Evaluation of Voronoi Meshes for Large Eddy Simulations of High Lift Aerodynamics

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AIAA SciTech Forum, National Harbor, MD

01/23/2023

Introduction

- LES addresses major challenges faced by RANS in shear-dominant flows such as take-off and landing of airplanes with deployed high-lift devices

- And it is becoming feasible at practical scale thanks to advancements in high-performance computing

- AIAA 4th High-Lift Prediction Workshop (HLPW4)
  - Nine participants submitted WMLES results, of which 6 used unstructured meshes
  - In contrast, HLPW3 had no WMLES submissions

- Results are extremely encouraging, but success highly depends on mesh density and quality

- High quality unstructured meshes can be generated at scale using Voronoi methods

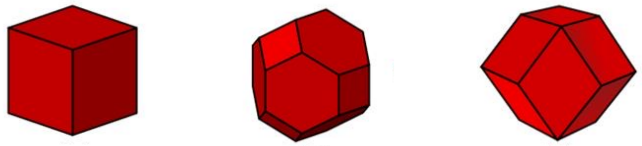
Voronoi Mesh Properties

- Voronoi diagrams have inherent special properties:
  - Cells are guaranteed to be convex
  - Faces are planar
  - Faces are located halfway between seed points
  - Face are orthogonal to the vector connecting the two seeds on either side

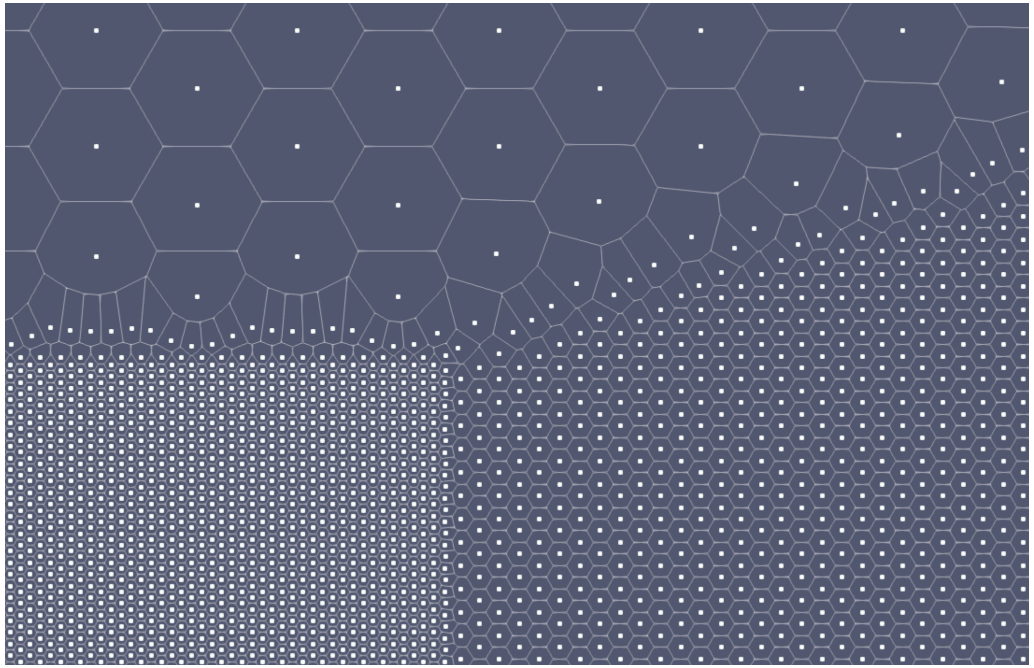
- These properties act to significantly improve robustness and reduce dissipation in CFD

- Various cell types can be generated:
  - Cartesian seeding – Cubic cells
  - Body-centered Cubic (BCC) – Truncated octahedral cells
  - Face-centered Cubic (FCC) – Rhombic dodecahedral cells

https://en.wikipedia.org/wiki/Voronoi_diagram



Voronoi Mesh Smoothing



- Coarse/fine interfaces, or irregular point distributions can be naturally smoothed
  - Lloyd procedure iteratively moves seed points to the generated cell's centroid
  - Results in a regularized point distribution
  - Cells converge towards a centroidal shape

- In practice, we apply the smoothing in a limited zone around mesh size transitions
  - Majority of the regularly seeded mesh is unaffected

Numerical Scheme

- LAVA Unstructured solver was used
  - Developed at NASA Ames Research Center
  - A decade of successful use for RANS simulations using arbitrary polyhedral meshes
  - Recently refactored and highly optimized for modern CPU's

- 2nd order accurate cell-centered finite volume method

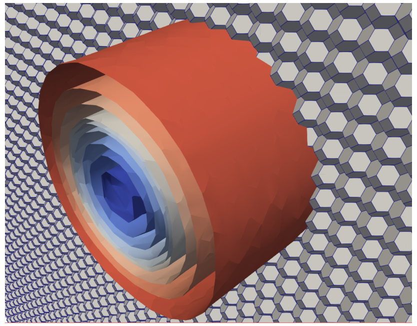
- Sensor based, blended upwind/central convective flux scheme

- Vreman Sub-Grid Scale (SGS) turbulence model

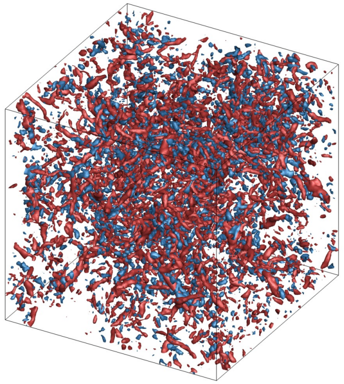
- Explicit 3rd order accurate time integration with a strong stability preserving, 3-stage Runge-Kutta scheme

- Blended log-layer explicit wall model

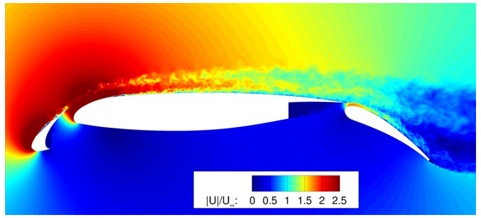
Test Cases



- Isentropic vortex propagation
  - Demonstrate kinetic energy preservation
  - Investigate effects of different Voronoi mesh types
  - Study coarse/fine interface effects



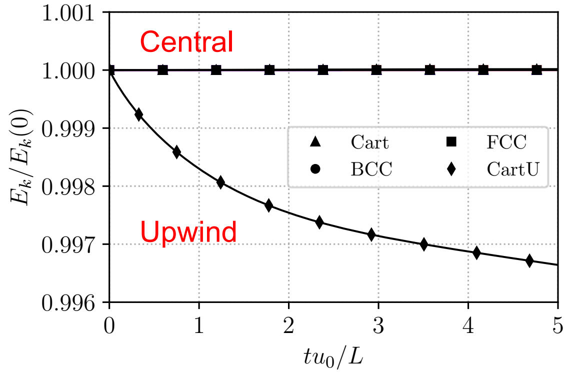
- Homogeneous Isotropic Turbulence (HIT)
  - Test SGS for non-linear robustness
  - Study the turbulent energy cascade

