



# Wall-Modeled Large-Eddy Simulations for High-Lift Configurations Using FUN3D

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# Introduction

- **Accurate and Efficient Simulations of High-Lift Configurations**

- Critical for commercial aircraft design, development, and product certification (Slotnick et al. 2021)
- Reynolds-averaged Navier-Stokes (RANS) models
  - Relatively low cost
  - Insufficient accuracy (Rumsey et al. 2019)
- Direct numerical simulation (DNS)
  - Prohibitively expensive
  - Limited to simple geometries and low Reynolds numbers
- Large-eddy simulation (LES)
  - Promising methodology
  - Expensive for wall-bounded flows
- Wall-modeled large-eddy simulation (WMLES)
  - Reduced cost by combining LES and RANS approaches
  - Hybrid RANS/LES and wall-stress modeling

- **Objective of Present Work**

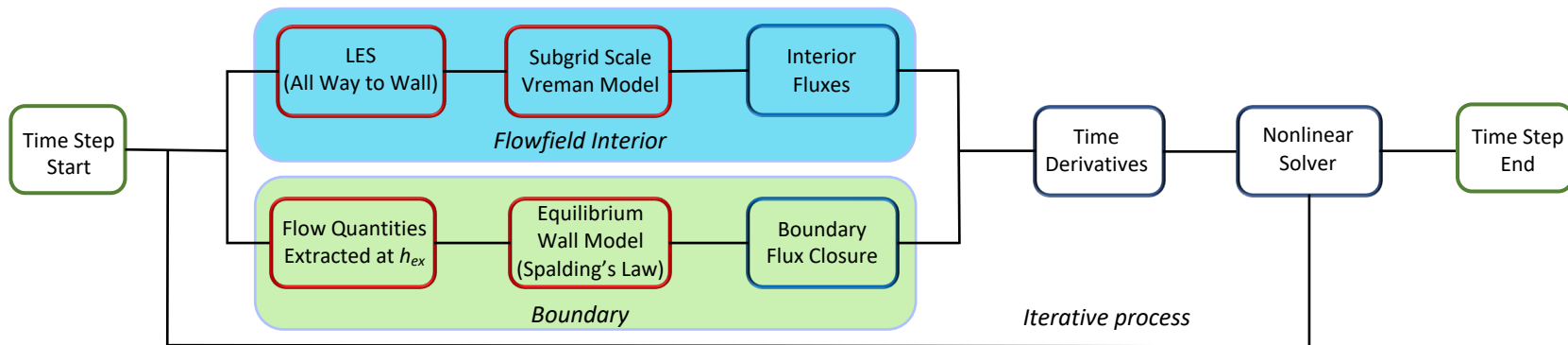
- Develop WMLES capability in FUN3D
- Apply to high-lift configurations for maximum lift ( $C_{L,max}$ ) predictions

# Computational Methodology

- **FUN3D Computational Fluid Dynamics (CFD) Code Developed at NASA Langley Research Center**

- Mixed-element, unstructured-grid, node-centered, finite-volume discretization
  - Second-order accuracy in space
  - Implicit and explicit temporal schemes with different orders of accuracy
  - Blended second- and third-order accurate BDF2OPT scheme is chosen
- Nonlinear solver
  - Defect-correction method
  - Strong hierarchical adaptive nonlinear iteration method (HANIM) (Wang et al. 2021)

- **WMLES Implementation Based on Wall-Stress Modeling Approach**

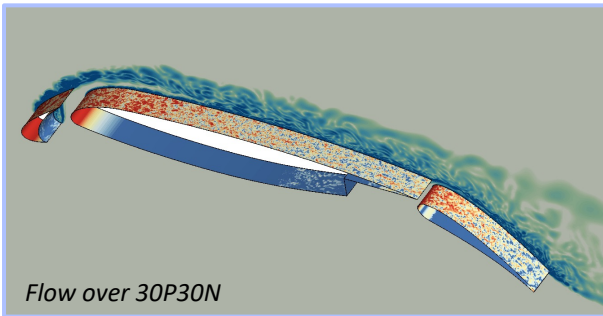


# WMLES Test Cases

## 30P30N Multielement Airfoil

| $M_\infty$ | Re        | $\alpha$                      |
|------------|-----------|-------------------------------|
| 0.2        | 9,000,000 | 8.10°, 16.21°, 21.34°, 23.28° |

- $Re$  based on chord of airfoil in undeflected position
- Grid statistics, solution methodology
- Comparisons of computed lift coefficients, pressure distributions, and velocity profiles with experiments

