



# Transition Analysis for the Pazy Wing

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# Outline

- Motivation
- Description of the Pazy wing, Flow conditions
- OVERFLOW and FUN3D
- Results and discussion
- Simplified periodic representation
- Summary

# Sagged Pazy Wing

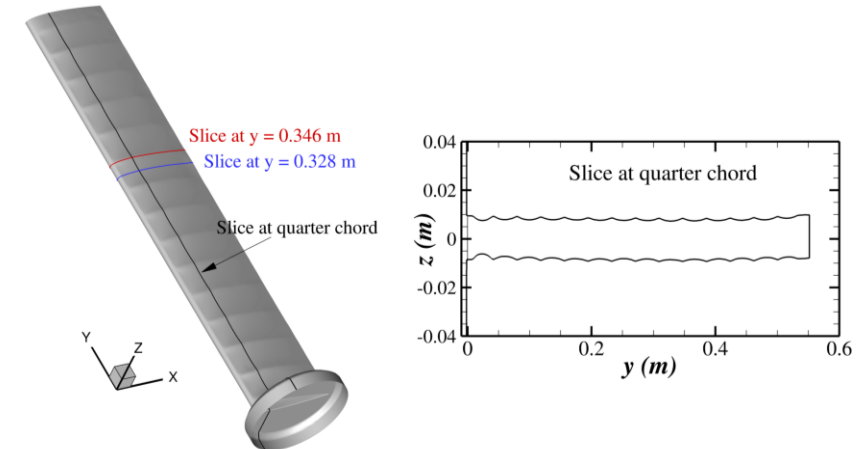
- Created as a benchmark for highly flexible wings subjected to substantial deformations
- Distinctive geometry with spanwise-varying static deformation and low Reynolds number flow condition
- Complicated flow phenomena such as 3D laminar separation bubbles (LSBs) and intricate transition patterns



## Motivation

To investigate transition behavior on the sagged Pazy wing under static loading

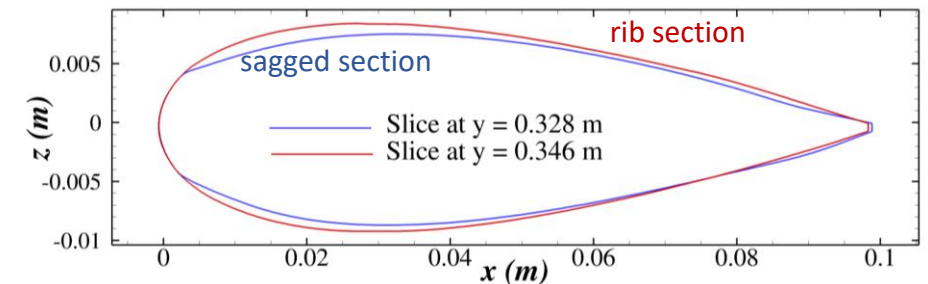
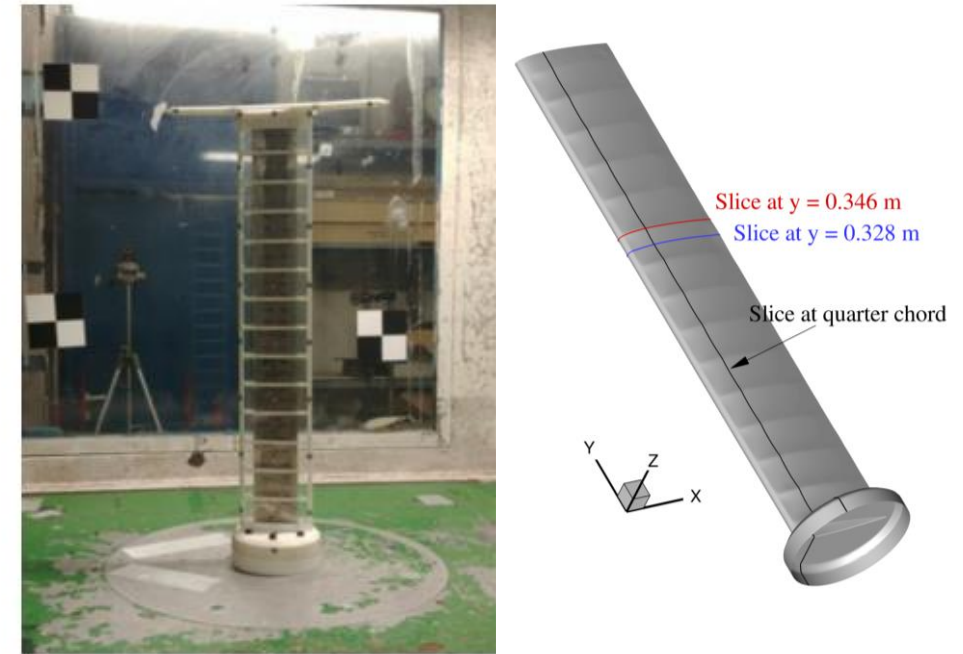
- Using SST-based Langtry-Menter  $\gamma - Re_{\theta t}$  transition model in the NASA OVERFLOW and FUN3D CFD solvers
- Identify the limitations of the LM model
- In preparation toward planned for aeroelastic computations using FUN3D



# Details on Pazy Wing and Flow Conditions

| Property                | Unit | Pazy Wing |
|-------------------------|------|-----------|
| Span                    | m    | 0.56      |
| Chord (without tip rod) | m    | 0.1       |
| Airfoil                 | -    | NACA 0018 |

- Rib structure with polyester foil wrapping
- Experiment carried out at Open jet facility at TU Delft<sup>1,2</sup>
- Assumed sea level conditions ( $P_\infty = 101325$  Pa and  $T_\infty = 288.15$  K)
- Experimental condition:  $Re_c = 120,000$  ( $M_\infty = 0.053$ )
- AoA =  $0^\circ$ ,  $4^\circ$ ,  $6^\circ$ ,  $8^\circ$ , and  $10^\circ$
- To be consistent with DLR's computational studies<sup>3</sup>
  - Majority of computations:  $Re_c = 342,165$  ( $M_\infty = 0.1469$ )
  - $Tu = 0.3$  %



1. Avin, O., Raveh, D. E., Drachinsky, A., and Ben-Shmuel, Y. , "An Experimental Benchmark of a Highly Flexible Wing," AIAA Paper 2021-1709, 2021.
2. Mertens, C., Guerra, A. G., van Oudheusden, B., Fehrs, M., and Ritter, M. R., "Analysis of the Boundary Layer on a Highly Flexible Wing based on Infrared Thermography Measurements," STAB-Symposium, Berlin, Germany, Nov 2022.
3. Ritter, M., Fehrs, M., Mertens, C., "Aerodynamic and Static Coupling Simulations of the Pazy Wing with Transitional CFD for the Third Aeroelastic Prediction Workshop," AIAA Paper 2023-0762, 2023.

