Investigation of Grid-Based Vorticity-Velocity LES Off-Body Solvers for Hybrid Overset CFD

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14th Symposium on Overset Composite Grids and Solution Technology

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Background

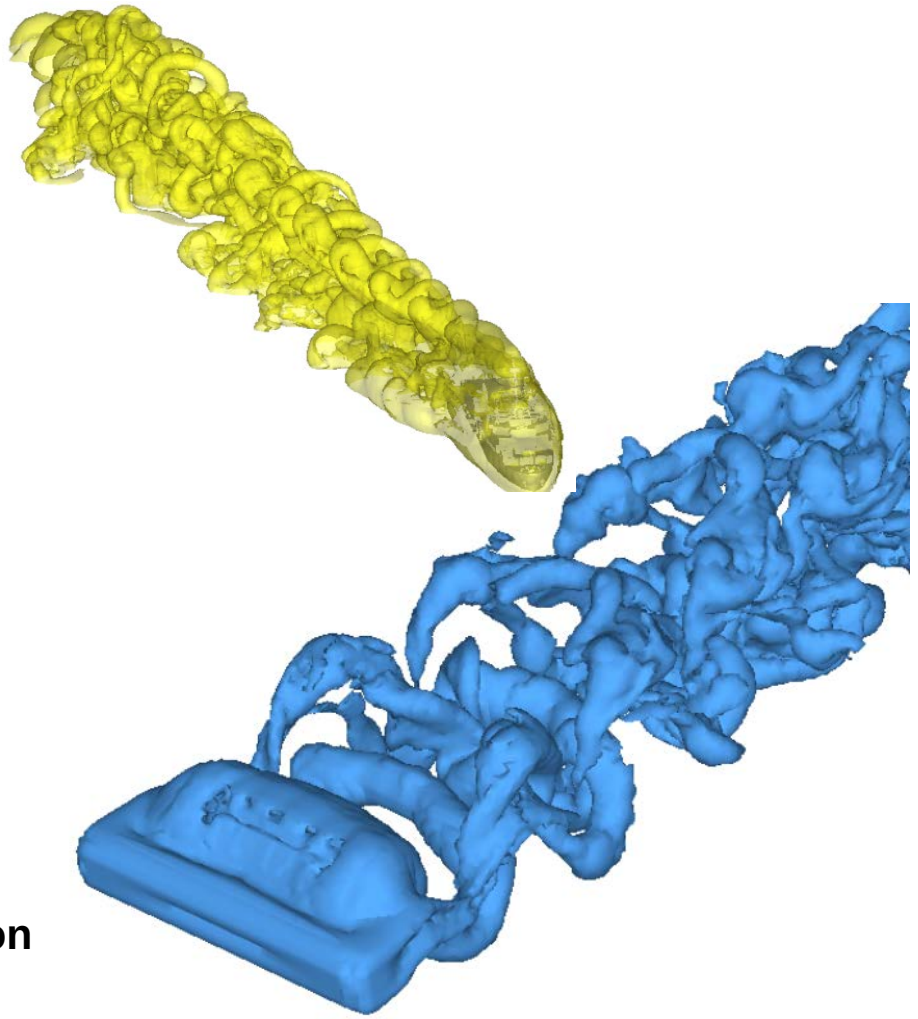
Background (cont'd)

- **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 …

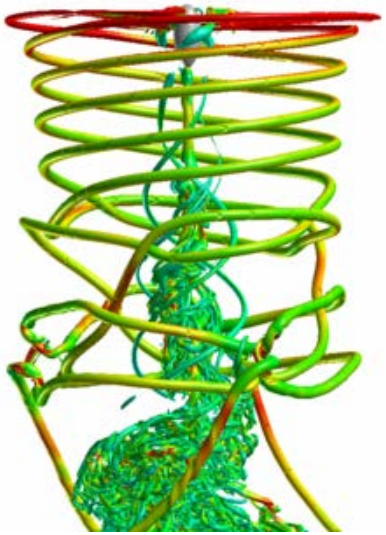
- **Conventional CFD formulations have high relatively numerical diffusion of vorticity on practical engineering grids**

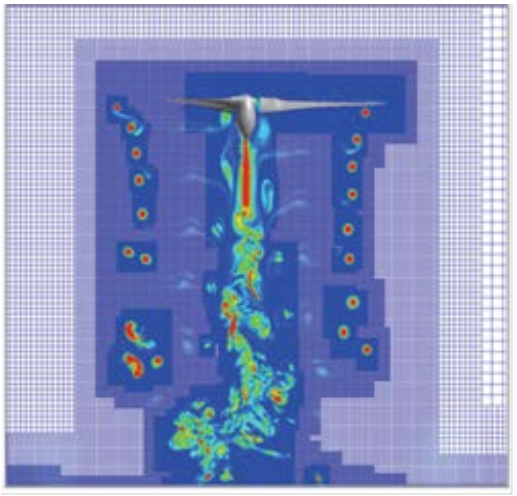


CFD/VorTran-M prediction of a ship air wake and the wake behind a wing at 90^{o} angle of attack

Background (cont'd)

- **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.)
    - Reduce the cost of "adequately" resolving the off-body
    - 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



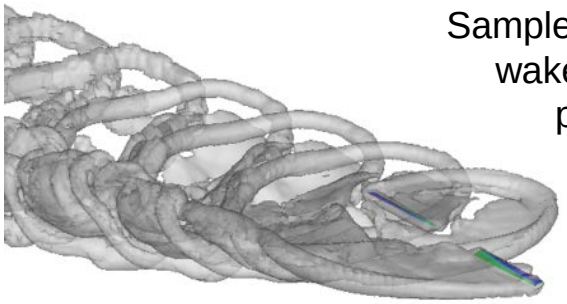


HELIOS prediction of hovering TRAM rotor with ~120M cells

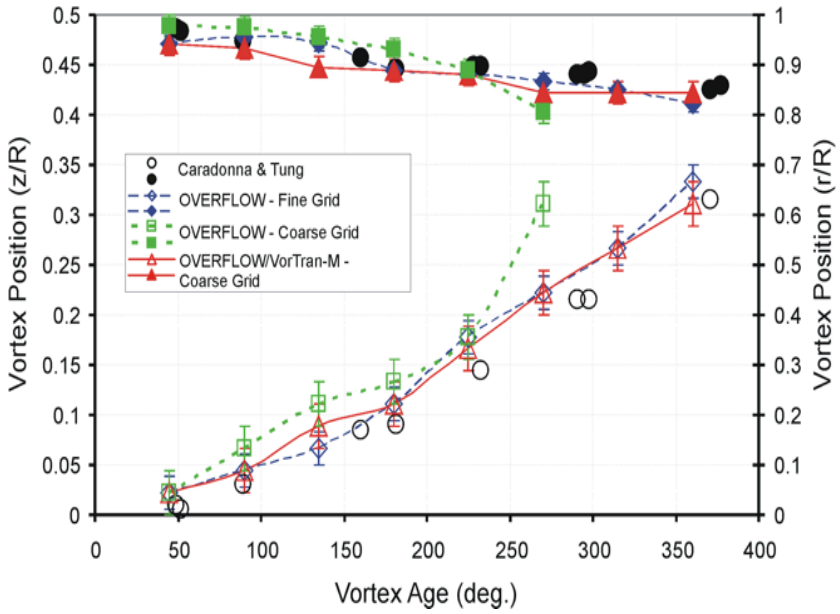
Background (cont'd)

