Unsteady, Unstructured Overset Mesh Adaptation with an Efficient Parallel Localization Scheme

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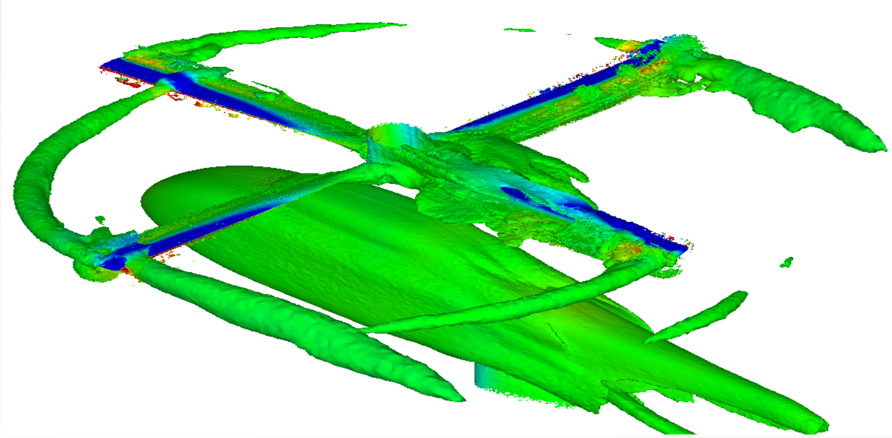
Introduction

- Complex wake physics require high fidelity methods for short and long age wake computations
- Applications include rotorcraft and wind turbine wakes
- Researchers have improved accuracy and capabilities:
  - **Mesh adaptation** is more efficient than uniform refinement
  - **Overset grids** enable moving body functionality and is popular for dynamic simulations
- Unstructured grids permit body-fitting of complex geometries



Computational Method

FUN3D – developed at NASA Langley

- Mixed-element unstructured, node-centered, finite volume solver
- Second-order accurate in space
- Second-order implicit time-integration (BDF2opt)
- Several turbulence models including hybrid RANS-LES (HRLES) – *Lynch, (GT 2011)*
- Overset functionality with DiRTlib/SUGGAR++ (PSU) – *O'Brien, (GT 2006)*
- Metric-based grid adaptation for tetrahedral elements

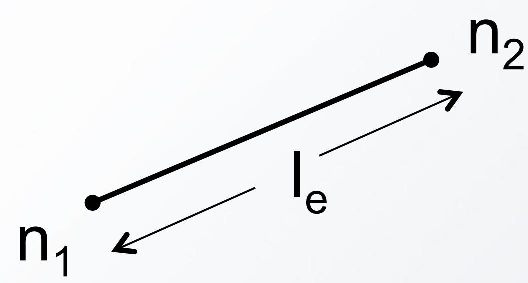
Feature-Based Error Estimators

Vorticity Magnitude

$$F_{e,\omega} = \ell_e \frac{|\omega|_{n_1} + |\omega|_{n_2}}{2}$$

Pressure Difference

$$F_{e,p} = \ell_e \left| p_{n_1} - p_{n_2} \right|$$



Q-criterion: $\frac{1}{2}\left(\|\Omega\|^2 - \|S\|^2\right)$ Separates regions of high rotation rate **Ω** from high strain rate **S**

Nondimensional Q-Criterion
Kamkar et al. (JCP 2012)

$$F_{e,Q-crit.} = \max_{n_1,n_2}\left[\frac{1}{2}\left(\frac{\|\Omega\|^2}{\|S\|^2} - 1\right)\right]$$

Metric-Based Adaptation

Intensity at each node →

$$\hat{I} = \max_{edges}\left(\frac{F_e}{F_{tol}}\right)$$

F_e: *error-estimate formulation (calculated on each edge)*

F_{tol}: *user-defined tolerance*

Such that **~10 nodes** resolve vortex core

- By obtaining adaptation intensity at each node, isotropic spacing is obtained
- Anisotropy reduces cost by stretching element
  - Introduced by computing a Hessian-based grid metric
  - The grid metric gives shape to each grid element
- Adaptation mechanics are performed based on the grid metric
  - Boundary layer mechanics are currently unavailable
  - More details in *Park et al. (AIAA, 2008)*

Extension to Overset Grids

Component grids

Stationary Grid (Fuselage) | **Near-body dynamic grids (Blades)** —**Assembly**→ **Composite grid**

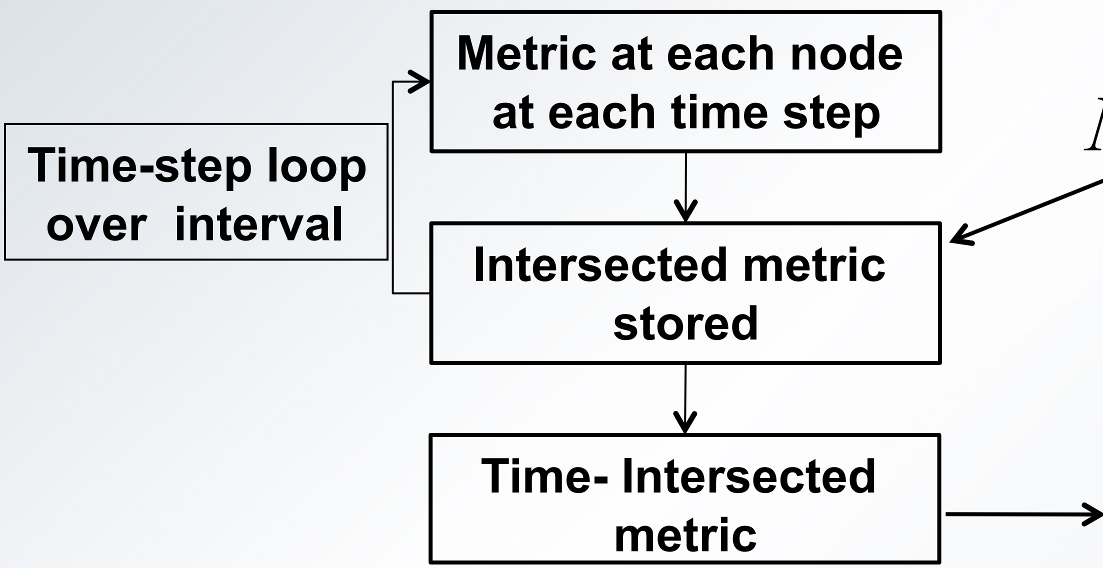
1. Adaptation performed on the **composite grid**
   - **All component grids** are **adapted** outside of the boundary layer
2. Hole-cutting of adapted grid is handled by SUGGAR++

   Adapted composite grid broken down into component grids and SUGGAR++ is called to obtain new domain connectivity
3. Designed a node indexing protocol for agreement between FUN3D and SUGGAR++

Time-Dependent Adaptation

Adapt grid over time-evolving interval(s)

