Hybrid Overset Methods: Opportunities, Applications and Pitfalls

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Overview of the Presentation

- **Background and opportunities**
  - What are hybrid methods
  - Why hybrid methods
  - Alternative approaches
- **Common methods**
  - Advantages and disadvantages
- **Limitations & pitfalls**
  - Divergence
  - Cost
  - Viscous terms
  - Overset interface
- **Success stories**
  - Rotorcraft
  - Ship airwake
  - Wind turbines
  - Viscous vortex ring phenomena
- **Areas for ongoing and future work**
- **Conclusions**
- **Acknowledgements**

Background

Background

- **What are hybrid overset methods?**
  - Near and off-body solvers with different formulations
- **Examples include**
  - RANS/Euler
  - RANS/Euler/Potential flow
  - Vortex embedding (Potential flow/Free-wake)
  - RANS/Free-wake
  - RANS/Particle method
  - RANS/Vorticity-velocity
  - Lifting line/Vorticity-velocity
  - Panel method/free-wake
- **Focus on CFD/vorticity-velocity methods**
  - Lagrangian (free-wake and particle methods)
  - Eulerian

- **Vorticity-velocity methods**
  - Solve the vorticity transport equation

$$\frac{\partial}{\partial t}\omega + u \cdot \nabla \omega - \omega \cdot \nabla u = \upsilon \nabla^2 \omega + S$$

  - In conjunction with the Poisson relation

$$\nabla^2 v = -\nabla \times \omega$$

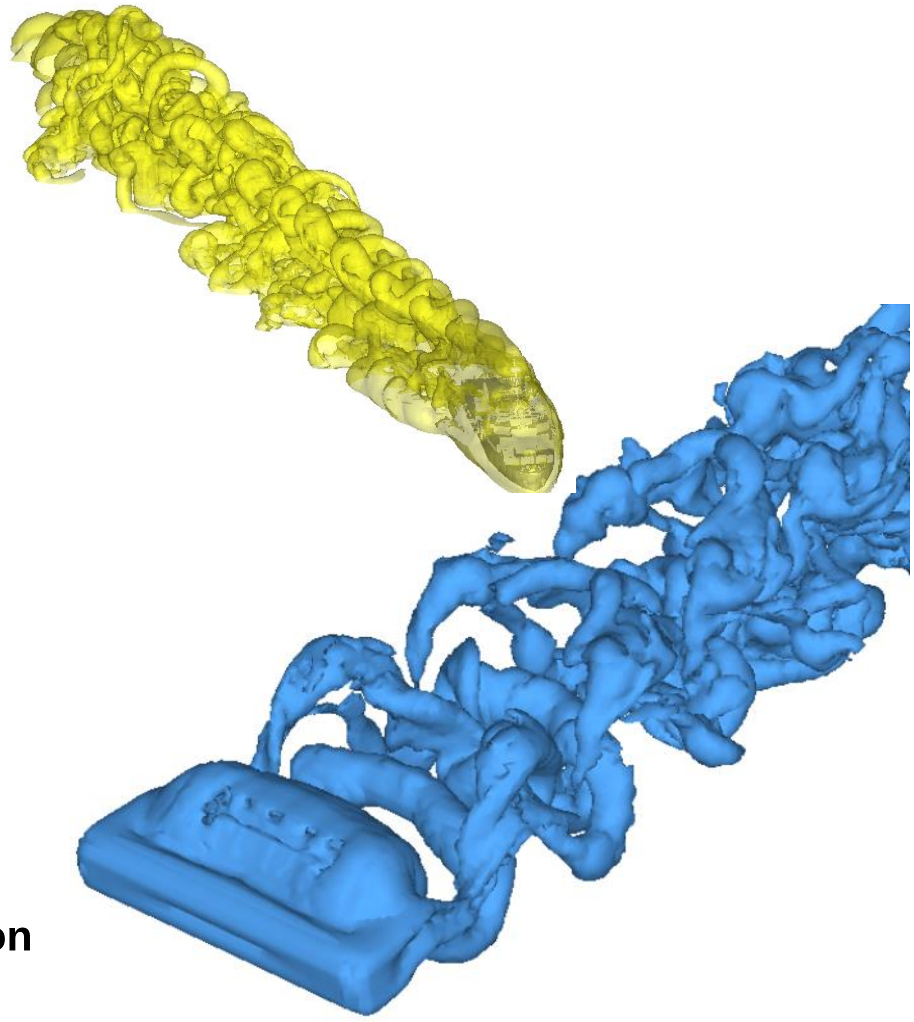
Background (cont'd)

- **Reliable and efficient flow prediction is critical for a variety of vorticity-dominated applications**
  - Rotorcraft
  - Ship airwakes
  - Architectural flows
  - Wake breakup
  - Bluff bodies

- **This requires accurate first-principles modeling of the wake structure unsteady loading and fluid-structure interactions**

But …

- **Conventional CFD formulations have high relatively numerical diffusion of vorticity on practical engineering grids**

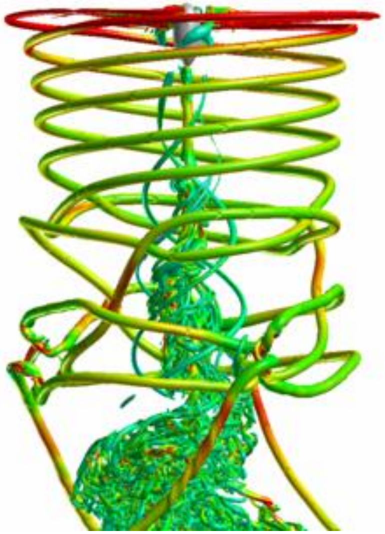


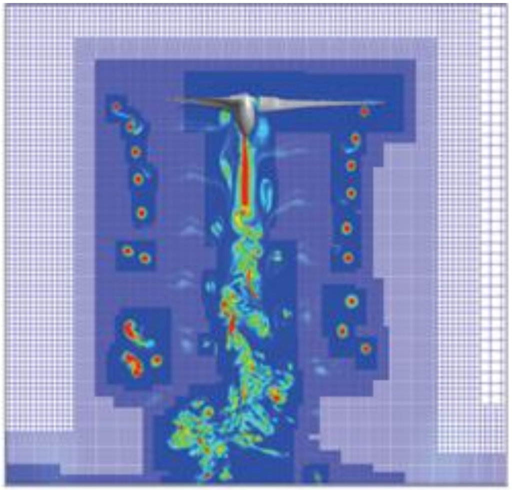
Hybrid overset prediction of a ship air wake and the wake behind a wing at 90º angle of attack

Background (cont'd)

Solutions

- **Increase CFD grid density (locally or globally)**
  - Promising results,but **costly**
- **Higher order methods**
  - First order near steep gradients; complicated and may still require increased grid density
- **Hybrid CFD**
  - Couple CFD to an alternative "background" flow solver (vorticity-velocity, potential flow etc.)
  - Focus CFD resources near to surfaces (viscous, compressible regions)
  - Should be able to obtain significant reductions on turnaround time
  - Some successes, but results have been mixed in terms of quality, fidelity, stability and cost





