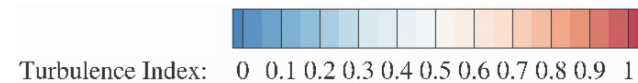
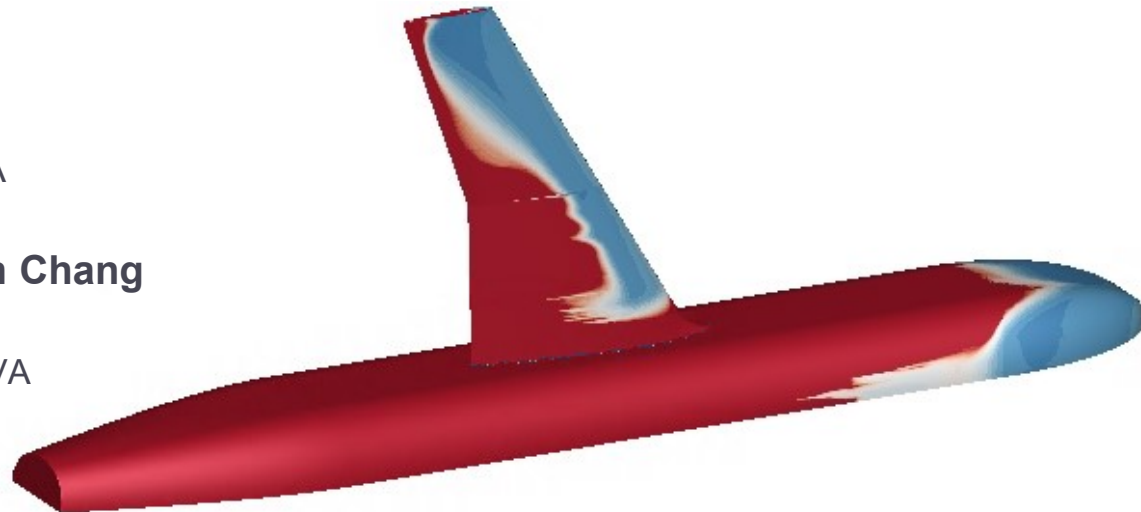


Pretest Computational Assessment of Boundary Layer Transition in the NASA Juncture Flow Model with an NACA 0015-Based Wing

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Objectives

NASA Juncture flow model

- Previous NASA Juncture flow model experiments with DLR-F6 swept-wing model
 - Assessment of CFD in prediction of onset and extent of 3D separated flow near wing-juncture trailing edge region
- **New experiment with NACA 0015-based swept wing in early 2022**
 - Assessment of CFD to capture incipient separation and transition

Use pretest CFD for selected flow conditions to characterize trends in boundary layer transition, to reveal dominant transition mechanisms, and to assess the influence of transition on the onset and size of the separated flow, so as to inform the 2022 wind tunnel test

- Stability analysis using linear parabolized stability equations and RANS-based transition models
- Blind assessment of both stability and RANS-based transition models and eventual refinement of these models

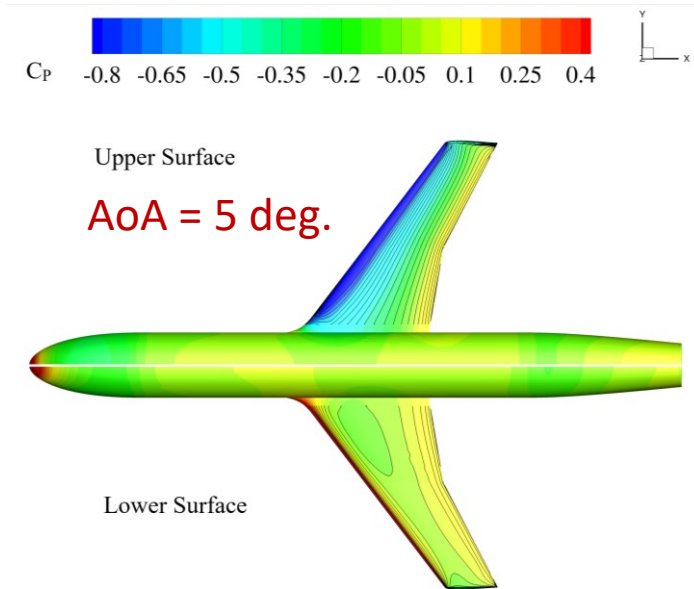
Juncture Flow Model with NACA 0015-based Wing

- Full span wing-fuselage body*
- Fuselage - nominal length 4.839 m
- Wing based on NACA 0015 shape at the root
 - Wing span (tip-to-tip) = 3.327 m
 - Crank chord = 0.581 m
 - LE sweep = 37.3 deg.
 - Top-bottom symmetric

Flow Conditions:

- Re based on crank chord = 2.4 Million
- Mach = 0.189
- Angle of Attack (AoA) = 0, 2.5, 5.0, and 7.5 deg.
- Freestream Turbulence Intensity (FSTI) = 0.08% (tunnel characterization)
- Surface roughness = 3.3 μm (assumption based on painted surface)

