Investigation of Hybrid Overset Grid-Based CFD Methods for Rotorcraft and Ship Airwake Flow Analysis

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Overview of the Presentation

- **Motivation**
  - Current issues
  - Contemporary strategies
  - New hybrid overset approach
- **Overview of VorTran-M**
- **CFD integration: Solver types**
  - Unstructured
  - Cartesian
  - Structured overset
- **CFD integration: Coupling strategy**
- **Information exchange: Cell intersection**
  - Vorticity-based coupling
- **Information exchange: Overset**
  - Velocity-based coupling
- **Ongoing and future work**
- **Conclusions**
- **Acknowledgements**

Motivation

Motivation

- **Reliable flow prediction is essential to the development of rotorcraft and the support of flight operations**
- **This requires accurate first-principles modeling of the rotor wake structure to predict blade airloads, fuselage loads and interactional aerodynamics**

But …

- **Conventional grid-based CFD codes have high numerical diffusion of vorticity**
- **Lagrangian methods conserve vorticity, but have formulational limitations (i.e. core models, divergence, stability, cost)**

AH-64 empennage evolution

Motivation (cont'd)

Contemporary Strategies (focus on conventional CFD)

- **Increase grid density**
  - Costly
- **Higher order methods**
  - First order near steep gradients; complex; limited adaptation
- **Modify Navier-Stokes equations to conserve angular momentum**
  - More expensive; smearing of vorticity reduced, but still significant
- **Modify error terms**
  - Base convergence error on vorticity rather than primitive variables (2D)

RAH-66 empennage evolution

Motivation (cont'd)

Hybrid grid-based solution

- **CFD code coupled to VorTran-M**
  - General interface exploiting modular/library construct of VorTran-M
- **Advantages**
  - Exploits features of both solvers (i.e. NS near to surfaces and VorTran-M in the wake)
  - Not constrained by configuration (i.e. rotorcraft only)
  - Solve the same fundamental equations
  - Enables automatic exploitation of both ongoing and future solver developments
- **Impact**
  - Improved capturing and preservation of complex wake structures (leading to reduced development costs)

X-2TD empennage evolution

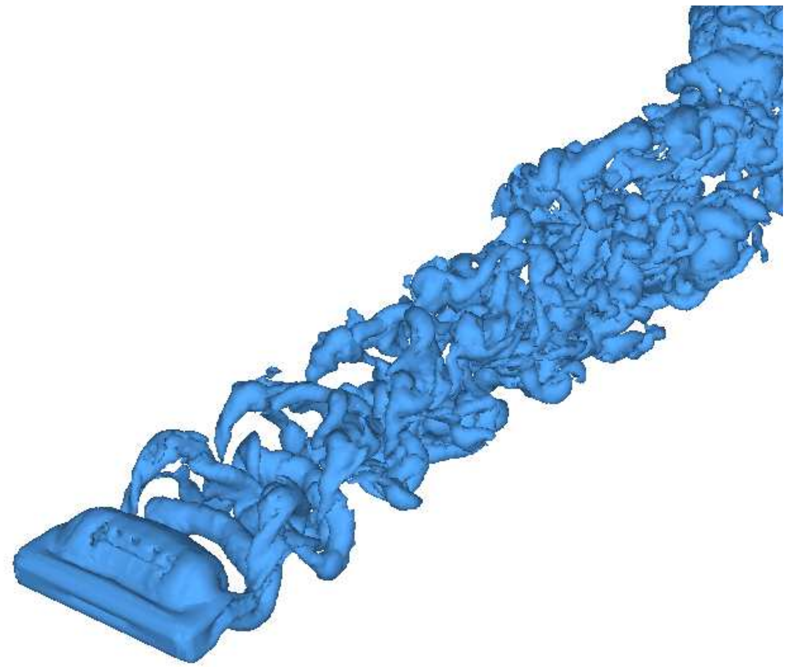
Overview of VorTran-M

Overview of VorTran-M

VorTran-M: Overview

- **Modularized and extended version of the CFD solver employed by Brown's VTM**
  - Module/software library
  - Adaptable interface source code
    - Whitehouse et al, Overset Grid Symposium 2006
    - Whitehouse *et al,* AHS Forum 2007
    - Keller *et al, I/ITSEC* 2007
    - Whitehouse and Tadghighi, AHS Aeromechanics Conference, 2010
    - Whitehouse *et al,* AHS Forum 2010

- **General coupling interface strategy**
  - Supports multiple "inner solver" formulations and grid constructs
  - Supports multiple simultaneous solver types



CFD/VorTran-M prediction of the wake behind a wing at 90º angle of attack

Overview of VorTran-M (cont'd)

VorTran-M: Flow solver

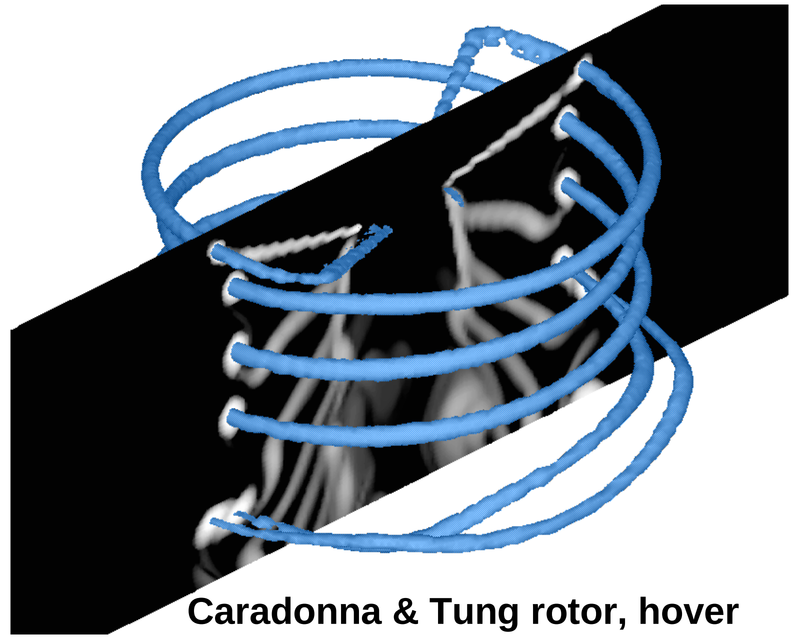
- **Solves the incompressible Navier Stokes equations (vorticity-velocity form)**

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

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

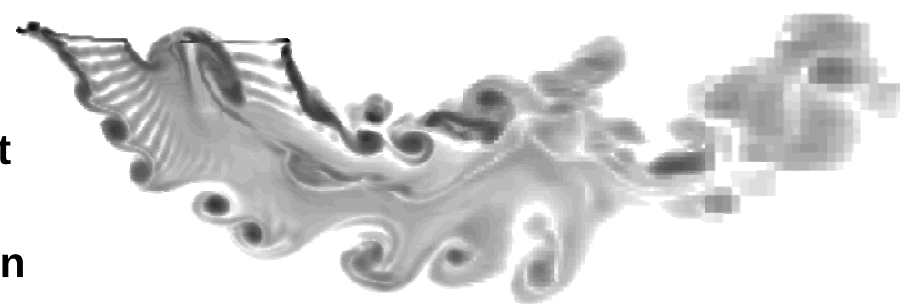
  using a variant of Toro's WAF scheme

- **Cell centered adaptive grid scheme**
- **Fast Biot-Savart / Poisson solvers**
- **Over 10 years of continued development**
- **Extension to compressible flow has been formulated**



Caradonna & Tung rotor, hover

800,000 cells. 50 cells/R, 6 cells/c



Harris rotor, μ=0.04

370,000 cells, 40 cells/R, 2.8 cells/c

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CFD Integration: Solver Types

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CFD Integration: Solver Types

Target host solvers

- **Goal is to interface with a wide variety of solver and grid types**
  - RANS/Euler
  - Structured
  - Unstructured
  - Moving and deforming grids
  - Overset

