RDECOM

10th Symposium on Overset Grids and Solution Technology

September 20-23, 2010

NASA Ames Research Center

Moffett Field, CA USA

Application of Strand Meshes to Complex Aerodynamic Flow Fields

AMRDEC

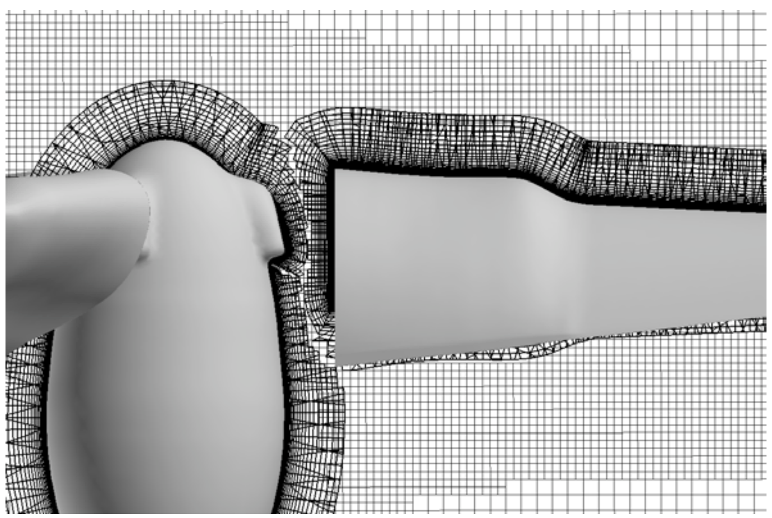
STRENGTH THROUGH TECHNOLOGY

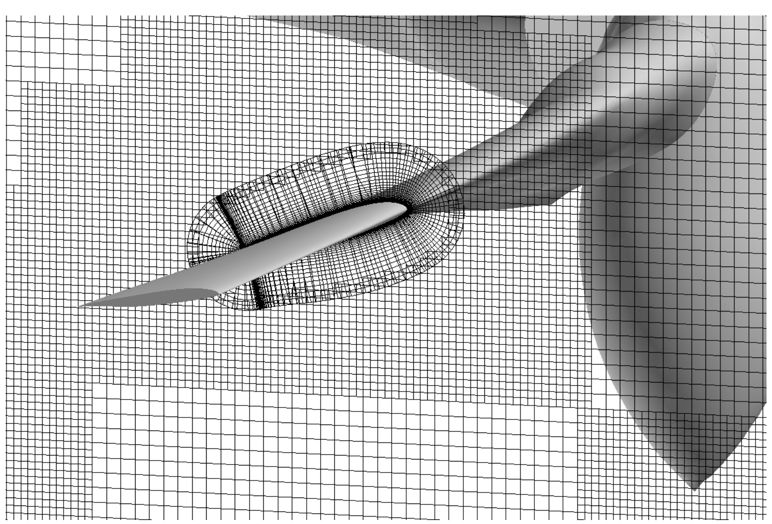
Aaron Katz

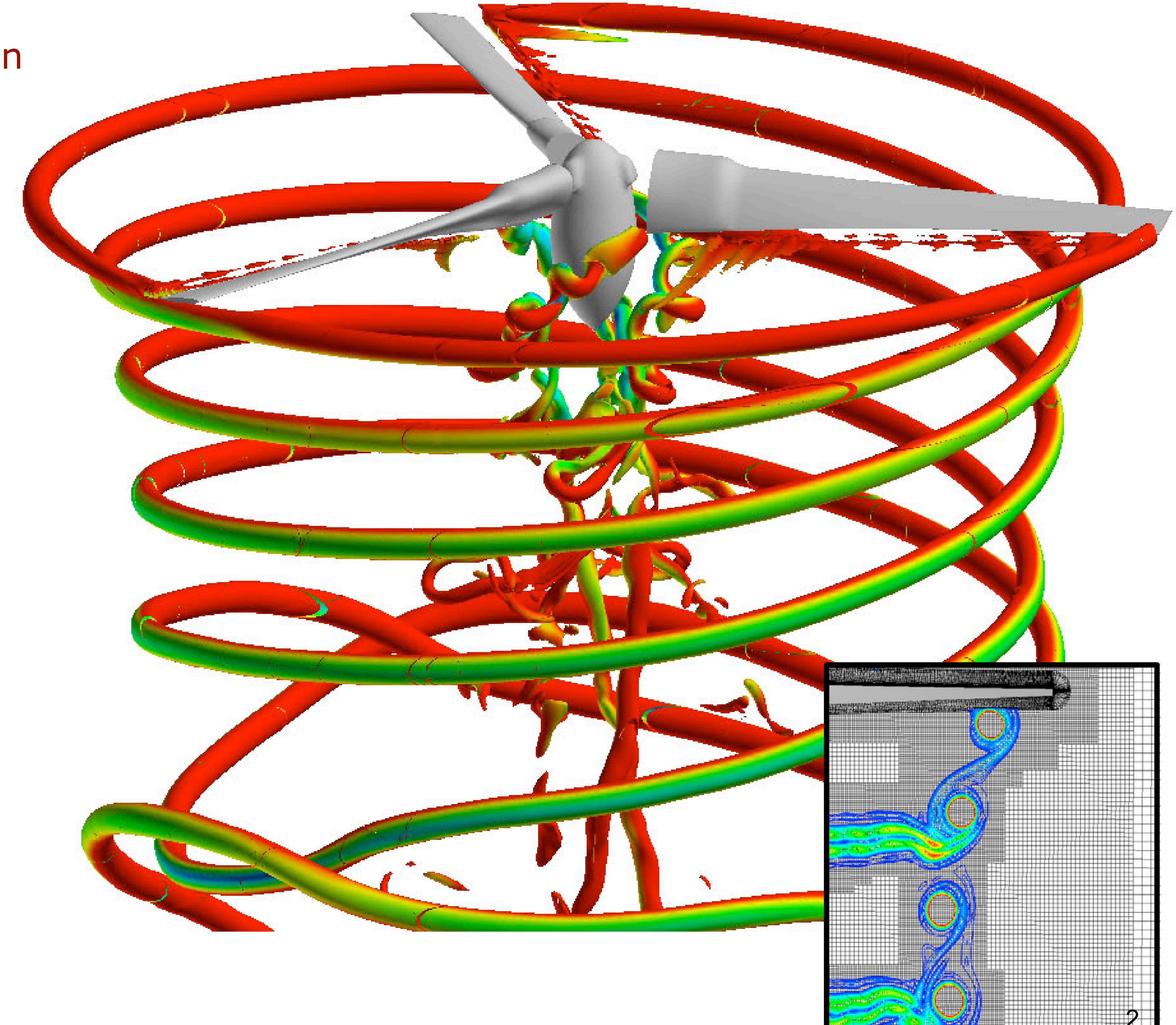
US Army Aeroflightdynamics Directorate
Aviation and Missile Research, Development and Engineering Center
Moffett Field, CA

The Strand/Adaptive Cartesian Overset Approach for Engineering Design

- Automated + Accurate + Timely
- Advantages:
  - automatic mesh generation
  - high-order accuracy
  - scalable, adaptable
  - compact grid definition
- Rotorcraft applications





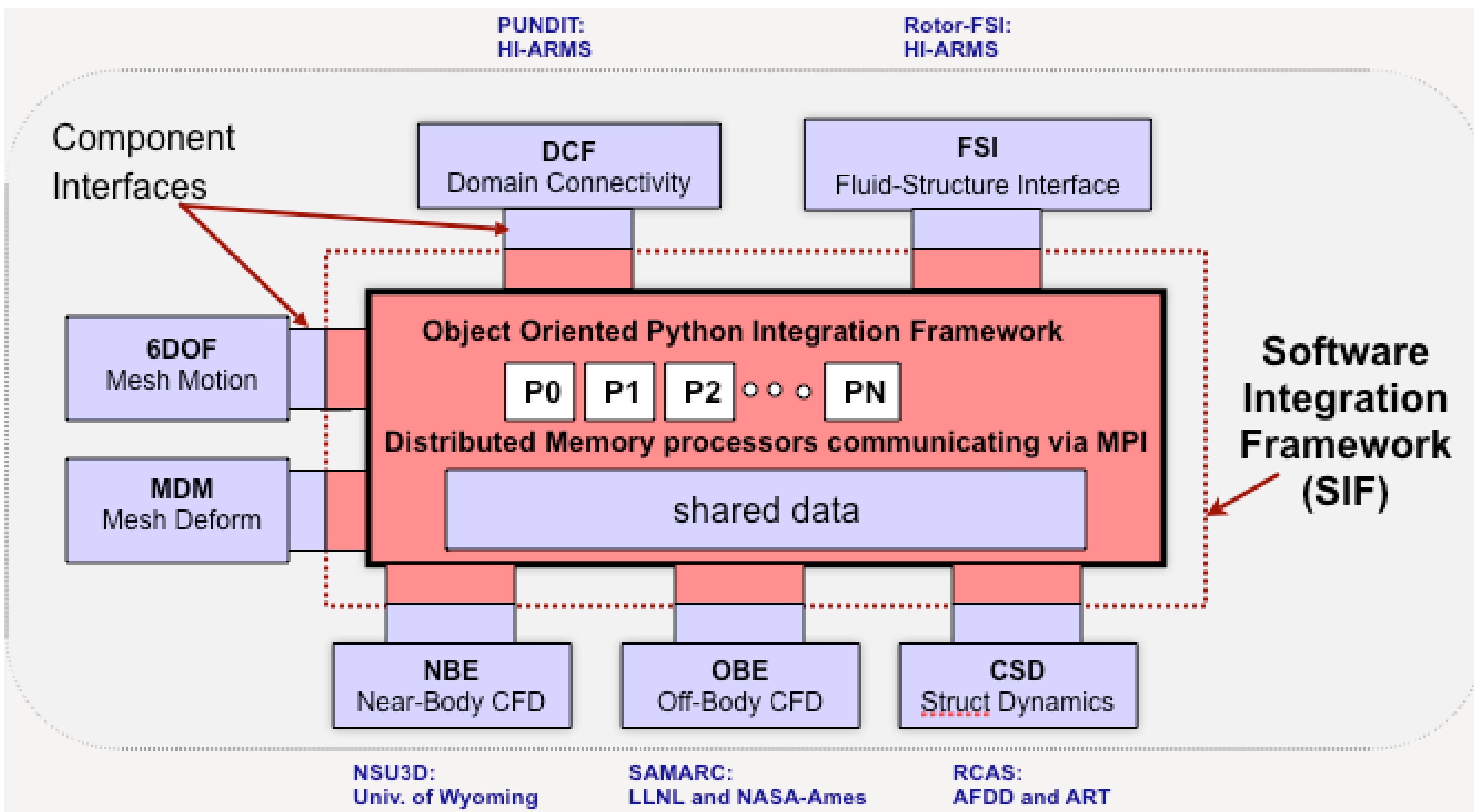


Objectives and Scope

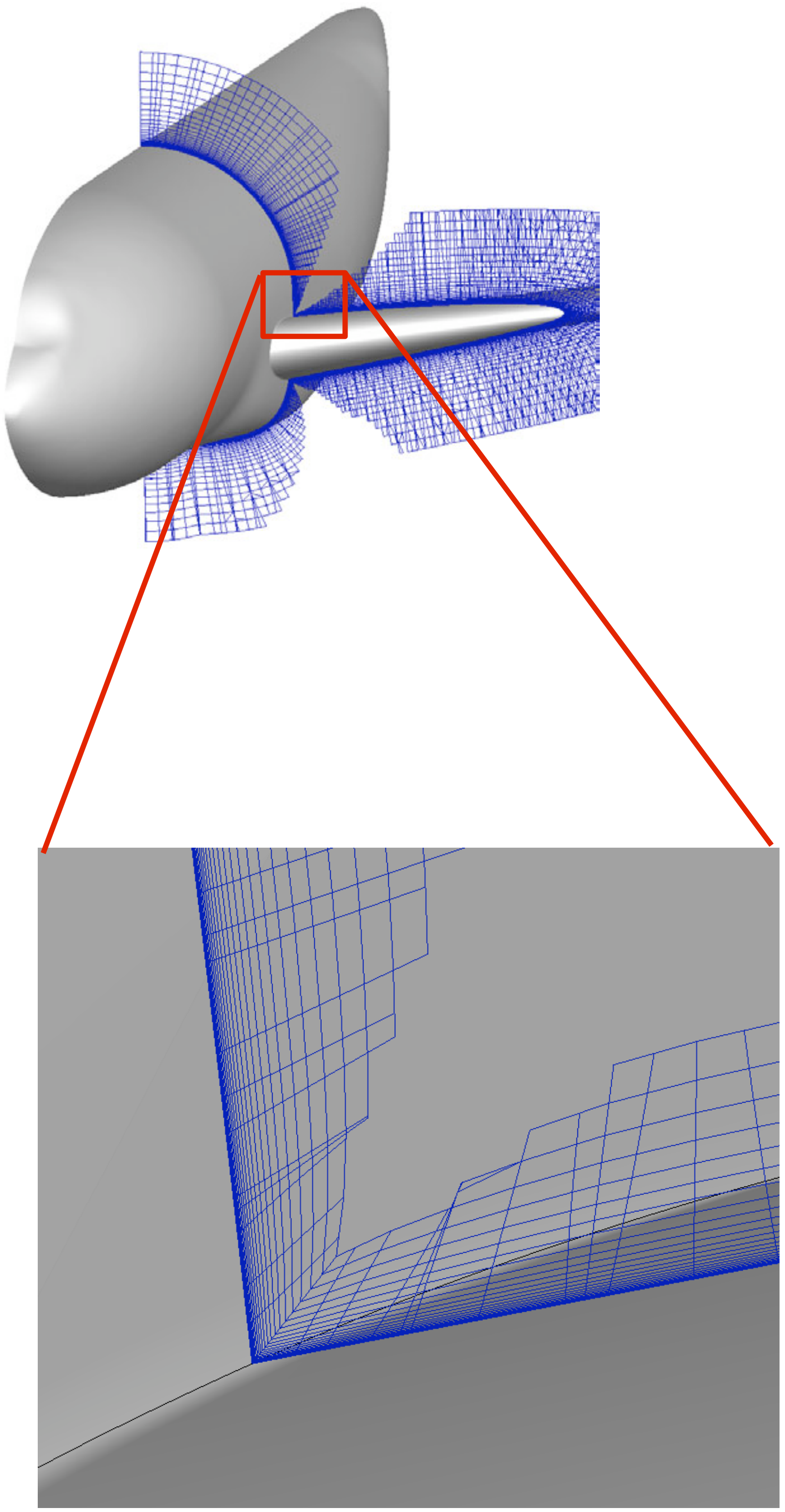
- Description of strand/adaptive Cartesian approach
  - strand parameters: length, bending
- Validation results
  - parametric studies
  - test cases: wing, TRAM rotor, wing-body from DPW3
- Progress in strand grid development
  - strand discretization strategy
  - AMR multigrid convergence

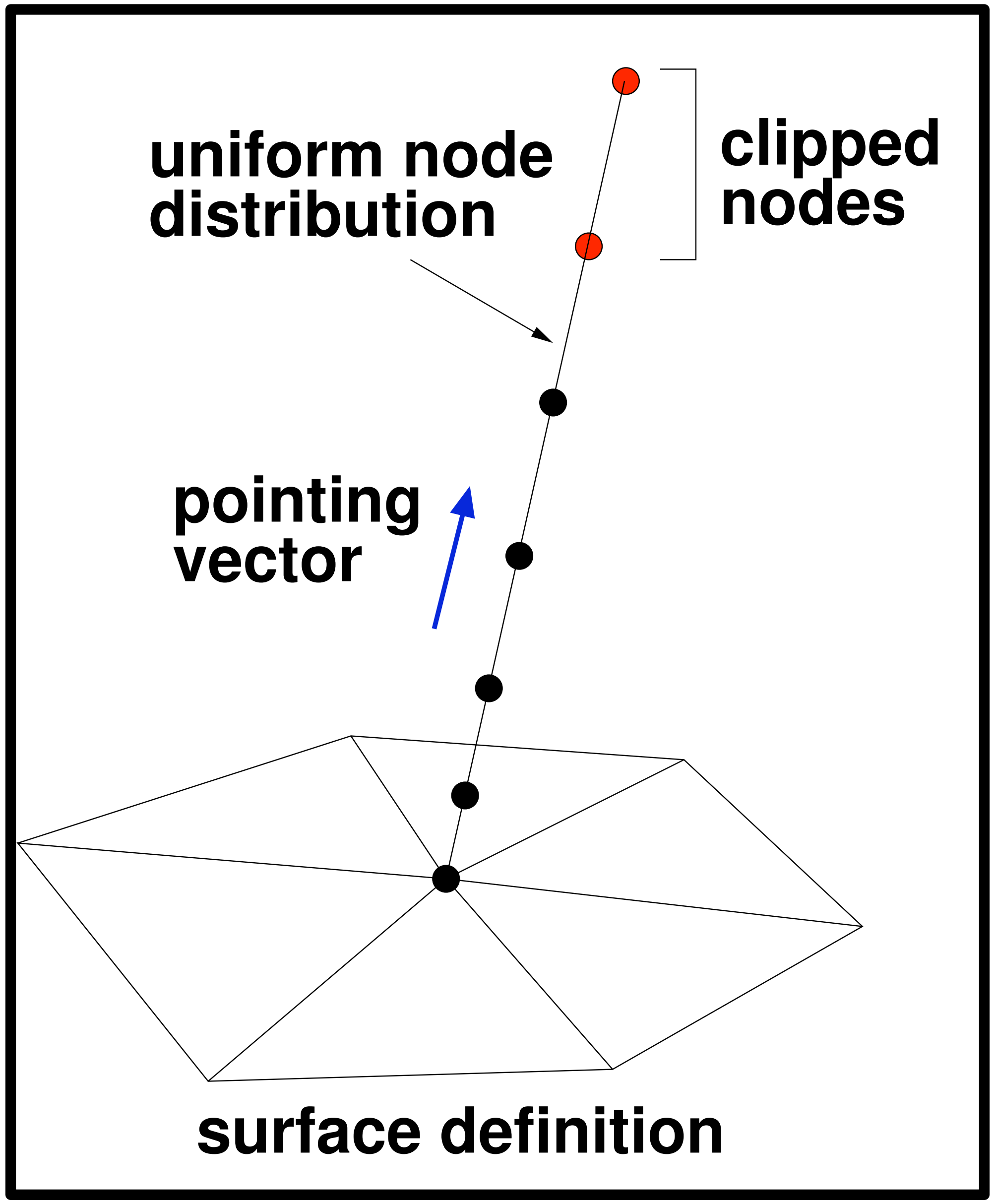
Helios Infrastructure

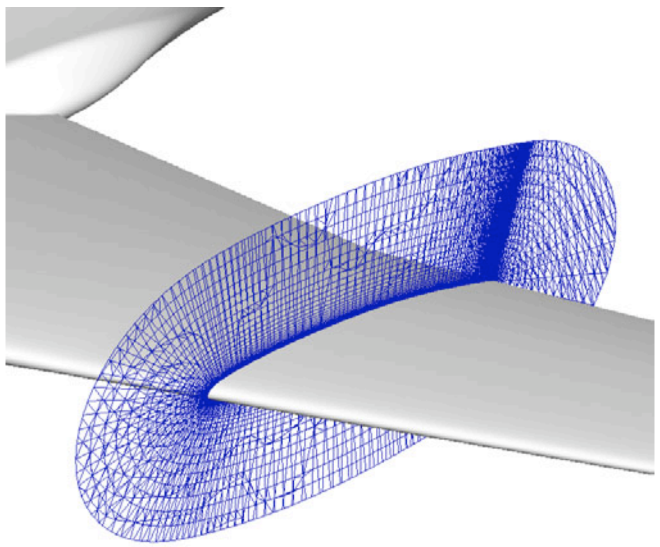
- Helios - computational design tools for defense acquisition
  - Computational Research and Engineering Acquisition Tools and Environments (CREATE)
  - HPC Institute for Advanced Rotorcraft Modeling and Simulation (HIARMS)
- Multi-code Python-based parallel execution
  - near-body strand-grids (NSU3D)
  - off-body adaptive Cartesian grids (ARC3DC)
  - Chimera overset communication