Steady-state computations under semispan assumptions (see Paper for details on grids, boundary conditions, etc.,)



* https://turbmodels.larc.nasa.gov/Other_exp_Data/JunctureFlow_0015/junctureflow_0015_exp.html

Details on CFD & Stability Analysis Tools

OVERFLOW 2.3b¹

- Implicit structured overset grid Navier-Stokes solver

LASTRAC 3.d Solver²

- General purpose physics-based transition prediction tool
- Linear stability theory (LST), Parabolized stability equations (PSE)

RANS-based transition models (studied in this work)

- Langtry-Menter (LM) model
- Amplification Factor Transport (AFT) model

1. SST-2003 + LM2009

Can model natural, bypass and separation-induced transition scenarios

2. SST -2003 + LM2015 (LM2009 + Crossflow)

Accounts for stationary crossflow instability through a correlation based on surface roughness levels

3. SA + AFT 2017b version

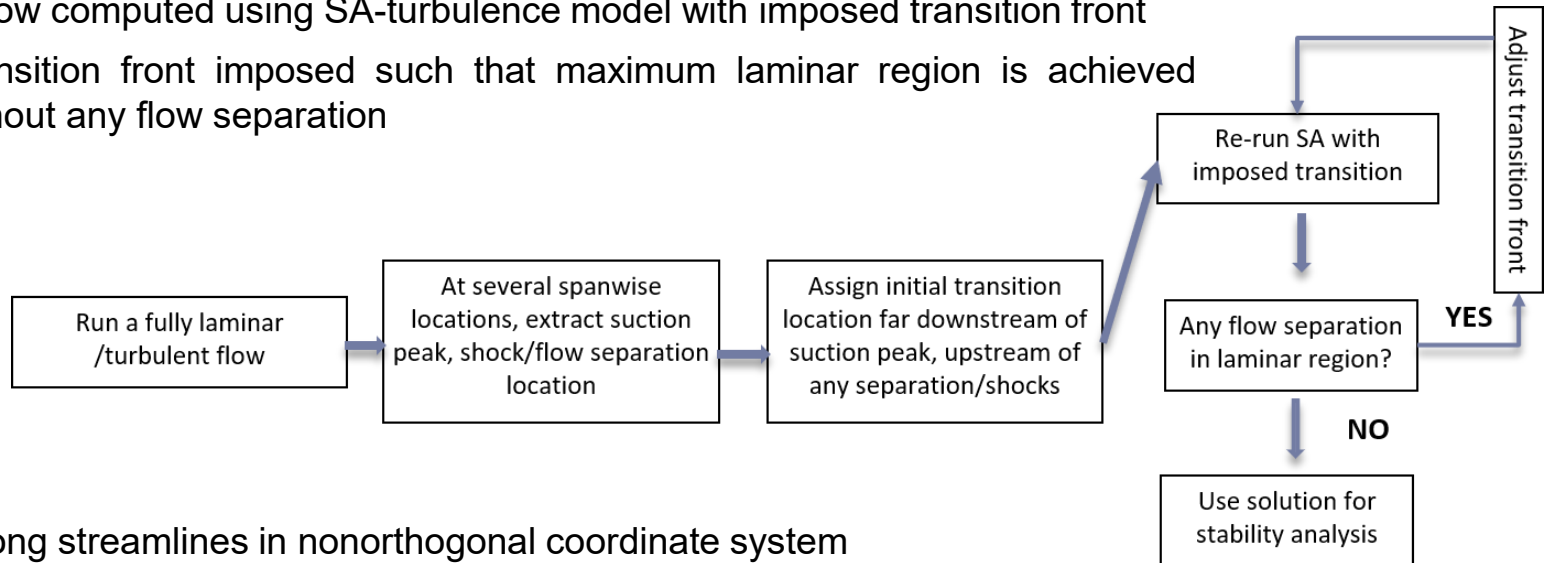
Accounts for TS instabilities alone and no crossflow

1. 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.
2. Chang, C.-L., "LASTRAC 3d: Transition Prediction in 3D Boundary Layers," AIAA Paper 2004-2452, 2004.

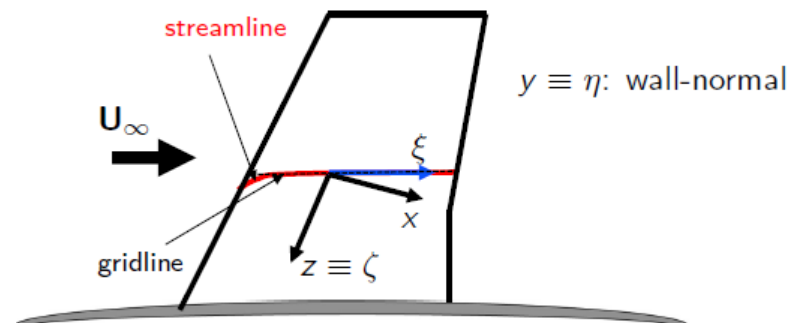
Details on CFD & Stability Analysis Tools (contd..)

