Overset Methods for Rotorcraft Simulations Using the Helios Code

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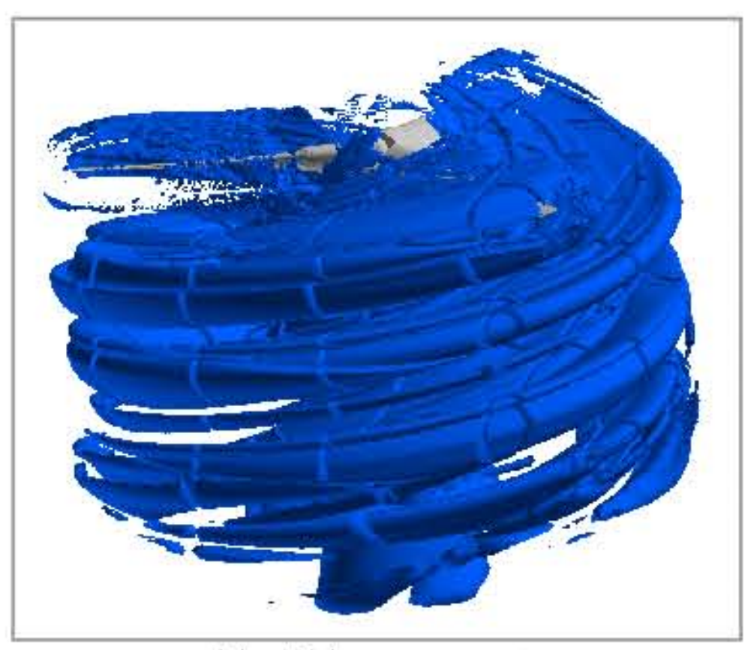
Motivation

Feature detection can be used to control AMR for rotorcraft flows.
However, using dimensional vorticity can be cumbersome.

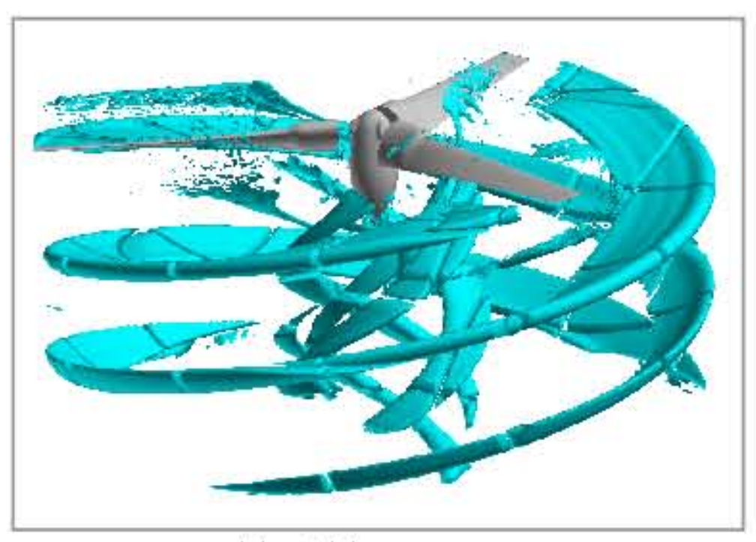
(V-22 TRAM rotor case)