- **Solvers investigated**
  - RSA3D
    - Rotor Stator Aeroelastic analysis in 3D
    - Developed for NASA GRC by CDI
    - Multiple 3D unstructured deforming moving grids (sliding interface)
    - Tightly coupled nonlinear FE solver
    - AIAA-1994-0415, AIAA-1994-2269, Whitehouse *et al* AHS Forum 2007

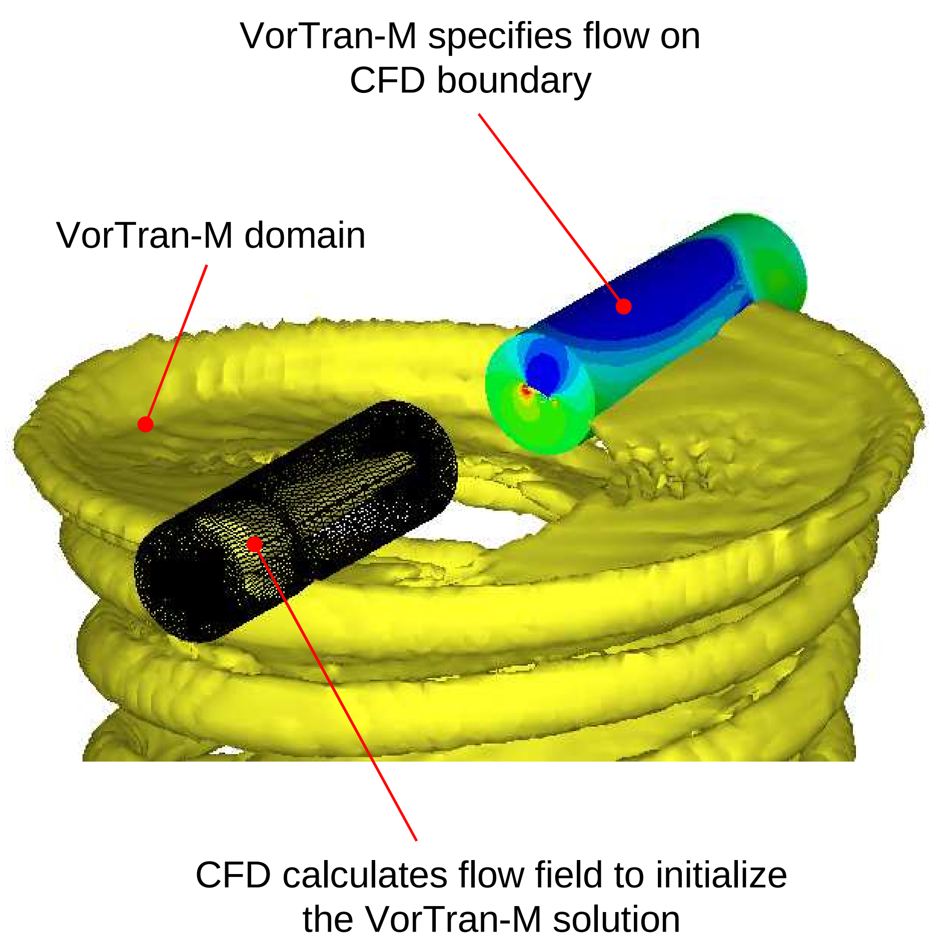
- **Solvers investigated (cont'd)**
  - CGE
    - Cartesian Grid Euler solver
    - Developed by CDI for design apps.
    - 3D adaptive Cartesian grid
    - Support for imperfect geometries
    - AIAA-1994-0415, AIAA-1994-2269, Keller *et al* I/ITSEC 2007
  - OVERFLOW
    - NASA structured overset grid RANS solver
    - AIAA-1999-3302, AIAA-2009-3988 etc
  - FUN3D
    - NASA unstructured grid RANS solver
    - NASA TM-4295, AIAA-2009-1360 etc

CFD Integration: Coupling Strategy

CFD Integration: Coupling Strategy

Overview of Coupling Strategy

- **CFD solver calculates near-body flow field**
- **CFD solver sets VorTran-M solution in suitably defined overlap region**
- **Evaluation of Biot-Savart law in VorTran-M accounts for all contributions:**
  - Vorticity evolved in VorTran-M
  - Flow field transferred from CFD solver
- **VorTran-M solution feeds into CFD domain at outer boundaries**
- **Minimizing extent of CFD domain allows higher resolution within the domain and less numerical diffusion**



Schematic of coupling strategy

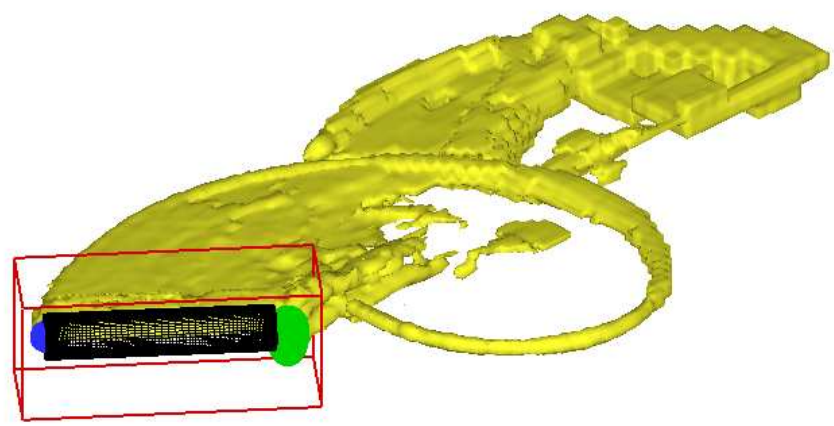
Information Exchange: Cell Intersection

Information Exchange: Cell Intersection

Vorticity-based coupling

- **Vorticity in CFD domain calculated by finite differencing**
- **Intersection between CFD cells and VorTran-M cells performed**
  - Establish relationship between each CFD cell and corresponding VorTran-M cell
- **Volume weighted vorticity inserted into VorTran-M**
- **If inviscid, then include the vorticity on the surface (i.e. bound vorticity)**
- **CFD outer BCs set by VorTran-M**

- **Implemented in**
  - RSA3D (unstructured)
  - CGE (Cartesian grid)
  - OVERFLOW 2.1 (overset structured)

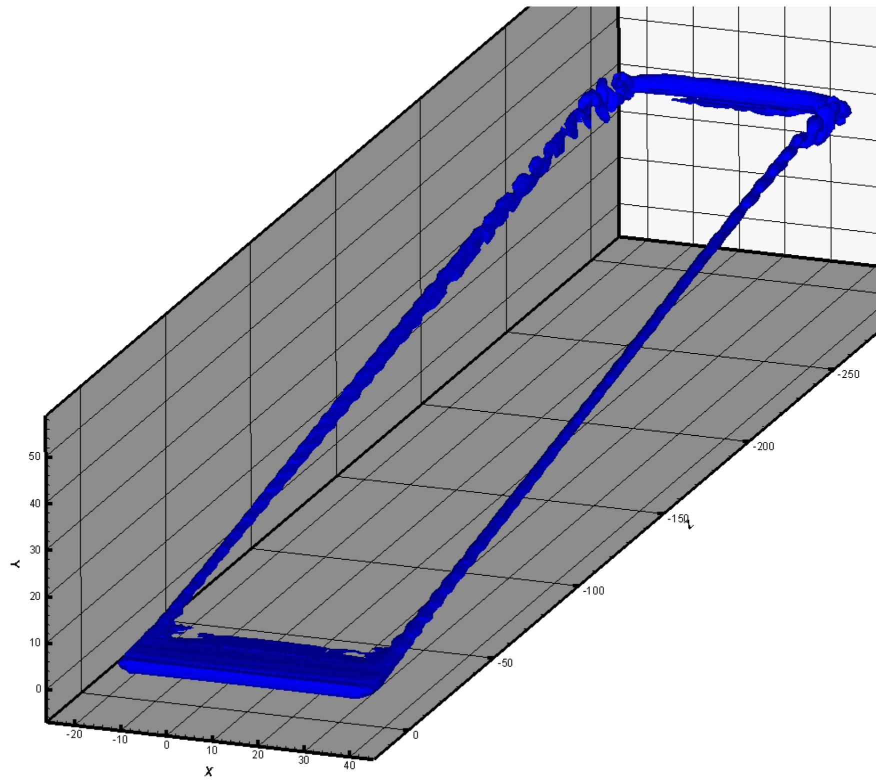


Iso-surface of vorticity magnitude for single bladed rotor in forward flight (OVERFLOW/VorTran-M)