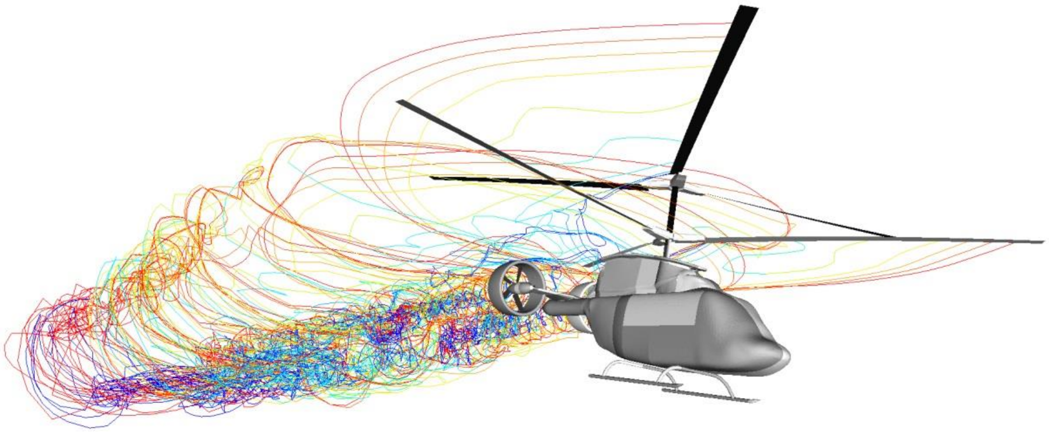
HELIOS prediction of hovering TRAM rotor with ~120M cells

Common Methods

Common Methods

Vorticity-Based methods

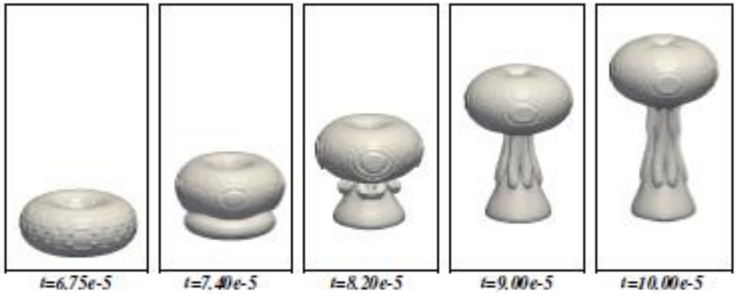
- **Filament Methods**
  - CHARM (CDI)
  - MFW (University of Maryland)
  - GT-Hybrid (Georgia Tech)



CHARM filament wake for an advanced coaxial compound

- **Particle Methods**
  - PVTM (NIA)
  - Zhao and He (ART)
  - Winckelmans, Leonard, Cottet *et al* (Caltech, Université Joseph Fourier ETH)
  - Quackenbush *et al* (CDI & Caltech)

- **Grid-based Methods**
  - VTM (IC, UG, US and CDI)
  - VorTran-M/VorTran-M2 (CDI)
  - Harris *et al* (CFDRC)

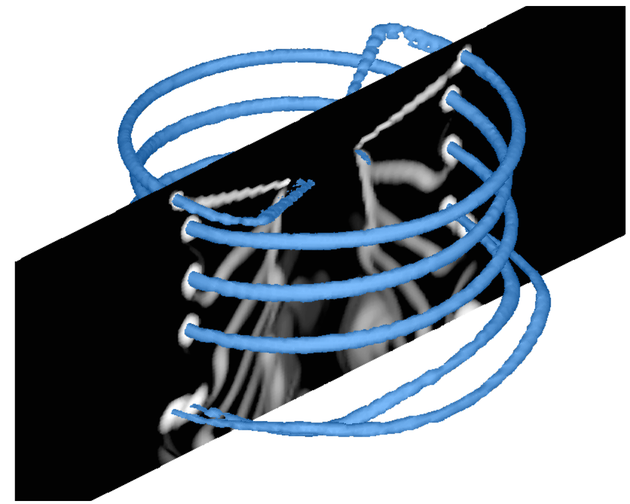


Grid-based prediction of viscous vortex ring evolution from Harris *et al* AIAA-2010-1072

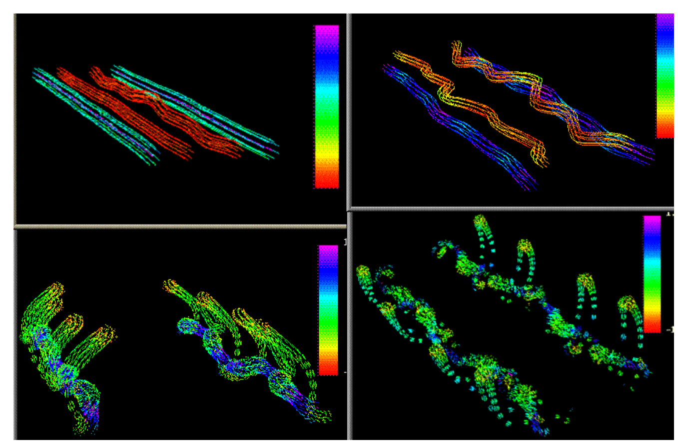
Common Methods (cont'd)

Advantages and Disadvantages

- **Filament Methods**
  - Automatically divergence free*
  - Can be fast (CHARM)
  - Cannot predict details of vortex-vortex interactions
- **Particle Methods**
  - Ideal for vortex-votex interactions
  - High cost (for adequate resolution)
  - Must address divergence constraints
- **Grid-based Methods**
  - Ideal for vortex-vortex interactions
  - Can address numerical diffusion (VTM/VorTran-M/VorTran-M2)
  - Must address divergence constraints (VorTran-M2)



Grid-based prediction of hovering rotor wake



t = 0.01 t = 0.03

t = 0.06 t = 0.09

Particle method prediction of crow instability

Limitations and Pitfalls of Hybrid Methods

Limitations and Pitfalls of Vorticity-Based Methods (cont'd)

Divergence Free Vorticity Field

$$\nabla \cdot \omega = 0$$

- **Problem**
  - Vorticity should be a solenoidal field (i.e. vorticity should form closed loops that do not terminate in the flow)
  - Not automatically guaranteed in particle and grid based methods
  - Not guaranteed in filament methods at the end of the last filament unless a boundary condition is imposed (*but usually far away and un-important*)

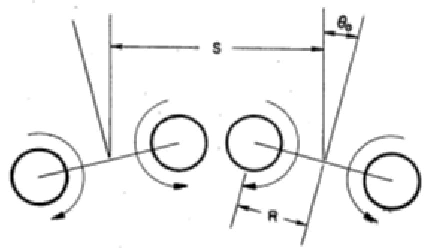
- **Consequence**
  - Vorticity magnitude spuriously increases as a result of stretching
  - Reduced time steps and re-meshing required to prevent numerical instability
  - Without remediation the solution becomes increasingly inaccurate