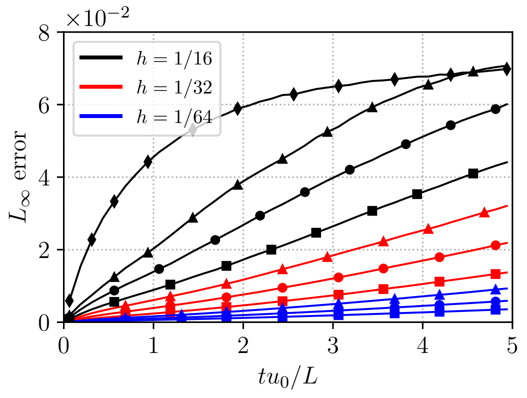


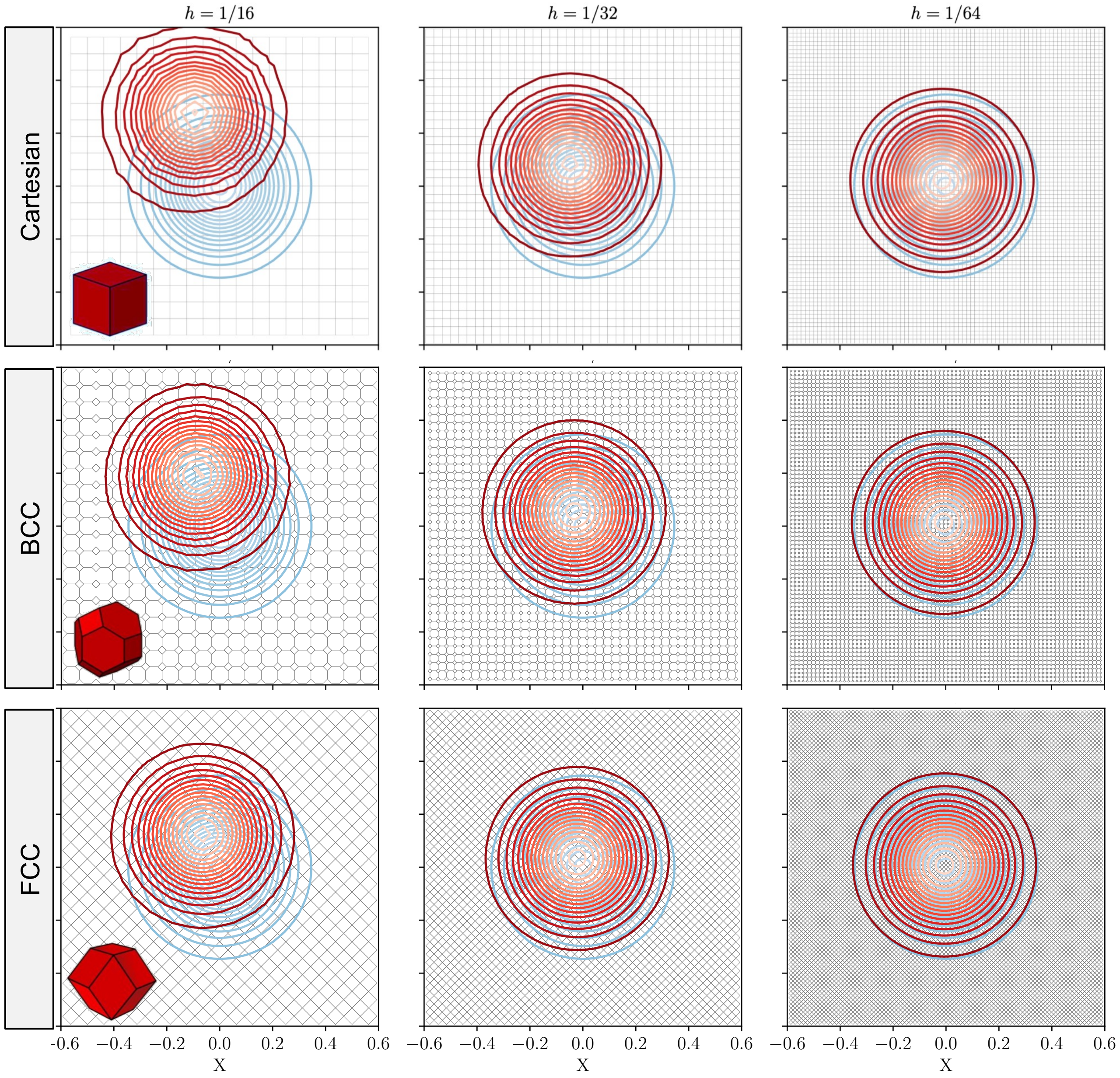
- McDonnell Douglas 30P30N multi-element airfoil
  - Compare high-lift aerodynamics predictions to experimental data
  - Demonstrate results for different Voronoi mesh types
  - Verify current numerical approach’s suitability for WMLES

Isentropic Vortex Propagation – Uniform Mesh Results

- Inviscid vortex tube traveling in x-direction
  - Triply periodic domain with extents [-2, 2]
  - Measured integrated kinetic energy and pressure error for 5 pass-through periods
- Voronoi mesh types: Cartesian, BCC & FCC
- Central convective flux is non-dissipative, with 2nd order solution error convergence for all grid types
- Dispersion errors manifest as drift
- For the same grid spacing, Cartesian has the largest error, FCC has the least



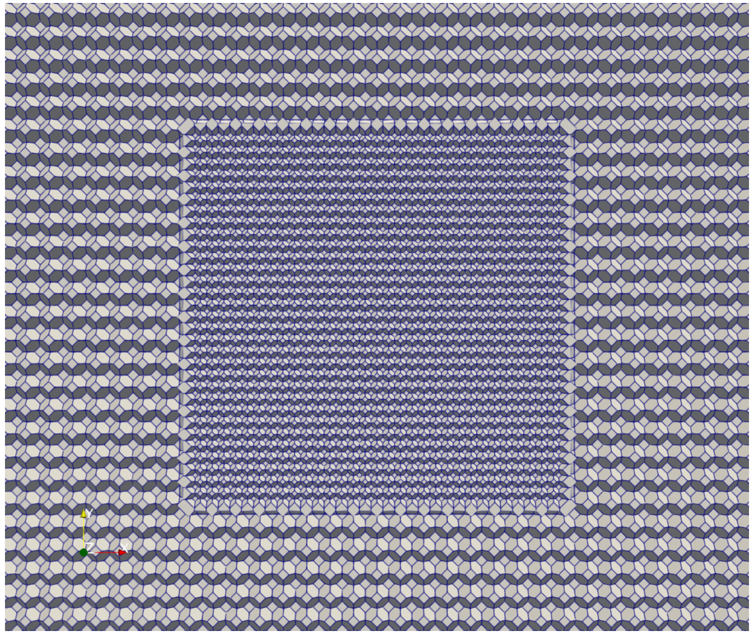




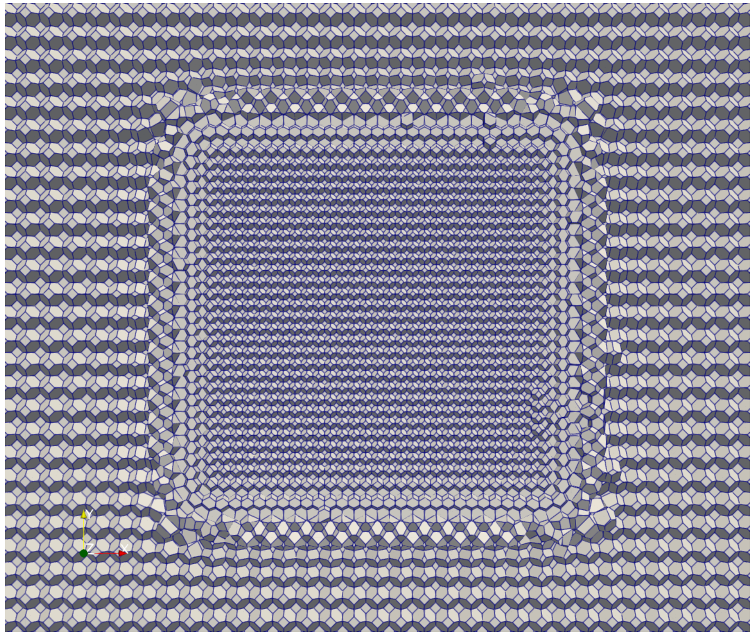
Isentropic Vortex Propagation – Coarse/Fine Interfaces