# Langtry–Menter Model (LM2009/LM2015/LM-CFHE)

Solves two additional scalar equations ( $\gamma$ ,  $Re_{\theta t}$ ), implemented upon SST model (2003 version)<sup>1</sup>

- Baseline model LM2009: models natural, bypass, and separation-induced transition scenarios
- LM2015, LM-CFHE: two different implementations to account for crossflow

## NASA CFD Solvers

### OVERFLOW (2.3e)<sup>2</sup>

- Implicit structured overset grid Navier-Stokes solver
- SSOR implicit solution algorithm
- Third-order accurate discretization (convective terms), second-order accurate (gradients)

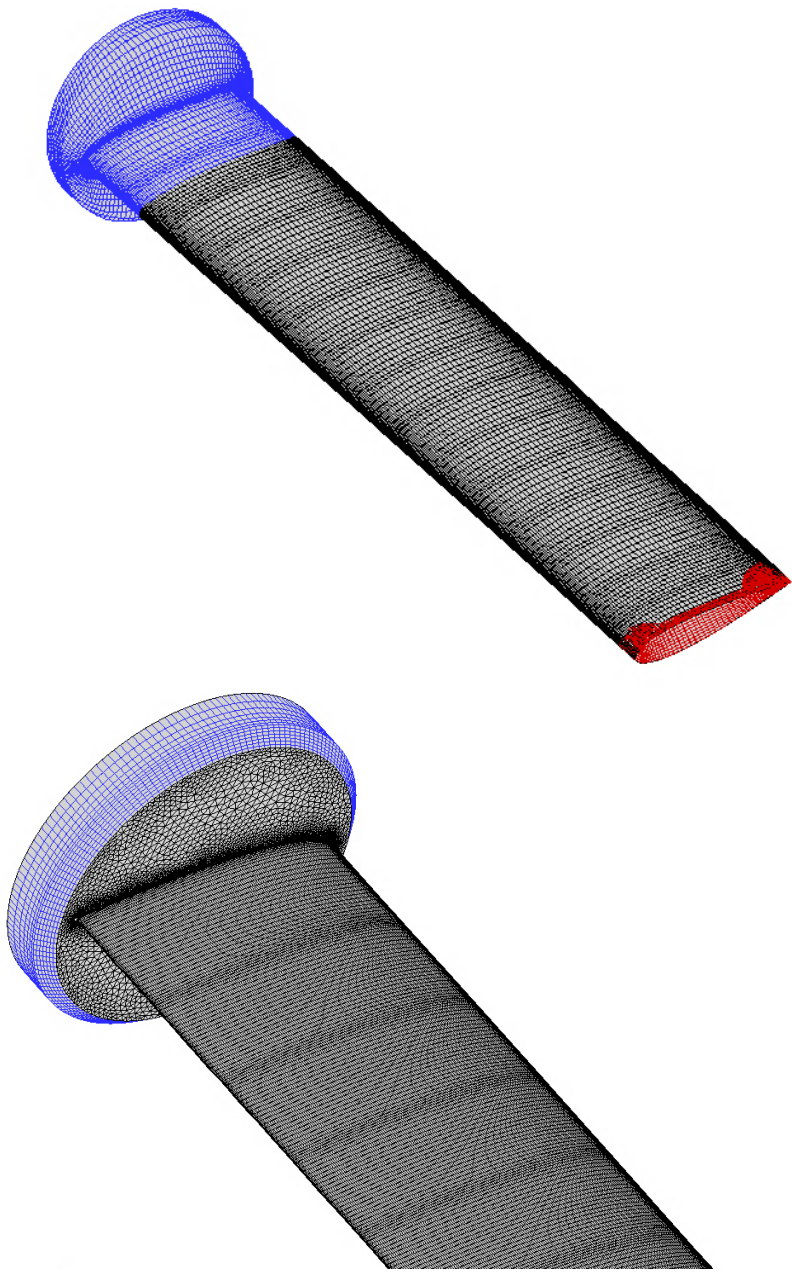
### FUN3D (13.7)<sup>3</sup>

- Implicit unstructured node-centered Navier-Stokes solver
- Point implicit or implicit line relaxation algorithm
- Second-order accurate discretization (first-order accurate for convective terms of turbulence/transition model equations)

1. Langtry, R. B., and Menter, F. R., “Correlation-Based Transition Modeling for Unstructured Parallelized Computational Fluid Dynamics Codes,” *AIAA Journal*, Vol. 47, No. 12, 2009, pp.2894–2906.
2. Nichols, R. H., and Buning, P. G., “User’s Manual for OVERFLOW 2.3, Version 2.3,” NASA Langley Research Center, Hampton, VA, Oct 2019.
3. Biedron, R. T., Carlson, J.-R., Derlaga, J. M., Gnoffo, P. A., Hammond, D. P., Jacobson, K.E., Jones, W. T., Kleb, B., Lee-Rausch, E. M., Nielsen, E. J., Park, M. A., Rumsey, C., Thomas, J. L., Thompson, K. B., Walden, A. C., Wang, L., and Wood, W. A., “FUN3D Manual: 13.7,” NASA/TM-0205010139, 2020.