- **Typical Solutions**
  - Ignore and hope that solutions are not contaminated
  - Implement viscous terms and assume that viscous diffusion counters the divergence
  - Helmholtz decomposition to actively correct vorticity

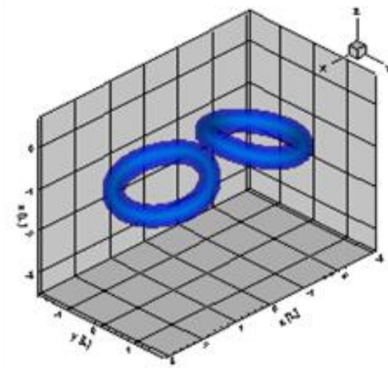
Limitations and Pitfalls of Vorticity-Based Methods (cont'd)

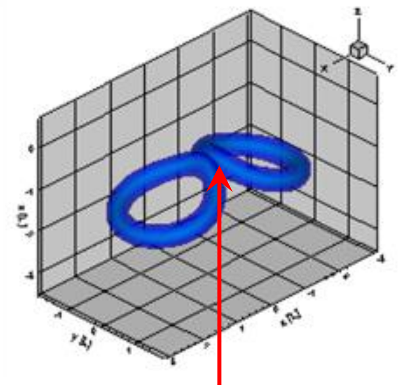
Impact of Divergence Free Vorticity Field

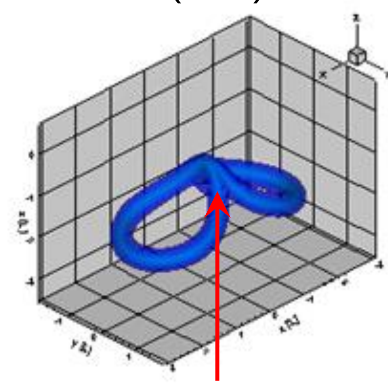
- **Pair of equal strength vortex rings**

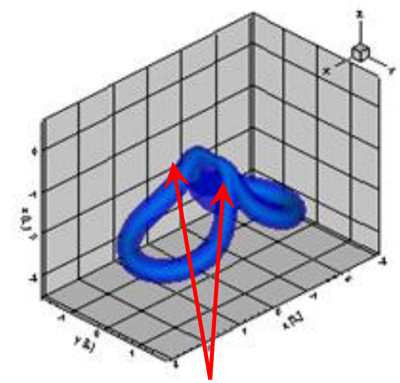


- **Observations**
  - As vortex rings merge pinch-off occurs and they form a single ring
  - Significant stretching during pinch-off
  - Divergence induces instability in regions with significant stretching


Two separate rings approach each other (t=4s)


Rings first start to merge (t=6s)


Pinch-off starts to occur (t=8s)

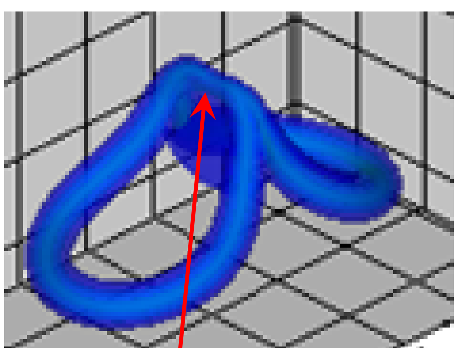

Significant pinch-off and merging in full effect (t=10s)

Evolution of merging inclined vortex rings

Limitations and Pitfalls of Vorticity-Based Methods (cont'd)

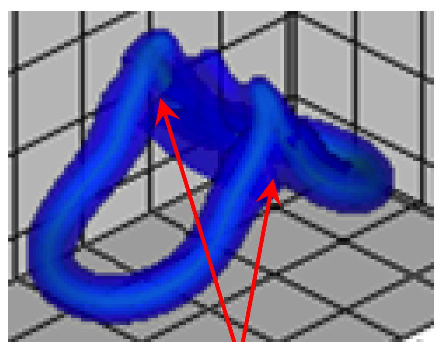
Impact of Divergence Free Vorticity Field (cont'd)

- **Impact of divergence correction**
  - Prevents instability
  - Prevents spurious increase in vorticity in pinch-off region due to stretching

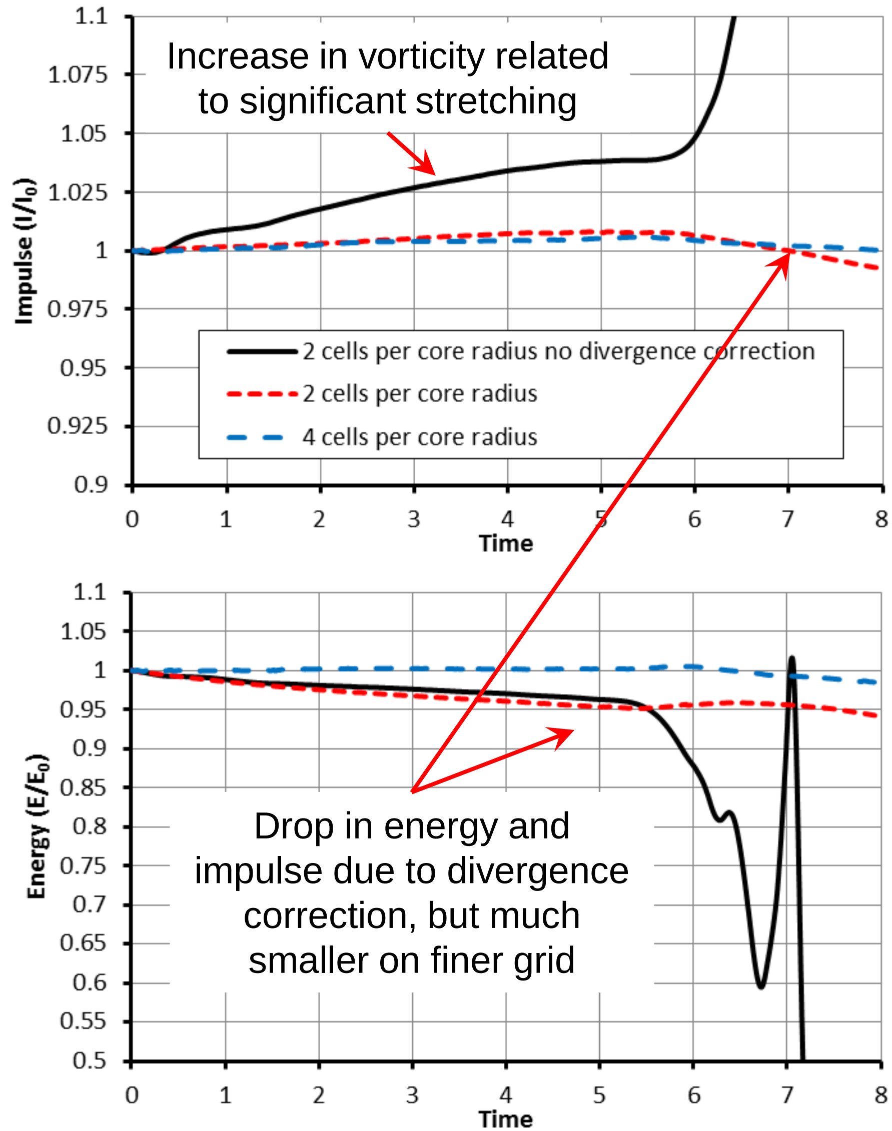


Divergence correction forces the formation of closed loops of vorticity

t=10s



Premature merging due to stretching and increase in vorticity at pinch-off locations