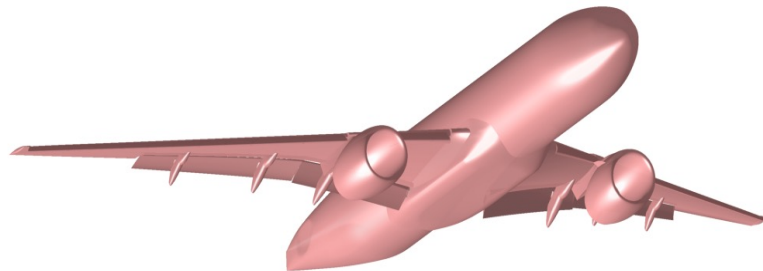


*Details  
in paper*

## NASA High-Lift Common Research Model (CRM-HL)

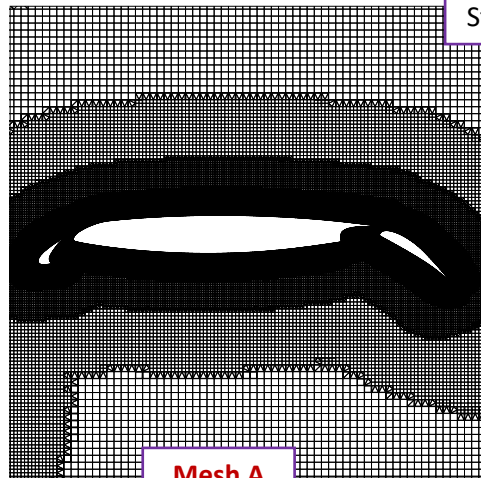
| $M_\infty$ | Re        | $\alpha$ (wall corrected)                             |
|------------|-----------|-------------------------------------------------------|
| 0.2        | 5,490,000 | 7.05°, 11.29°, 17.05°, <b>19.57°</b> , 20.55°, 21.47° |

- $Re$  based on MAC of 275.8"
- Representative high-lift aircraft configuration
- Half-span model, free-air simulations
- Landing configuration at 40°/37° inboard/outboard flap deflection
- 1000/2000 time steps per MAC



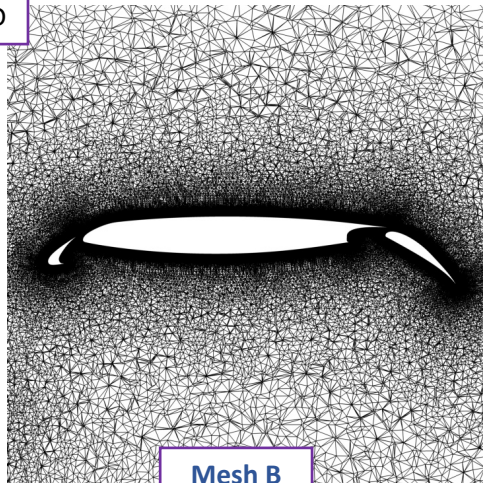
# Computational Grids for NASA CRM-HL

| Metrics                | Mesh A | Mesh B | Mesh C |
|------------------------|--------|--------|--------|
| Nodes                  | 418 M  | 156 M  | 143 M  |
| Cells                  | 812 M  | 475 M  | 342 M  |
| Surface points         | 7.4 M  | 5.0 M  | 7.0 M  |
| Nominal $\Delta y_w^+$ | 100    | 100    | 385    |

