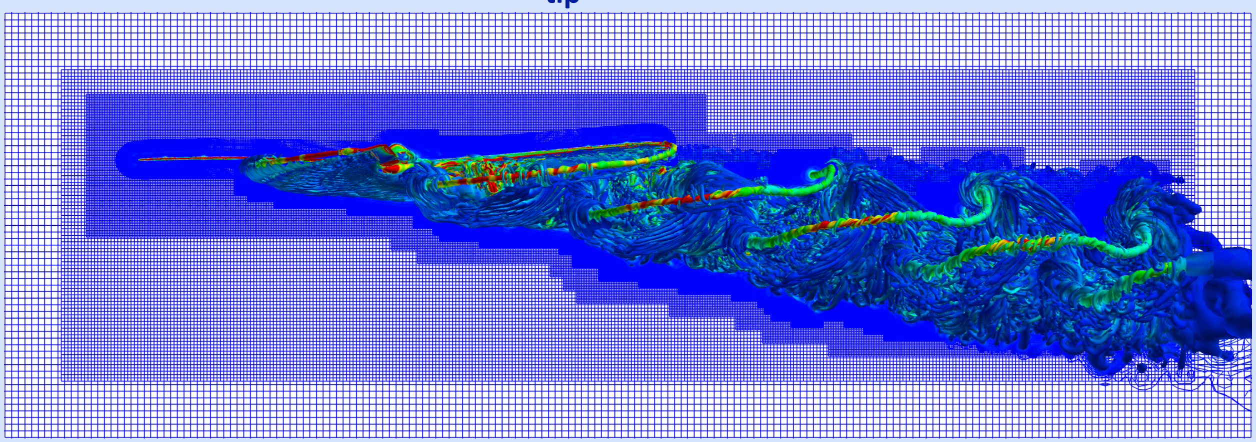
AMR Grid Systems: C8534

- AMR efficiently captures wake without grid refinement
    - ❖ 80 million grid points with uniform 10% c_{tip} grid
- AMR allows for efficient/automatic grid refinement

AMR0: Δ=10% c_{tip}, 960 grids, 61 million grid points



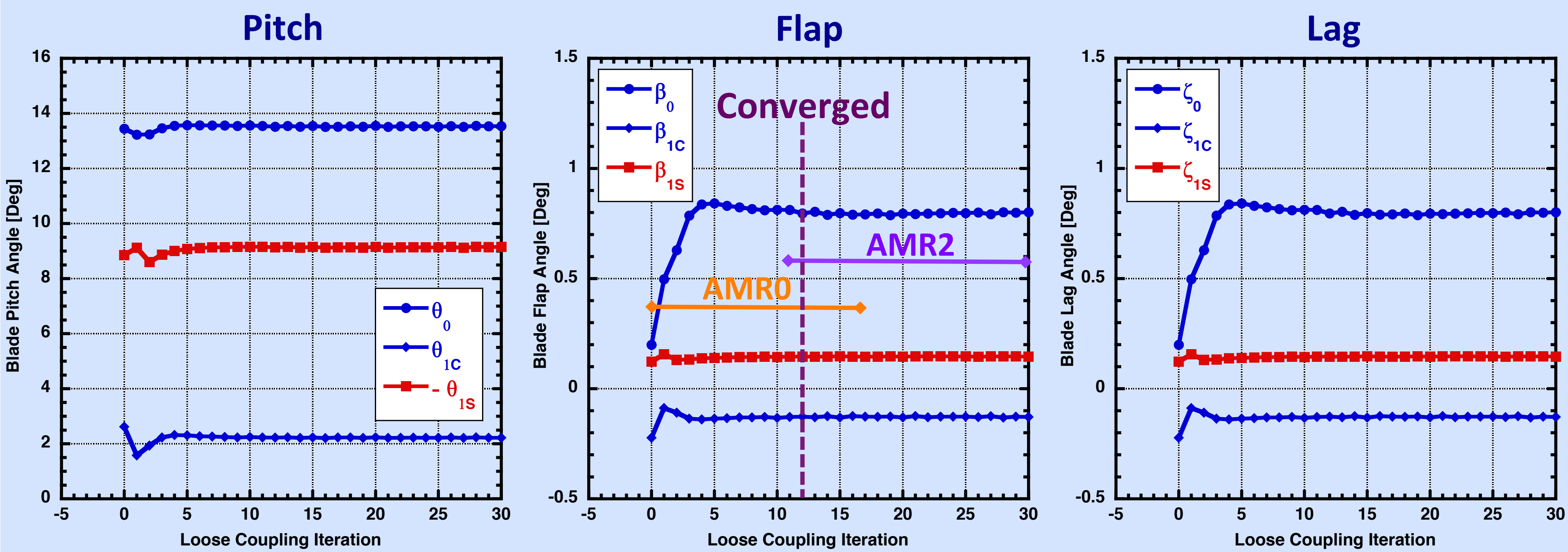
AMR2: Δ=10%, 5%, and 2.5% c_{tip}, 18,500 grids, 754 million grid points



OVERFLOW/CAMRAD-II Loose Coupling Convergence

Control Angle Convergence

- **AMR0:** Run for 4.5 revs
- **AMR2:** Run for 5.0 revs (Started from AMR0, 3 revs)
- Both AMR0 and AMR2 are converged at coupling iteration 12



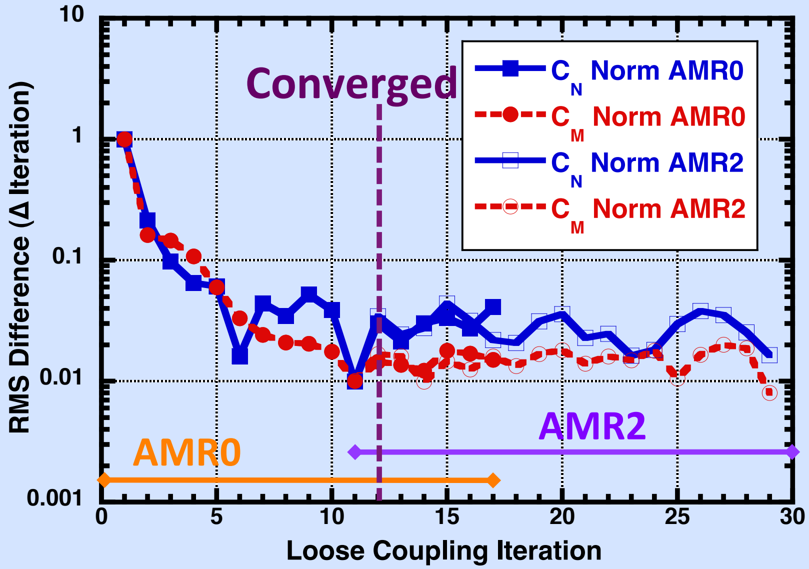
OVERFLOW/CAMRAD-II Loose Coupling Convergence