Limitations and Pitfalls of Vorticity-Based Methods (cont'd)

Computational Cost

- **Problem**
  - 6 equations and 6 unknowns must be solved (grid based and particle methods) (not including divergence correction and unsteady pressure calculation overset)
  - Velocity calculation is an N-body problem ($O(N^2)$) if using Biot-Savart
  - Resolution required to resolve features of interest

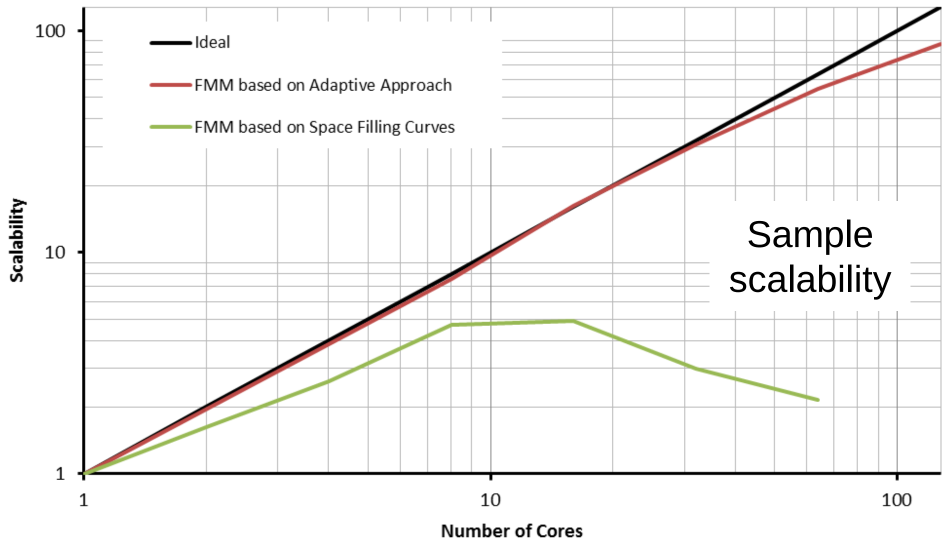
- **Consequence**
  - Vorticity-velocity methods can be relatively expensive

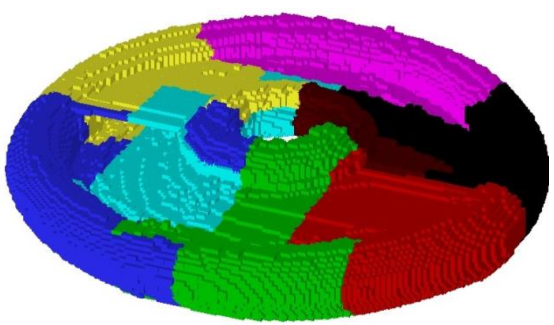
- **Typical Solutions**
  - Parallel direct N-body problem (still $O(N^2)$)
  - Serial tree-code/FMM for velocity calculation ($O(N\log(N))$)
  - Recently parallel FMM, but scalability is sensitive
  - Distance-based agglomeration (particle and filament methods)
  - Octree-based Cartesian grids or nested structured grids
  - Flux limiters to reduce grid resolution requirements

Limitations and Pitfalls of Vorticity-Based Methods (cont’d)

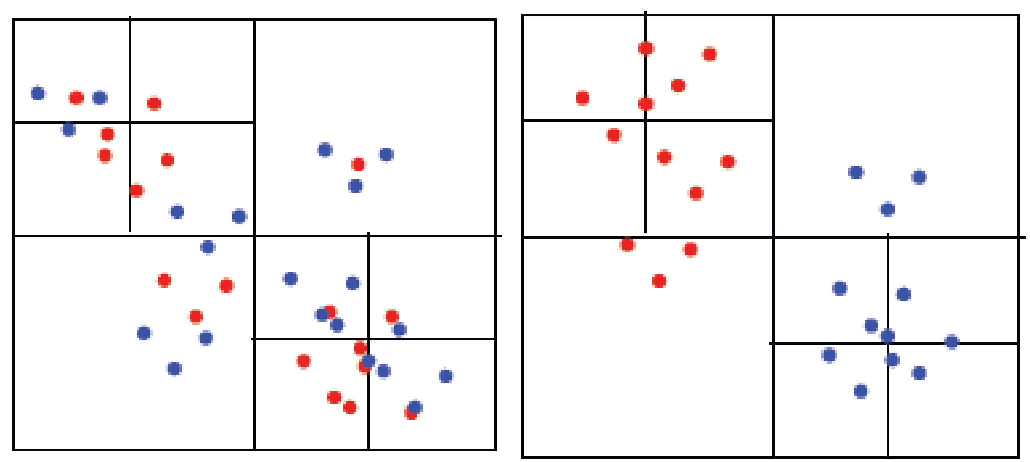
Computational Cost Example

- **Domain decomposition**
  - Equal cost
  - Not equal number of vortex elements/cells
- **Parallel tree-based methods**
  - Sensitive to domain shape
  - Sensitive to proximity





Sample domain decomposition using space filling curves



Sample domain decomposition *

Marzouk, Y.M. and A.F. Ghoneim. *K-Means Clustering for Optimal Partitioning and Dynamic Load Balancing of Parallel Hierarchical N-Body Simulations*. in *16th International Conference on Domain Decomposition Methods* 2005. New York, NY.

Limitations and Pitfalls of Vorticity-Based Methods (cont'd)

Viscous Terms

- **Problem**
  - Typically neglected (filaments and grid-based schemes)
  - Modeled empirically (filaments)
  - Prone to significant discretization error (particle and grid-based schemes)

- **Consequence**
  - Inviscid/empirical approximations constrain accuracy
  - Expense of resolving the viscous terms

- **Typical Solutions**
  - "Tuning" of empirical terms based on experiments
  - Re-meshing locally to ensure sufficient particle overlap (particle methods)
  - Selection of sufficiently fine mesh (grid-based methods)