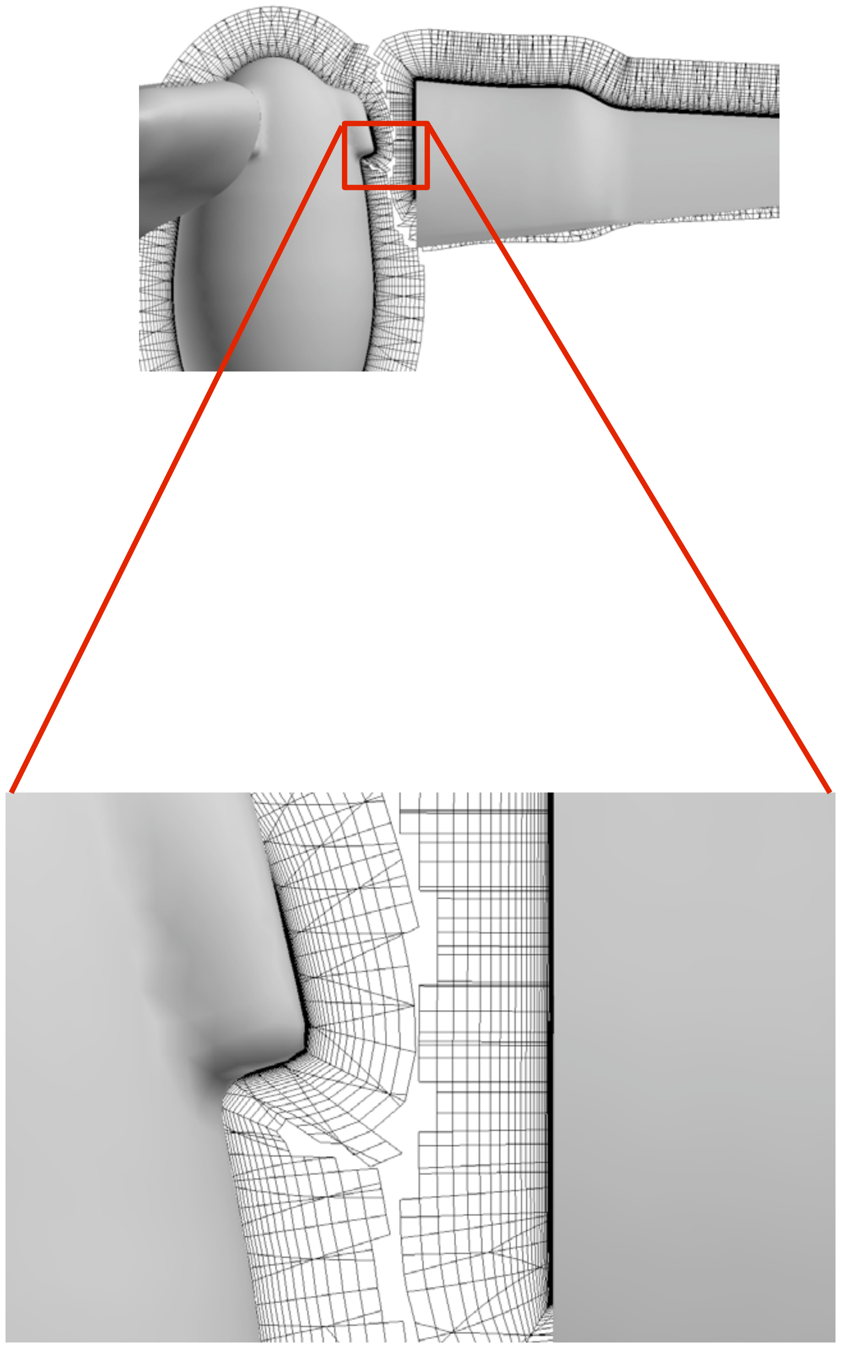


Strand-grid Components









Determining Strand Length

- Boundary layer thickness estimates*:
  - assumptions: flat plate, incompressible, zero pressure gradient

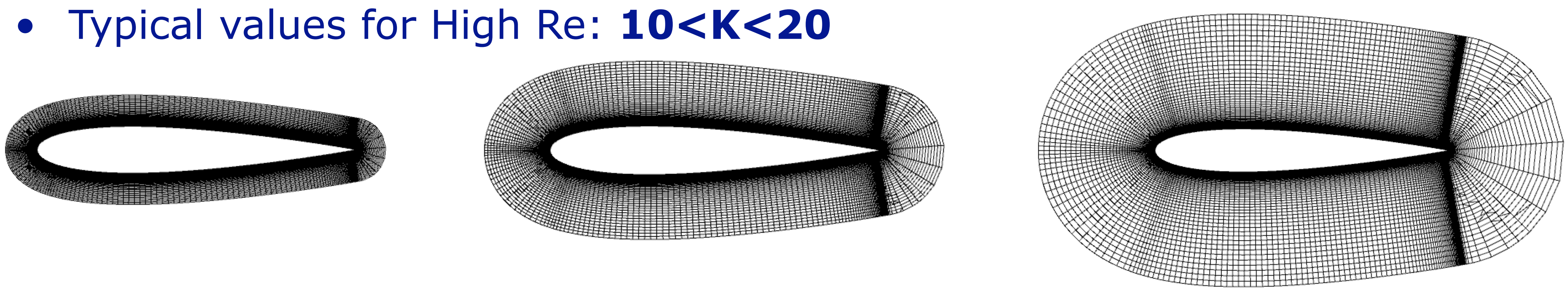
$$\delta(x)_{lam} \approx 5.0xRe_x^{-\frac{1}{2}}$$

$$\delta(x)_{turb} \approx 0.37xRe_x^{-\frac{1}{5}}$$

- Strand length parameter, *K*, for characteristic length, *L*:

$$l = K\delta(L)$$

- Typical values for High Re: **10<K<20**



K=5 *K*=10 *K*=20

*Schlichting, H., *Boundary-Layer Theory (7th Edition)*, New York, 1979.

Strand Vector Smoothing

- Smooth pointing vectors to
  - avoid self-intersection
  - provide adequate coverage for sharp corners
- Initial pointing vectors are surface normals
- Smoothing optimization procedure:

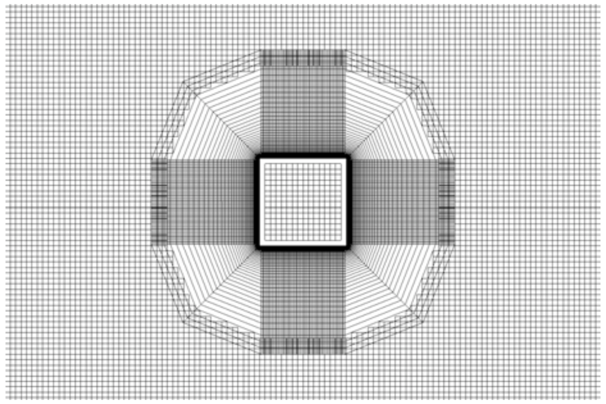
$$f(\boldsymbol{n}_0) = \sum_i (1 - \boldsymbol{n}_0 \cdot \boldsymbol{n}_i), \quad i = 1, \ldots, N$$

- Smoothness measure:

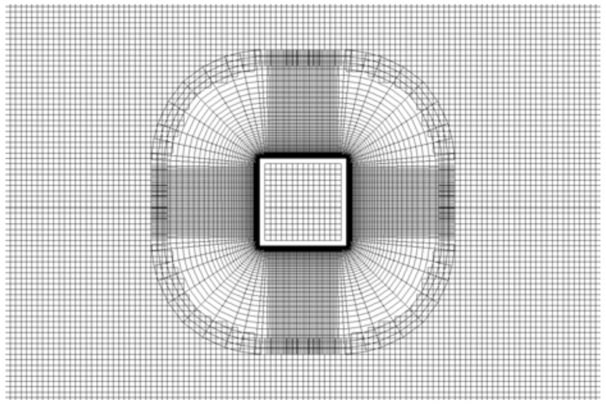
$$r_{s,0}^k = 1 - \boldsymbol{n}_0^k \cdot \boldsymbol{n}_0^{k-1}$$