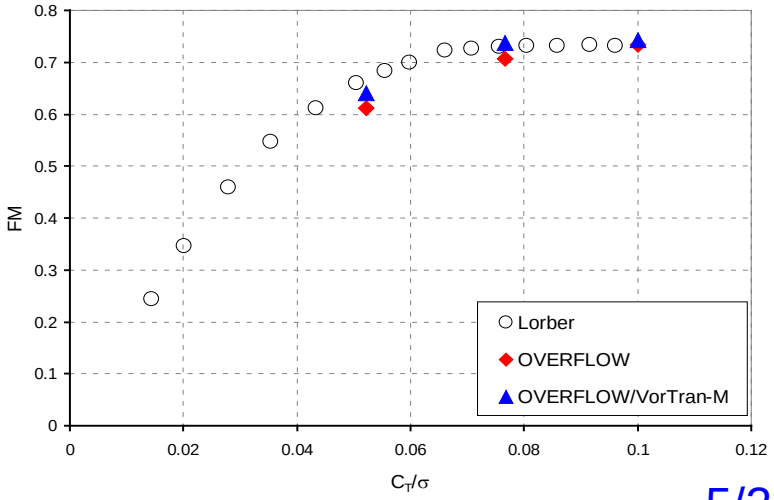
Promising hybrid solver: VorTran-M

- **Solves the inviscid unsteady Navier-Stokes equations in velocity-vorticity form**
  - Extended version of Brown's VTM solver
  - Explicitly conserves vorticity
  - Innovative Riemann solver to prevent smearing
  - Vorticity-tracking adaptive grid scheme
- **General coupling interface**
  - General overset approach
  - No double counting



Sample CFD/VorTran-M wake and airloads predictions

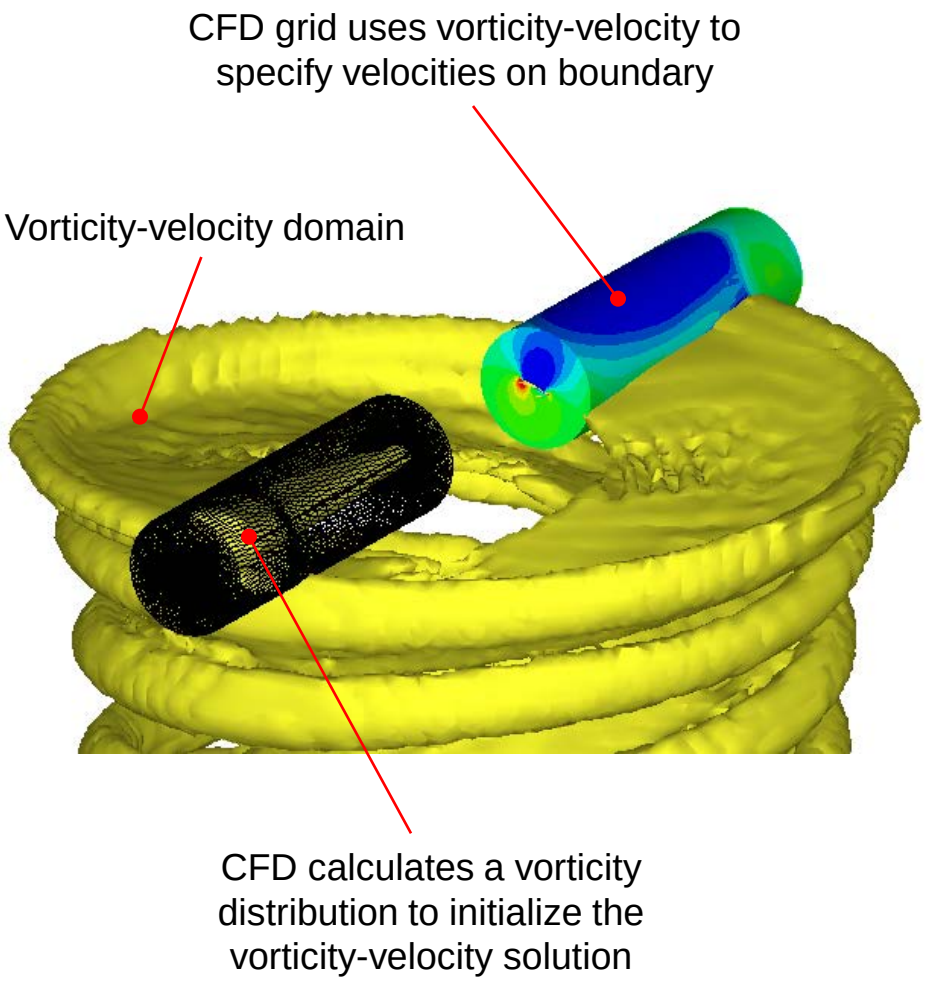




Background (cont'd)

Hybrid CFD/Vorticity-Velocity Overset Interface

- **Near-body CFD solver calculates near-body flow solution**
- **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**
  - Conventional overset hole cutting cannot be used
  - Can be expensive to calculate the vorticity in every near-body cell



Recent Developments:
VorTran-M2

Overview of VorTran-M2

- **Solves the incompressible viscous Navier Stokes equations in vorticity-velocity form**

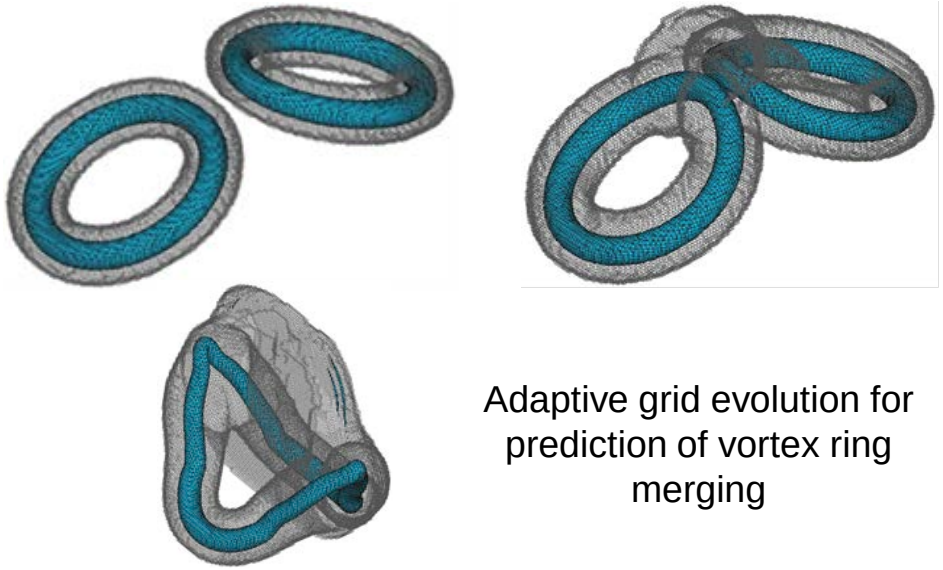
$$\frac{\partial}{\partial t}\omega + u\cdot\nabla\omega - \omega\cdot\nabla u = \upsilon\nabla^2\omega + S$$

using a direct numerical solution

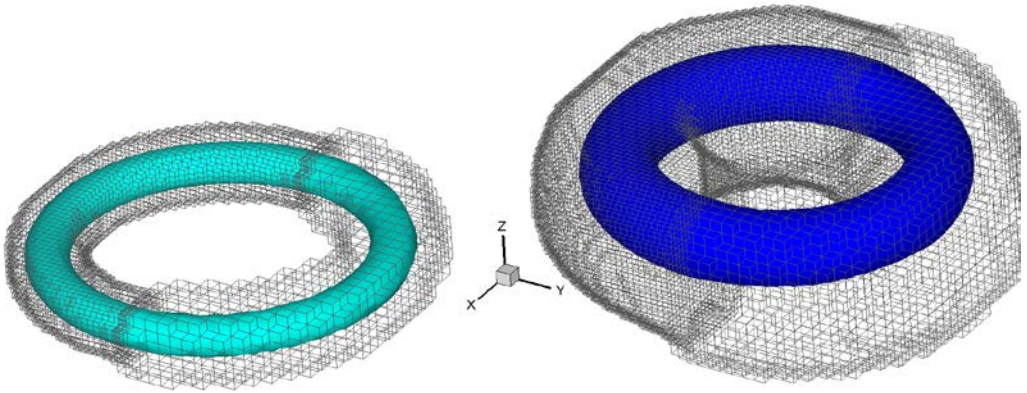
- **Multi-resolution flow-tracking adaptive grid**

- **At each time step a parallel FMM is used to solve the Biot-Savart relation for the velocity**

