Oral presentation | Turbulence simulation (DNS,LES,RANS)

Turbulence simulation(DNS,LES,RANS)-III

Thu. Jul 18, 2024 10:45 AM - 12:45 PM Room B

[10-B-03] Comparison of wall-modeled and wall-resolved large eddy simulation of the high-lift Common Research Model

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Keywords: Large eddy simulation, High order methods , Unstructured meshes

Comparison of Wall-Modeled and Wall-Resolved LES of the High-Lift Common Research Model

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Outline

- Introduction
  - LES
  - WMLES vs WRLES
- Pacing items towards industrial LES
  - High-order
  - GPU computing
- LES of HL-CRM
  - WMLES vs WRLES
  - Comparison
- Summary and future plan

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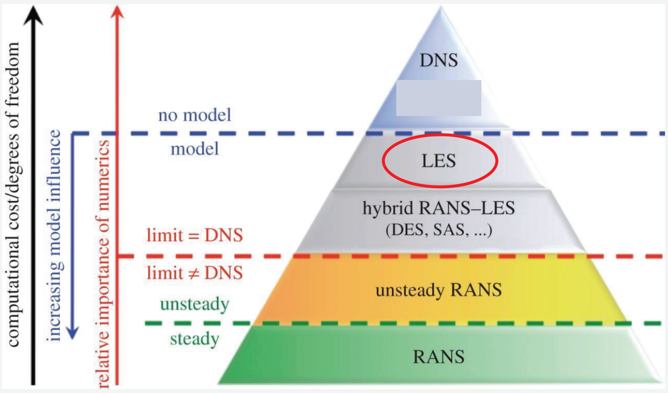
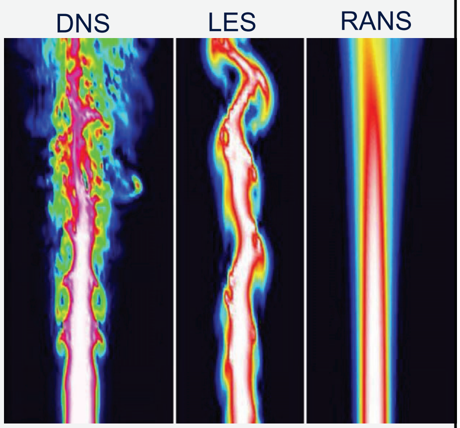
Resolution vs Cost





A. Maries, University of Pittsburgh

Sébastien Deck, Fabien Gand, Vincent Brunet and Saloua Ben Khelil, High-fidelity simulations of unsteady civil aircraft aerodynamics: stakes and perspectives. Application of zonal detached eddy simulation, https://doi.org/10.1098/rsta.2013.0325

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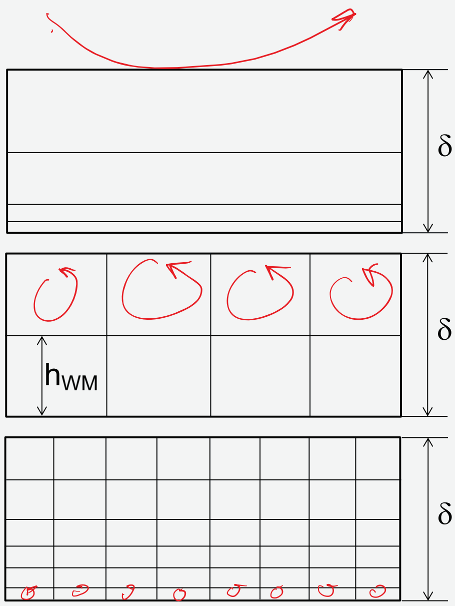
Different Flavors of LES

- Hybrid RANS/LES
  - Normally RANS used in the boundary layer
  - LES used outside the boundary layer
  - Transition not predicted
- Wall-modeled LES
  - Near wall eddies modeled while outer boundary layer eddies captured
  - Transition not predicted
- Wall-resolved LES
  - Near wall eddies captured.
  - Laminar/turbulent transition part of the solution
  - High cost