# Details on Mesh

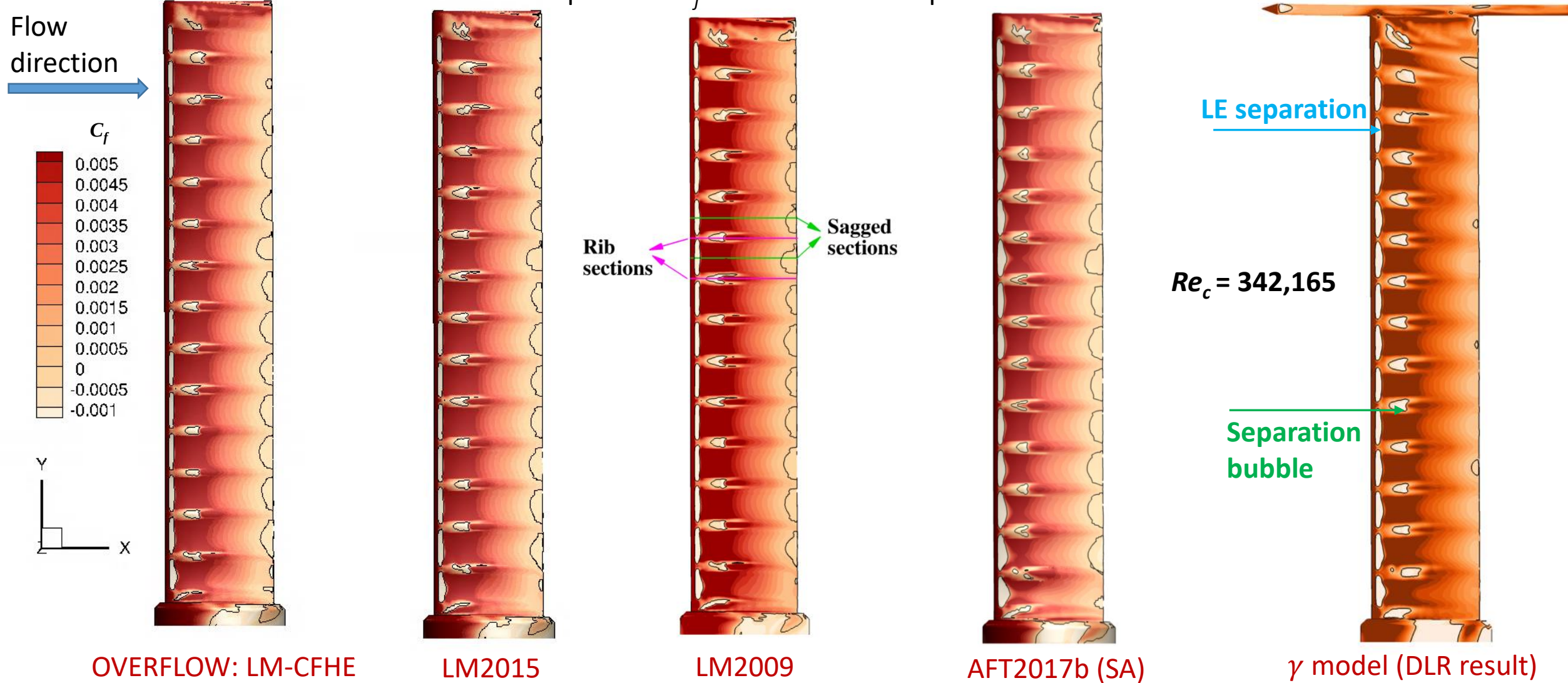
|                        | OVERFLOW                                               | FUN3D                                    |
|------------------------|--------------------------------------------------------|------------------------------------------|
| Wing-tip rod           | No                                                     | Yes                                      |
| Grid type              | Overset structured                                     | Hybrid unstructured (hex + tertrahedral) |
| Chordwise resolution   | 0.036 mm – 1 mm (457 points)                           | 0.3 mm – 0.7 mm                          |
| Spanwise resolution    | 1.1 mm – 1.8 mm (361 points)                           | 1mm (average)                            |
| Wall normal resolution | $Y^+ \sim 0.25$ ( $1.3 \times 10^{-6}$ m) (261 points) | $Y^+ \sim 0.46$ (44 layers; 1.16 growth) |
| Overall grid count     | 70M Nodes (near body 65M; 1.5x chord)                  | 7.2M Nodes                               |



The unstructured grid was generated by DLR and the resolution is representative of the kind that may be used for aeroelastic computations

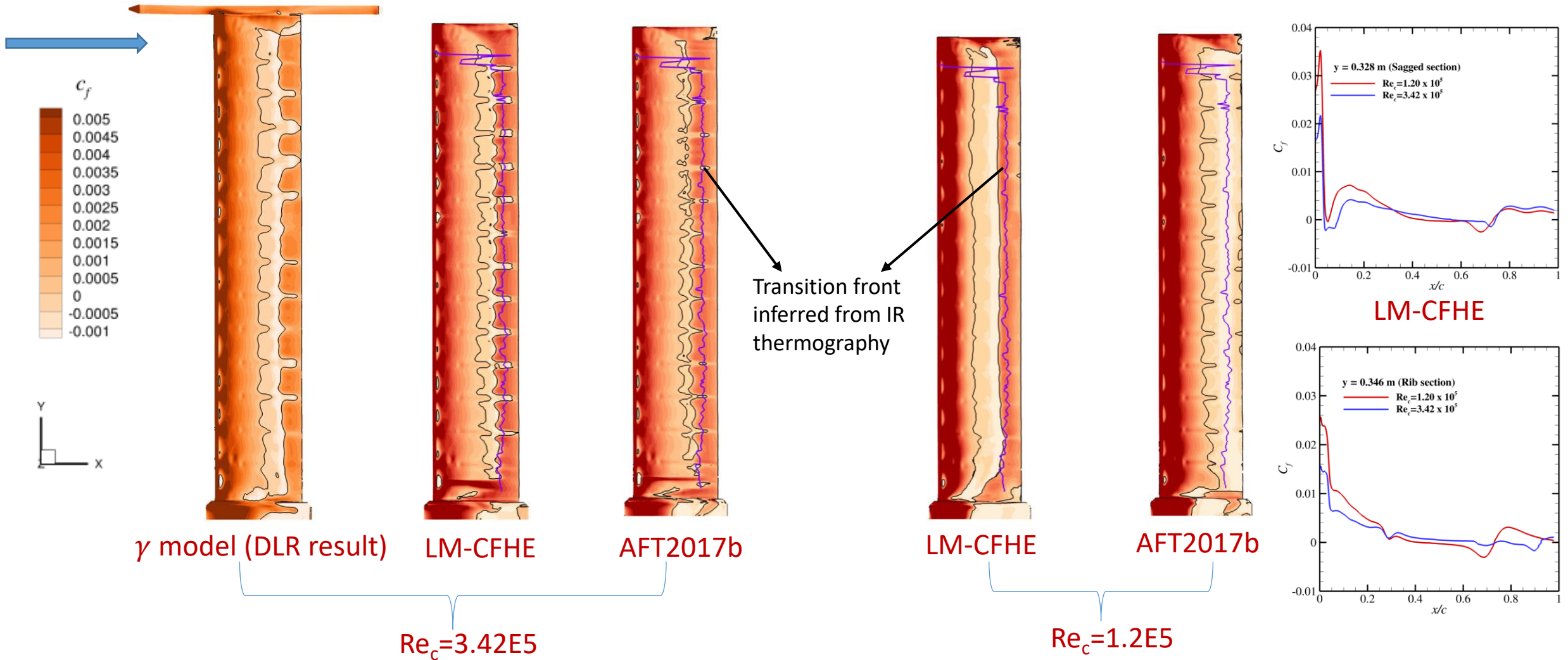
# Results from using transition model variants $\alpha = 8.0^\circ$

