Mesh Adaptation for Unsteady Flows

Mike Park

Kevin Jacobson

Bil Kleb

NASA Langley Research Center, Hampton, VA, USA

Goals Today

- Motivate unstructured mesh adaptation development
- Review steady RANS mesh adaptation and how it matured
- Motivate continued collaboration on unstructured mesh adaptation
- Discuss applications of mesh generation and unsteady mesh adaptation to DDES and WMLES
- Motivate investments toward automating meshing for eddy-resolving simulations

Status, Emerging Ideas and Future Directions of Turbulence Modeling Research in Aeronautics

- Duraisamy et al., NASA TM-2017-219682 summarizing a three-day Turbulence Modeling Symposium
- Reynolds-averaged Navier–Stokes (RANS) modeling development may stagnate or reach an ultimate accuracy barrier
- Wall-modeled large eddy simulation (LES) and hybrid RANS/LES (HRLES) continue to gain traction with their share of failures and controversy

CFD 2030 Vision

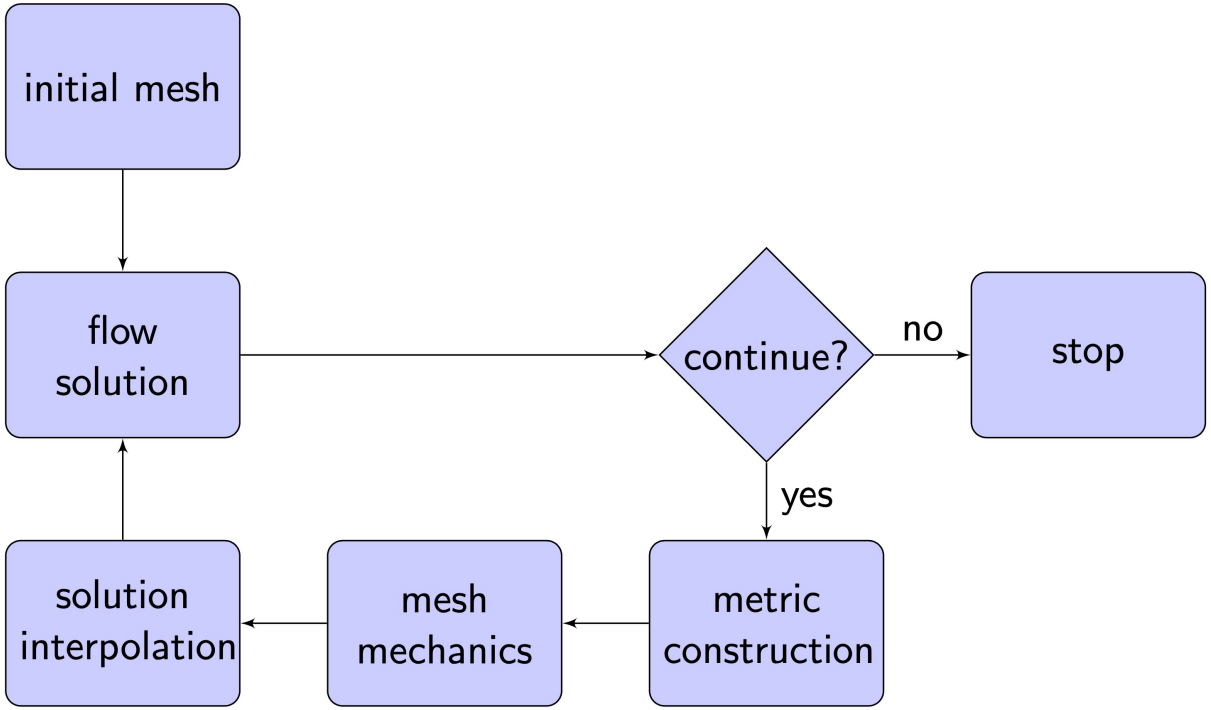
- Slotnick et al., NASA CR-2014-218178
- “The use of CFD in the aerospace design process is severely limited by the inability to accurately and reliably predict turbulent flows with significant regions of separation. . . Hybrid RANS-LES and wall-modeled LES offer the best prospects for overcoming this obstacle although significant modeling issues remain to be addressed here as well.” - Finding 3 of the CFD Vision 2030 Study
- “Mesh generation and adaptivity continue to be significant bottlenecks in the CFD [Computational Fluid Dynamics] workflow, and very little government investment has been targeted in these areas.”
- **“Ultimately the mesh generation process should be invisible to the CFD user or engineer.”**

A Guide for Aircraft Certification by Analysis

- Mauery et al., NASA CR-20211025404
- “The ability to numerically simulate the integrated system performance and response of full-scale airplane and engine configurations in the flight and/or ground- test environment in an accurate, robust, and computationally efficient manner.” - Element 1
- How can CFD mesh adaptation support Certification by Analysis?
  - Provide the accurate simulation of steady and time-dependent separated flows for complex configurations (e.g., maximum lift of transport aircraft)
  - Improved automation and robustness for complex geometry models and database creation (outside center of flight envelope where CFD typically applied)
  - Rigorous verification and validation exercises for the entire adaptive mesh toolchain

Mesh Adaptation Process

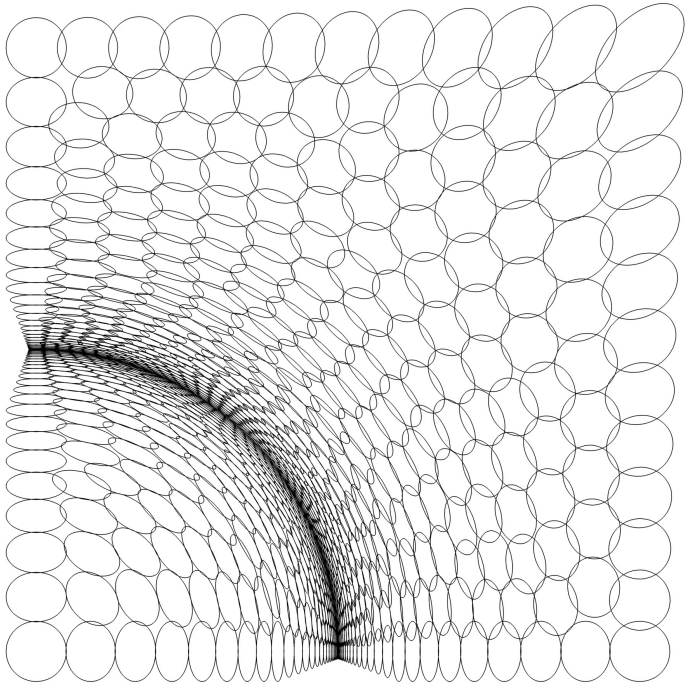
- Verifying the flow solver implementation is necessary, but not sufficient for mesh adaptation



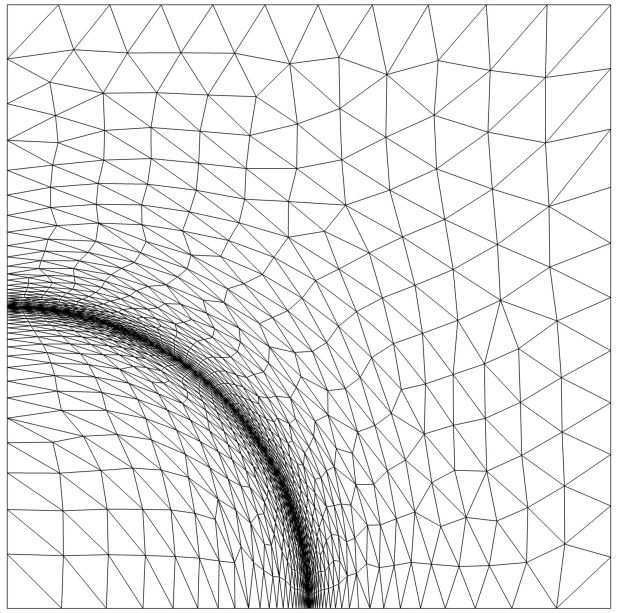
Adapted Meshes

- Metric constructed to control a solution interpolation error estimate
- Meshes conforming to anisotropic metric

Metric field sampled with ellipses

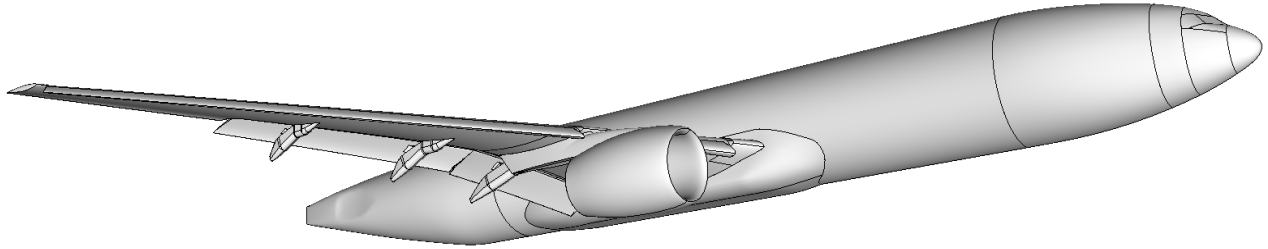


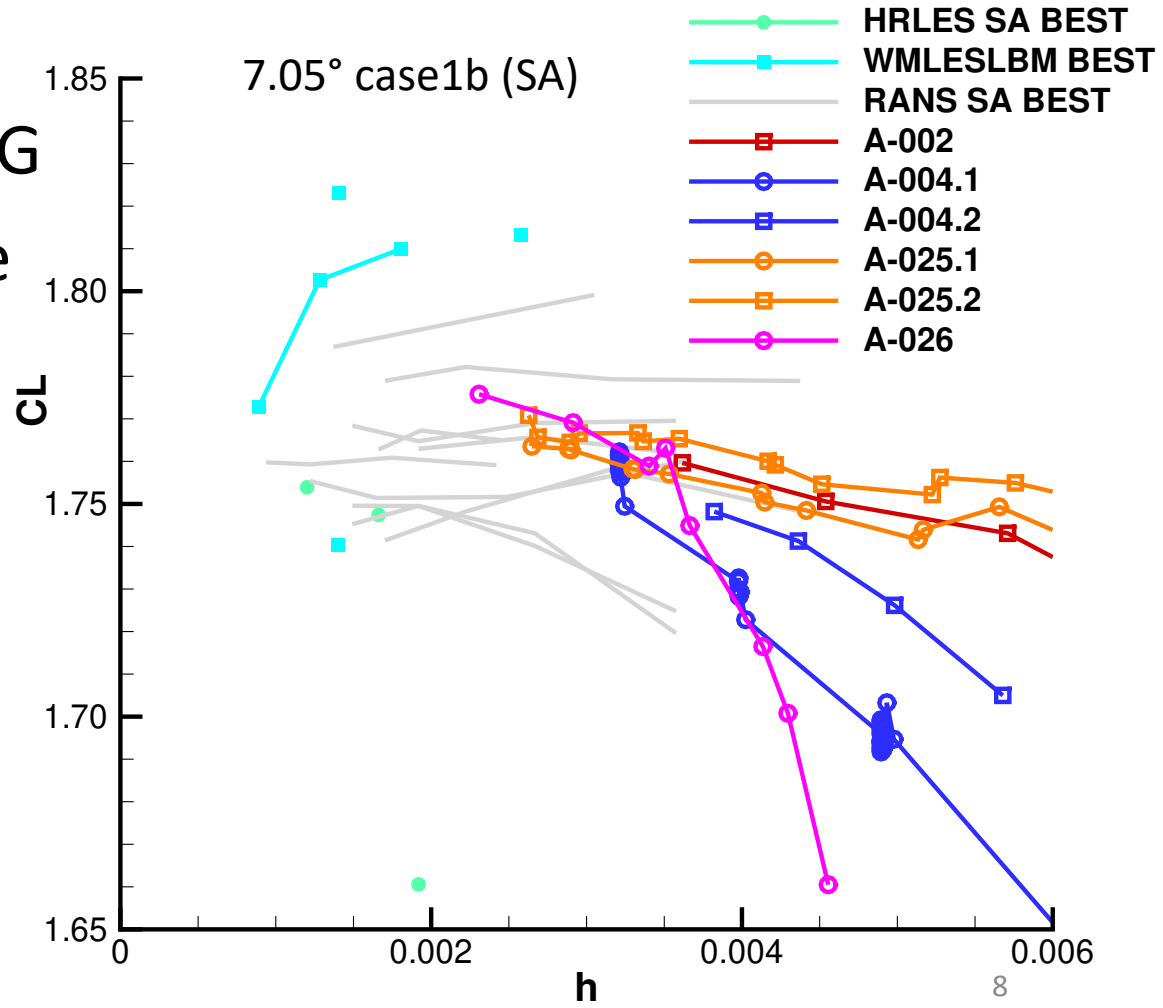
Metric-conforming or unit mesh



HLPW-4/GMGW-3: Mesh Adaptation for RANS Technology Focus Group Workshop Summary

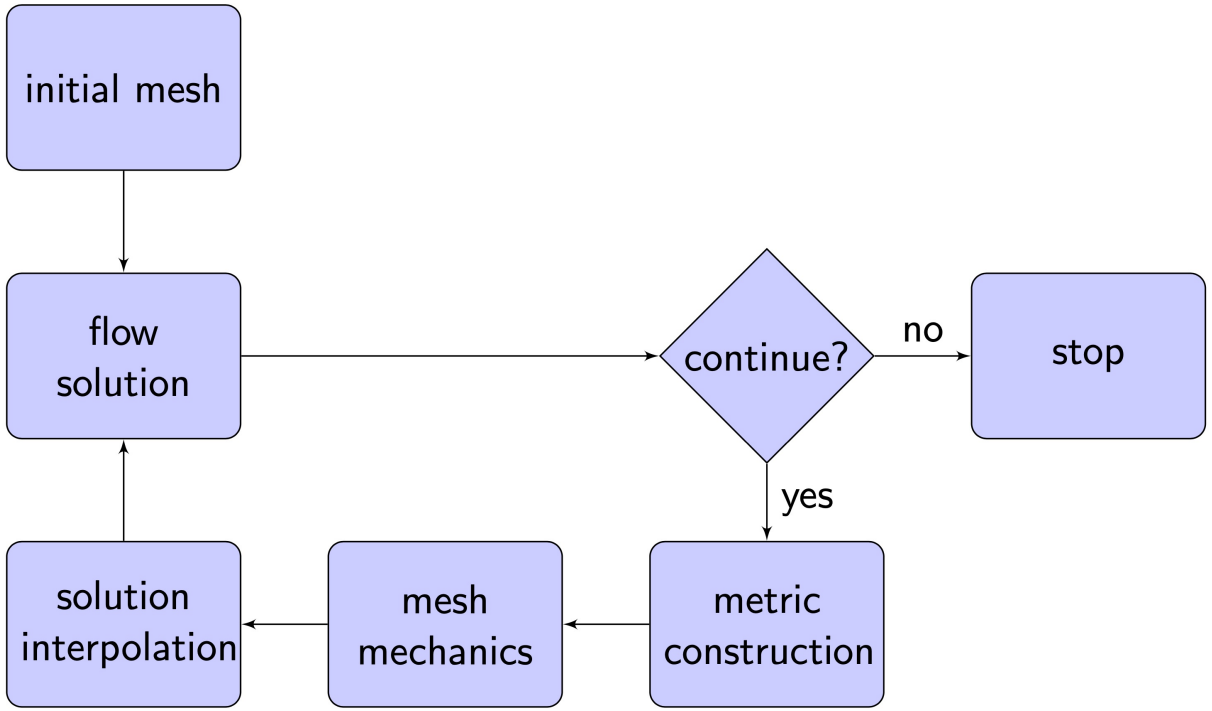
- Lower variation and than other TFG
- Mesh sizes are smaller than other TFG
- Mesh adaptation appears to increase the consistency of RANS
- Does consistency assist RANS turbulence model development?
- Does the same potential for eddy-resolving methods exist?





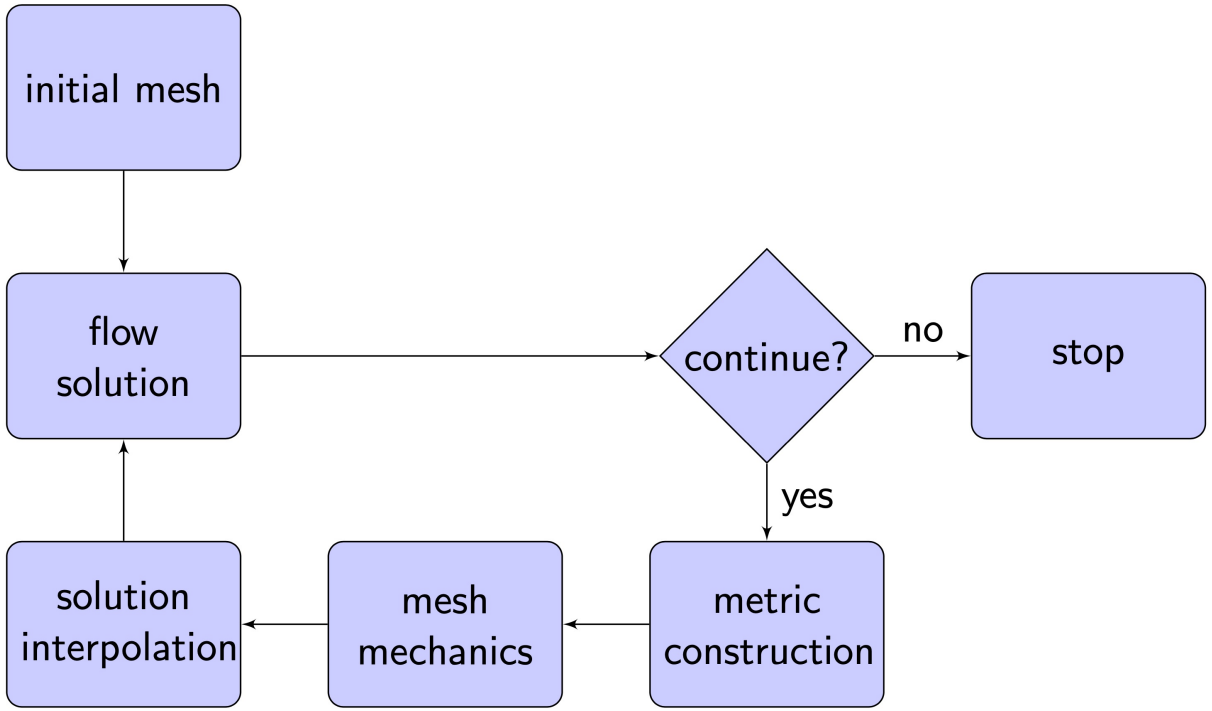
How Did Mesh Adaptation Mature for RANS?

- Implement these boxes and run the CRM-HL?



How Did Mesh Adaptation Mature for RANS?

- ~~Implement these boxes and run the CRM-HL?~~
- Are there lessons learned from maturation of RANS mesh adaptation that apply to eddy-resolving methods?



Unstructured Grid Adaptation: Status, Potential Impacts, and Recommended Investments Toward CFD Vision 2030

- Park et al., AIAA Paper 2016-3323
- Literature survey
- Unstructured mesh adaptation status and 15-year forecast
- **Recommendations for investment** and their potential impacts
- *Strategies to defuse technology*

Unstructured Grid Adaptation Working Group

- Informal working group
  - Started at a lunch table International Meshing Roundtable IMR25 Washington, DC (2016)
  - NASA, Boeing, INRIA, MIT, ODU, Cadence, Middlebury Collage, Imperial College London, Sandia National Laboratories
  - Monthly virtual meetings
- Diffuse verified adaptive mesh technology to displace fixed meshes where appropriate
- Test cases available for analysis or developing new methods https://UGAWG.GitHub.io
- Encourage new entrants
- Investments
  - Metric and boundary conforming meshing (RANS boundary layers)
  - Geometry interaction with common MCAD sources
  - Error estimation and metric construction
  - Suitability for flow solution
  - Parallel execution
  - Component and system level verification
  - System level performance in terms of accuracy and execution time

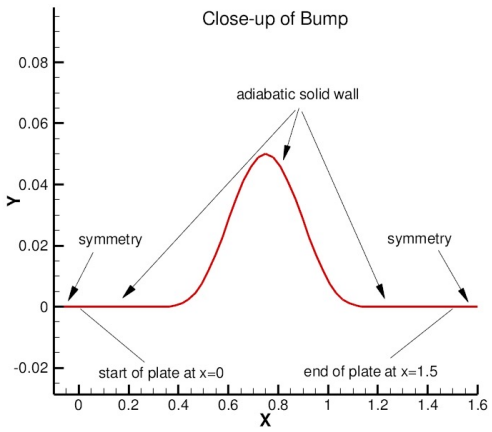
Verify Independently Developed Implementations of These Investments

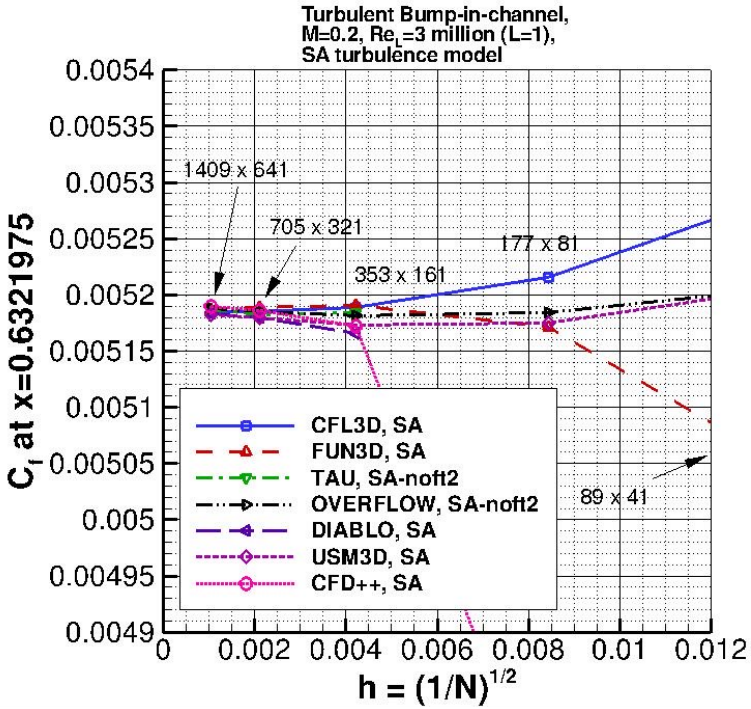
- Metric conformity for analytic geometry and analytic metric field **[6 Authors]** “First Benchmark of the Unstructured Grid Adaptation Working Group” Procedia Engineering 2017
- Analytic solution and laminar wing **[13 Authors]** “Verification of Unstructured Grid Adaptation Components” AIAAJ 2020
- ONERA M6 **[6 Authors]** “Comparing Anisotropic Error Estimates for ONERA M6 Wing RANS Simulations” AIAA-2018-920 and **[7 Authors]** “Verification of Anisotropic Mesh Adaptation for RANS Simulations over ONERA M6 Wing” AIAAJ 2020
- CRM-HL airfoil **[9 Authors]** “Comparing Unstructured Adaptive Mesh Solutions for the High Lift Common Research Model Airfoil” AIAAJ 2021
- Goal-oriented metrics **[9 Authors]** “Verification of Viscous Goal-Based Anisotropic Mesh Adaptation” AIAA-2021-1362 and **[10 Authors]** “Anisotropic Goal-Based Mesh Adaptation Metric Clarification and Development” AIAA-2022-1245
- MCAD evaluation and initial meshing, **[8 Authors]** “Geometry Modeling for Unstructured Mesh Adaptation” AIAA-2019-2946
- Boundary representation tolerance and geometry surrogates, **[5 Authors]** “Boundary Representation Tolerance Impacts on Mesh Generation and Adaptation” AIAA-2021-2992
- Parallel execution **[5 Authors]** “Parallel Anisotropic Unstructured Grid Adaptation” AIAAJ 2021

Analogous Approach to Unsteady Adaptation

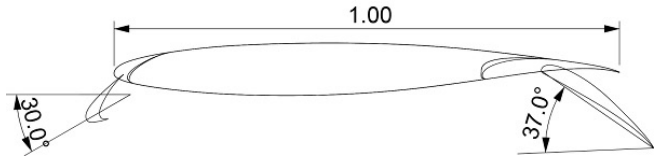
- Analytic metric to model needs of unsteady adaptation
- Analytic unsteady sensor scalar field (and displacement)
- 2D geometries (not physically relevant, but allows clear feedback)
- 2D geometries extruded to finite span
- Simple 3D geometries
- Complex 3D geometries