SRW

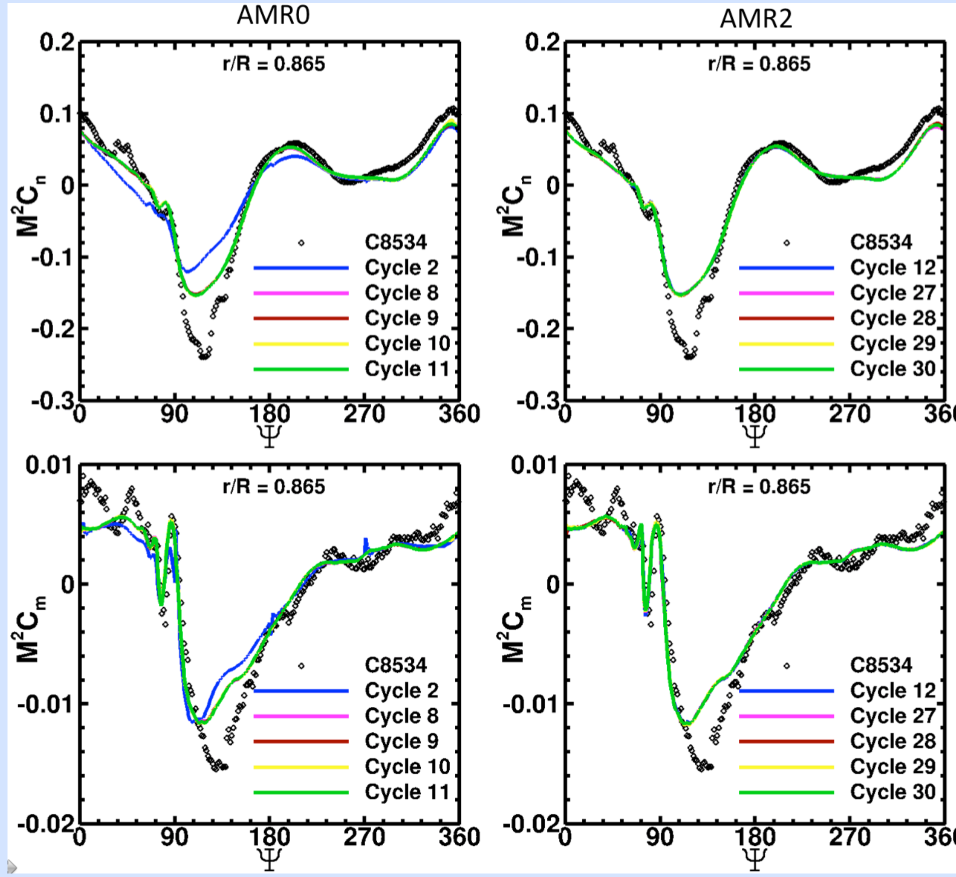
RMS, Normal Force and Pitching Moment Coefficients

- RMS difference between successive iterations (ΔN_i)
- Both AMR0 and AMR2 RMS values are converged at cycle 12
- Both AMR0 and AMR2 loads show little change past 12th cycle

RMS Difference



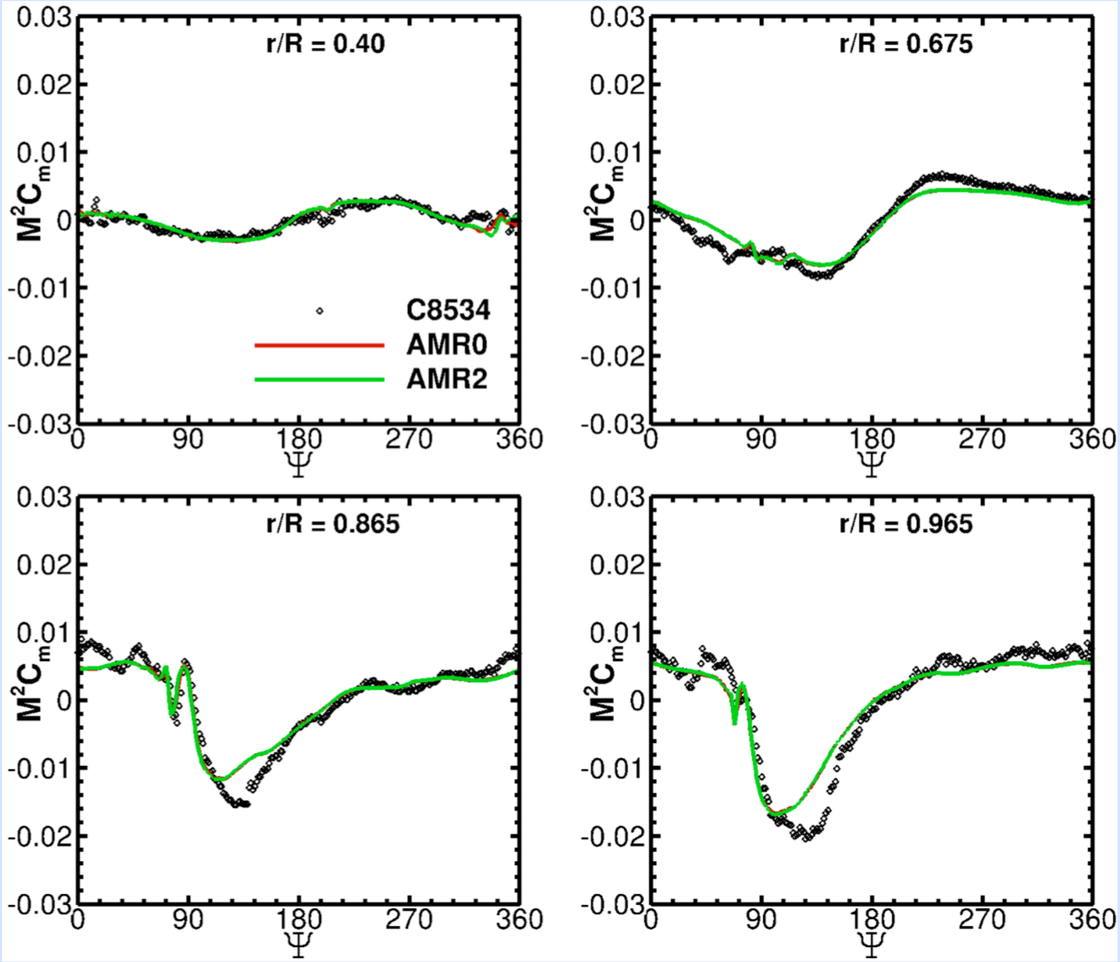
Convergence of Normal Force and Pitching Moment Coefficients