Based on *Alauzet et al: AIAA 2007*



Grid Adaptation

Metric Intersection

$$M_{i,\max} = \bigcap_{n=1}^{N} M_{i,n}$$

Store the max. metric magnitude (highest error) at each node

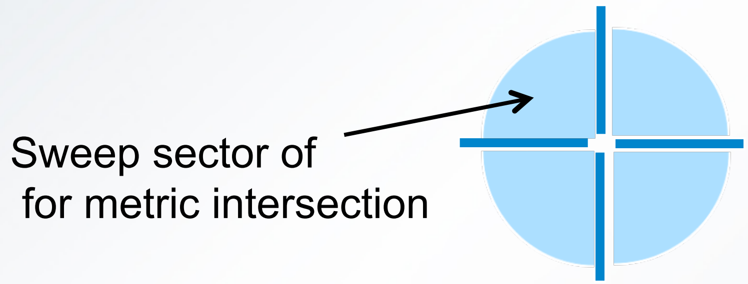
To handle implicit time integration:

1. Back plane metrics are included in metric intersection
2. Back plane grid motion is updated

Time-Dependent Adaptation

- Periodic interval adaptation
  - Rigid, prescribed motion
  - Adapt over a period and use new grid to get improved predictions and repeat until convergence

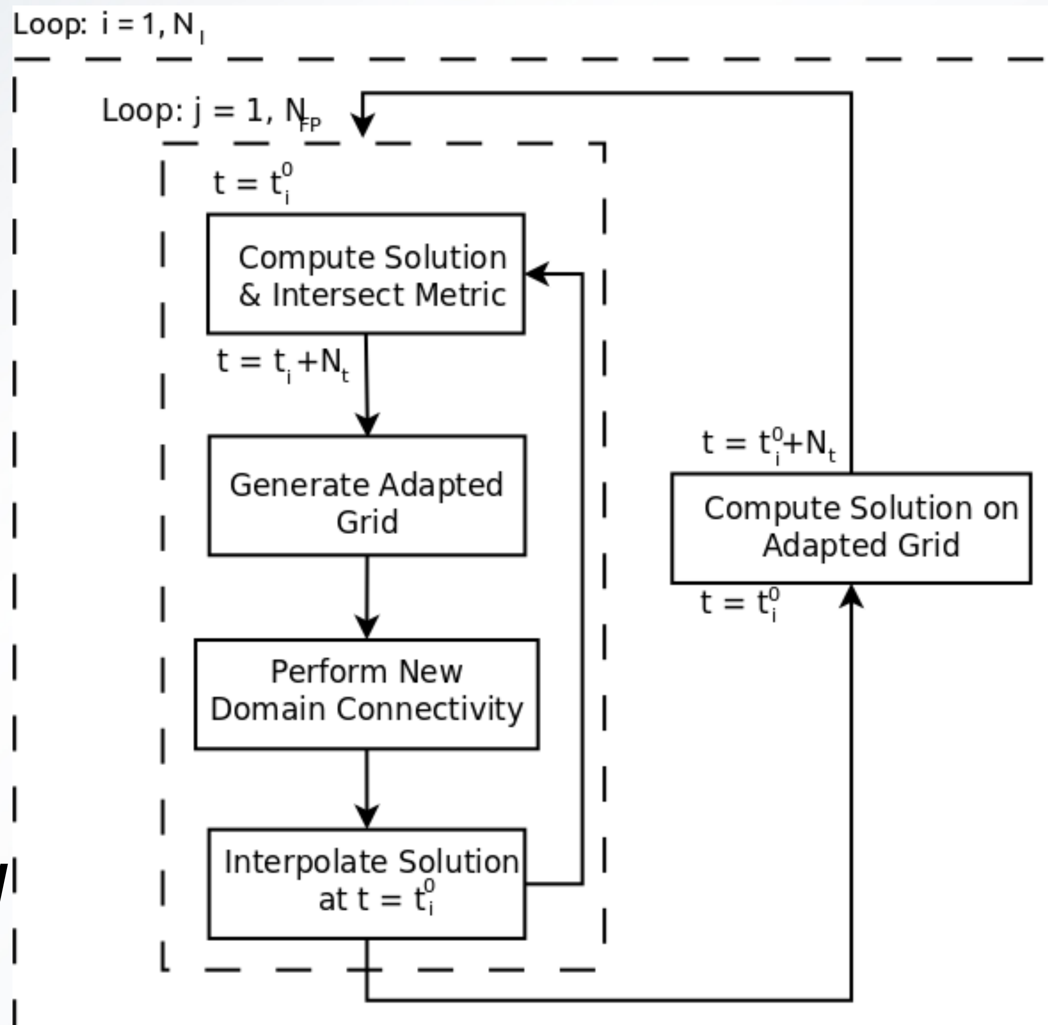
Rigid-body rotorcraft – $1/N_{blades}$ rev. after periodicity achieved



- General (non-periodic) interval adaptation
  - Adapted over several time intervals using a transient fixed-point algorithm (*Alauzet et al, AIAA 2007)*
  - For each interval, perform adaptation and solution transfers and compute improved solution on adapted grid

Transient-Fixed Point Algorithm

	Definition
N_{FP}	No. of fixed point iterations
N_I	No. of adaptation intervals
t_i^0	Start time of interval *i*



Unlike previous methods, back plane complexity is handled

Efficient Localization Scheme

- Developed a novel *parallel* scheme to efficiently search for interpolation stencils over massively distributed systems
- Compatible with mixed-element overset grids
- Uses collective communication (one thread per processor)
- Features that make the scheme fast:
  - Relies on **neighbor walks**, so searches are linear in space
  - **Parallel advancing front** keeps search space small *(new feature)*
- To avoid search failures, there are robustness features:
  - **Hierarchical prioritization** prevents search failure on realistic geometries *(new feature)*
  - **Random selections** to terminate cyclic searches
  - Defaults to **kd-tree method**, *Lynch et al. C&F 2014*

Box Grid Test Case

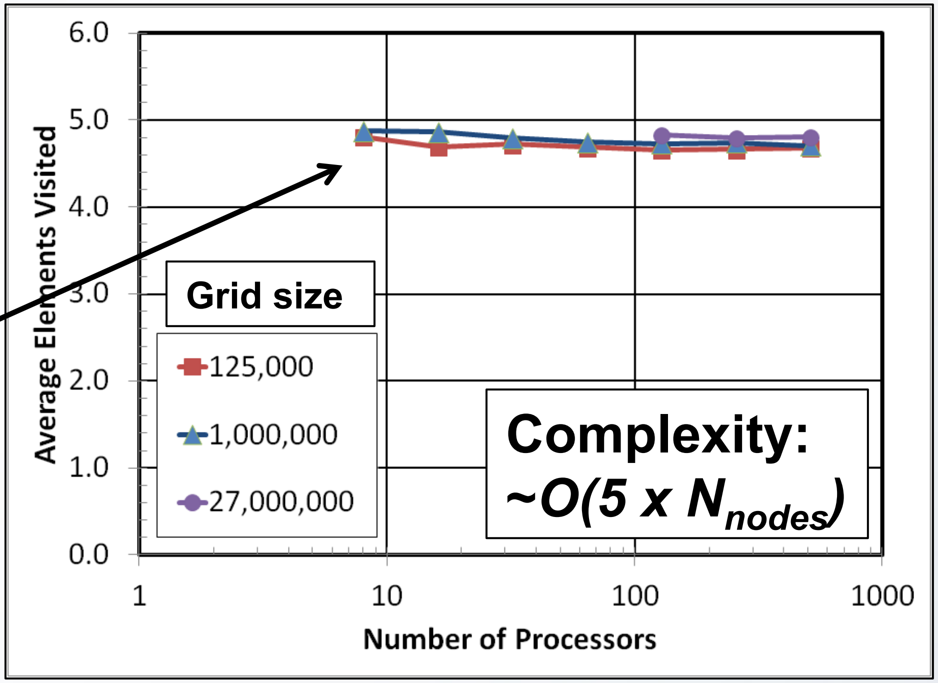
- Simple box domain with no geometry
- Test for cost and parallelization
- Three grids: 125k, 1M, and 27M nodes
- Number of processors: 8 … 512
- Averages done on five trials for consistency (randomness of neighbor walk)
- Assessments performed on NASA Langley's K cluster
- Monitor **complexity** and **required wall time**