$$r_{s,RMS} = \sqrt{\frac{\sum_i (r_{s,i}^k)^2}{\mathrm{REAL}(nNodes)}}$$

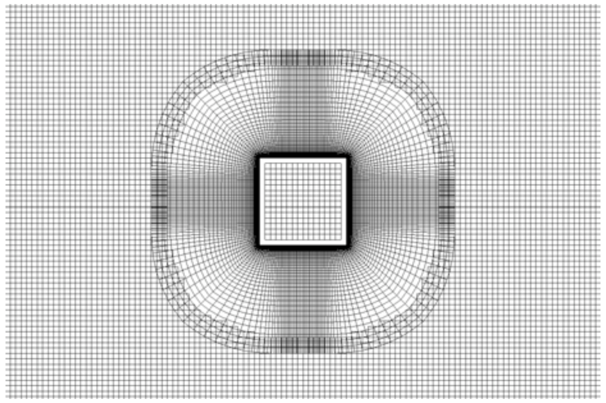
no bending



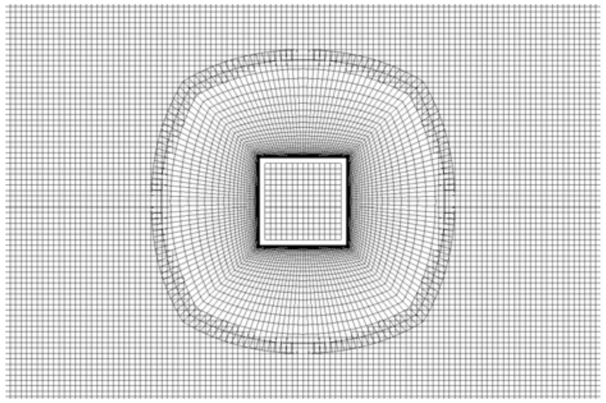
$r_{s,RMS} = 10^{-4}$



$r_{s,RMS} = 5\text{x}10^{-6}$

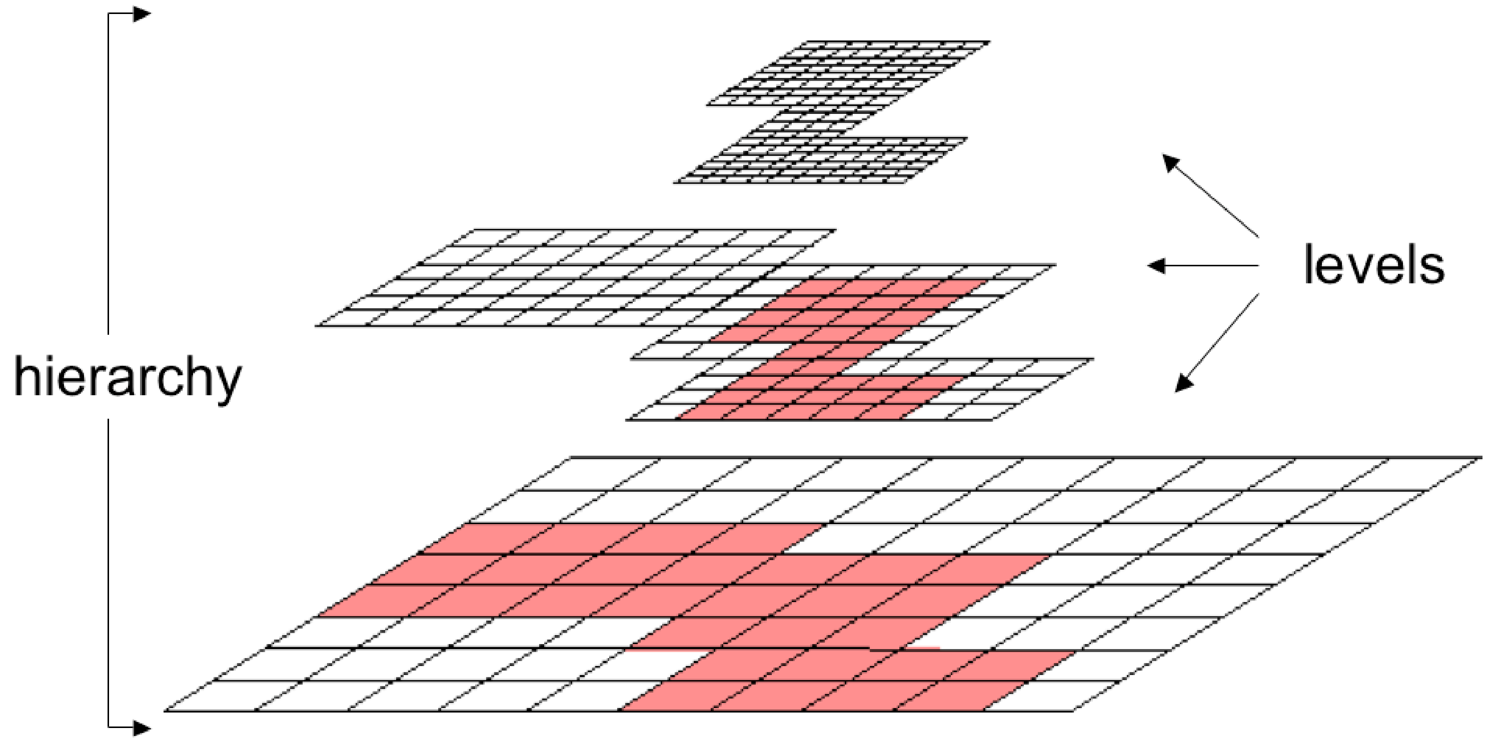


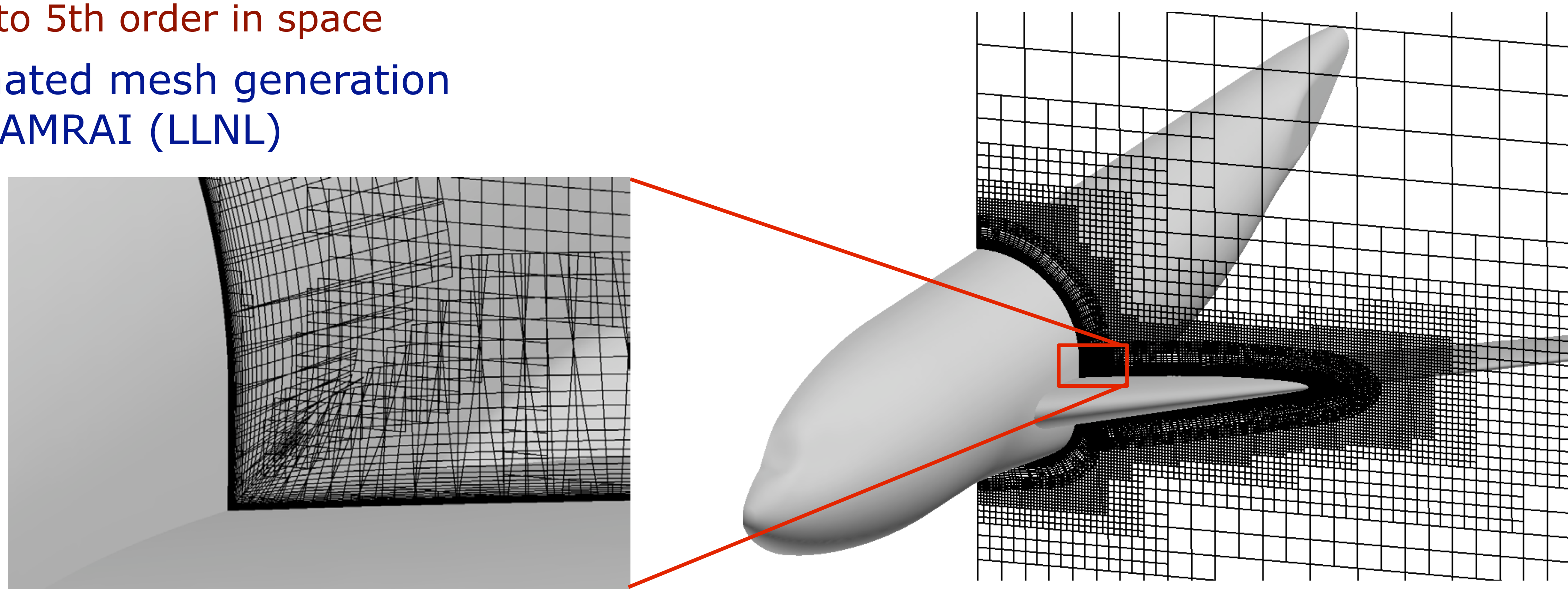
$r_{s,RMS} = 10^{-7}$



Adaptive Cartesian Grids

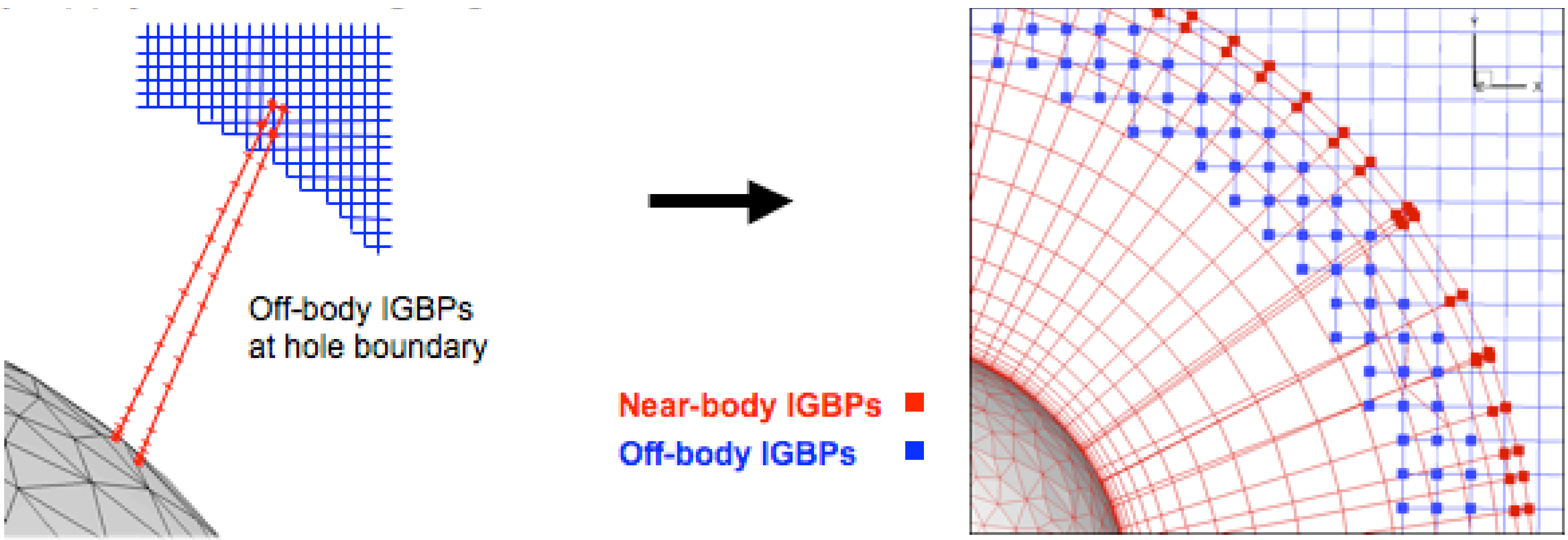
- Stored as multi-level block structured hierarchy
  - high-order methods
  - multigrid algorithms
- Automatic refinement
  - Geometry refinement to spacing at clipping index
  - Solution refinement to features, vorticity
- Solver is ARC3DC
  - 3rd order in time
  - up to 5th order in space
- Automated mesh generation with SAMRAI (LLNL)





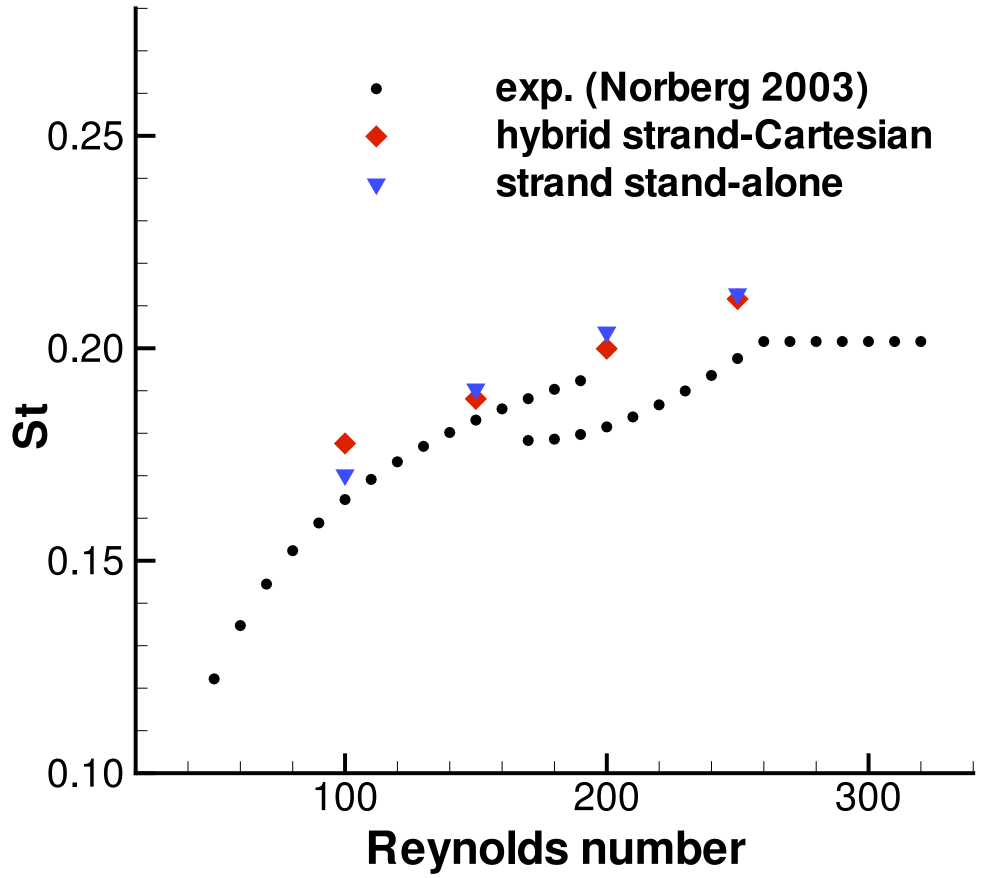
Domain Connectivity

- Parallel Unsteady Domain Information Technology (PUNDIT) (Sitaraman 2010)
  - explicit or implicit hole-cutting
  - intergrid boundary points
  - linear interpolation

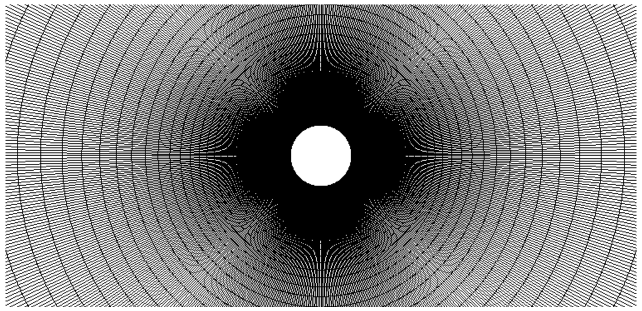


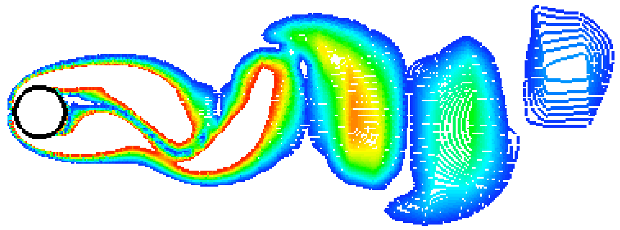
Strand Length Study

- Shorter strands are preferred
  - transition sooner to more accurate Cartesian grids
  - enhanced wake resolution

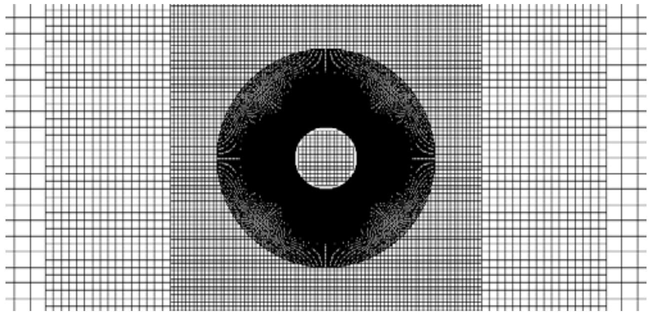


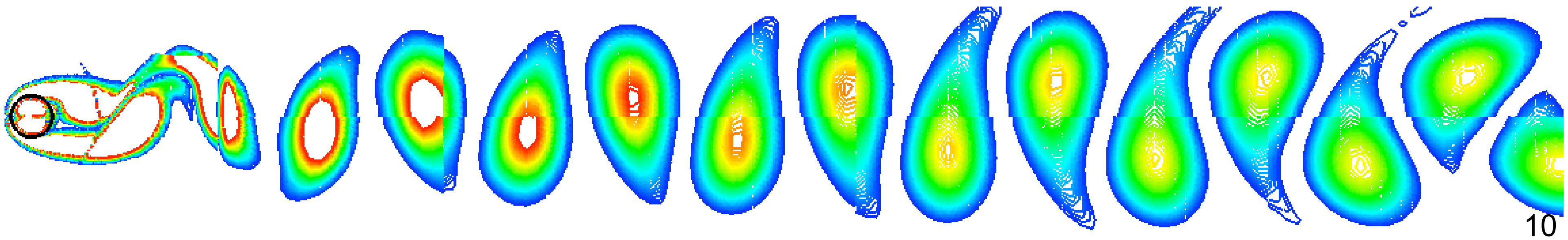
NSU3D stand-alone



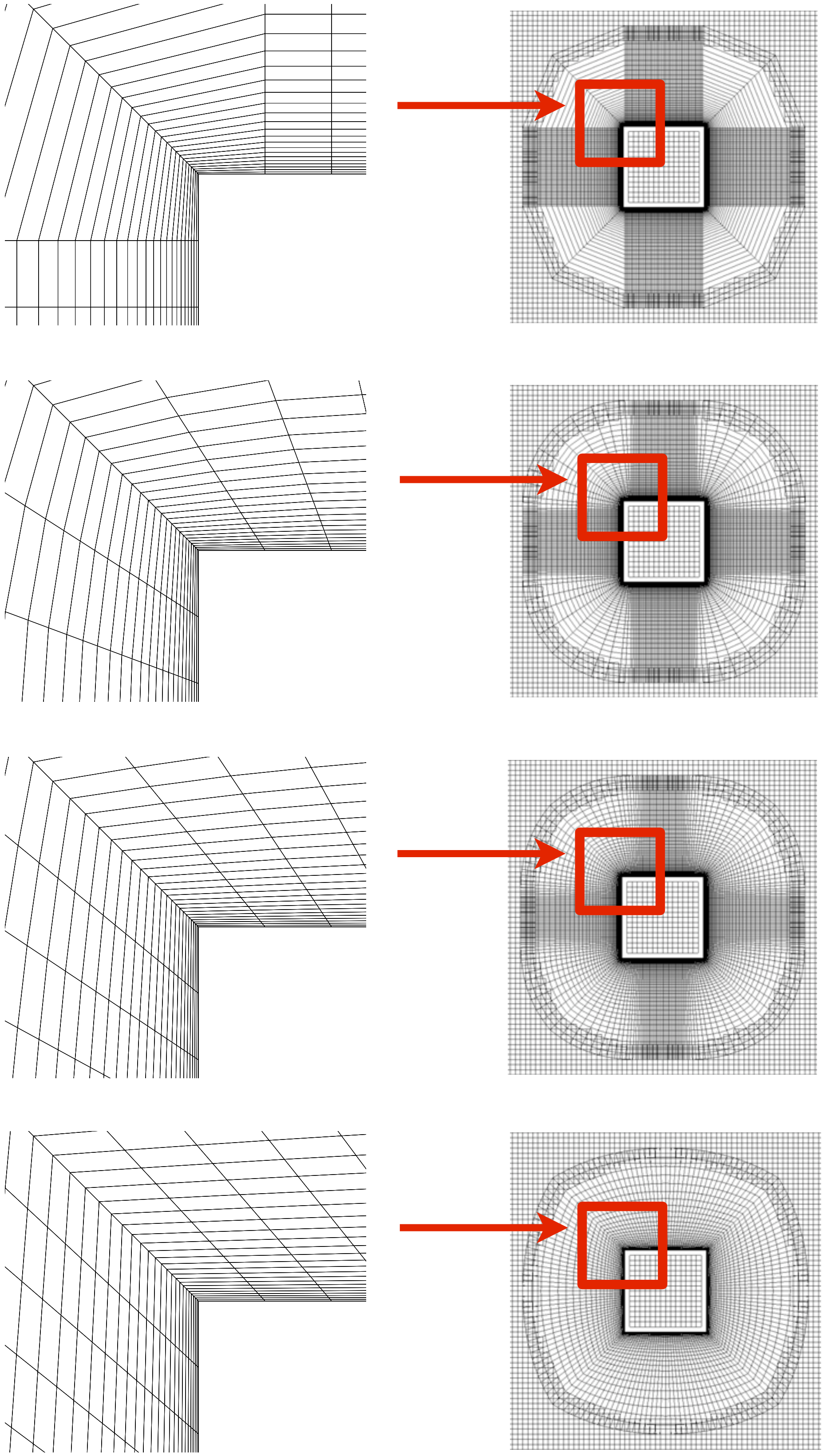


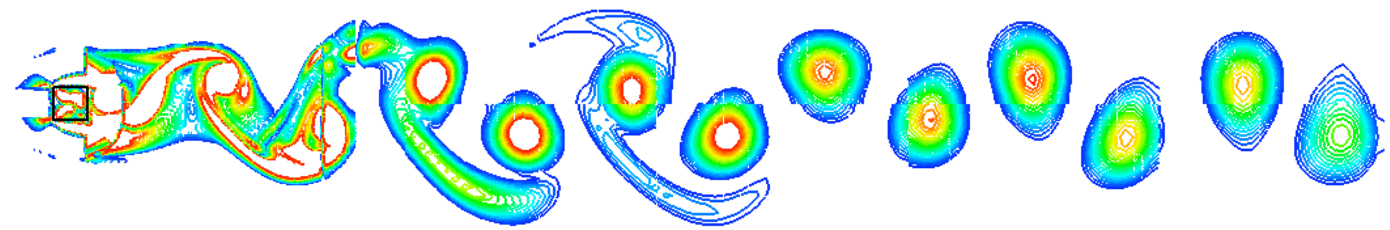
strand/Cartesian mesh



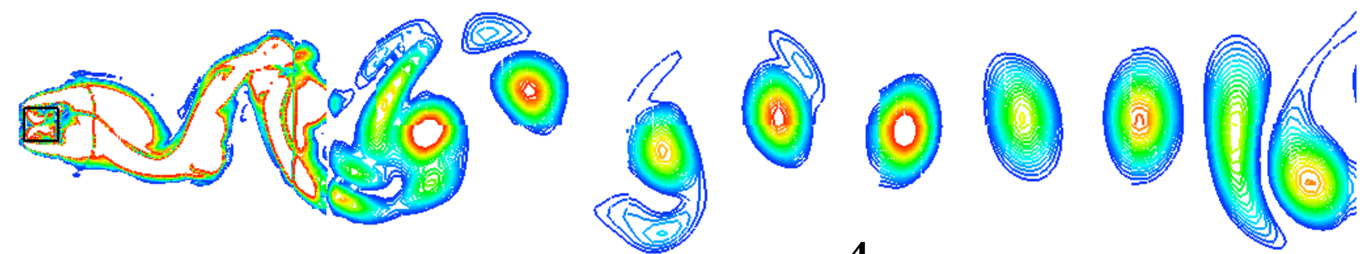


Strand Bending Study (1)