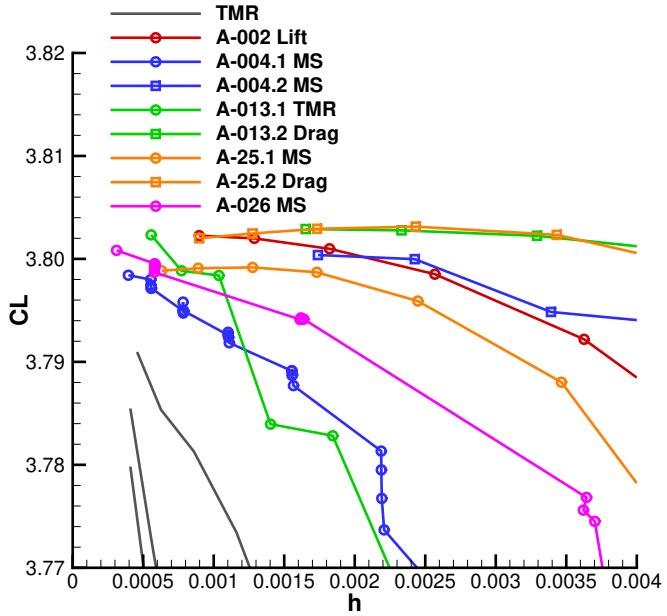
Leveraged RANS Solver Verification





- Turbulence Modeling Resource
  - Cases and Grids for Turbulence Model Numerical Analysis
- Special Sessions on Benchmark Turbulent Flows
  - AIAA 2015-1746, AIAA-2018-1102, etc.
- High Fidelity CFD Workshop 2022
- Verification test cases in multiple AIAA Prediction Workshops: DPW, HLPW, etc.
- Consistent implementations
- Robust nonlinear solvers





Verification of Eddy-Resolving Solvers

- HRLES, WMLES, and LB verification cases out-of-scope for HLPW-4
- International Workshop on High-Order CFD Methods
- High Fidelity CFD Workshop will emphasize verification in future
- Wall-modeled Large Eddy Simulation Resource
- Lack of consensus on subgrid, blending, and wall models presents challenges
- Modeling often coupled to the mesh via a filter width
- Exchange location for wall model is an additional degree of freedom or constrained by the mesh
- Convergence of temporal and spatial dimensions
- Unstructured simplex meshes less common
- Can mesh adaptation accelerate the verification of these methods?

refine

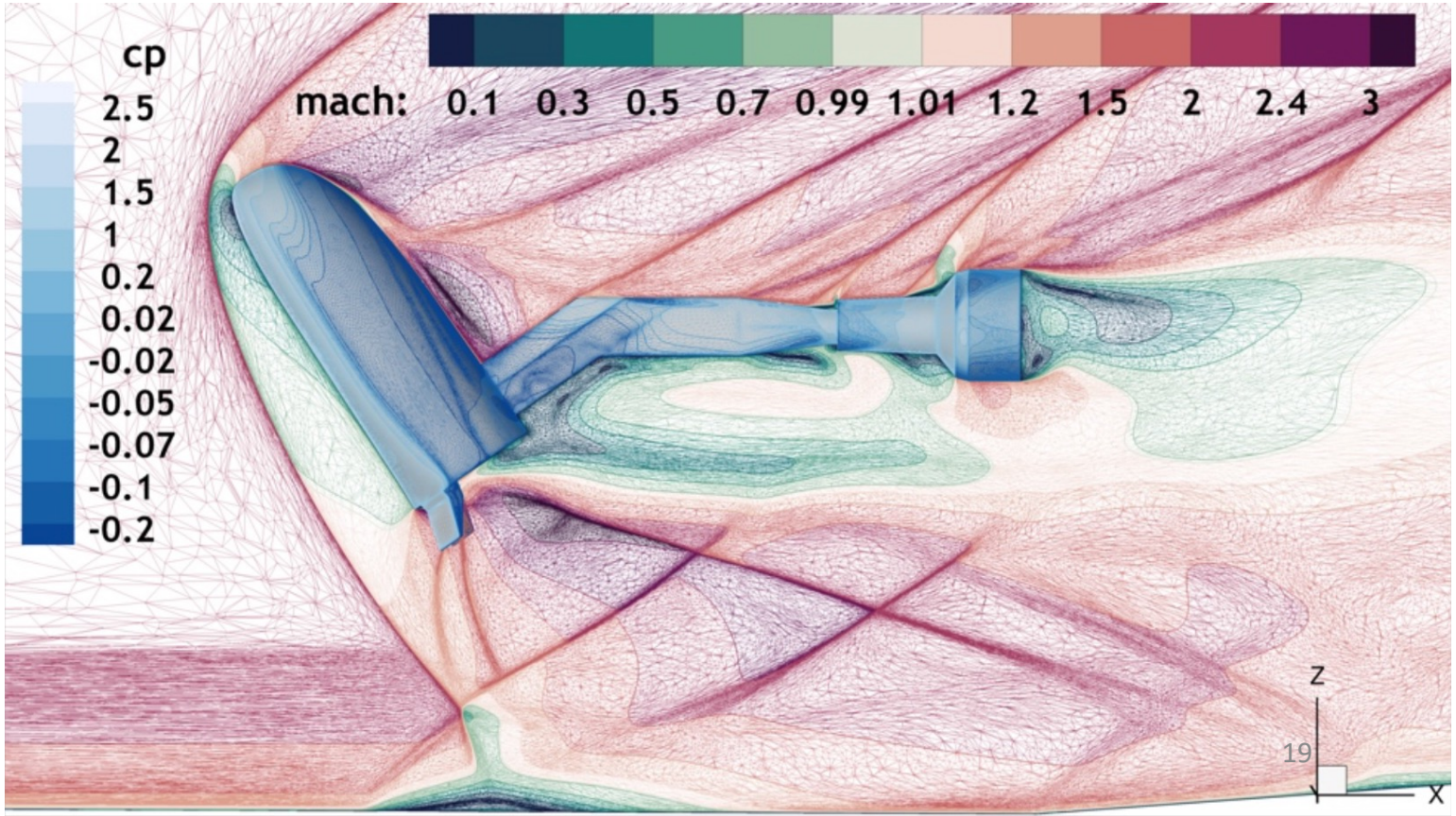
- Mesh adaptation infrastructure (Park, PhD Thesis, MIT, 2008)
  - https://GitHub.com/NASA/refine
  - Metric construction
  - Remeshing
  - Utilities (file translation, solution interpolation, partitioning, visualization)
- Geometry generation/import and evaluation
  - Engineering Sketch Pad (AIAA 2013-3073)
  - OpenCSM (AIAA 2013-701)
  - EGADS (AIAA 2012-683)

Multiscale Metric

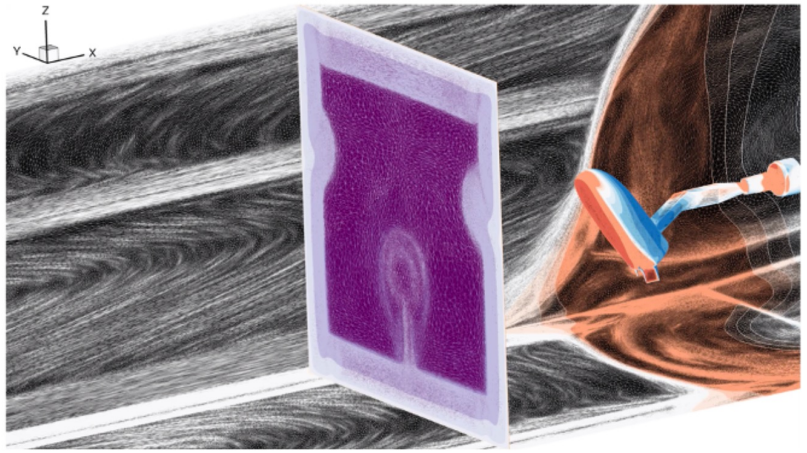
- Hessian reconstructed from solution
- Local scaling to control interpolation error L^P-norm of smooth and nonsmooth features simultaneously
- Without local scaling classical Hessian methods control the L^∞-norm (nonsmooth features only)
- Does not require adjoint solution
- Requires more mesh than goal-based metrics for equivalent accuracy
- Tolerant to incomplete iterative convergence
- Extension to unsteady possible (i.e., chaotic flow)

CobraMRV Supersonic Control-Surface Effectiveness (AIAA 2021-2964)

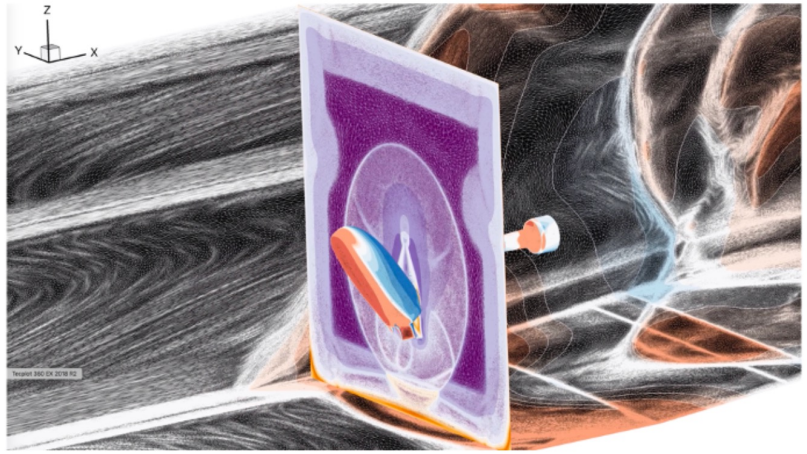
- Simulate the wind tunnel test including model interaction with wind tunnel walls



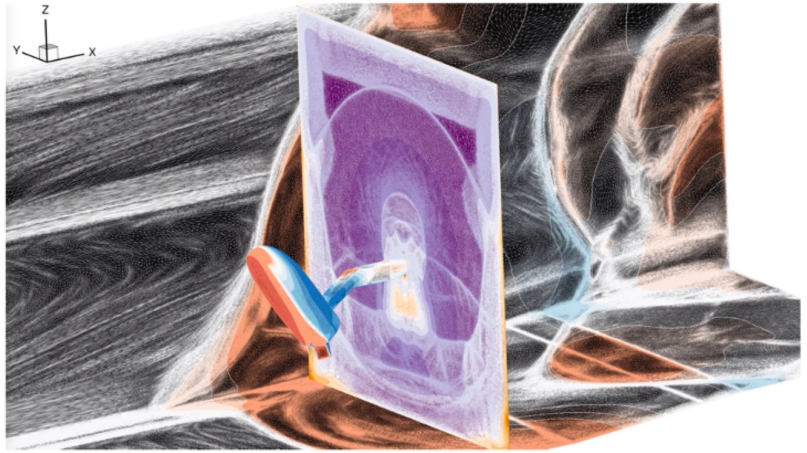
CobraMRV Supersonic Control-Surface Effectiveness (AIAA 2021-2965)



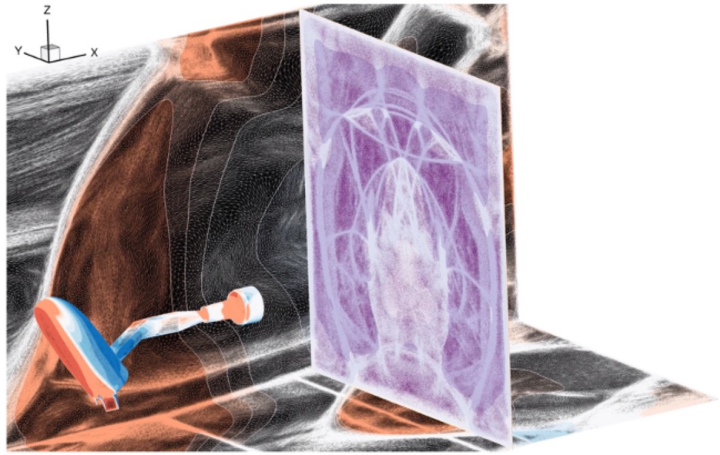
(a) Upstream of CobraMRV



(b) Flaps and aft body

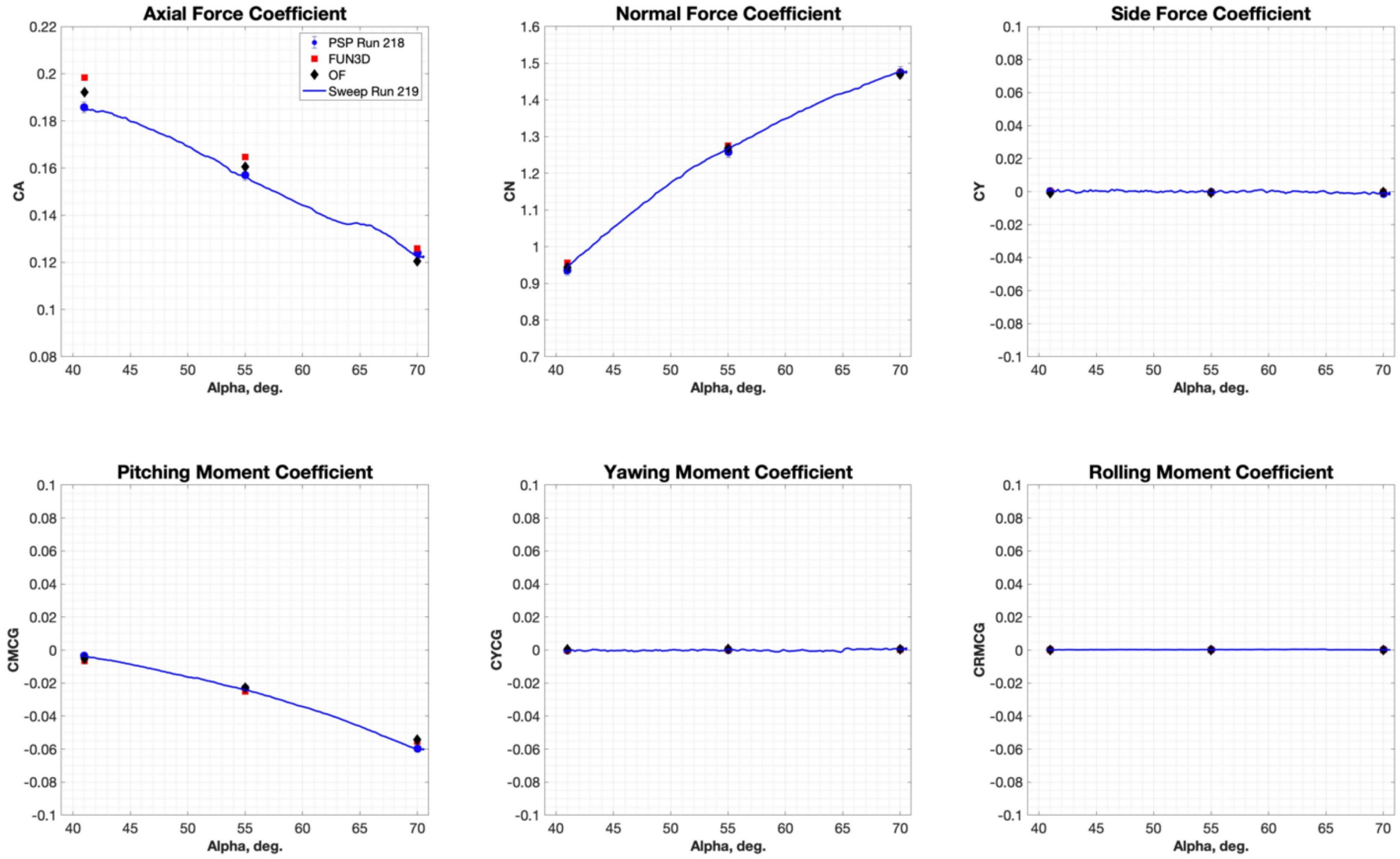


(c) Sting end



(d) Downstream of model

CobraMRV Supersonic Control-Surface Effectiveness (AIAA 2021-2964)

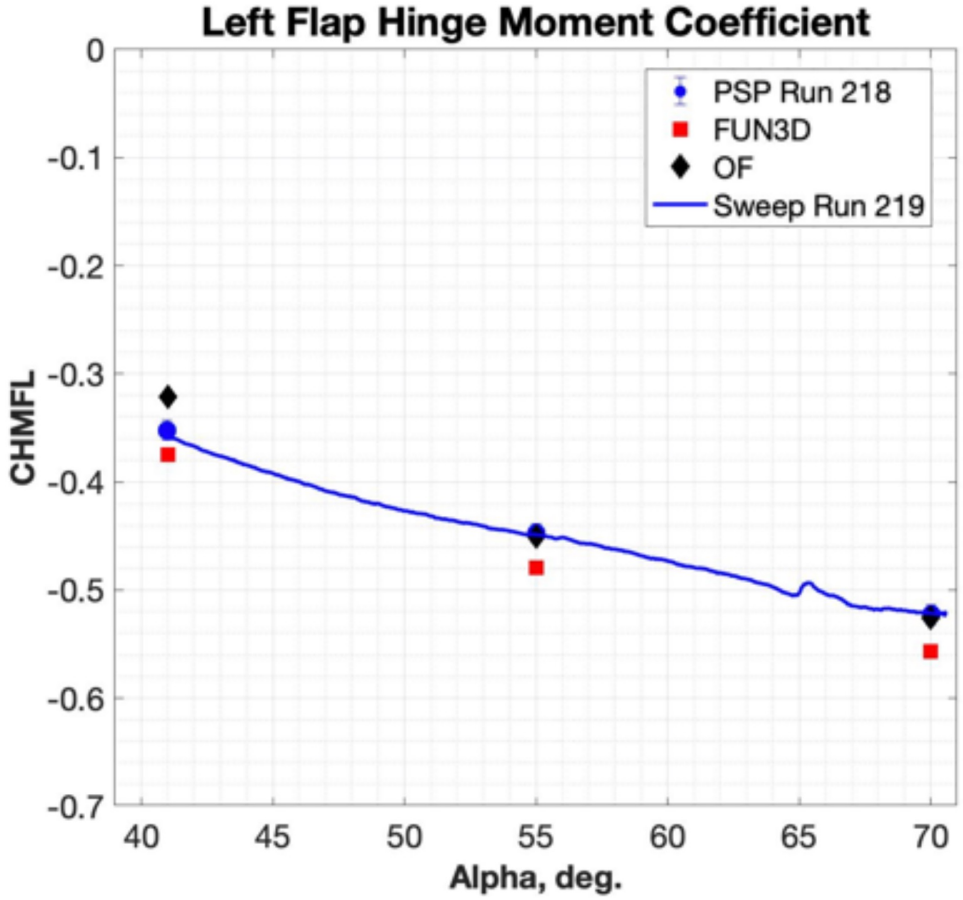


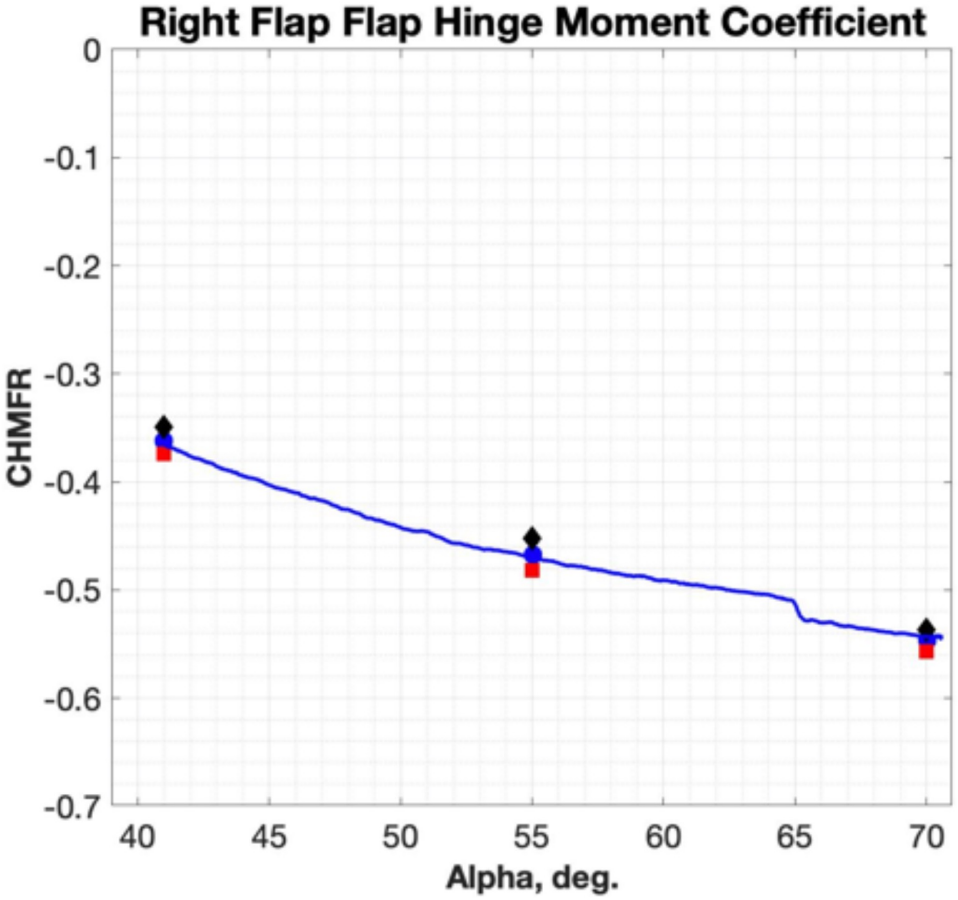
Pressure Sensitive Paint (PSP) with uncertainty

OVERFLOW (OF) adapted 400M

FUN3D adapted 20M

CobraMRV Supersonic Control-Surface Effectiveness (AIAA 2021-2964)