Over Refined



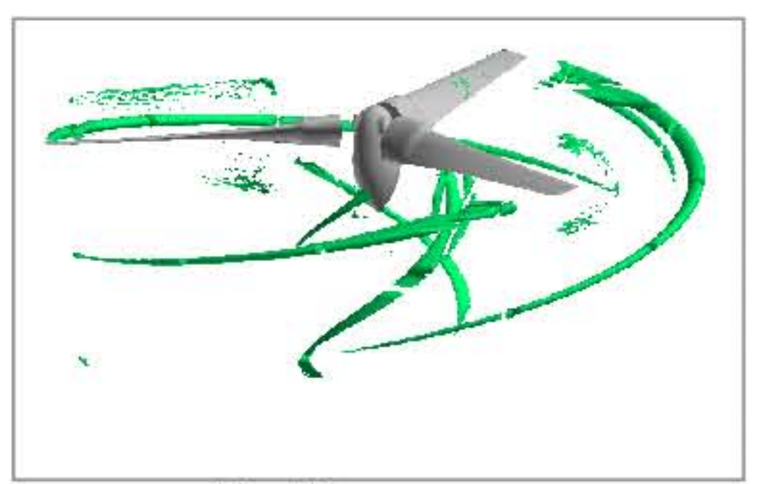
$||\vec{\omega}|| = 0.4$

Nearly Adequate



$||\vec{\omega}|| = 1.0$

Under Refined

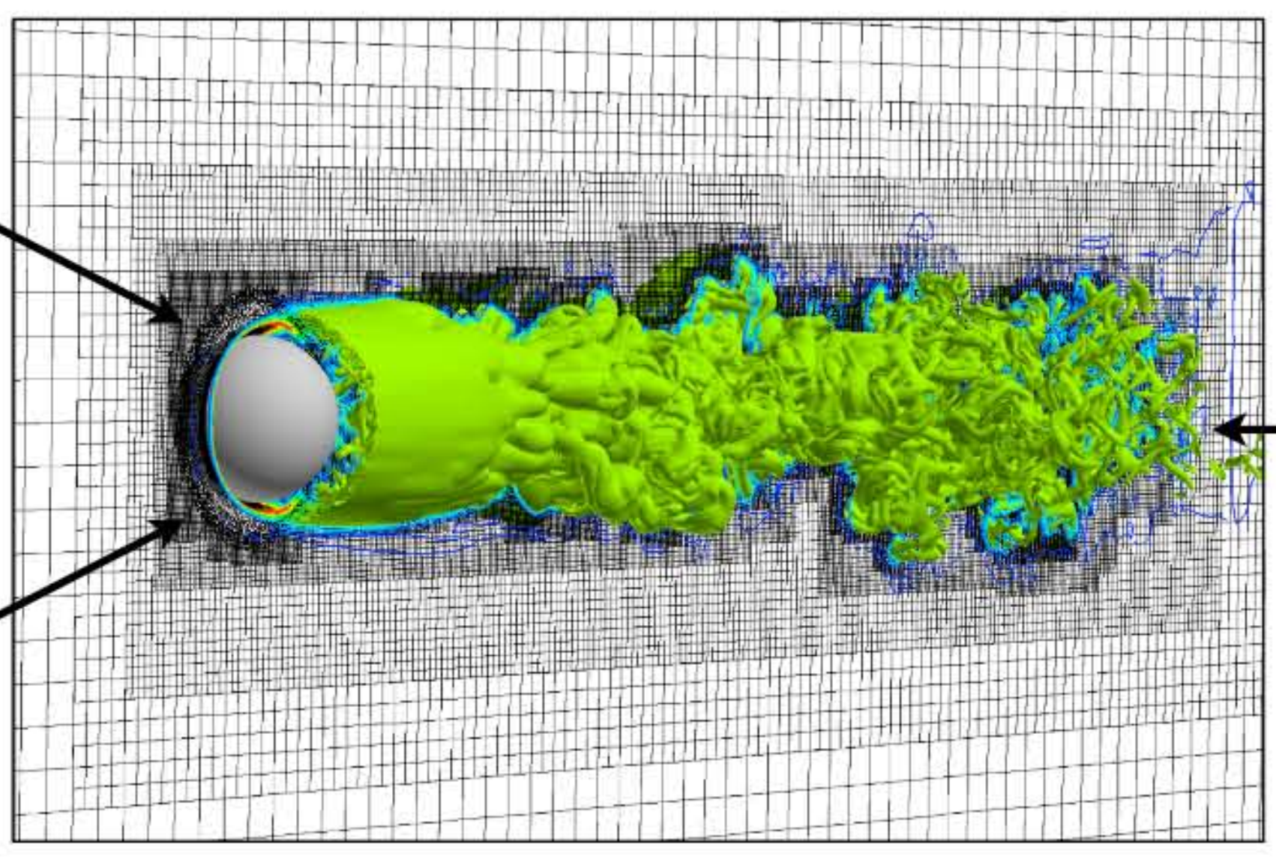


$||\vec{\omega}|| = 1.6$

Threshold values are very problem- and case-dependent.

Overset Approach

Dual Mesh Paradigm within Helios



Unstructured near-body domain resolves complex geometry and computes Navier-Stokes solution.

Overset data exchanges between the two grid types.

Structured-AMR Cartesian off-body domain resolves wake and computes higher-order (5th/3rd order-accurate in space/time) Euler solution.

Project Goals

1. Control the off-body refinement process for unsteady flows.
   1. Locate where to refine, based on features.
   2. Determine proper resolution, based on solution error.
2. Ensure overall automation and efficiency.

V-22 Osprey in hover

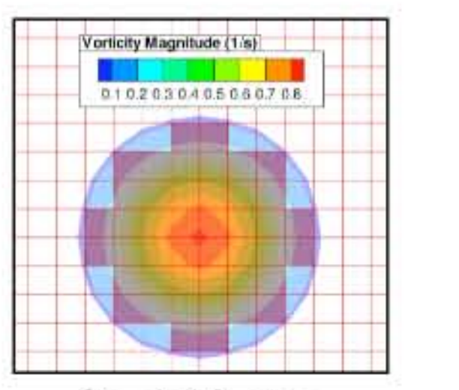
Automated Feature Detection[†]

Non-dimensional Methods

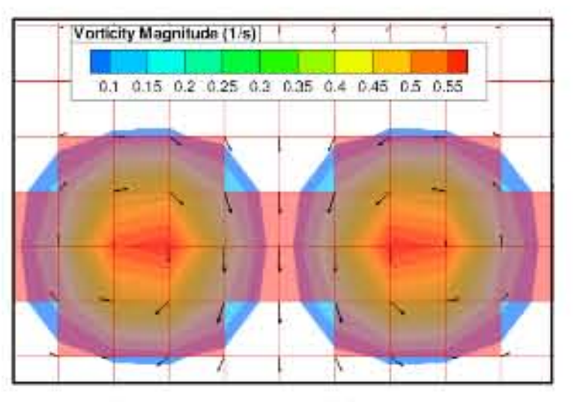
1. Q (Normalized), difference between strain and rotation rates
2. λ₂ (Normalized), corresponds to pressure minima
3. Mod.-Δ, eigenvalue of velocity gradient tensor
4. S-Ω Corr., highly correlated regions of strain and rotation

Validation

Cells tagged if functional value exceeds threshold.