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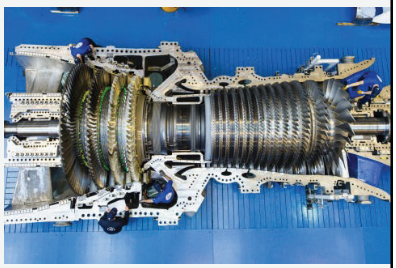
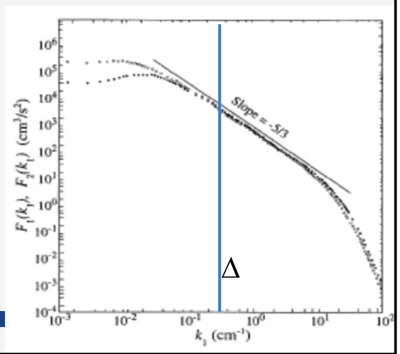
LES – the Challenges

- Cost!
  - 3D time accurate simulations
  - Disparate turbulent length and time scales at high Reynolds numbers
  - Wall Modeled LES ~ $Re^{1.3}$
  - Wall Resolved LES ~ $Re^{2.5}$
- Other challenges
  - Complex geometries
  - Wall and subscale stress models
  - Scalable and efficient time integration schemes
  - …





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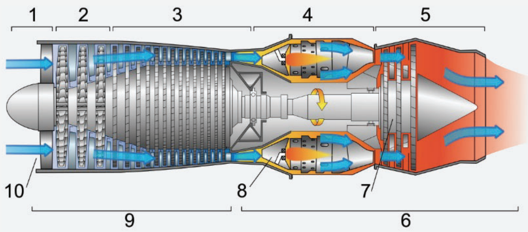
How We Address the Challenges

- Cost
  - High-order methods in space
  - Implicit time integration approaches on CPU/GPU clusters
  - Wall-modeled LES
- Other challenges
  - Complex geometries
    - High-order unstructured meshes
  - Robustness
    - Explicit (Vreman model)/implicit LES
- Vision
  - High-order methods + GPU computing for industrial LES



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High-Order Methods

FR/CPR Method

- Flux reconstruction developed by Huynh in 2007. It is a differential formulation like "finite difference" for

$$\frac{\partial u}{\partial t} + \frac{\partial f(u)}{\partial x} = 0$$

- The DOFs are solutions at a set of "solution points"

$$\frac{\partial U_i(x)}{\partial t} + \frac{\partial F_i(x)}{\partial x} = 0, \quad U_i(x) \in P^k, \quad F_i(x) \in P^{k+1}$$

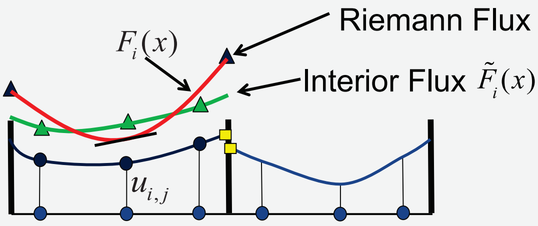
FR/CPR (cont.)

- Find a flux polynomial $F_i(x)$ one degree higher than the solution, which minimizes

$$\left\| \tilde{F}_i(x) - F_i(x) \right\|$$

- The use the following to update the DOFs

$$\frac{du_{i,j}}{dt} + \frac{dF_i(x_{i,j})}{dx} = 0$$



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Scalable Time Integration Schemes

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Need for Low Memory Implicit Schemes

- Explicit schemes
  - Good performance demonstrated for Runge-Kutta schemes with 1 element per core if p is reasonably high
  - Time step limited by the smallest cell with global time-stepping
  - Time accurate local time-stepping viable alternative, but not trivial to parallelize
- Implicit schemes
  - Time discretization
    - BDF2, optimized BDF2, DIRK, IRK, …
  - Linear (non-linear) solvers
    - GMRES with various preconditioners (memory depends on the preconditioner)
    - Block LU-SGS approach (but memory ~ p6)

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Experience with Various Time Integration Schemes