OVERFLOW/CAMRAD-II Pitching Moment Coefficient

Flight Counter C8534, Mean Removed

- AMR0 and AMR2 results virtually identical
  - ❖ This result is expected due to the lack of BVI
- Good agreement of RMS differences with flight-test data* (to 2.5%)

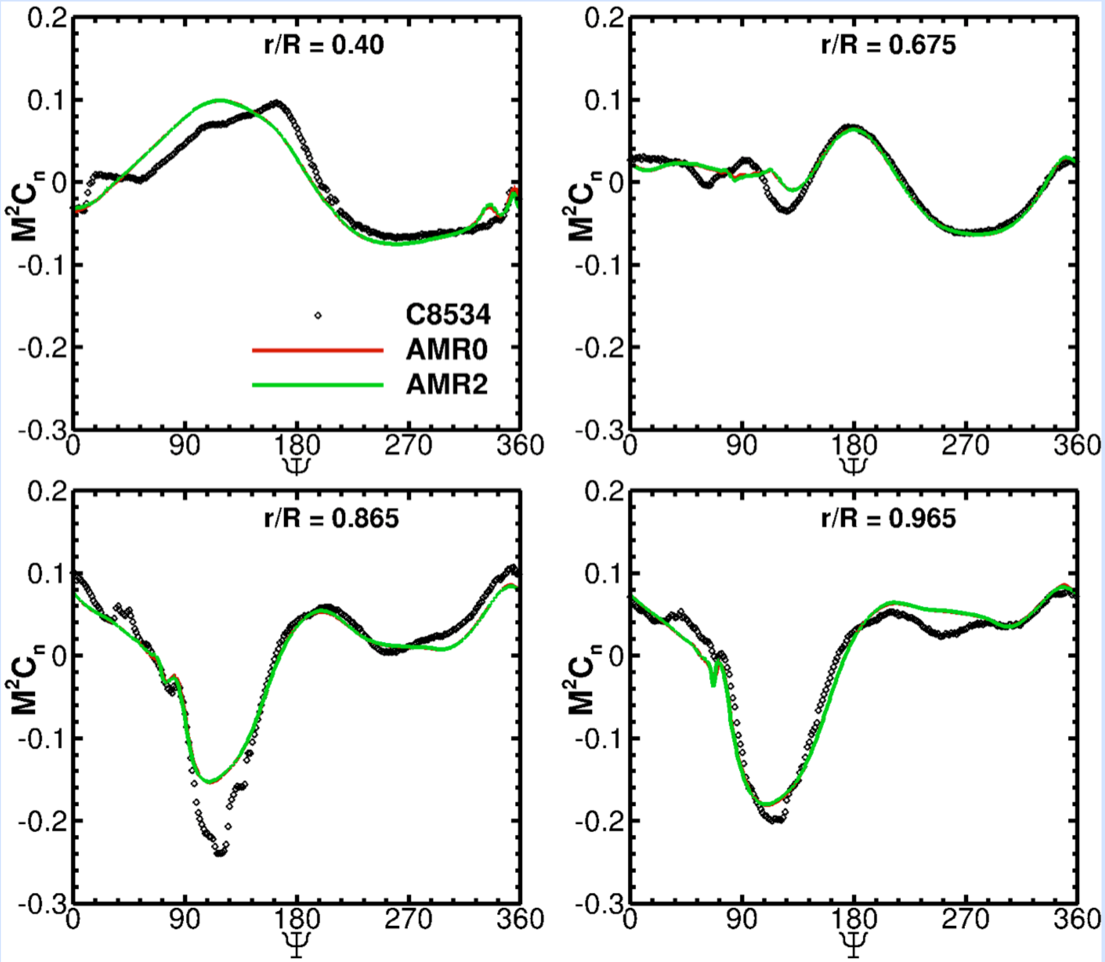


*Gloria K. Yamauchi and Larry A. Young, "A Status of NASA Rotorcraft Research," NASA/TP–2009-215369, September, 2009.