Information Exchange: Cell Intersection (cont'd)

RSA3D

- **Formal intersection between RSA3D's tetrahedral and VorTran-M's cubic cells**
- **Impulsively started wing at 8º**
  - Inviscid
  - NACA 0012
  - Aspect Ratio = 8.8
  - M=0.2
  - 128 points around airfoil (270K tets.)
  - 1.5c upstream, 2.5c downstream
  - VorTran-M cell size = 0.18c
- **Predicted lift coefficient on coarse grid to within 1.1% of inviscid theory**

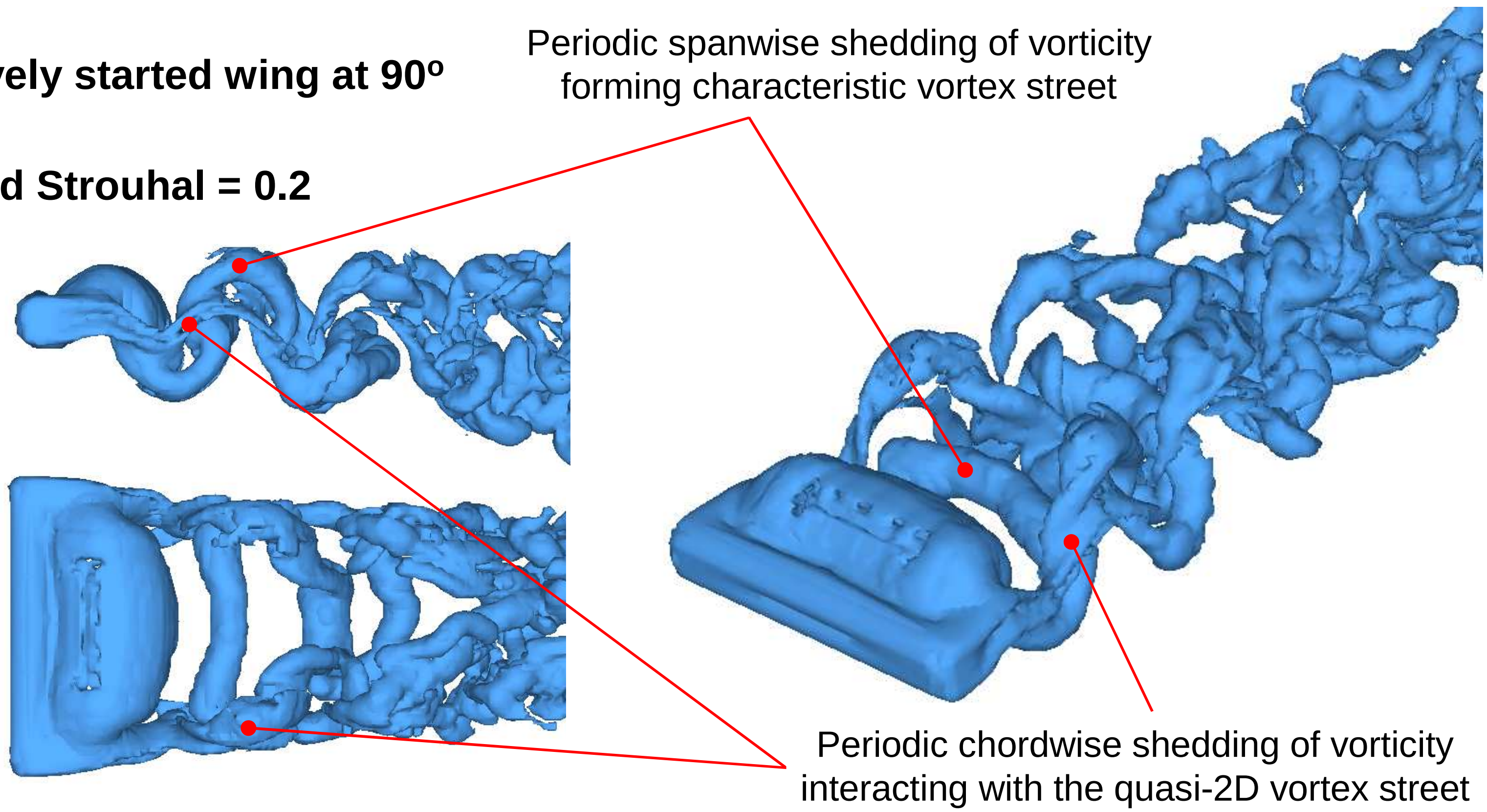


Perspective view of the developing wake structure for the impulsively started wing

Information Exchange: Cell Intersection (cont'd)

RSA3D (cont'd)

- **Impulsively started wing at 90º**
- **Predicted Strouhal = 0.2**

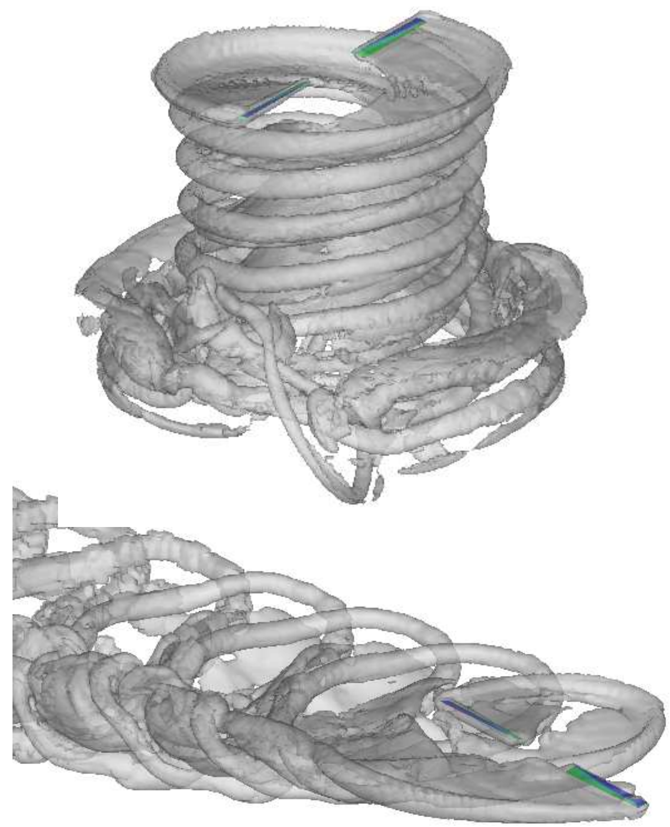


Iso-surface of vorticity magnitude showing near wake behind a wing at 90º angle of attack

Information Exchange: Cell Intersection (cont'd)

RSA3D (cont'd)

- **Untrimmed 2-bladed rotor**
  - VR12
  - 10^{o} twist
  - 72K tets. per blade
  - Open root section (i.e. no root vortex)
  - Blades are disjoint
- **Demonstrated overset-moving grid capability of the interface**