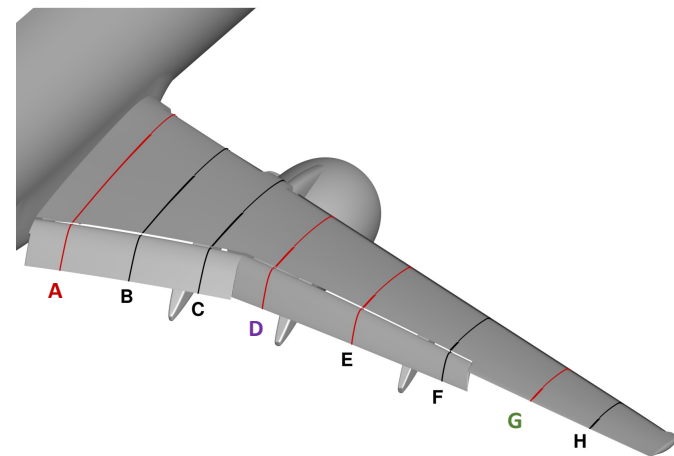


Mesh A

Station D

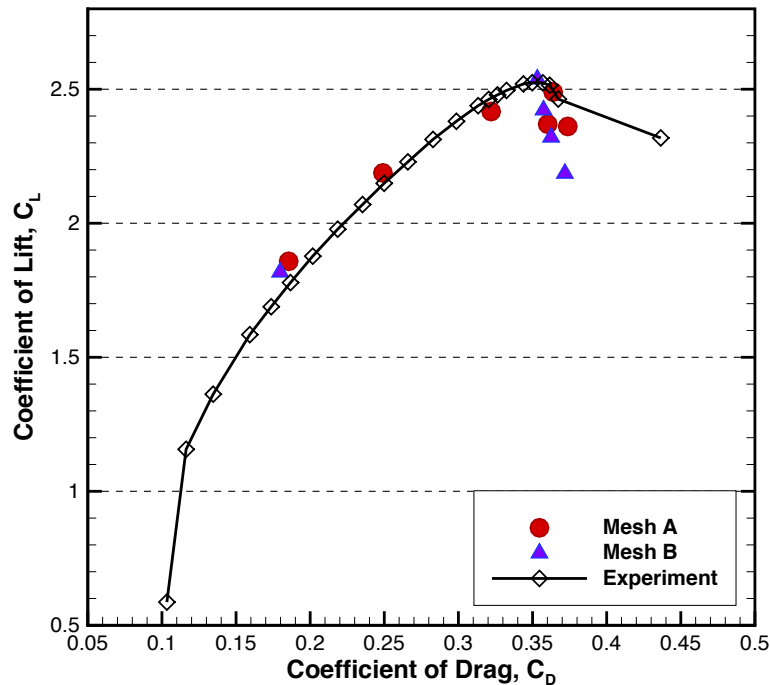
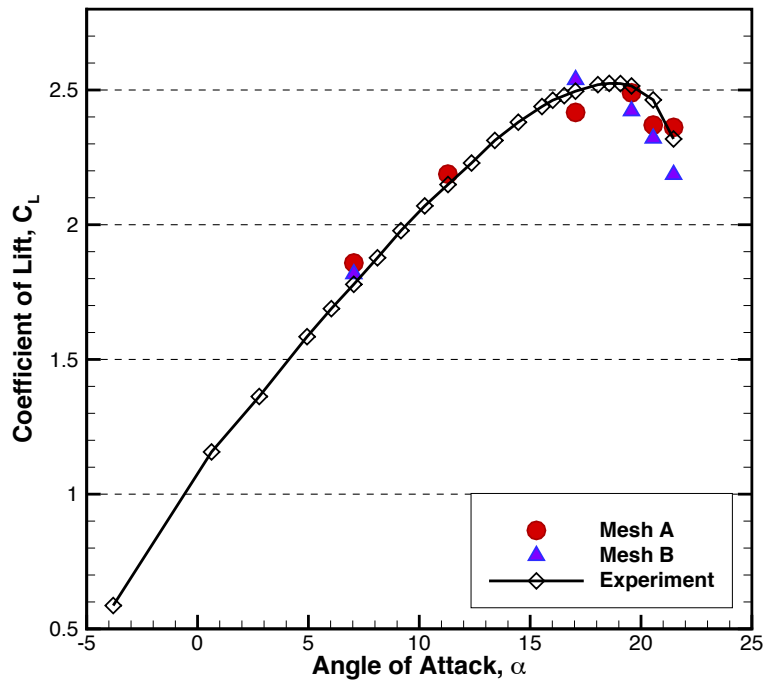