Scheme	Time Step	Memory Use
GMRES + ILU(n)	Largest $\sim\Delta t_{physical}$	Most (CPUs) $\sim p^6$
GMRES + Block Jacobi	Large $\sim 0.1\Delta t_{physical}$	Medium (CPUs) $\sim p^6$
BLU-SGS	Medium $\sim 10\text{-}100\Delta t_{explicit}$	Medium (CPUs) $\sim p^6$
GMRES + No Precond	Medium $\sim 10\text{-}100\Delta t_{explicit}$	Little (CPUs + GPUs)
RK3	Small $\sim\Delta t_{explicit}$	Least (CPUs + GPUs)

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Equilibrium Wall Model

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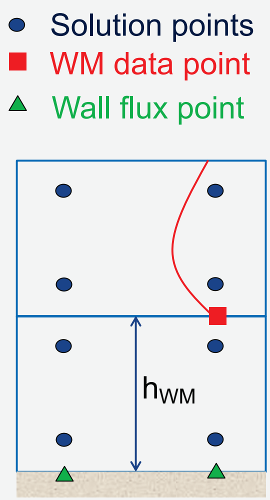
Basic Steps in a Wall Model (WM)

- Obtain WM data from the interface between 1st and 2nd element
  - Efficiency and accuracy
  - Wall parallel velocity, density, viscosity and distance to wall
- Compute τ_w based on a wall function (SA Model)
  - Need an iterative Newton solver
- Use the wall stress in the boundary condition
  - The viscous flux at the wall flux point needed
  - Turbulence in the first element not resolved!



Larsson, J., Kawai, S., Bodart, J., and Bermejo-Moreno, I., "Large-eddy simulation with modeled wall-stress: Recent progress and future directions," Mechanical Engineering Reviews, Vol. 3, No. 1, 2016, pp. 15–418. doi:10.1299/mer.15-00418.

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Study of Vortex-Dominated Flows Using hpMusic

(hp-adaptive MUlti-physics SImulation Code)

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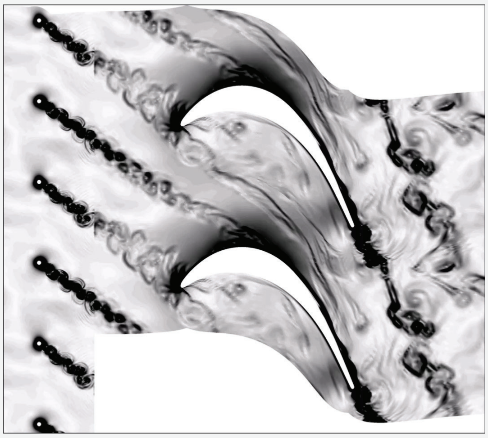
High-Order FR/CPR LES Solver: hpMusic

- Key features
  - Mixed meshes in CGNS or Gmsh format
  - Explicit and implicit time integration schemes
  - High-order accuracy (up to 6th order)
  - Overset and sliding meshes for moving grids
  - Wall-resolved or wall modeled
  - Explicit (Vreman SGS) or implicit LES
  - Highly scalable on CPU and GPU clusters including Summit and Frontier



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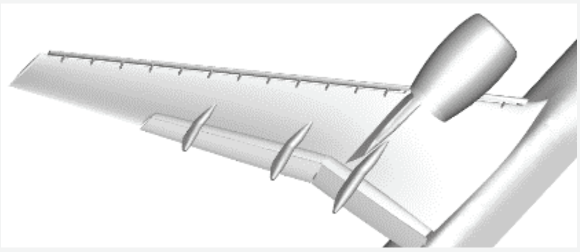
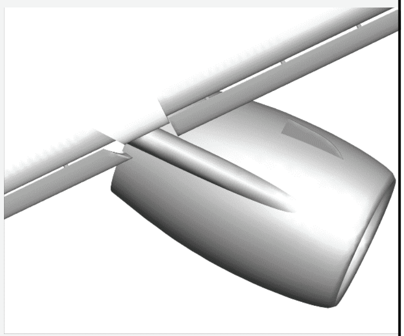
WMLES and WRLES of CRM-HL Configuration