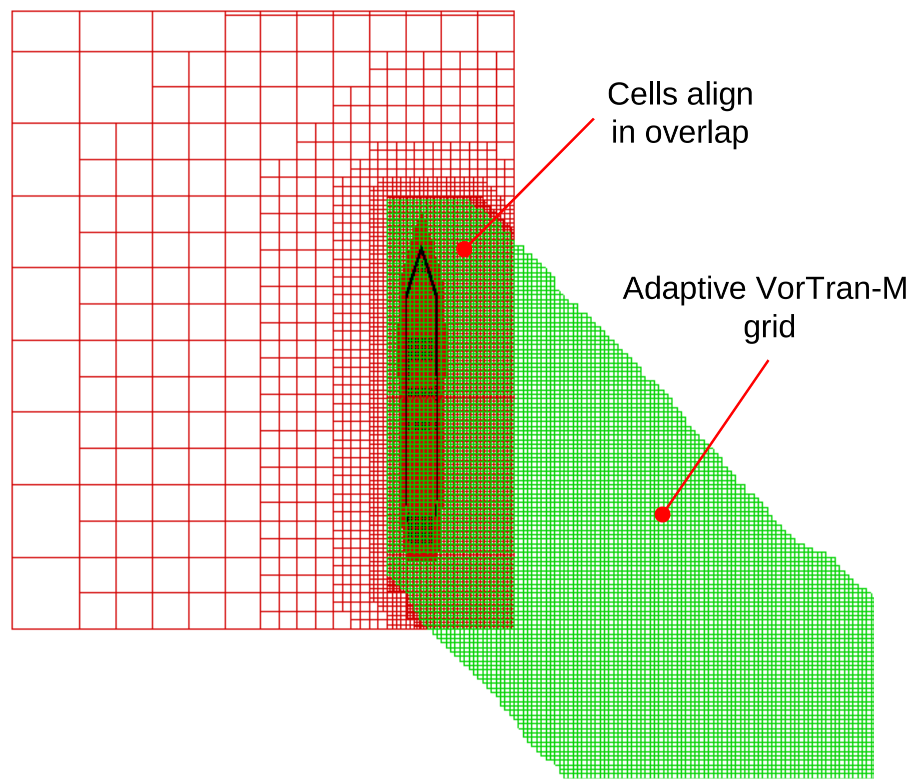


RSA3D/VorTran-M rotor wake predictions: two bladed untrimmed rotor in slow speed ascent (upper) and two bladed untrimmed rotor in forward flight (lower)

Information Exchange: Cell Intersection (cont'd)

CGE

- **Formal intersection between Cartesian grid and VorTran-M cells**
  - Trivial since tight control placed over Cartesian grid
- **Ship airwake calculations**
  - Undertaken during development of ship airwake database for CAE (MH-60R/SH-60B TOFT)
  - >192 ship/wind combinations
  - First commercially-generated ship airwake database
- **NACA 0015**
  - Lift within 0.65% of experiment
  - Tip vortex position within 1%
  - Tip vortex core within 1.6% at 4c



CGE/VorTran-M grid intersection

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Information Exchange: Cell Intersection (cont'd)

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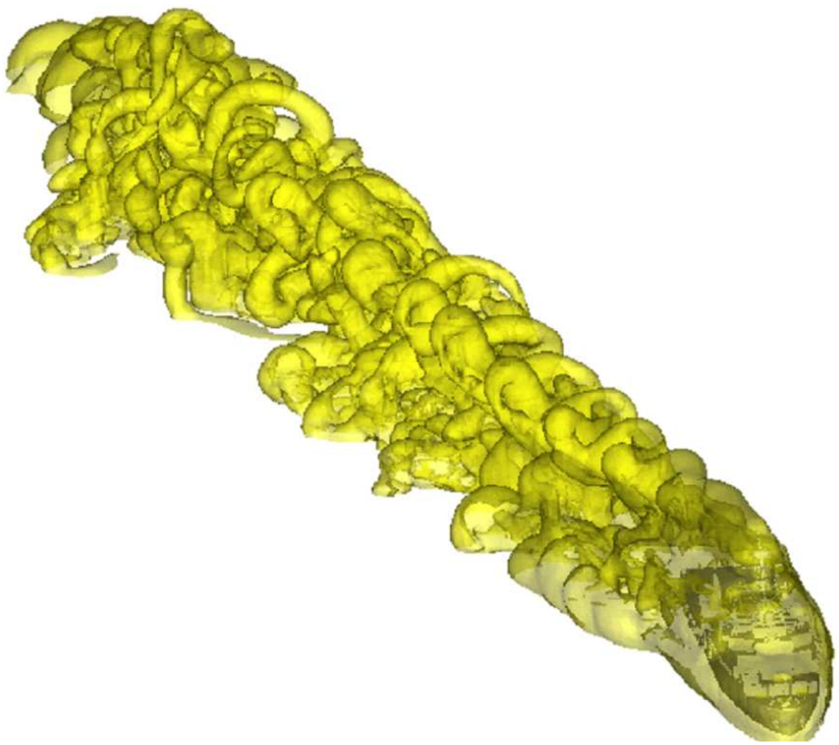
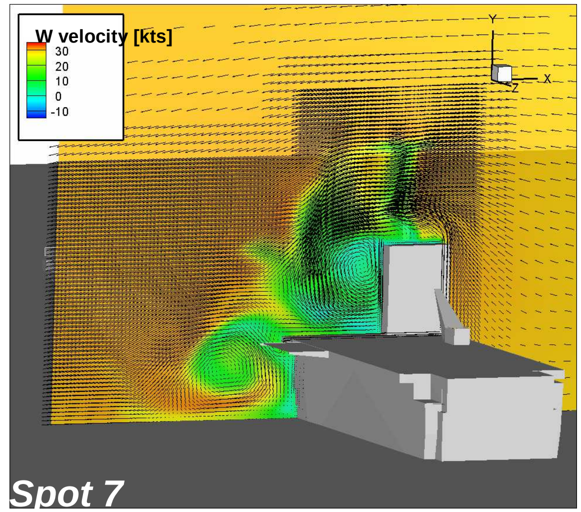
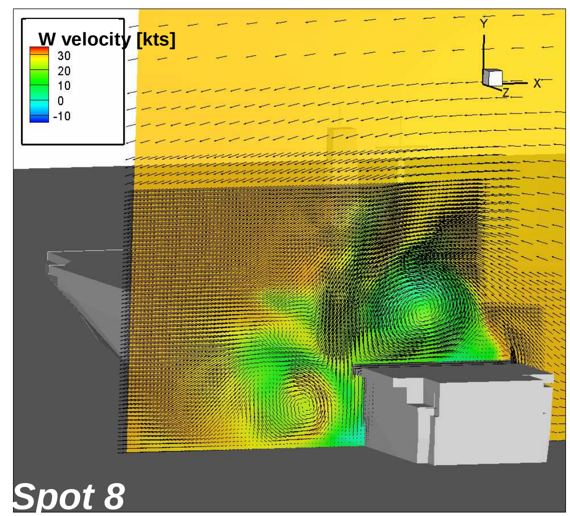
CGE (cont'd)



LPD-4 ship airwake



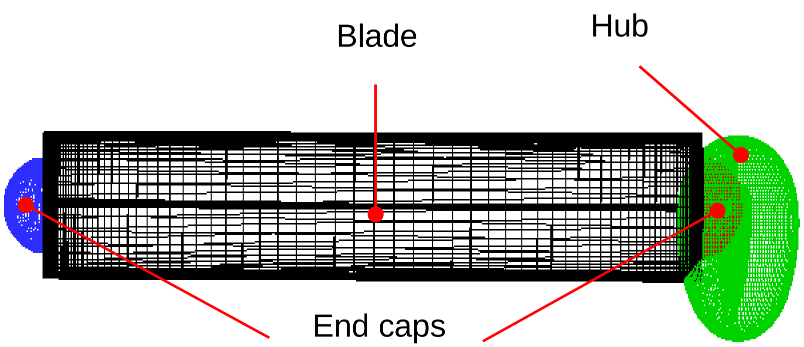


Velocity contours and vectors of an LHA airwake in a crosswind

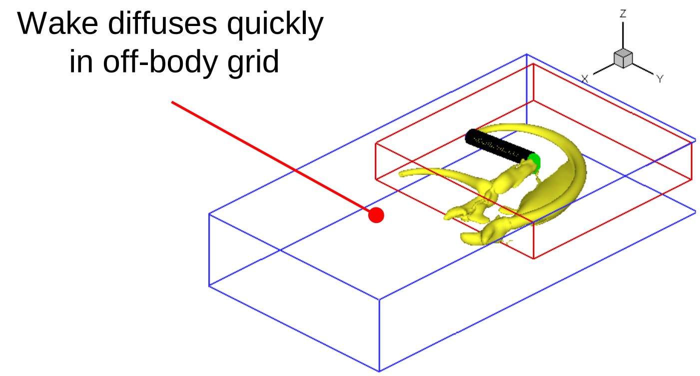
Information Exchange: Cell Intersection (cont'd)