OVERFLOW/CAMRAD-II Normal Force Coefficient

Flight Counter C8534, Mean Removed

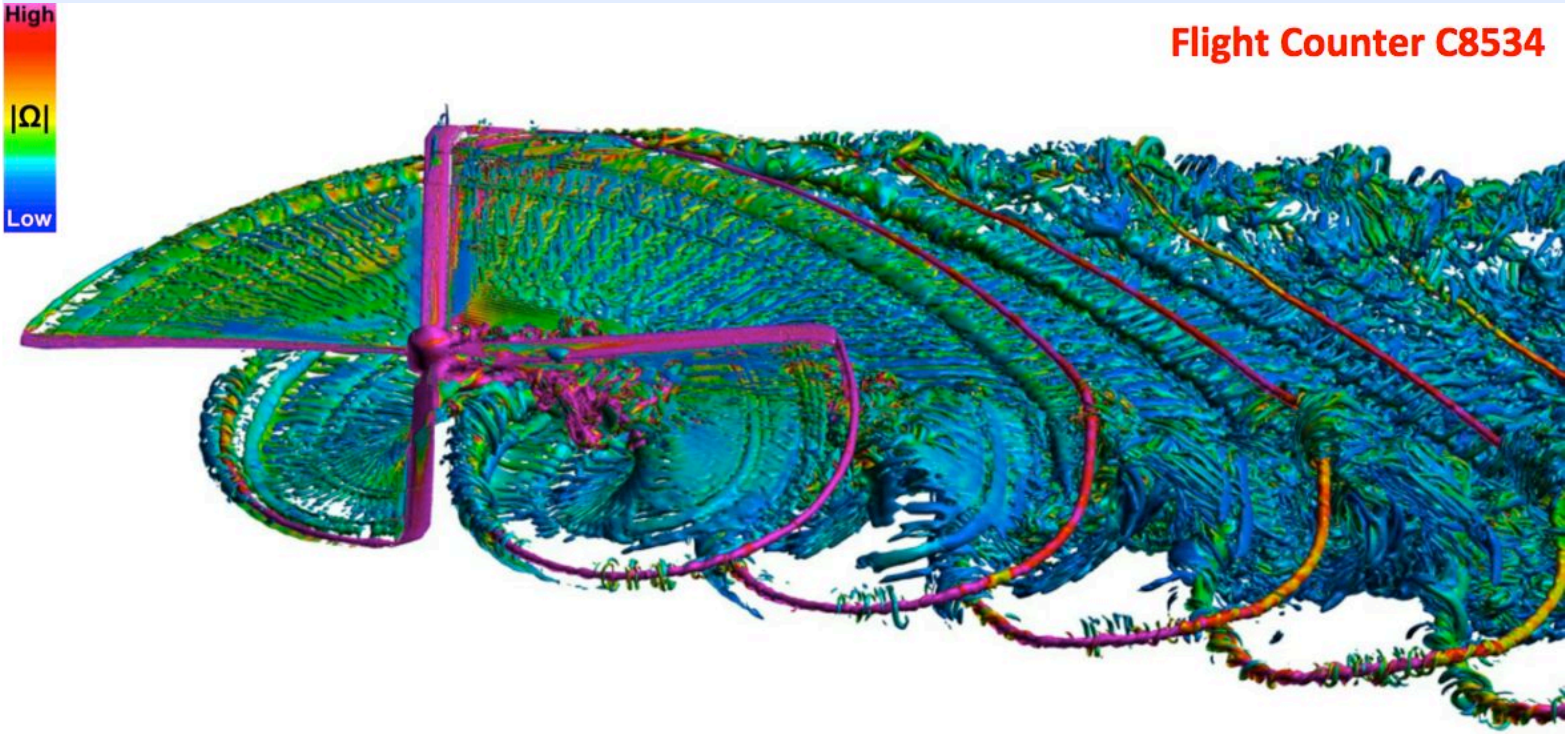
- AMR0 and AMR2 results virtually identical
  - ❖ This result is expected due to the lack of BVI
- Good agreement of RMS differences with flight-test data (to 2.1%)



*Gloria K. Yamauchi and Larry A. Young, "A Status of NASA Rotorcraft Research," NASA/TP–2009-215369, September, 2009.