Single Vortex



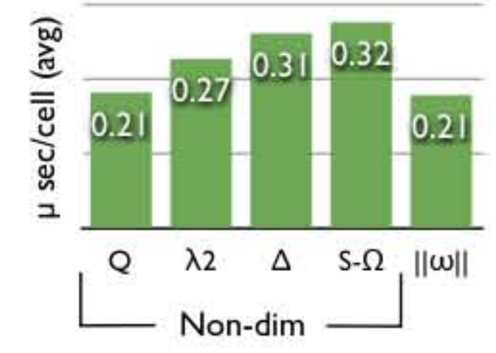
Interacting Vortices

Regardless of size, strength, and resolution, using a constant threshold adequately tags vortex.

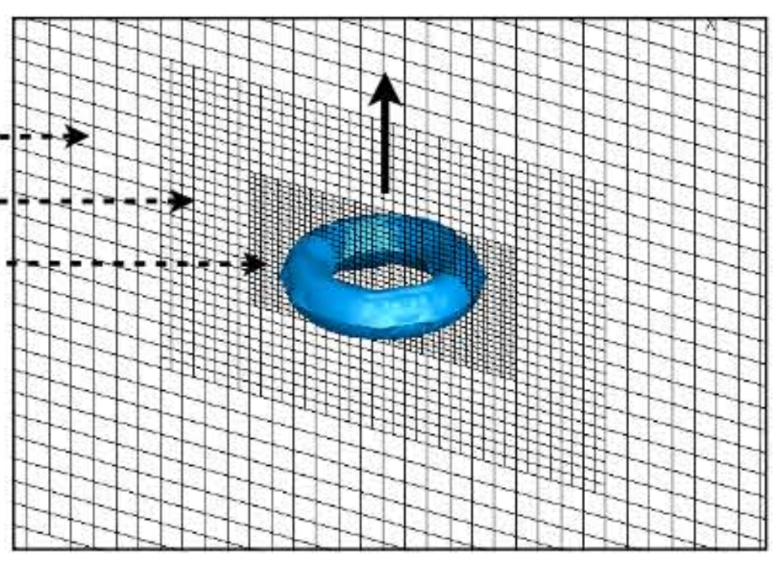
Applied to Unsteady 3-D Ring Vortex

Adaptive v. Uniform Refinement

	grid points	sec/time-step
Med-Coarse	1.07×10^5	0.461
Med-Fine	8.34×10^5	3.51
Fine	6.59×10^6	27.3
Non-dim Q (adaptive)	**1.87×10^5**	**0.649** **(42x faster)**

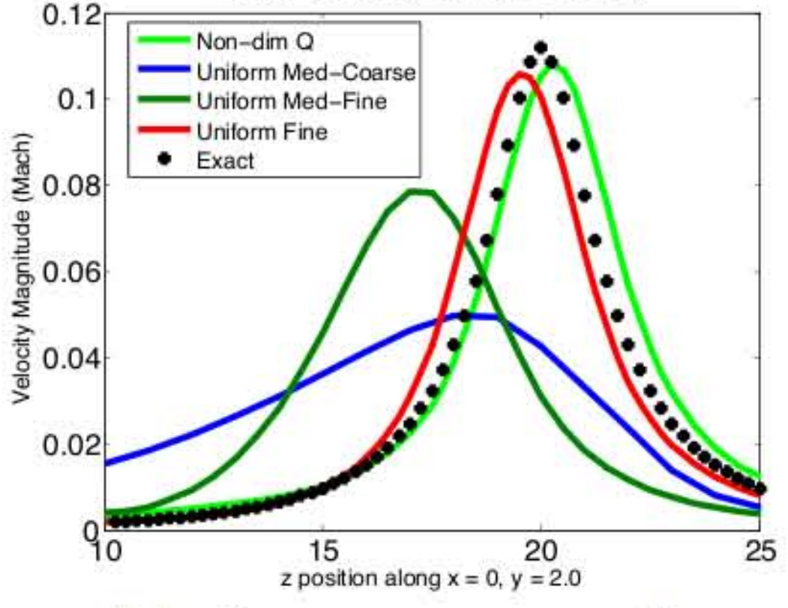


Runtimes of new schemes are commensurate with vorticity.



Ring naturally convects upward; travels 20 core widths.

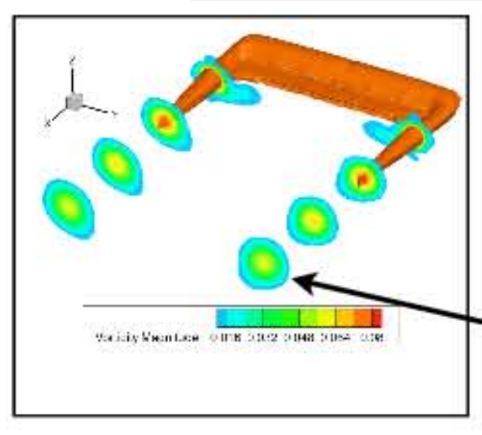
Grid Refinement Study



Adaptive accuracy comparable to uniform fine solution.