OVERFLOW (2.1ab)

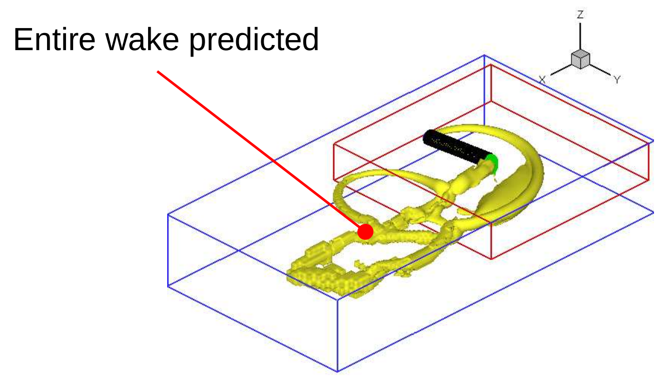
- **Vorticity inserted at cell centroid**
  - Tight control placed on grid surrounding rotor (aligns with VorTran-M)
- **1-bladed rotor in forward flight**
  - 5 overlapping near-body grids
  - OVERFLOW/VorTran-M and OVERFLOW calculations on similar grids



Blade and hub grids

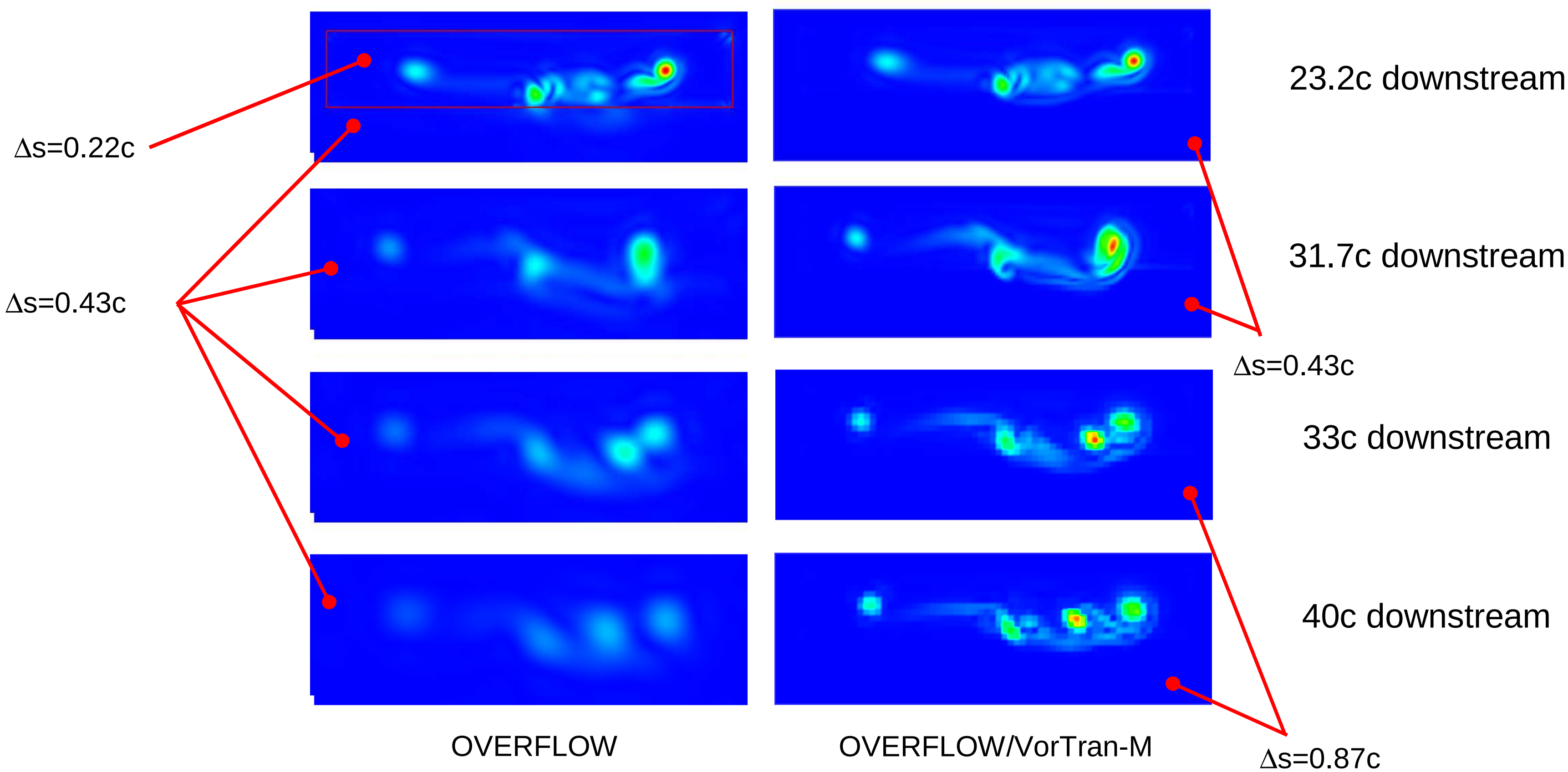


Iso-surface of vorticity magnitude OVERFLOW



Iso-surface of vorticity magnitude OVERFLOW/VorTran-M

Information Exchange: Cell Intersection (cont'd)

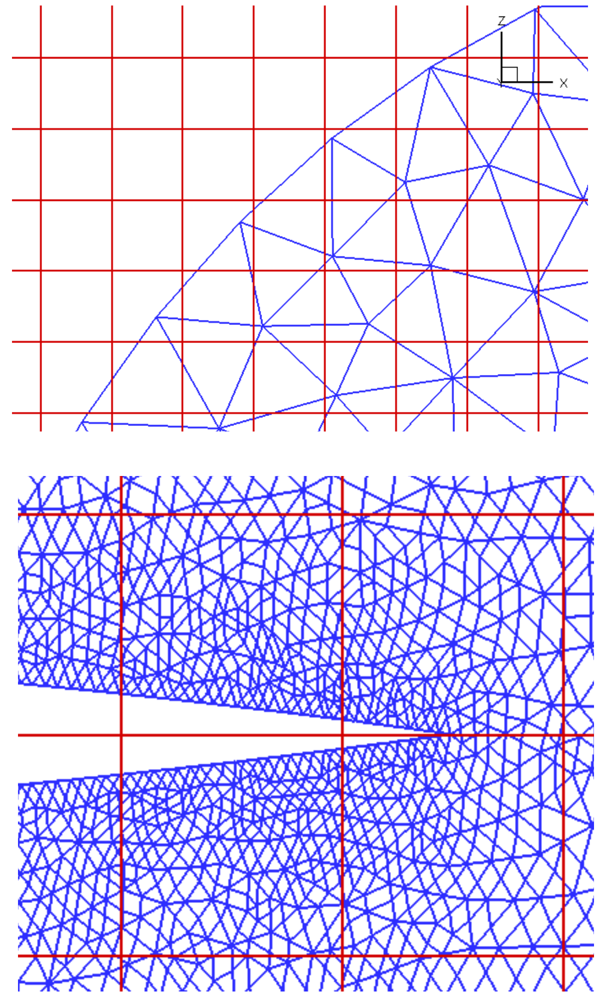


Slices through the grid for a 1-bladed rotor in forward flight

Information Exchange: Cell Intersection (cont'd)