Flow Visualization Using the Q-criterion

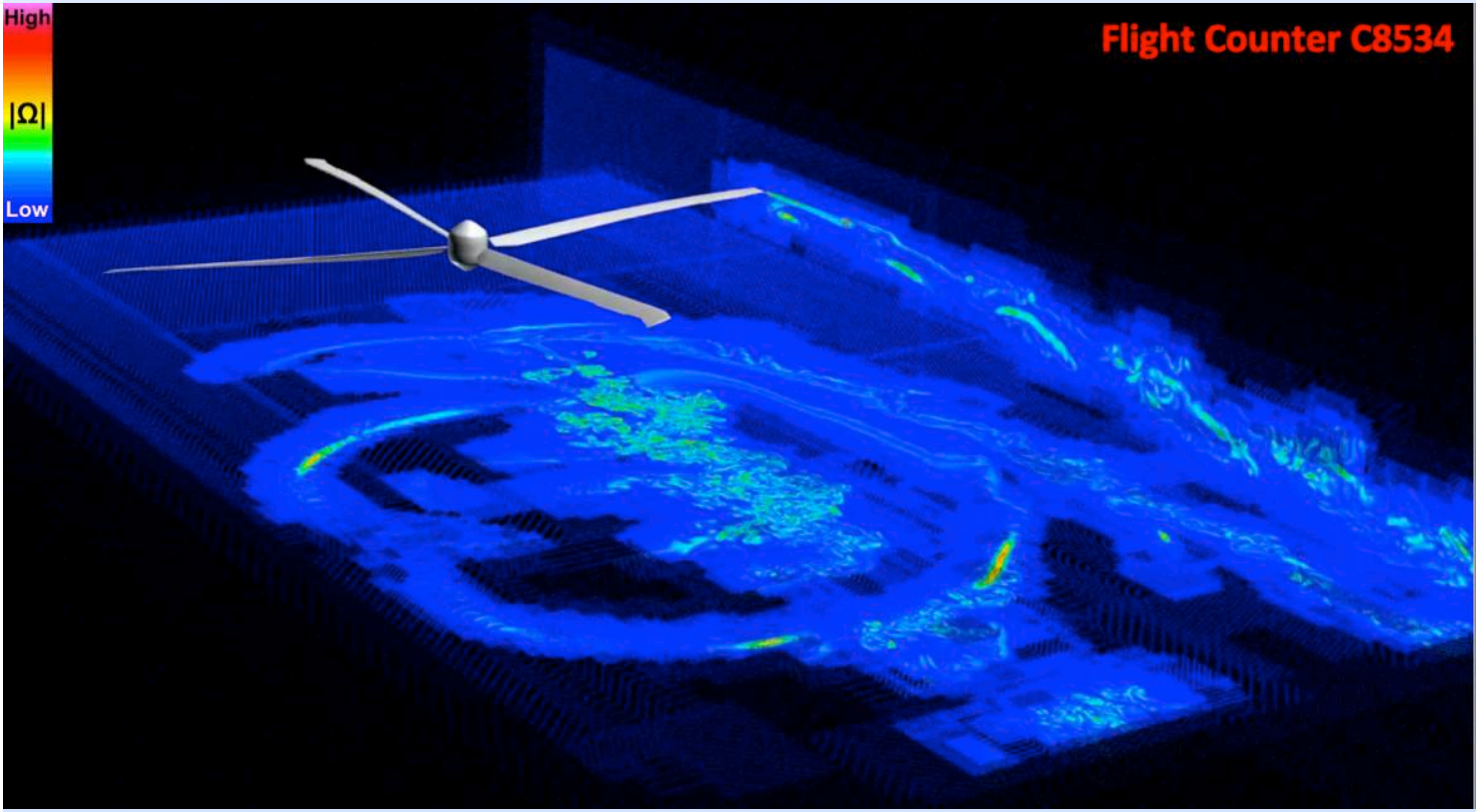
AMR2: Δ=10%, 5% and 2.5% c_{tip}



Flow Visualization Showing AMR Tracking Vortices

Rendered on Horizontal and Vertical Planes

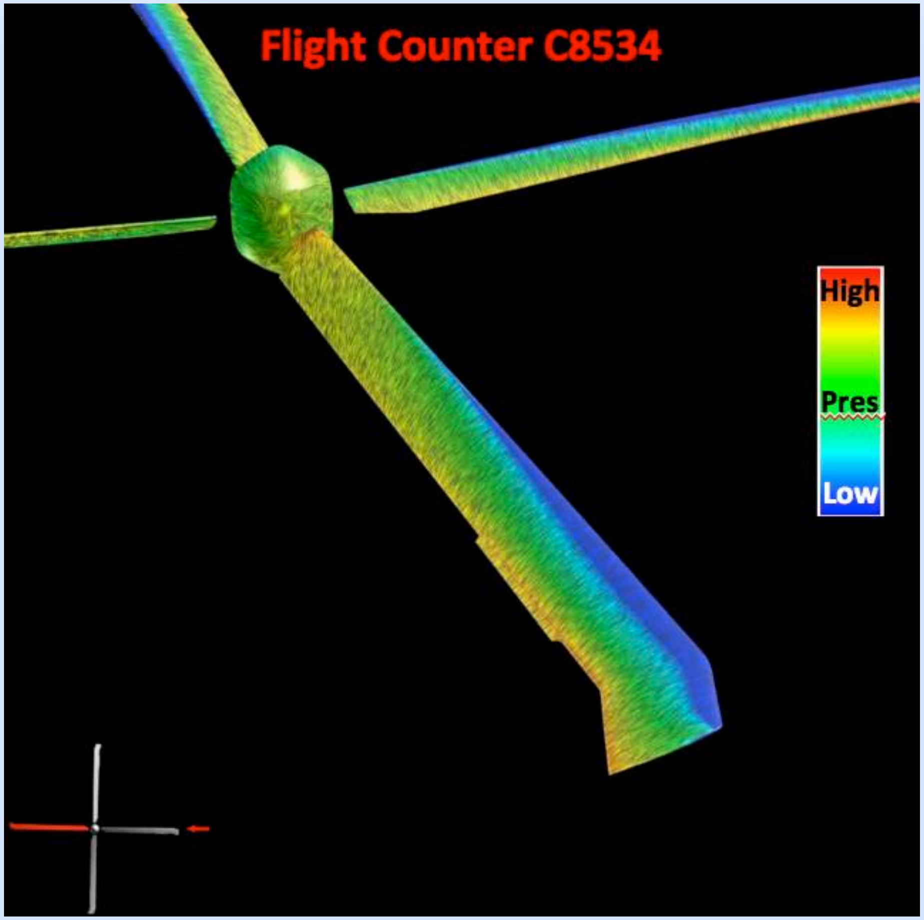
AMR2: Δ=10%, 5% and 2.5% c_{tip}



Time-Dependent Surface Flow

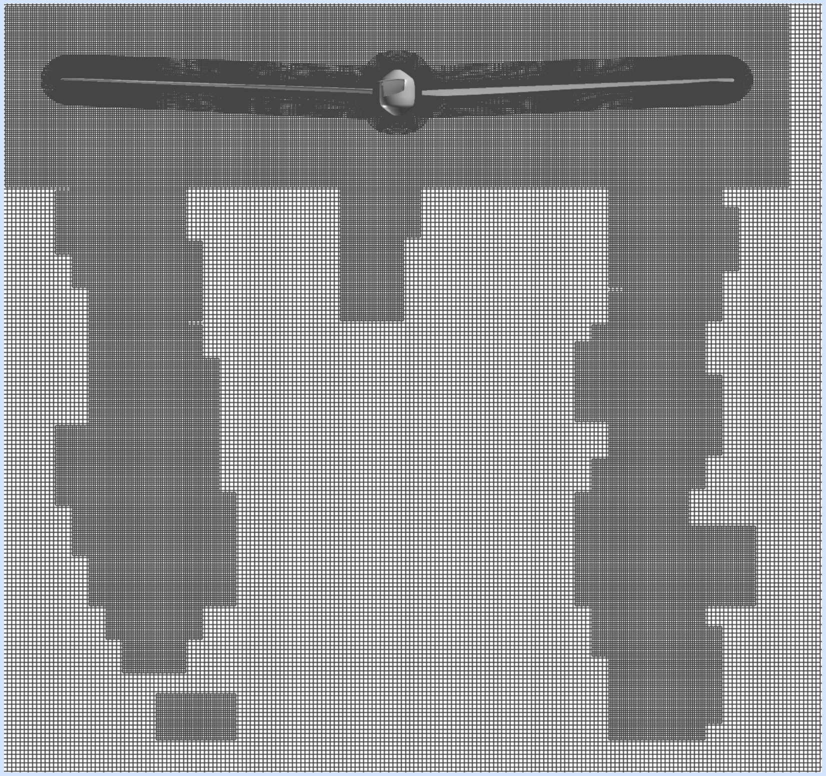
Texture Mapping Colored by Pressure

AMR2: Δ=10%, 5% and 2.5% c_{tip}

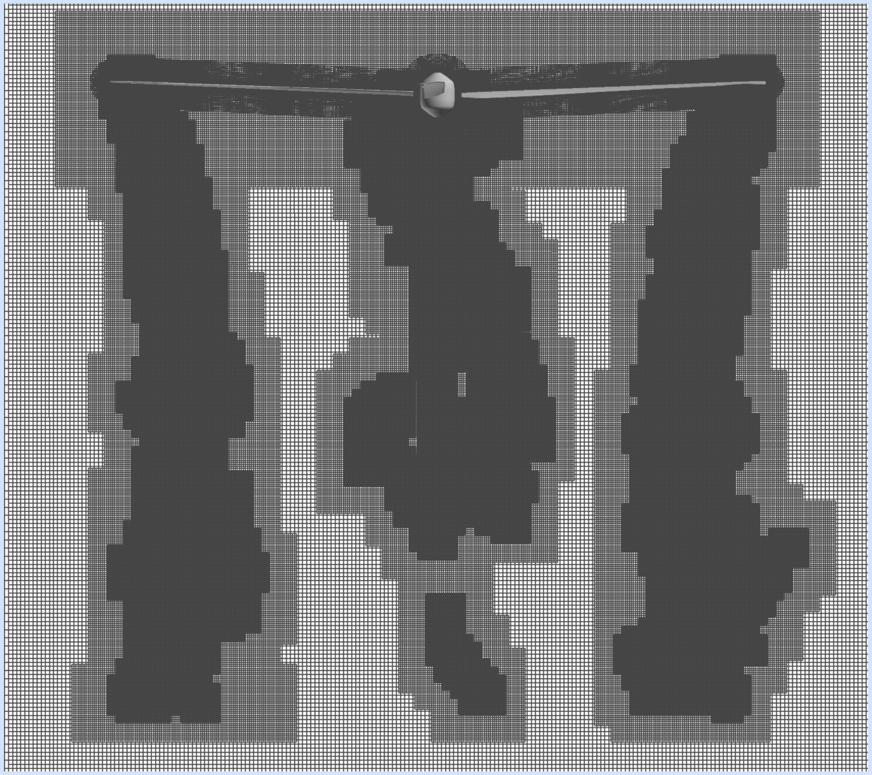


OVERFLOW/CAMRAD-II UH-60 Rotor in Hover

AMR0: Δ=10% c_{tip}