Practical Feature-Driven Refinement[‡]

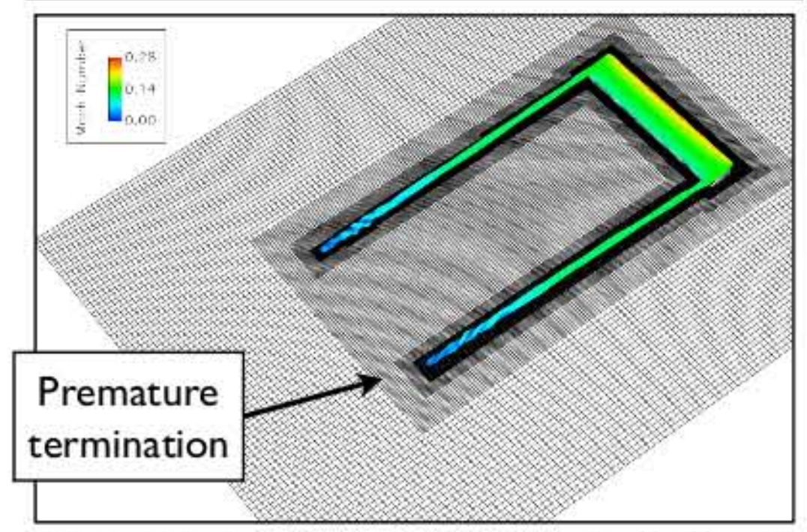
(NACA 0015 Flow-Field)