<u>Lessons learned</u>

- **Cell intersection exhibits positive results for a variety of solvers and applications**
- **In general, requires formal intersection**
  - Complicated
  - Costly
  - Invasive
- **For structured and Cartesian grid-based approaches, intersection costs can be reduced**
  - Tight control must be placed on grid
- **Requires vorticity to be calculated in every overlapping CFD cell**
  - Costly



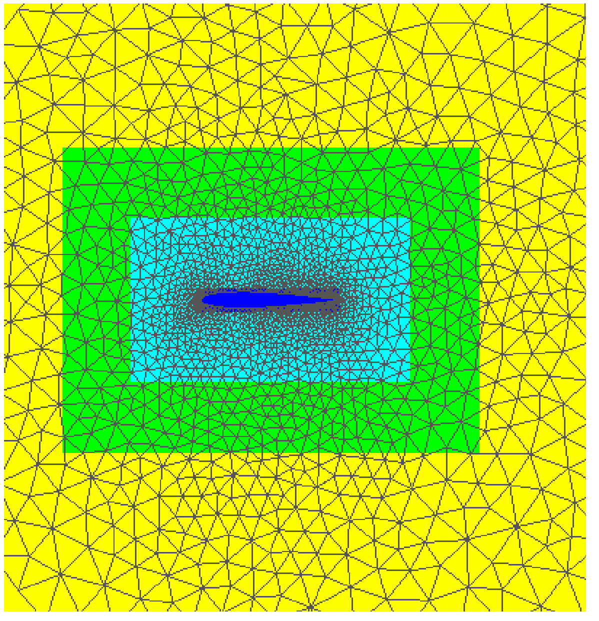
Intersection of unstructured (blue) and VorTran-M grids (red) at left and center

Information Exchange: Overset

Information Exchange: Overset

Velocity-based coupling

- **CFD solution (velocity) calculated at overlapping VorTran-M cell corners**
- **Overlap/buffer regions can be determined entirely in terms of VorTran-M cells**
  - IBLANK information
  - Simple surface-based cell marking
- **Velocity passed to VorTran-M**
- **CFD BCs set on outer boundary**
- **Implemented in**
  - OVERFLOW 2.1 (overset structured)
  - FUN3D (unstructured)



Sample surface-based cell marking

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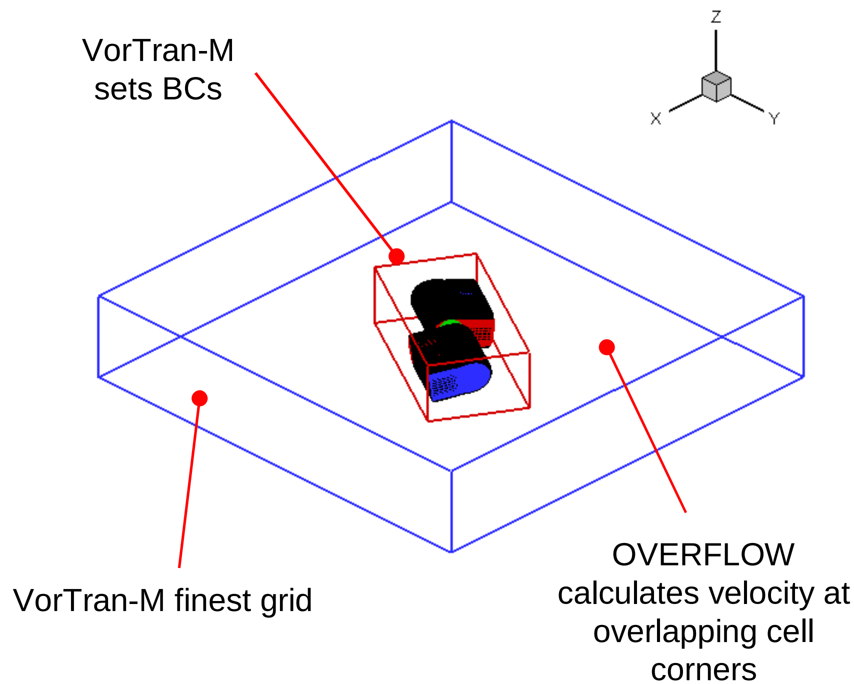
Information Exchange: Overset (cont'd)

OVERFLOW (2.1ab)

- **2-bladed Caradonna and Tung rotor**
  - 8^o collective
  - 1250 RPM
- **OVERFLOW/VorTran-M grids**
  - "Engineering scale" and strategy
  - 8 overlapping near-body grids
  - 2 rotor blades, each with
    - Main blade
    - 2 End caps
  - Body of revolution hub
  - 1 surrounding grid (cubic cells, rotates with blades)
  - ~6.4 Million OVERFLOW nodes
  - ~800,000 VorTran-M cells



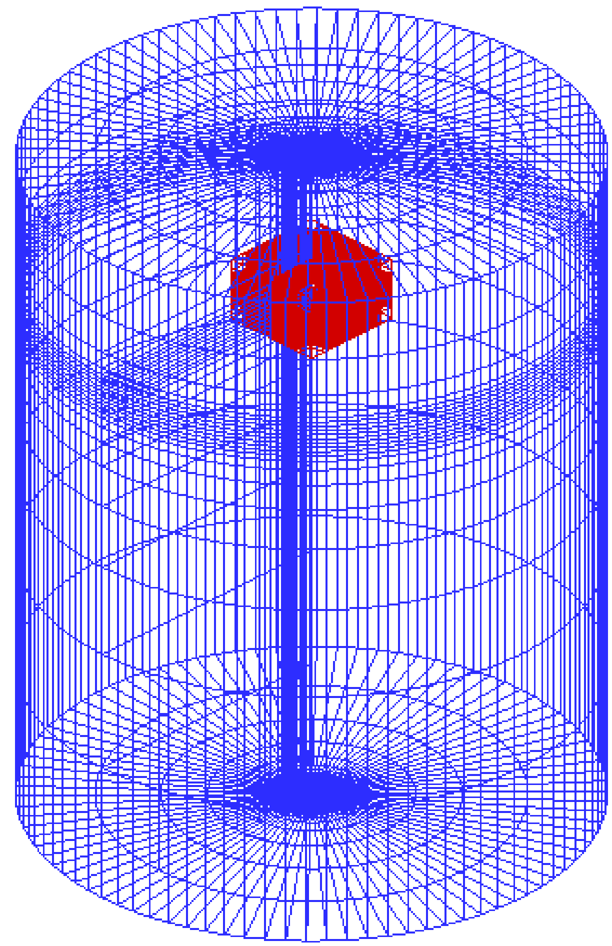
Schematic of OVERFLOW/VorTran-M velocity-based coupling

Information Exchange: Overset (cont'd)

OVERFLOW (2.1ab)

- **OVERFLOW (coarse grid)**
  - "Engineering scale" and strategy
  - Same NBGs as OVERFLOW/VorTran-M
  - Automatic off body grid generation (factor of 2 scaling)
  - ~19.8 Million Nodes

- **OVEFLOW (fine grid)**
  - Same NBGs as OVEFLOW/VorTran-M
  - Background rotating O-grid
  - Source BCs
  - ~24 Million Nodes



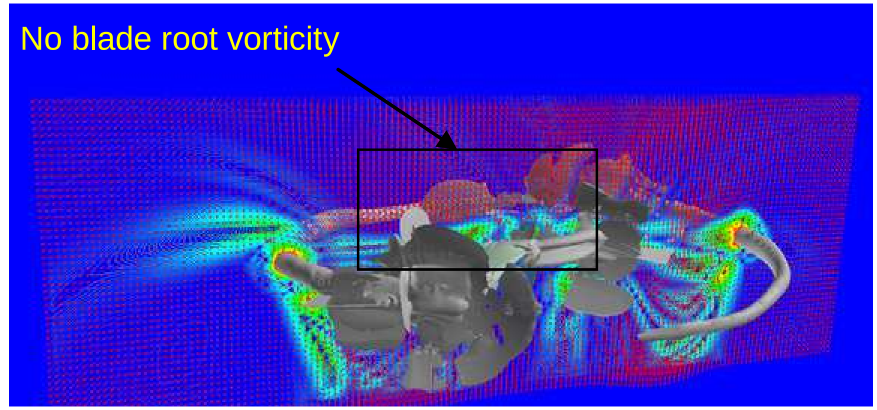
Fine OVERFLOW grid system

Information Exchange: Overset (cont'd)