- Flow conditions
  - Mach: 0.2
  - Reynolds number: 5.49 million (based on MAC)
  - AOAs: 19.57 degrees





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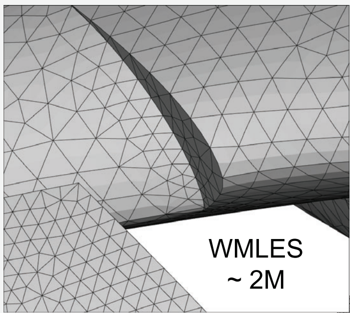
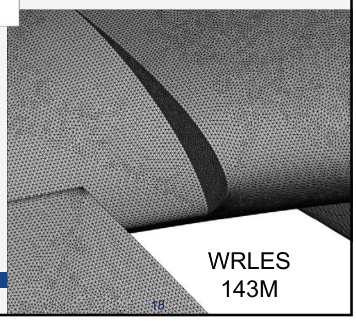
Comparison of Meshes for WMLES and WRLES

- Mesh for WMLES (~ 2M)
  - Isotropic tetrahedral mesh
  - Fuselage: 10 - 25 inches
  - Wing & Nacelle: 2.5 - 5 inches
  - Flap & Slat: 2.5 inches
- Mesh for WRLES (143M)
  - Hybrid prism/tet mesh
  - Wall normal: 0.008 inches
  - Fuselage: 2 inches
  - Bottom of wing: 1 inches
  - Top of wing: 0.5 inches





WMLES mesh generated by Barcelona Supercomputing Center and WRLES mesh generated by Cadence

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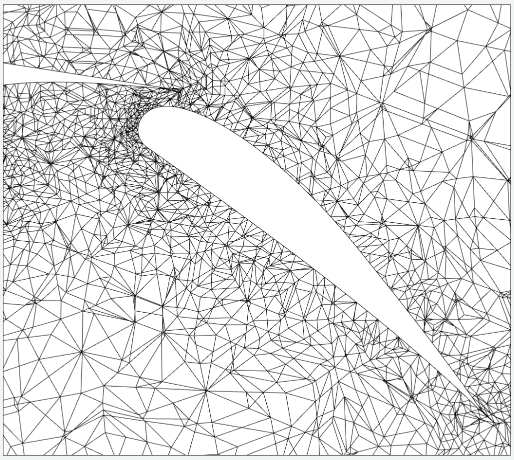
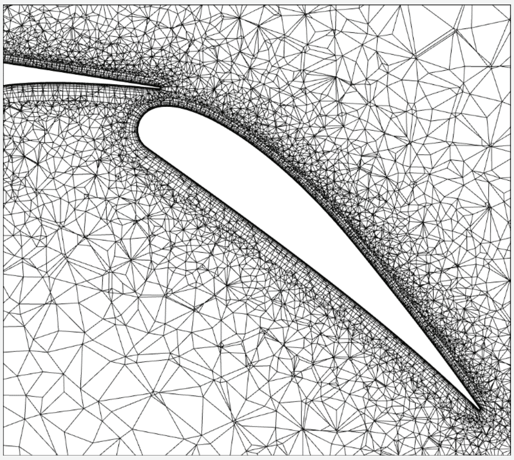
Comparison of Volume Meshes – Cutting Plane





WMLES ~ 2M
dt ~ 1.e-5

WRLES ~ 143M
dt ~ 1.e-6

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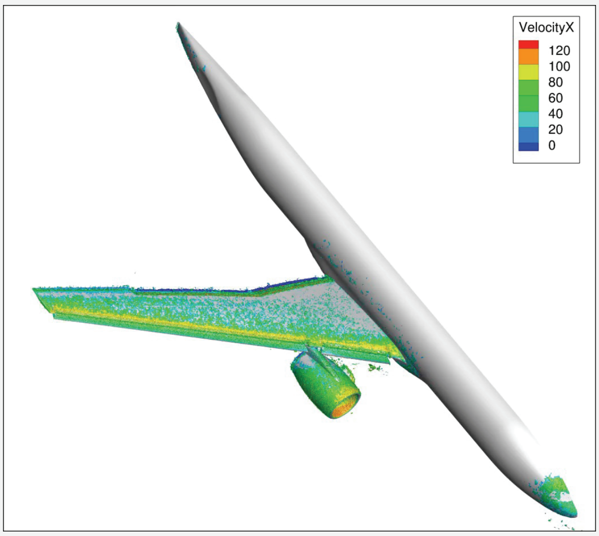
Q-Criterion Colored by Streamwise Velocity - WMLES