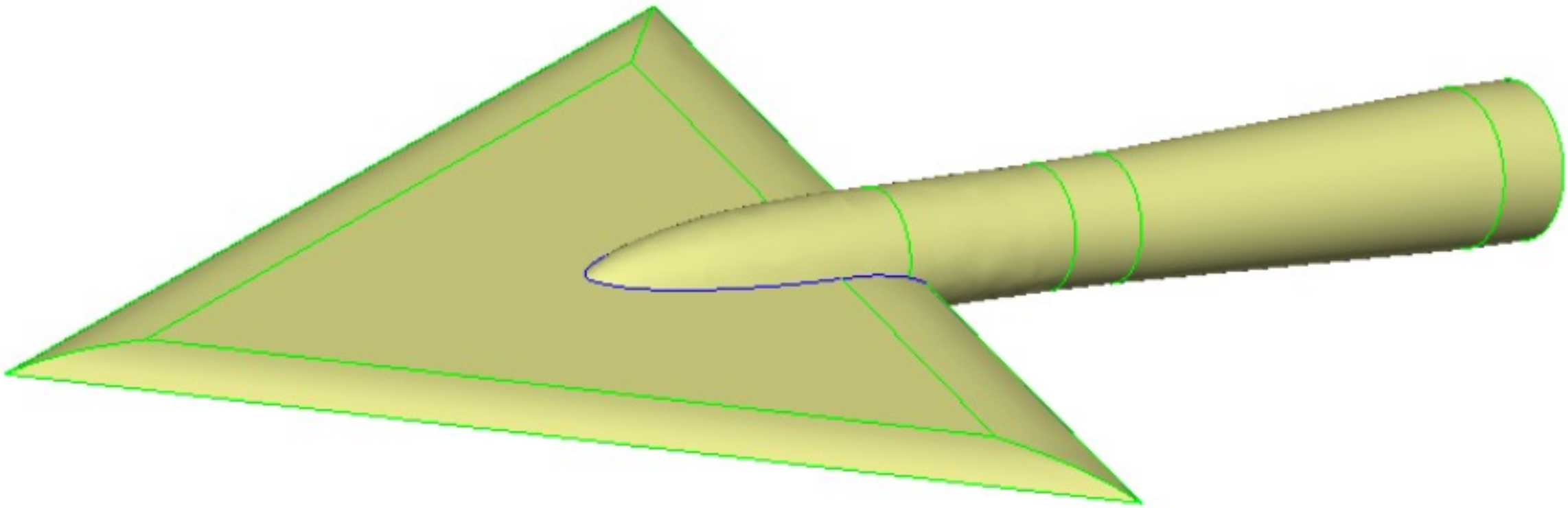


Fixed-Point Metric Applied to HRLES

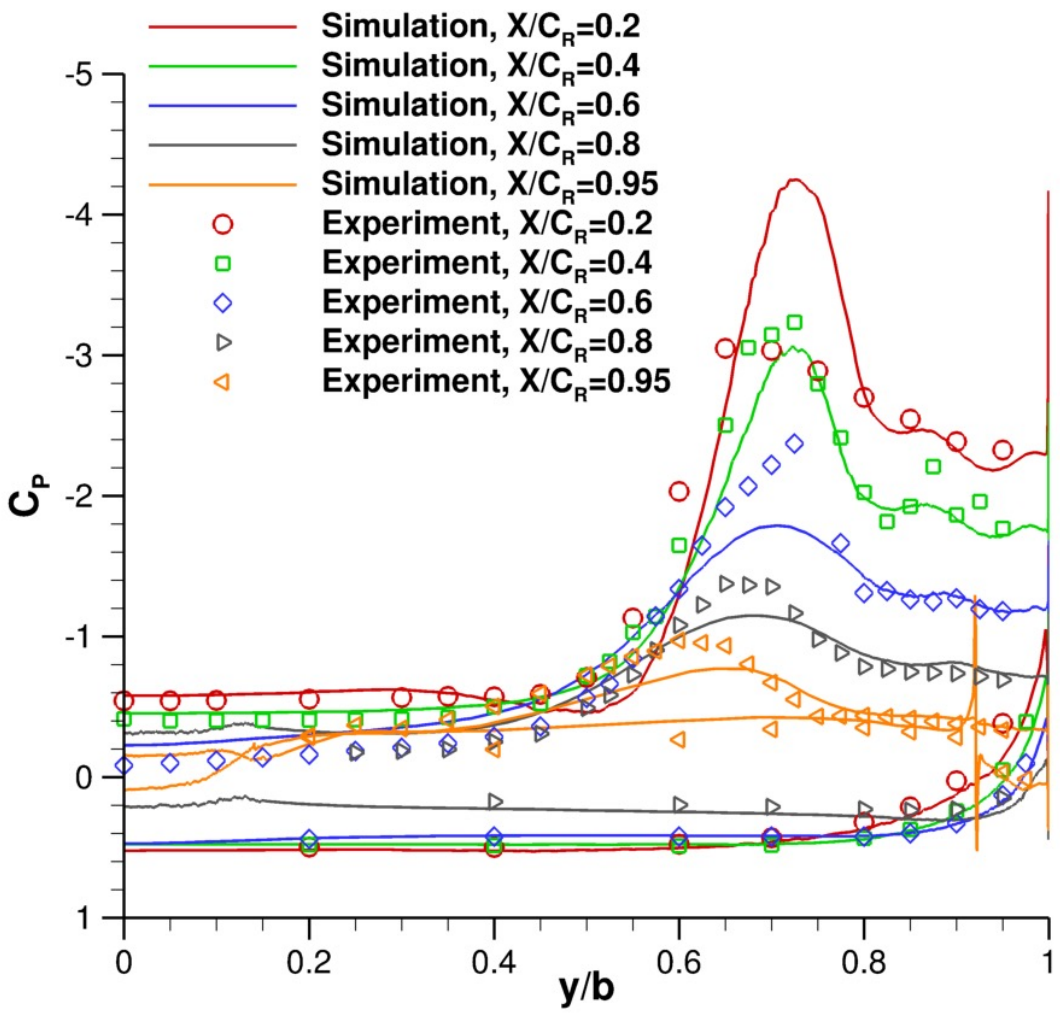
- Exploration is shown in AIAA 2020-1139
- Multiscale metric constructed by a L^1-norm of ensemble of Hessians from solution snapshots (reverts to multiscale in steady case)
- Appears to exacerbate the “Gray Area Problem” where modeled turbulence (RANS) is slow to transition to resolved turbulence (LES) due to anisotropy of the mesh in this transition region
- Used where RANS modeling error is large

65° Delta Wing with Sharp Leading Edge

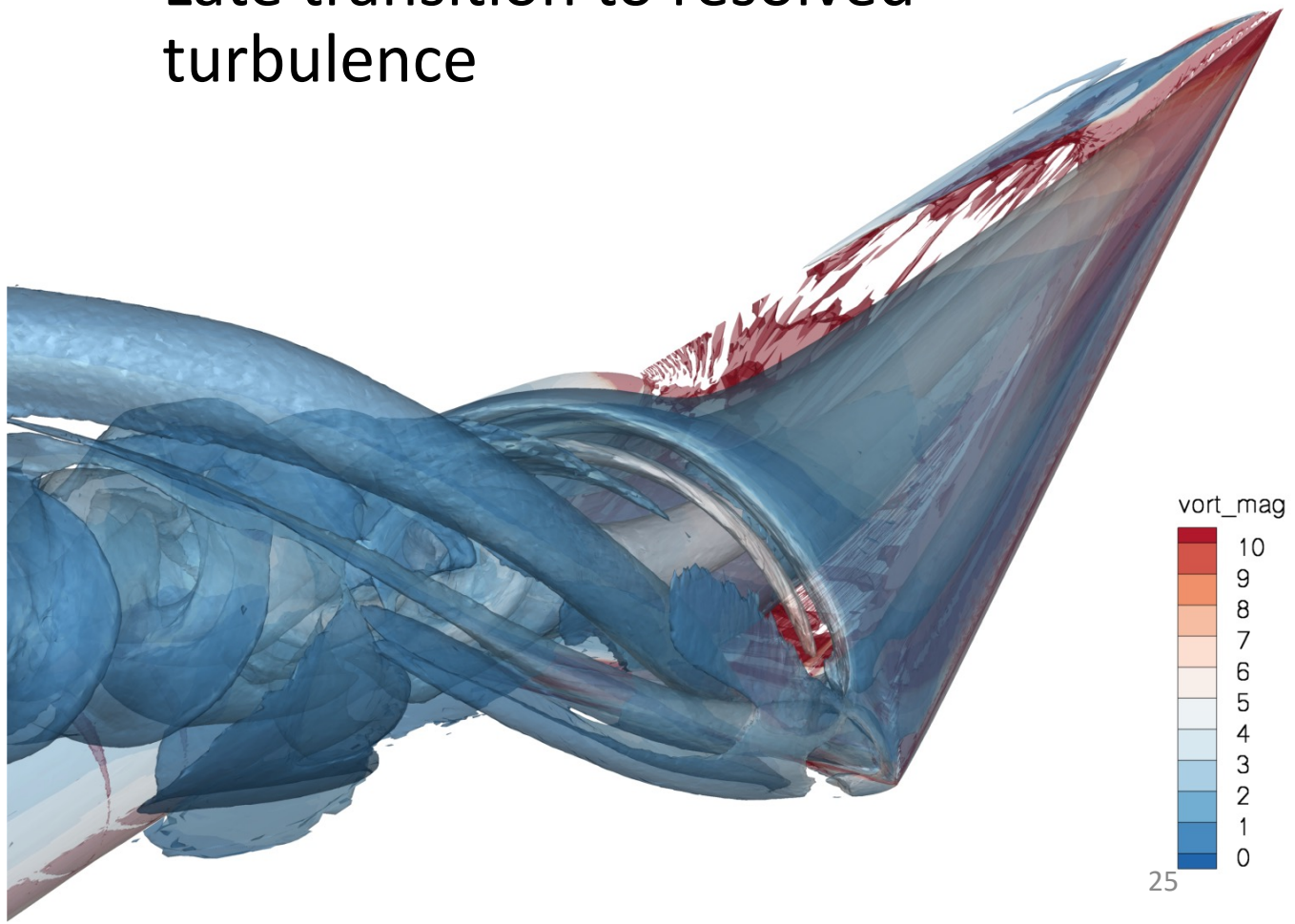
- Created with OpenCSM from drawings (Chu and Luckring, NASA TM-4645, 1996)



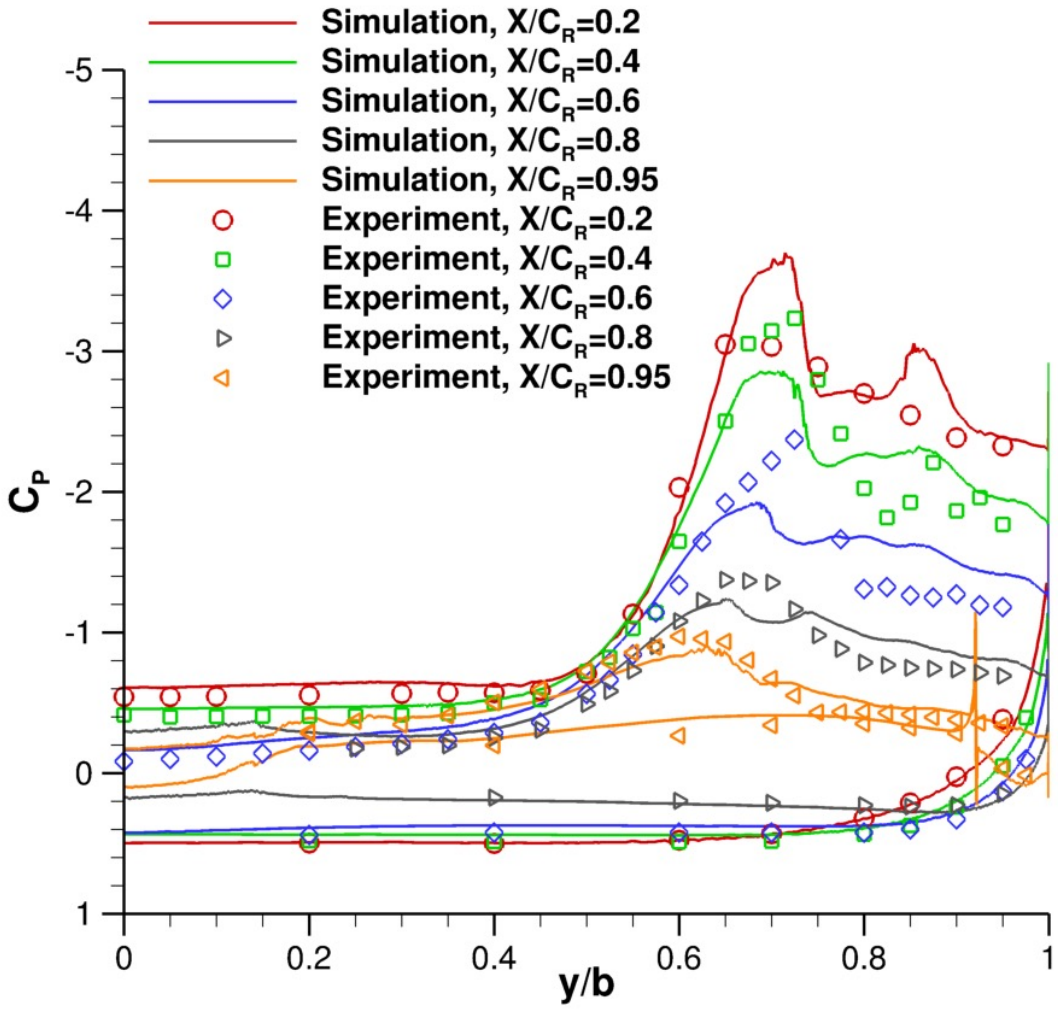
65° Delta Wing FUN3D-FV DDES-SA-RC Adapt

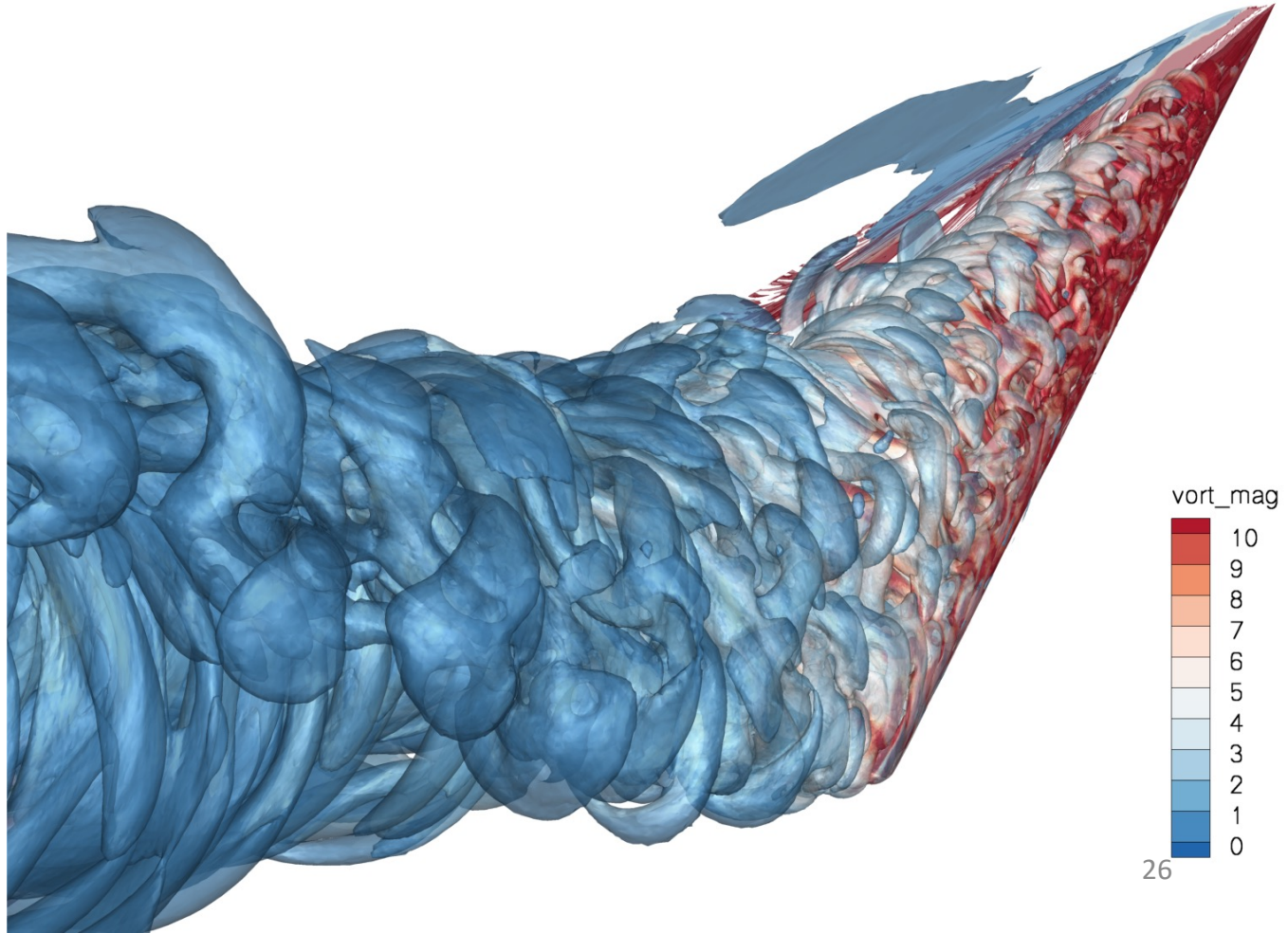


- Late transition to resolved turbulence



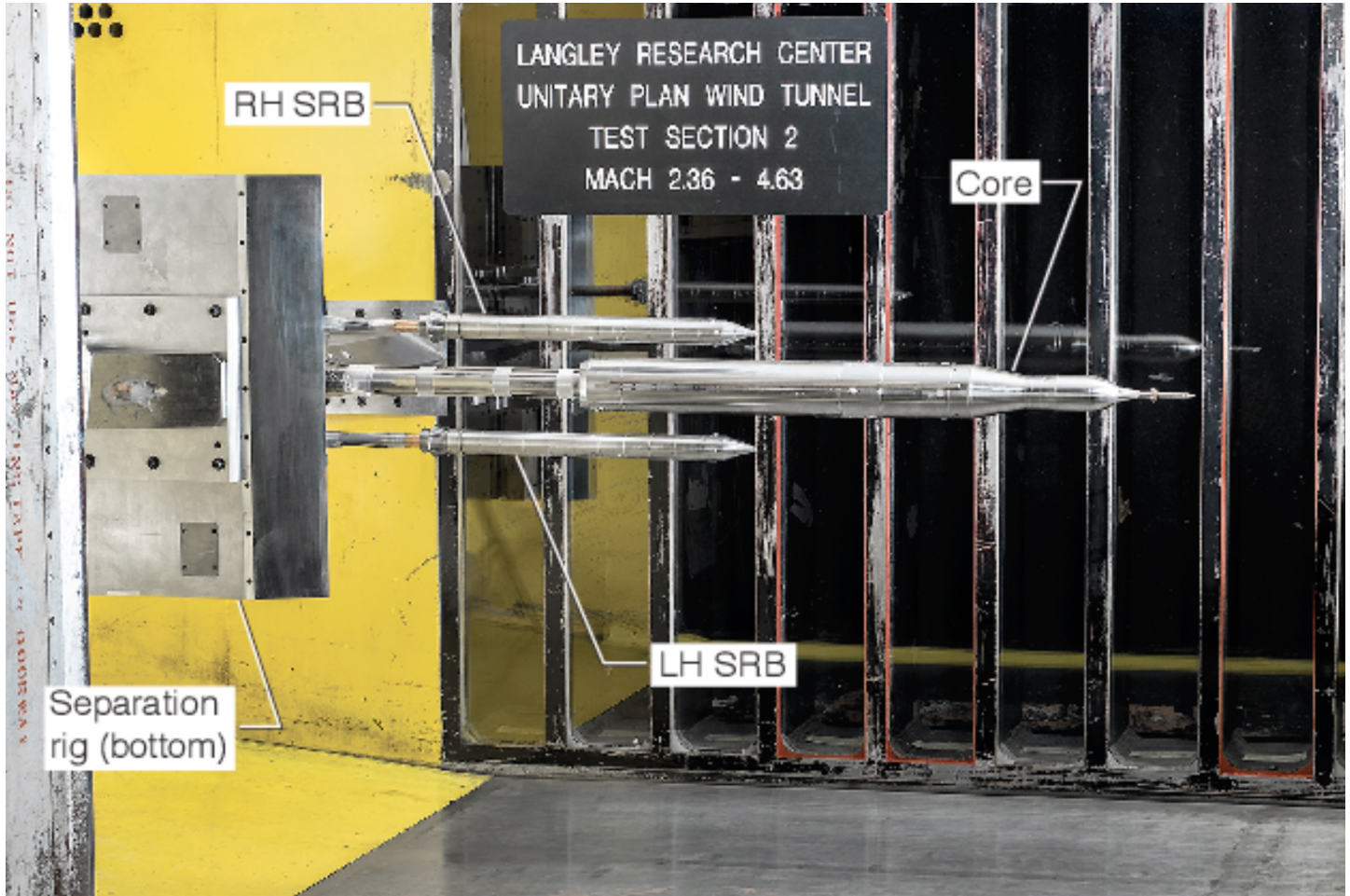
65° Delta Wing FUN3D-FV Laminar Adapt





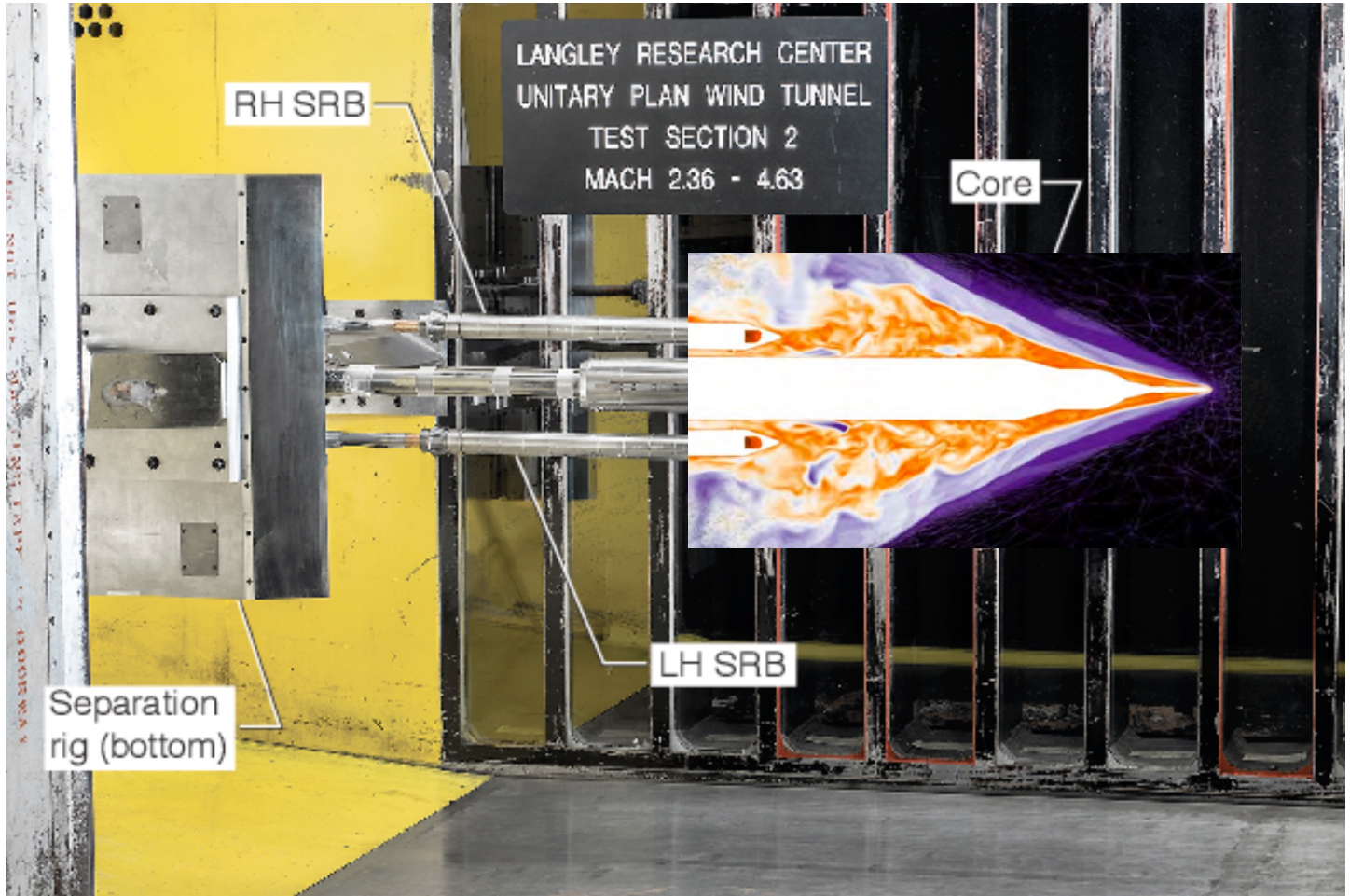
Space Launch System Solid Rocket Booster Separation (AIAA 2021-2961)

- Simulation of separation motors in tunnel with DDES



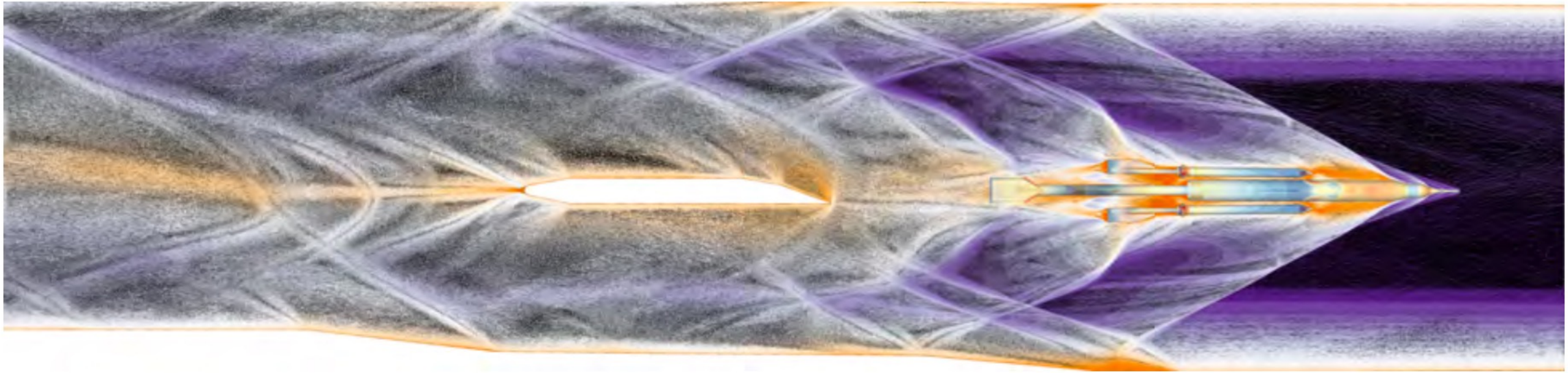
Space Launch System Solid Rocket Booster Separation (AIAA 2021-2961, AIAA 2021-2966)