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



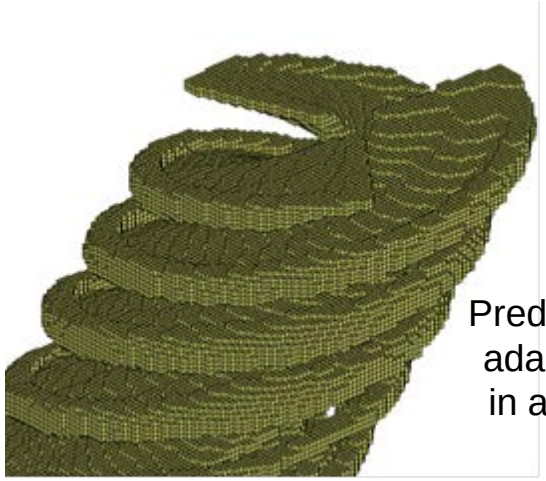
Adaptive grid evolution for prediction of vortex ring merging



Snap shots of diffusing vortex ring on a variable cell-size mesh

Overview of VorTran-M2 (cont'd)

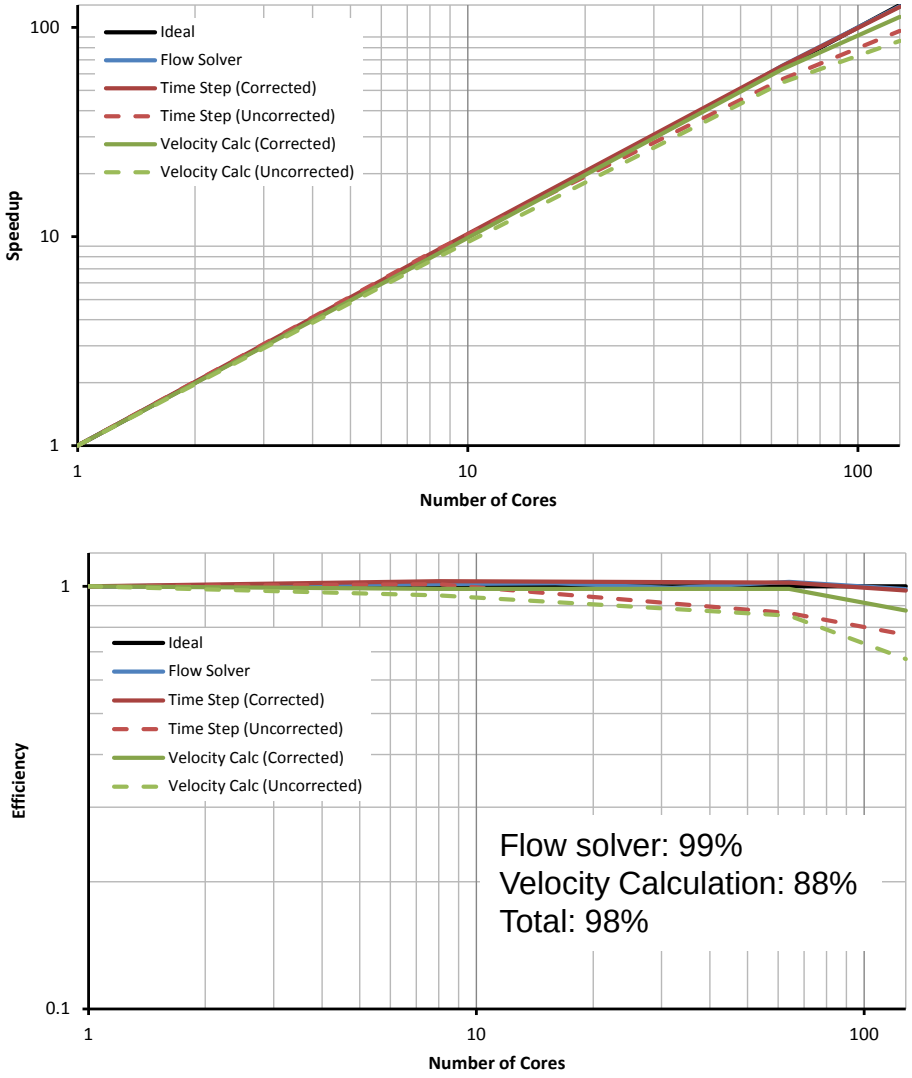
- **General multi-resolution adaptive grid scheme**
  - Octree-based Cartesian grid
  - Cell size can vary based on flow-metrics and/or grid location
  - Cells only active in regions of significant vorticity
  - Predictive adaptive grid rather than reactive adaptive grid
- **Divergence correction implemented using a Helmholtz decomposition to calculate a solenoidal field restoration (SFR) correction**
  - Implemented concurrently with velocity calculation to reduce cost
- **Viscous terms implemented**
  - Classic 7-point stencil in regions with uniform cell size
  - Diagonal interpolation stencil where the grid changes size
- **Calculation of unsteady pressure term**
  - For setting overset CFD BCs
- **Calculation of diagnostics and invariants**



Predictive flow-tracking adaptive grid for rotor in ascending forward flight

Overview of VorTran-M2 (cont'd)

- **Parallel flow solver**
  - Exploit the fact that the vorticity transport equation is linear in vorticity
    - If each process contains the same number of cells, then the scalability will be ideal
    - There will be some duplication due to the adaptive grid
    - There will be some optimal domain shape to minimize the number of buffer cells in the domain
  - Parallel FMM
    - FMM is the primary cost at a given time step
    - Parallelize over sources
  - Dynamic load balancing
    - K-means
    - Scaled weighted K-means



Scalability

Investigation of Turbulent Flows

Anecdote:

- CDI started ~40 years ago developing 2nd order closure/RSM methods (Bilanin and Teske) for turbulent flows

Investigation of Turbulent Flows

- **Prior work had suggested that VorTran-M/M2 may have implicit LES properties**
  - Predictions of spectra have shown $k^{-5/3}$ trends
  - 2^{nd} order scheme and flux limiting approach meets the numerical truncation error criteria laid out by Grinstein, Margolin et al

- **In this work**
  - Implemented Smagorinsky SGS model

    $v_t = (0.12\ \Delta)^2\ |\boldsymbol{\omega}|$

    based on Winckelmans et al 1996
  - Looked at different interpolation, flux schemes and time stepping schemes
  - No explicit filtering used
  - FFT-based Poisson solver for this application

- **Problems investigated**
  - Kida Pelz
    - Invisicid "higher frequency variation of TGV"
    - Used by mathematicians to test when/if a scheme goes singular
  - Taylor Green Vortex
    - Re=100
    - Re=1,600

Inviscid Kida Pelz (KP) Simulation

- **Kida Pelz**
  - Inviscid
  - Periodic domain, side length 2π
  - Initial condition (u_0=1)

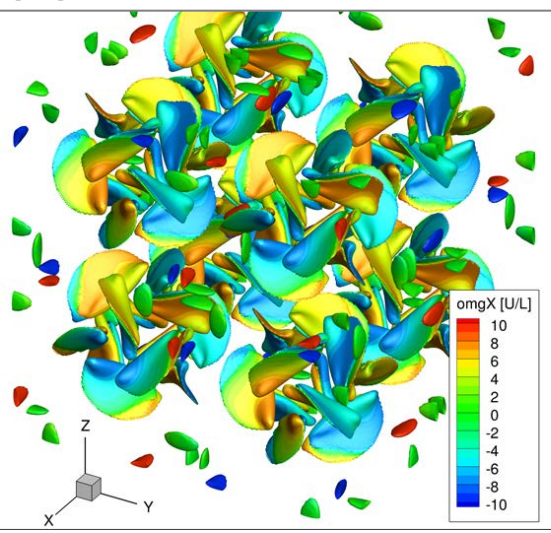
$$\mathbf{u}(x,y,z) = u_0 \begin{Bmatrix} \sin(x)[\cos(3y)\cos(z) - \cos(y)\cos(3z)] \\ \sin(y)[\cos(3z)\cos(x) - \cos(z)\cos(3x)] \\ \sin(z)[\cos(3x)\cos(y) - \cos(x)\cos(3y)] \end{Bmatrix}$$