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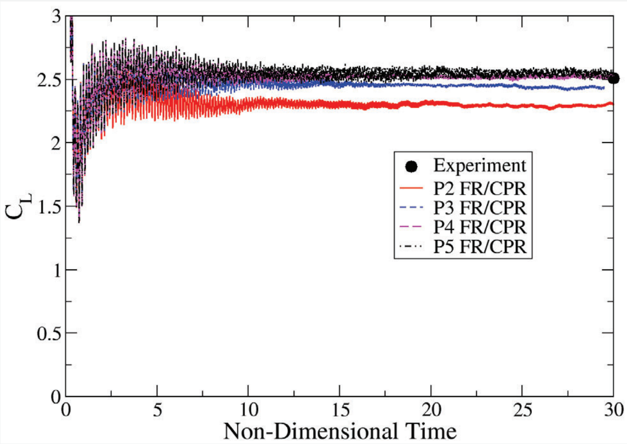
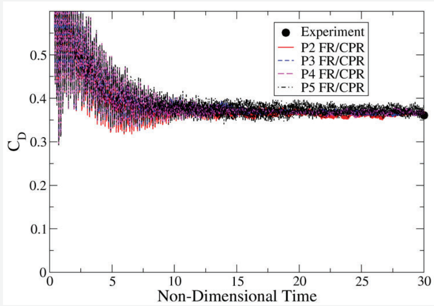
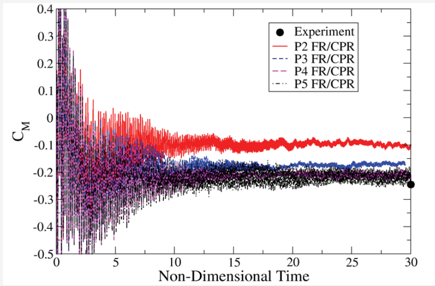
P-Refinement Study at AOA of 19.57°







WMLES

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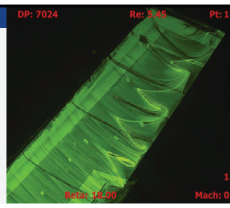
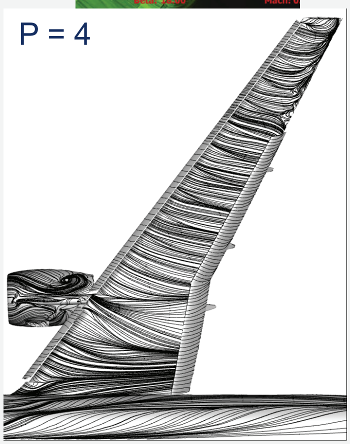
Oil Flows at AOA of 19.57° (WMLES)