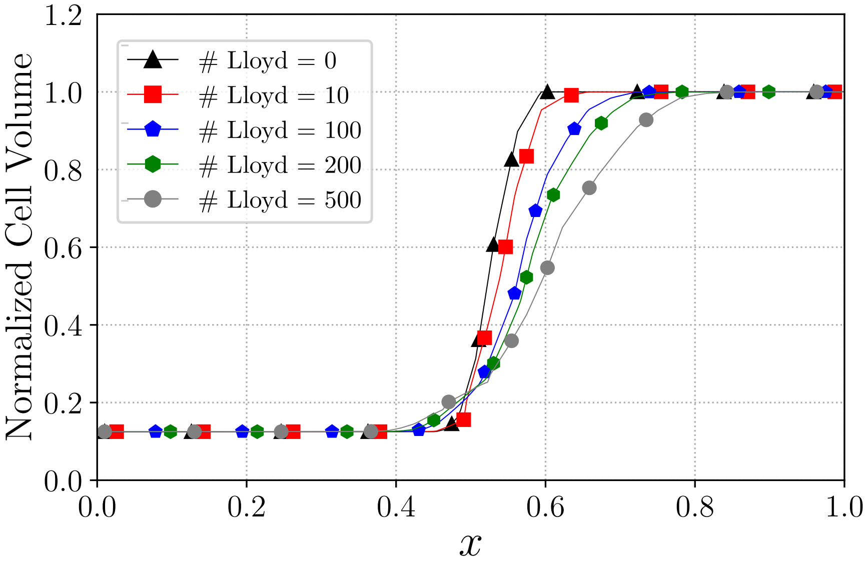
- A 1:2 coarse/fine interface was studied by embedding a cubic refinement region in the domain
- Interfaces of varying smoothness are generated via Lloyd iterations