Box Grid Localization Results

Serial complexity is $O(C \times N_{nodes})$ - Alauzet et al. (IJNM 2010)

- *C* should be approximately the average number of elements surrounding a node
- Observed *C* is approx. 5 for all decompositions
- **Consistent parallel complexity** of the localization scheme is confirmed

Average number of searches



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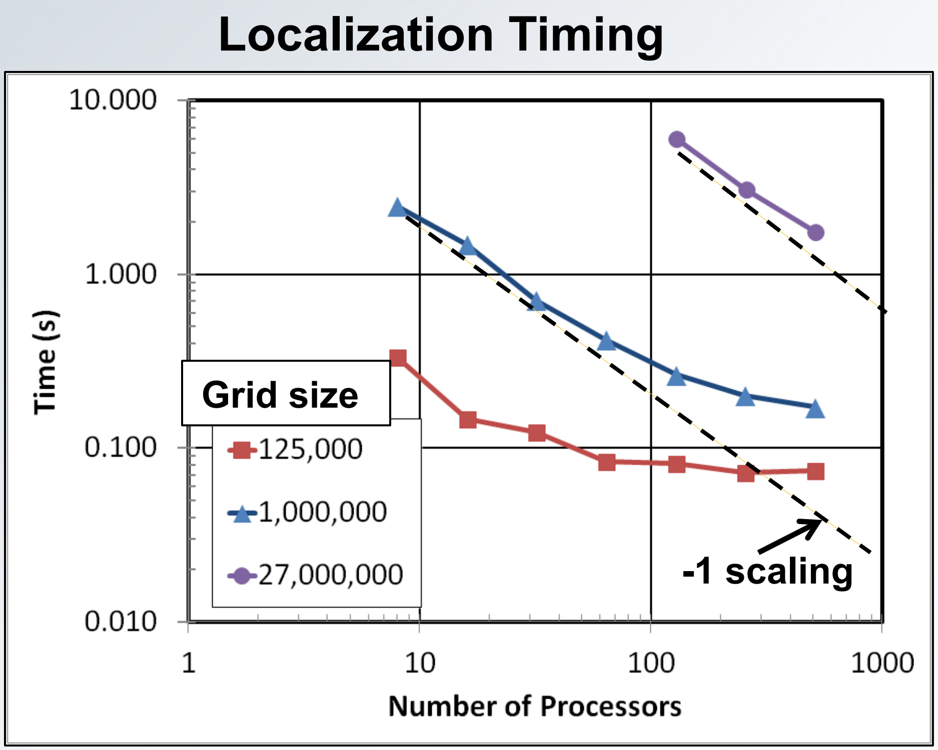
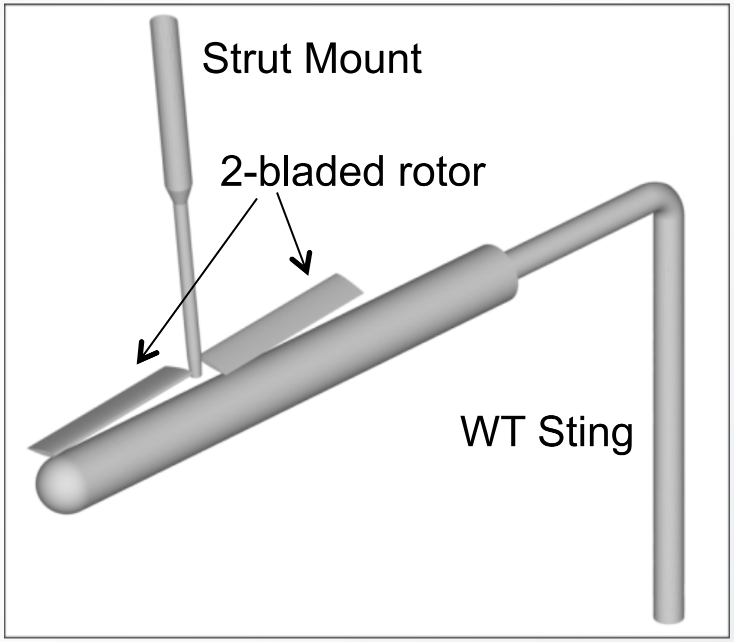
Box Grid Localization Results



- Time expected to decrease monotonically and ideal scaling should have a power -1
- Observed power is approx. **-0.89**
- Method is scalable with solver tested
- Localization is *cost effective* with respect to most processes that the solver handles

GT Rotor-Airfame Configuration

- Simple geometry to study RFI effects
- *Brand: PhD Thesis, 1989* for exp. data:
  - Time-averaged fuselage pressures
  - Instantaneous fuselage pressures