- Simulation of separation motors in tunnel with DDES



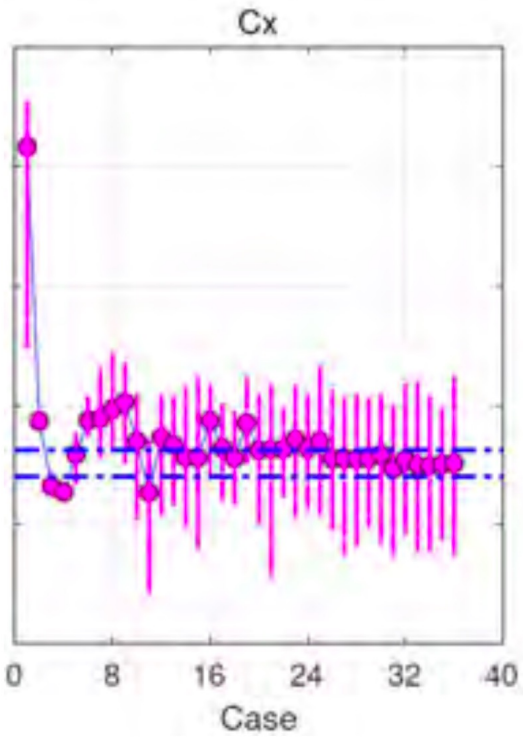
Space Launch System Solid Rocket Booster Separation (AIAA 2021-2966)

- Simulation of separation motors in tunnel with DDES

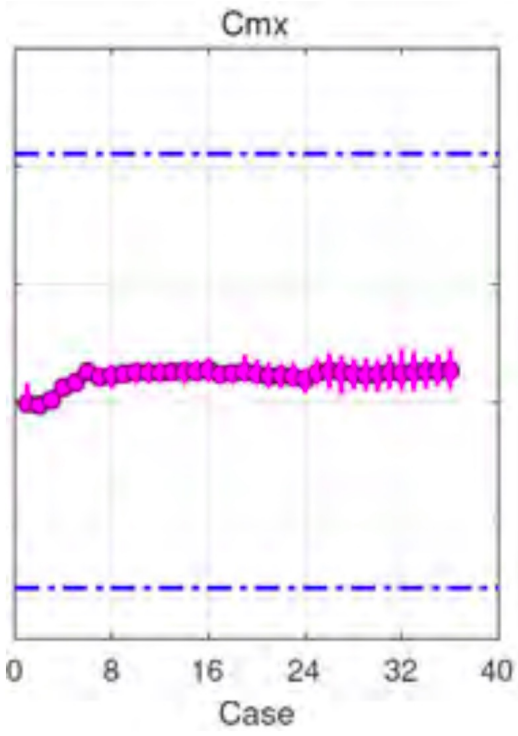


Space Launch System Solid Rocket Booster Separation (AIAA 2021-2966) Core

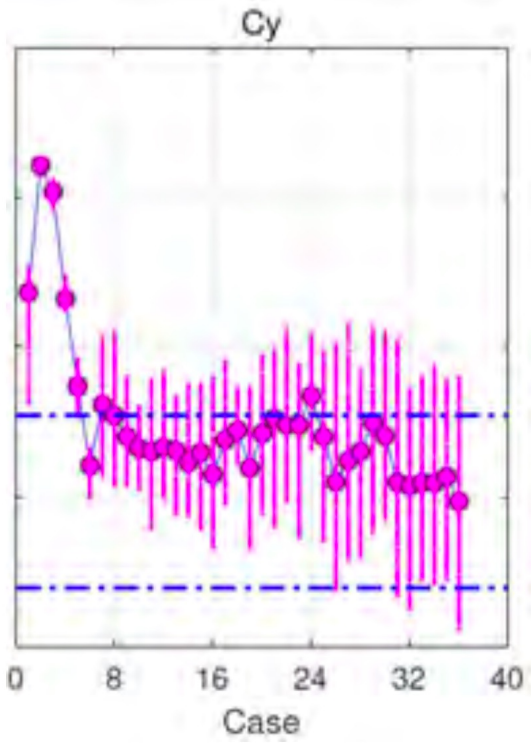
- Dot-dash lines represent 2-sigma balance uncertainty



(a) Nominal case C_x convergence for the core.



(b) Nominal case C_{mx} convergence for the core.

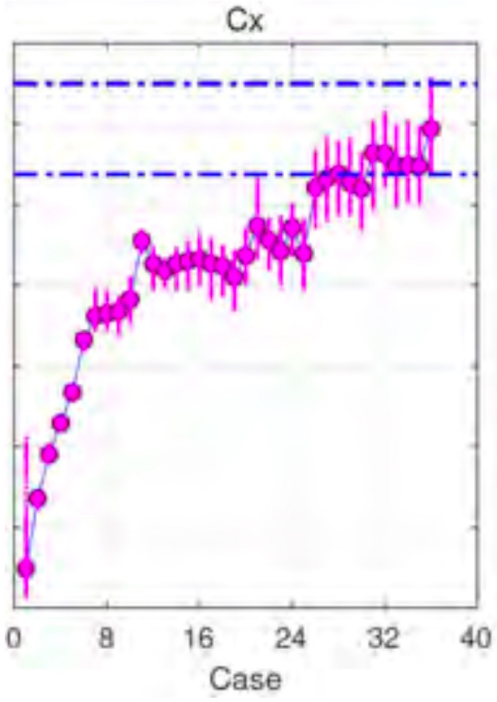


(c) Nominal case C_y convergence for the core.

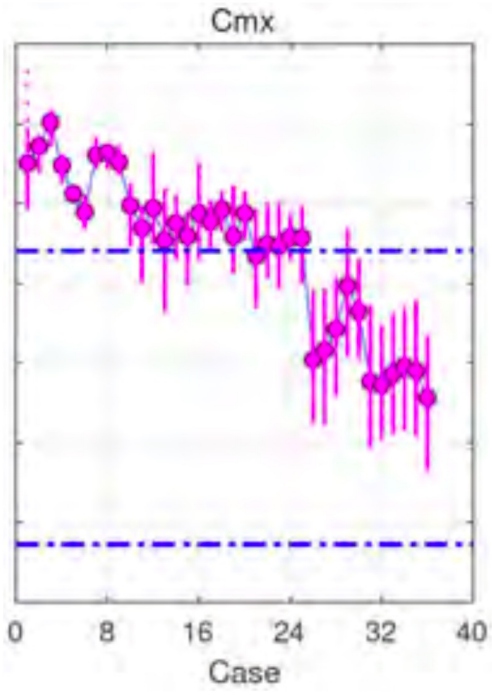
Cases are the series of adapted meshes from 1M to 64M

Space Launch System Solid Rocket Booster Separation (AIAA 2021-2966) Right Booster

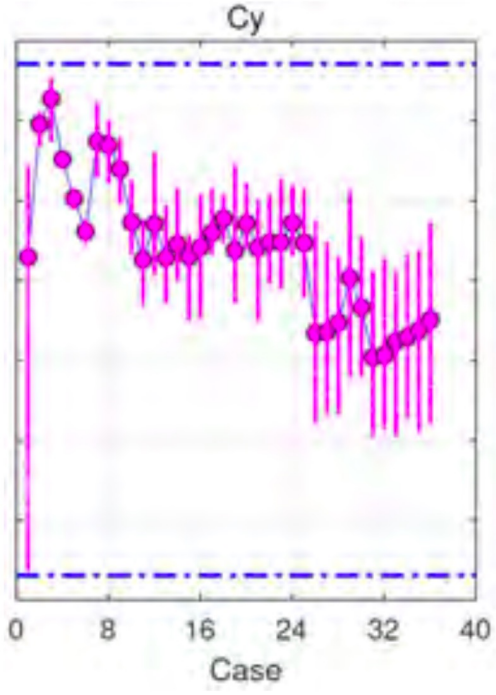
- Dot-dash lines represent 2-sigma balance uncertainty



(d) Nominal case C_x convergence for the right SRB.



(e) Nominal case C_{mx} convergence for the right SRB.

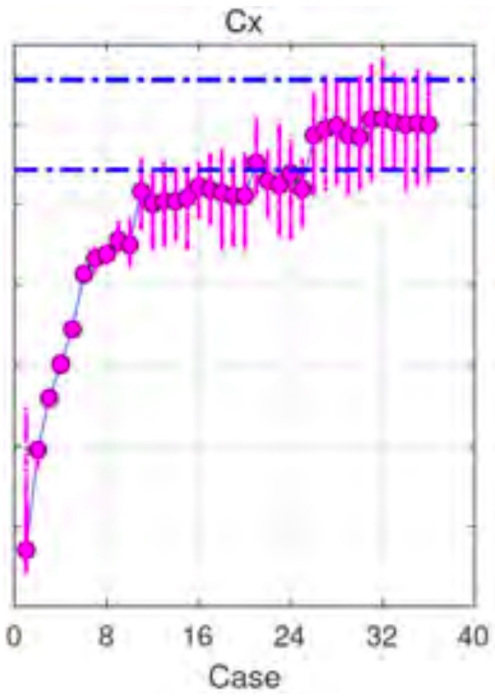


(f) Nominal case C_y convergence for the right SRB.

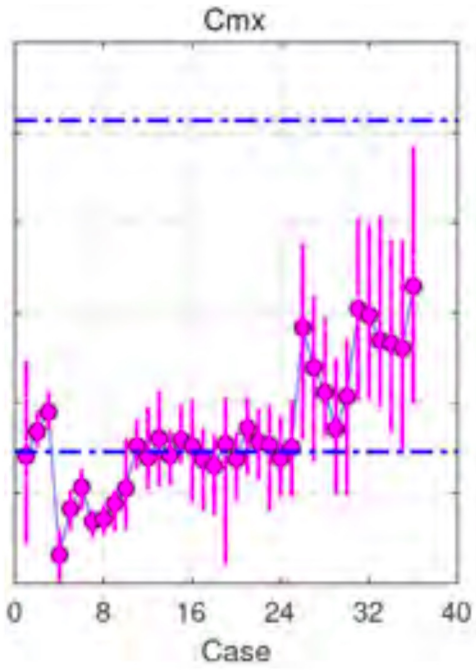
Cases are the series of adapted meshes from 1M to 64M

Space Launch System Solid Rocket Booster Separation (AIAA 2021-2966) Left Booster

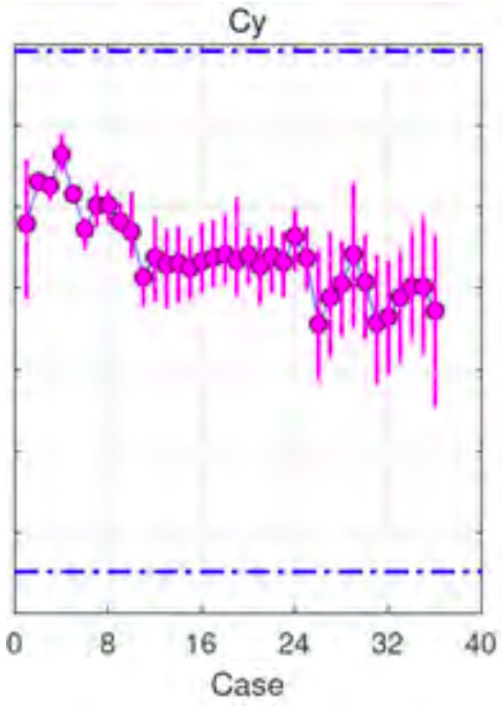
- Dot-dash lines represent 2-sigma balance uncertainty



(g) Nominal case C_x convergence for the left SRB.



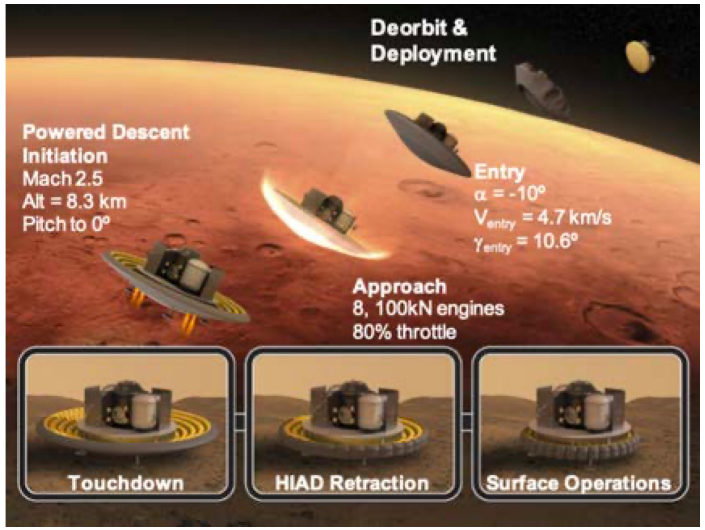
(h) Nominal case C_{mx} convergence for the left SRB.

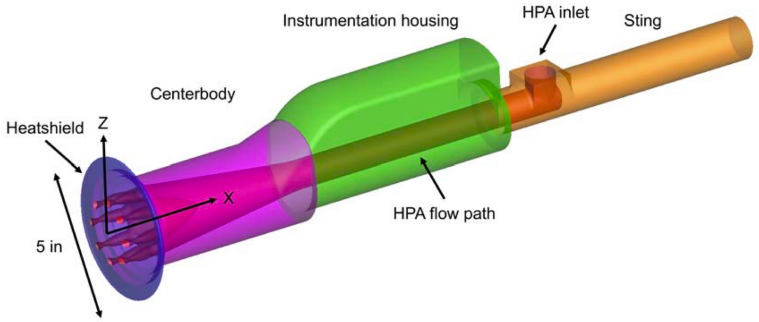


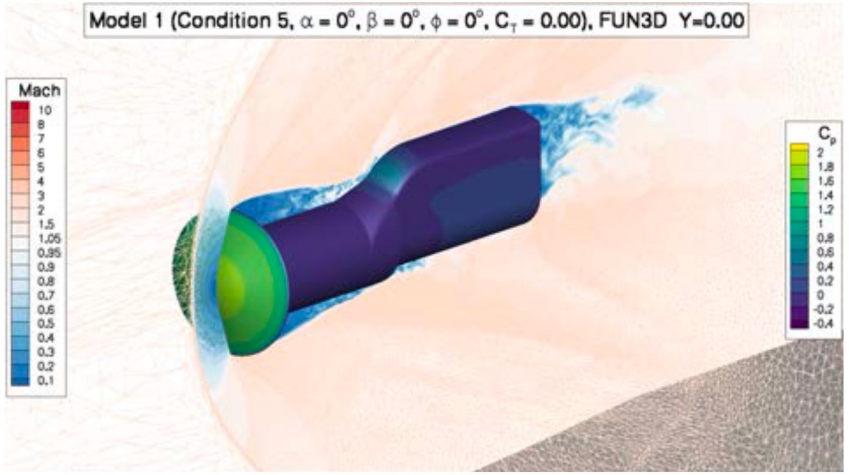
(i) Nominal case C_y convergence for the left SRB.

Cases are the series of adapted meshes from 1M to 64M

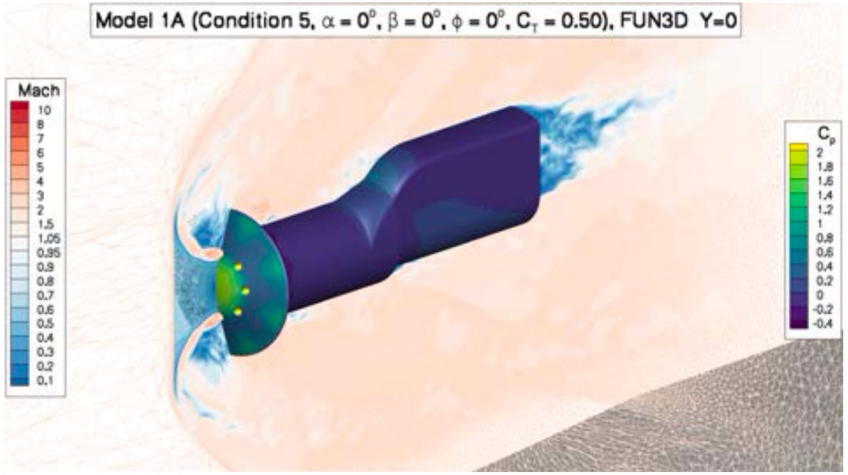
Mars Retropropulsion Concepts (AIAA-2022-912)



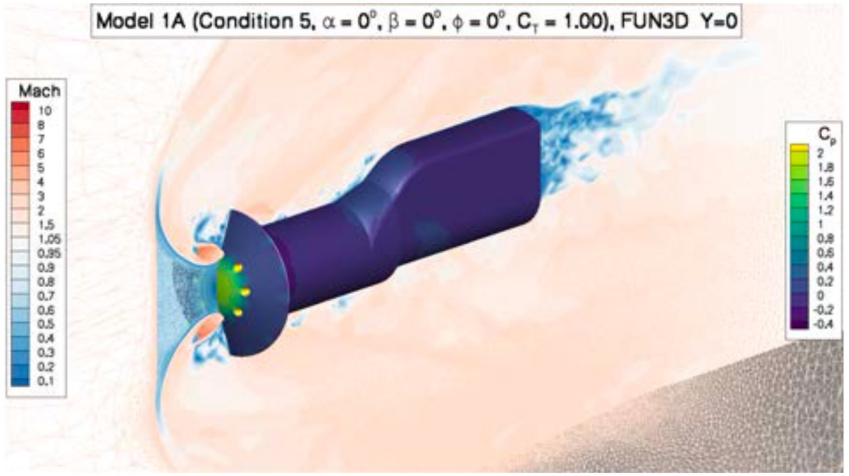




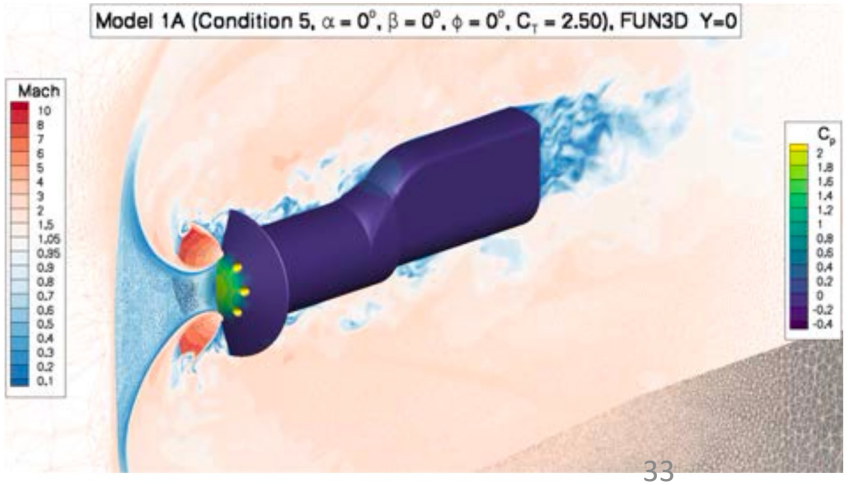
(a) $C_T = 0$



(b) $C_T = 0.5$

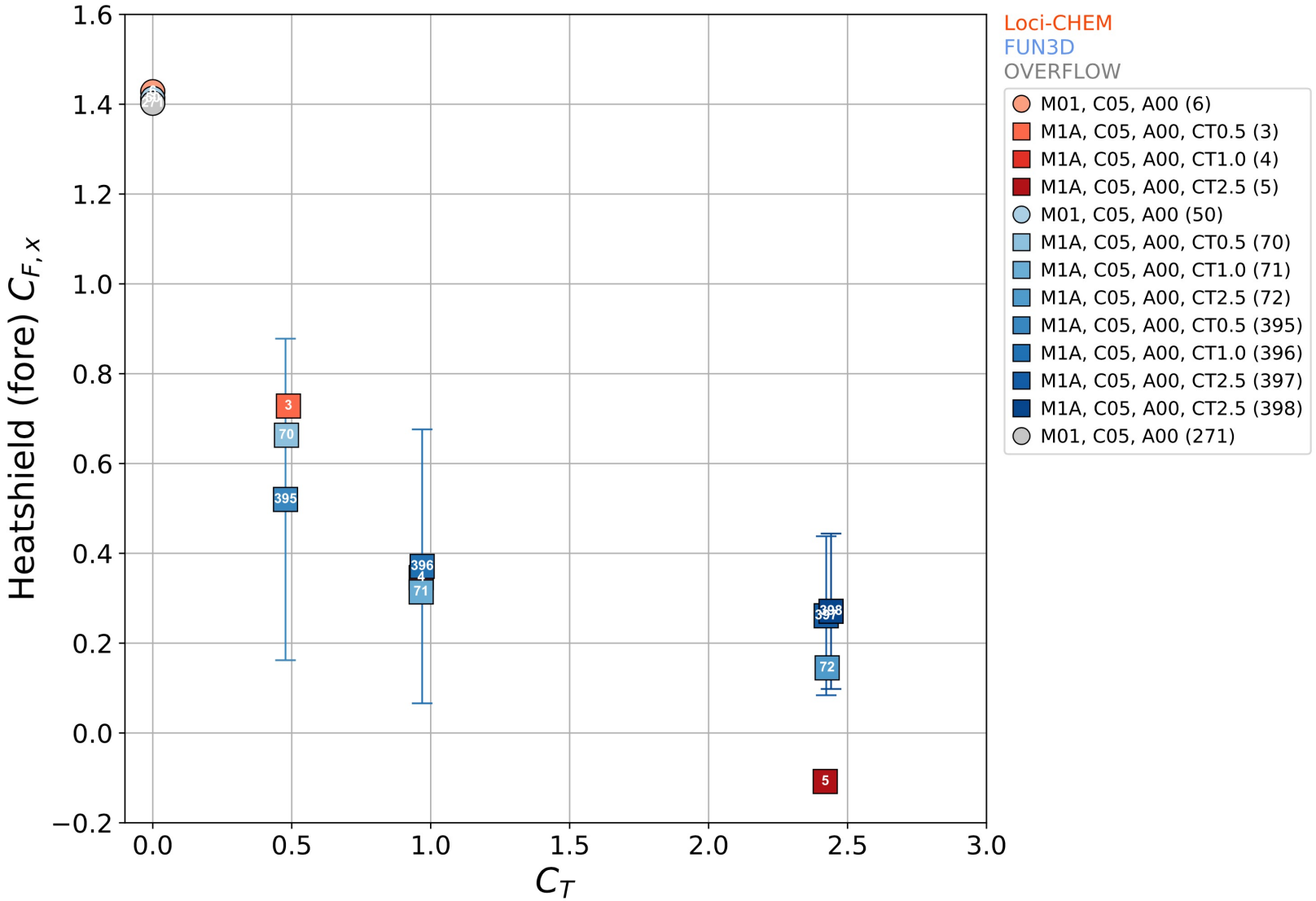


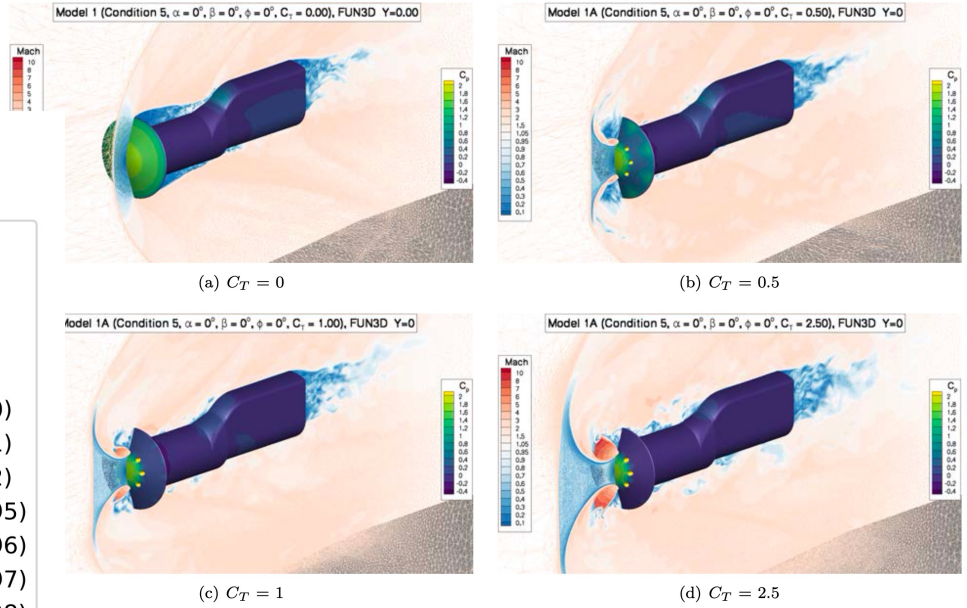
(c) $C_T = 1$



(d) $C_T = 2.5$

Mars Retropropulsion Concepts (AIAA-2022-912)