Mesh B



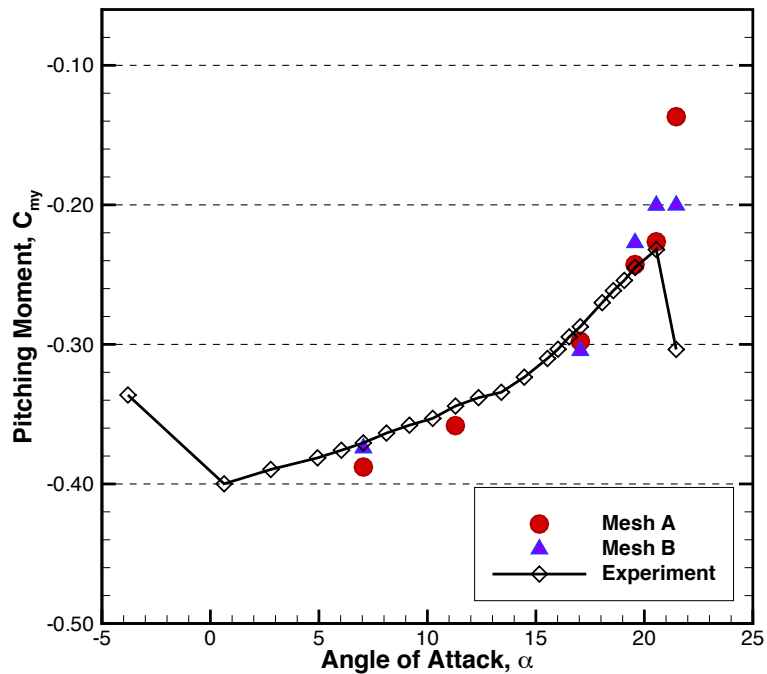
Slice locations

# Lift and Drag Coefficients



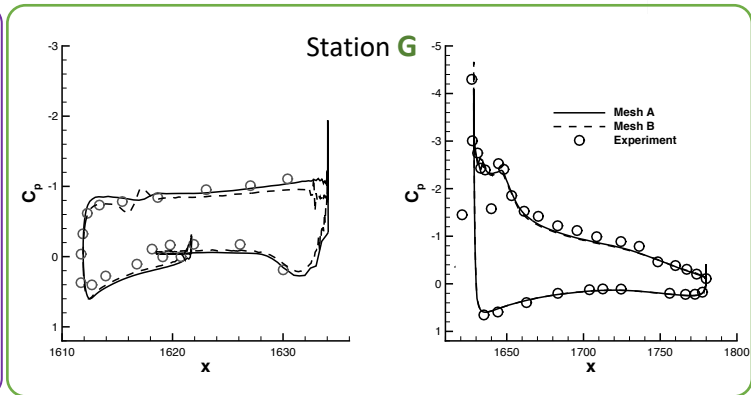
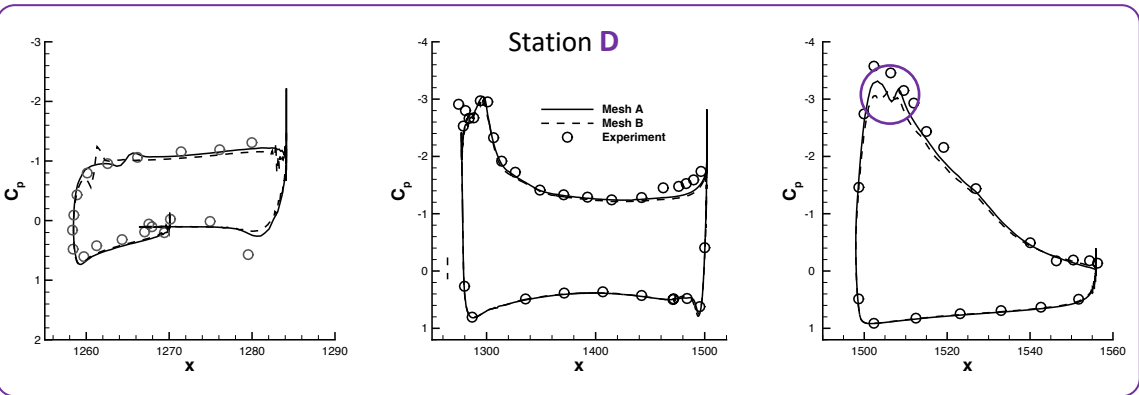
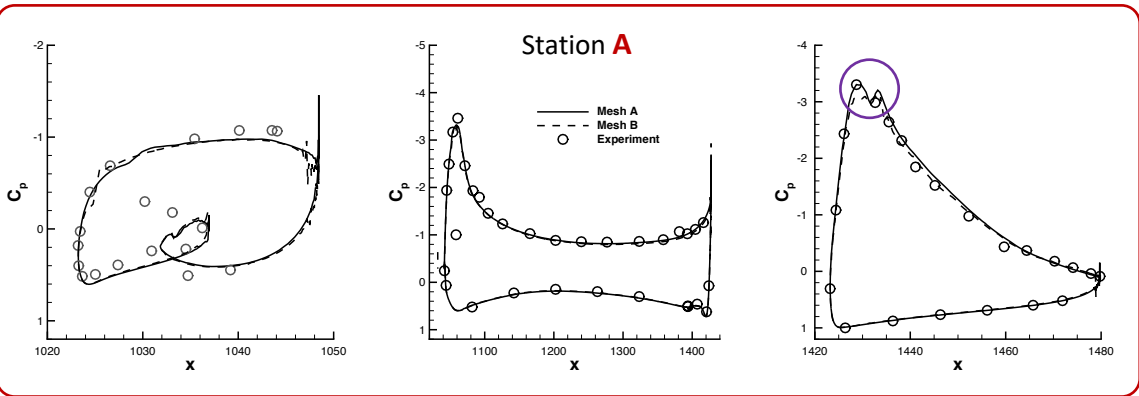
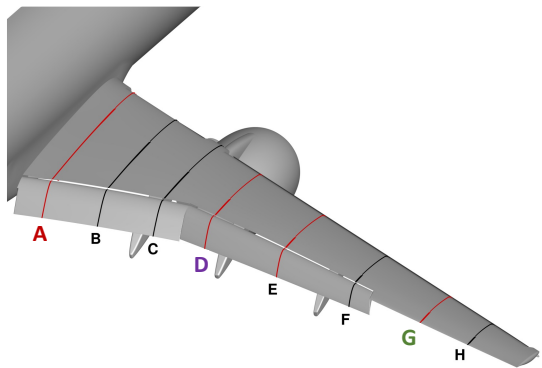
- Computed forces on **Mesh A** and **Mesh B** agree well with experiment up to  $C_{L,max}$
- Critical angle of attack corresponding to  $C_{L,max}$  predicted well on Mesh A

# Pitching Moment

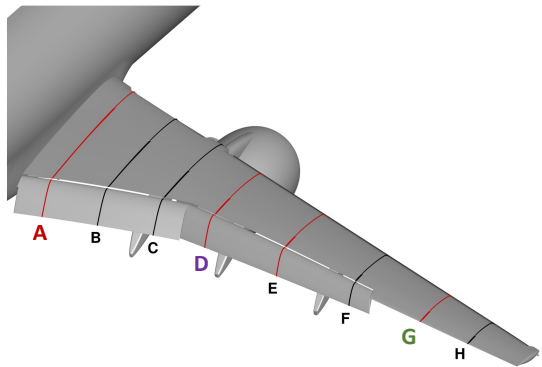


- Good agreement on **Mesh A** for all angles of attack *except* the post-stall  $\alpha = 21.47^\circ$
- At  $\alpha = 21.47^\circ$ , nose-down pitching moment is much smaller on **Mesh A** than on **Mesh B**

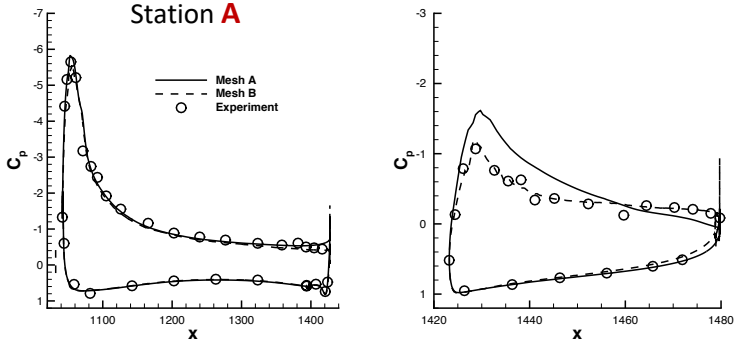
# Pressure Distributions ( $\alpha = 7.05^\circ$ )