M = 0.1235,
AoA = 12°,
Re = 1.5×10^6

Strong off-body dissipation of vortex cores

Intermediate Solution

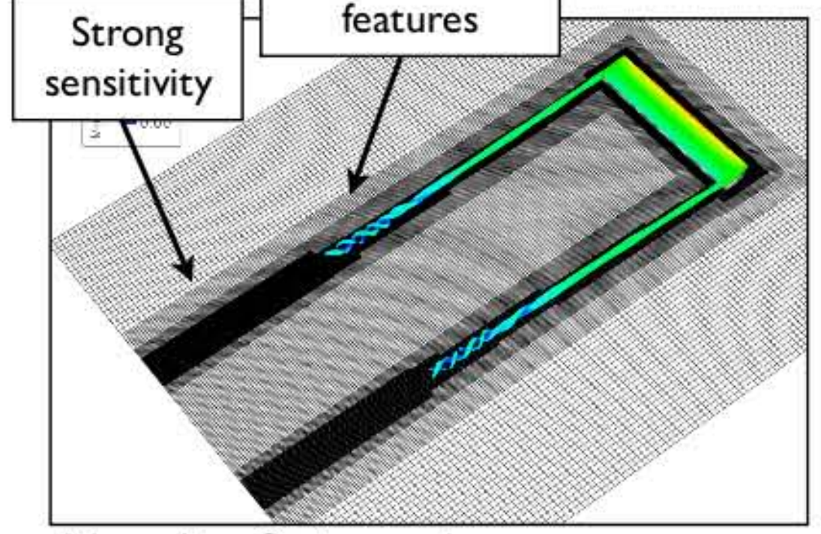


Premature termination

Vorticity Magnitude (optimal), $||\omega|| = 0.5$

Strong sensitivity

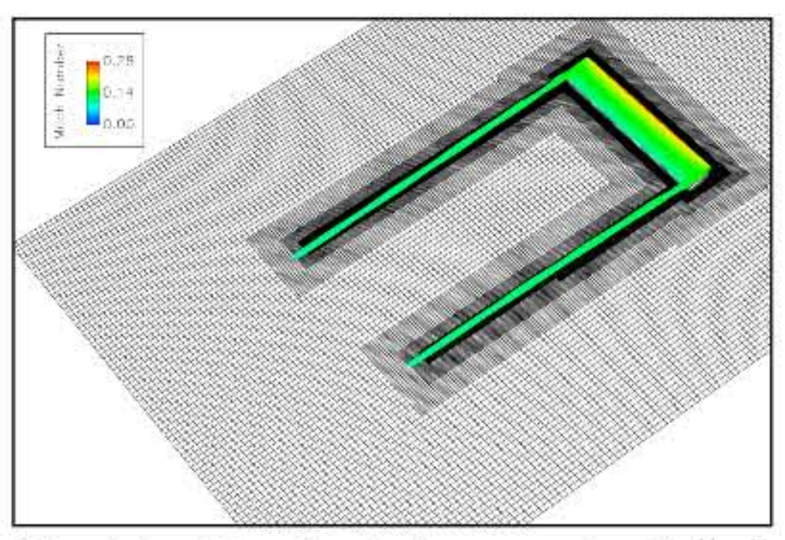
Fully developed features



Non-dim Q, $t_{val} = 1$

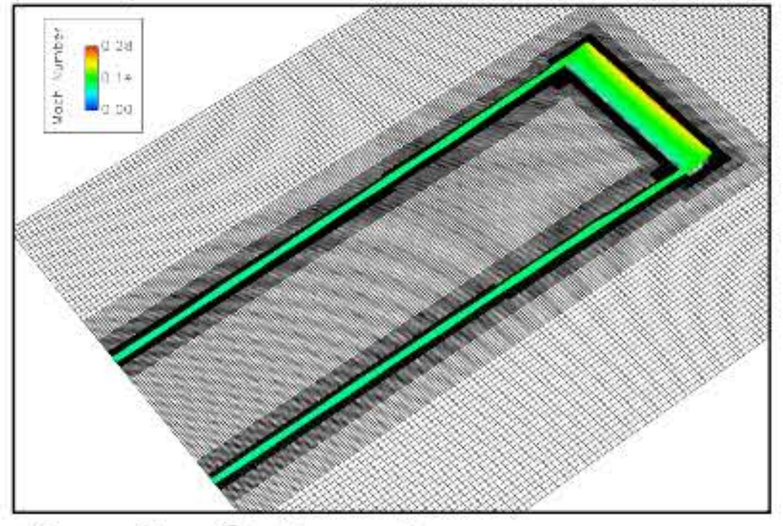
Final Solution

With the same threshold, non-dim methods select the proper regions for refinement and help preserve vortices over 20 chords downstream.

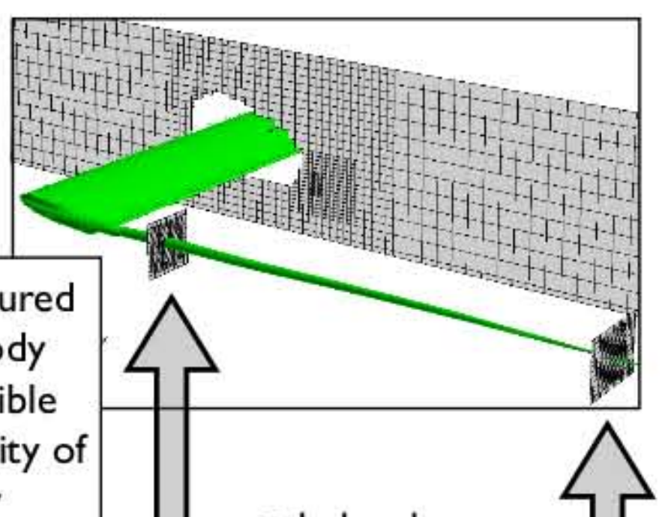


Vorticity Magnitude (non-optimal), $||\omega|| = 0.1$

(similar performance by other non-dim methods)