  - Hypothesized to produce singular flow near t*~2

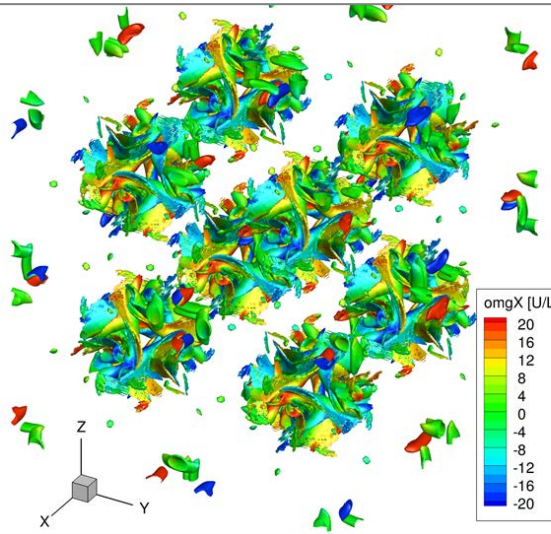
- **Reference solution from**
  - Chichowlas and Brachet, Fluid Dynamics Research, 2005

- **VorTran-M2 energy variation**
  - ~0.6%

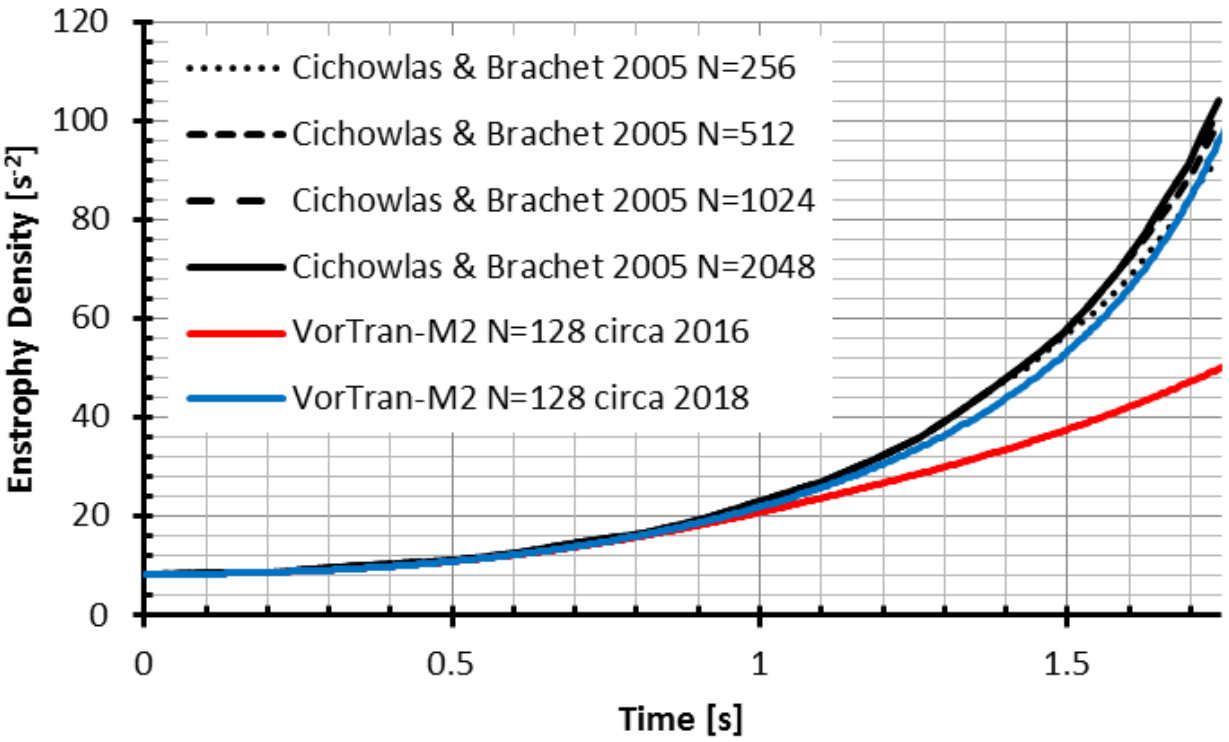
|ω|=10s^{-1} isosurface at t=1.18s



|ω|=20s^{-1} isosurface at t=1.65s



Inviscid Kida Pelz (KP) Simulation



Taylor Green Vortex

- **Taylor Green Vortex**
  - Periodic domain, side length 2π
  - Initial wave number, k=1
  - Initial condition (u_0=1)

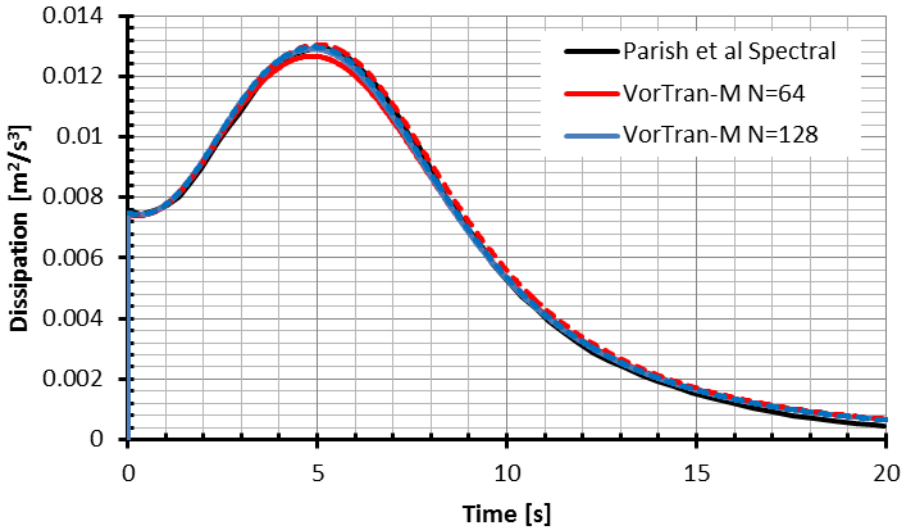
$$\mathbf{u}(x,y,z) = u_0 \cos(z) \left\{ \begin{array}{ccc} \cos(x)\sin(y) & -\sin(x)\cos(y) & 0 \end{array} \right\}$$

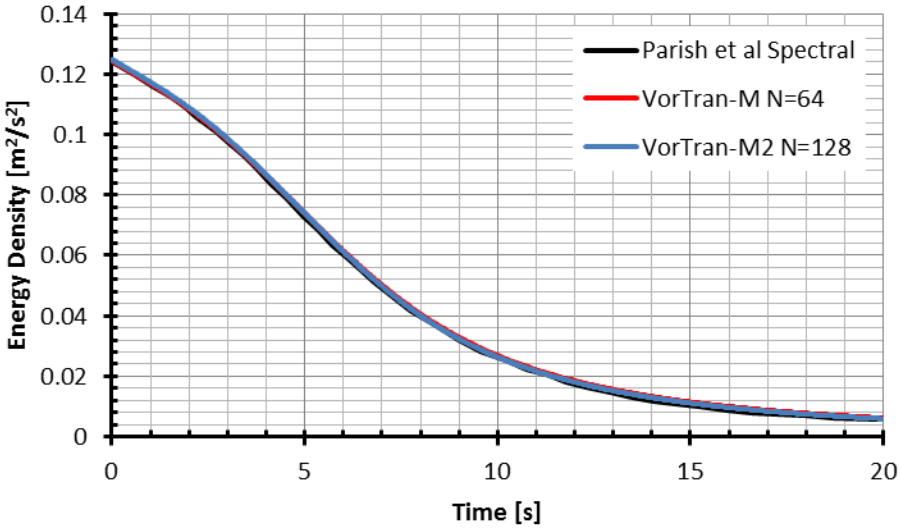
  - Evolution simulates turbulent breakdown since stretching produces smaller, more intense, vortical structures until diffusion processes dominate