Solid black line corresponds to  $c_f = 0$  in the contour plots shown here onward



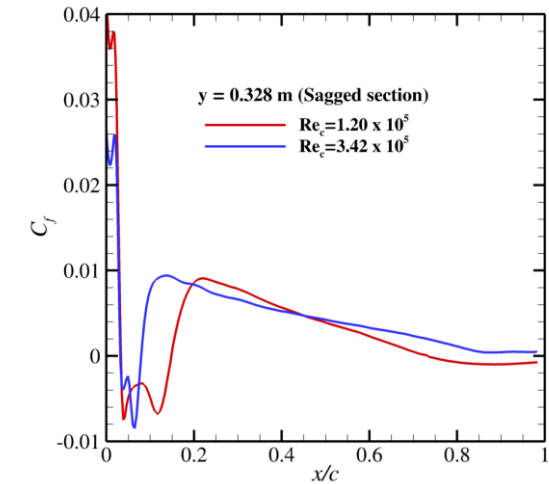
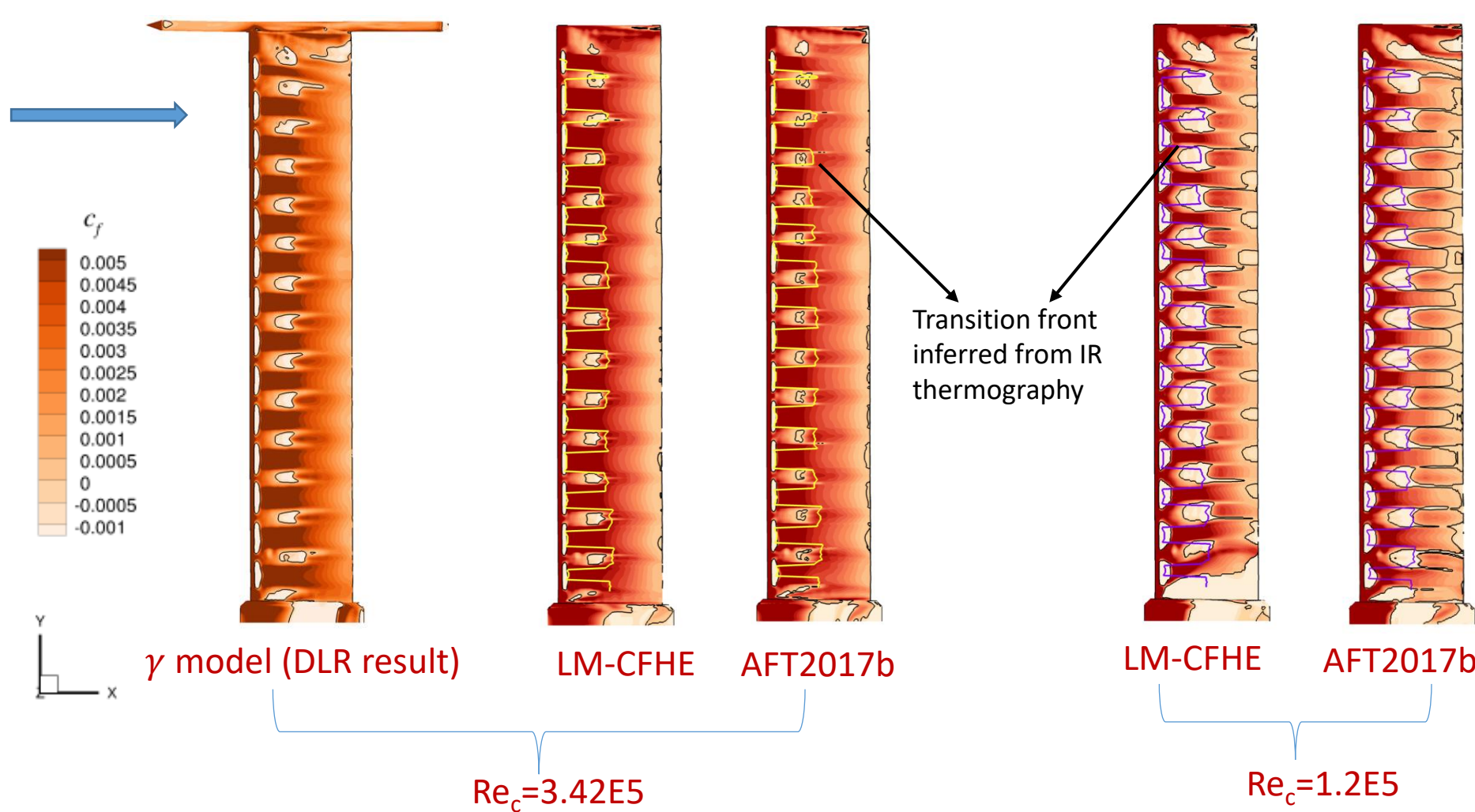
No significant variation; crossflow not important; indicative of separation-induced transition being the dominant mechanism