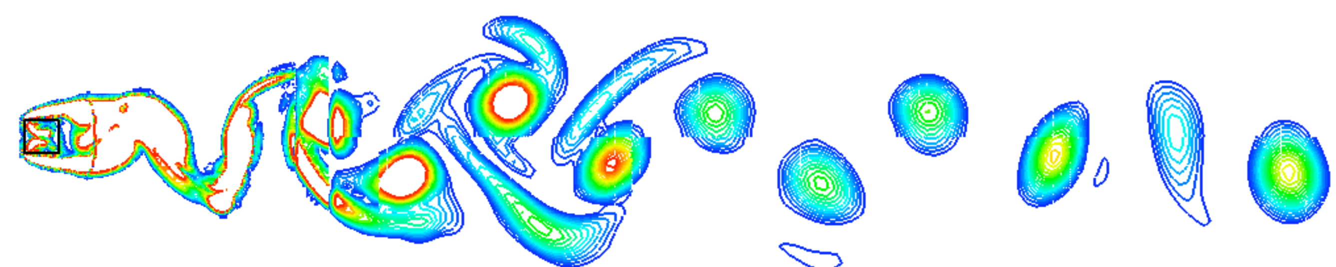




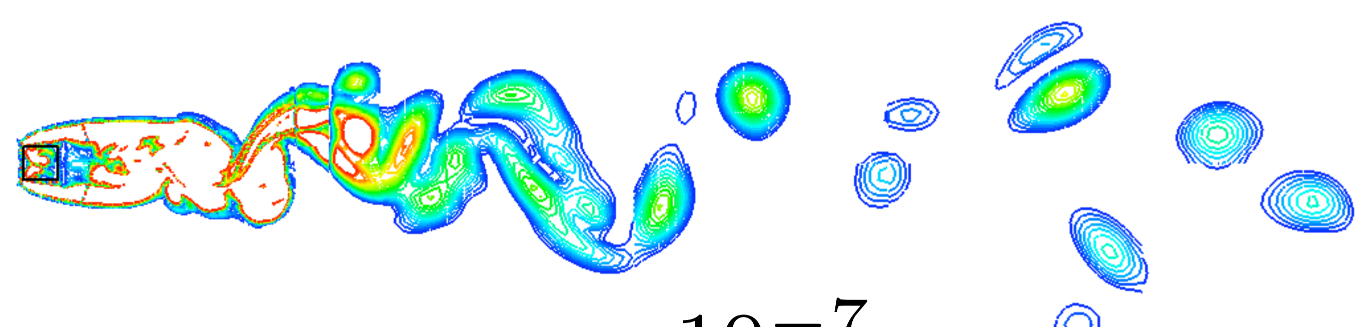
$r_{s,RMS} = 10^{-2}$ (no bending)



$r_{s,RMS} = 10^{-4}$



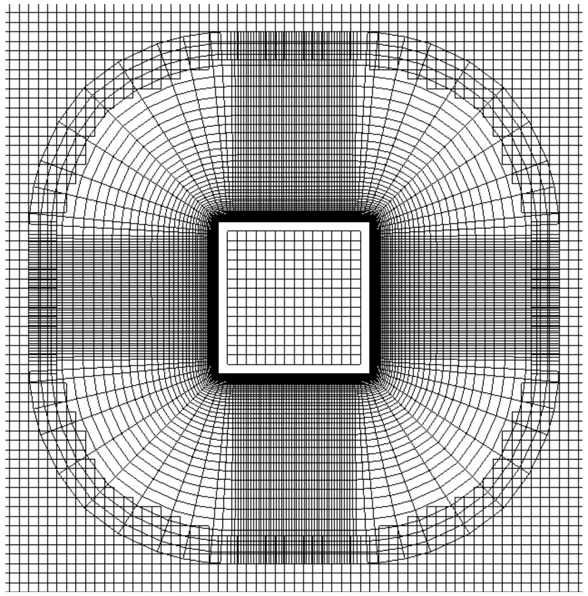
$r_{s,RMS} = 5\text{x}10^{-6}$



$r_{s,RMS} = 10^{-7}$

Strand Bending Study (2)

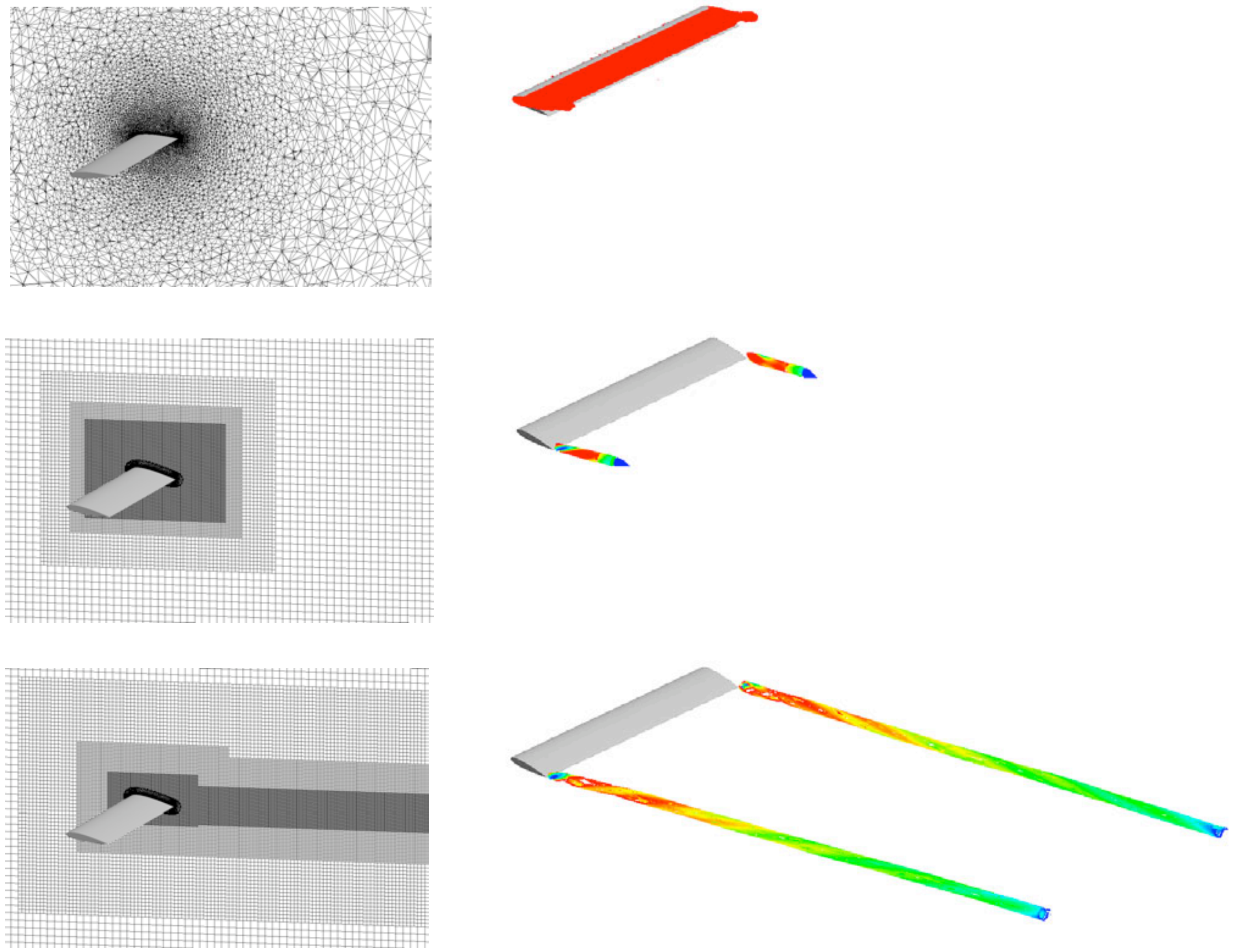
- Shedding pattern degrades with excessive smoothing
- Optimal amount: $r_{s,RMS} = 10^{-4}$
  - generally maintains orthogonality
  - provides adequate coverage for sharp corners



$r_{s,RMS}$	number of smoothing iter.	St
exp.	-	.142
10^{-2}	0	.139
10^{-3}	1	.140
10^{-4}	7	.141
10^{-5}	15	.143
$5\text{x}10^{-6}$	32	.157
10^{-6}	65	.163
10^{-7}	208	chaotic

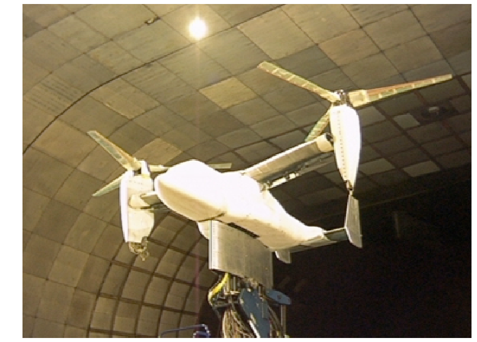
NACA 0015 Wing

- Flow conditions:
  - Mach = 0.1235
  - angle of attack = 12 deg.
  - Reynolds number = 1.5 million
- Strand Grid Parameters:
  - strand length = 1/5 chord, $K = 10$
  - strand smoothing, $r_{s,RMS} = 10^{-4}$

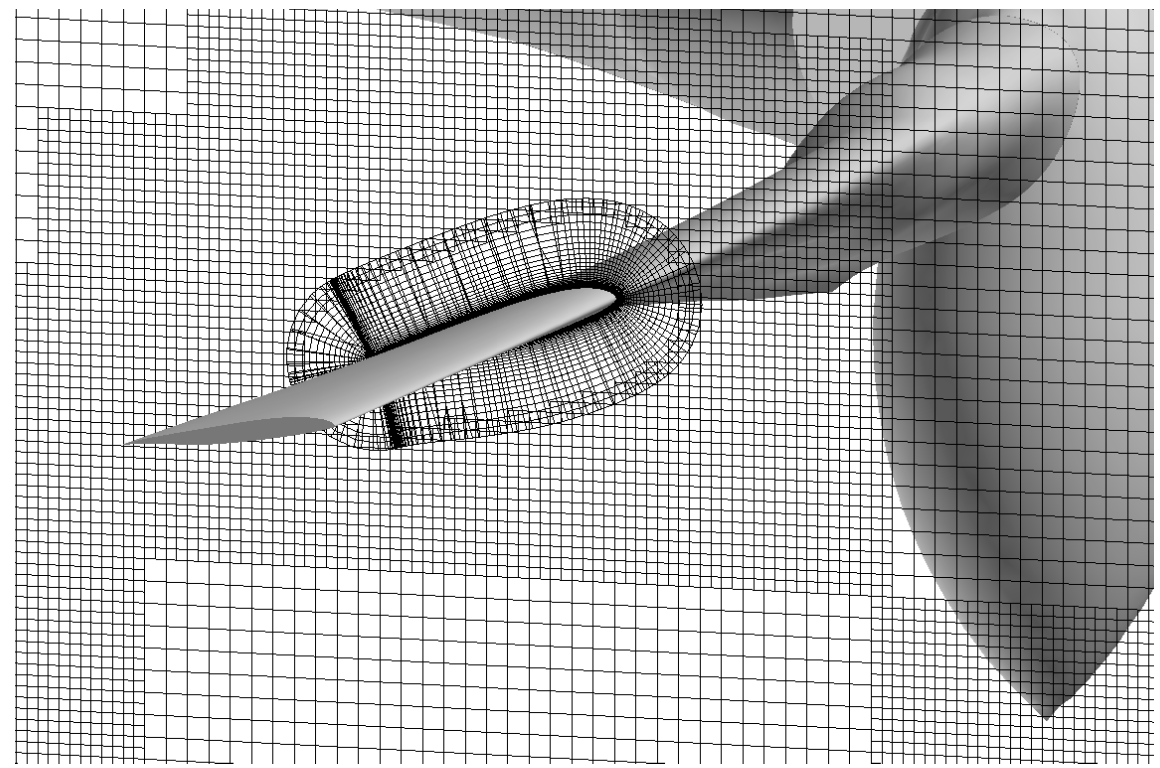


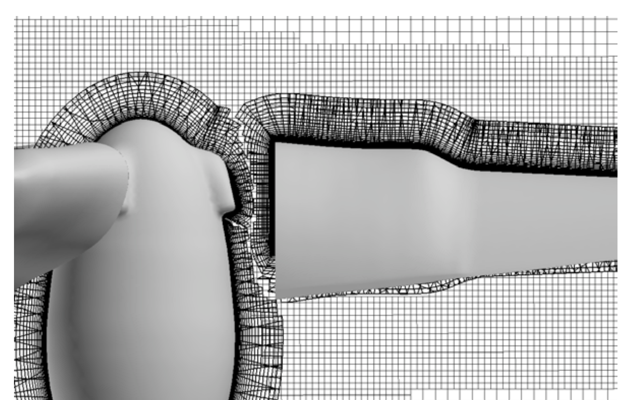
configuration	near-body pts.	off-body pts.	C_L	C_D
stand-alone	4.8e6	0	0.913	0.0576
hybrid-unstructured	4.5e6	2.1e6	0.919	0.0562
hybrid-strand	7.5e6	13.1e6	0.915	0.0564
hybrid-strand, adapted	7.5e6	55.0e6	0.916	0.0562

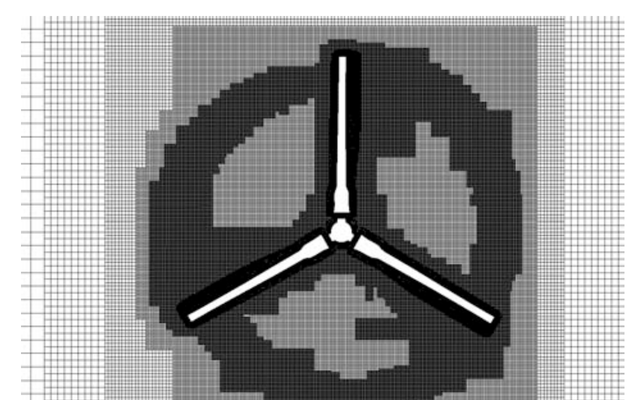
TRAM Inertial Hover (1)



- Tilt Rotor Aeromechanics Model (TRAM)
  - 1/4-scale model of Bell/Boeing V-22 Osprey isolated rotor
  - tip Mach number = 0.625
  - collective pitch = 14 deg.
  - tip Re = 2.1 million
- Strand grid/Cartesian parameters
  - strand length = 40% of tip chord, $K = 20$
  - smoothing residual, $r_{s,RMS} = 10^{-4}$
  - 8 Cartesian levels (finest is 5% of tip chord)