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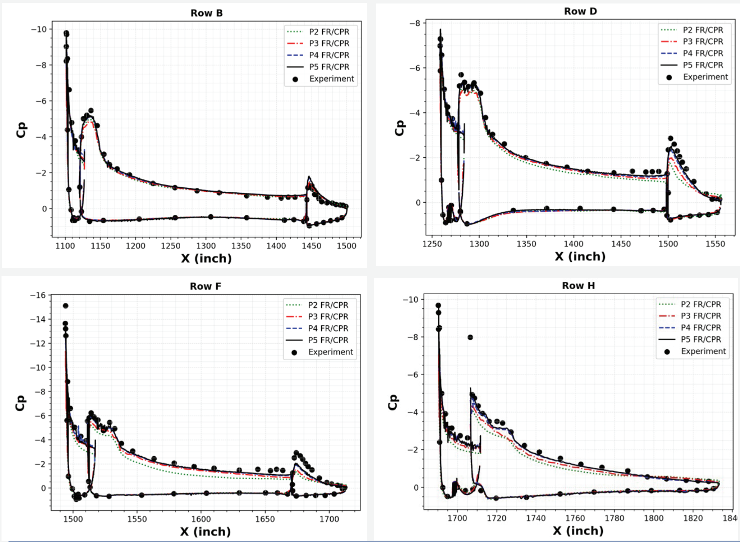
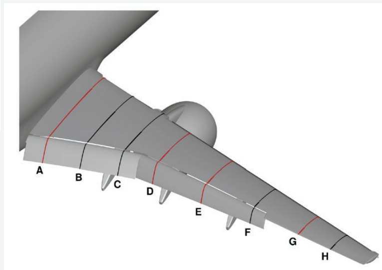
Comparison of Cp Profiles at AOA of 19.57º (WMLES)





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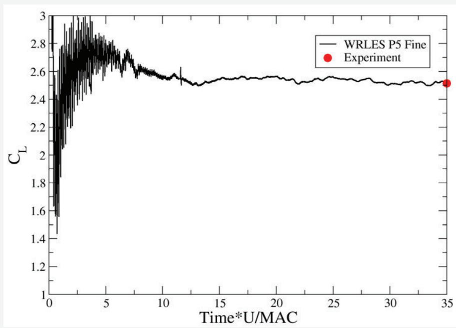
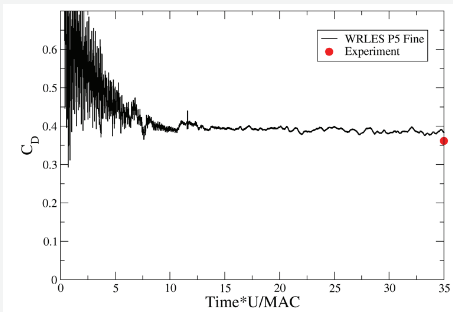
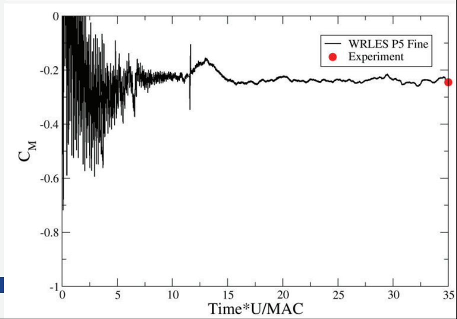
WRLES - P5 Simulation at AOA of 19.57º

- Details
  - 14 billion DOFs/equ
  - 1000 Summit nodes used (6,000 V100s)
  - Averaging done between 20 – 35 convection times







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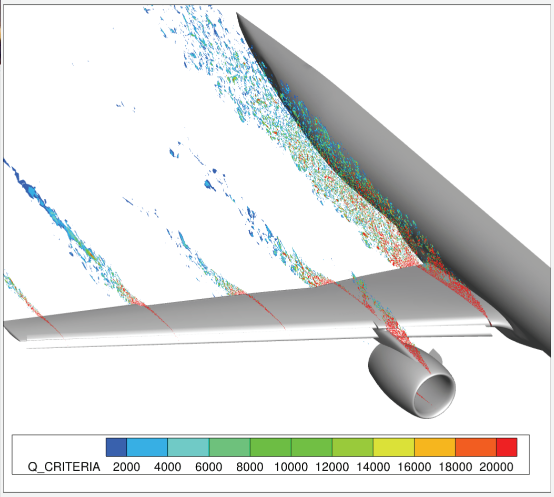
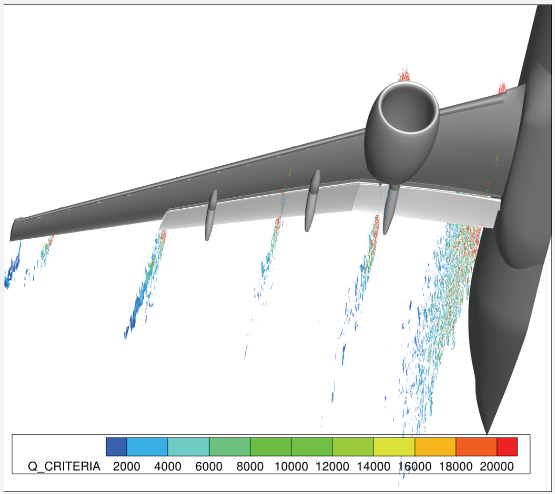
Flow Field Visualization (P5) at AOA = 19. 57º (WRLES)