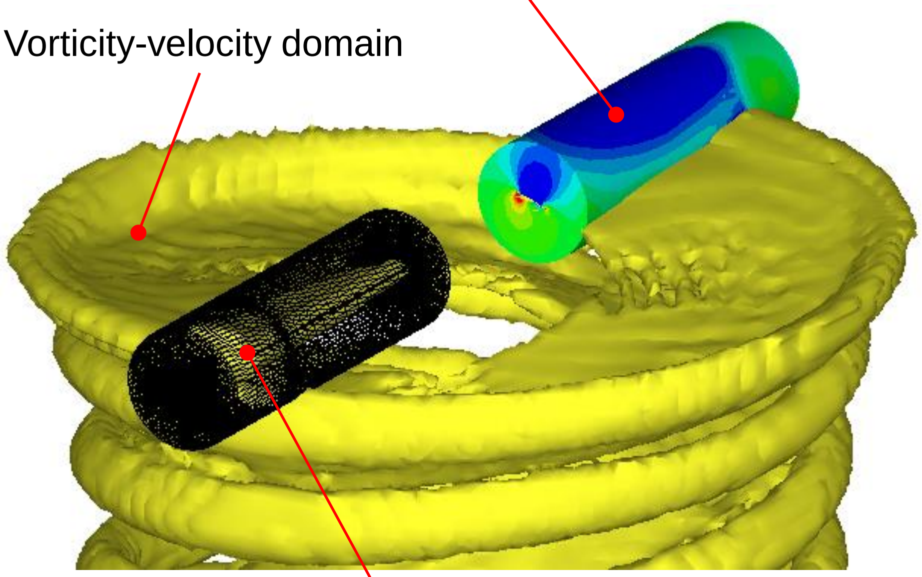
Limitations and Pitfalls of Vorticity-Based Methods (cont'd)

Hybrid CFD/Vorticity-Velocity Interface

- **Near-body CFD solver calculates near-blade vorticity**
- **Off-body vorticity-velocity solution feeds into near-body domain at outer boundaries.**
- **Vorticity-velocity solution needs to know the vorticity in the near-body grid to evolve the off-body flow correctly**
  - Convectional overset hole cutting cannot be used
  - Can be expensive to calculate the vorticity in every near-body cell

CFD grid uses vorticity-velocity to specify velocities on boundary

Vorticity-velocity domain



CFD calculates a vorticity distribution to initialize the vorticity-velocity solution

Limitations and Pitfalls of Vorticity-Based Methods (cont'd)

Hybrid CFD/Vorticity-Velocity Interface (cont'd)

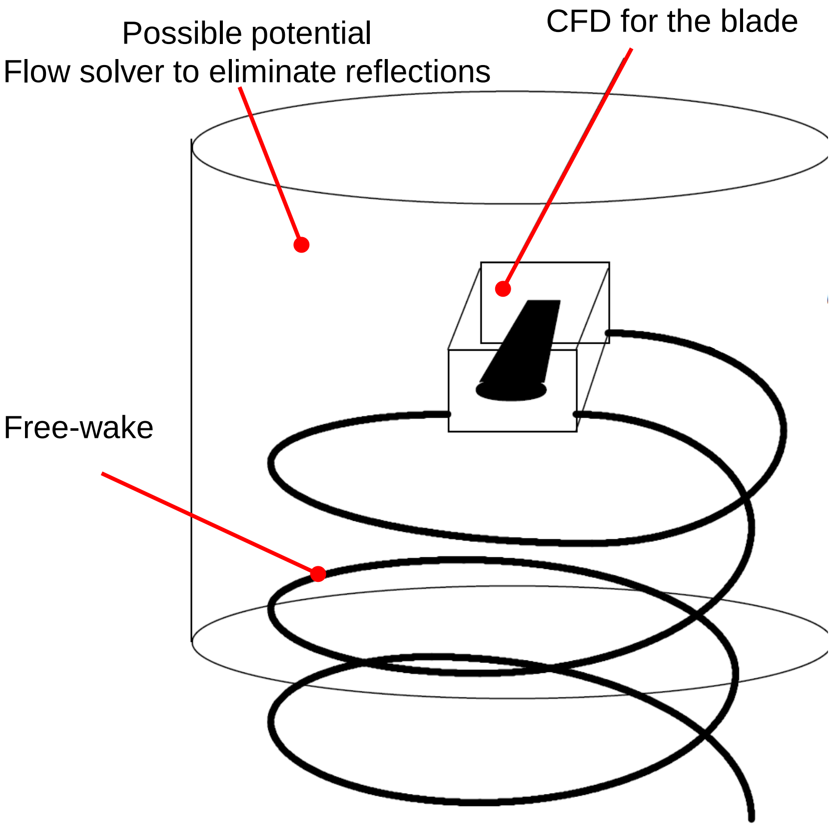
- **Problem**
  - Double counting where CFD and vorticity-velocity methods overlap
  - Incorrect accounting of vorticity in the CFD domain in the velocity calculation
  - Incomplete setting of boundary conditions/feedback on CFD solution (**neglecting unsteady pressure term**)

- **Consequence**
  - Lack of generality of hybrid method
  - Poor stability
  - Poor results near to surfaces (i.e. blade/vortex passage on fuselage)

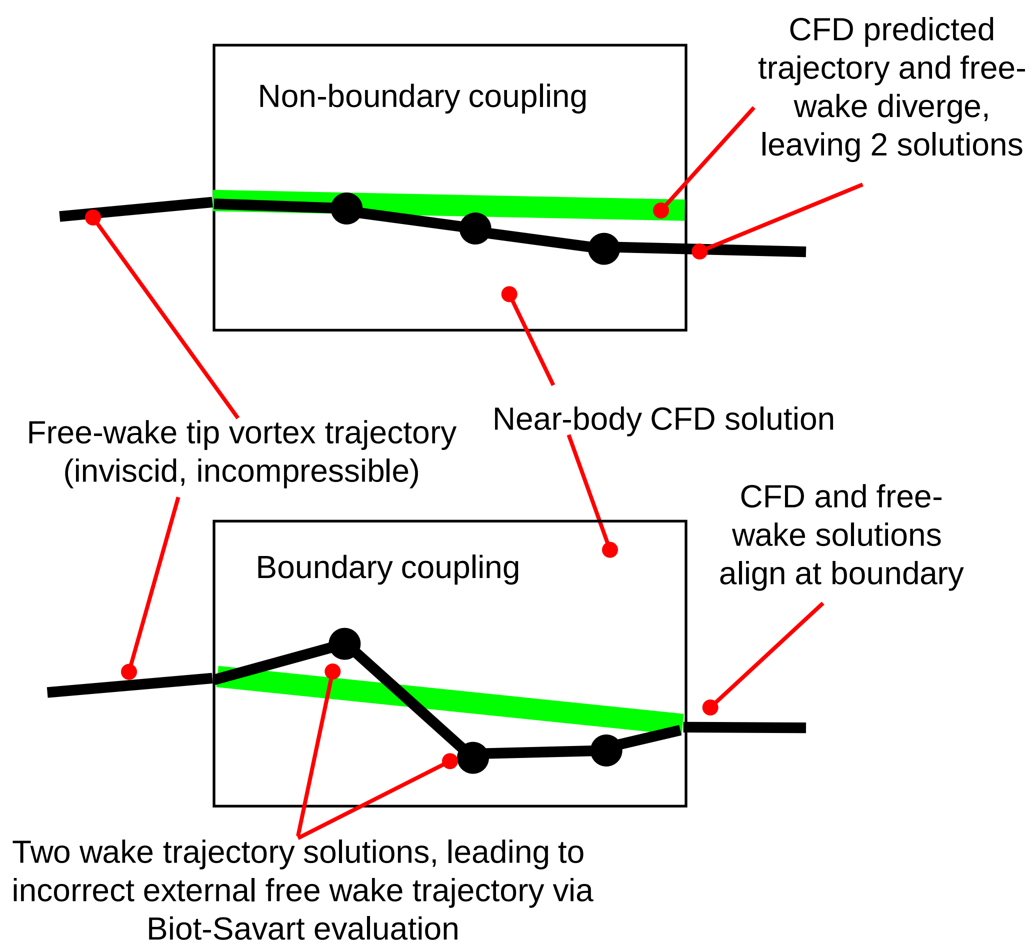
- **Typical Solutions**
  - Ignore
  - Solution overwrite in overlapping region
  - Attempts to decouple the problem spatially or into steady/unsteady components
  - Set BCs based on velocity (and steady pressure Bernoulli) only