0 Lloyd Iterations



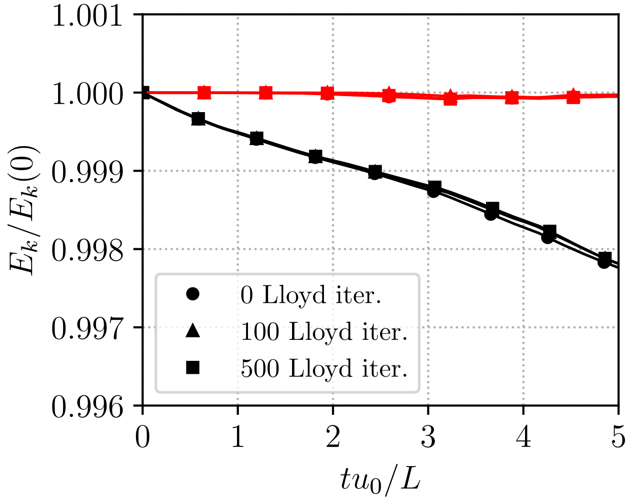
500 Lloyd Iterations

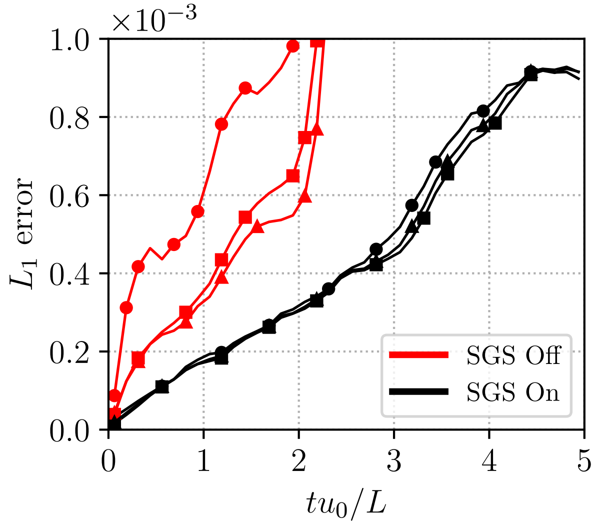


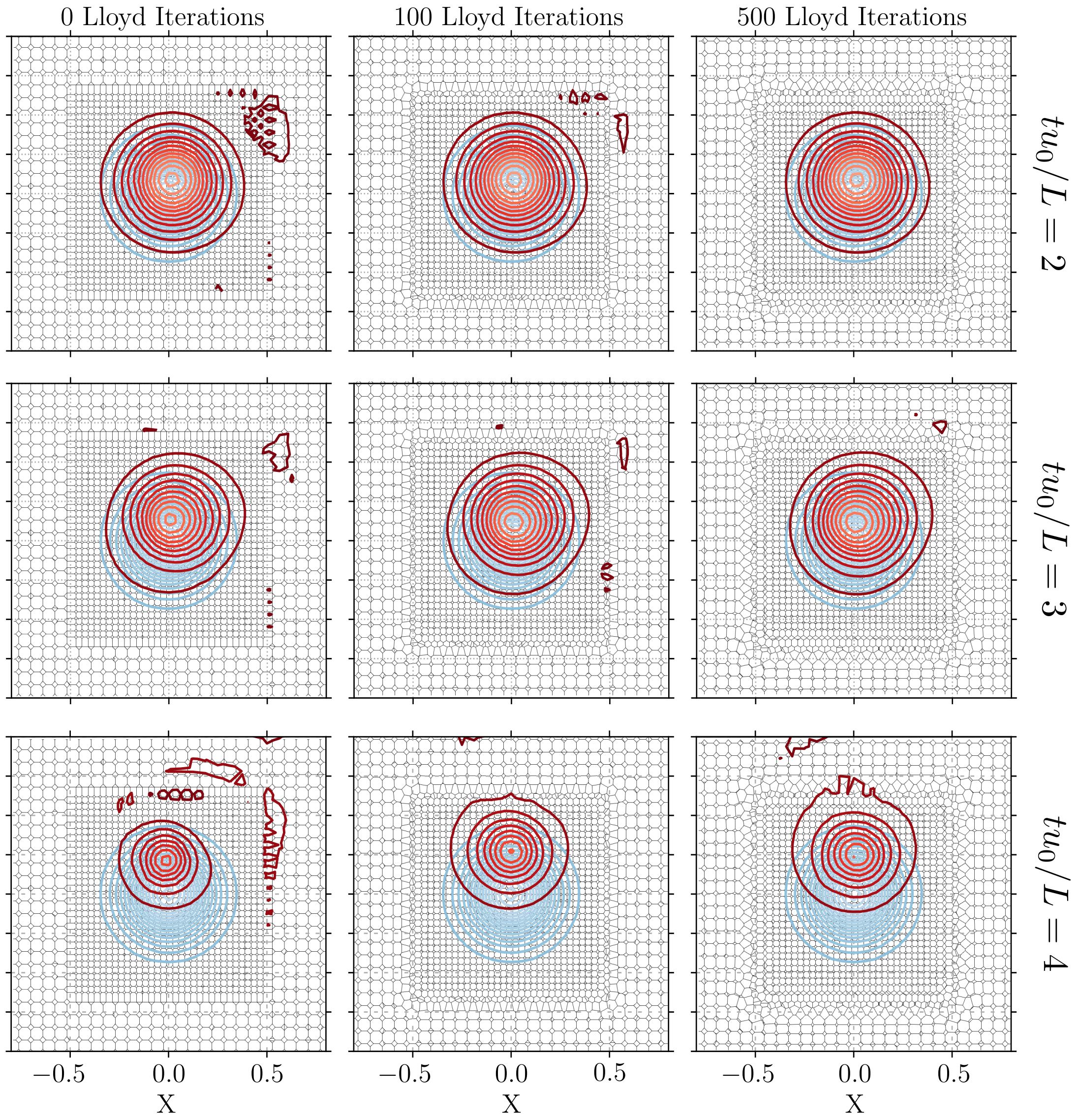


Isentropic Vortex Propagation – Coarse/Fine Interfaces

- Only BCC Voronoi meshes were used in this test
- Simulations without SGS is not stable when coarse/fine interface present
  - No mechanism to attenuate the errors due to the interface
  - Kinetic energy is preserved
- SGS was provided sufficient stability without any upwinding
- Smoother interface: Less energy decay, and less pressure error
- But the difference is marginal