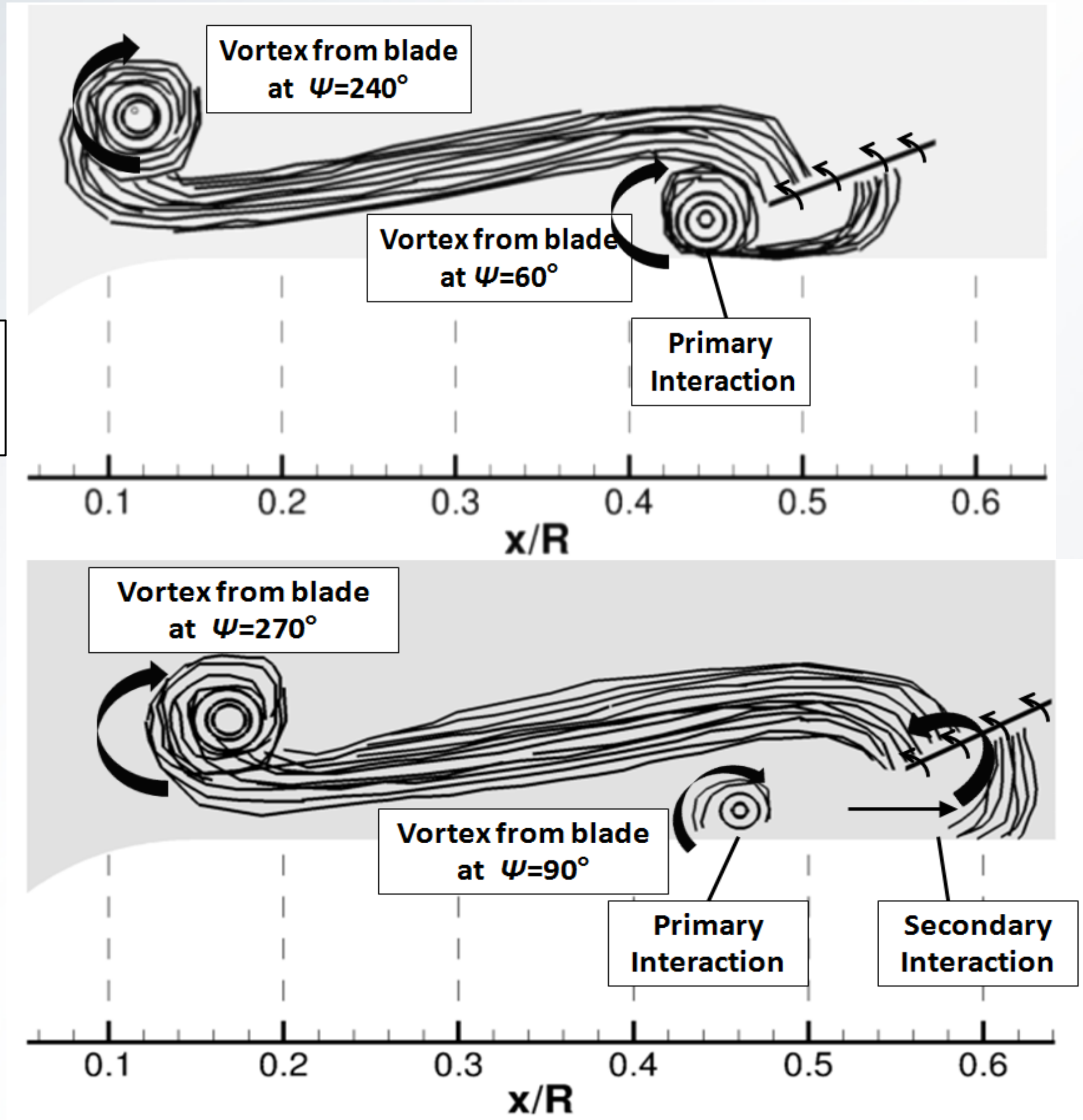


- Advance ratio of 0.10
- Time-step equivalent to 1º azimuth
- Hybrid RANS-LES computations
- Periodic time interval: 180º sweep
- Adaptation interval study