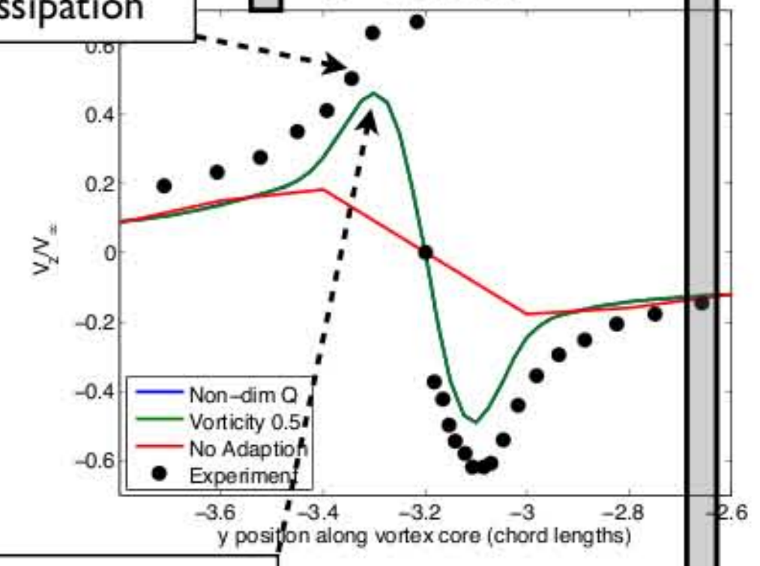


Non-dim Q, $t_{val} = 1$



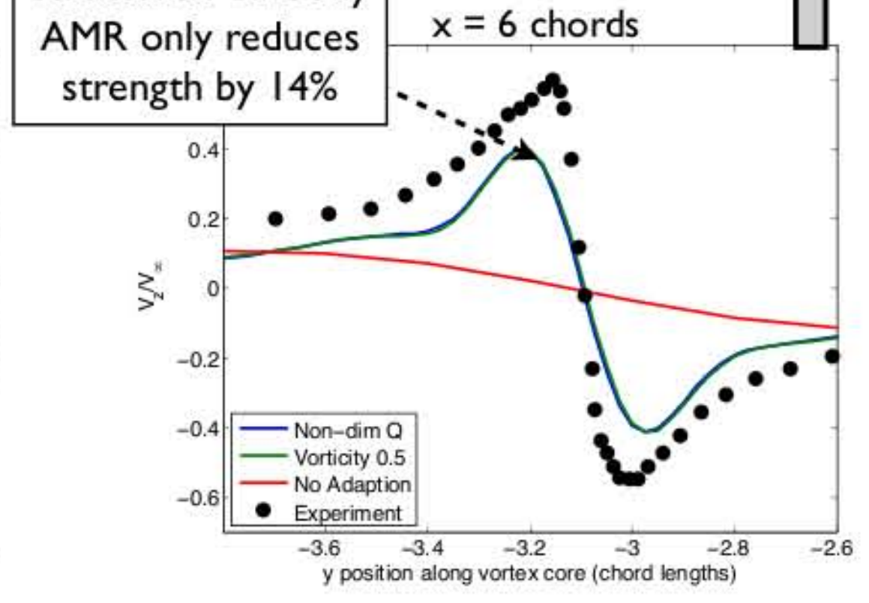
Unstructured near-body responsible for majority of early dissipation

x = 1 chord



Structured off-body AMR only reduces strength by 14%

x = 6 chords



Richardson-based Error Estimation[‡]

Method

Basic formulation:

Exact solution equals discrete and error; function of mesh size (h), and order of accuracy (p):

$$u = w_h + C_0 h^p$$

With two grid levels (h and h/2), error computed by:

$$\mathcal{E} = w_{h/2} - w_h$$

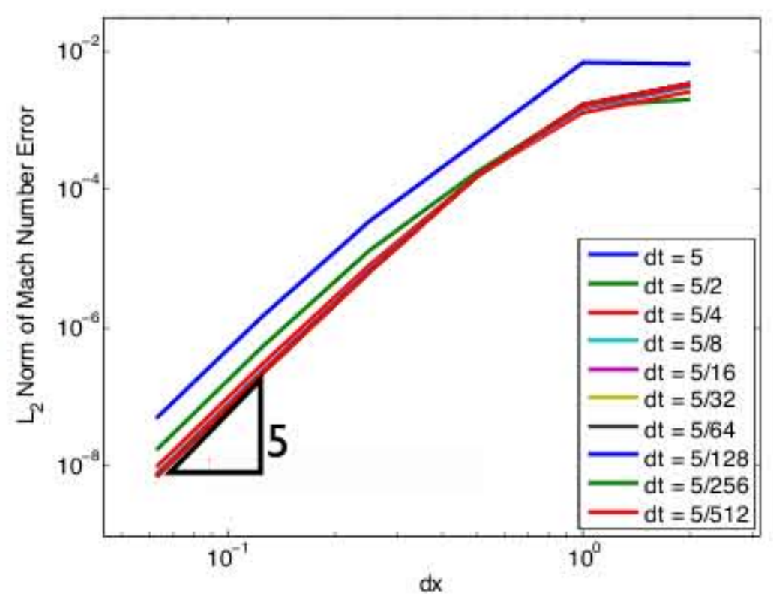
Assumptions:

1. Uniform and systematic refinement: Cartesian-based
2. Smooth and asymptotic solutions: No shock-like features; asymptotic when terminating refinement.
3. Dominant discretization error: Compared to iterative and round-off

Validation

Spatial accuracy study for advecting vortex explores wide CFL range.

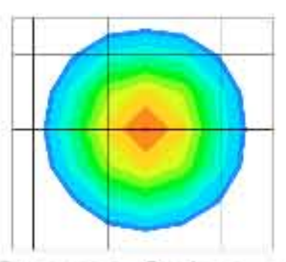
Optimal convergence of spatial discretization error. (5th order)



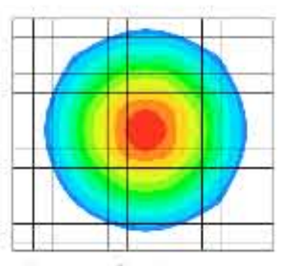
Approach: Terminate refinement if error drops below value

Local Error Computation

Fine grids are compared with their overlapping coarse parent.