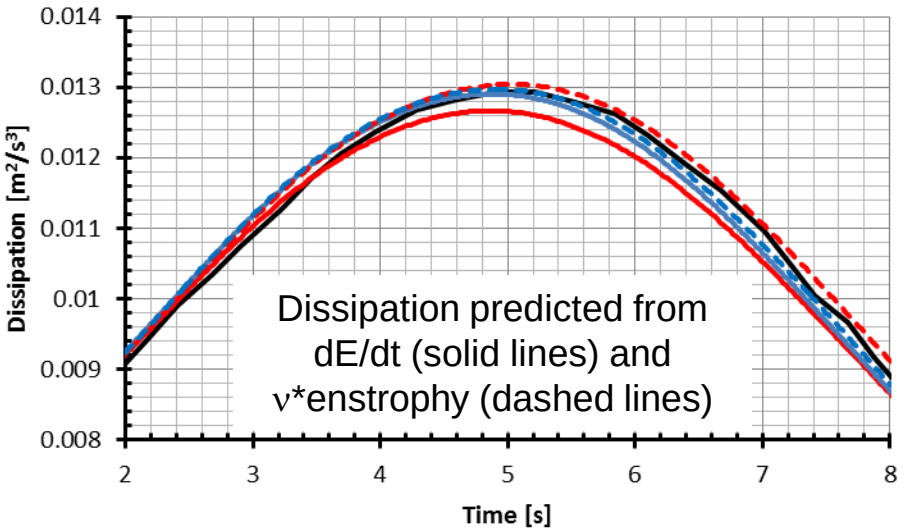
- **References solutions**
  - Re=100 from Parish, Duraisamy & Chandrashekar, J. Comp. Fluids, 2016
  - Re=1600 from 1st and 3rd International Workshop on High-Order CFD Methods

Taylor Green Vortex: Re=100

- **Taylor Green Vortex**
  - Re=100
  - Dissipation range: no cascading breakdown into smaller length scales

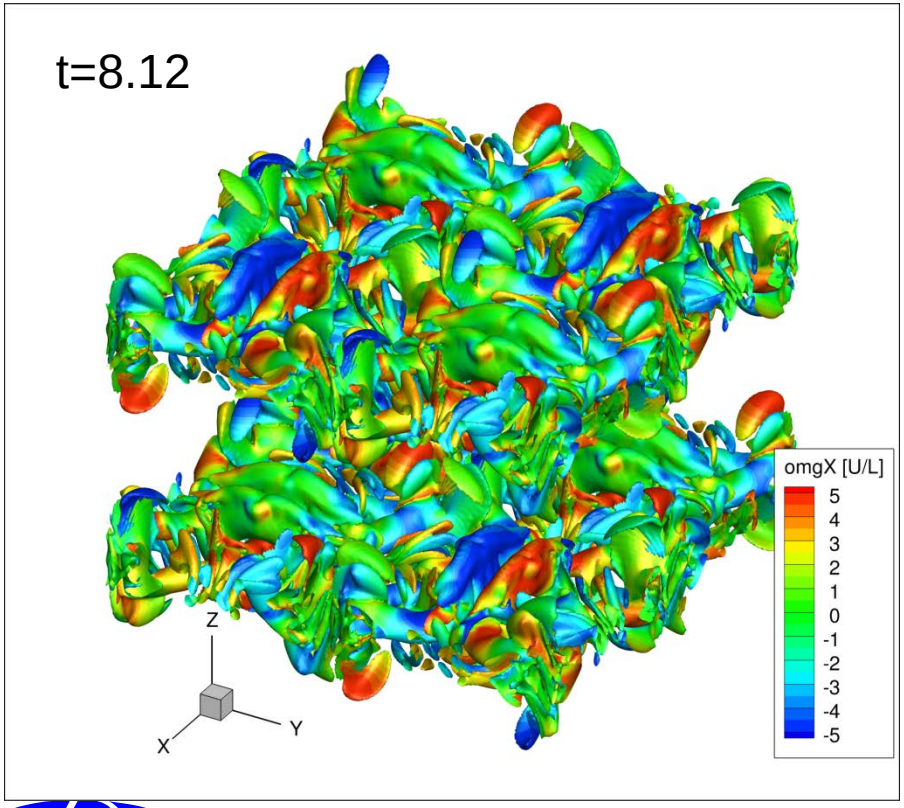


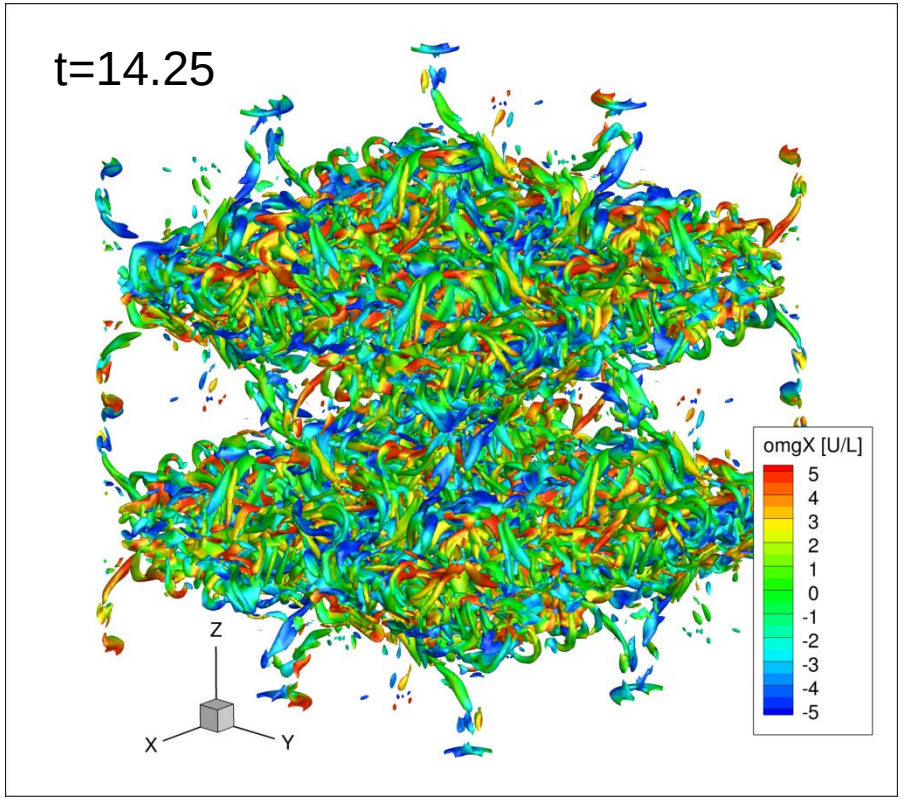




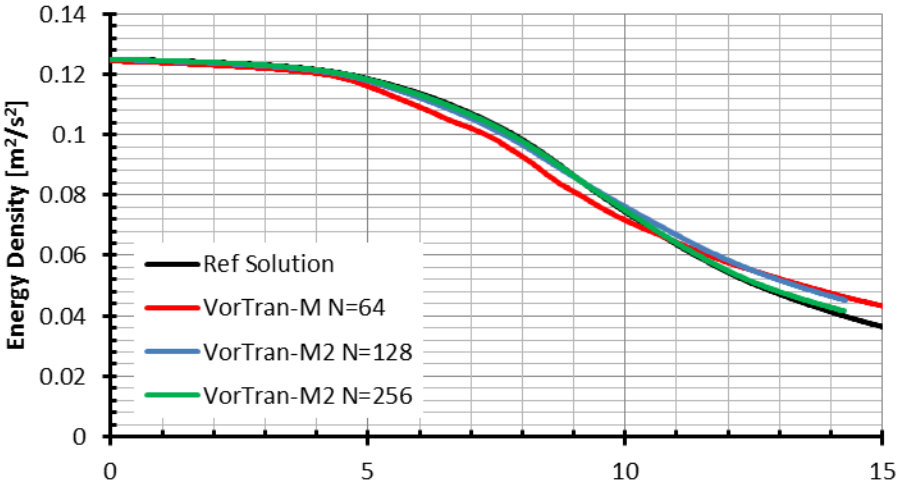
Taylor Green Vortex: Re=1,600

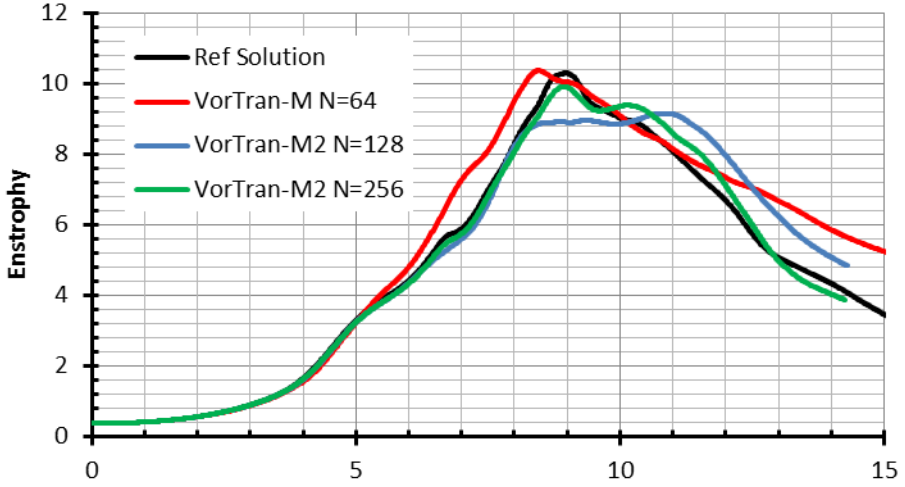
- **Taylor Green Vortex**
  - Re=1,600
  - Cascading breakdown into smaller length scales