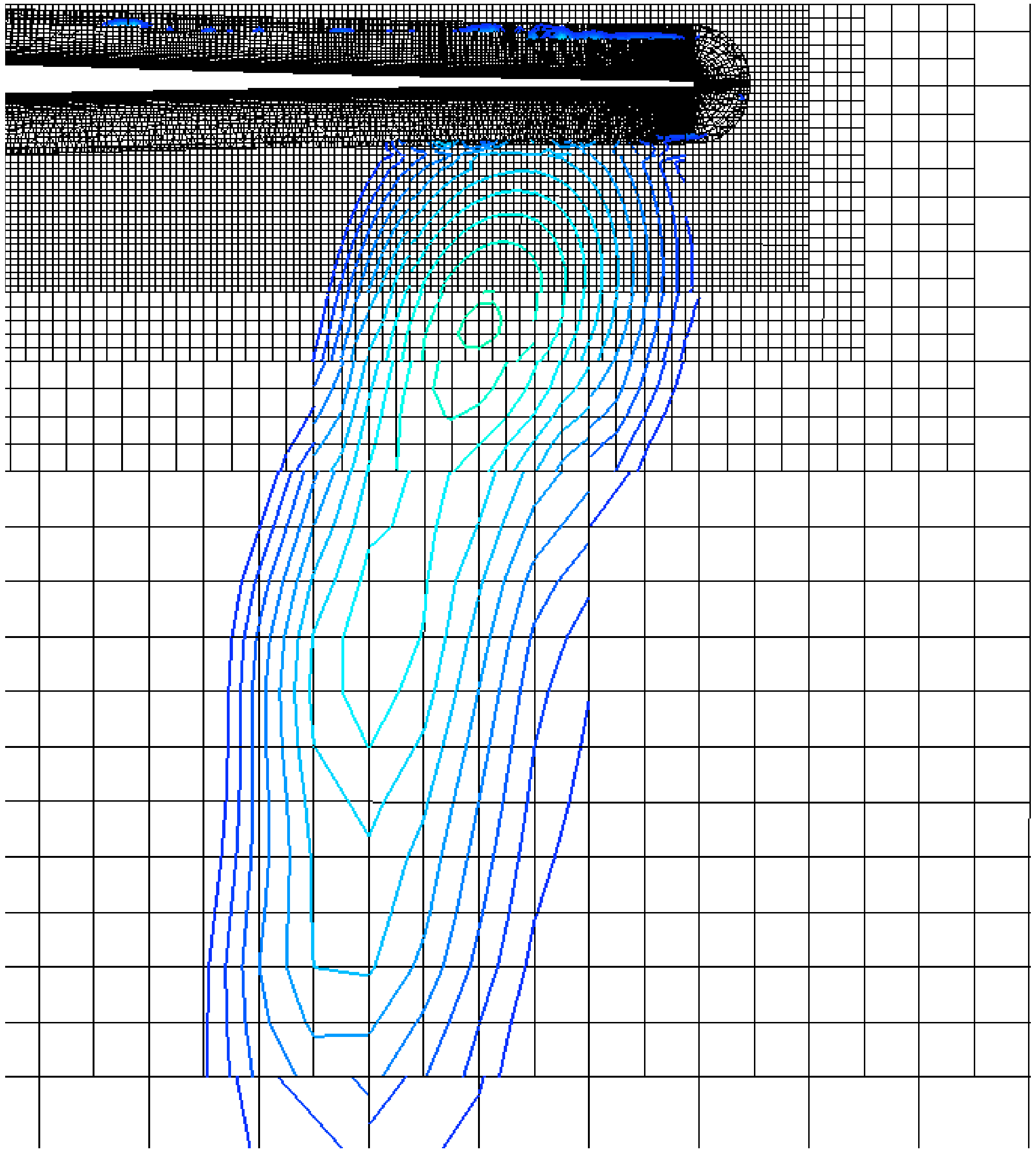




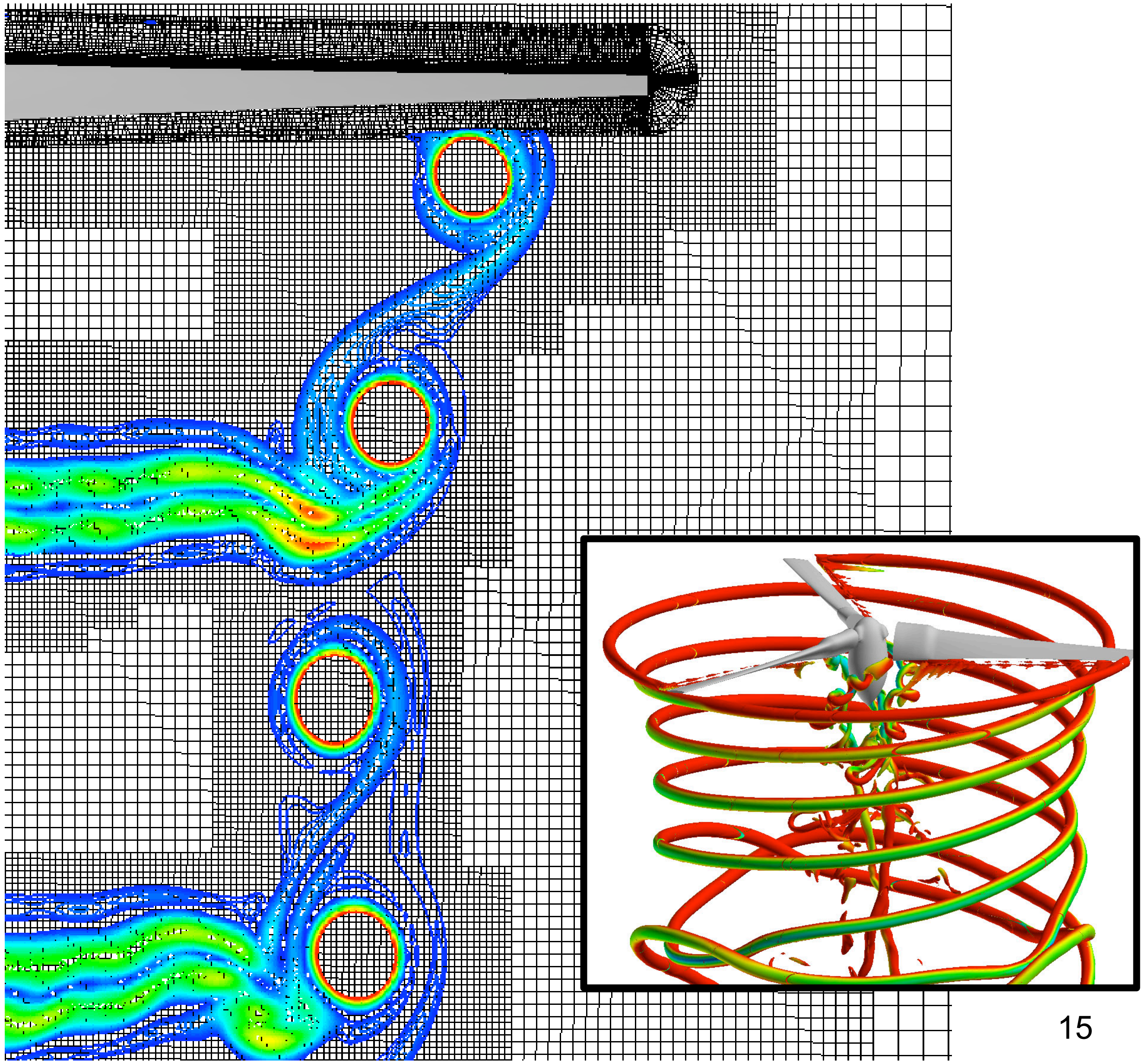
TRAM Inertial Hover (2)

surface mesh	adapt	near-body pts.	off-body pts.	C_T	C_Q	FM
coarse	no	1.99e6	3.90e6	0.0141 (-5.4%)	0.00174 (5.5%)	0.683 (-12.3%)
fine	no	9.08e6	3.98e6	0.0145 (-2.7%)	0.00171 (3.6%)	0.717 (-8.0%)
fine	yes	9.08e6	102.5e6	0.0150 (0.7%)	0.00170 (3.0%)	0.760 (-2.4%)

fine surface, no adapt



fine surface, adapt (vorticity)

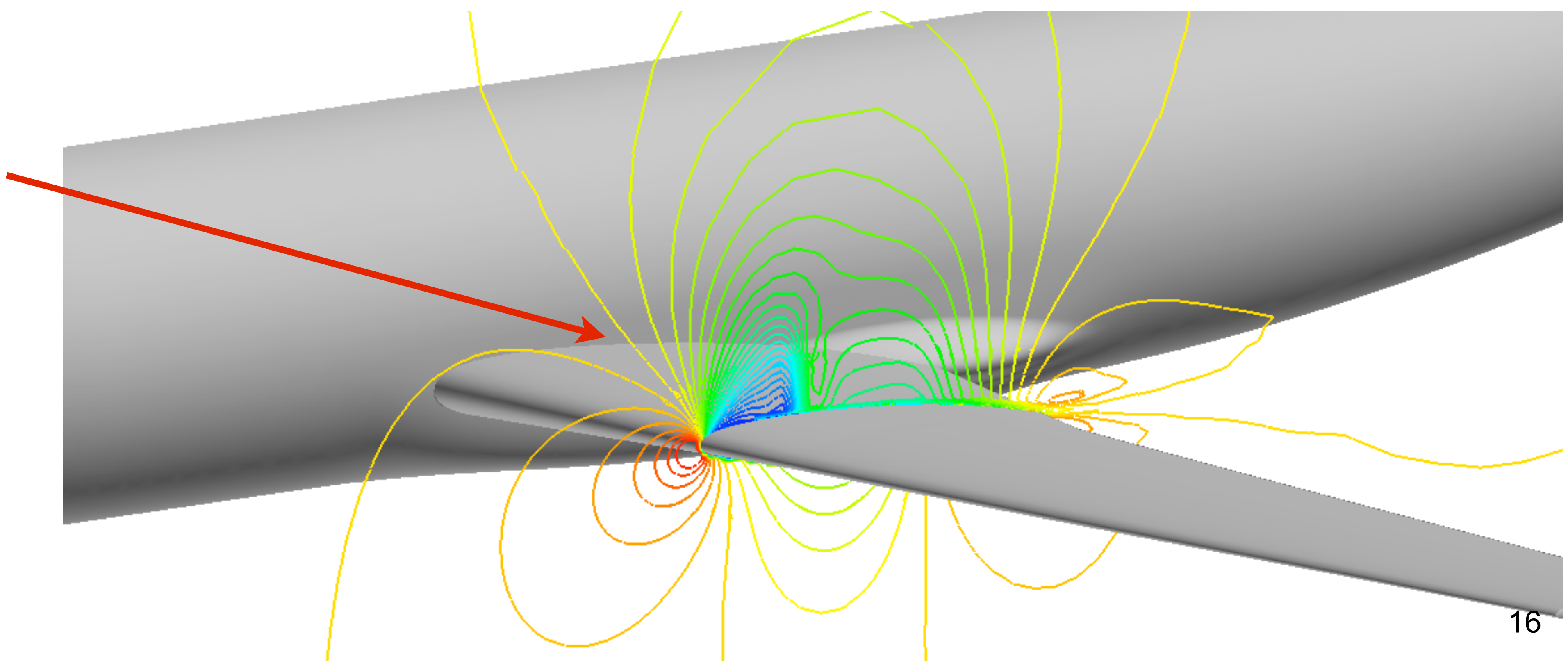


DLR F6 Wing-Body-Fairing (1)

- 3rd AIAA drag prediction workshop
  - Mach number = 0.75
  - angle of attack = 0.5 deg.
  - Reynolds number = 2.1 million
- Strand grid/Cartesian parameters
  - strand length = 1/6 of ref. chord, $K = 10$
  - smoothing residual, $r_{s,RMS} = 10^{-4}$
  - 10 Cartesian levels

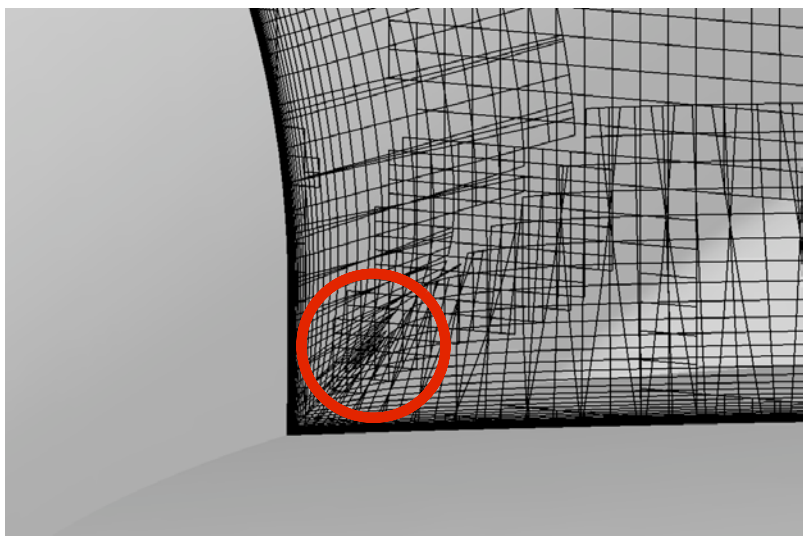
configuration	half/full-span	near-body pts.	off-body pts.	C_L	C_D
stand-alone	full	11.0e6	0	0.558	0.0282
hybrid-unstructured	full	10.0e6	5.0e6	0.557	0.0282
hybrid-strand	half	6.3e6	21.5e6	0.559	0.0271

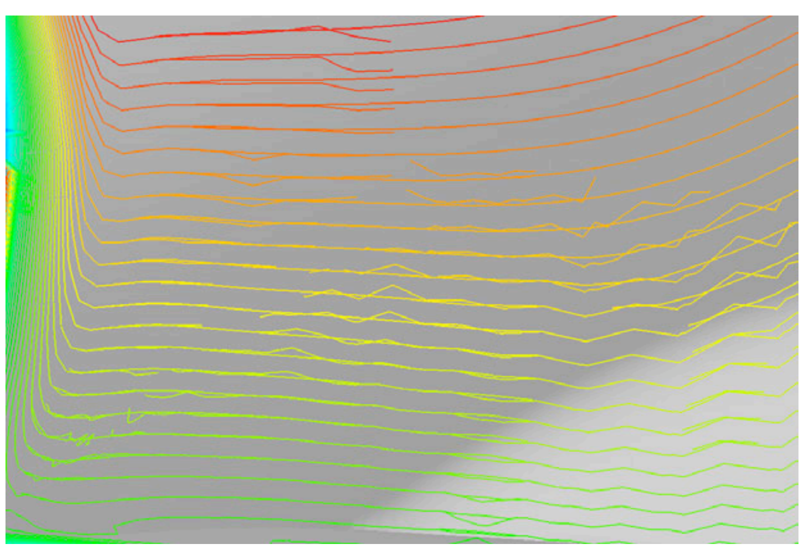
- Smooth transition between strand grids and Cartesian grids

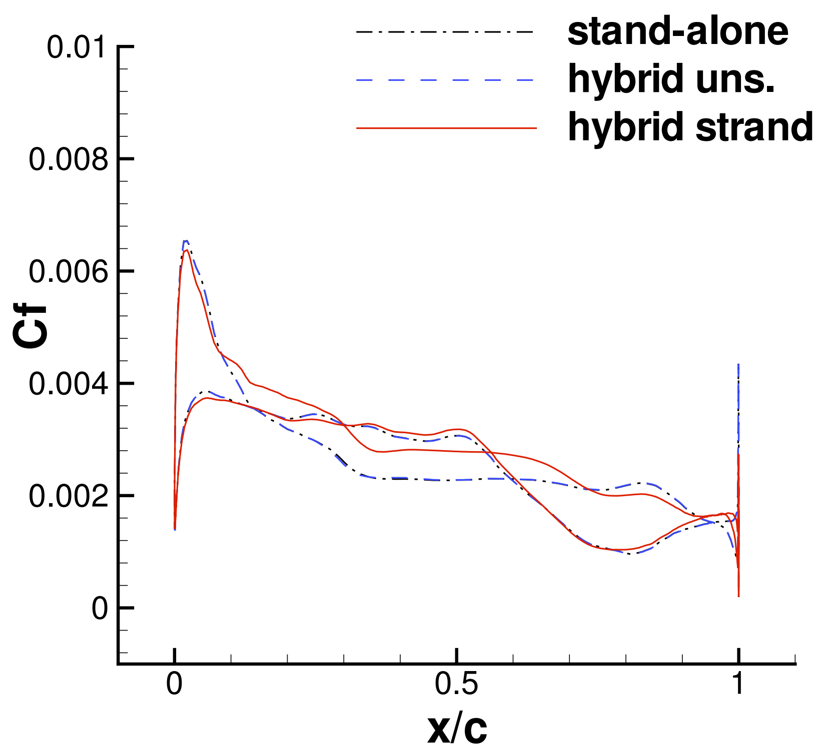


DLR F6 Wing-Body-Fairing (2)

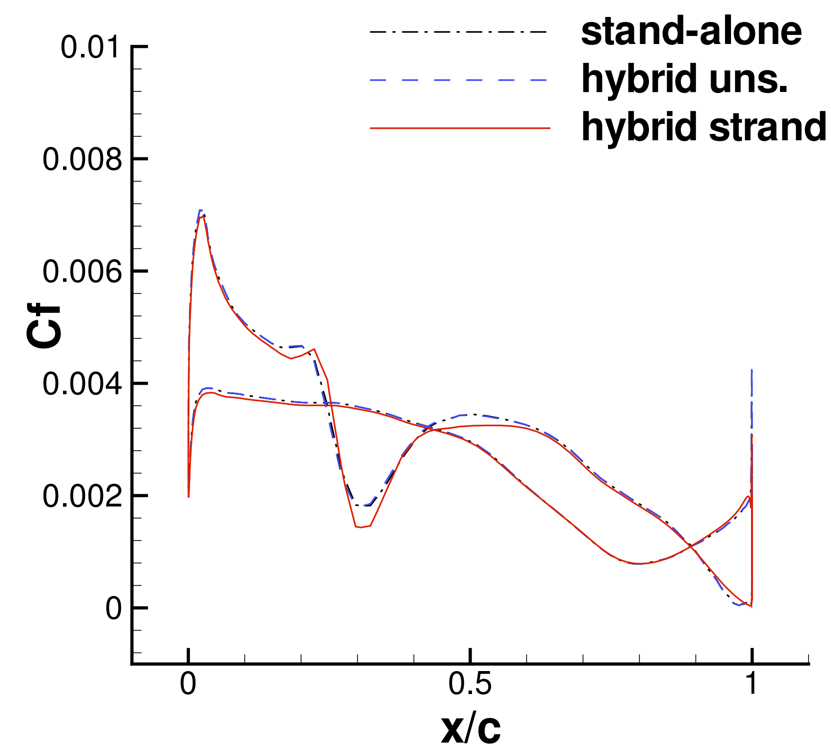
- Skin friction coefficient
- local discrepancy at 3% span near wing-body junction
  - due to clipping near geometry surface (K=0.05)