18 B elements and 14 B points for visualization (subdivided)





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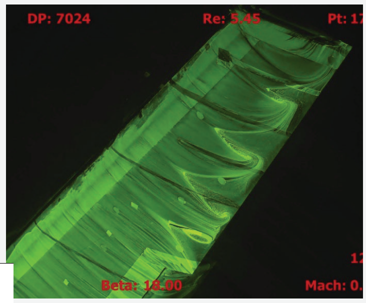
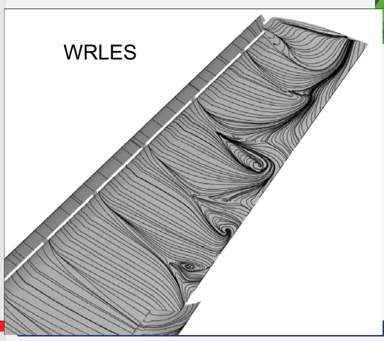
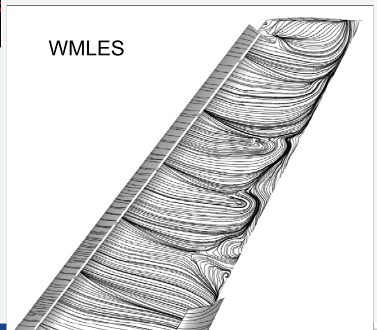
Comparison of Oil-Flows (AOA – 19.57º)







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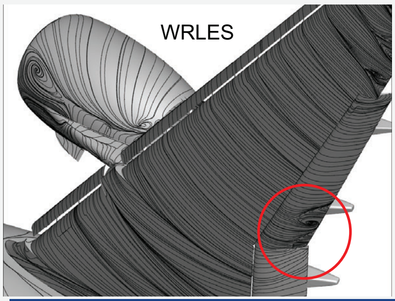
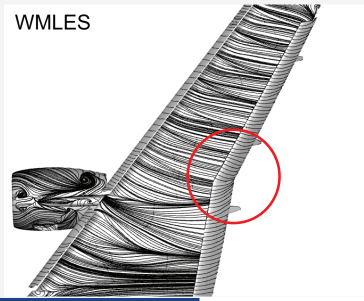
Comparison of Oil-Flows (AOA – 19.57º)