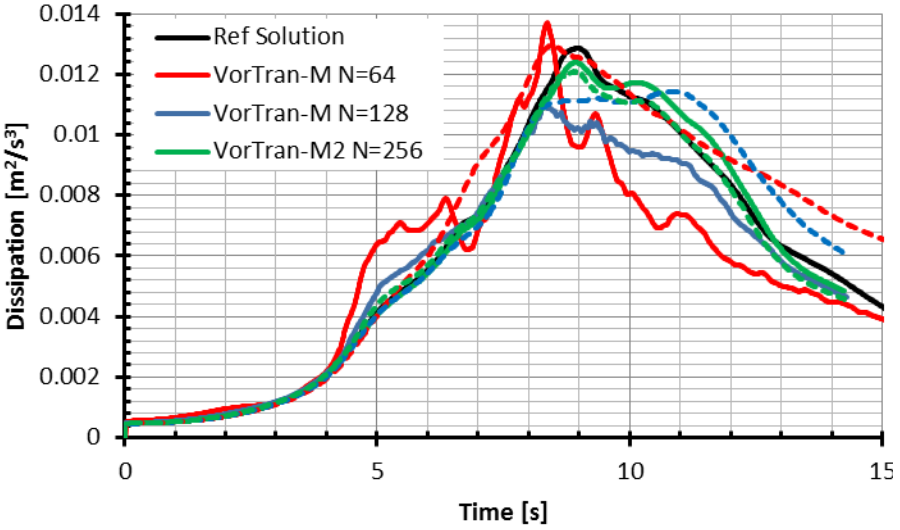


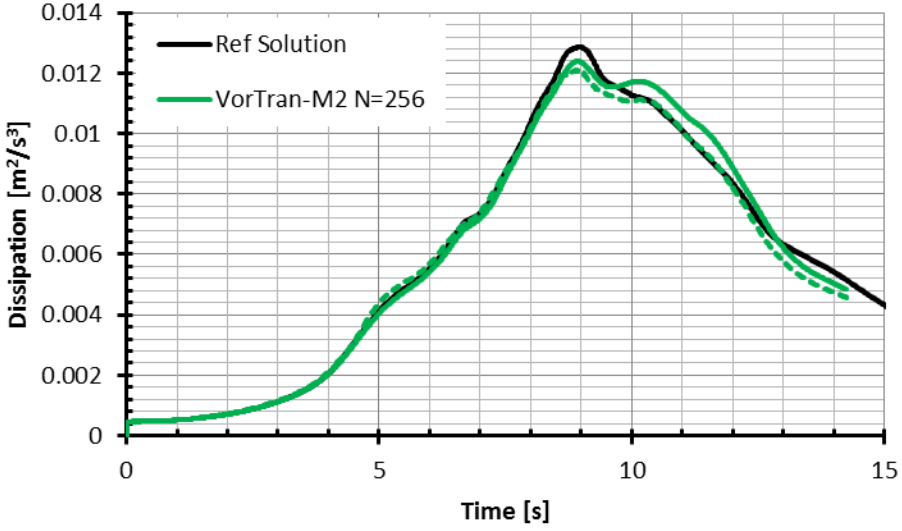


Taylor Green Vortex: Re=1,600









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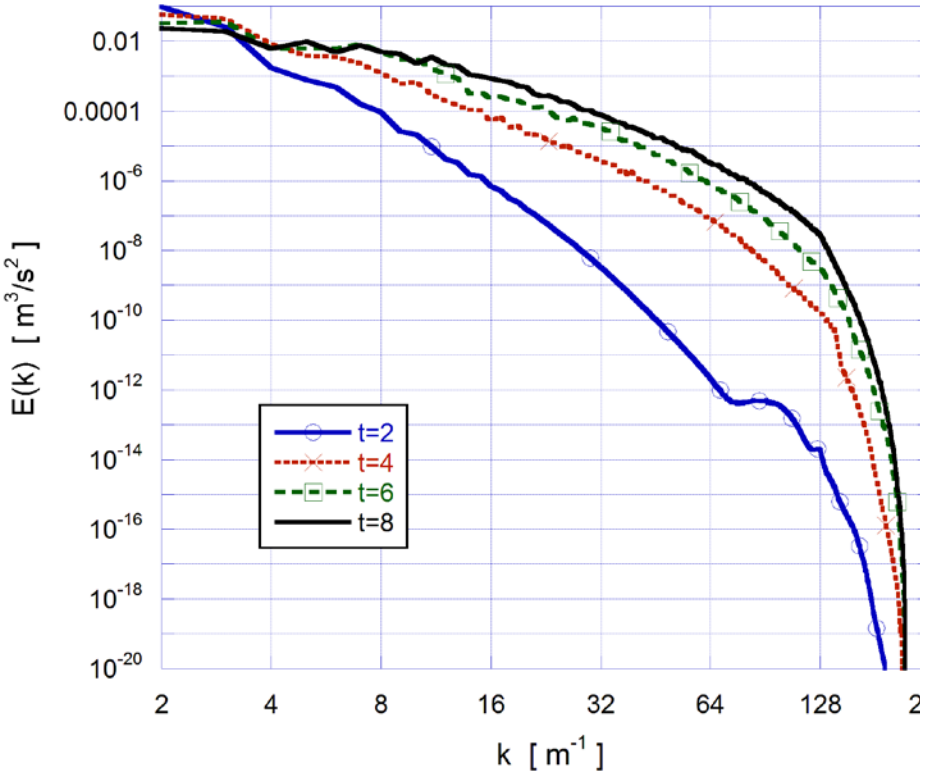
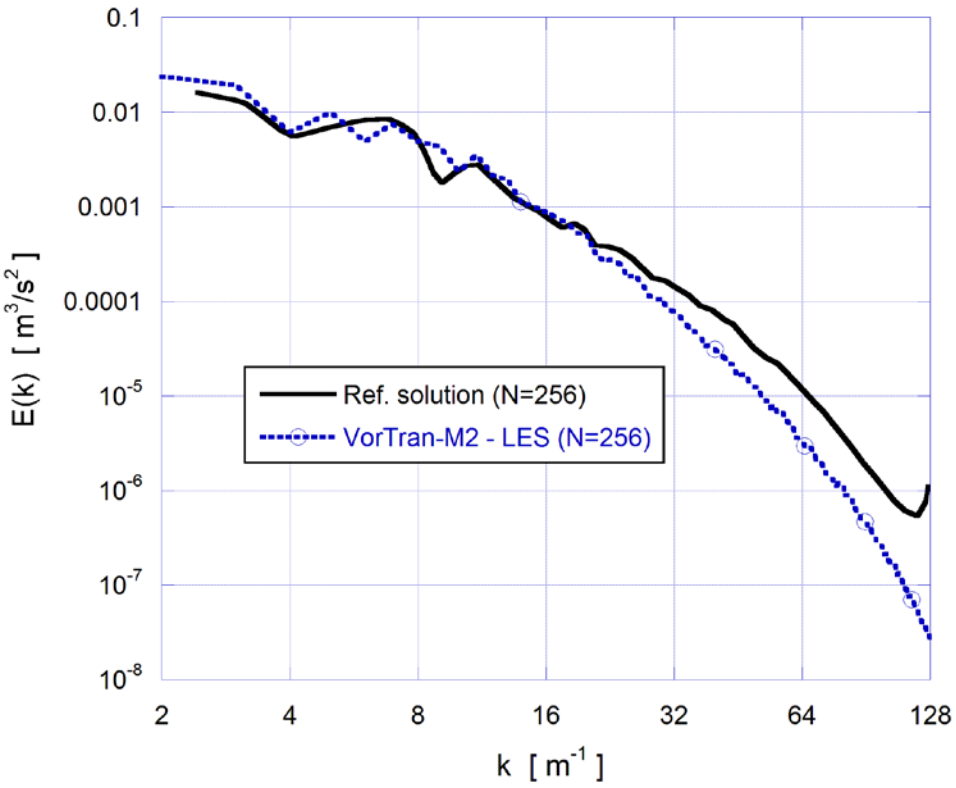
Dissipation predicted from dE/dt (solid lines) and ν*enstrophy (dashed lines)