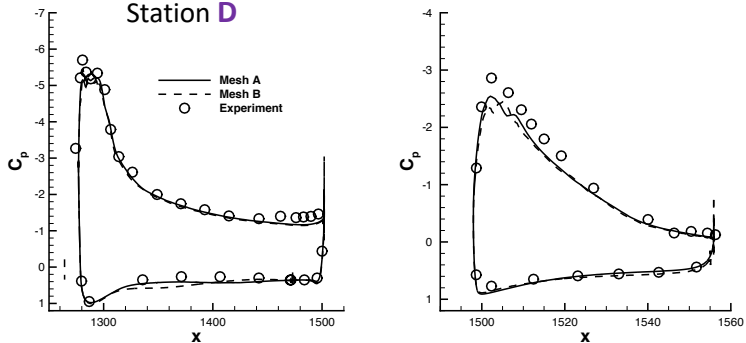
# Pressure Distributions ( $\alpha = 19.57^\circ$ )



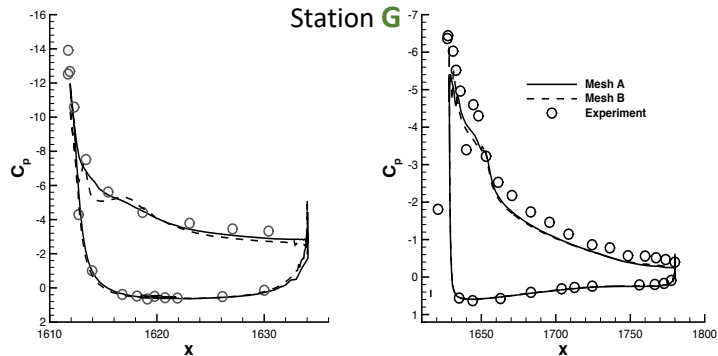
**Station A**



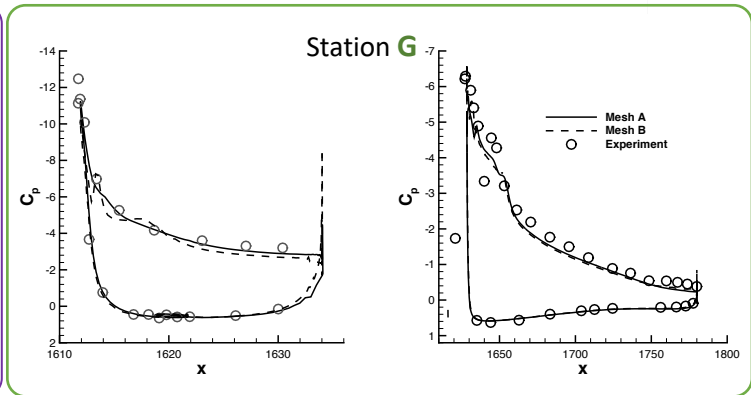
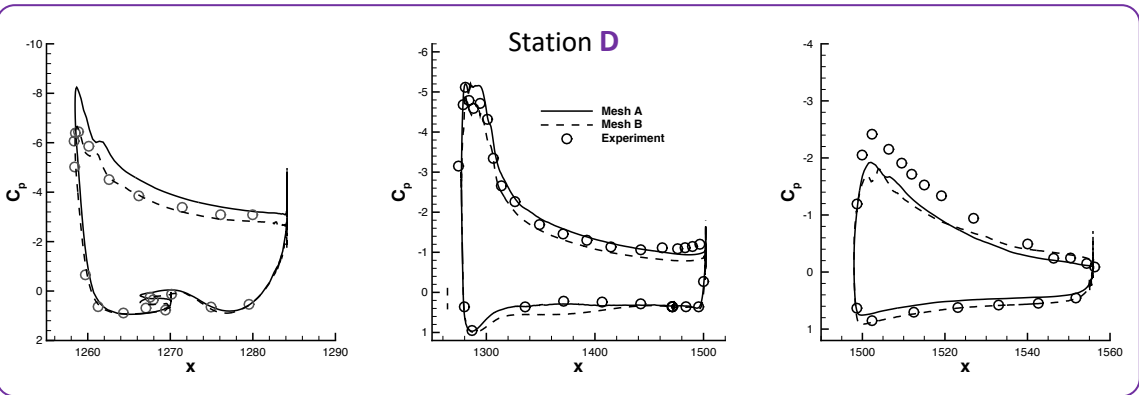
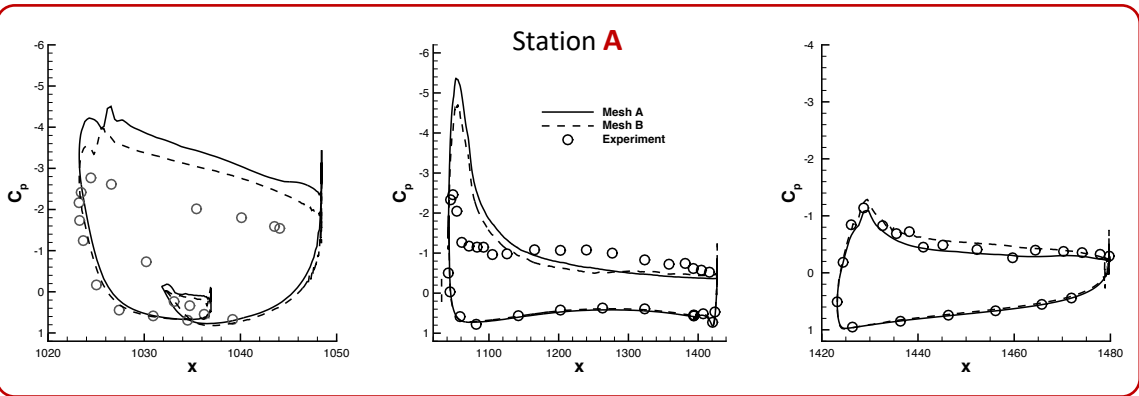
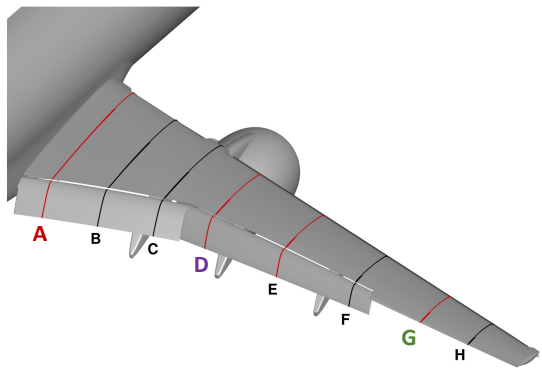
**Station D**