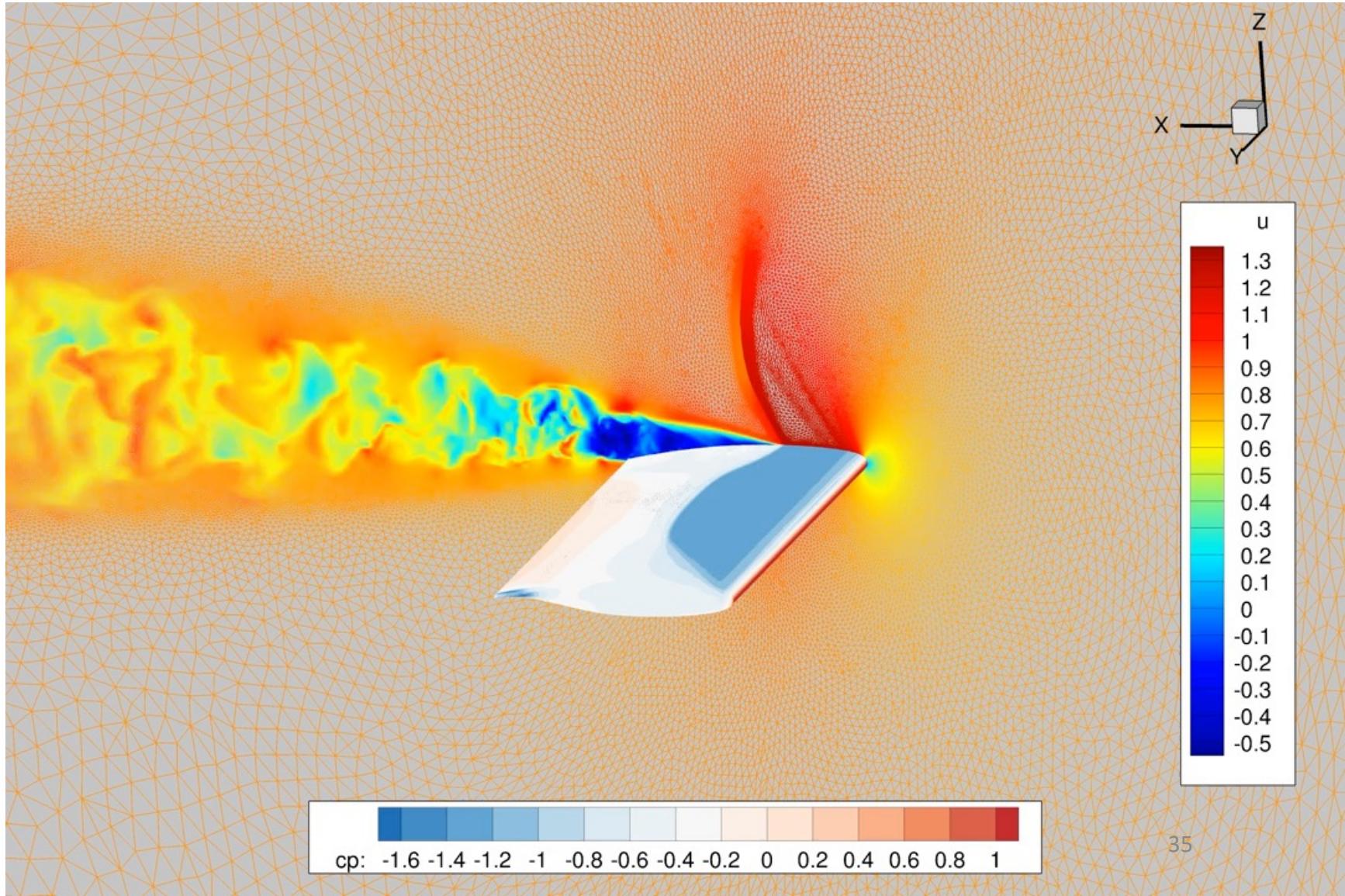


(a) $C_T = 0$ (b) $C_T = 0.5$ (c) $C_T = 1$ (d) $C_T = 2.5$

- Loci-CHEM 200M expert-crafted RANS
- FUN3D 25M and 12.5M adapted DDES
- OVERFLOW 250M adapted URANS

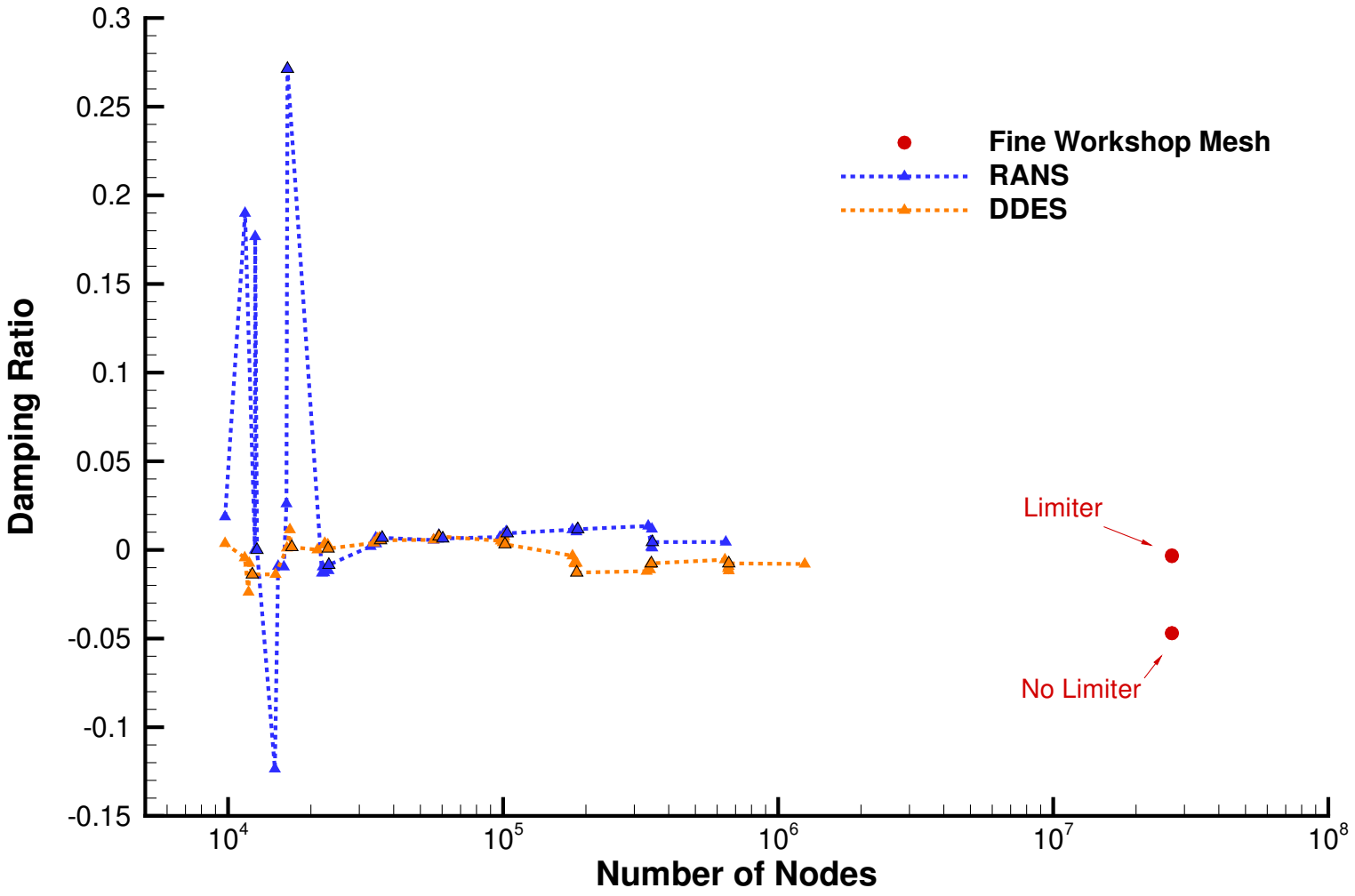
Benchmark Supercritical Wing (BSCW)

- Mach 0.85
- DDES-SA
- More shock movement than unsteady SA
- Metric extended to deforming meshes, but mesh deformation not robust



Benchmark Supercritical Wing (BSCW)

- Mach 0.85
- DDES-SA
- Damping on adapted meshes approaches 20x larger expert-crafted meshes

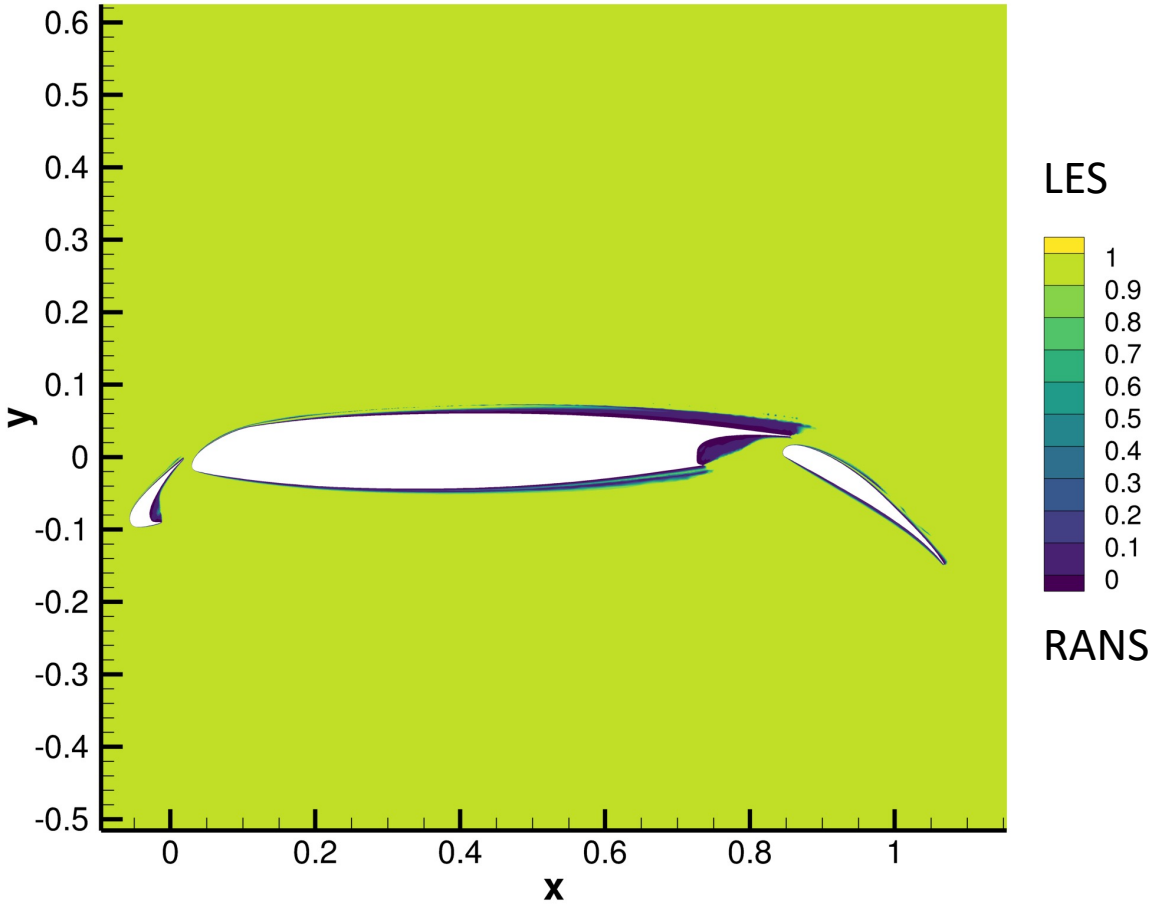


HRLES Recent Progress

- The fixed-point metric contains the mean solution anisotropy
- Anisotropy suppresses the eddy formation and sustainment
- Using the RANS/LES blending to set aspect ratio to one for LES
- Only as good as the underlying HRLES scheme (modeled-stress depletion)
- Improvements to the HRLES scheme are expected to improve mesh adaptation

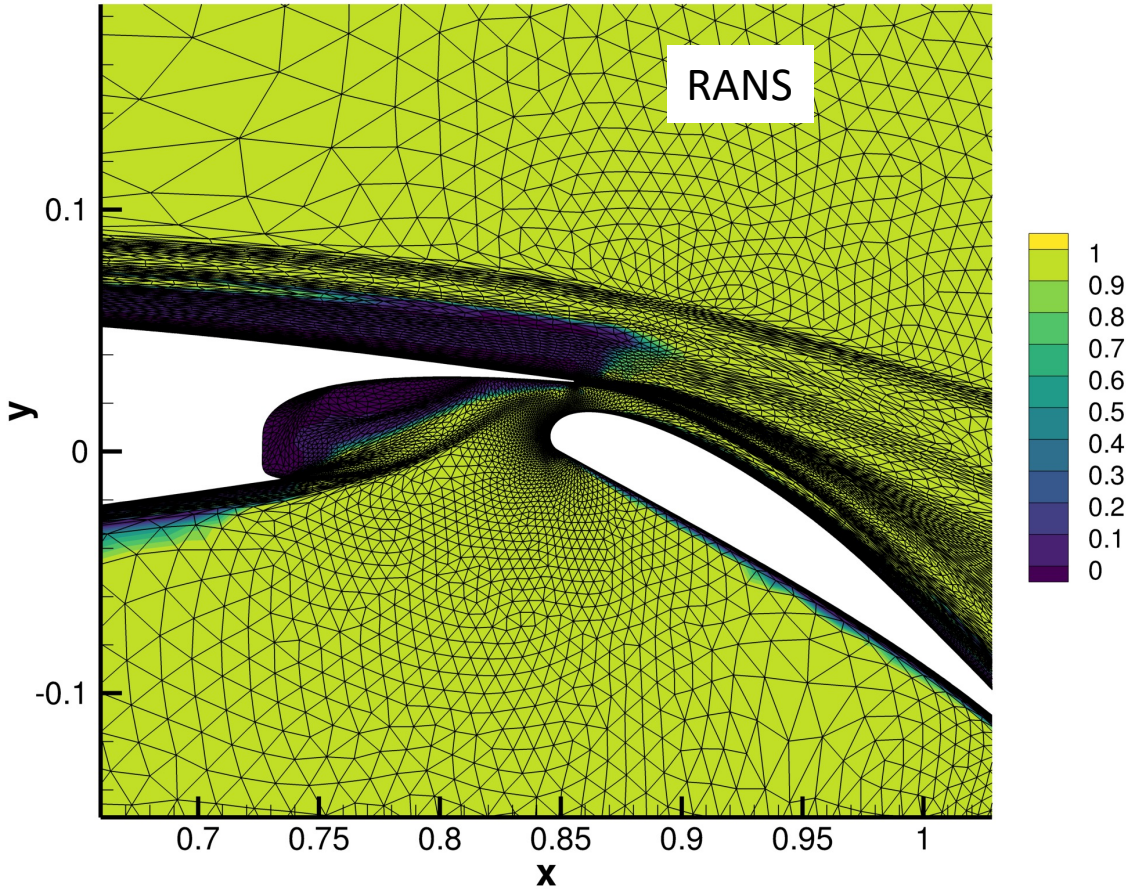
CRM-HL 2D Airfoil, 16° Angle of Attack

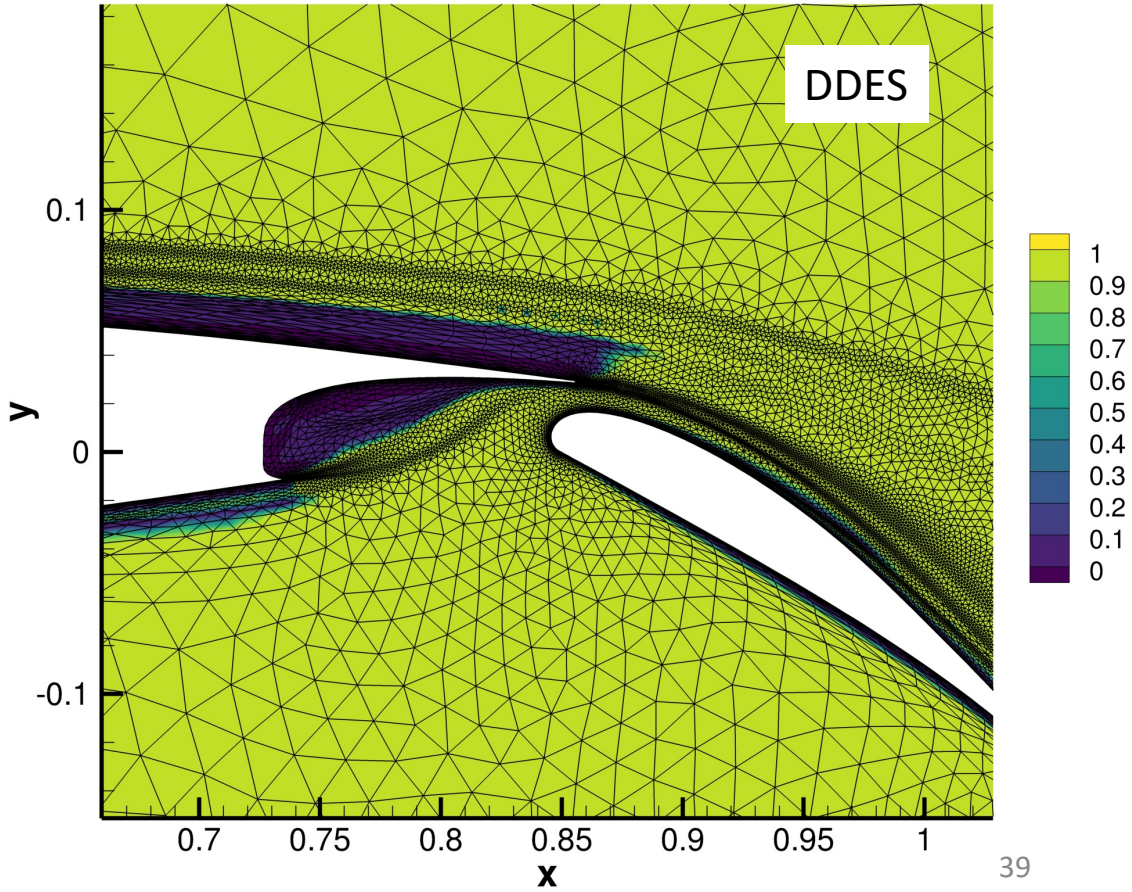
- DDES f_d blending function for adapted RANS-SA