1,800 grids, 78 million grid points

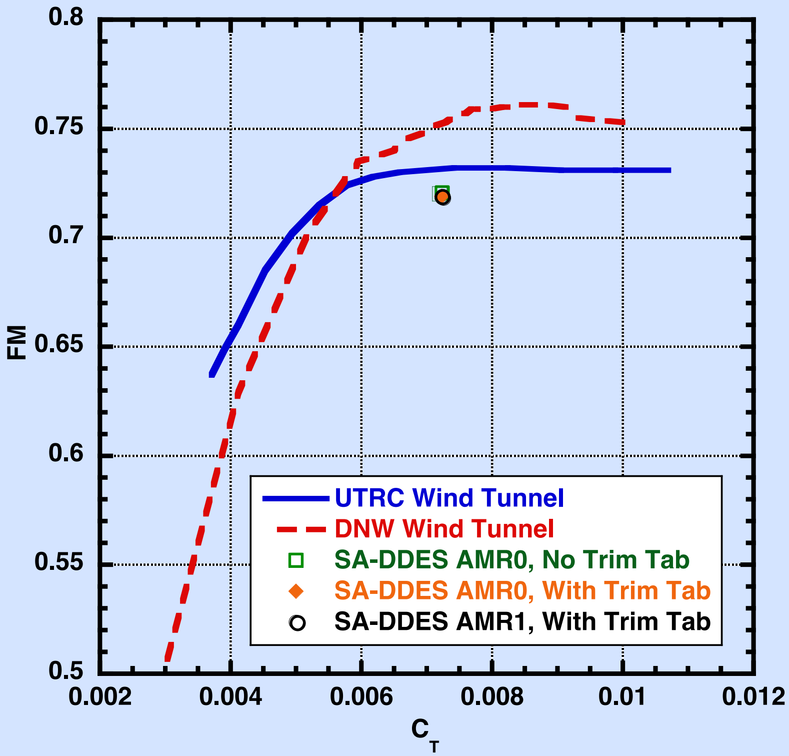


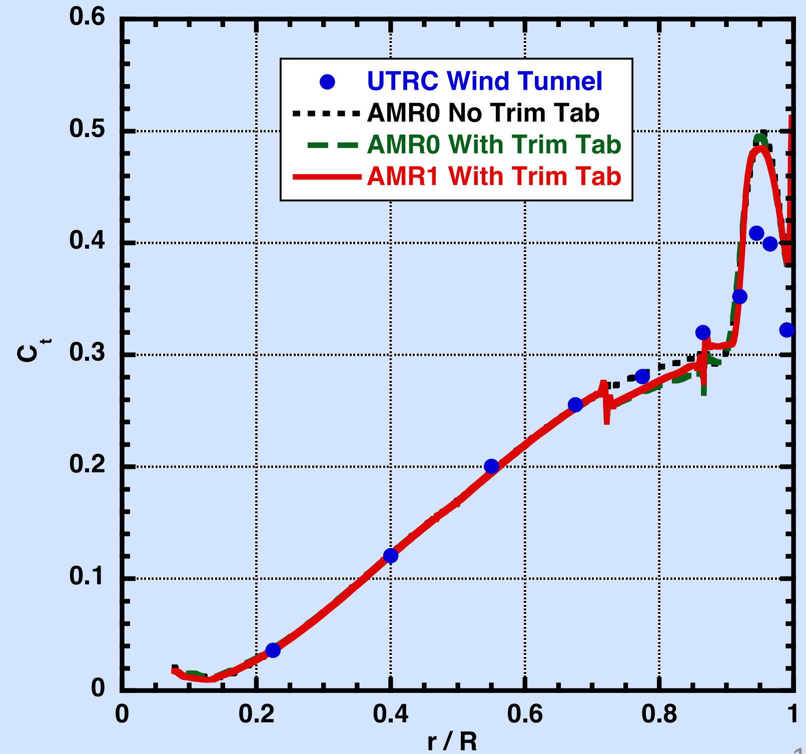
AMR1: Δ=10% and 5% c_{tip}
7,700 grids, 302 million grid points



OVERFLOW/CAMRAD-II UH-60 Rotor in Hover

- AMR0 and AMR1 FM in close agreement with each other
  - ❖ 2% difference from UTRC test
  - ❖ Experimental uncertainty unknown
- AMR0 and AMR1 sectional thrust coefficient in good agreement with UTRC test
- CFD accuracy has improved
  - ❖ Further validation requires test data uncertainties