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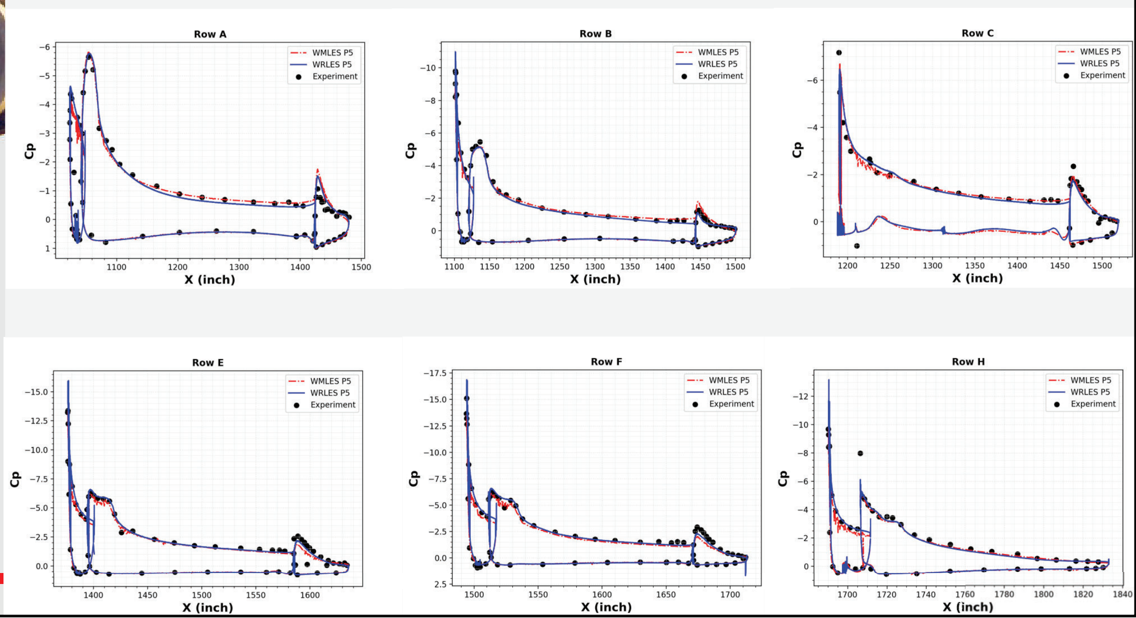
Comparison of Cp Profiles (WRLES vs WMLES)



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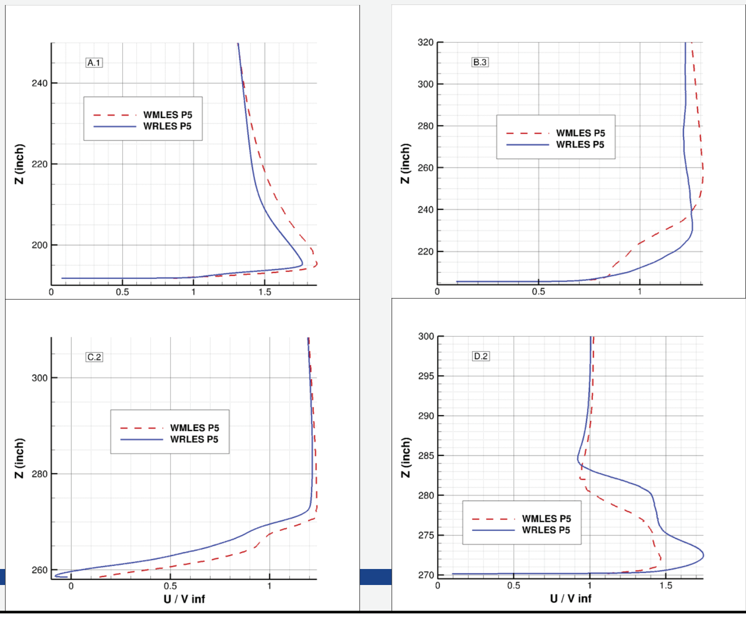
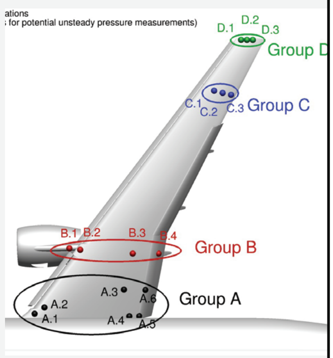
Comparison of Velocity Profiles (WRLES vs WMLES)





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Research Summary and Outlook

- Progress in the last decade has enabled high-order LES to be used more in industry, especially in turbomachinery (WRLES) and HL-CRM (WMLES)
- GPU computing is the game changer for high-order LES in real-world applications
- WRLES is at least 3 orders more expensive than WMLES but does agree better with the experiment in oil flows and pressure coefficient
- Future work
  - Improved wall-models,
  - Multi-physics (combustion, FSI, coupled CFD/flight dynamics and control, …)

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- AFOSR for supporting the research
- DOE's INCITE program to provide GPU node hours to the team of KU, NVIDIA and Cadence Design Systems
- NVIDIA and Cadence for the fruitful collaboration

Questions ?

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