CRM-HL 2D Airfoil, 16° Angle of Attack

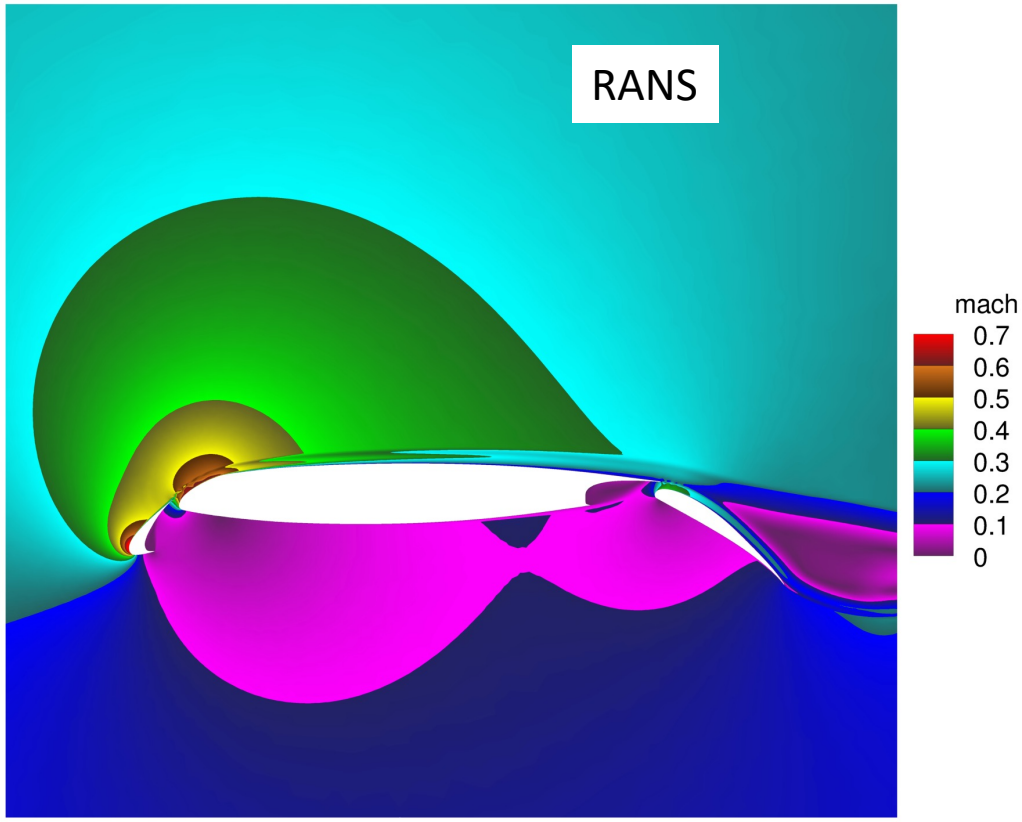
- Anisotropy determined by DDES f_d

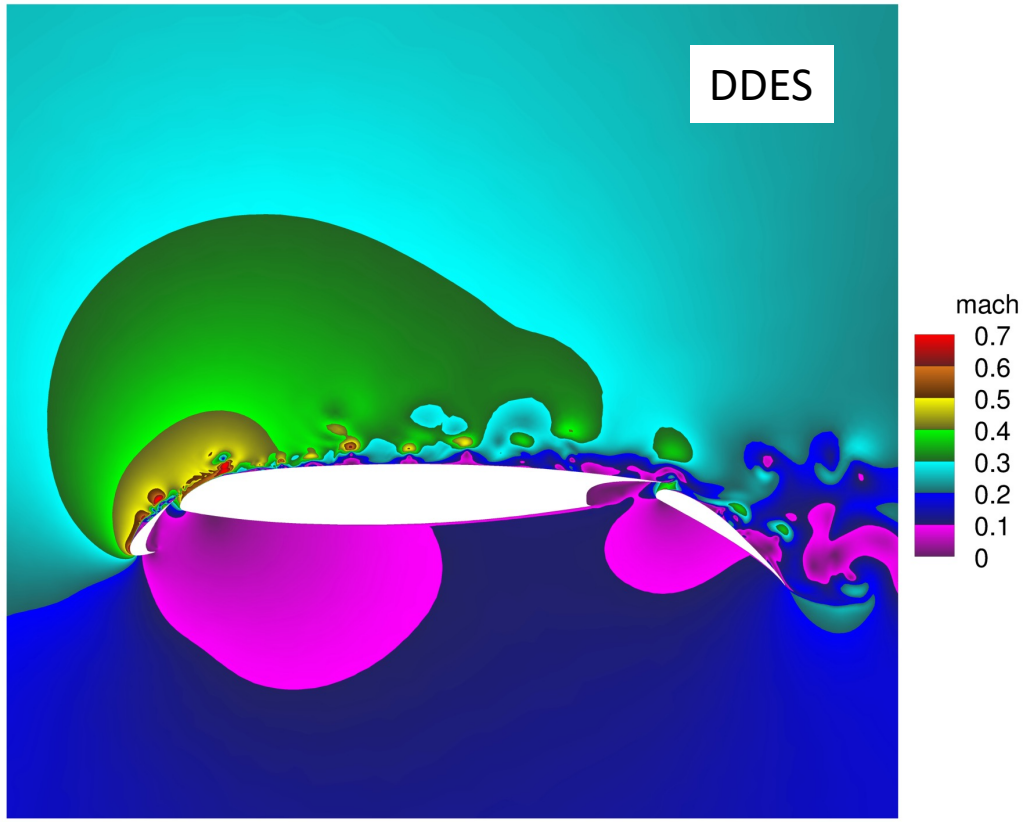




CRM-HL 2D Airfoil, 16° Angle of Attack

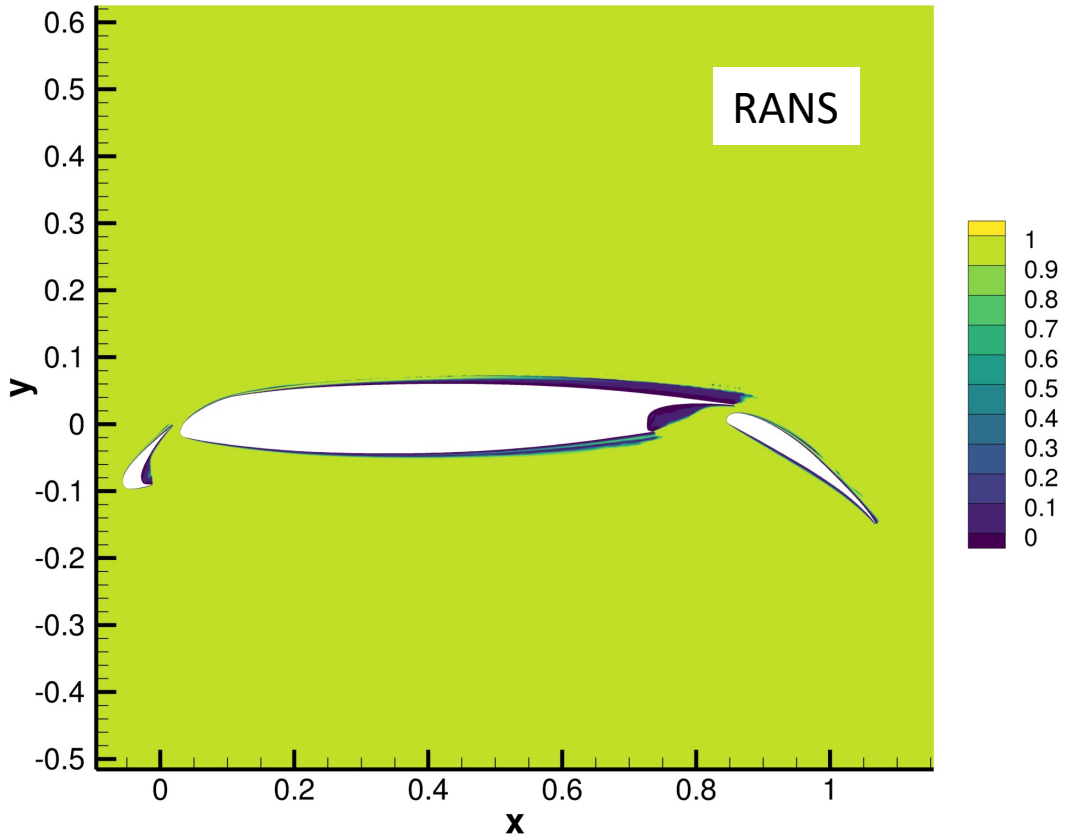
- Mach number

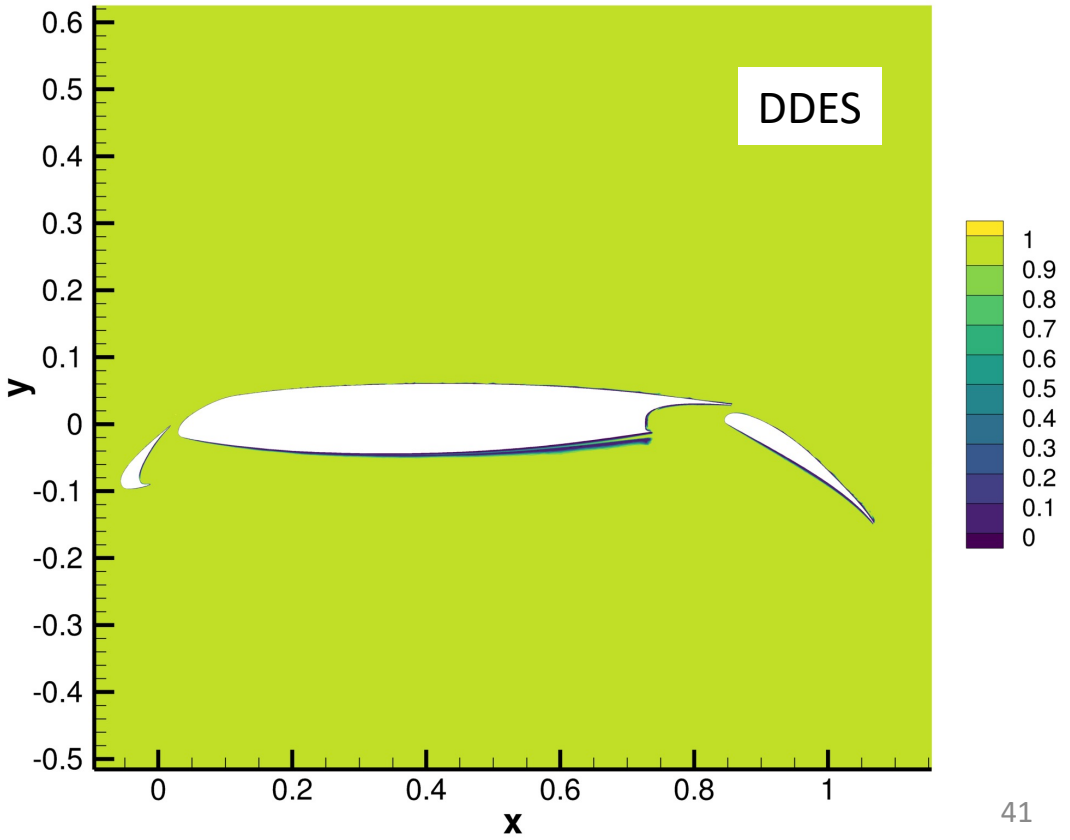




CRM-HL 2D Airfoil, 16° Angle of Attack

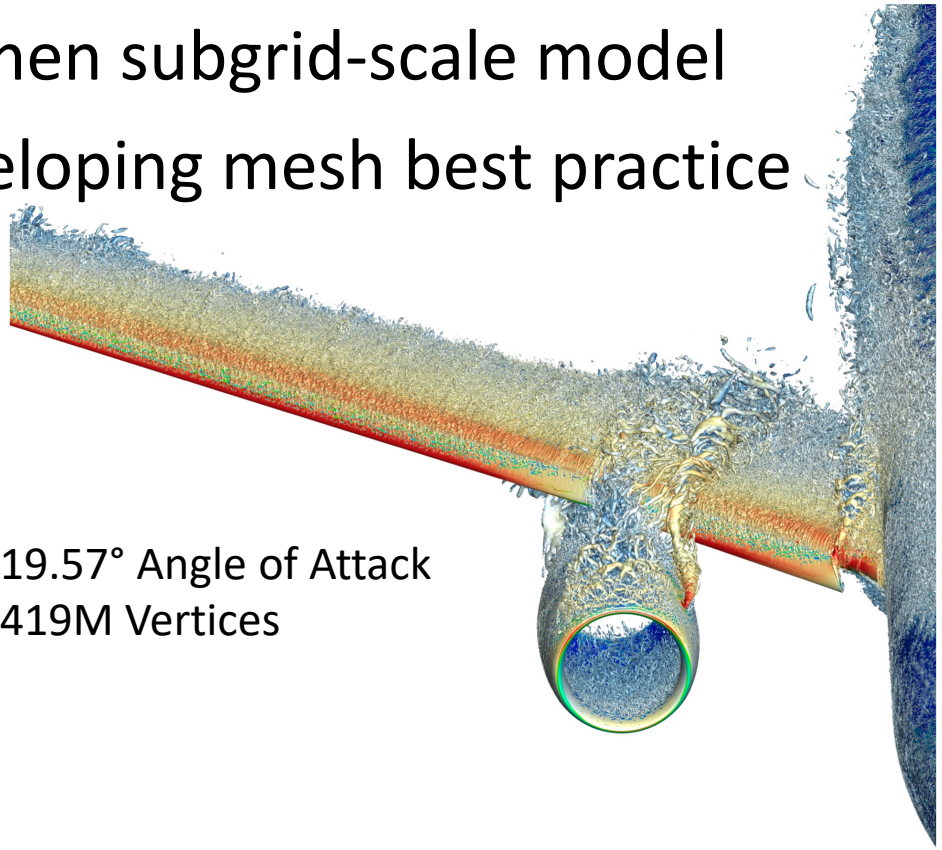
- Standard DDES model exhibits modeled-stress depletion with multiple adaptations



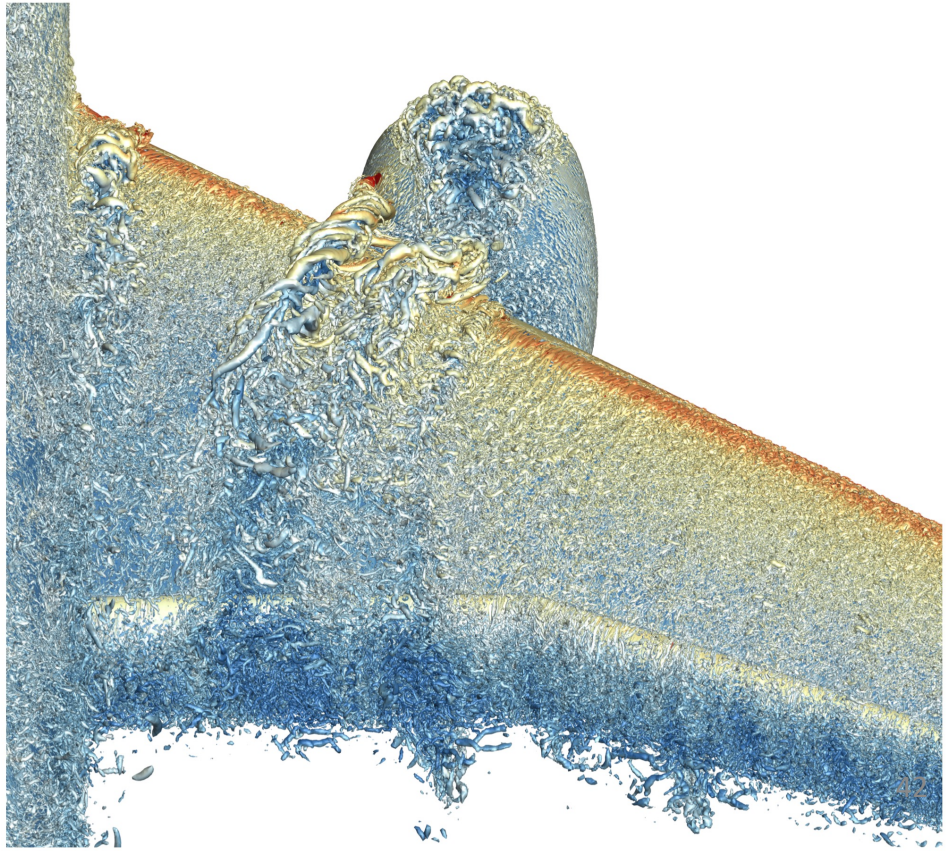


WMLES Implementation in FUN3D-FV

- AIAA 2022-1555
- Low dissipation through UMUSCL blend of central differencing
- Vremen subgrid-scale model
- Developing mesh best practice



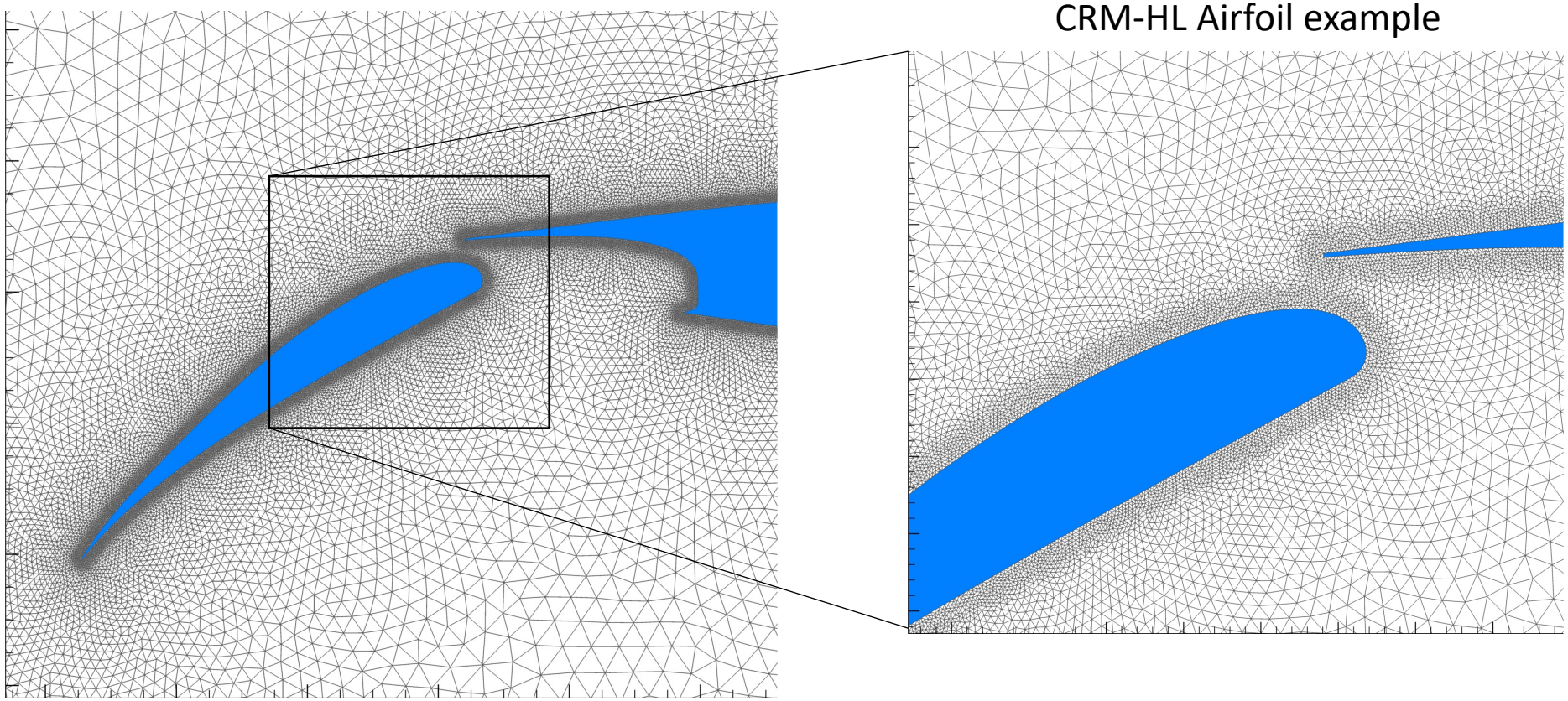
19.57° Angle of Attack
419M Vertices



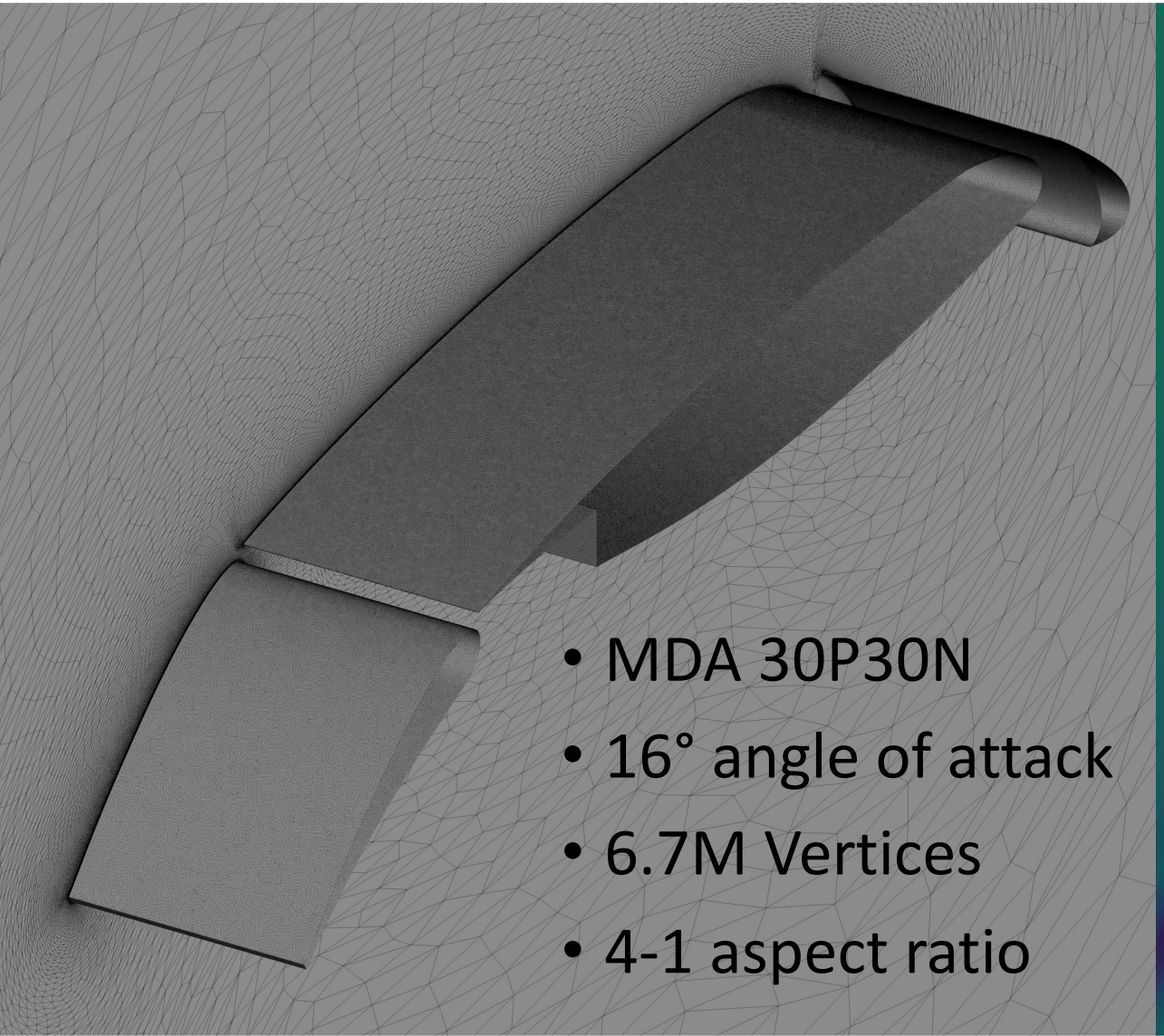
WMLES a priori Meshing

- Define isotropic spacing as a function of wall distance (Anderson, JCP 1994) and adapt with refine