# Influence of chord Reynolds number ( $\alpha = 0.0^\circ$ )

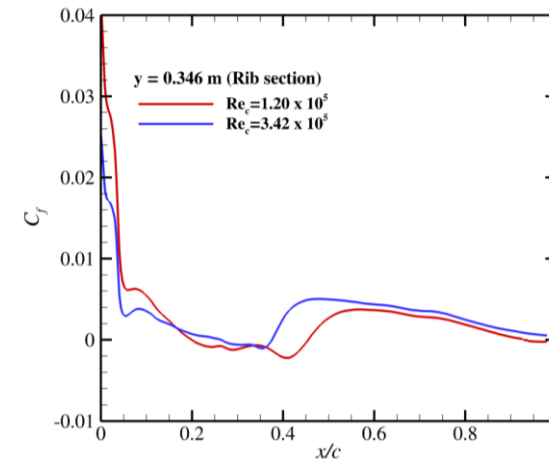


- Separation pattern from the thermography images appear to be similar to those seen from higher  $Re_c$  computations
- Both LM and AFT are inaccurate at lower  $Re_c$  in different aspects

# Influence of chord Reynolds number ( $\alpha = 6.0^\circ$ )



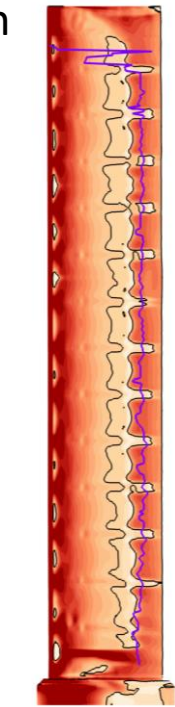
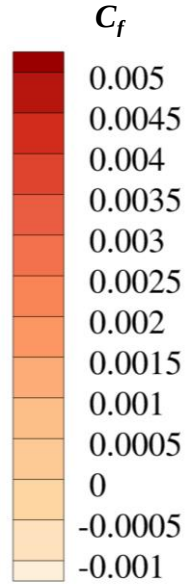
LM-CFHE



- Thermography images appear to be similar to those seen from higher  $Re_c$  computations made with LM
- Both LM and AFT are inaccurate at lower  $Re_c$  (larger separation bubbles near the LE and in the rib section)

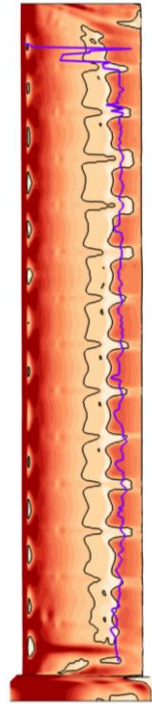
# Code-to-Code comparison: AoA sweep

Flow direction



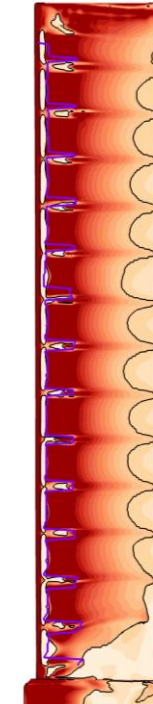
OVERFLOW

$\alpha = 0.0^\circ$



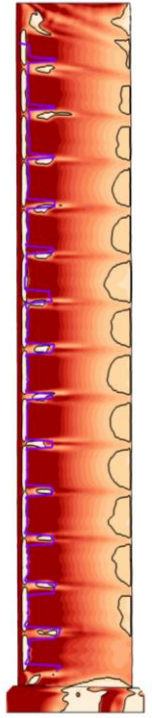
FUN3D

- In general, the onset of transition near the ribs is further downstream than that within the sagged portion
- With an increase in the angle of attack
  - The upstream separation bubbles in the sagged portions of the wing become more elongated in the spanwise direction
  - The separation bubbles concentrated around the ribs appear to shrink in size and move upstream

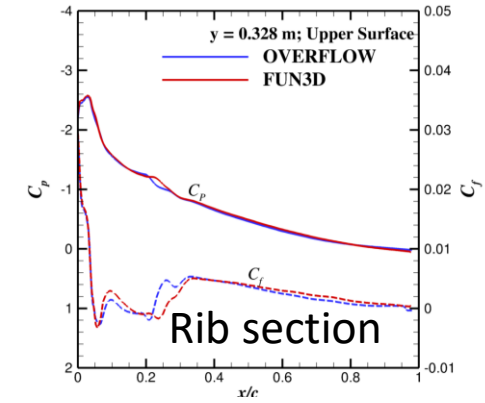
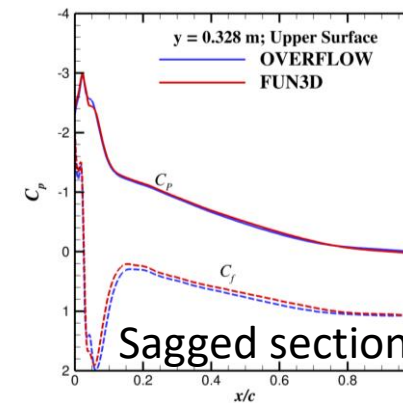
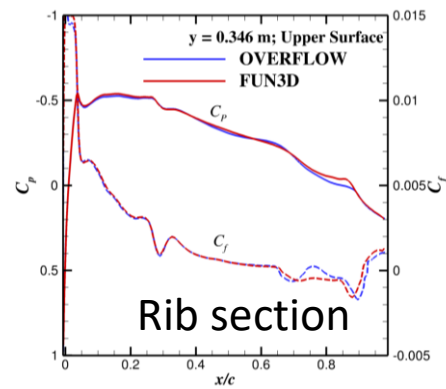
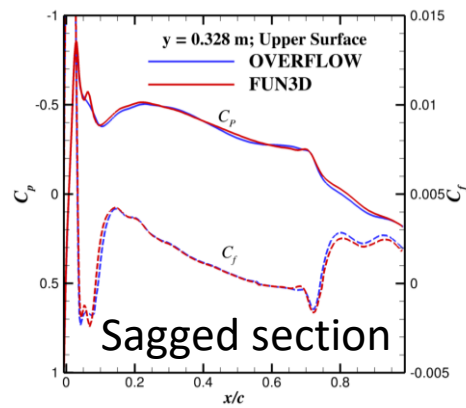