Taylor Green Vortex: Re=1,600 – Energy Spectra



Predictions with N=256 & LES
at t=2, 4, 6, 8

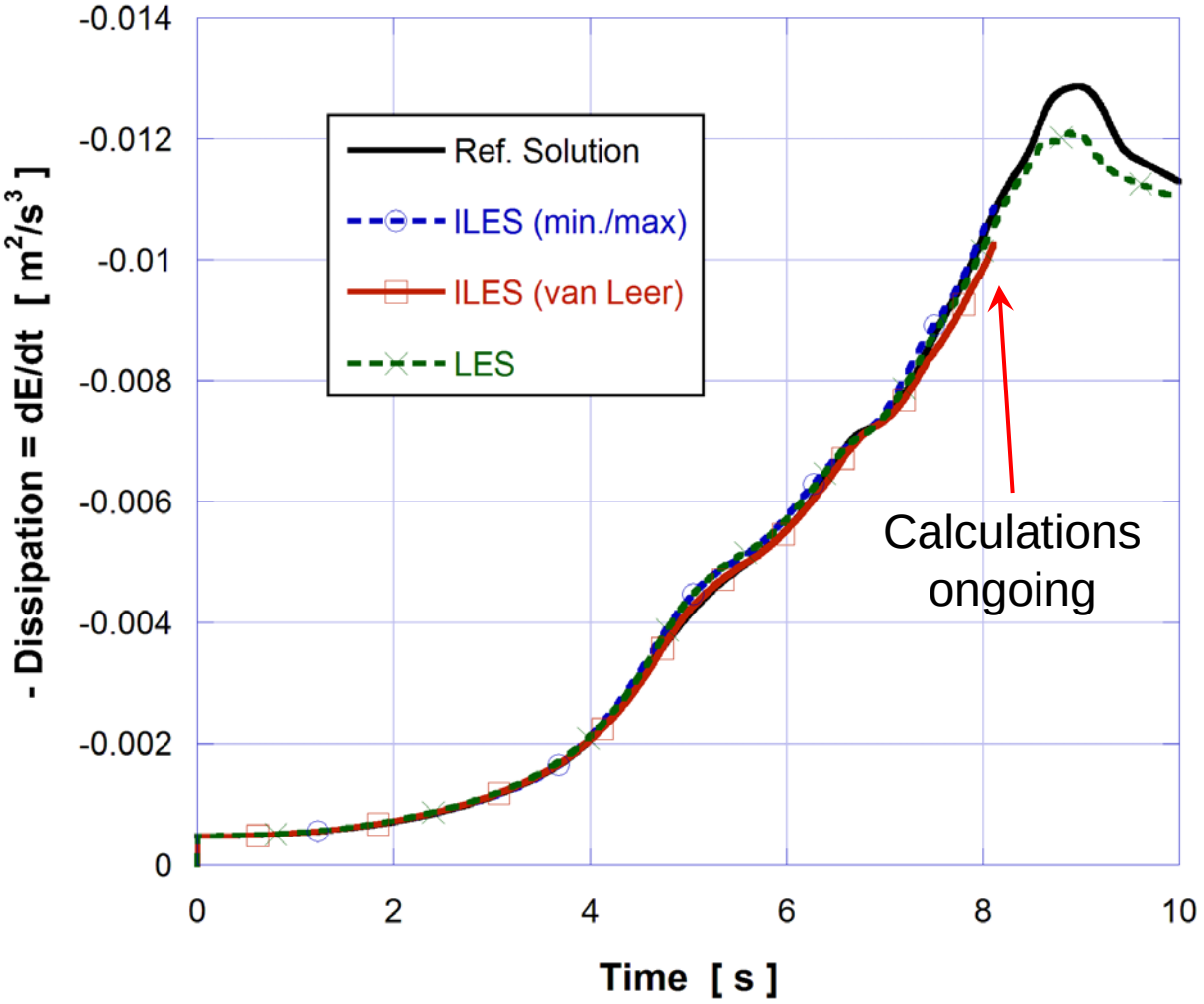


Comparison with published data at t=8

Ref. solution from Hillewaert & deWiart
presentation at 1st Int. Workshop on High-Order CFD Methods (2012)
(http://dept.ku.edu/~cfdku/hiocfd/summary/c3.5_summary.pdf)

Taylor Green Vortex: Re=1,600 – Prelim. ILES

- N=256
- min./max limiter result closely follows ref. solution
- Additional limiters under review



Conclusions

Conclusions

- **Documented the development of a new grid-based vorticity-velocity off-body solver for standalone and overset applications**
  - Predictive-adaptive multi-resolution grid system
  - Efficient divergence-free correction scheme
  - Consistent and efficient implementation of the viscous terms
  - Demonstrated performance and grid convergence for turbulence-like flows
  - Efficient calculation of the unsteady pressure terms
  - Parallel coupling interface
  - Parallel dynamic domain decomposition

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science Small Business Innovative Research (SBIR) program under Award Number DE-SC0013231.