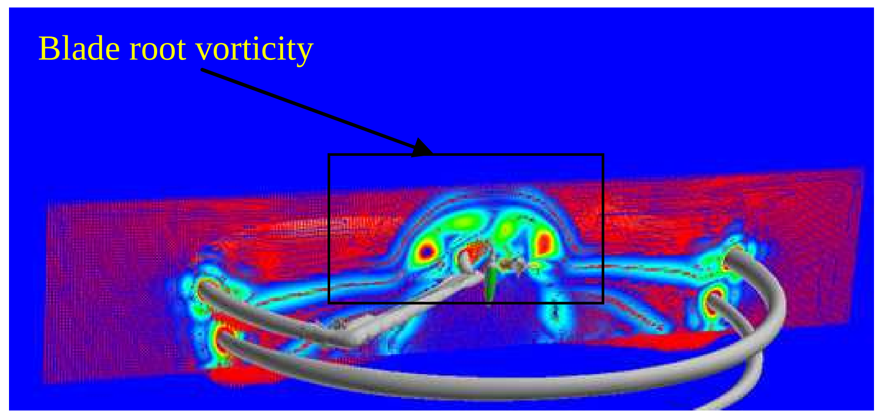
OVERFLOW (2.1ab) (cont'd)

- **Comparisons**
  - General wake prediction
  - Loading
  - Tip vortex trajectory

- **Trim**
  - Experiment
    - C_T=0.046
  - OVERFLOW (coarse grid)
    - C_T=0.0432
    - 94% of experimental value
  - OVERFLOW (fine grid)
    - C_T=0.0492
    - 102% of experimental value
  - OVERFLOW/VorTran-M
    - C_T=0.0458
    - 99.6% of experimental value



OVERFLOW (coarse grid) predictions of the wake near to the rotor

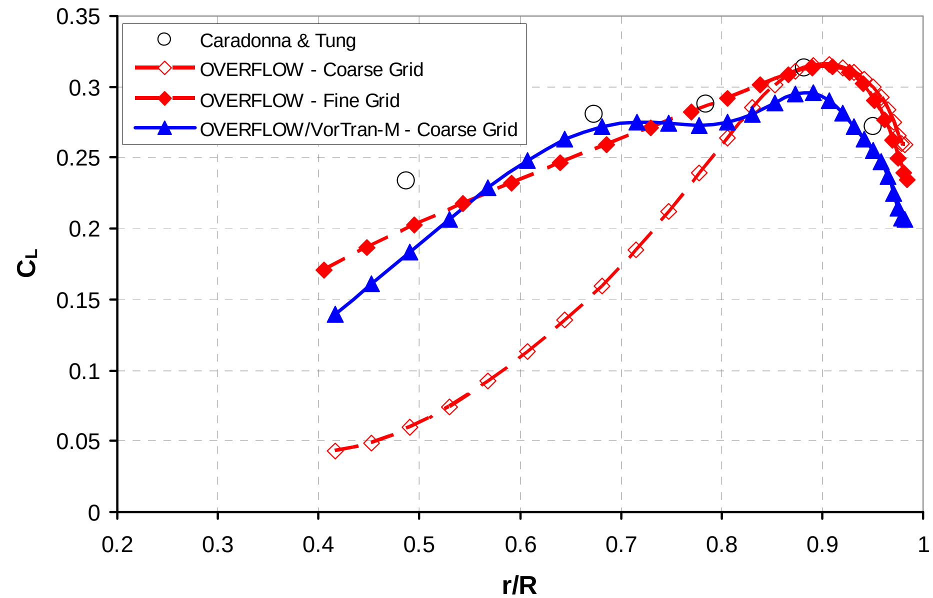


OVERFLOW/VorTran-M predictions of the wake near to the rotor

Information Exchange: Overset (cont'd)

OVERFLOW (2.1ab) (cont'd)

- **OVERFLOW (coarse grid)**
  - Very little inboard loading
  - Overprediction at tip
- **OVERFLOW (fine grid)**
  - More accurate inboard loading
  - Slight overprediction at tip
- **OVERFLOW/VorTran-M**
  - Slight underprediction of tip loading
  - More accurate mid-span loading
  - Underprediction of inboard loading



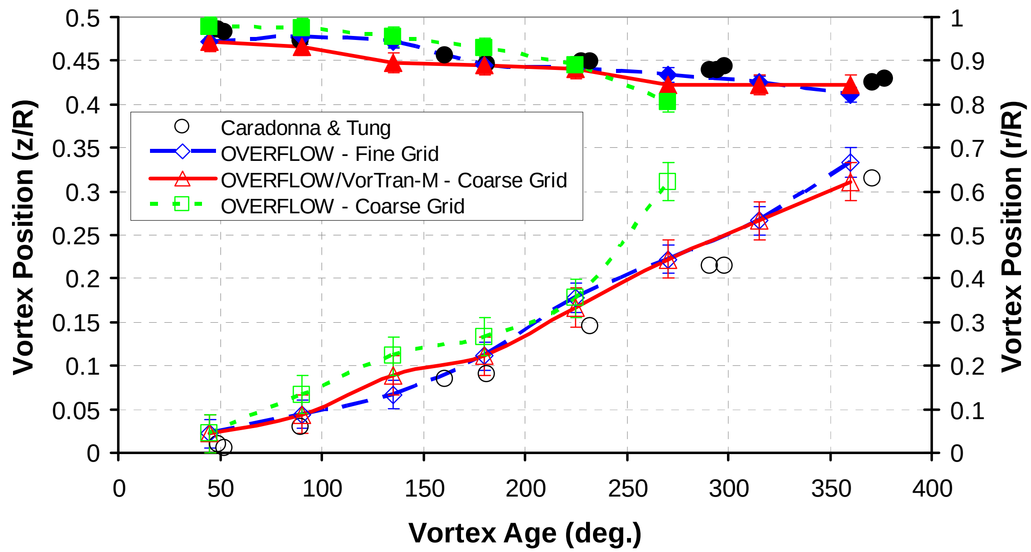
Comparison of measured and predicted spanwise loading

Information Exchange: Overset (cont'd)

OVERFLOW (2.1ab) (cont'd)

- **OVERFLOW (coarse grid)**
  - Tip vortex diffuses significantly after ~135º, identification is impossible after ~ 270º
  - Tip vortex is outboard and lower than measurements
  - Significant increase in descent rate after ~180º

- **OVERFLOW (fine grid) and OVERFLOW/VorTran-M**
  - Vertical and radial tip vortex position predicted correctly
  - Radial contraction asymptote predicted correctly