**Station G**



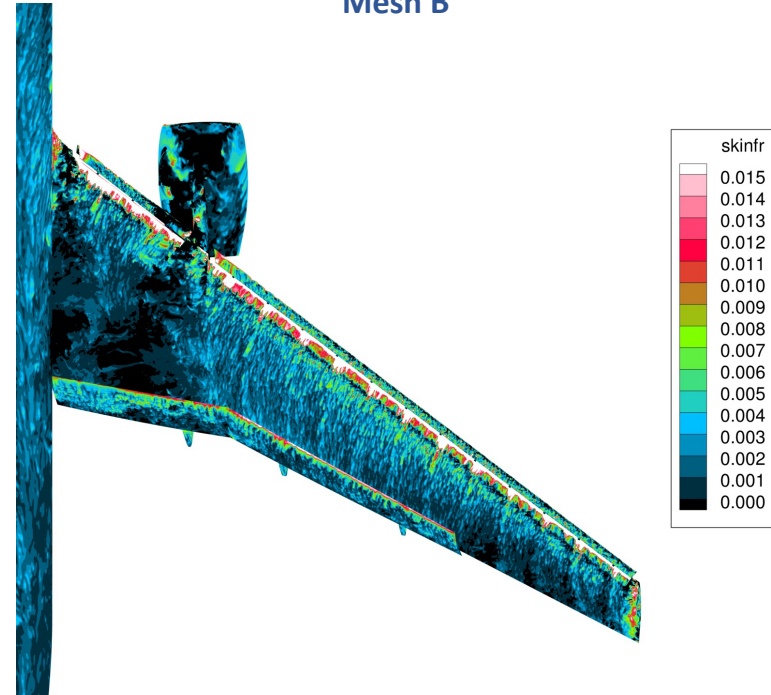
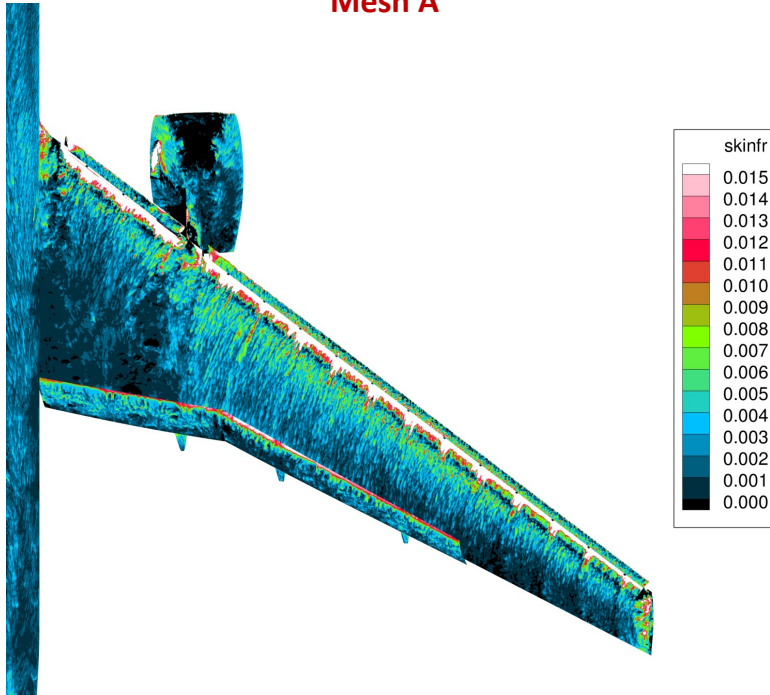
# Pressure Distributions ( $\alpha = 21.47^\circ$ )