Method	Tolerance (F_{tol})
$\|\omega\|$	0.001
Δp	0.003
Nondim. Q-criterion	0.01

Vortex-Fuselage Impingement Physics

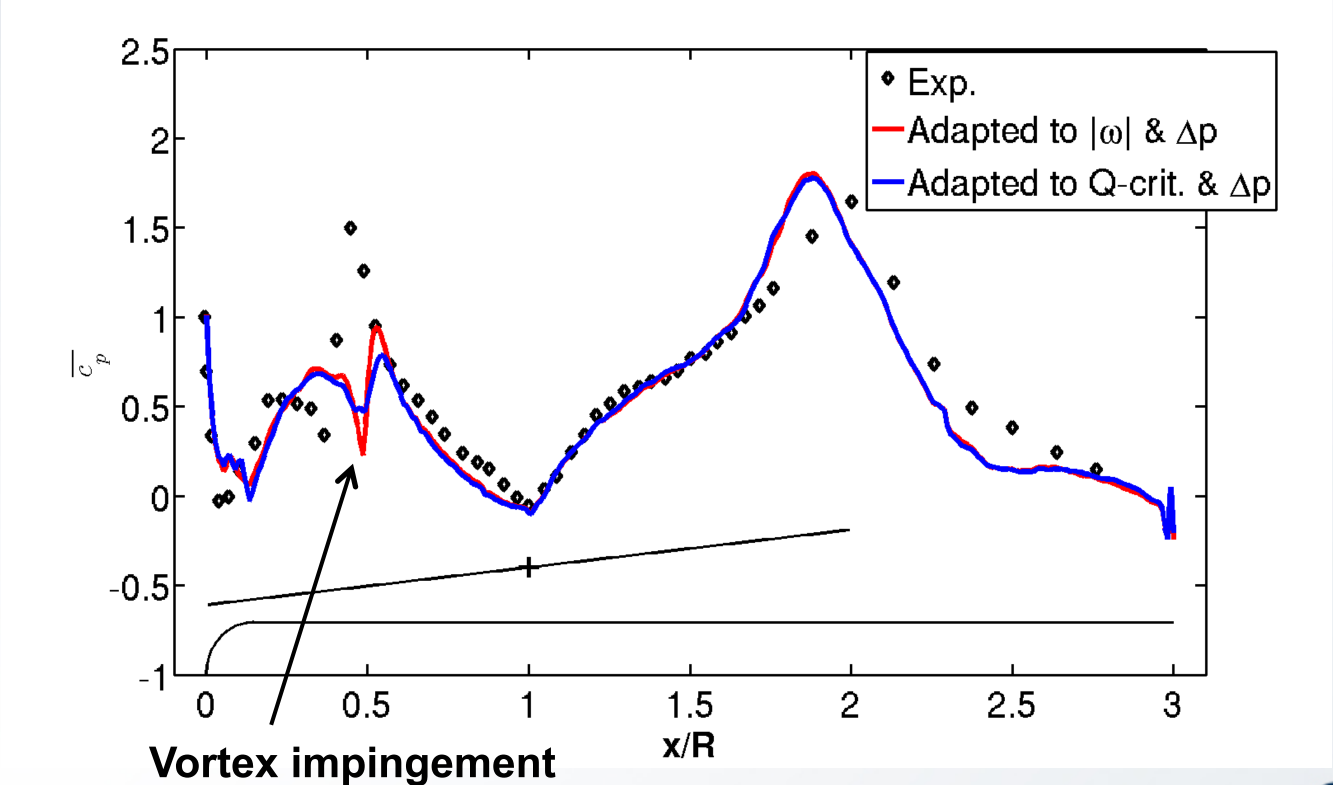
Sketch of Fuselage Symmetry Plane



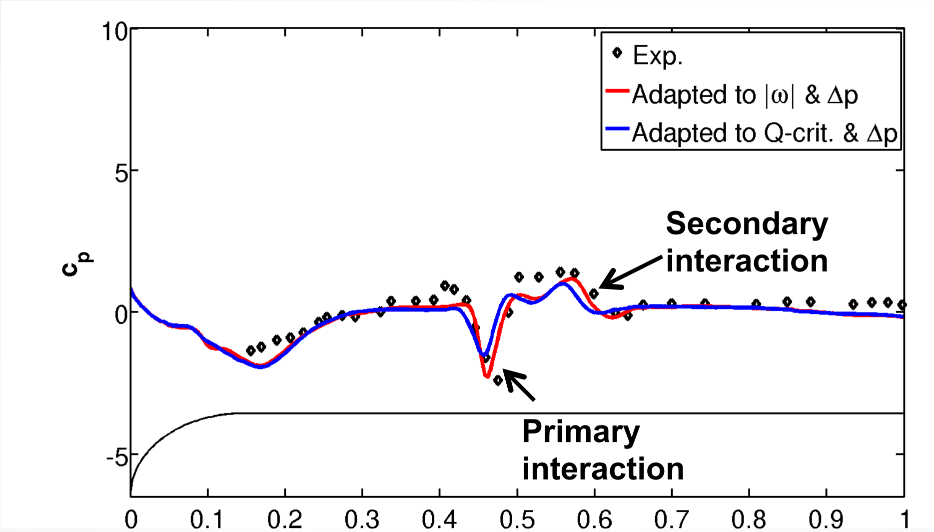
Average Pressures

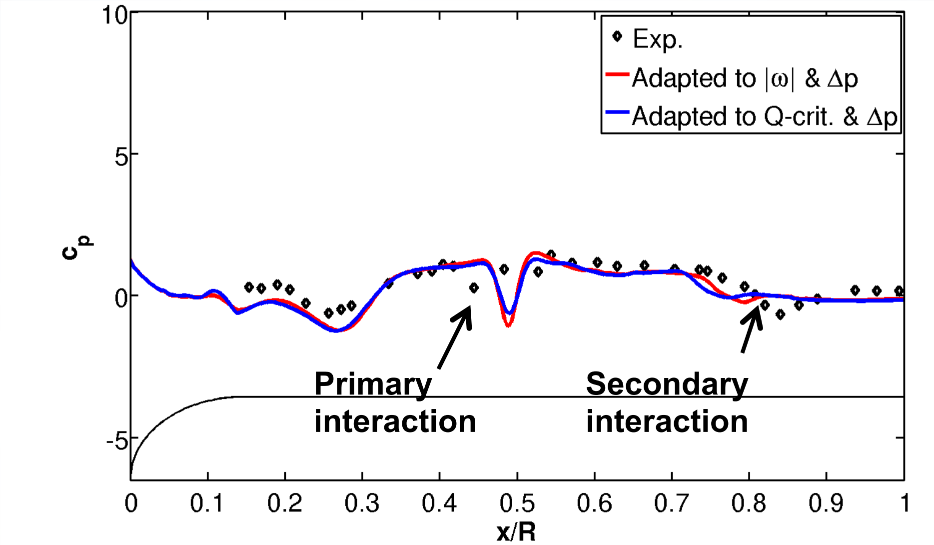
Upper fuselage centerline pressures are time-averaged

Vorticity mixed scheme: |ω| & Δp
Q-crit. mixed scheme: Q-crit. & Δp



Instantaneous Pressures

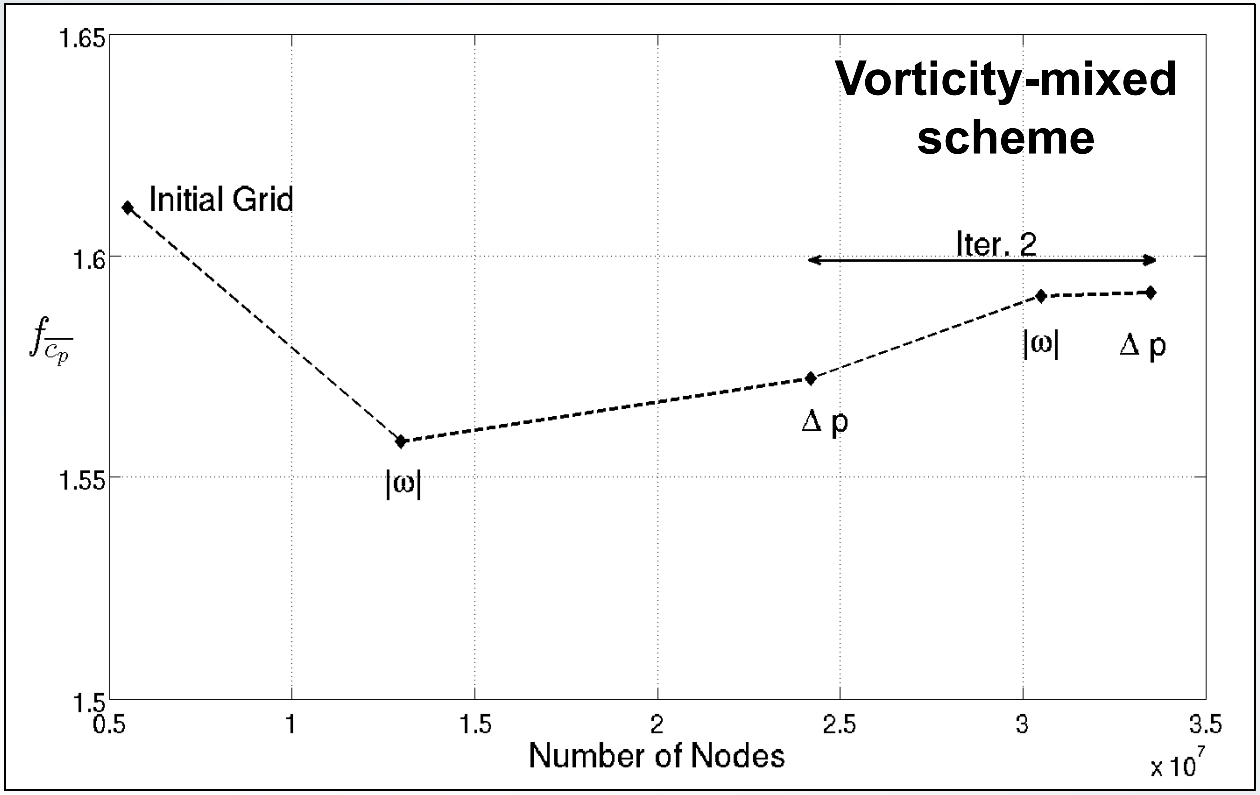




Adaptation Convergence

Integrated averaged centerline pressure coefficient

$$f_{\bar{c}_p} = \int_0^{3R} \bar{c}_p \, dx$$



Iter. 2: ~1.0% change

Adaptation Interval Sensitivity

- Investigated effect of time intervals:
  - 5° requiring 72 intervals/rev
  - 15° requiring 24 intervals/rev
  - Periodic (180°) adaptation – 1 interval same grid re-used
- Vorticity-mixed scheme used