Presentation End

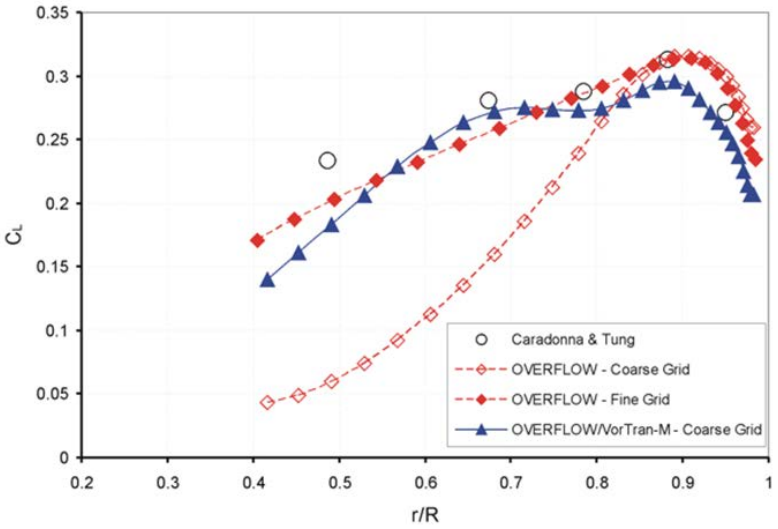
Success Stories: Grid-Based

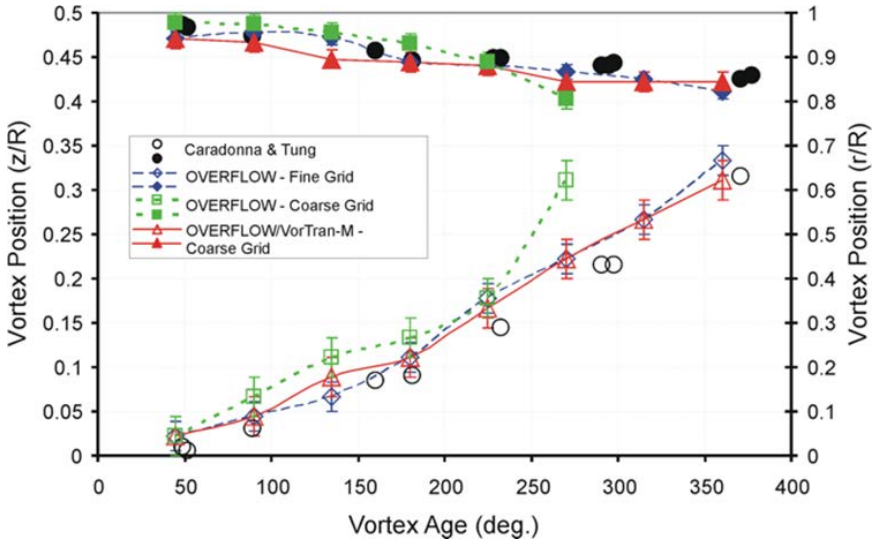
Hovering Rotor Predictions

- **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



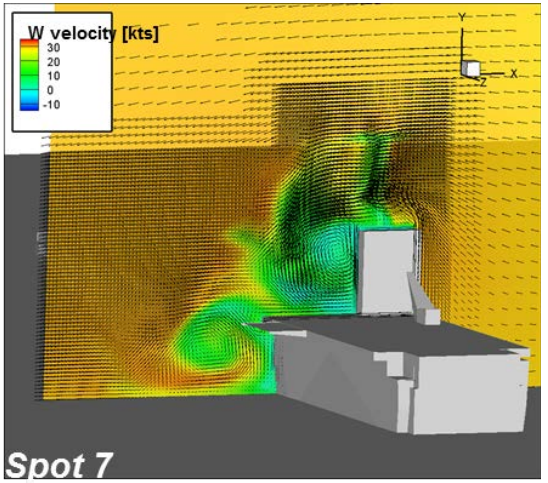


Predicted loading and tip vortex trajectory

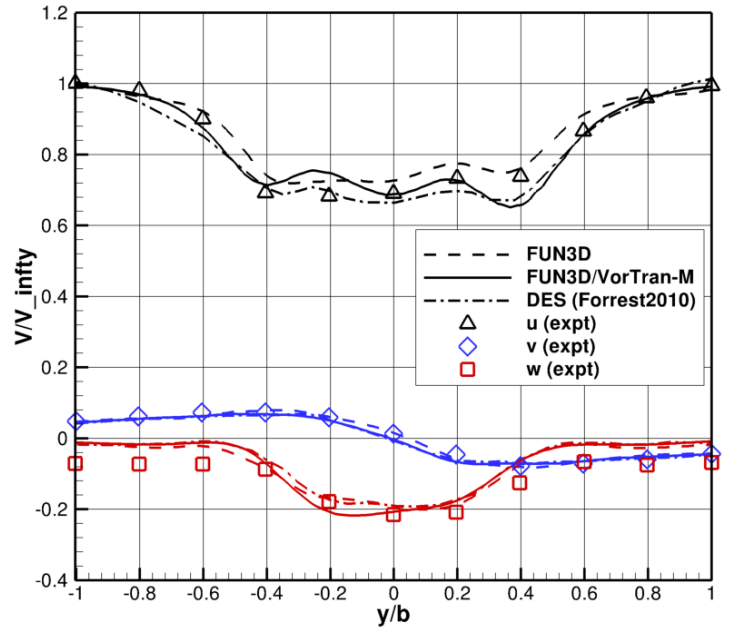
Success Stories: Grid-Based

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

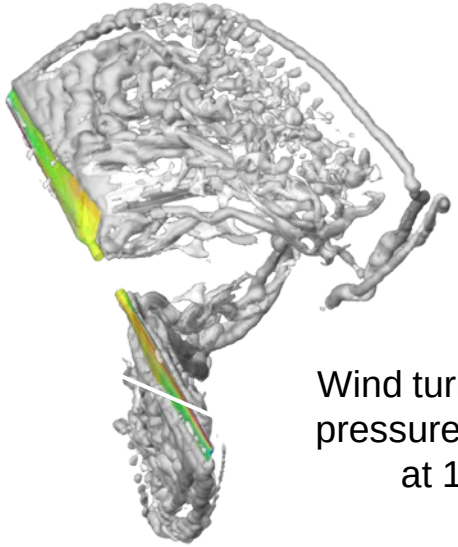
Success Stories: Grid-Based

Wind Turbine Prediction

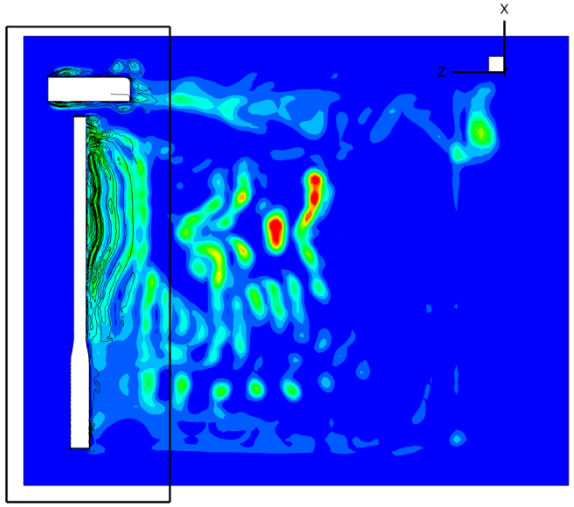
- **Quon, Smith, and Whitehouse, "A Novel Computational Approach to Unsteady Aerodynamic and Aeroelastic Flow Simulation," International Forum on Aeroelasticity and Structural Dynamics, 2013**

- **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

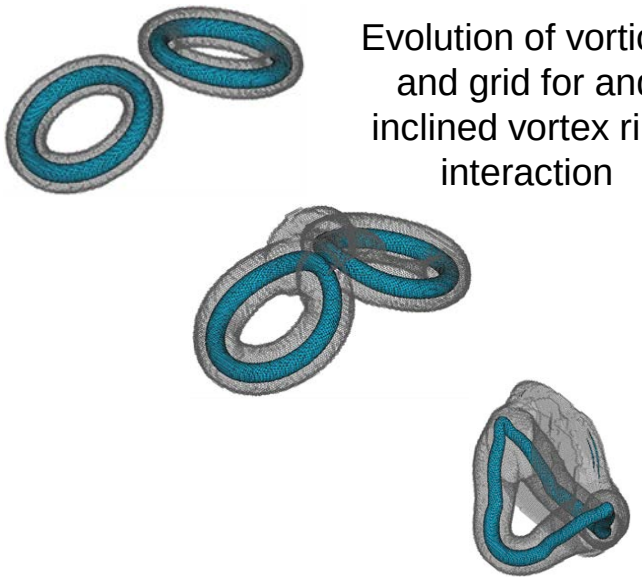
Success Stories: Grid-Based

Self Propagating Vortex Ring Moderate Re

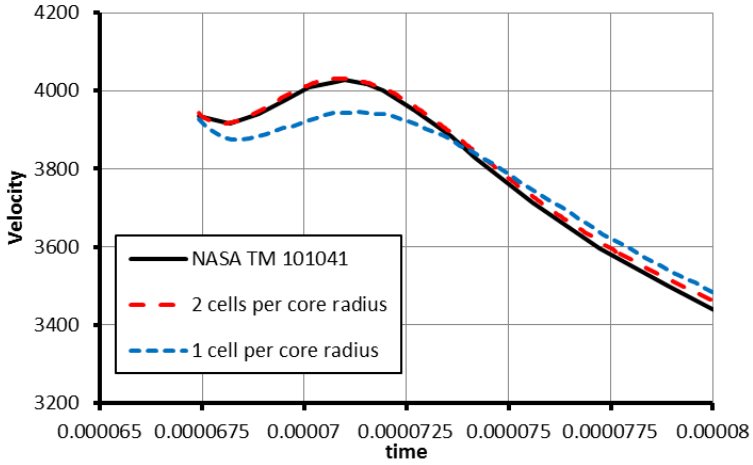
- **Whitehouse and Boschitsch, "Innovative Grid-Based Vorticity–Velocity Solver for Analysis of Vorticity-Dominated Flows", AIAA Journal, to appear, DOI: 10.2514/1.J053493**

- **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