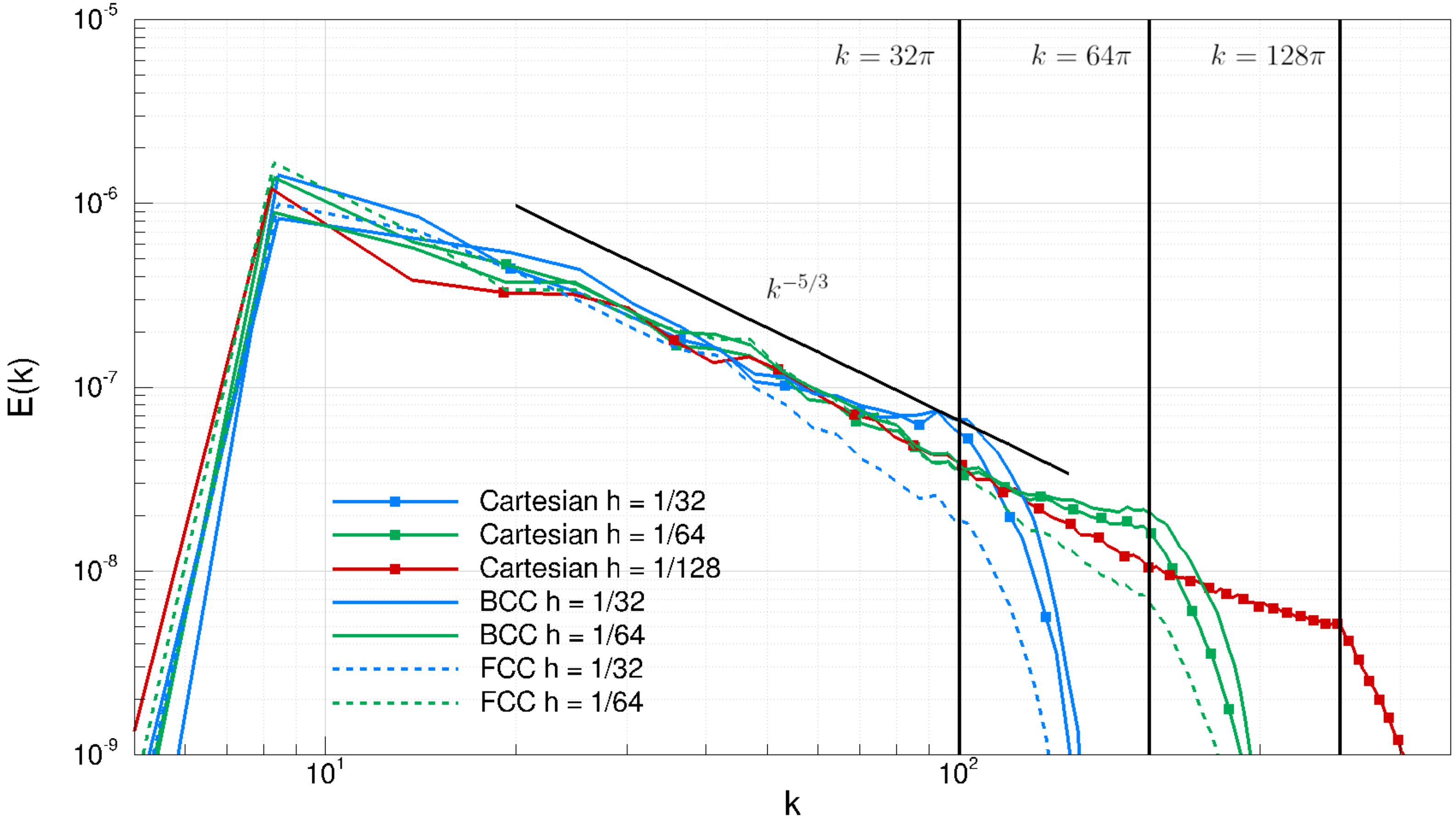






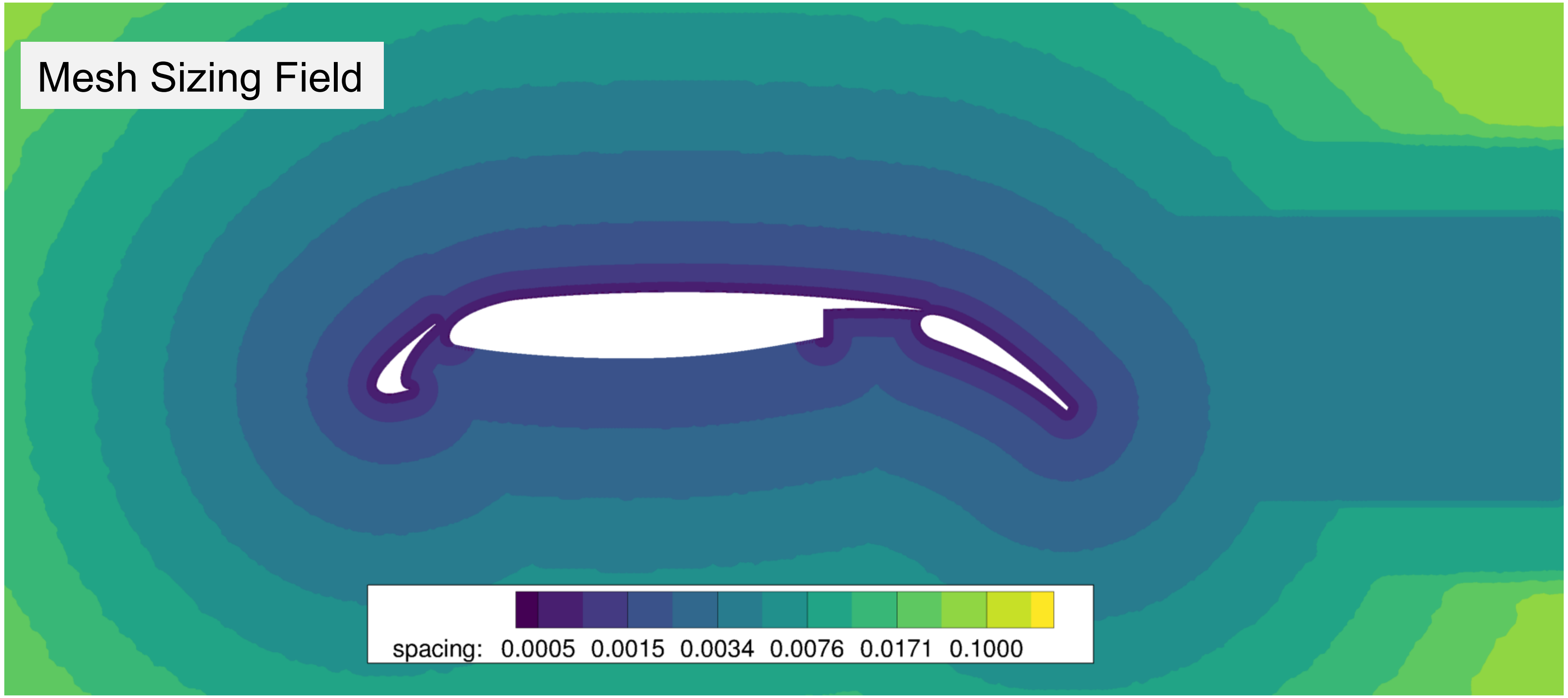
Homogeneous Isotropic Turbulence (HIT)

- HIT with a momentum forcing source was studied
- Energy decay rate at the inertial rate is correctly predicted
- Onset of rapid dissipation at the sub-grid scale is captured at correct Nyquist wave numbers