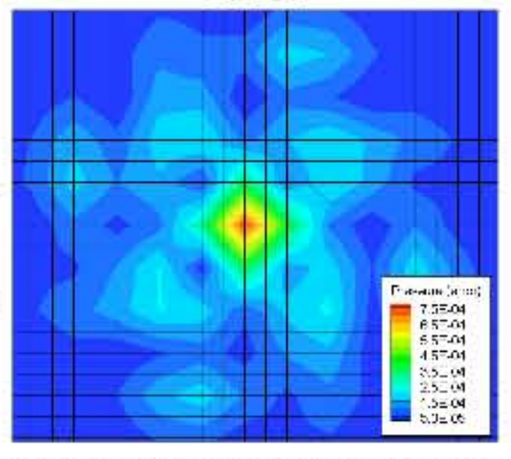


Coarse Solution



Fine Solution

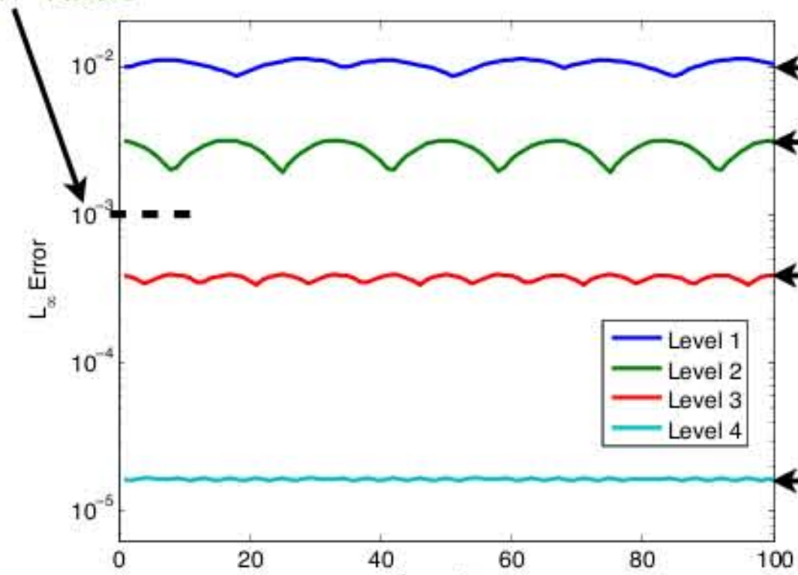
Error



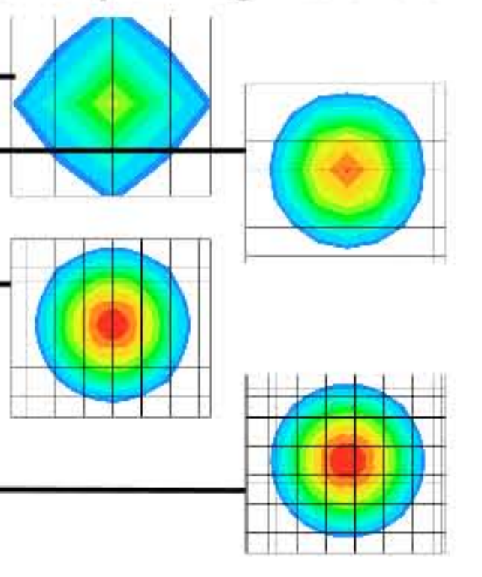
Pressure-based error for Vortex (locally normalized by pressure)

Dynamic Error Computation

Calculated Error on Level



Corresponding Resolution

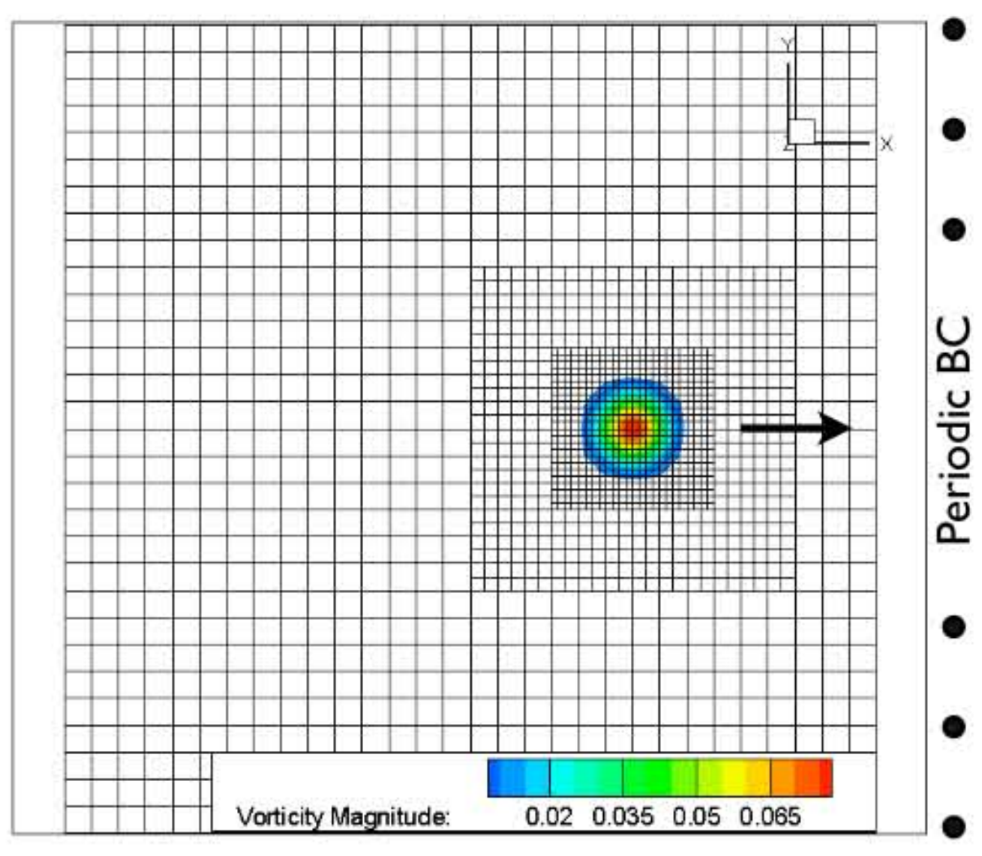


No major overhead;
150 error computations = 1 flow solution

Coupling Detection and Error Estimation

(Current Work)