Limitations and Pitfalls of Vorticity-Based Methods (cont'd)

Hybrid CFD/Vorticity-Velocity Interface (cont'd)



Schematic of idealized CFD/free-wake coupling



What really happens with CFD/free-wake coupling

Success Stories

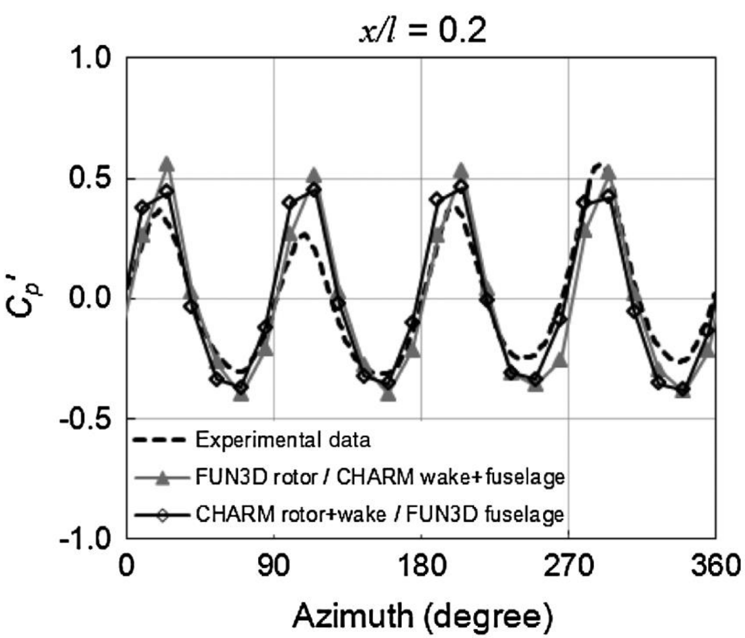
Success Stories: Filament-Based

Rotor-Fuselage Interaction in Forward Flight

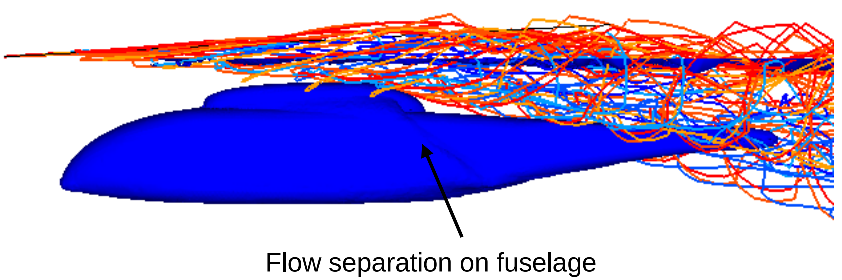
- **Quon, Smith, Whitehouse and Wachspress, “Unsteady Reynolds-Averaged Navier–Stokes-Based Hybrid Methodologies for Rotor–Fuselage Interaction,” Journal of Aircraft, 2012, DOI:10.2514/1.C031578**

- **ROBIN configuration**
  - CFD/free-wake/panel method
  - Multiple overset arrangements examined
    - CFD rotor, panel fuselage, filament wake
    - Lattice rotor, filament wake and CFD fuselage

- **Conclusions**
  - Order of magnitude cost reduction
  - Importance of unsteady pressure term



Unsteady pressure on the fuselage



Sample wake prediction

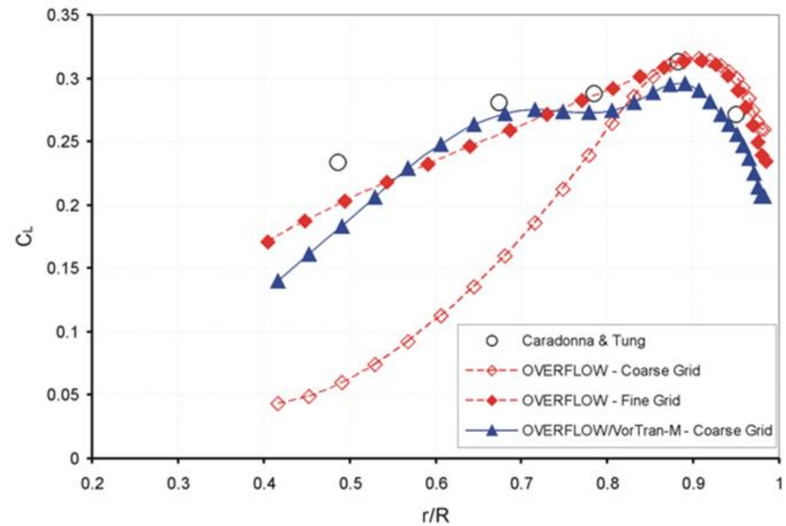
Success Stories: Grid-Based

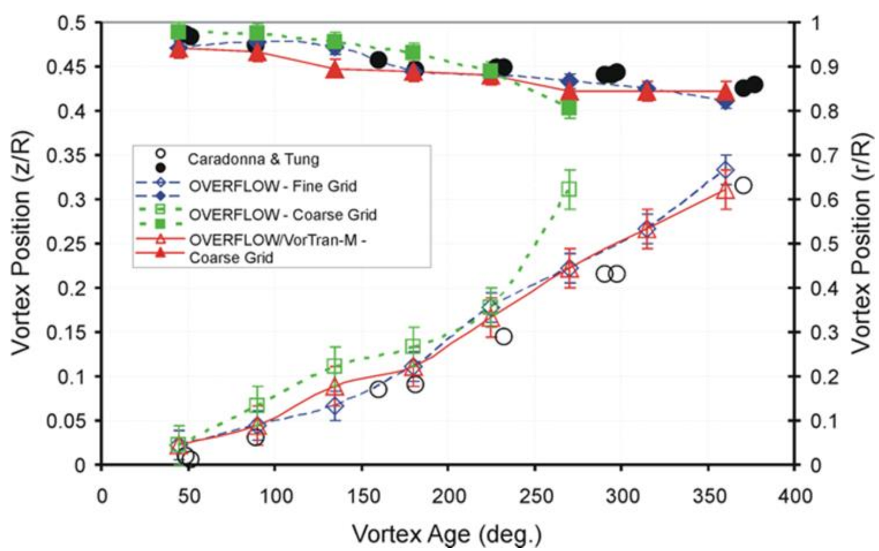
Hovering Rotor Predictions

- **Whitehouse and Tadghighi, "Investigation of Hybrid Grid-Based CFD Methods for Rotorcraft Flow Analysis," Journal of the American Helicopter Society, 2011, DOI:10.4050/JAHS.56.032004**