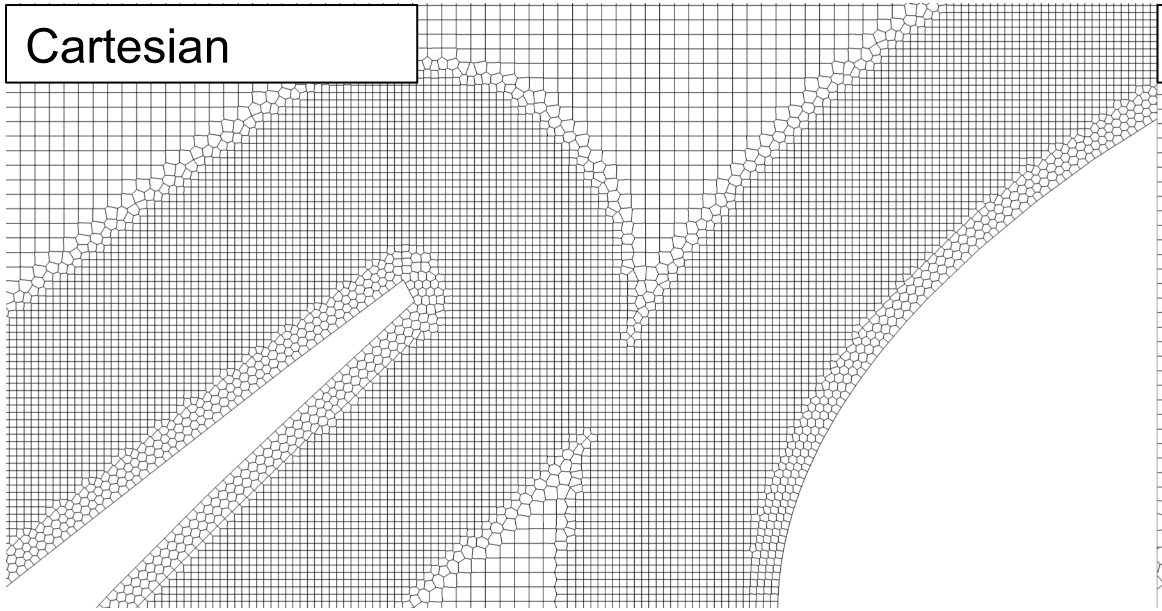


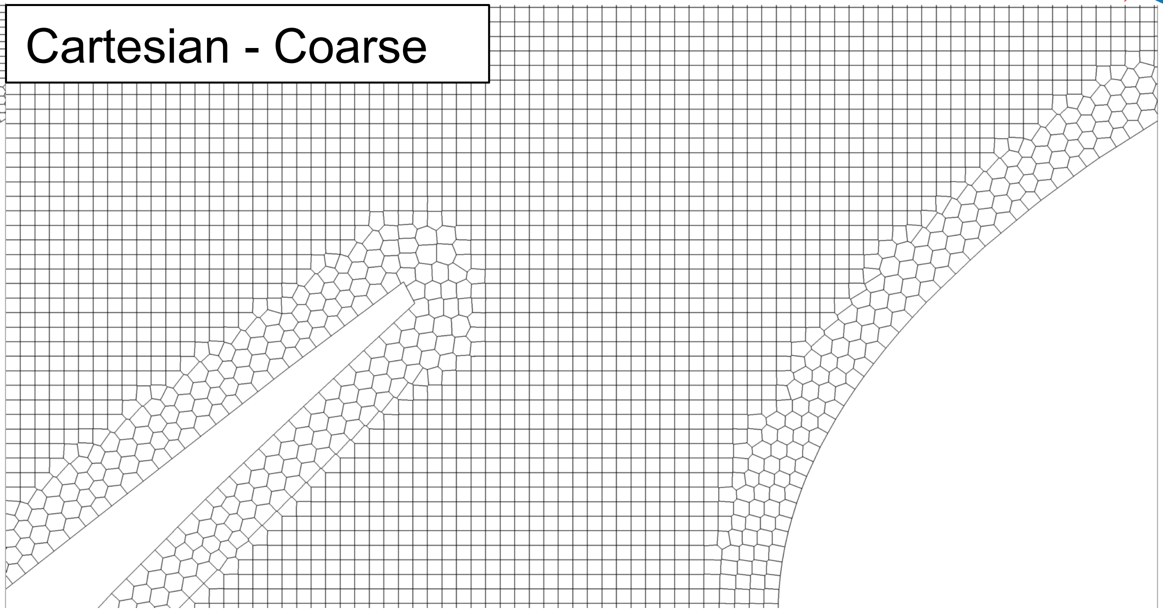
30P30N Setup

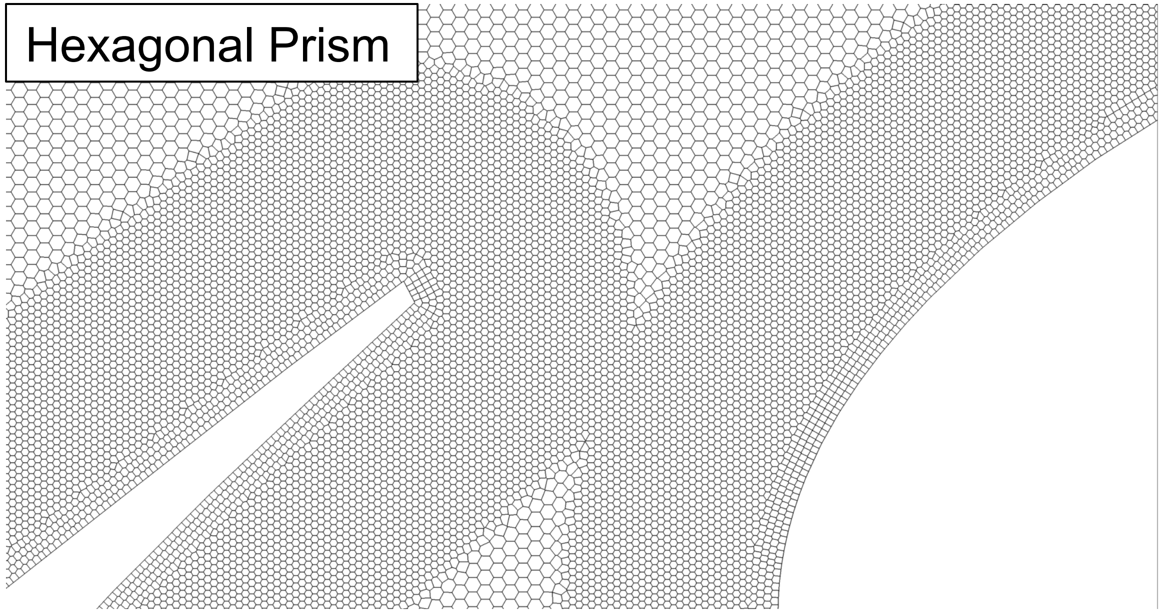
- Ma = 0.2, Re = 9e6
- 10%c span length simulated with periodic boundary conditions on end planes
- Meshes are created in 2D, extruded spanwise with a constant spacing of 1e-3c
- Two different Voronoi mesh types tested: Cartesian seeded and Hexagonal seeded



30P30N Meshes – Slat Gap Close-up





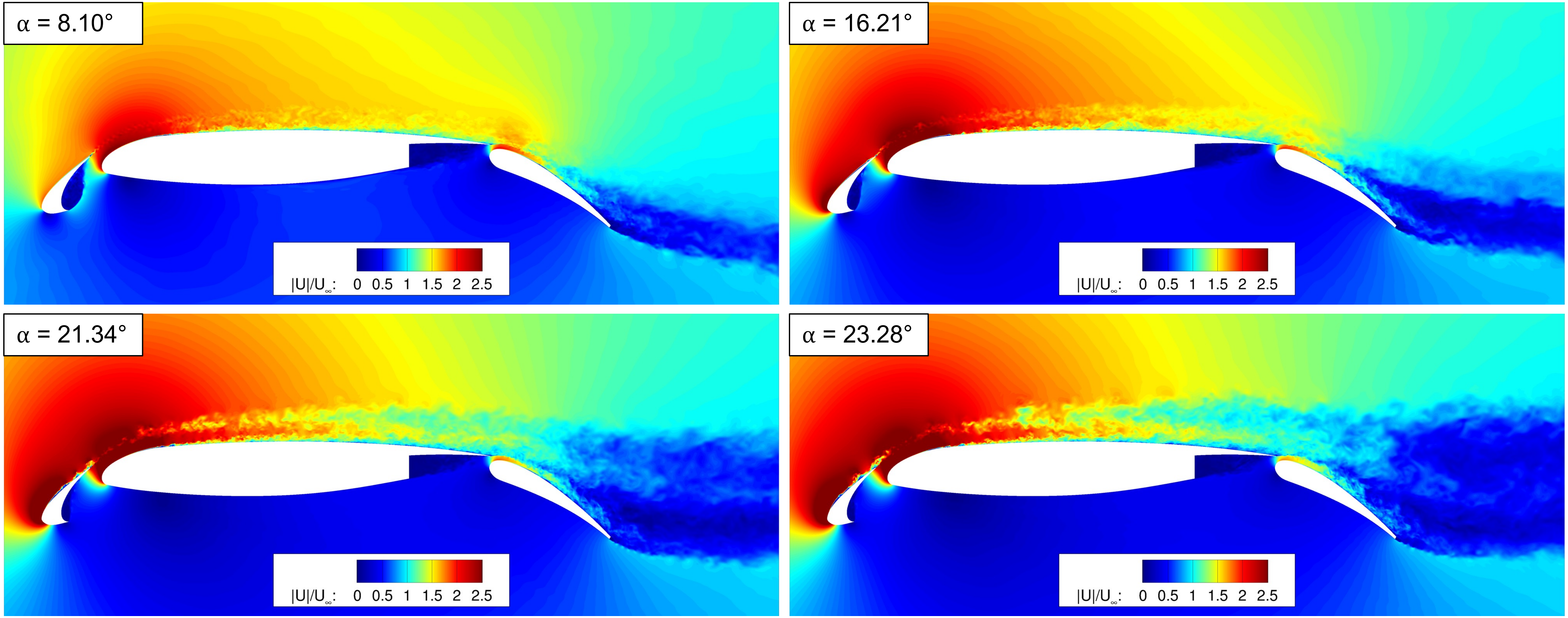


- Refinement regions of same sizing contoured around different elements seamlessly join together
- 4 wall-aligned layers, 15 Lloyd smoothing iterations
- Smoothed cells in Cartesian mesh naturally morph into hexagonal cells and other transitional cell types
- Cartesian – Coarse mesh simply skips the finest sizing region

	Spacing (chord normalized)					# Cells	# Faces
Mesh	Slat	Main Upper	Main Lower	Flap	Spanwise	(million)	(million)
Cartesian Voronoi - Coarse	1e−3	1e−3	2e−3	1e−3	1e−3	31.8	101.3
Cartesian Voronoi	5e−4	5e−4	2e−3	5e−4	1e−3	41.7	133.8
Hexagonal Prism Voronoi	5e−4	5e−4	2e−3	5e−4	1e−3	50.9	198.3

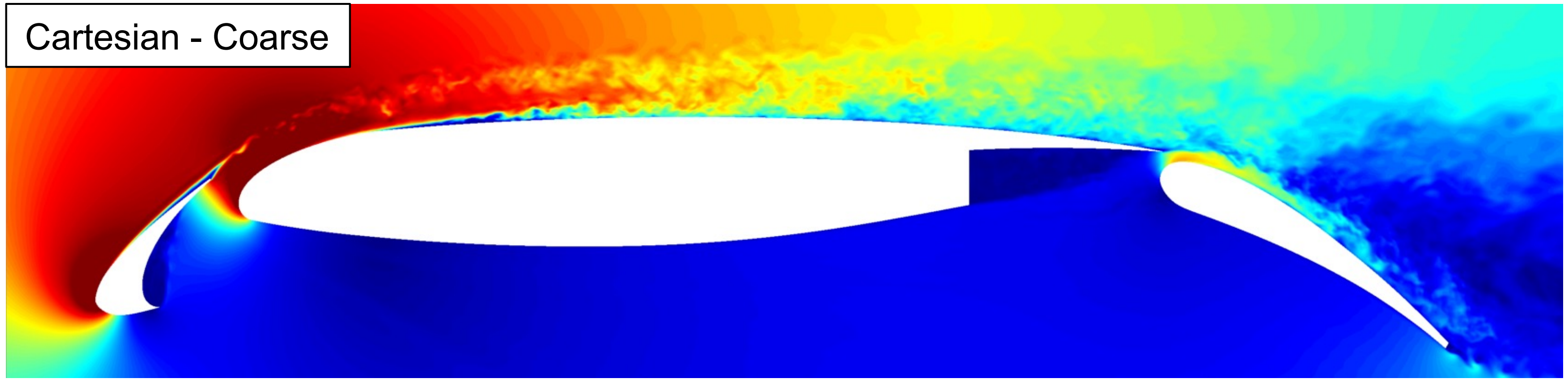
30P30N Results – Instantaneous Velocity Magnitude Field