Advecting Vortex

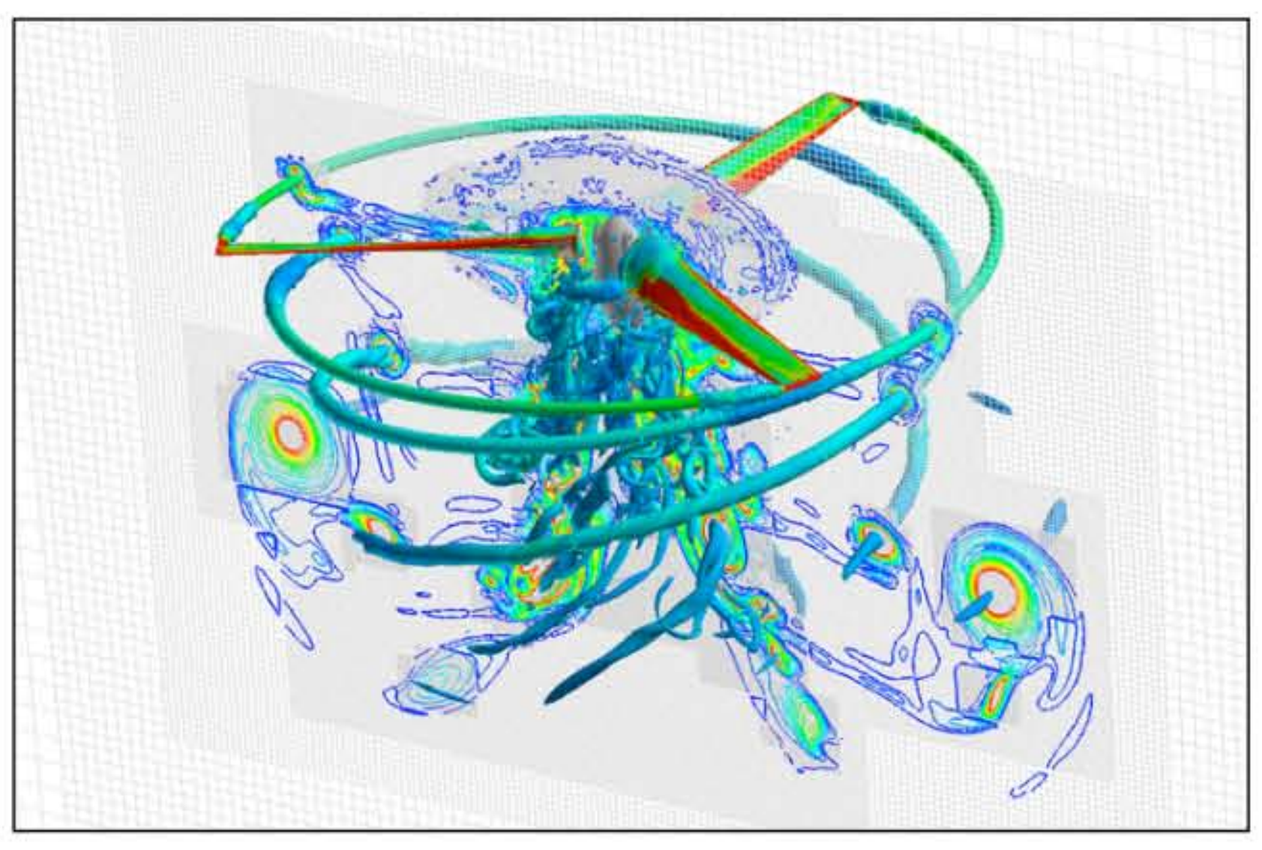


Feature detection and error estimator shown to work for isolated vortex.

Successfully terminates refinement when necessary with error tolerance of 10^{-3}.

Solution accuracy remains constant, and resolution is automatically set.

TRAM: V-22 1/4-scale model



Preliminary solution with refinement controlled by Non-dim Q ($t_{val} = 1$), without application of error estimator.

Coherent vortex structures after several blade revolutions.

Future: Include error-based refinement control, rather than applying maximum refinement.

☞ Material presented on this poster is a product of the CREATE-AV Element of the Computational Research and Engineering for Acquisition Tools and Environments (CREATE) Program sponsored by the U.S. Department of Defense HPC Modernization Program Office.

[†] Kamkar, et al., "Automated Grid Refinement Using Feature Detection," 47th AIAA Aerosciences Conference, Jan 2009, AIAA Paper 2009-1469

[‡] Kamkar, et al., "Feature-Driven Cartesian Adaptive Mesh Refinement in the Helios Code," 48th AIAA Aerosciences Conference, Jan 2010, AIAA Paper 2010-171

[‡] Kamkar, et al., "Using Feature Detection and Richardson Extrapolation to Guide Adaptive Mesh Refinement for Vortex-Dominated Flows," 6th International Conference on CFD (ICCFD), July 2010, St. Petersburg, Russia