OVERFLOW

$\alpha = 10.0^\circ$

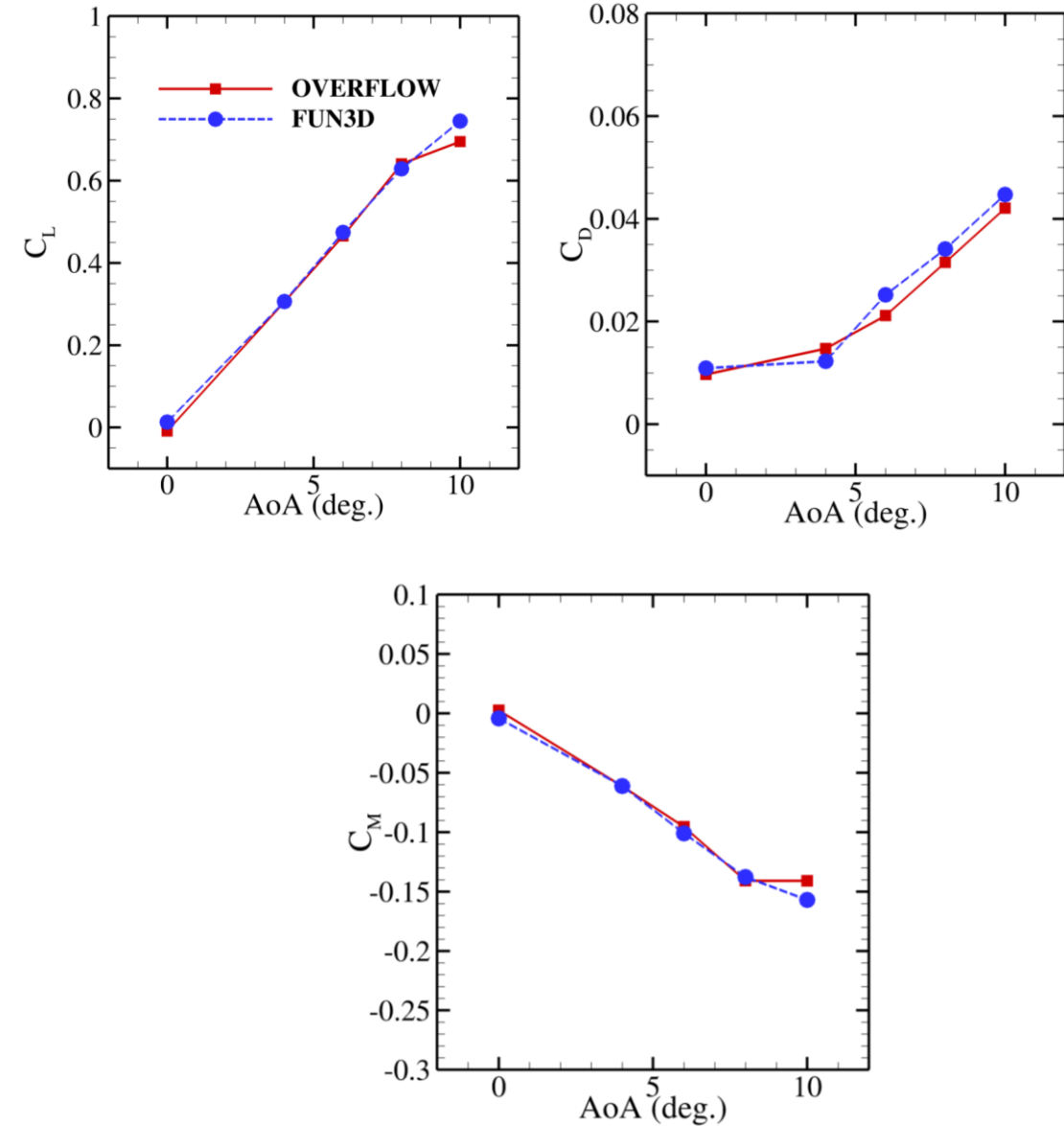


FUN3D



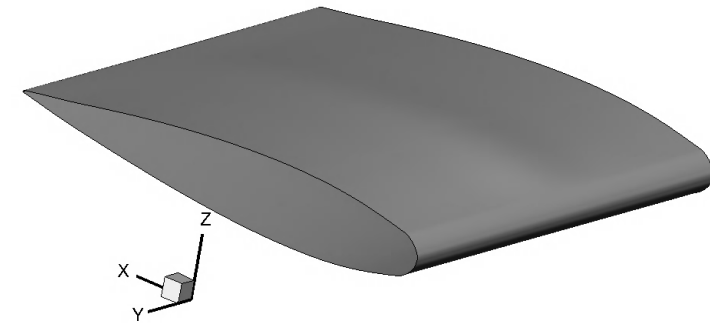
# Code-to-Code comparison: AoA sweep

- A good match between the results obtained with FUN3D and OVERFLOW
  - In terms of  $C_f$  contours, the overall pattern of flow, and force/moment coefficients.
  - Qualitatively consistent with those of the DLR computations by Ritter et al.
- Difference in  $Re$  prevents direct comparison against experiments, but results from the higher  $Re_c$  computations look qualitatively like the IR thermography images