Wall time/rev. (hours) on 480 processors

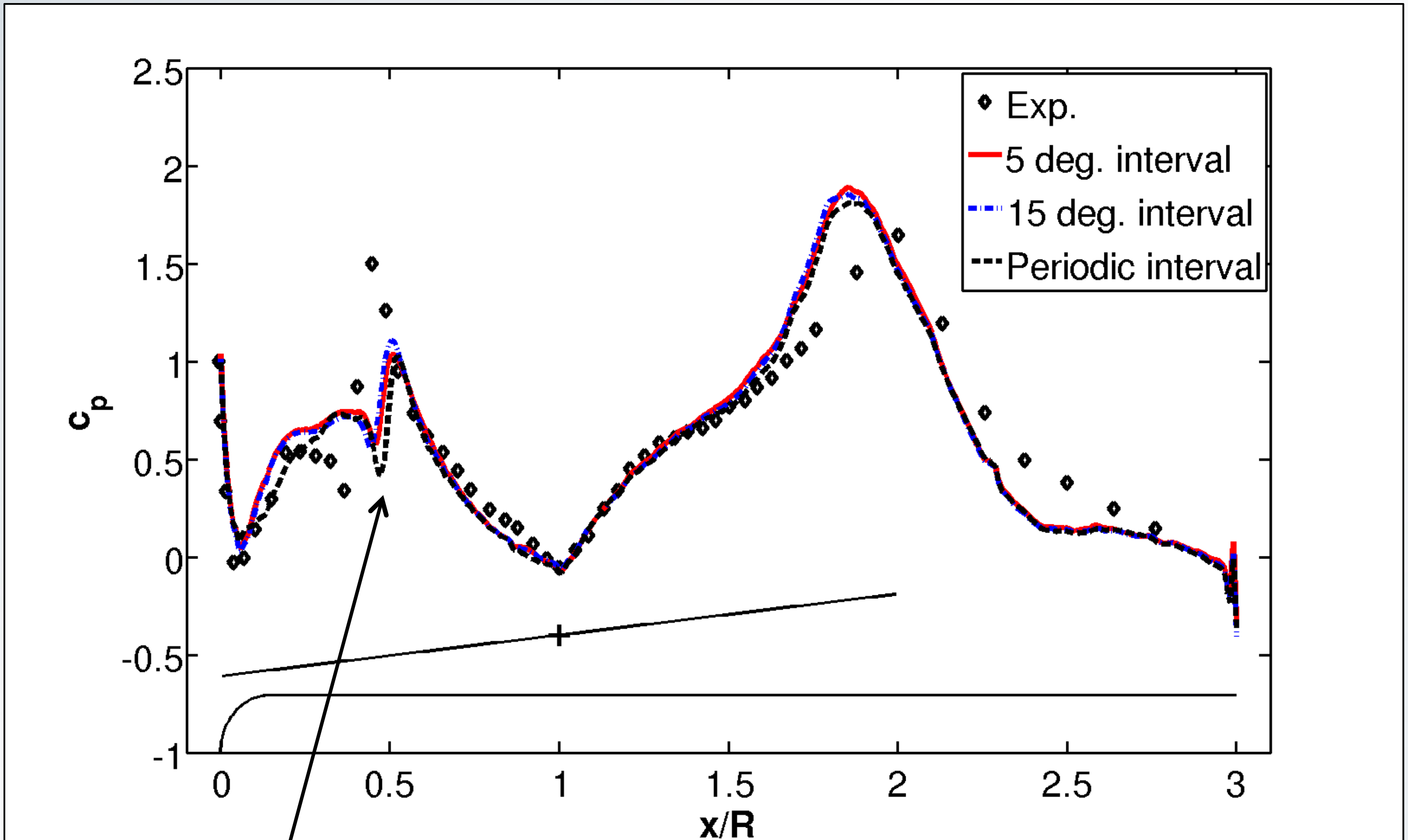
	5 deg	15 deg	Periodic
Flow Solver	24.0	22.8	16.7
Adaptation & Interpolation	7.2	4.2	0.3
Domain Connectivity	13.2	4.8	1.2
Total	**44.4**	**31.8**	**18.2**

2.4x *cost of periodic case*

1.75x *cost*

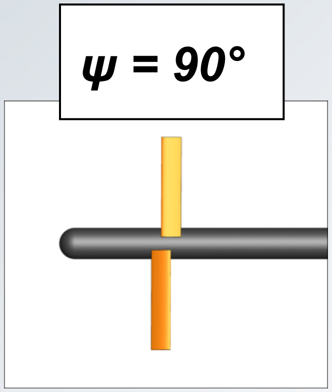
Note: Substantial cost increase due to overhead tasks; may be better streamlined

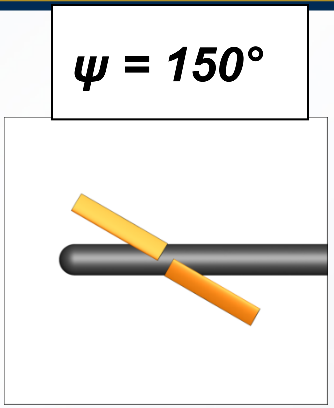
Interval Sensitivity (Average Pressures)

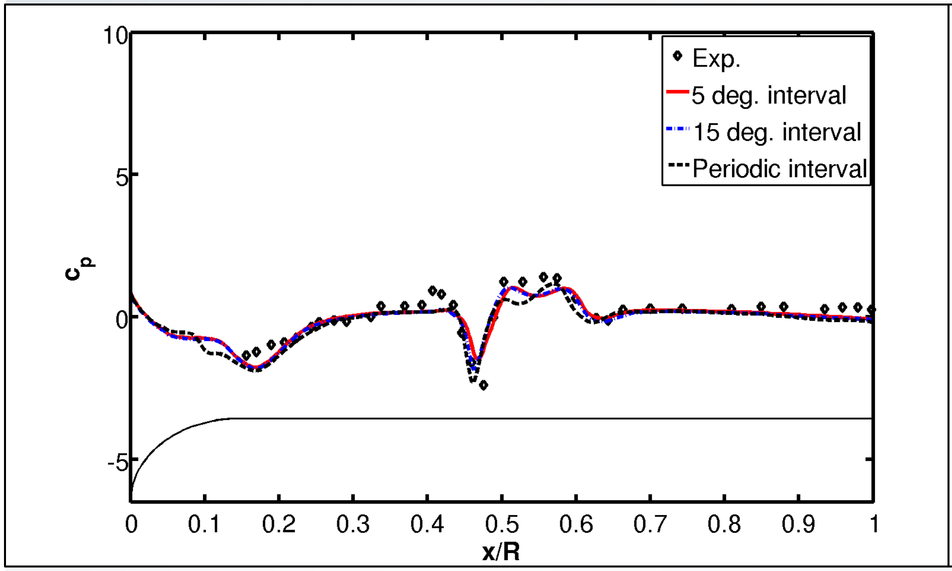


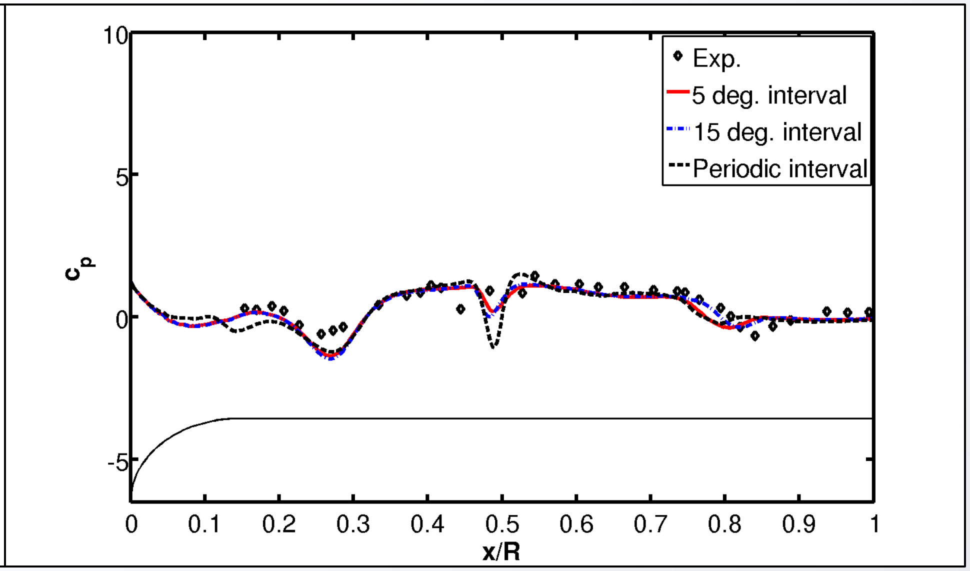
Minor difference in impingement location