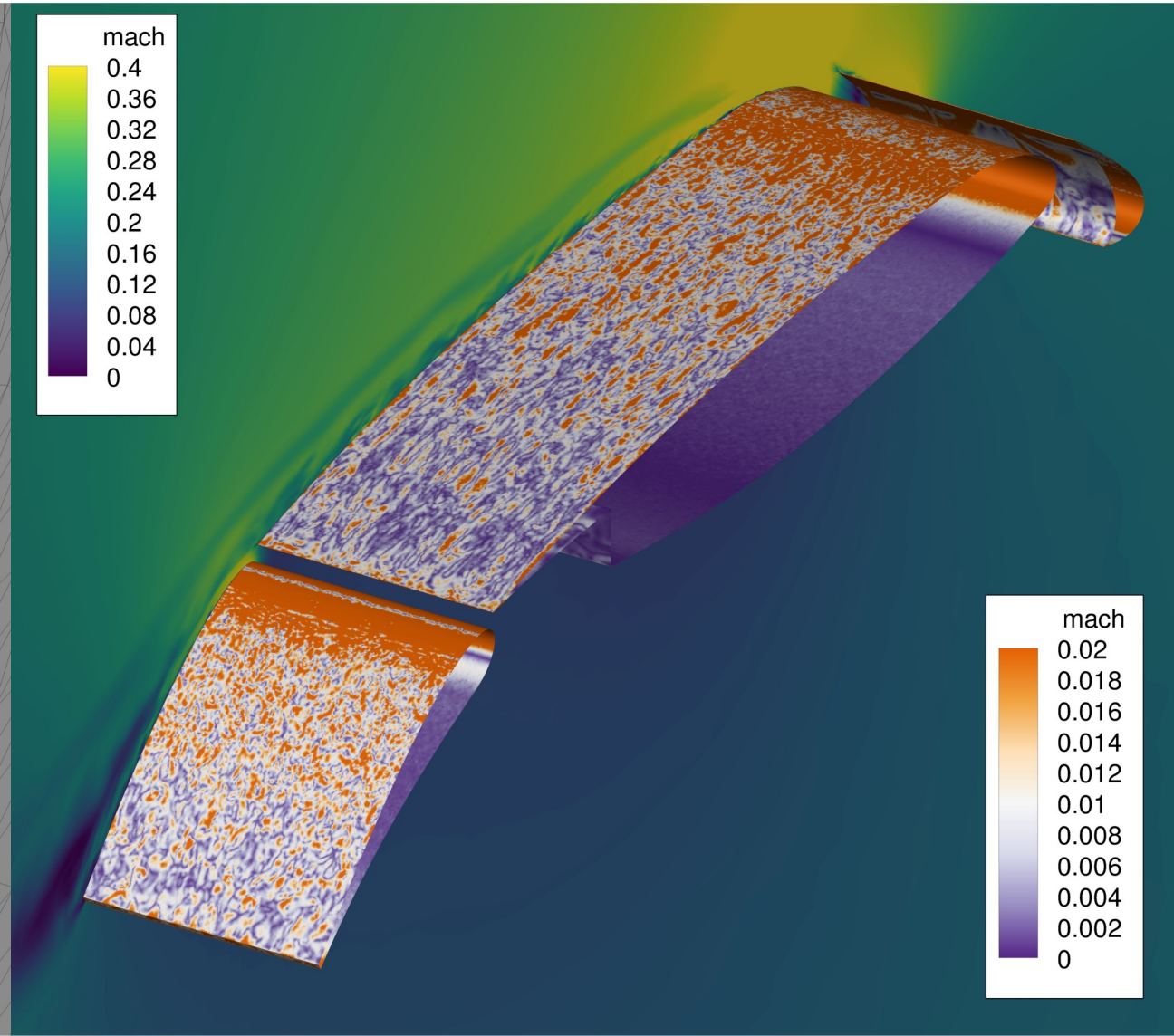
CRM-HL Airfoil example



WMLES a priori Meshing Extension to 3D

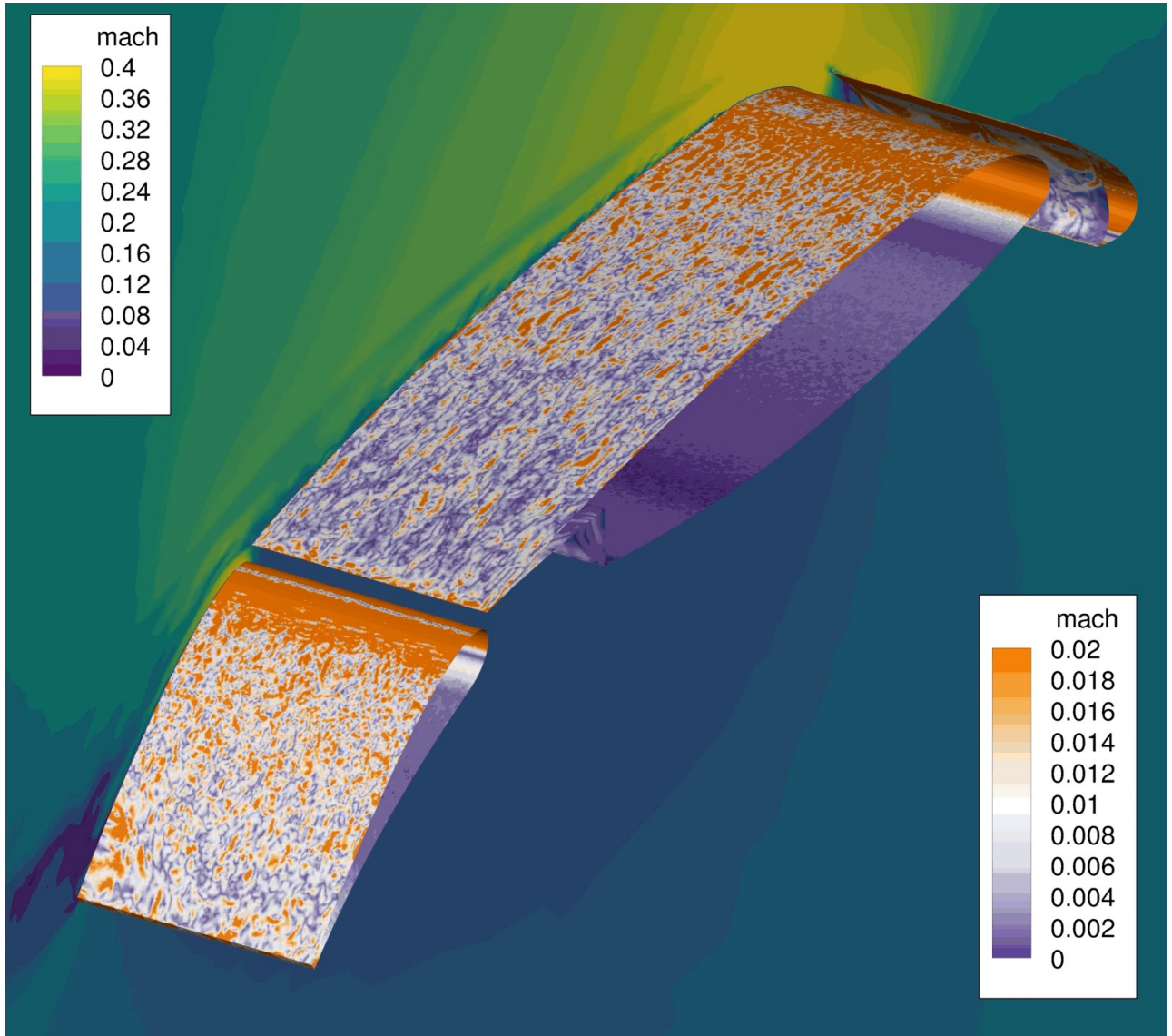


- MDA 30P30N
- 16° angle of attack
- 6.7M Vertices
- 4-1 aspect ratio



WMLES a priori Meshing Extension to 3D

- MDA 30P30N
- 16° angle of attack
- 6.7M Vertices
- 4-1 aspect ratio

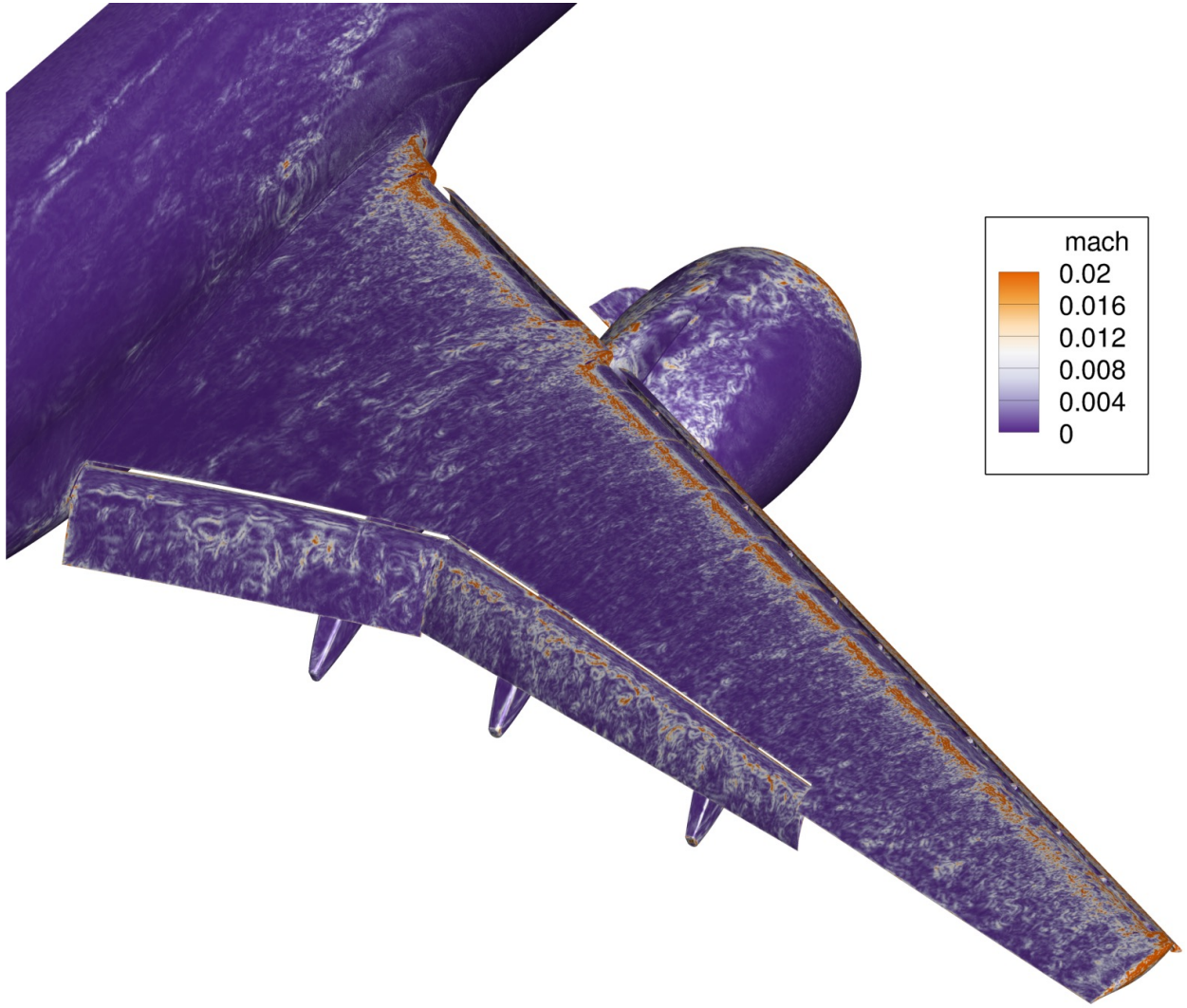


WMLES Solution Adaptive Meshing

- Wall model is a source of interpolation error for the metric
  - Override with floor of a multiple of the viscous length scale
- Wall model has slip velocity and makes the flow appear inviscid to the error estimate
  - Treat like other weak boundaries and impose strong BCs on sensor for coarse meshes
- Assume LES benefits from isotropic cells (maybe 2-4 AR at wall that quickly goes isotropic)
- CRM-HL
- CRM-HL 2D Airfoil example
- Extruded MDA30P30N

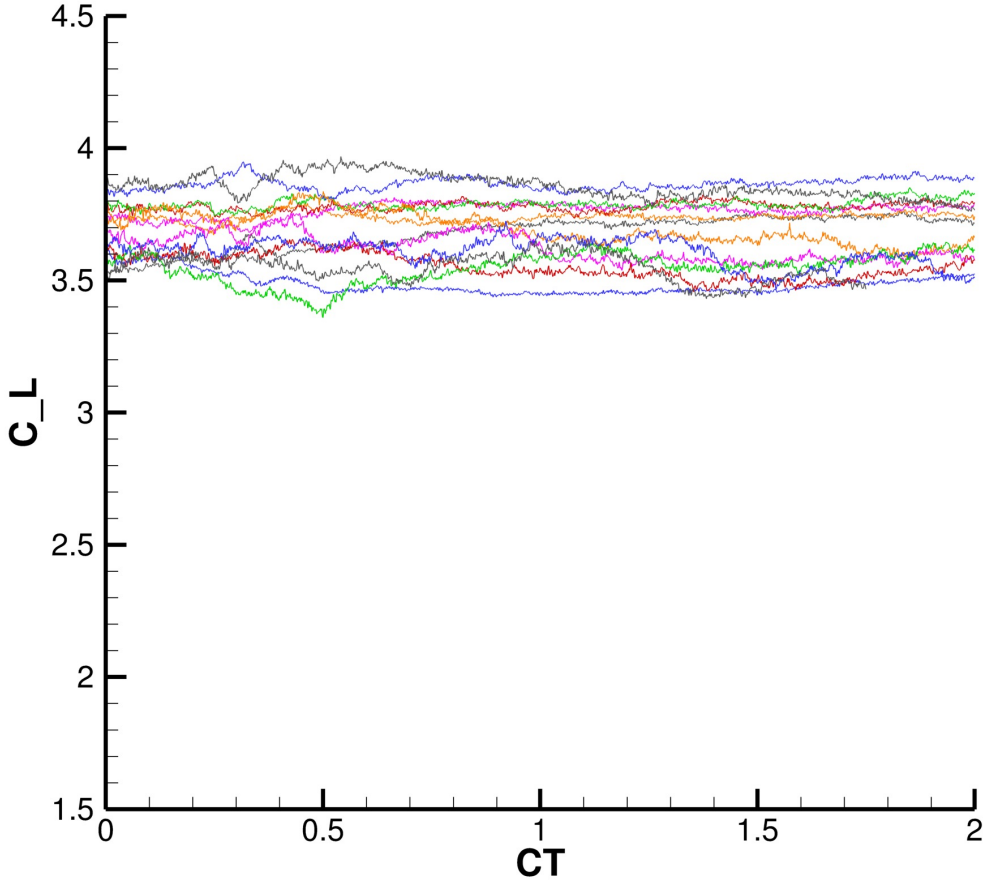
WMLES Mesh Adaptation

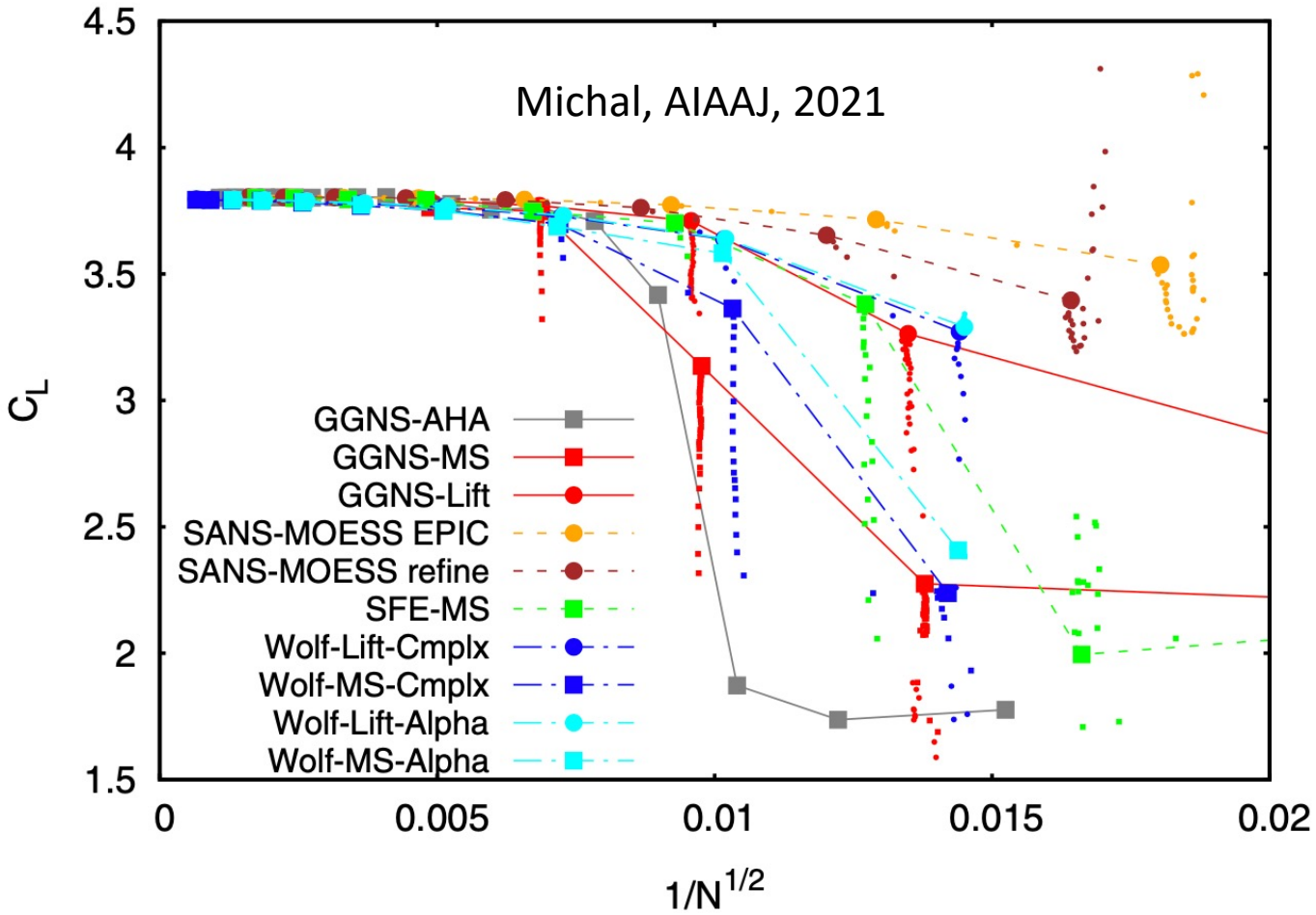
- CRM-HL, 19.57° angle of attack
- Started with y^+=160 a priori mesh
- 25M vertices
- Adapted once with unmodified fixed-point multiscale, average y^+=133
- y+ spacing continues to decrease without accounting for wall function in metric



CRM-HL 2D Airfoil

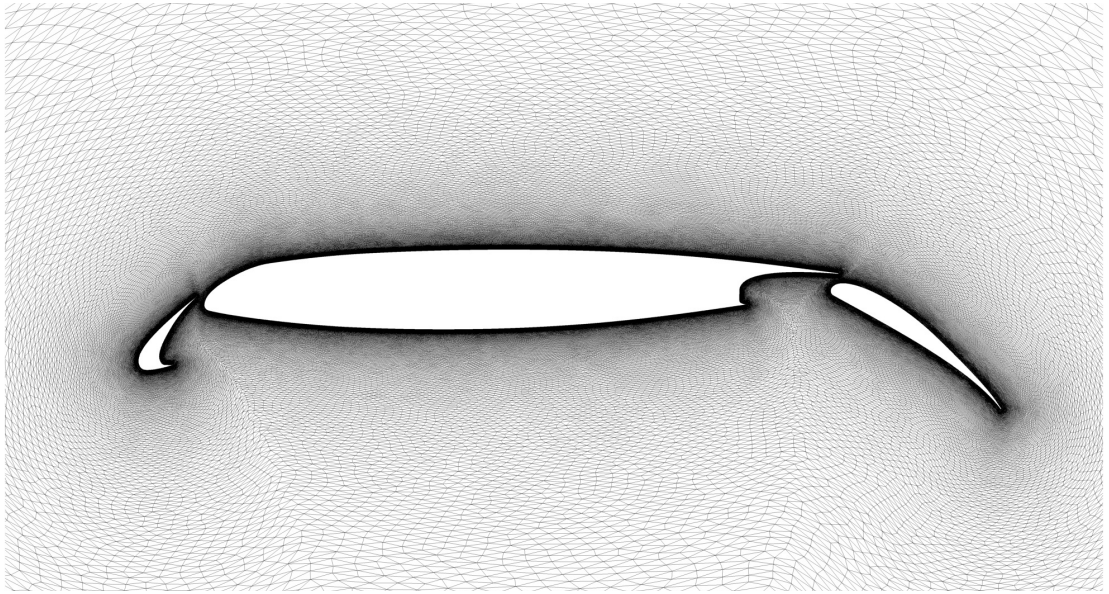
- Isotropic with y^+=50 global floor on spacing

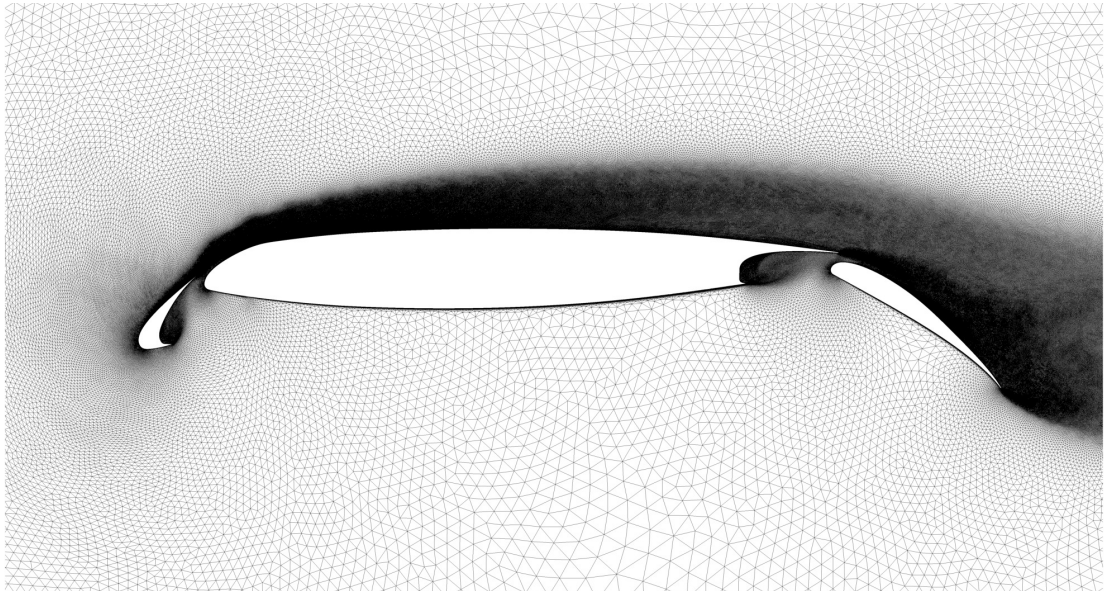




CRM-HL 2D

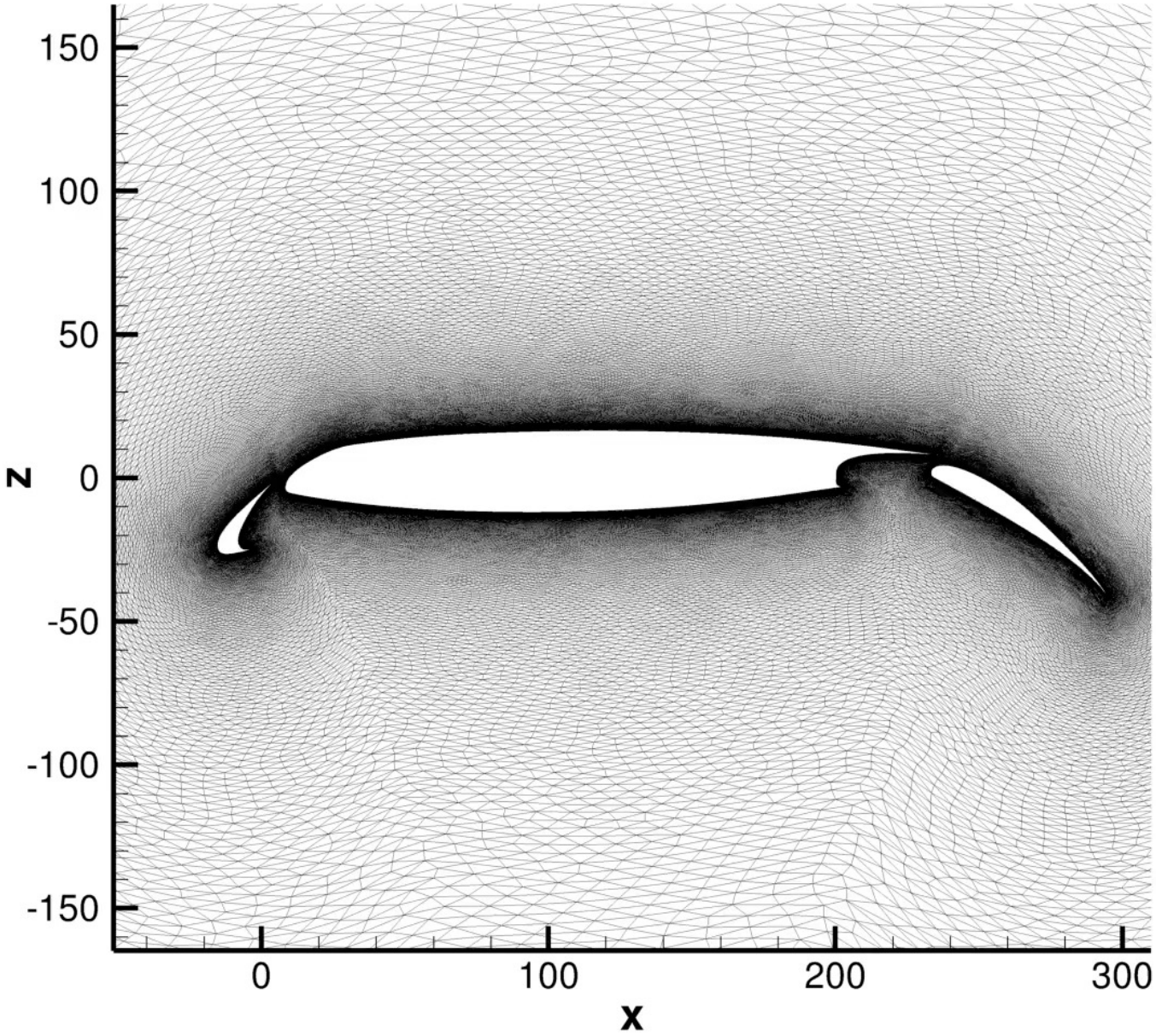
- Initial a priori mesh
- Isotropic fixed-point multiscale with $y^+=50$ global floor on spacing





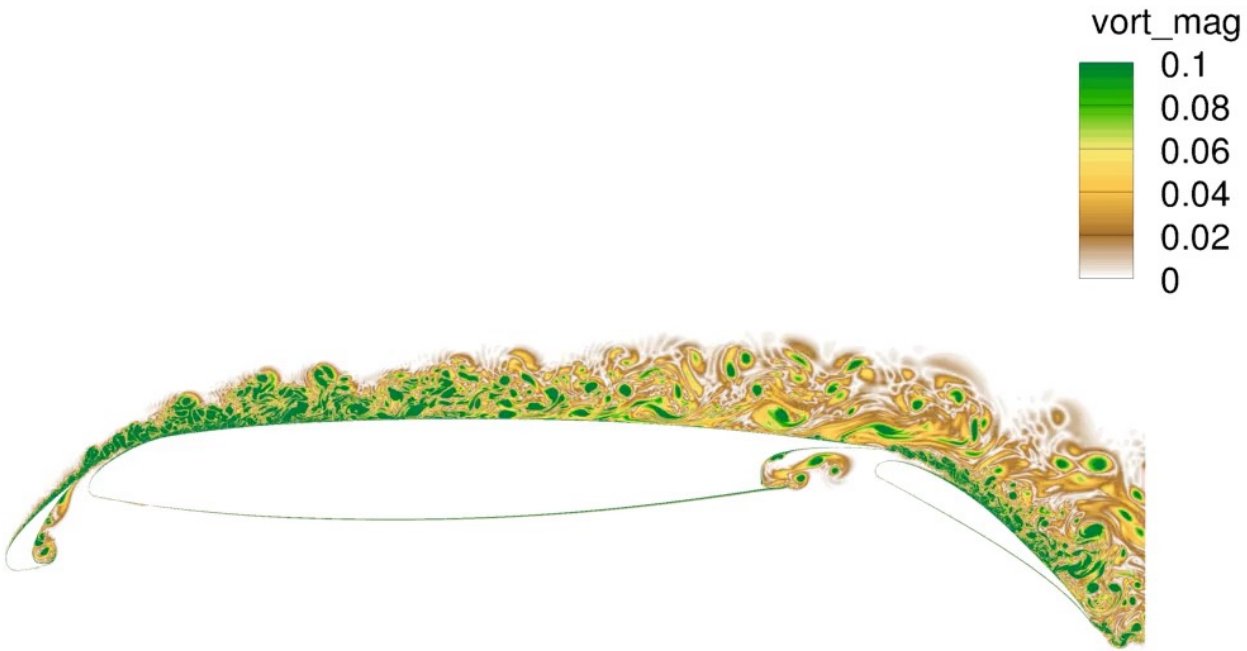
CRM-HL 2D

- Initial a priori mesh
- Isotropic fixed-point multiscale with $y^+=50$ global floor on spacing