- **Isolated rotor in hover**
  - 2-blades
  - Fixed collective
  - Identical blade grids (6.4M nodes)

- **Conclusions**
  - Improved convergence
  - Reduced off-body grid requirements
    - ~800K cells for hybrid
    - 17M cells for CFD



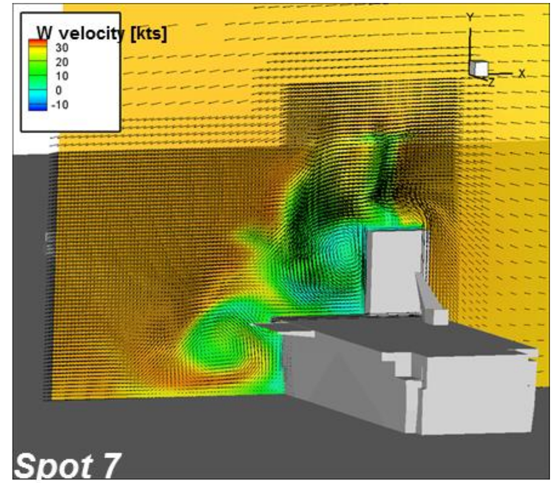


Predicted loading and tip vortex trajectory

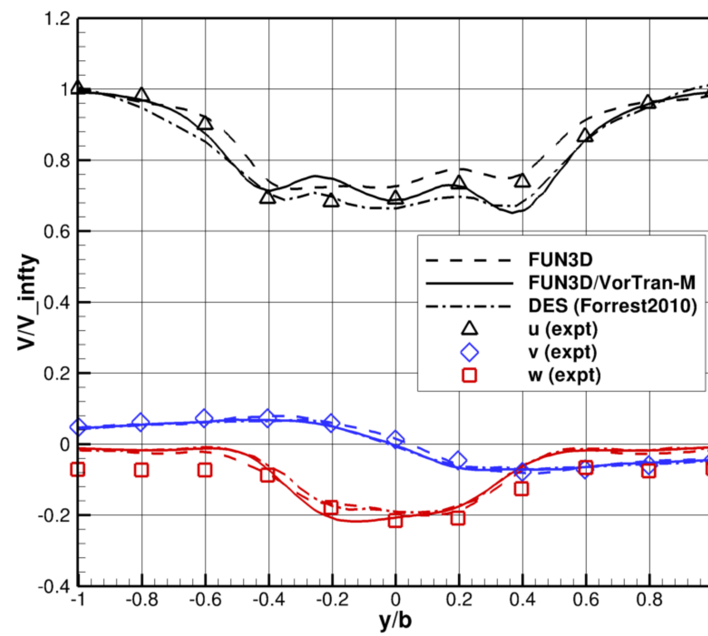
Success Stories: Grid-Based

Ship Airwake Prediction

- **Keller, Whitehouse*, et al*, “Computational Fluid Dynamics for Flight Simulator Ship Airwake Modeling,” I/ITSEC 2007**
- **Quon, Cross, *et al*, “Investigation of Ship Airwakes Using a Hybrid Computational Methodology,” 70th AHS Forum, 2014**
- **Various ship airwake configurations**
  - SFS-2 wind tunnel model
  - >192 real ship wind combinations
- **Conclusions**
  - Comparable predictions to DES over the deck
  - Reduced turnaround time and off body grid requirements



LHA airwake



Predicted airwake velocity across the SFS-2 deck

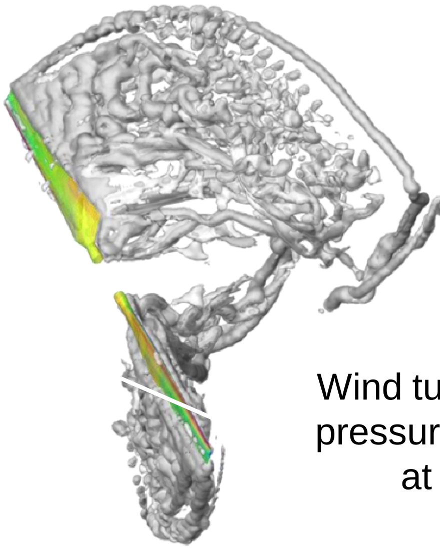
Success Stories: Grid-Based

Wind Turbine Prediction

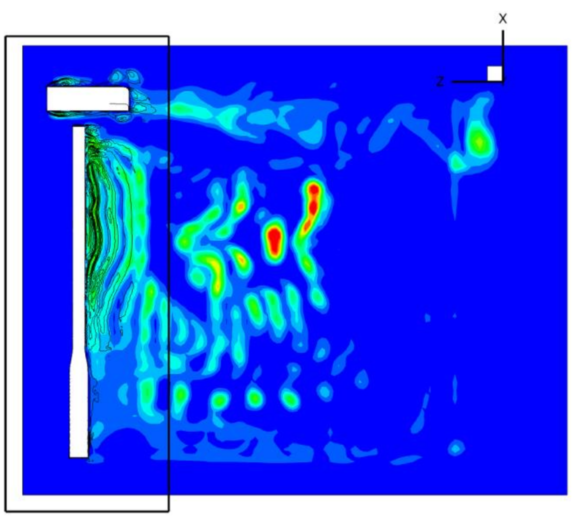
- **Quon, Smith, and Whitehouse, "A Novel Computational Approach to Unsteady Aerodynamic and Aeroelastic Flow Simulation," International Forum on Aeroelasticity and Structural Dynamics, 2013**

- **NREL Phase VI configuration**
  - Isolated two-bladed turbine
  - Full turbine with tower and nacelle

- **Conclusions**
  - Order of magnitude reduction in steps required to converge
  - <50% the cost of comparable overset URANS