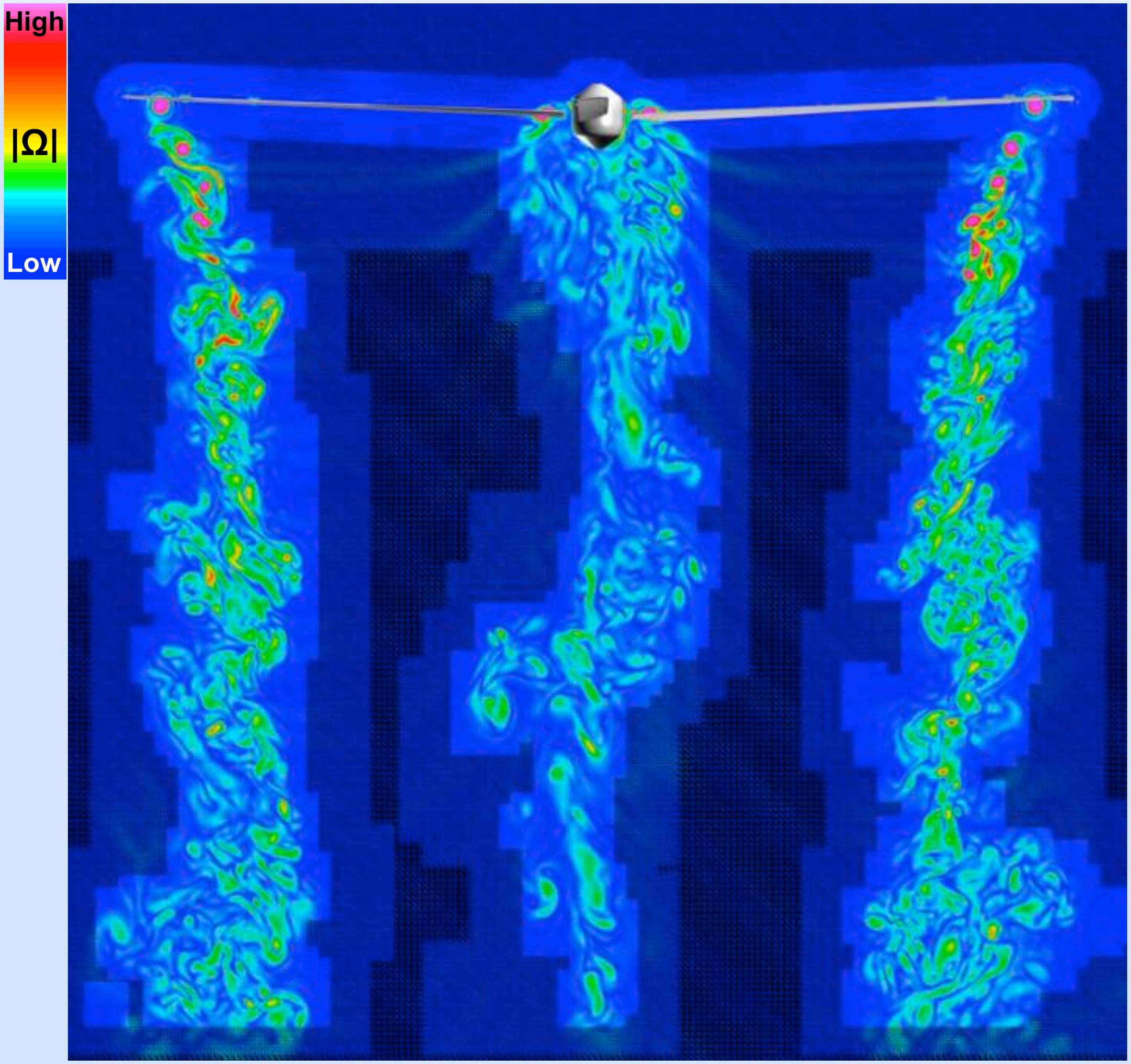




Flow Visualization Showing AMR Tracking Vortices

AMR1: Δ=10% and 5% c_{tip}

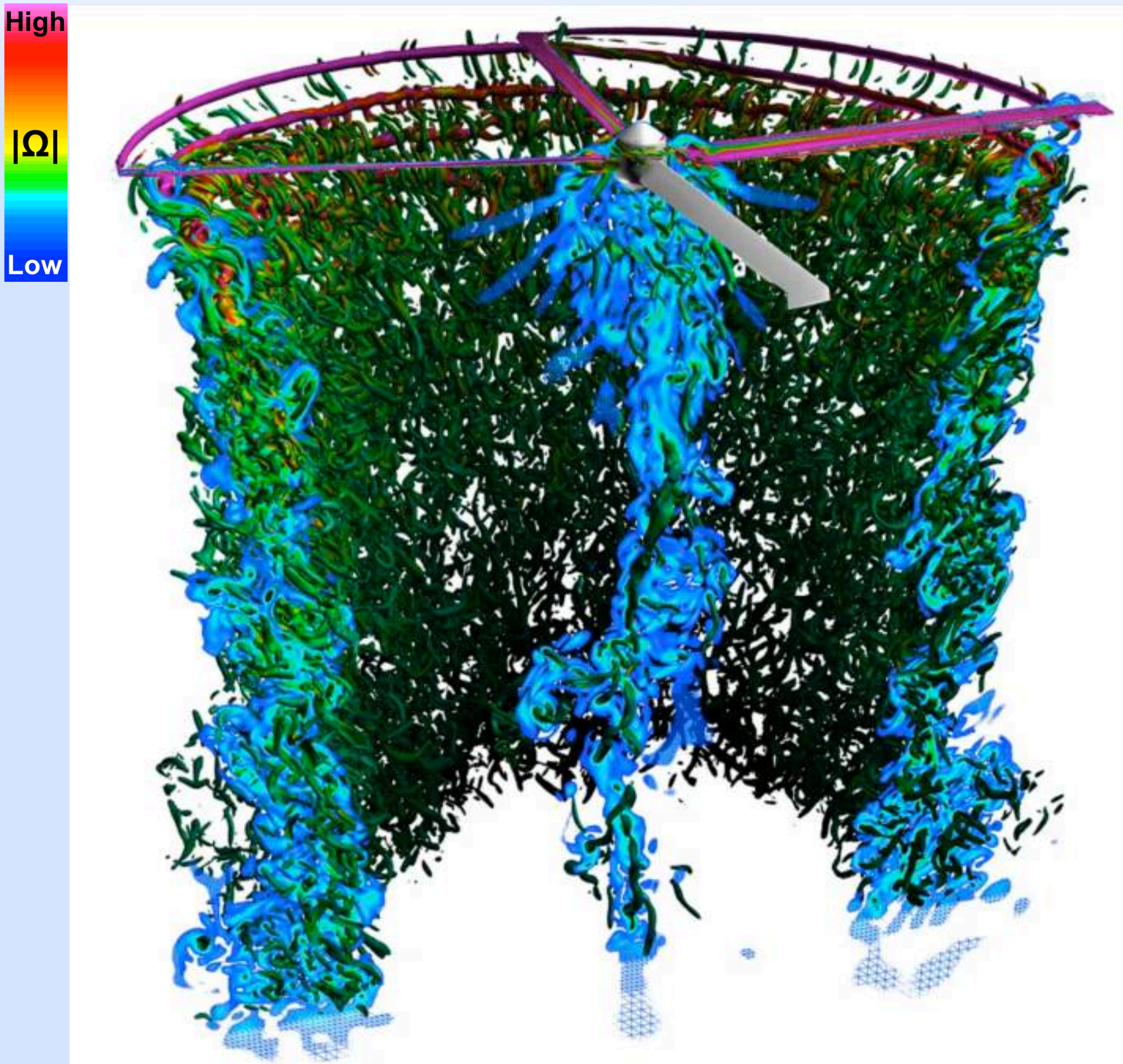
7,700 grids, 302 million grid points



Cut-Away View of Vortices and Worms

AMR1: Δ=10% and 5% c_{tip}

7,700 grids, 302 million grid points

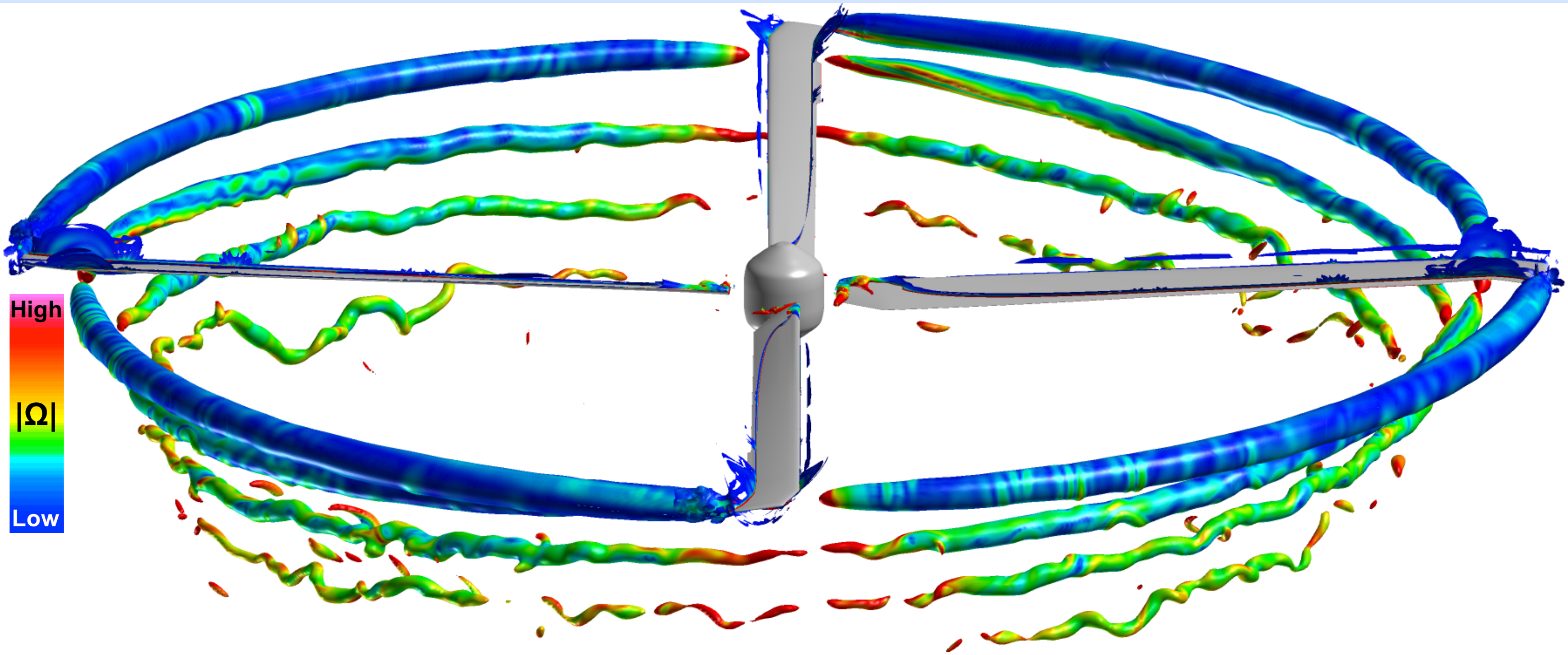


Pressure Iso-surface for the UH-60 in Hover

AMR1: Δ=10% and 5% c_{tip}

7,700 grids, 302 million grid points

- Pressure iso-surface similar to viewing natural condensation of tip vortices
  - You can not see any worms (Typically 0.5%-1% of tip vortex strength)
  - Worms are evident by bands of vorticity on the iso-surfaces



Computer Run Times

- OVERFLOW was executed on NASA's Pleiades supercomputer system using Intel 2.93GHz Westmere nodes and MPI
  - Each Westmere node has 12 cores and 24GB of memory
  - Wall clock timings are not optimal, but reflect what is possible given computer resources and deadlines

Case	Grid Points (millions)	Number of Cores	Wall Clock Time (hrs/rev)	Relative Processing Rate
C8534 AMR0	61	1,536	5.4	0.13
C8534 AMR2	754	3,072	23.8	0.71
Hover AMR0	78	1,536	5.8	0.15
Hover AMR1	302	4,608	10.1	1.00

Conclusions