# Instantaneous Skin Friction ( $\alpha = 21.47^\circ$ )

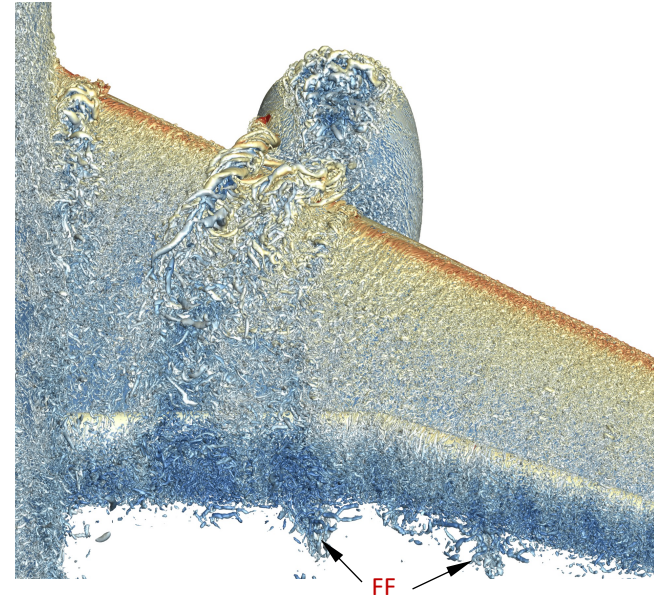
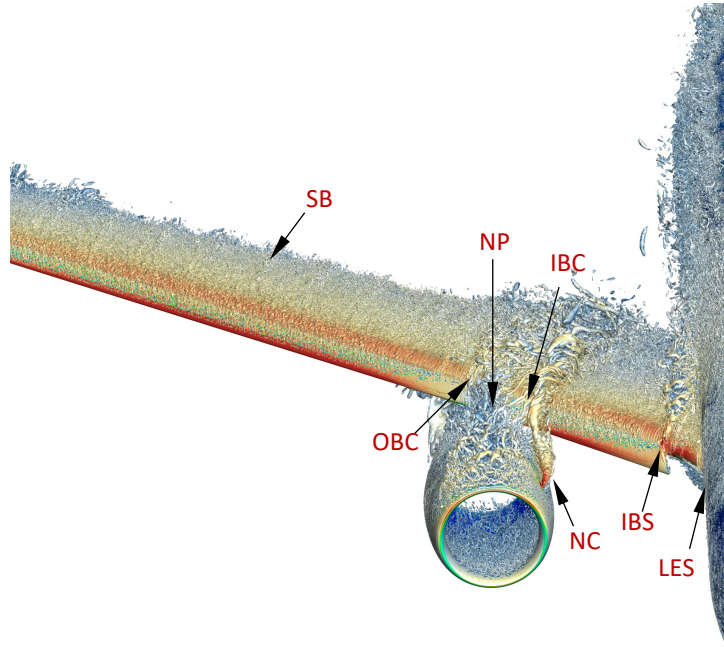
Mesh A

Mesh B



- Slightly more inboard separation on **Mesh B**, consistent with stronger nose-down moment
- No significant outboard separation (i.e., no “pizza-slice” separation)

# Instantaneous Isosurfaces of Q-Criterion ( $\alpha = 19.57^\circ$ )



- **Small-scale** flow features captured
- Vortical structures generated from various geometric components
- Complex interactions

**LES** - Leading-edge strake vortex  
**IBS** - Inboard slat vortex  
**NC** - Nacelle chine vortex  
**NP** - Nacelle/pylon vortex  
**IBC** - Inboard slat cutout vortex  
**OBC** - Outboard slat cutout vortex  
**SB** - Slat bracket vortex  
**FF** - Flap fairing vortex

# Conclusions

- Wall-modeled large-eddy simulation (WMLES) capability has been implemented in FUN3D
- WMLES methodology has been evaluated for high-lift configurations
  - Multielement 30P30N airfoil at various angles of attack (shown in paper)
  - NASA High-Lift Common Research Model at a large range of angles of attack
    - Free-air simulations conducted using half model on three computational grids
    - Integrated aerodynamic forces, moments, and pressure distributions agree well with experiments up to  $C_{L,max}$
    - Critical angle of attack corresponding to  $C_{L,max}$  predicted accurately
    - Nose-down moment at the post-stall angle of attack ( $\alpha = 21.47^\circ$ ) is not strong enough to exhibit “pitch break”
    - Eddy visualization techniques illustrate vortex flows and highly resolved content
- Future Work
  - Continue investigations of post-stall flow conditions using enhanced mesh resolution
  - Improve solver performance and apply mesh adaptation techniques