Wind turbine blade pressure and wake at 15m/s



Slice though the tower and nacelle wake

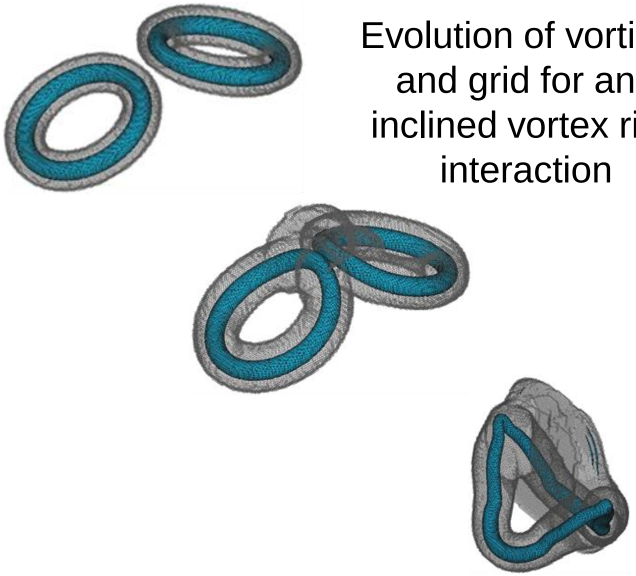
Success Stories: Grid-Based

Self Propagating Vortex Ring Moderate Re

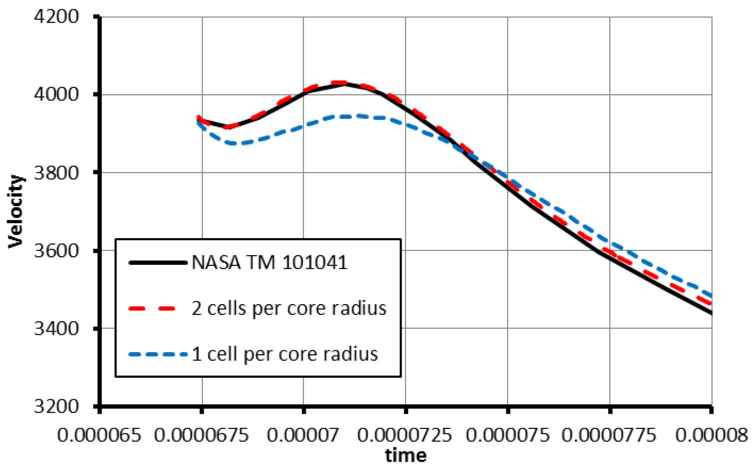
- **Whitehouse and Boschitsch, “Innovative Grid-Based Vorticity–Velocity Solver for Analysis of Vorticity-Dominated Flows”, AIAA Journal, to appear, DOI: 10.2514/1.J053493**

- **Vortex ring interactions**
  - Inviscid propagation
  - Viscous propagation
  - Inclined ring interaction

- **Conclusions**
  - Inviscid predictions are numerically stable
  - At least an order of magnitude reduction in resolution required to accurately predict vortex ring phenomena



Evolution of vorticity and grid for and inclined vortex ring interaction

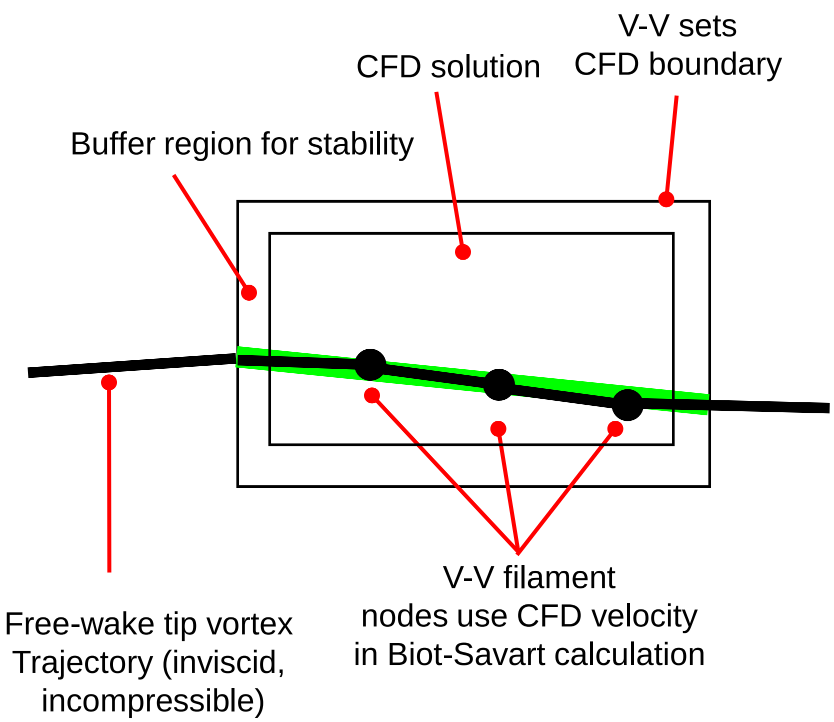


Predicted ring velocity for a viscous vortex ring

Areas of Ongoing and Future Work

Areas of Ongoing and Future Work

- **Parallel performance of vorticity-velocity methods**
  - Low cost dynamic load balancing
  - Scalable parallel FMM
- **Overset interfacing**
  - Addressing overlap region in Lagrangian formulations
  - Automatic testing for overlapping split grids
  - Efficient handling of near-body vorticity
- **Advanced issues**
  - Independent dynamic load balancing

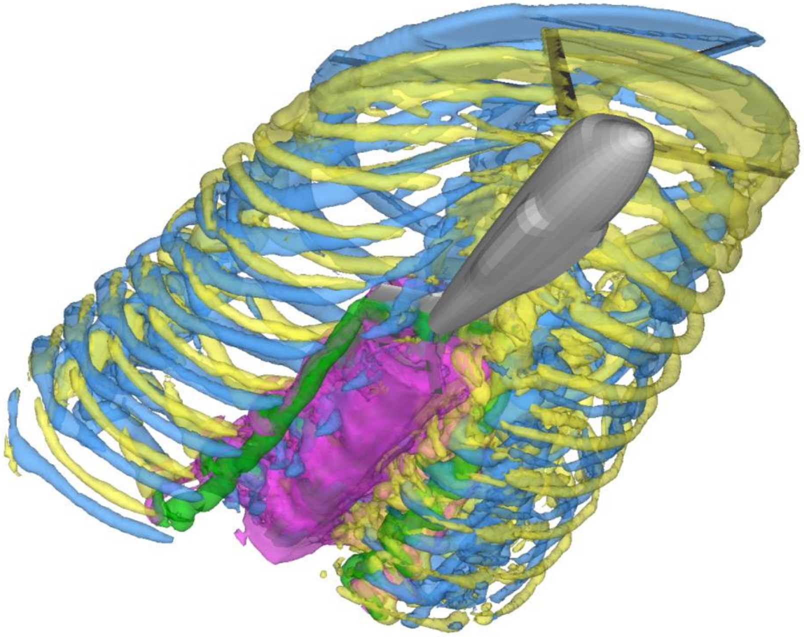


Hybrid approach applied to CFD/Free-wake

Conclusions

Conclusions

- **Hybrid overset methods offer some unique capabilities**
  - Reduced run-time
  - Improved convergence
  - Lower resolution requirements in off-body
- **Unique issues**
  - Formulation
  - Overset interface
  - Performance
- **Care must be made to select the method appropriate for the problem at hand**
  - What are we trying to solve?
  - What do we need to resolve?



If we only need to get the unsteady aerodynamic loading, can we really predict this type of a flow with ~1M cells any other way?

Acknowledgements

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Hormoz Tadghighi, Boeing

Presentation End