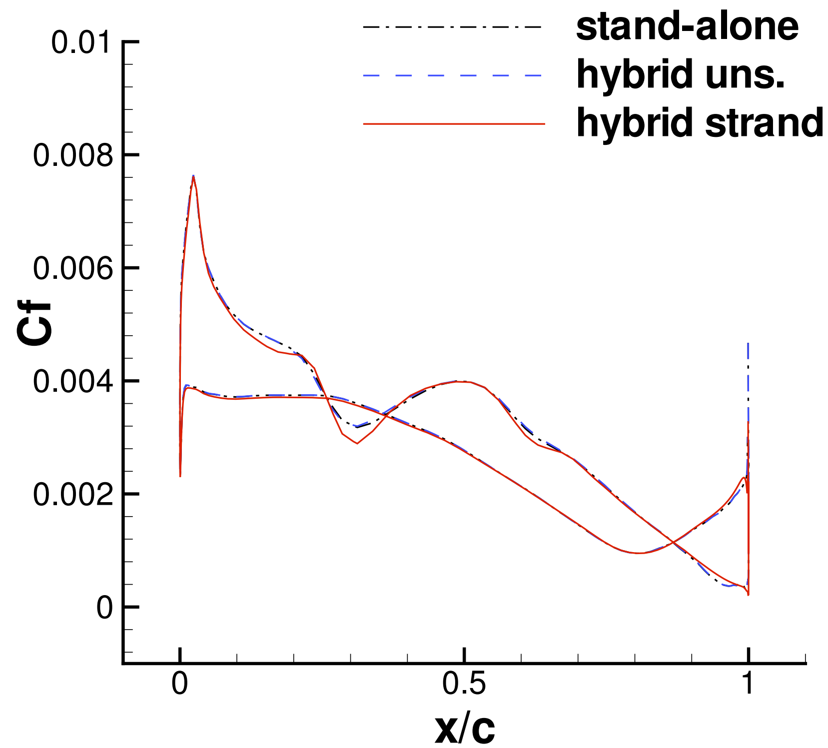




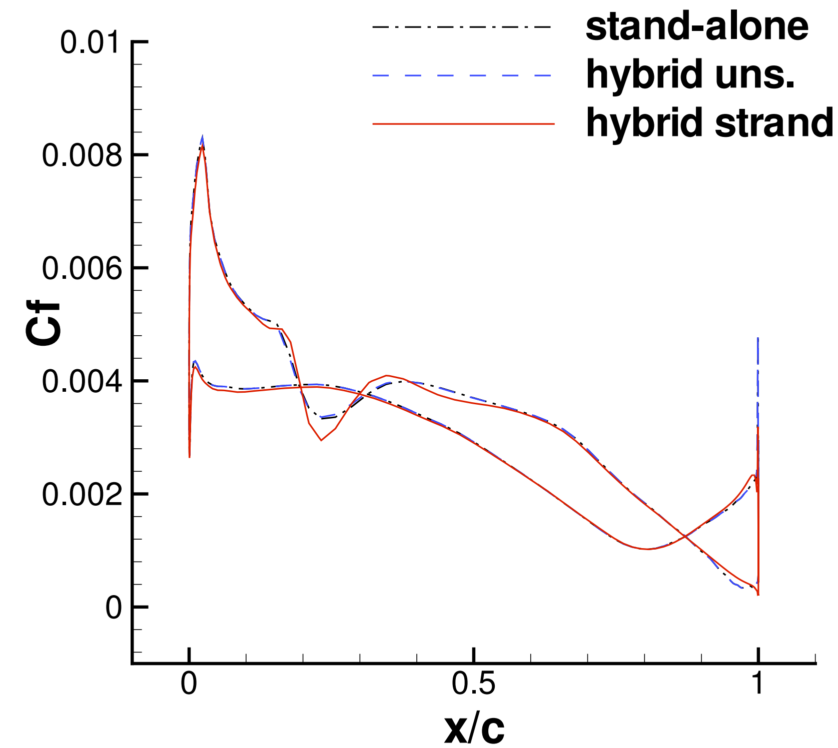
3% span



24% span



44% span



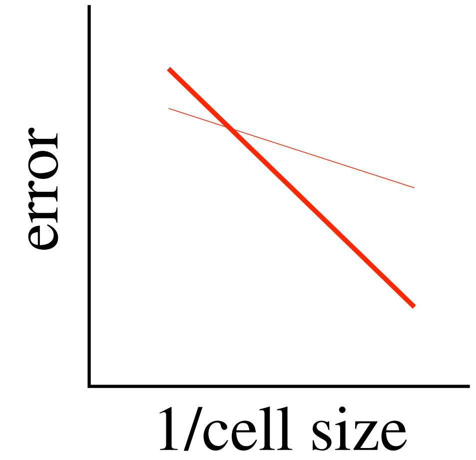
83% span

Progress in Strand Grid Development

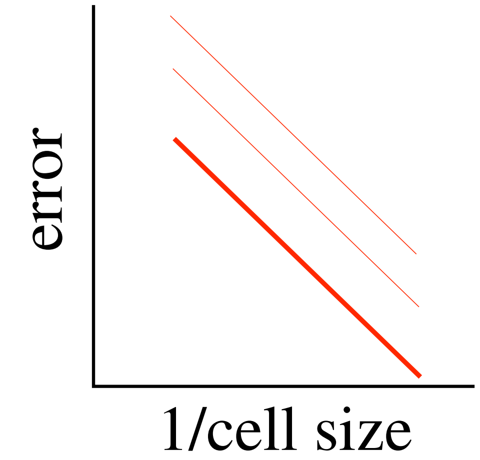
- July 2010
  - obtain validation results with NSU3D solver on strand grids
  - preliminary 3d strand solver complete - inviscid, directional multigrid
- October 2010
  - full 3d strand solver complete - viscous, unsteady, moving mesh
  - 2d solver + PUNDIT + adaptive Cartesian, in progress
- January 2011
  - complete 2d strand infrastructure
  - 3d solver + PUNDIT + adaptive Cartesian, in progress
- July 2011
  - complete 3d strand infrastructure
- October 2011
  - preliminary testing of 3d strand method complete

What is the "best" discretization for Anisotropic Meshes?

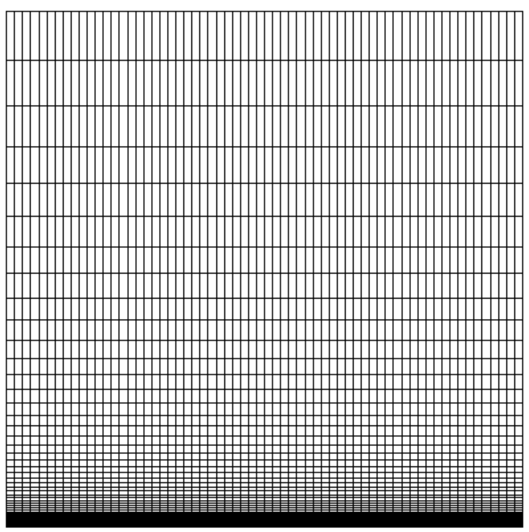
- Discretization schemes
  - node-, cell-centered, corrected (new)
- Cell types
  - quadrilateral, equilateral tri., right tri.
- Physical models
  - inviscid, viscous
  - method of manufactured solutions