- Instantaneous velocity magnitude contours shown for the hexagonal prism mesh

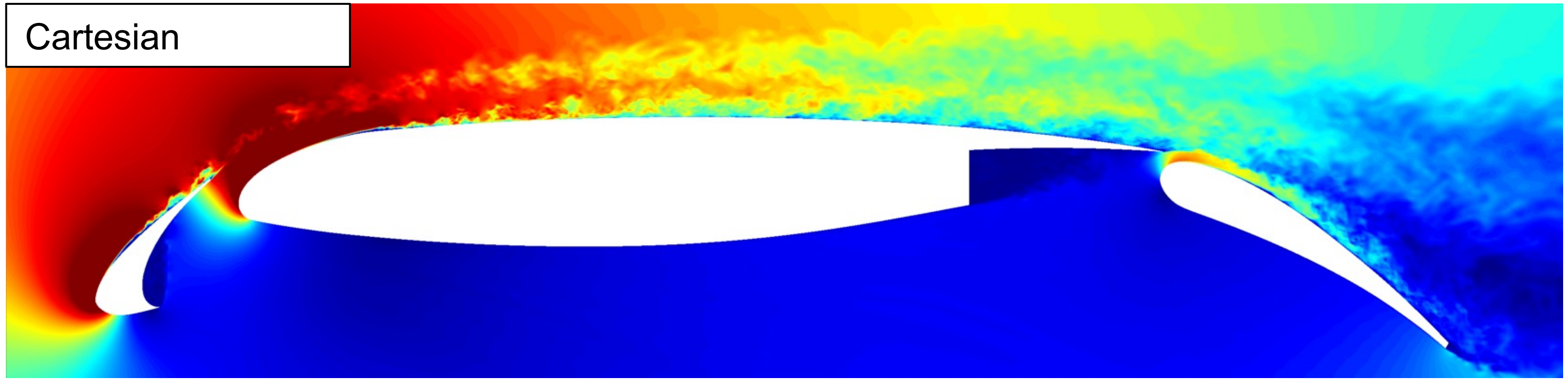


30P30N Results – Mesh Sensitivity at $C_{L,max}$ (α = 21.34°)

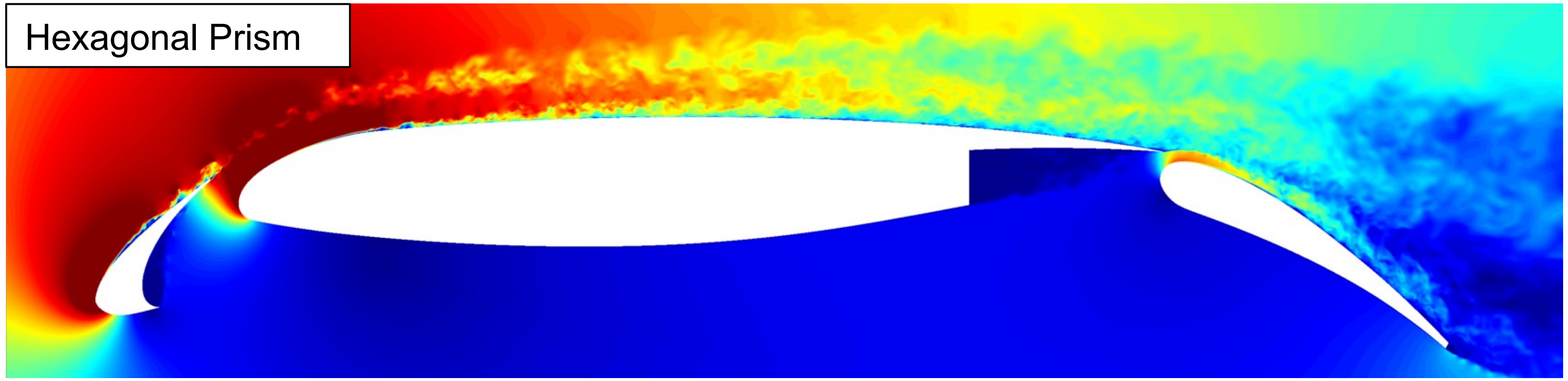
- Slat upper surface stays laminar and attached