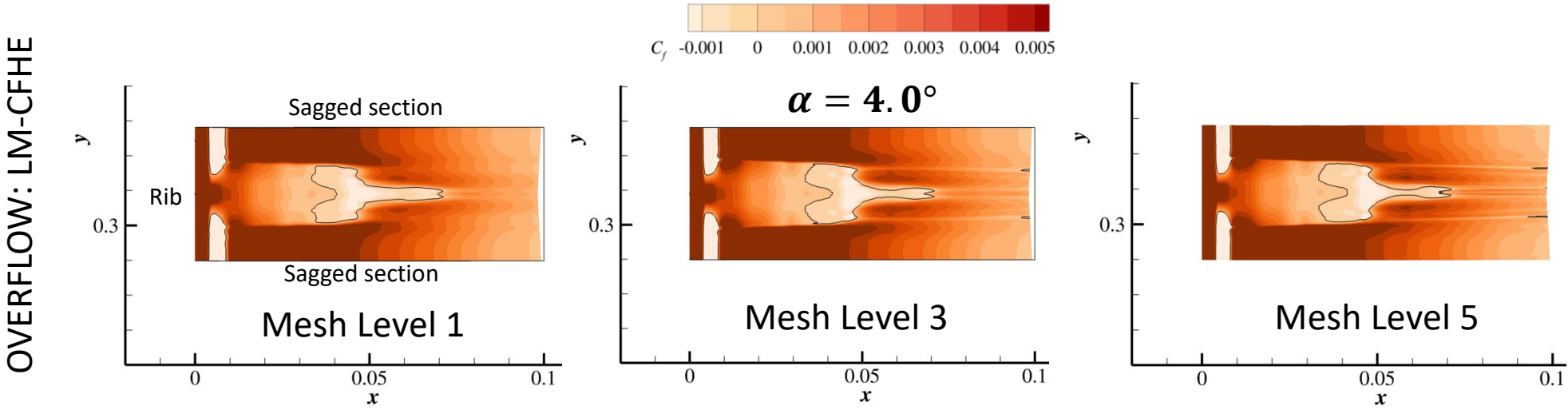


# Simple Periodic Representation

- A simplified periodic representation of the Pazy wing geometry was created
  - Quasiperiodic patterns across the span observed from the experiments and computations
- Cost-effective, systematic, comprehensive analysis of the flow
  - Application of stability analysis tools (toward calibrating RANS-based transition models)
- Geometry creation:
  - Isolated a unit spanwise cell centered on one of the ribs in the midspan region
  - The thickness distribution was filtered by retaining only four spanwise Fourier harmonics
- Five levels of meshes with level 3 similar to the full-span mesh (6 M to 362 M points)
  - The number of grid points in every direction was doubled for every other grid level



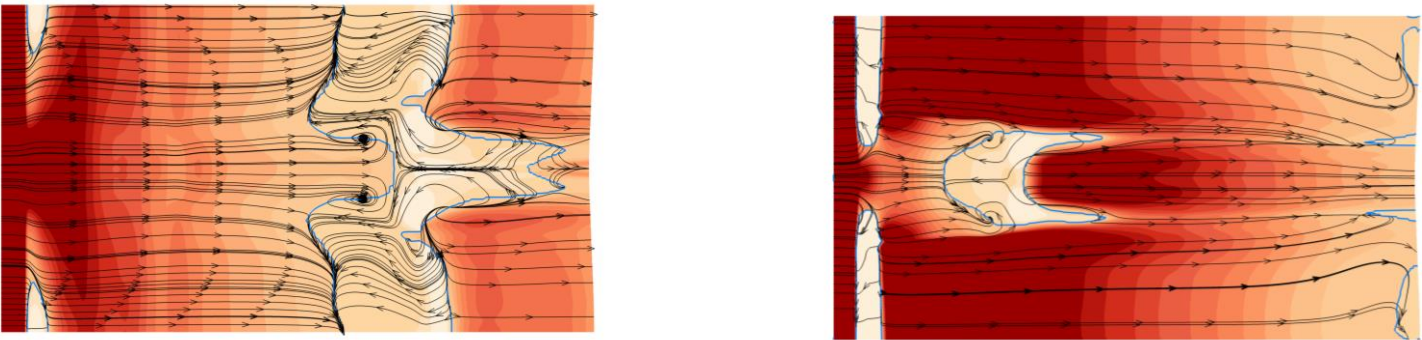
# Simple Periodic Representation



Flow direction

$\alpha = 0.0^\circ$

$\alpha = 6.0^\circ$

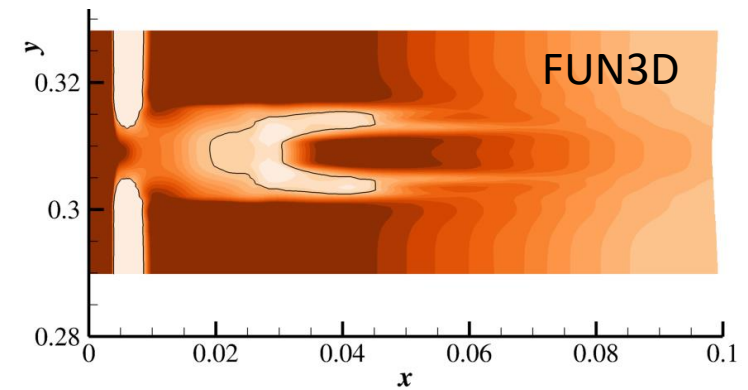
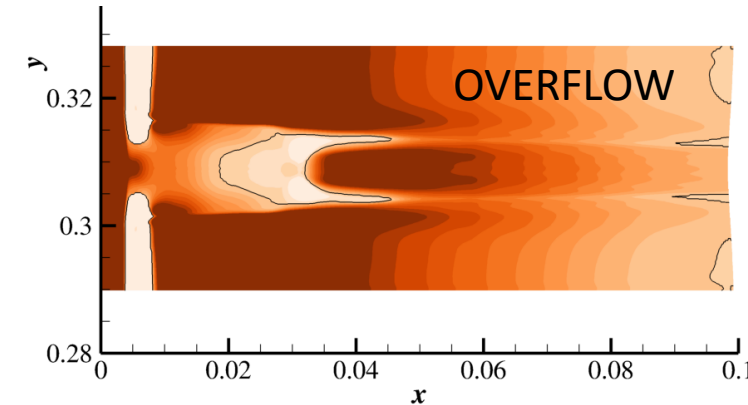


Skin-friction lines overlaid with skin-friction contour

# Simple Periodic Representation

- Mesh convergence achieved with OVERFLOW for mesh level 3 and above (in terms of  $C_f$  contours)
  - Asymptotic convergence of force/moment coefficients require additional mesh levels
  - FUN3D needed mesh level 4 and higher, due to its lower spatial accuracy
- Use of spanwise periodic BCs or symmetric BC did not significantly alter results
- Flow entrains from the rib portion into the sagged portion near the leading edge

Mesh Level 3



$$\alpha = 6.0^\circ$$

# Summary

- Transition analysis carried out using  $\gamma - Re_\theta$  model variants (LM2009, LM2015 and LM-CFHE) and two different flow solvers: OVERFLOW and FUN3D
- Steady-state 3D computations performed at  $Re_c = 120,000$  and  $342,000$  for  $\alpha = 0^\circ - 10^\circ$
- Separation-induced transition appears to be the main pathway for transition
  - Transition along the rib section appears to be downstream of that in the sagged portion
- Computations made with  $Re_c = 342,000$  appeared closer to thermography images from the experiment than for  $Re_c = 120,000$ 
  - Results highlight the inaccuracy of transition models at low to moderate Reynolds numbers and the need for further enhancements to modeling LSB transition
- Strong code-to-code comparison between FUN3D predictions and the predictions obtained with OVERFLOW and DLR models bolsters confidence in FUN3D's transition models for 3D LSBs
- Periodic representation of a unit cell of the Pazy Wing can act as a better/simpler configuration to understand the flow behavior and perform comprehensive grid refinement study