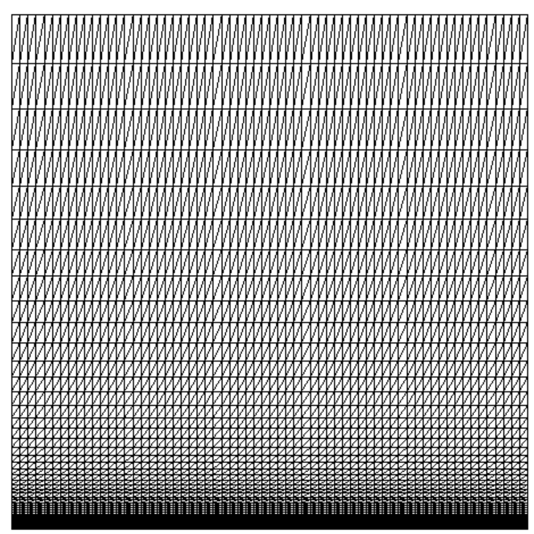


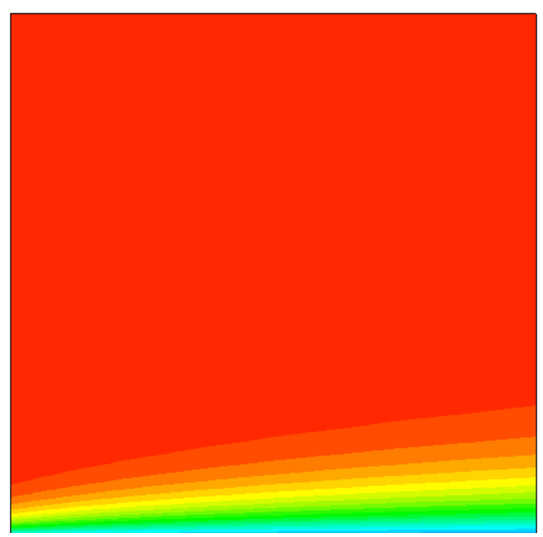
sharp 2nd order slope



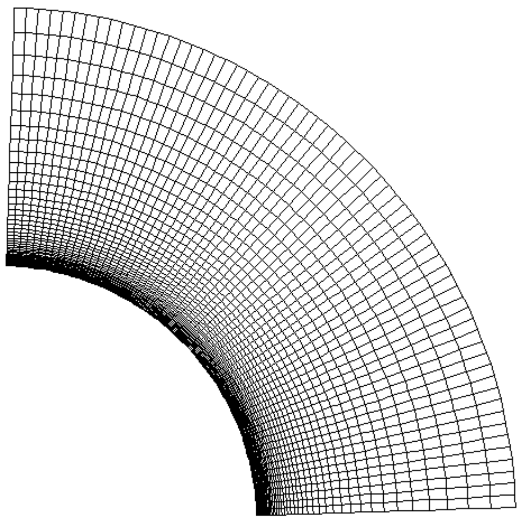
low magnitude of error

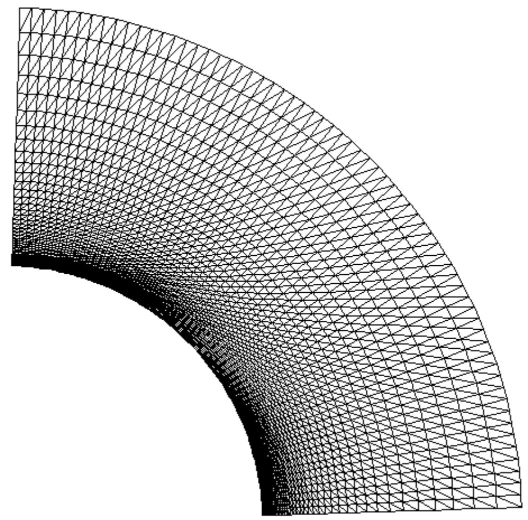


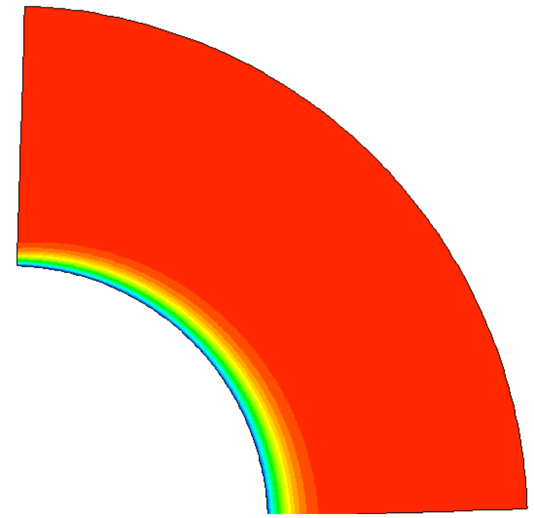




$$Q(x,y) = 1 - e^{\frac{-(y-y_0)}{\sqrt{c\mu(x-x0)}}}$$

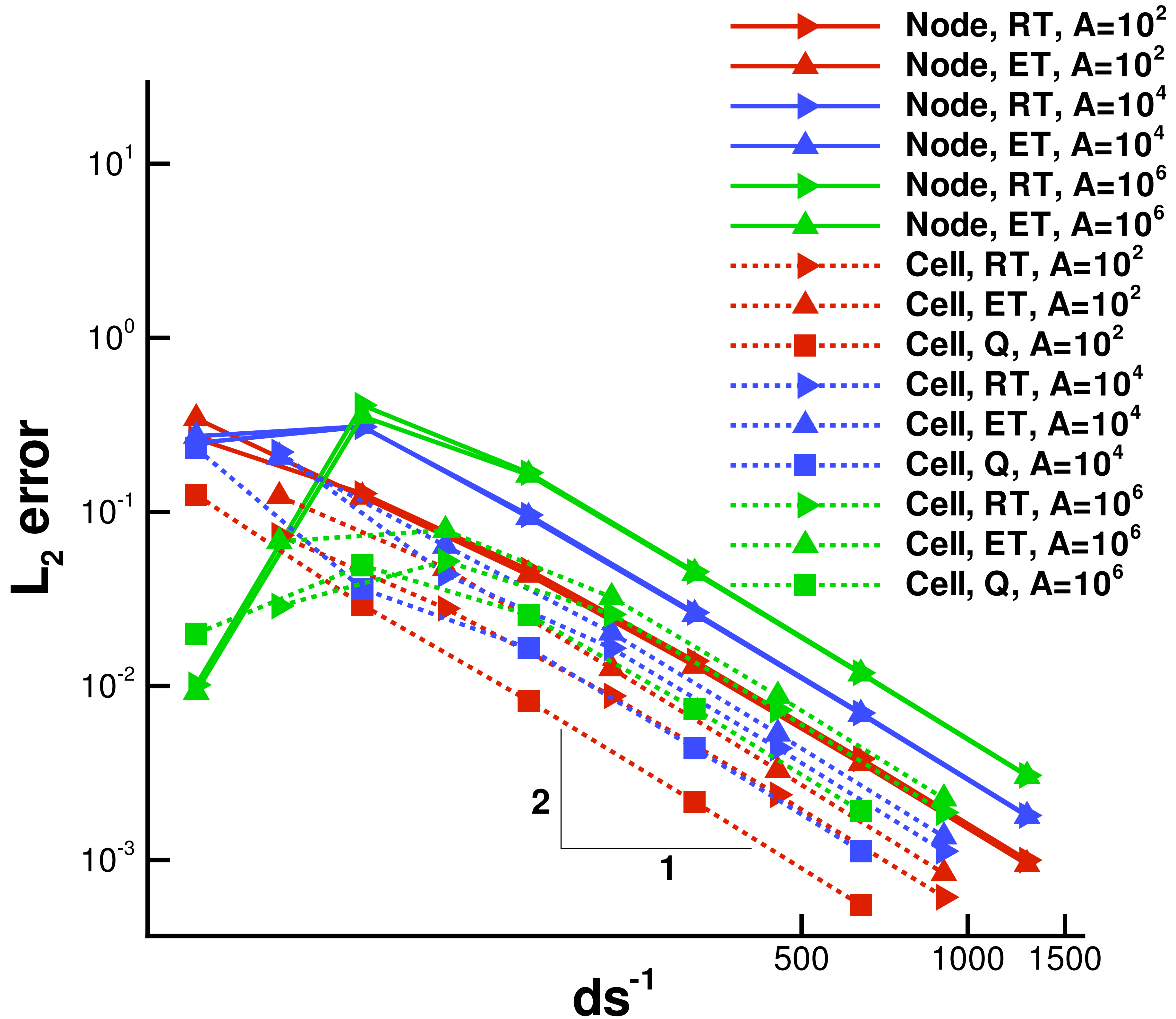




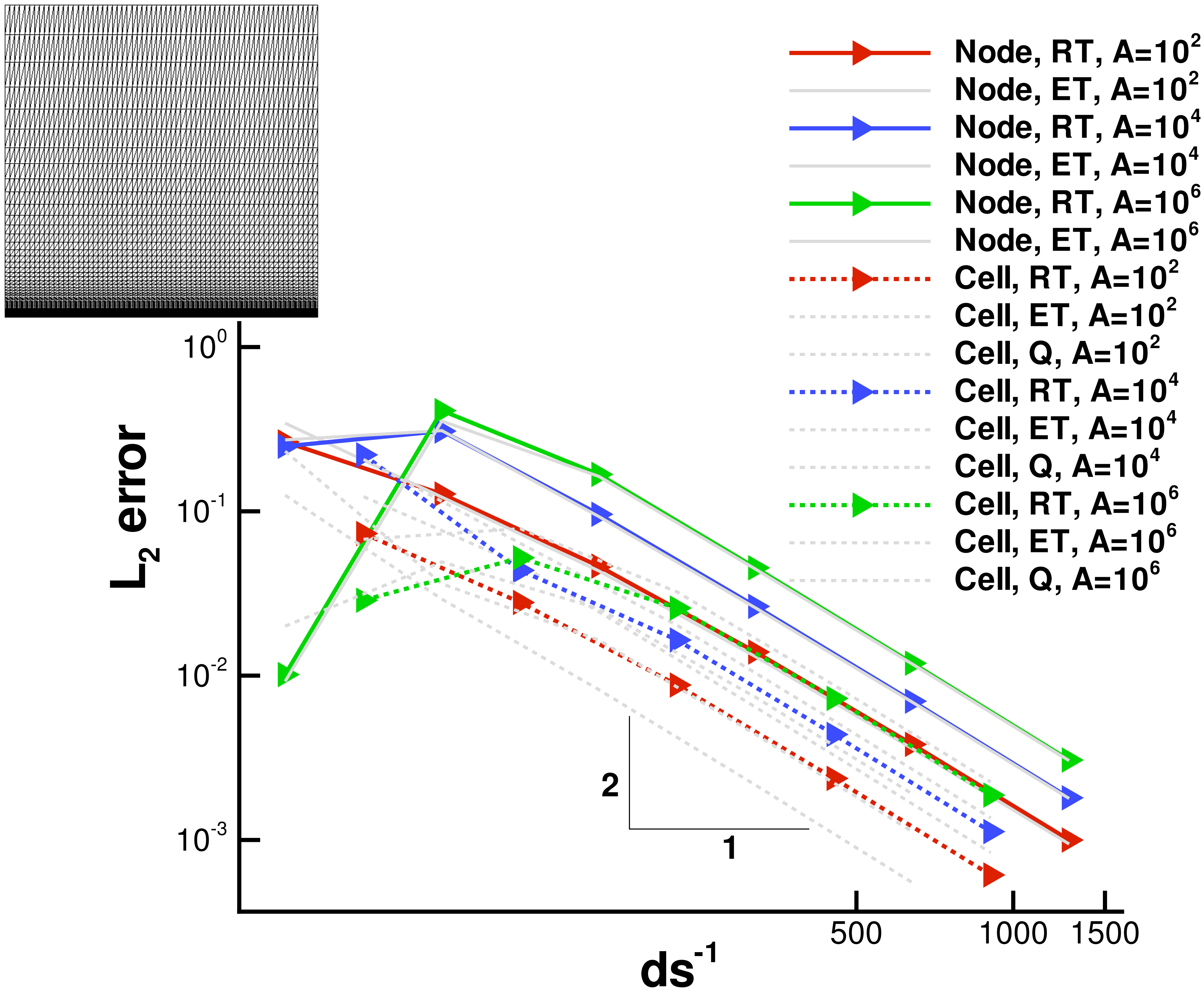


$$Q(r,\theta) = 1 - e^{\frac{-(r-r_0)}{\sqrt{c\mu(\theta_0-\theta)}}}$$

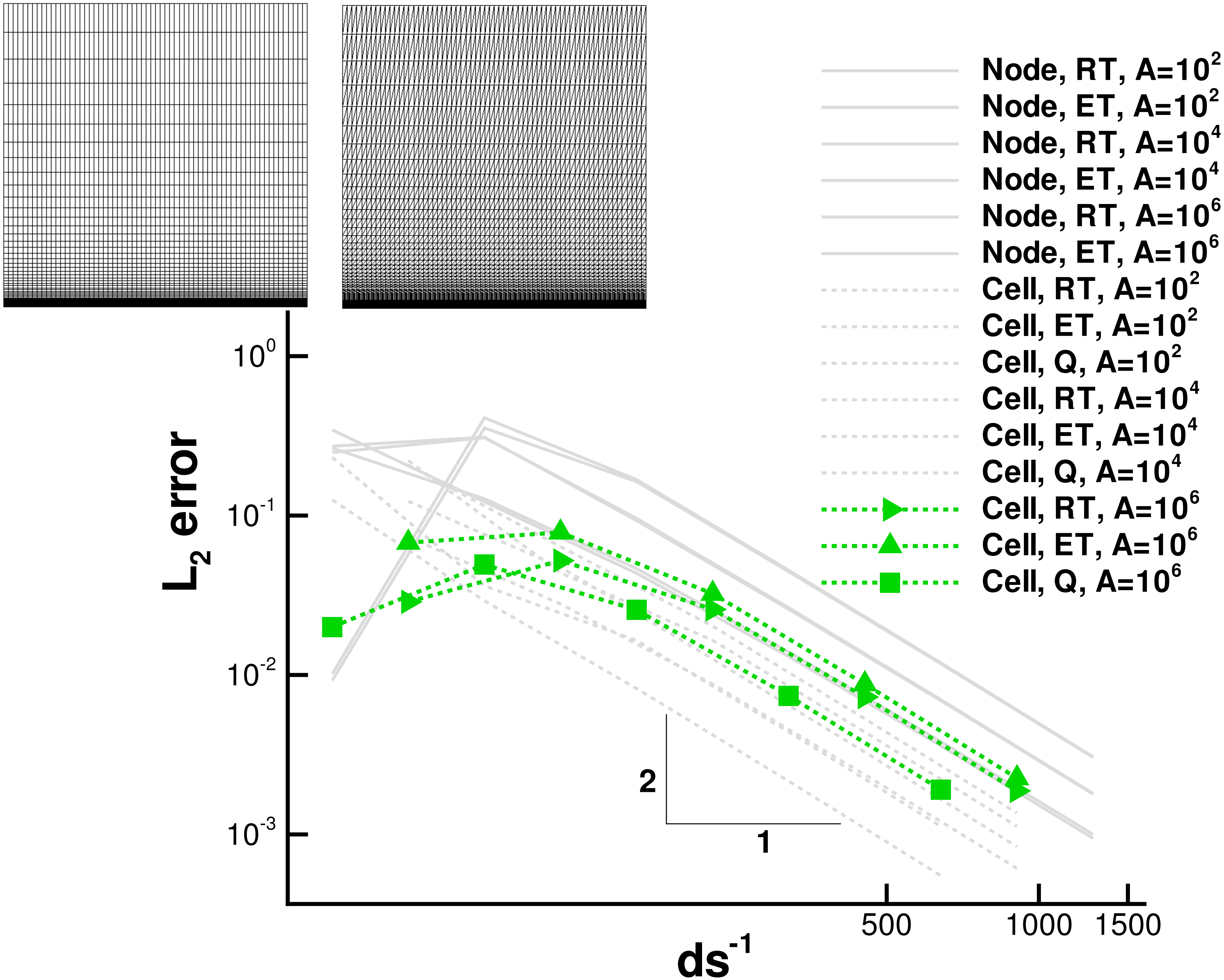
Anisotropic Grid Viscous Term Results



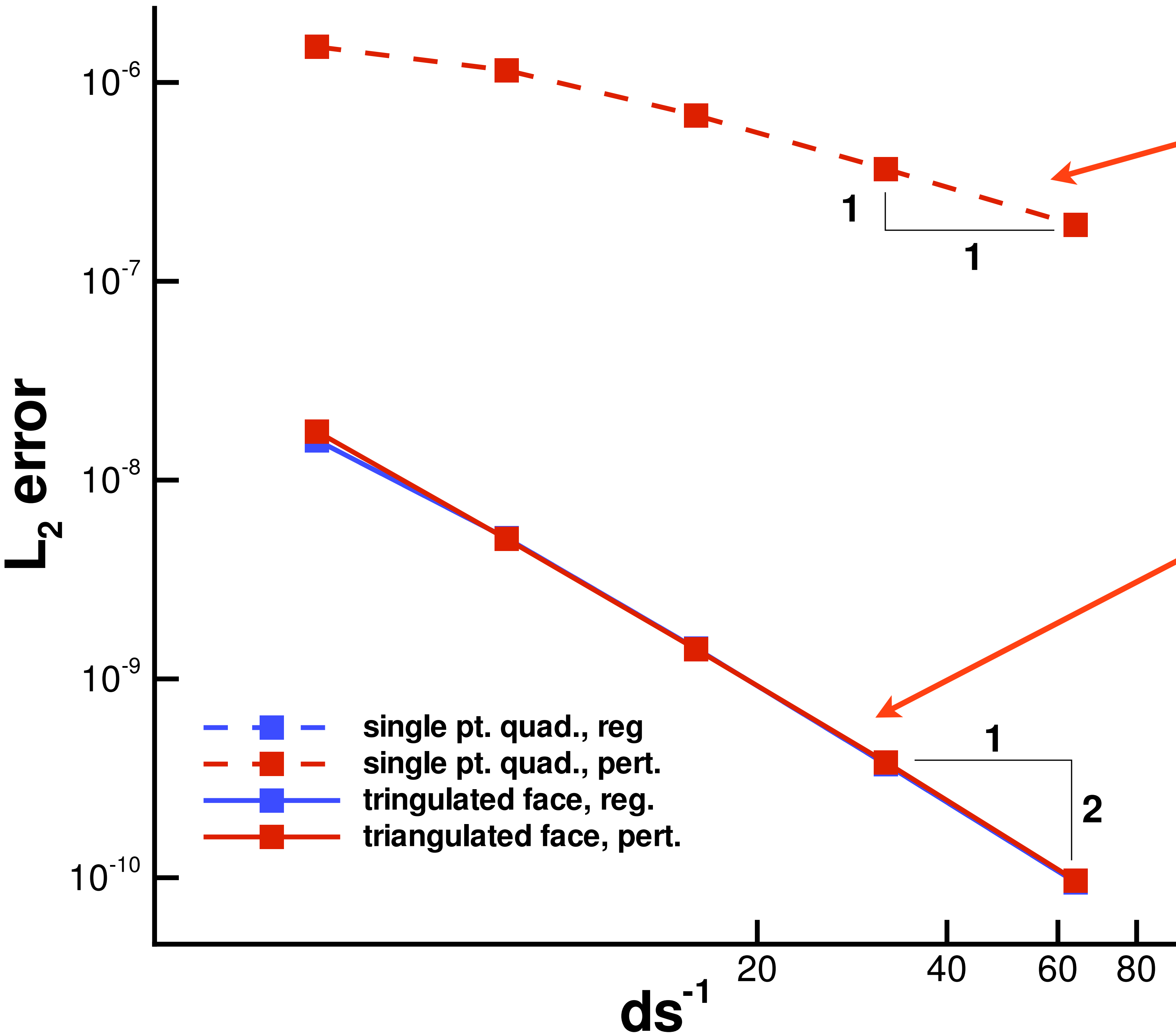
Cell-centered Produces Less Error than Node-centered

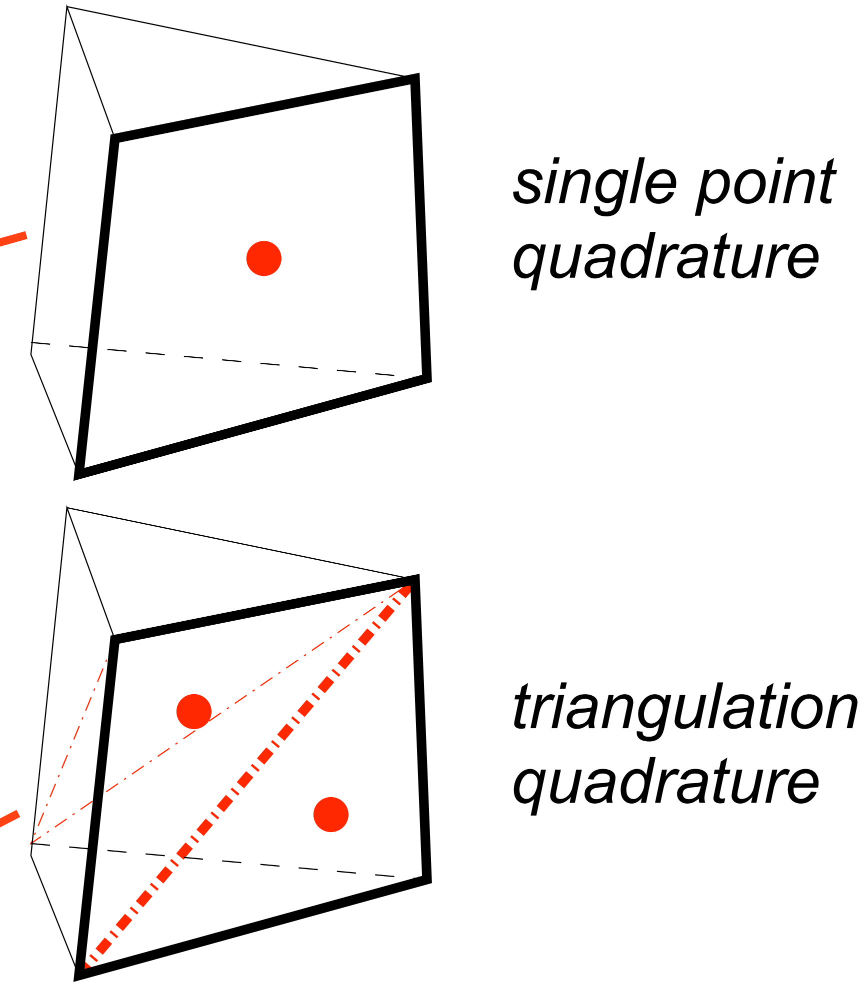


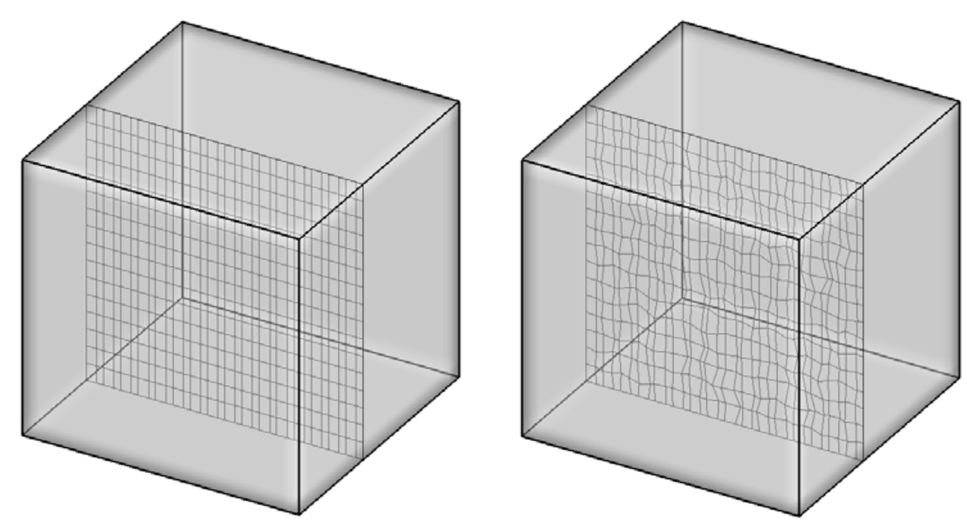
Quadrilaterals Produce Less Error than Triangles



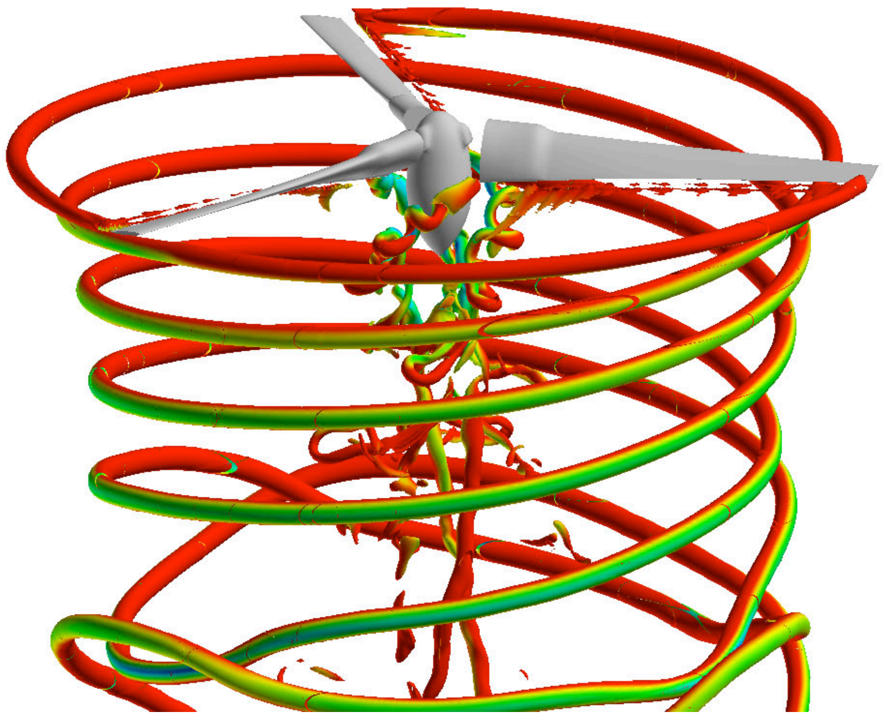
Triangulation of Non-Planar Faces in 3D

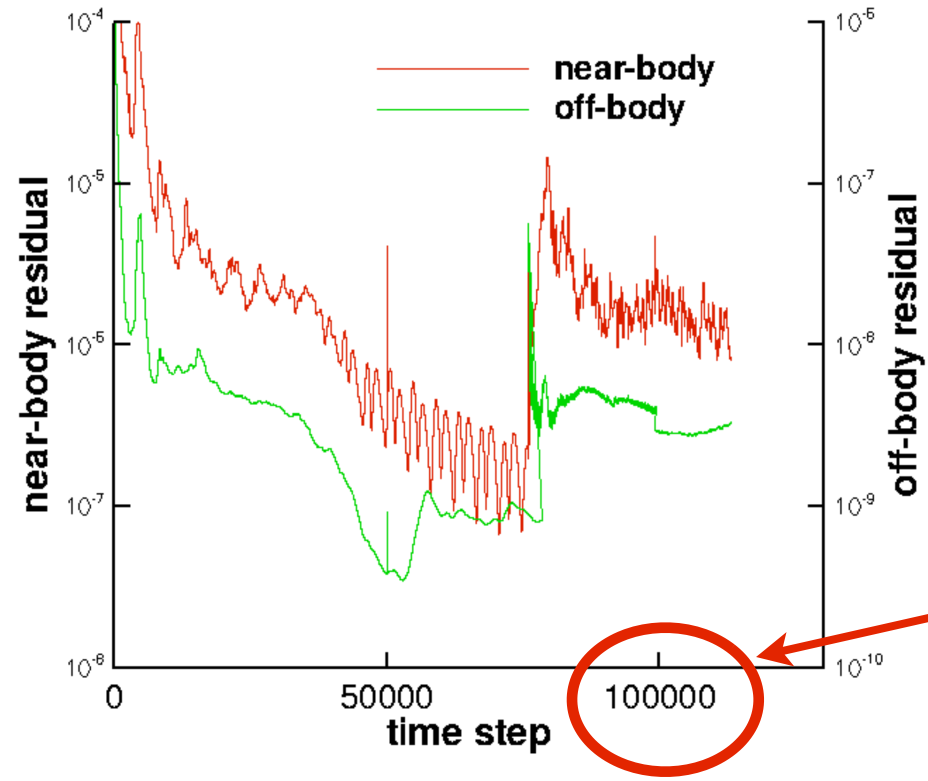




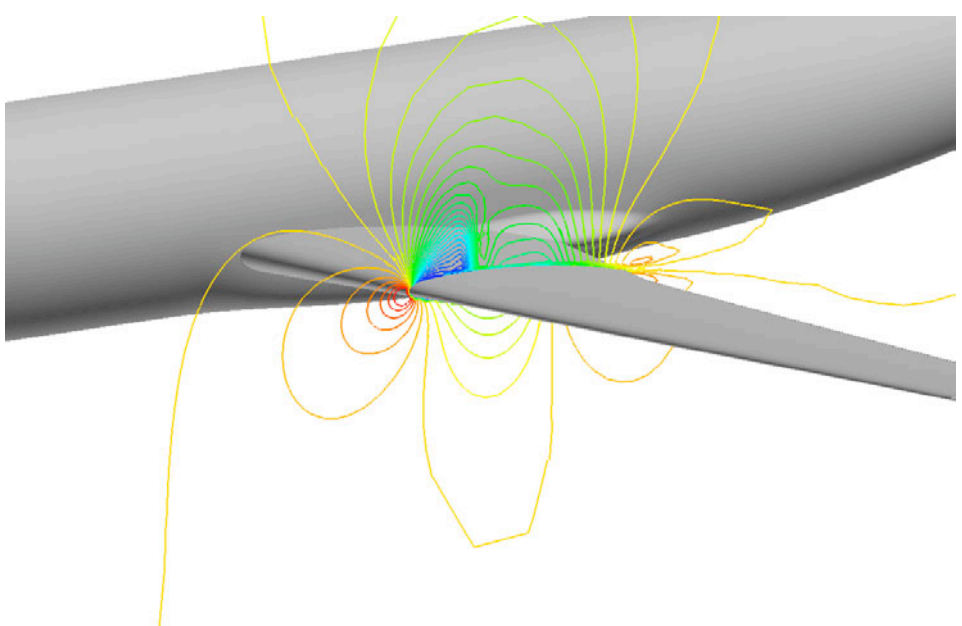


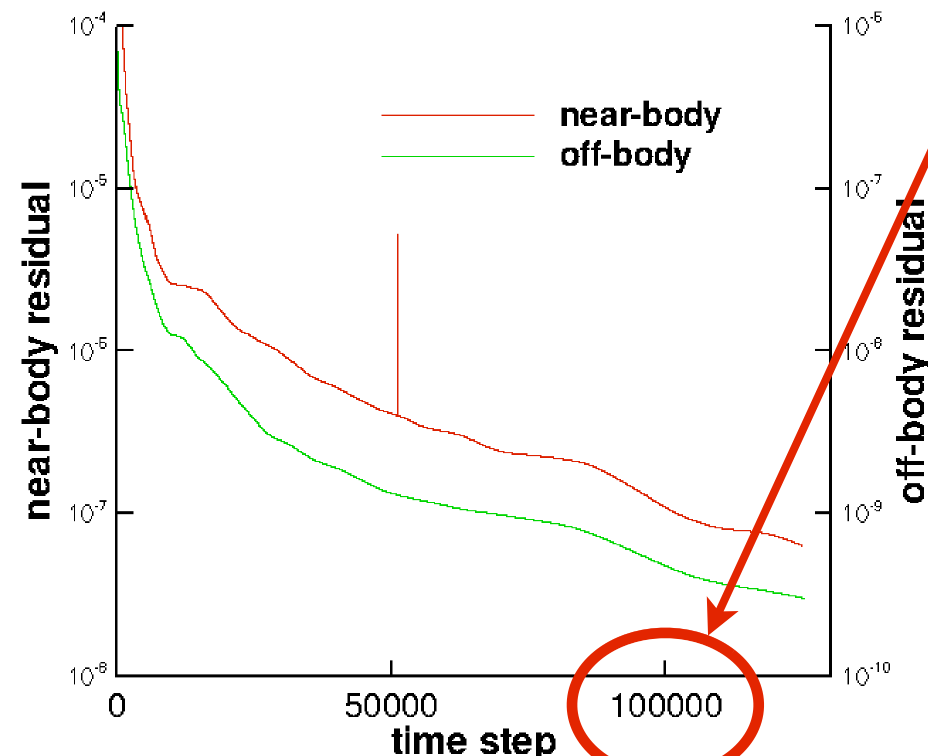
Slow Convergence - Explicit on Cartesian Grids