- Onset of transition over the slat
- Earlier transition over the main element

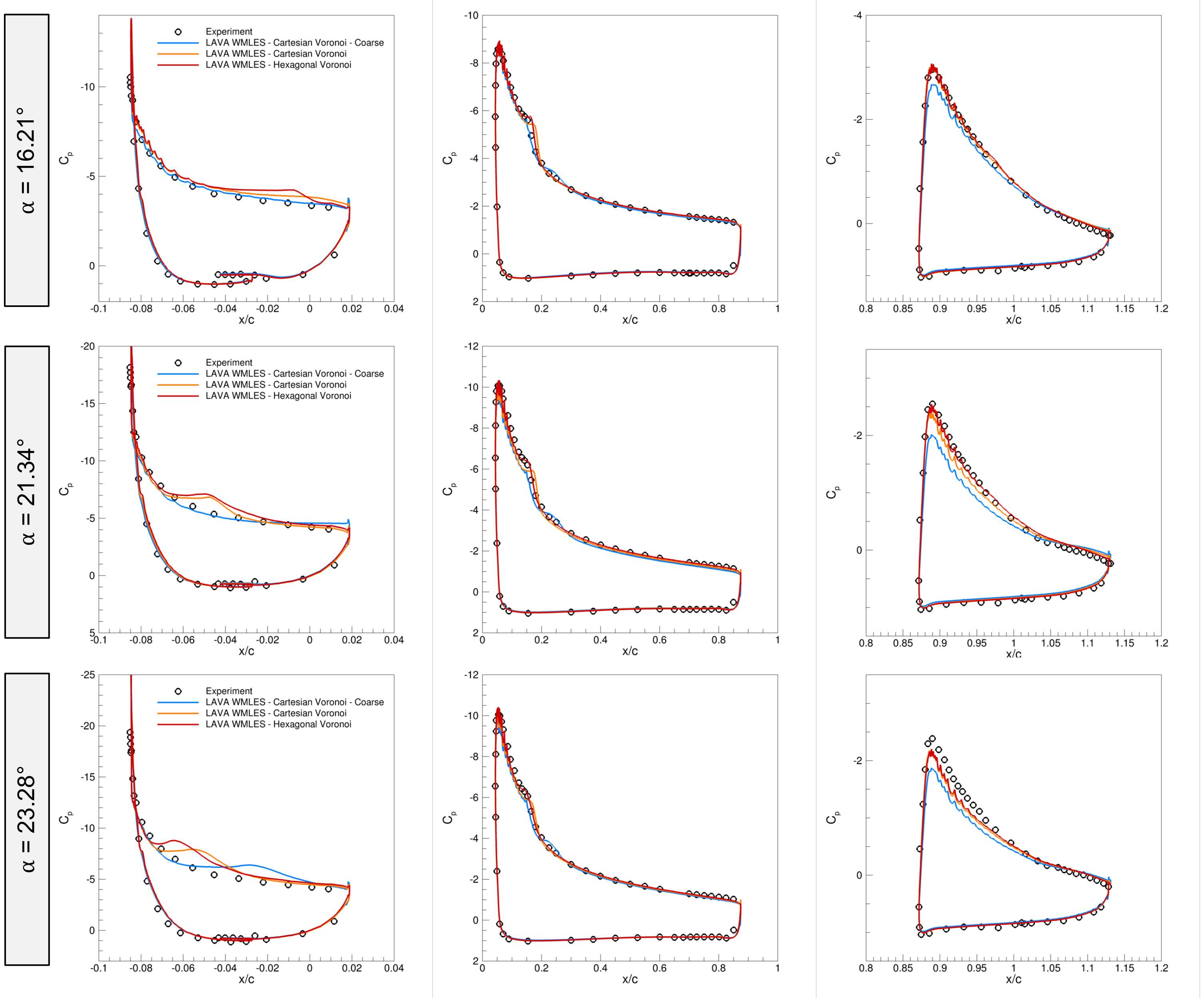


- Finer scale turbulence over the main element boundary layer
- Further breakdown of slat boundary layer
- Better definition near flap upper surface

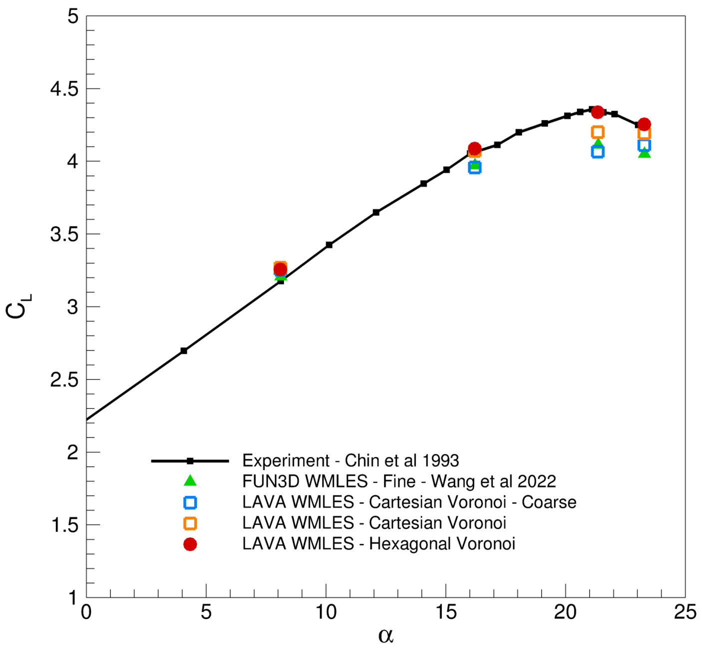


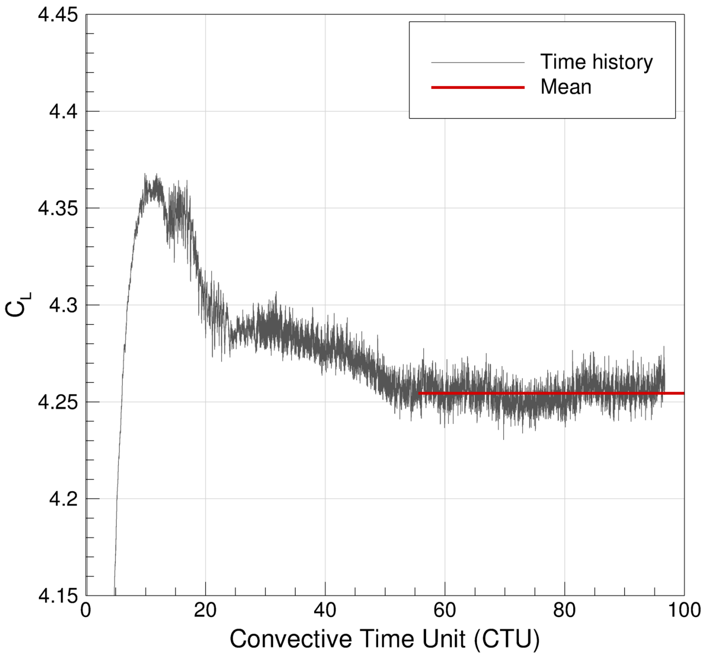
30P30N Results – Pressure Coefficient Distributions

- Time-averaged (~50 CTU's) pressure field, extract at mid-span
- Excellent agreement with the experiment over the main element
  - Hexagonal mesh doing slightly better
- Slat is transitional, while experiment doesn't show a sign of this
  - Coarse mesh doesn't show transition until the highest angle
  - Transition onset location moves upstream with refinement
  - Hexagonal mesh exhibits higher resolution compared to Cartesian mesh of same spacing
- Great agreement over the flap until post-stall
  - Results display higher mesh sensitivity compared to the main element
  - Predictions trend towards the experiment with mesh refinement
  - Hexagonal mesh results better capture the suction peak
    - Slight under-prediction at highest angle



30P30N Results – Lift Curve





- Integrated aerodynamic forces are time-averaged for about 50 CTU's
- Hexagonal mesh shows excellent agreement with the experimental lift
  - Slight overprediction at the lowest angle for all meshes
- Cartesian meshes underpredicts the lift at high angles
  - Mesh refinement trends toward experimental values

Summary & Conclusions

- A 2nd order accurate cell-centered finite volume unstructured scheme suitable for large eddy simulations has been presented and tested with model problems of increasing complexity.

- Isentropic vortex propagation:
  - The central scheme was able to preserve the integrated kinetic energy for all Voronoi mesh types tested
  - For the same mesh spacing, Cartesian mesh had the highest error, followed by BCC and FCC
  - When there is a coarse/fine interface, SGS was sufficient to stabilize the scheme
  - Coarse/fine interface smoothing made little difference; more smoothing → marginally less error

- Homogeneous isotropic turbulence:
  - SGS provided sufficient robustness without any upwinding
  - Both Cartesian, BCC and FCC meshes produced correct turbulent energy cascade

- 30P30N:
  - Excellent agreement with experiments when using the hexagonal prism Voronoi mesh
  - Cartesian mesh of same spacing was still mesh sensitive, displaying correct trend with refinement
  - Hexagonal mesh has higher effective resolution, although with higher computational cost

Acknowledgements

- This work is funded by NASA's Aeronautics Research Mission Directorate (ARMD) Transformational Tools and Technologies (T^3) project.

- We would like to thank the members of the LAVA Voronoi development team for their invaluable efforts in building the meshing tool that enabled this work. Apart from the co-authors, members of the Voronoi team include:
  - Dr. Mahesh Natarajan
  - Abram Rodgers
  - Keshav Sriram

- We are also thankful for our colleagues Dr. Gerrit Stich and Dr. Oliver Browne for their insightful feedback