Comparison of measured and predicted spanwise loading

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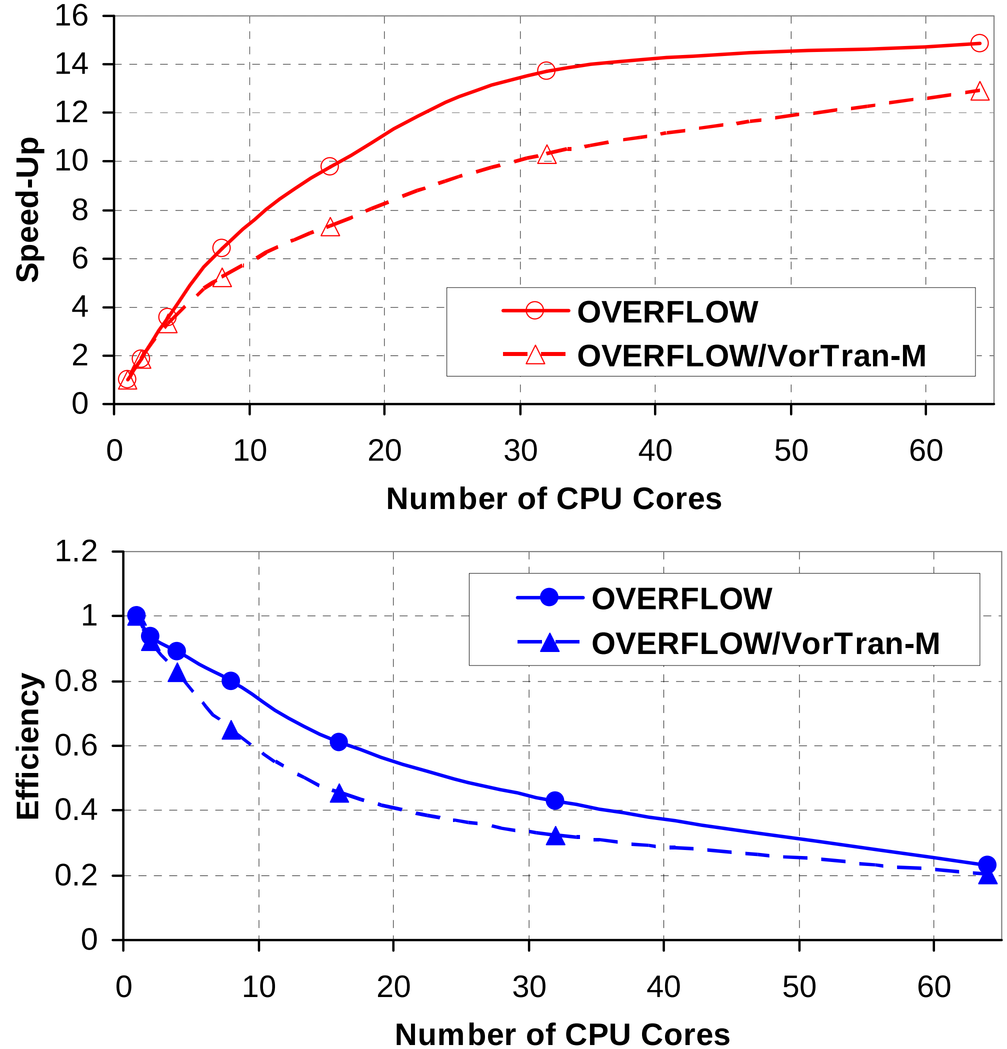
Information Exchange: Overset (cont'd)

OVERFLOW (2.1ab) (cont'd)

- **Porting**
  - Shared memory (SGI Altix)
  - Distributed memory (MJM and other beowulf clusters)
  - Assorted compilers (Intel, Portland, GNU)

- **Scalability**
  - Tested on 72 core Microway distributed memory cluster using both OpenMPI and MPICH

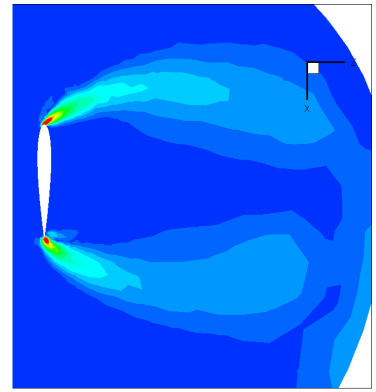


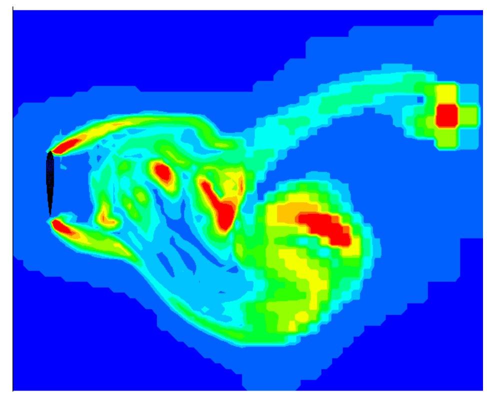
OVERFLOW/VorTran-M Scalability

Information Exchange: Overset (cont'd)

FUN3D

- **Impulsively started wing at 90º**
  - NACA 0012
  - Aspect Ratio = 8.8
  - M=0.2
  - 128 points around airfoil (270K tets.)
  - 1.5c upstream, 2.5c downstream
- **Viscous**
  - Spalart-Allmaras turbulence model
- **Additional ongoing demonstrations presented in Quon E. "Not Your Father's Hybrid Code: Advancements in CFD-Based Hybrid Methods for a New Millennium"**



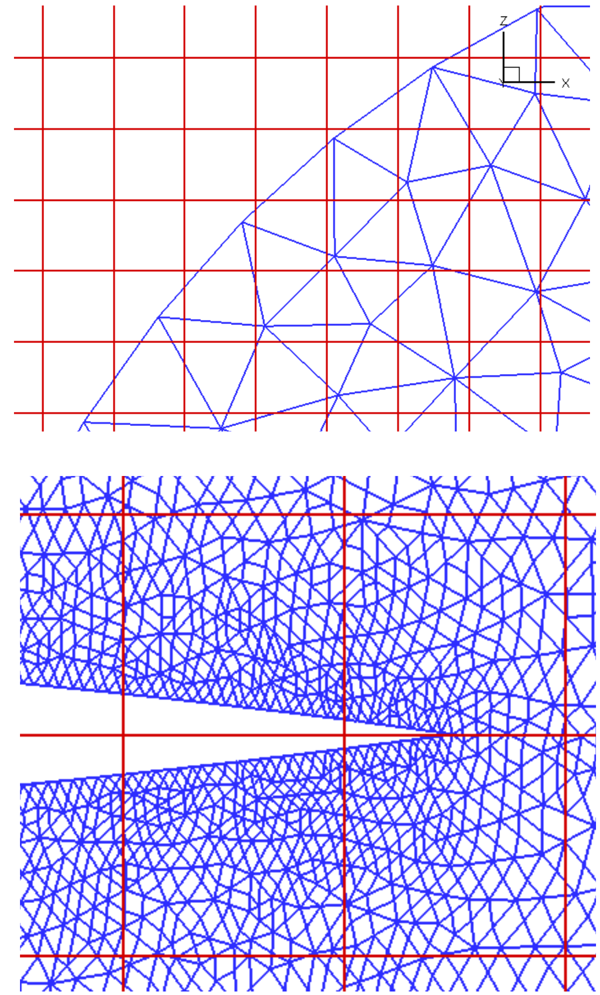


Mid-plane vorticity magnitude predicted by the FUN3D/VorTran-M coupled simulation for the NACA0012 wing at 90º angle of attack

Information Exchange: Overset (cont'd)

Lessons learned

- **Overset velocity-based approach addresses many of the limitations of the insertion method**
  - Intersection operations replaced with velocity interpolation procedures
    - Simpler and already available in many solvers
  - Less information exchanged between host solver and Module
    - Amount of information exchanged now determined by VorTran-M cell size, not local CFD cell size
  - Requires that the CFD solver can preserve the vorticity sufficiently in the overlap region



Intersection of unstructured (blue) and VorTran-M grids (red) at left and center

Conclusions

Conclusions

- **Demonstrated five CFD/VorTran-M couplings using two difference interfacing strategies**
  - Unstructured (RSA3D and FUN3D)
  - Cartesian (CGE)
  - Structured overset (OVERFLOW)

- **Demonstrated improved predictions**
  - Fixed wing
  - Bluff body
  - Isolated rotors

- **Observed improved efficiency**
  - Fewer cells required for comparable fidelity predictions
  - Simple mesh constructs and BC appear to be adequate for problems investigated to date

Acknowledgements

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Presentation End