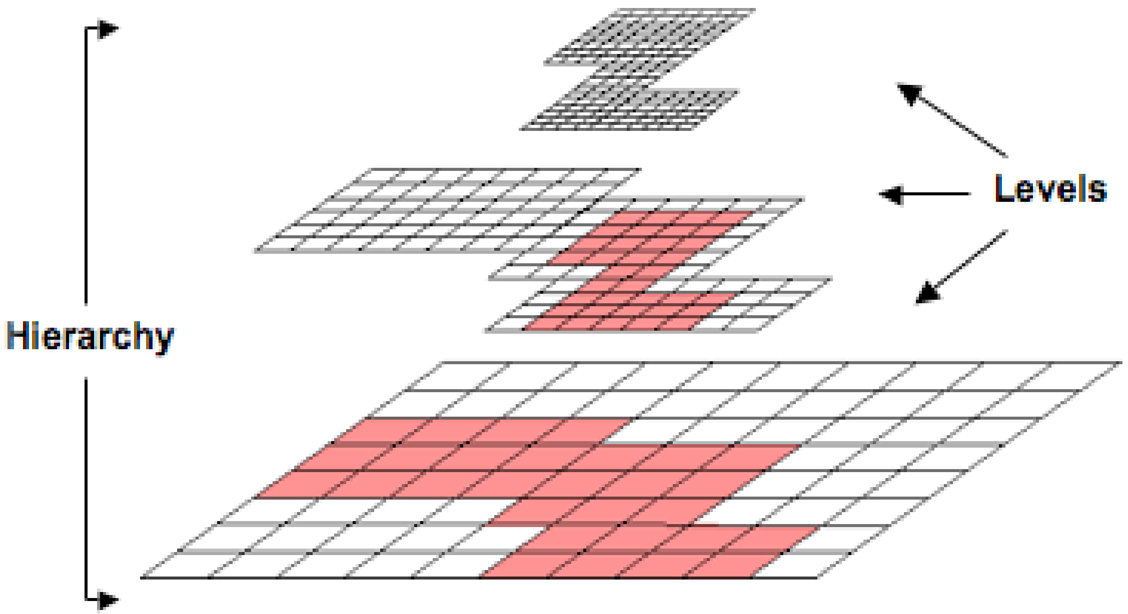


100,000 Explicit iterations to reach steady state!

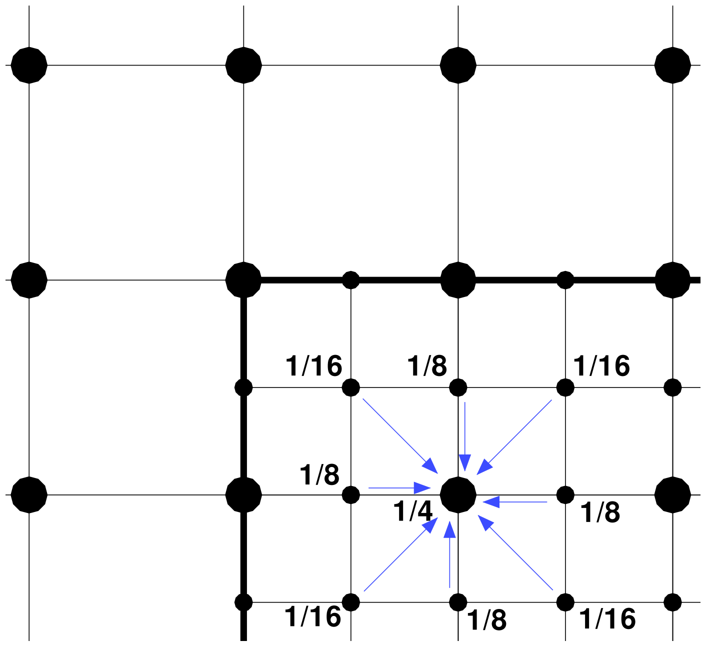




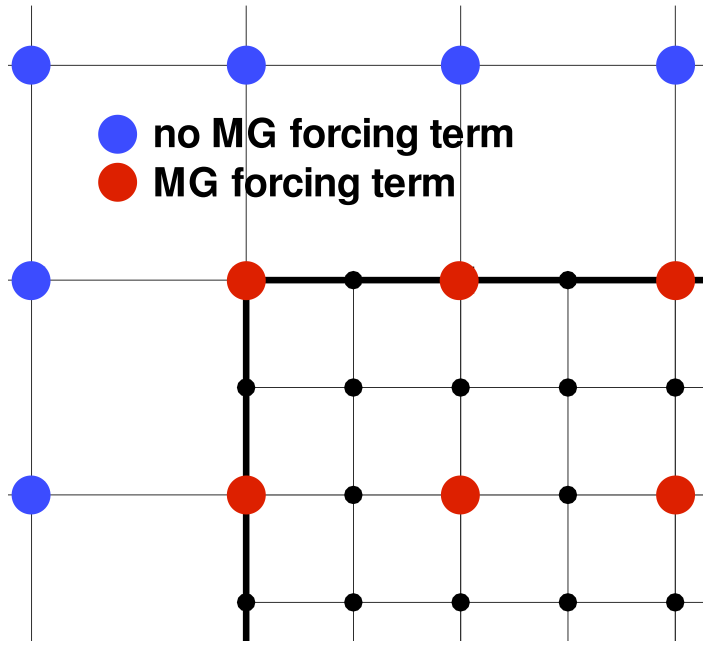
Full Approximation Storage Multigrid



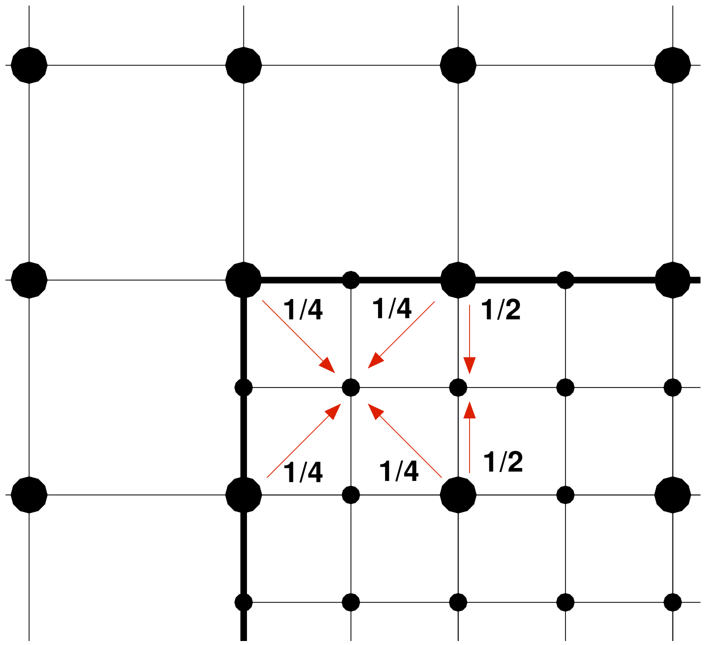
- Advantages of multigrid on AMR meshes
  - coarse meshes already exist
  - textbook O(N) convergence obtainable
  - transfer operators are trivial
- Other methods to consider
  - local time-stepping, sub-cycling, implicit



Residual Restriction

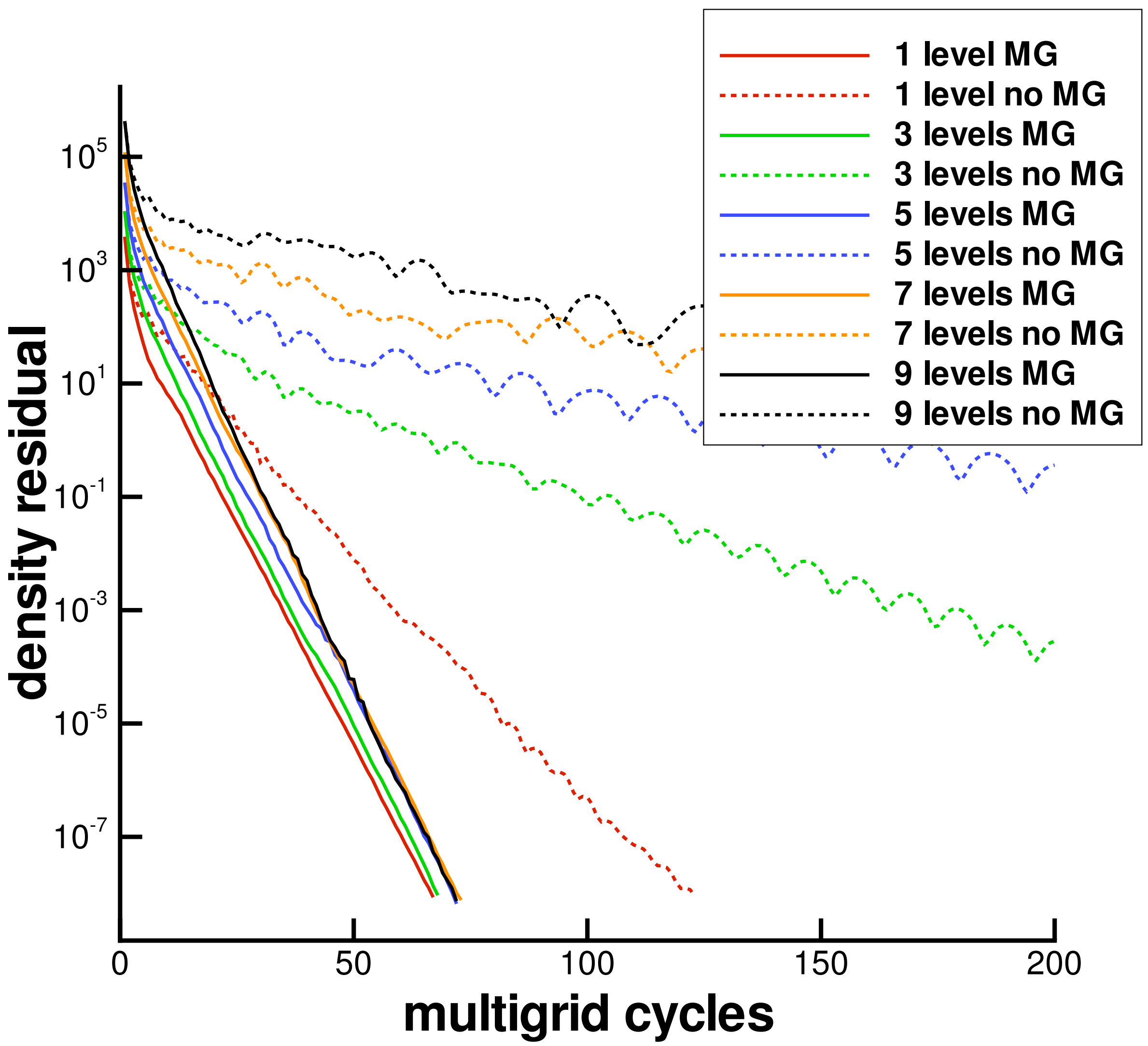


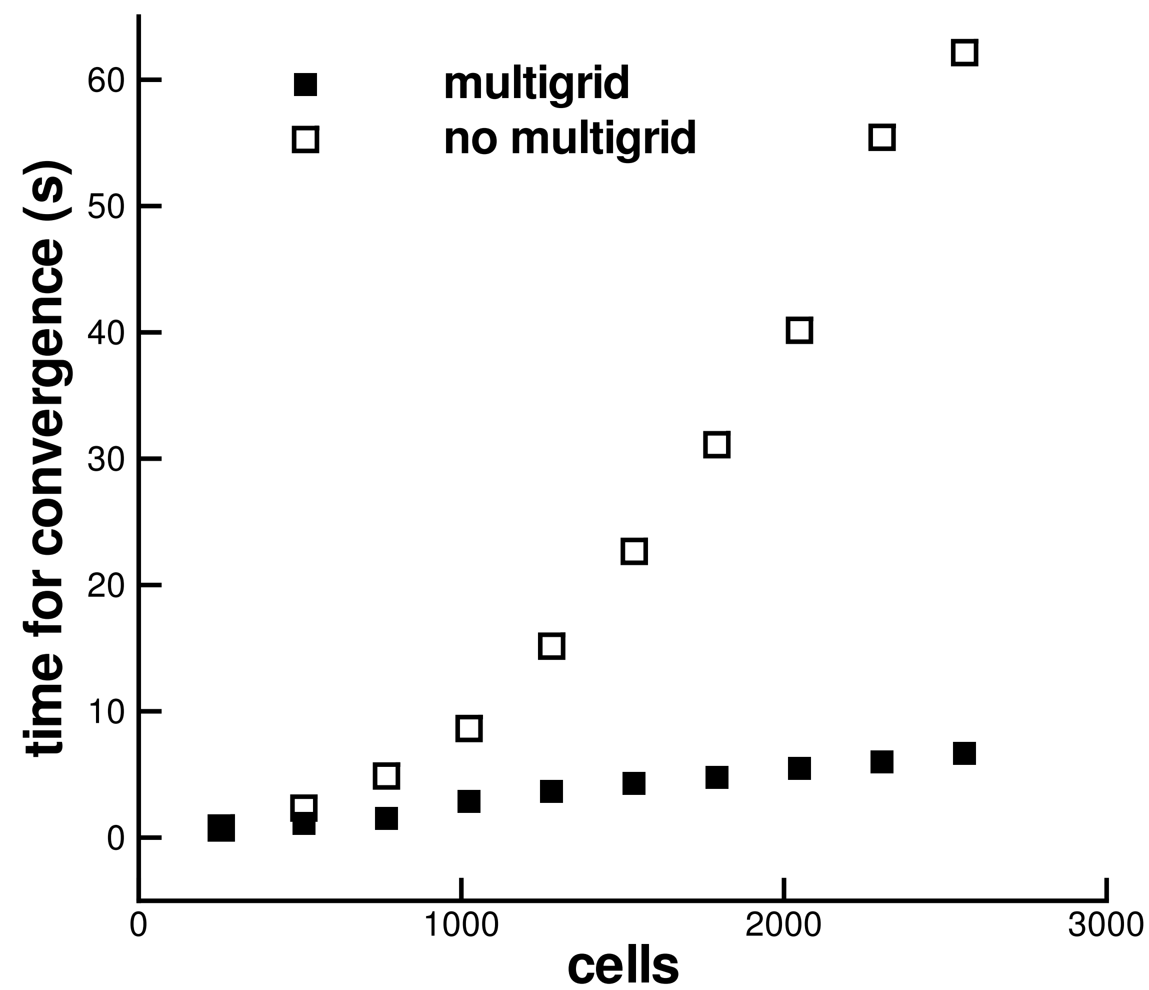
Forcing Term

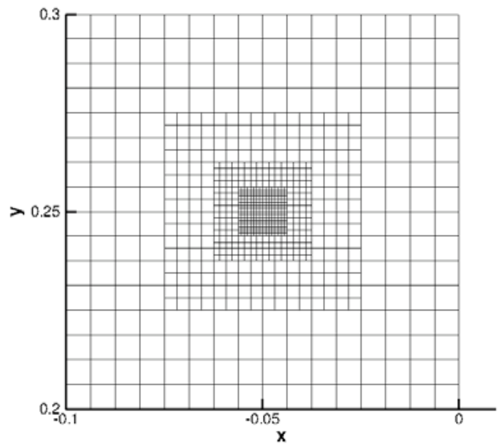


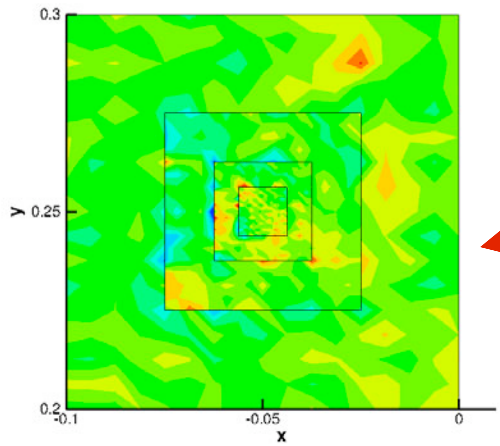
Prolongation

Demonstration of Multigrid on AMR Meshes









Test case: recovery of uniform flow

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