CRM-HL 2D

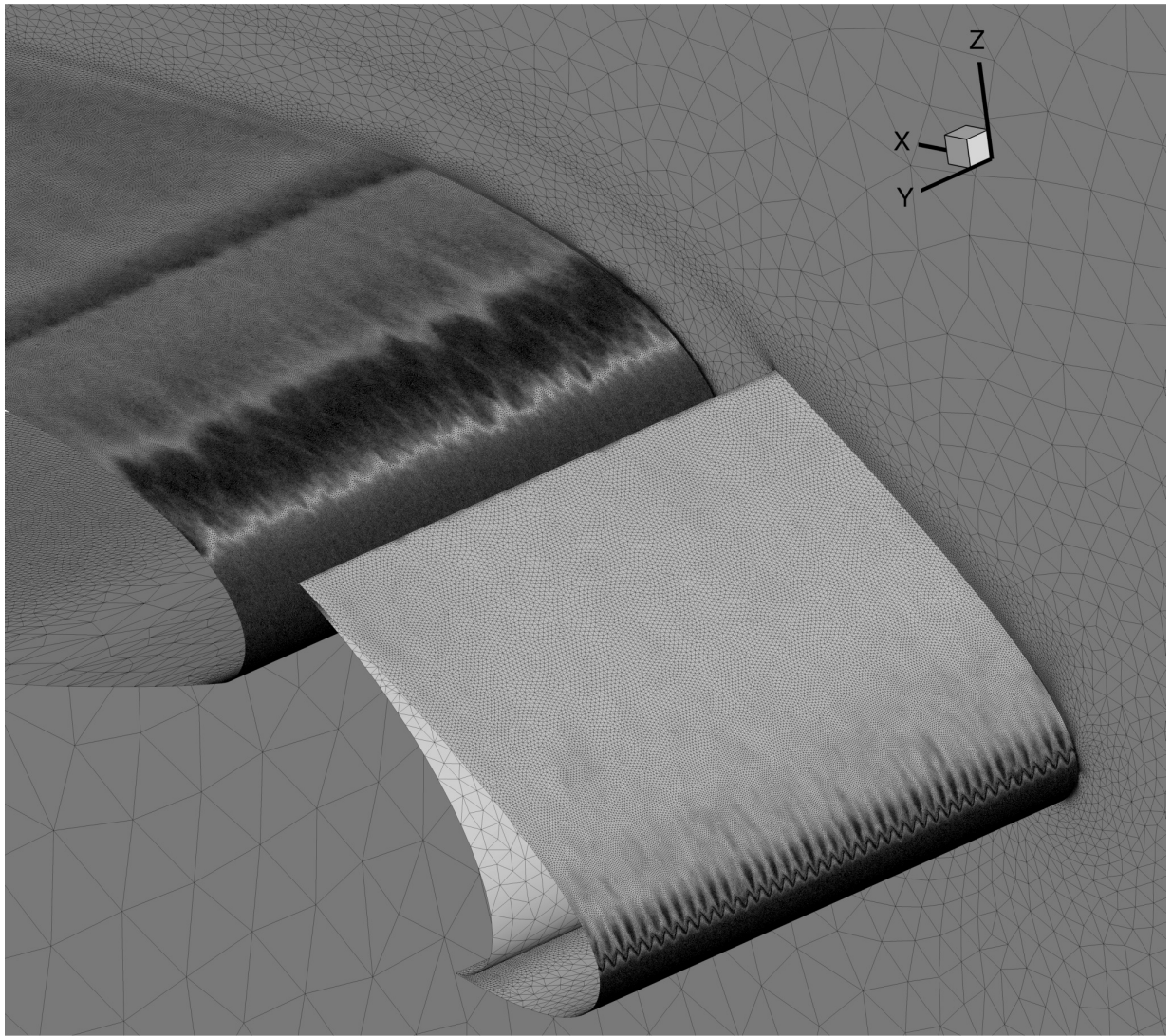
- Initial a priori mesh
- Isotropic fixed-point multiscale with $y^+=50$ global floor on spacing

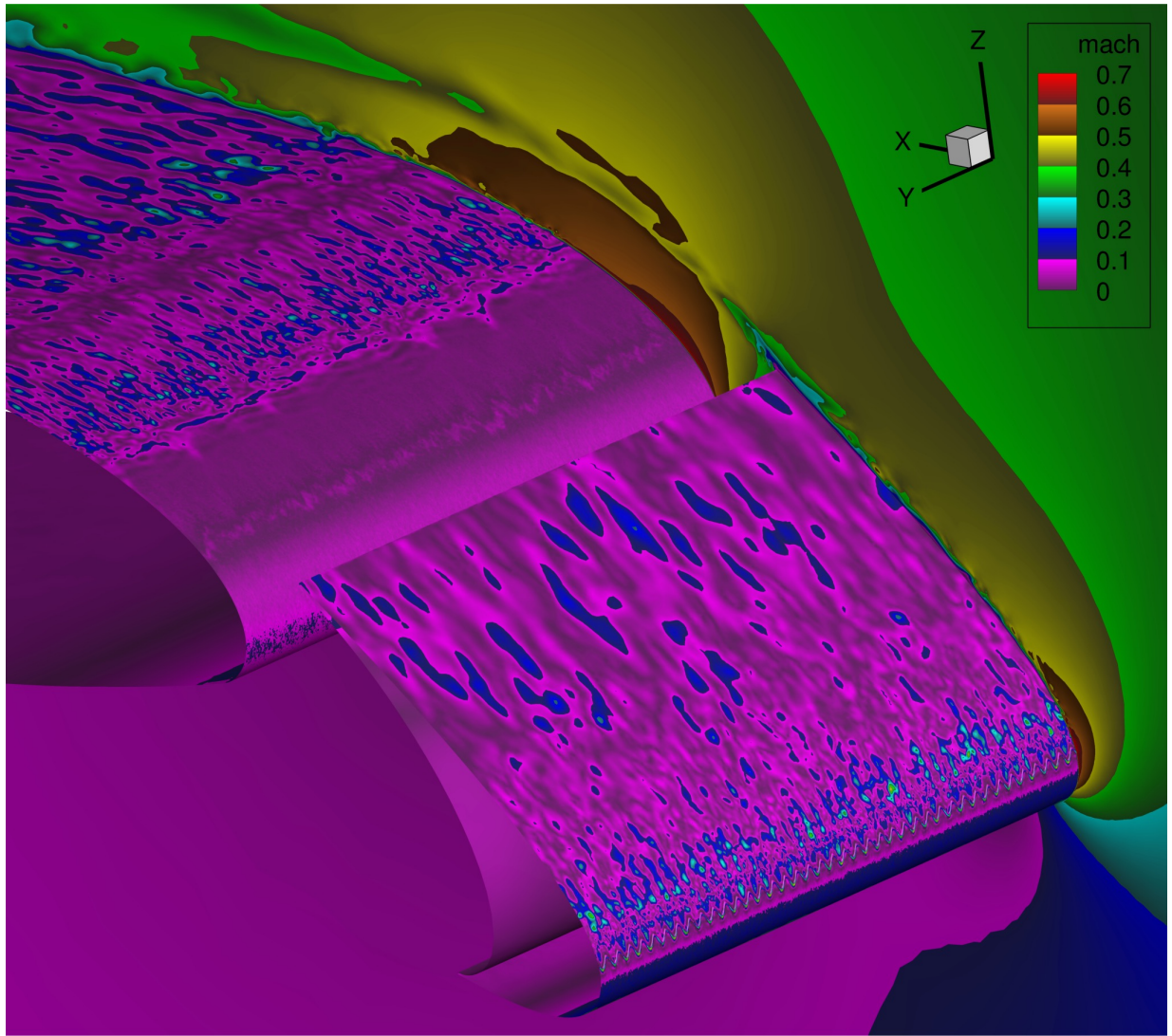


WMLES Solution Adaptive Meshing

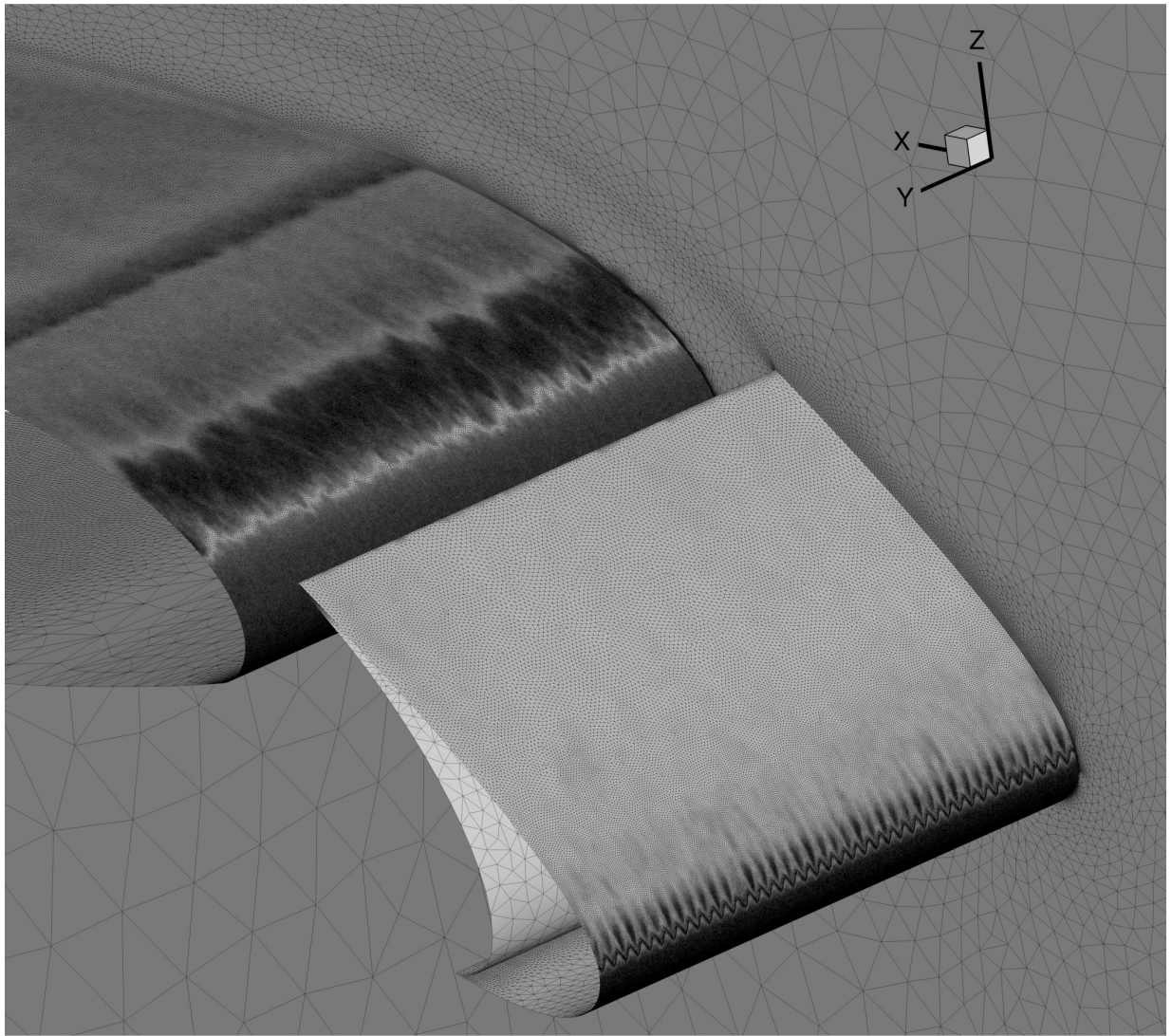
- Appears to be impacting the numerical transition to resolved turbulence
- Reinforce numerical laminar separation bubbles
- Meshing (and trip devices) are being to explored to mitigate

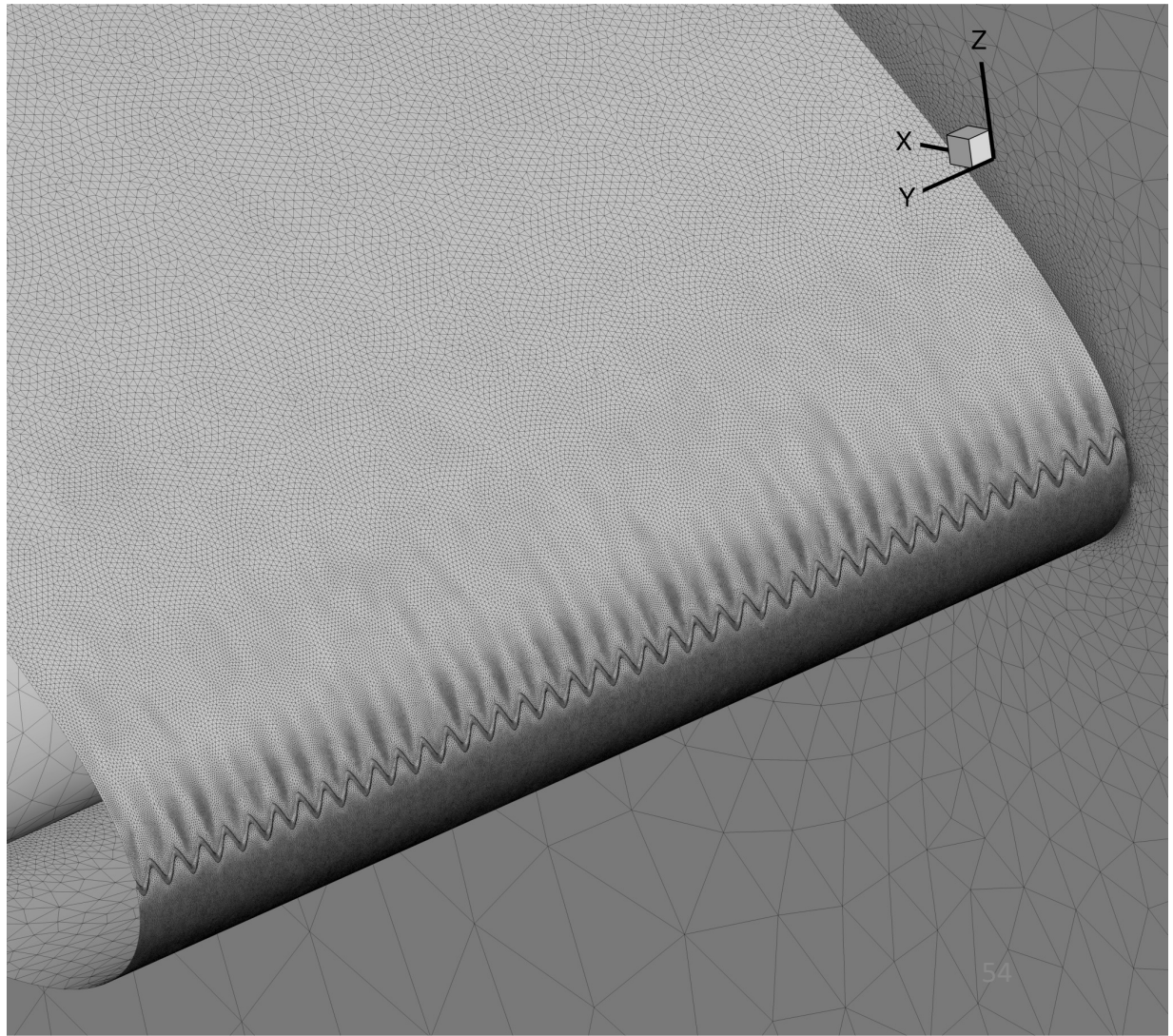
MDA 30P30N, 16° angle of attack, 6.3M, Y^+=50



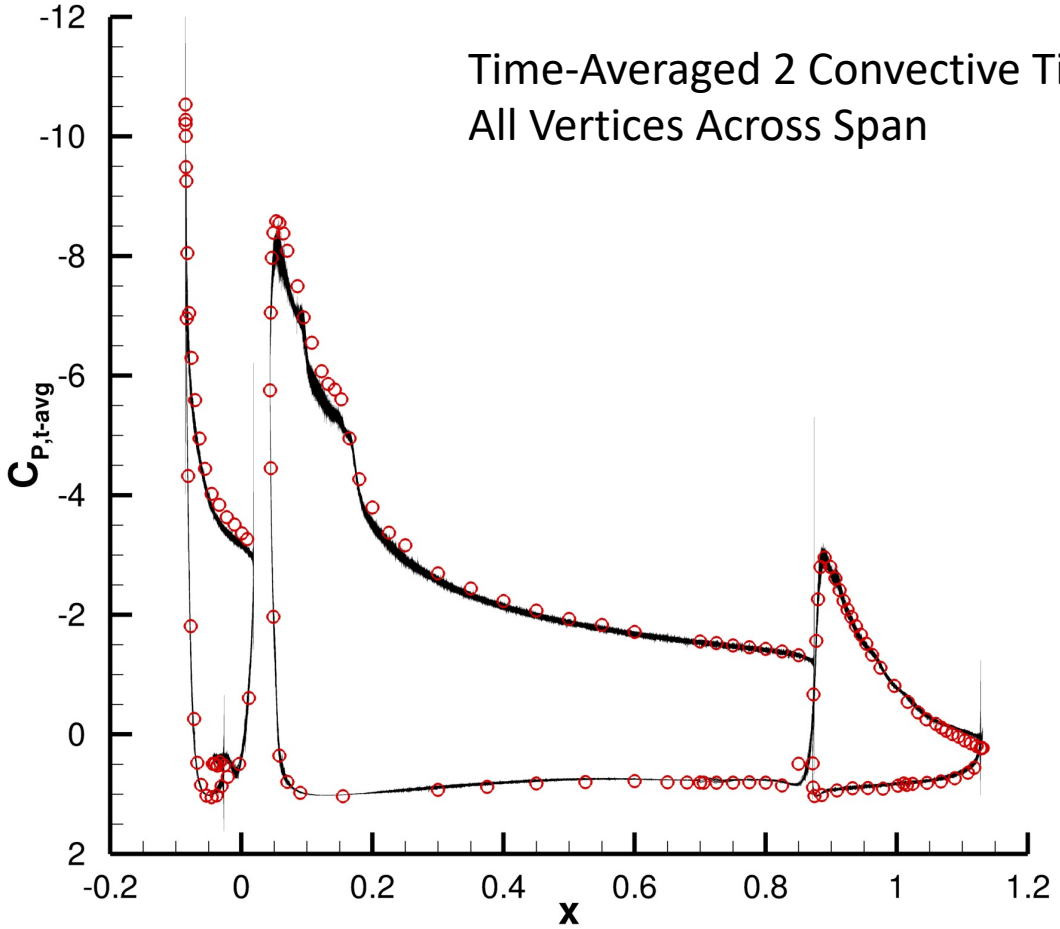


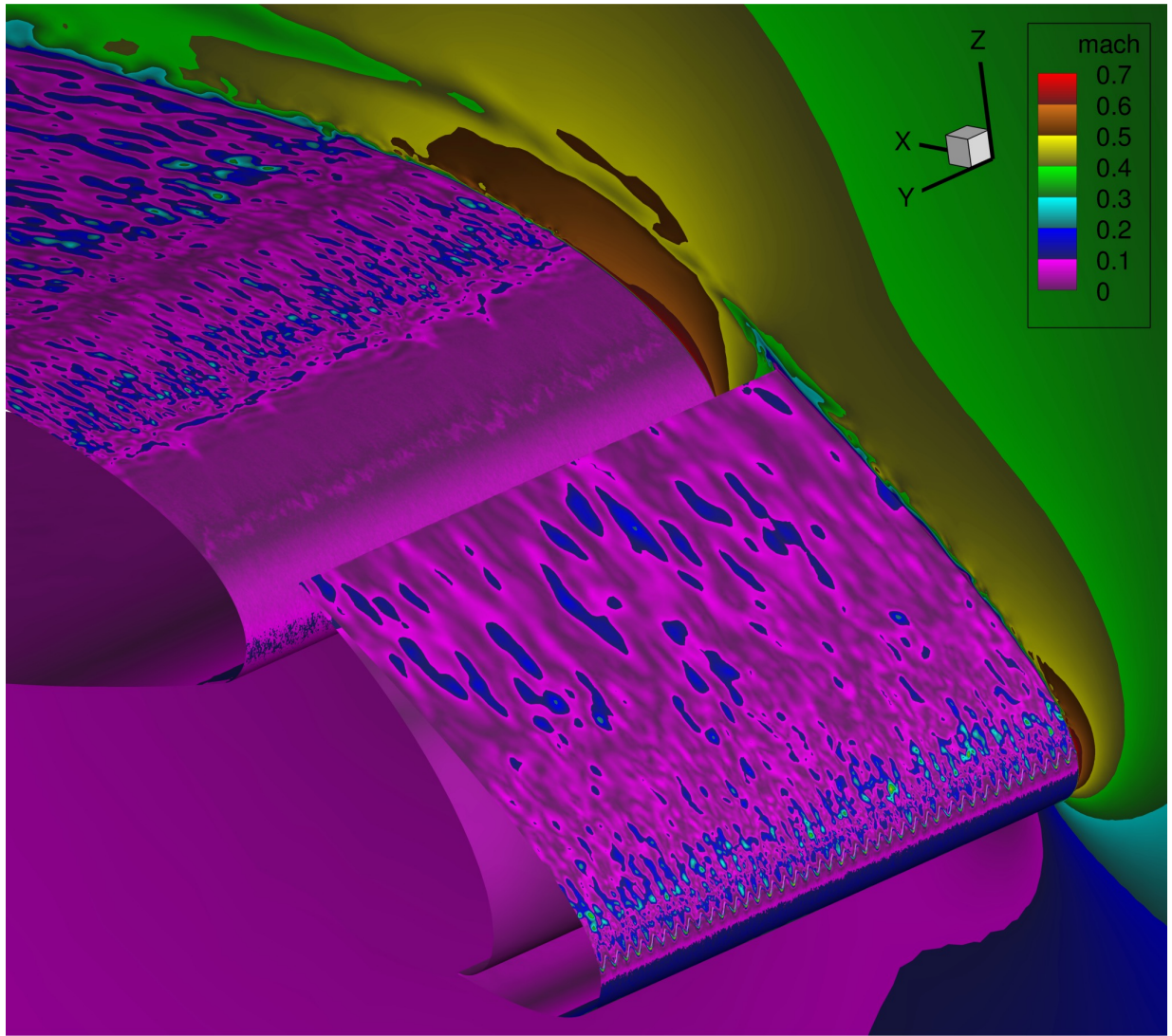
MDA 30P30N, 16° angle of attack, 6.3M, Y^+=50





MDA 30P30N, 16° angle of attack, 6.3M, Y^+=50





Recommendations

- Motivate and attract research partners to dispel perception that *LES is prohibitively expensive, imprecise, and risky
- Verify *LES implementations
- Analytic metric to model needs of unsteady adaptation
- Analytic unsteady sensor scalar field (and displacement)
- 2D geometries (not physically relevant, but allows clear feedback)
- 2D geometries extruded to finite span
- Simple 3D geometries
- Complex 3D geometries

Acknowledgments

- Li Wang, Eric Nielsen, Ponnampalam Balakumar, Kyle Anderson (NASA)
- Prahladh Iyer and Boris Diskin (NIA)
- Todd Michal, Josh Krakos, and Dmitry Kamenetskiy (Boeing)
- Frederic Alauzet and Adrien Loseille (INRIA)
- Marshal Galbriath (MIT)
- Cristos Tsolakis and Nikos Chrisochoides (ODU)
- Phil Caplan (Middlebury College)
- This work was partially supported by the Transformational Tools and Technologies (TTT) Project of the NASA Transformative Aeronautics Concepts Program (TACP) under the Aeronautics Research Mission Directorate.

Thirty Years of Development and Application of CFD at Boeing Commercial Airplanes

- Johnson, Tinoco, and Yu, Computers and Fluids, 2005
- “In industry, CFD has no value of its own. The only way CFD can deliver value is for it to affect the product. To affect the product, it must become an integral part of the engineering process for the design, manufacture, and support of the product.”