- Time-dependent Navier-Stokes simulations have been carried out by loosely coupling OVERFLOW with CAMRAD-II.
- Time accuracy of the Navier-Stokes equations was established within the asymptotic range, but required more sub-iterations/convergence than normally employed.
- OVERFLOW/CAMRAD-II loose coupling rapidly converged, even with AMR.
- AMR can be used to find vortex wakes without an apriori knowledge of the wake shape or location, allowing solutions with fewer grid points.
  - ❖ Useful for baseline or highly resolved wake simulation.
- Computed RMS differences of M^2C_N and M^2C_M for forward flight agreed with flight test data* to 2.1% and 2.5% respectively.
- Computed FM agreed with experiment to 2%
  - ❖ More experimental uncertainty data is needed for further CFD validation.
- Complex turbulent wakes interacting with vortices formed vortical worms, similar to last year's V-22 simulations.
- AMR had little affect on the rotor loads for forward flight due to weak BVI.

*Gloria K. Yamauchi and Larry A. Young, "A Status of NASA Rotorcraft Research," NASA/TP–2009-215369, September, 2009.

This Research Was Supported by NASA's Subsonic Rotary Wing (SRW) Project

UH-60 rotor/hub in hover
AMR1: Δ=10% and 5% c_{tip}
7,700 grids, 302 million grid points