Interval Sensitivity (Instantaneous Pressures)



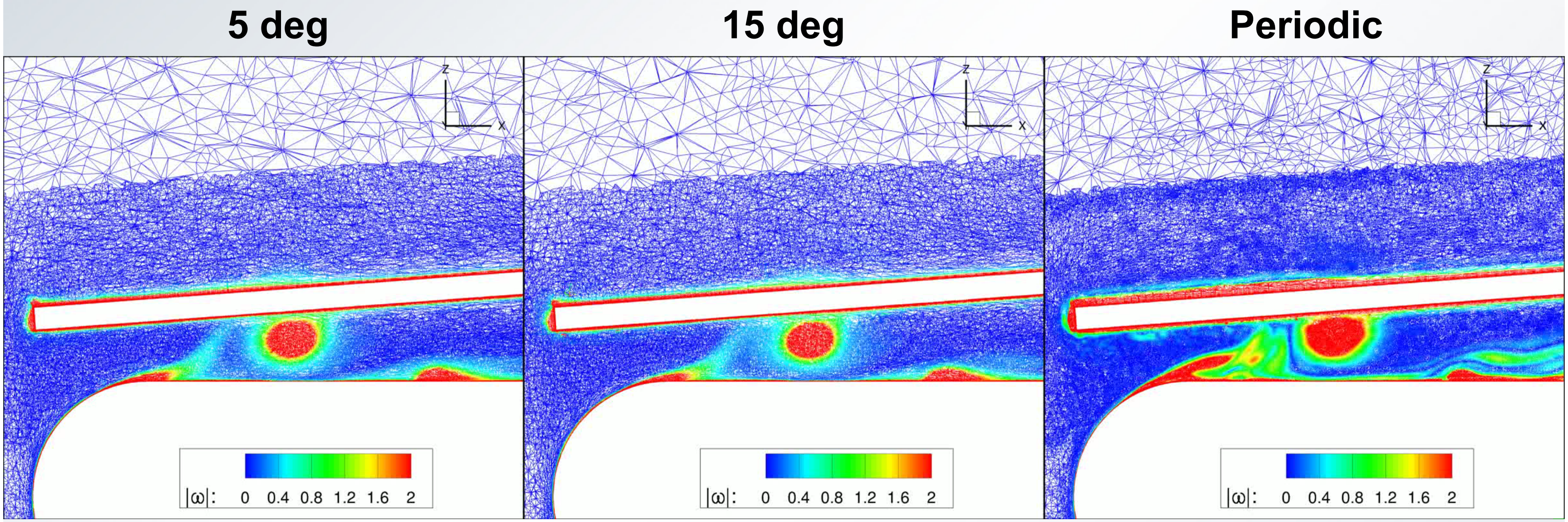






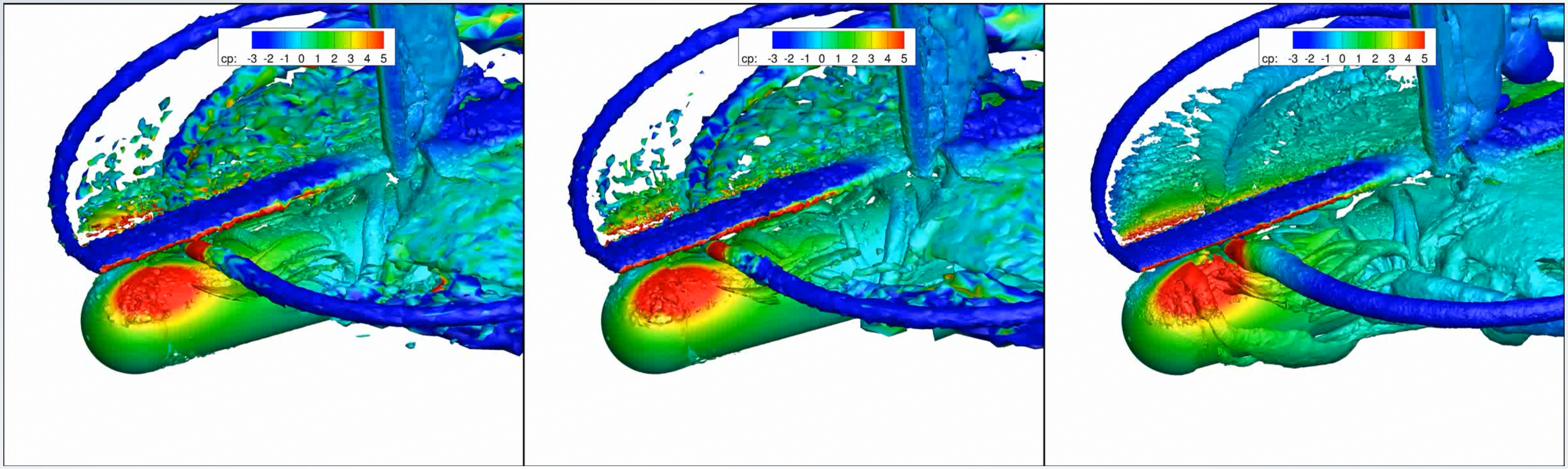
Consistent agreement and small differences in location and magnitude observed

Vorticity Mesh Contours



Q-Criterion Iso-Contours

5 deg 15 deg Periodic



More Information

All GT Theses and many datasets/presentations are freely available at:

https://smartech.gatech.edu/

(once you create an account – it is free, but you must register)

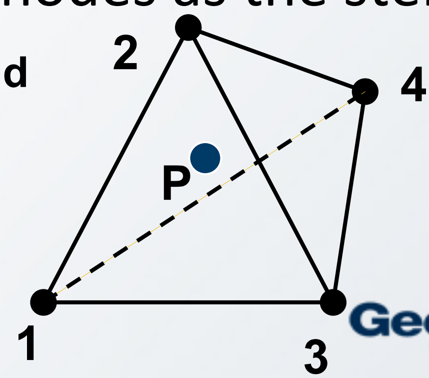
Rajiv Shenoy's Thesis:

https://smartech.gatech.edu/handle/1853/51796

Localization & Interpolation

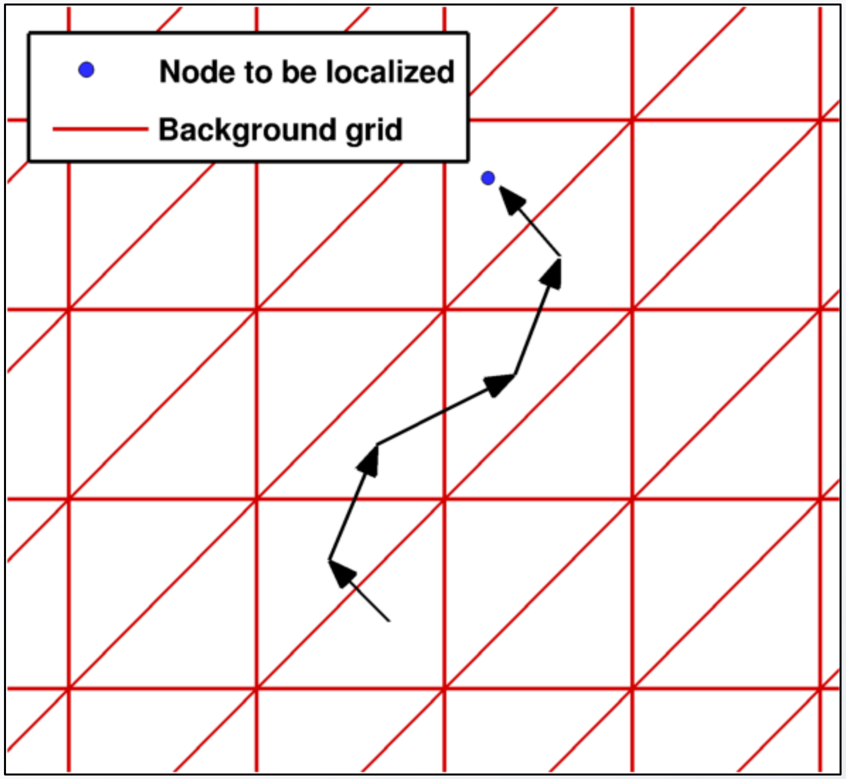
- **Background Grid:** Solution is known on this grid
- **New Grid:** Solution needs to be transferred to this grid
- **Localization:** Search process of a new grid node to find an enclosing element of background grid
- **Barycentric coordinates** (β_i) provide a natural basis to localize a node to a tetrahedral element
  - Provides information for search path (next step)
  - Serve as weights using the 4 tetrahedron nodes as the stencil
- **Interpolation:** $\phi_I(P) = \sum_{i=1}^{4} \beta_i \phi_i$

Interpolated solution: $\phi_I(P)$; Weights: β_i; Background solution: ϕ_i



Neighbor Walk

- Barycentric coordinates provide means of making neighbor steps
- Make steps until node is localized
- If multiple neighbor choices exist, then a step is randomly selected
  - Prevents infinite cyclic walks
- When cyclic walks are not avoidable, the search can default to a kd-tree search for those nodes

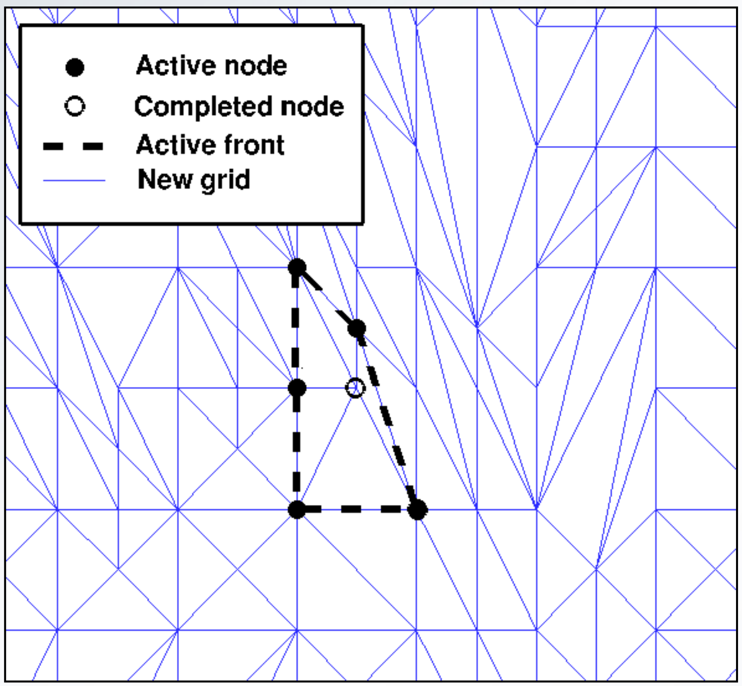


Requires background grid's list of cell adjacencies

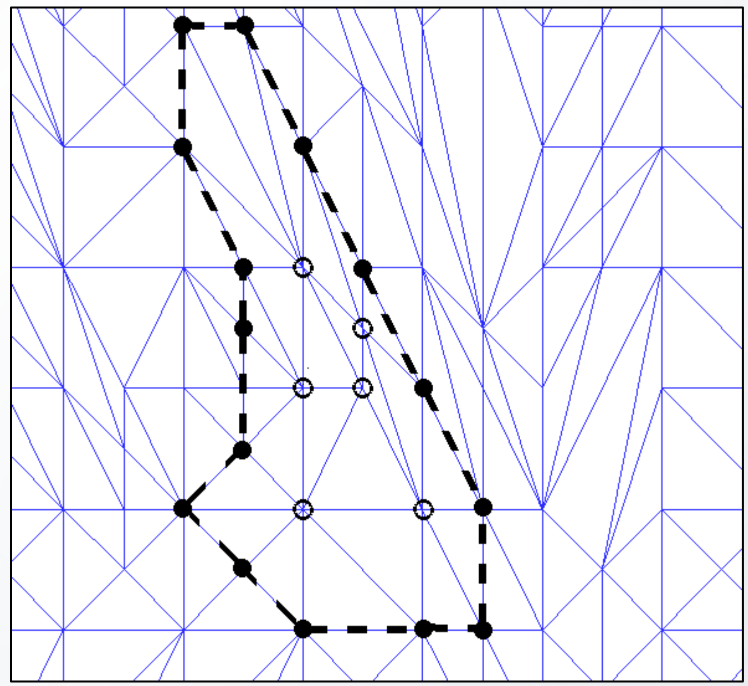
Advancing Front

- Enclosing element becomes a guess for node neighbors
- Subsequent searches become increasingly confined

Seeding the front with 1 node



Advancement of front



Requires new grid's list of node neighbors

Parallelization of Localization Scheme

- Relies on collective communication (MPI)
- Keep track of the *guess element* and *partition number*
- What happens if the walk hits a partition boundary?
  - Communicate to neighboring partition (processor)
  - Information about a boundary node is provided
  - On that partition, one element surrounding that node is *randomly* selected as the guess element and the neighbor walk continues
- Once a node is localized, its **enclosing element**, **partition**, and **weights** are stored for interpolation

Robustness Features

- These searches are linear and can potentially encounter geometry boundaries especially for realistic problems
- Therefore localize nodes in hierarchical fashion:
  - Corner nodes: where three boundary faces coincide
  - Edge nodes: where two boundary faces coincide
  - Surface and volume nodes (bulk of the grid)
- Use kd-tree search method, *Lynch et al. C&F 2014*, to localize **corner** an**d edge nodes**, generally < 1% of grid
- Surface and volume nodes are then localized using the parallel advancing front scheme

Other Enhancements

- Handling mixed-element grids
  - Non-tetrahedral elements are used in the boundary layer
  - Can use barycentric approach by converting elements into tetrahedra (only data structures)
- For overset grids, localize each component grid