# Acknowledgments

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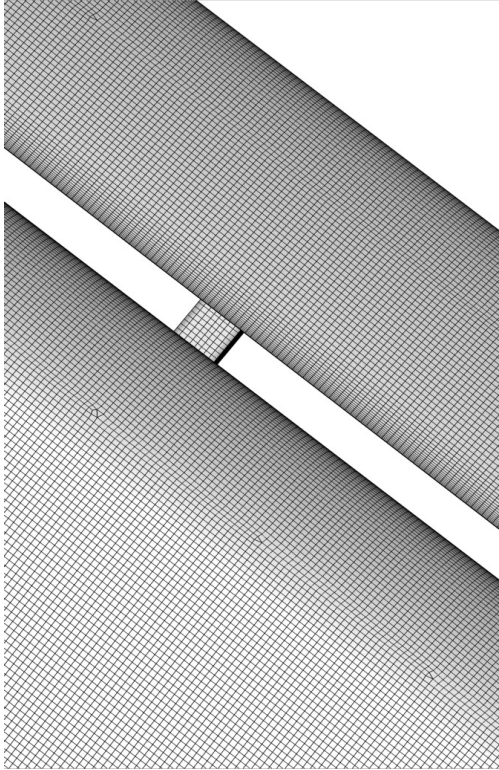
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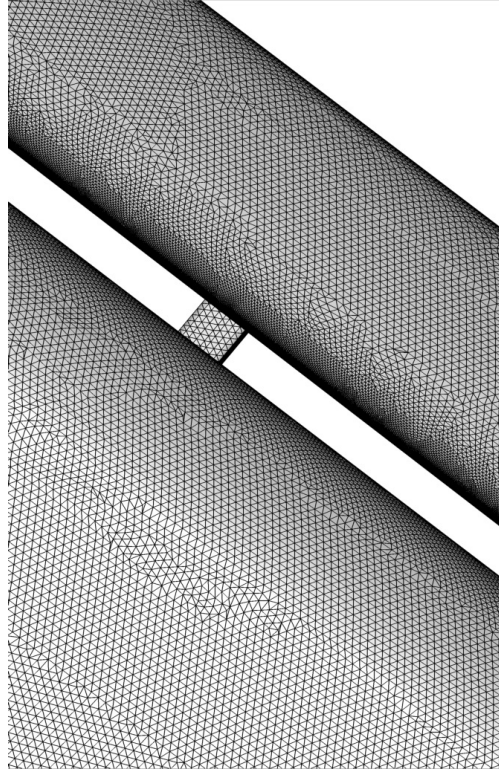


## Backup Slides

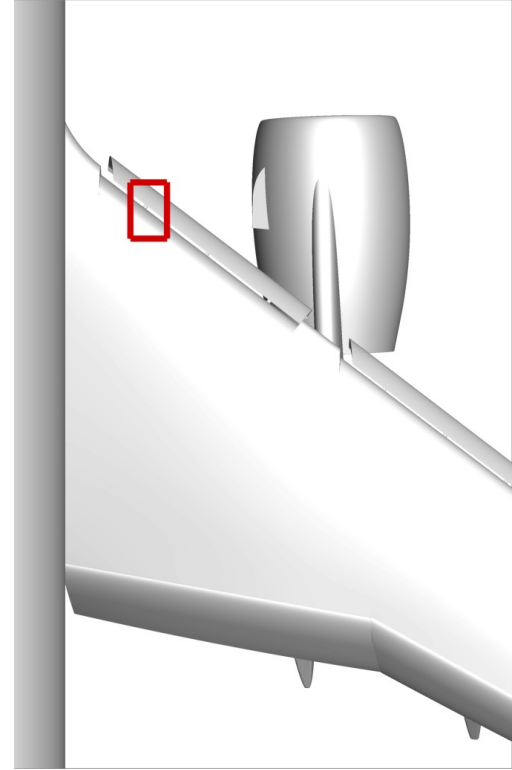
# Computational Grids for NASA CRM-HL



**Mesh A**



**Mesh B**



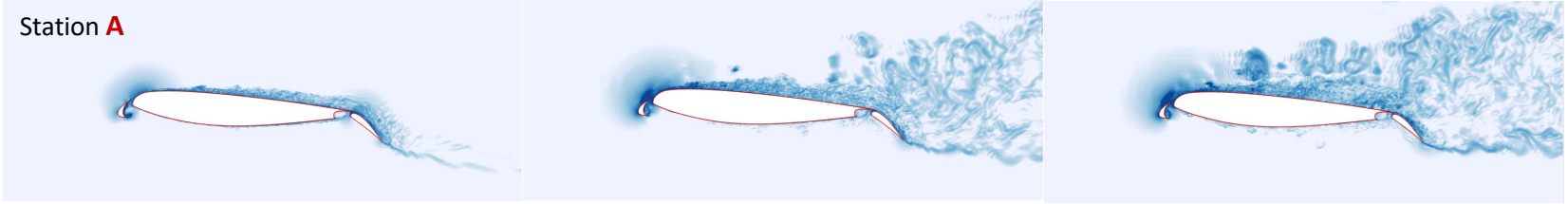
# Instantaneous Density-Gradient Magnitude (Mesh A)

$\alpha = 7.05^\circ$

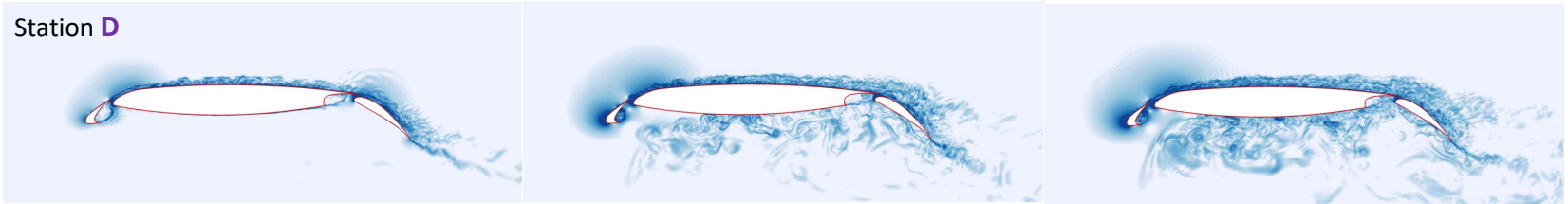
$\alpha = 19.57^\circ$

$\alpha = 21.47^\circ$

Station **A**



Station **D**



Station **G**