## Future Work:

- Additional runs in time-accurate mode to ascertain unsteadiness and its influence on transition locations
- Aeroelastic calculations will be performed to further assess the effect of transition on the wing response

# Acknowledgments

- Research Funded by: NASA Transformational Tools and Technologies (TTT) Project
- Dr. Markus Ritter of the German aerospace agency (DLR) for providing the unstructured CFD grid, as well as for sharing data from CFD computations by DLR
- Dr. Christoph Mertens of the Royal Netherlands Aerospace Centre (NLR) for providing the transition fronts from the experiment
- Dr. Joseph Derlaga at NASA LaRC for help with OVERFLOW
- LaRC K-Midrange Cluster resources and NASA Advanced Supercomputing (NAS) resources at ARC

**Thank You! Questions?**

# Additional Backup Slides

# Details on Mesh

## OVERFLOW:

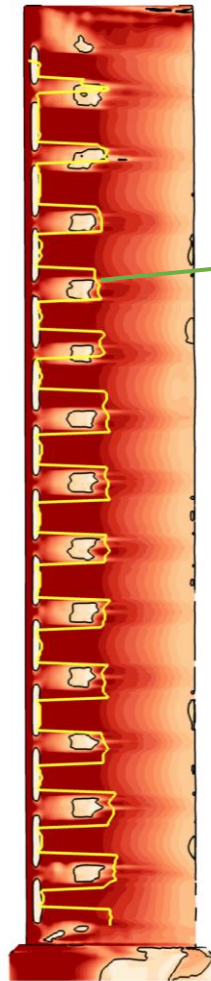
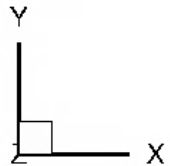
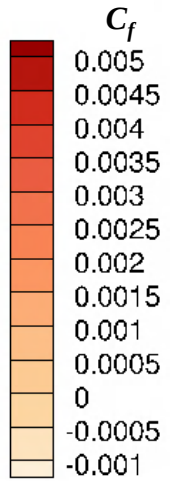
- Wingtip rod was excluded
- Includes clamping section and the floor wall (slip-wall treatment)
- Structured Overset grid
- Wall normal:  $Y^+ \sim 0.25$  (based on quarter chord;  $1.3 \times 10^{-6}$  m)
- Nearbody grid of the wing portion: 457 (chordwise; 0.036 mm – 1 mm) x 361 (spanwise; 1.1 mm – 1.8 mm) x 265 (wall-normal)
  - Excludes the base portion and wing tip
  - Extends up to 1.5x chord in the wall-normal direction
- Overall grid count: 70M (65M in the nearbody grid)
  - Inflow/outflow/farfield boundaries placed 300 x chords away from the center of the wing

## FUN3D:

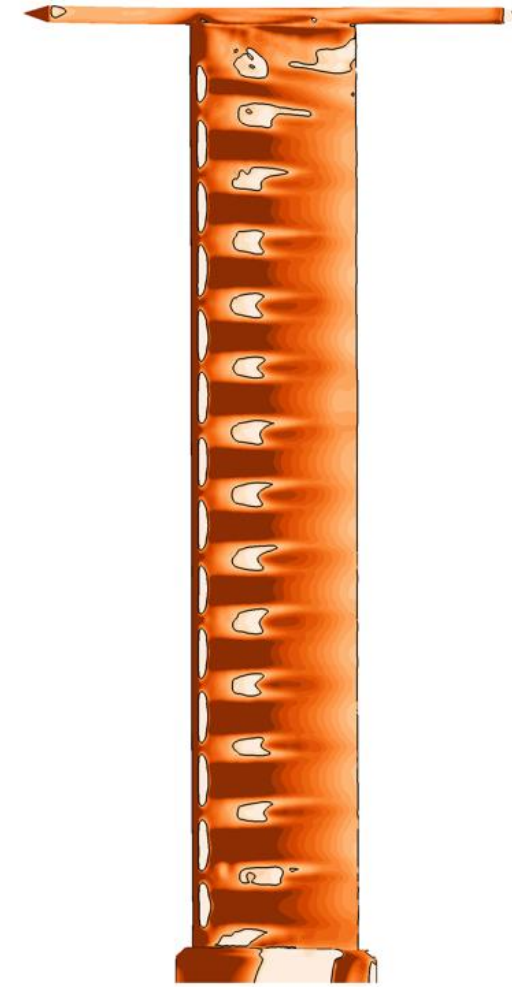
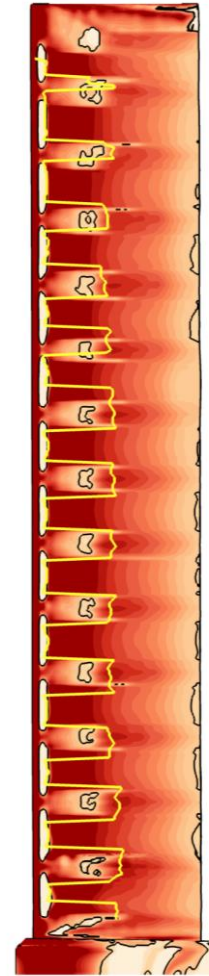
- Hybrid unstructured grid generated by DLR (Ritter et al.) (hexahedral + tetrahedral elements)
- Included wingtip rod
- Quadrilateral meshes on the surface of the wing
  - Chordwise spacing: 0.3 mm – 0.7 mm; spanwise spacing: 1 mm (average)
- Wall normal:  $Y^+ \sim 0.46$  (based on quarter chord;  $2.4 \times 10^{-6}$  m)
  - Extruded from wing surface; 44 layers with growth rate of 1.16
- Overall grid count: 7.2 M nodes (12 M elements)
  - Farfield was 80 x chords away

# LM-CFHE vs AFT2017b for $\alpha = 6.0^\circ$

Flow direction



Transition front  
inferred from IR  
thermography



OVERFLOW: LM-CFHE (SST2003)

OVERFLOW: AFT2017b (SA)

$\gamma$  model (DLR result)

Separation bubble in the rib section is smaller in the AFT computations. Otherwise, similar predictions of laminar and turbulent regions