Stability Analysis (LASTRAC.3d)

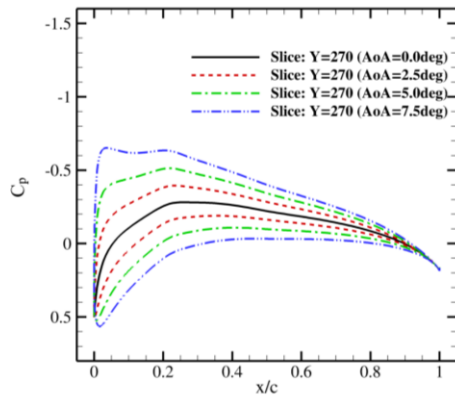
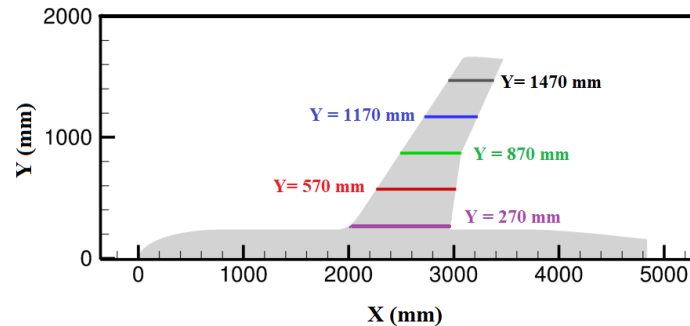
- Mean flow computed using SA-turbulence model with imposed transition front
 - Transition front imposed such that maximum laminar region is achieved without any flow separation



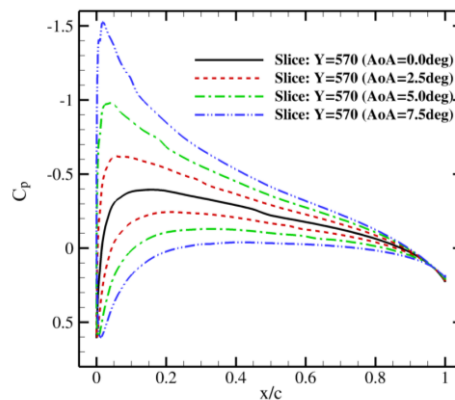
- PSE along streamlines in nonorthogonal coordinate system
 - Allows clear distinction between stationary CF and planar TS waves
 - Includes surface curvature and nonparallel mean flow effects



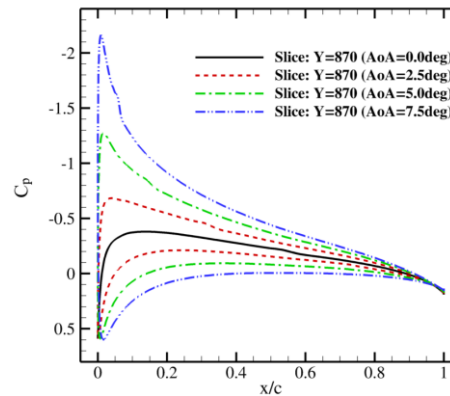
Mean flow – Pressure distribution



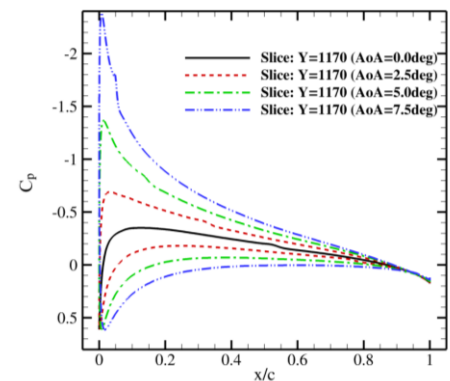
$y = 270\text{mm}$



$y = 570\text{mm}$



$y = 870\text{mm}$

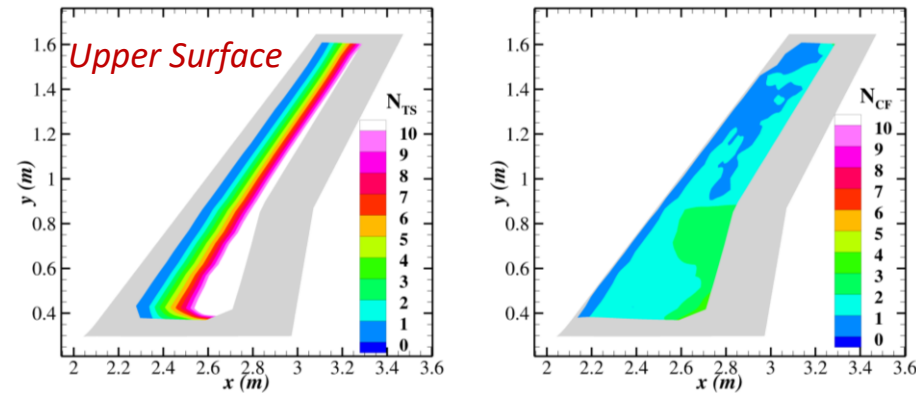


$y = 1170\text{mm}$

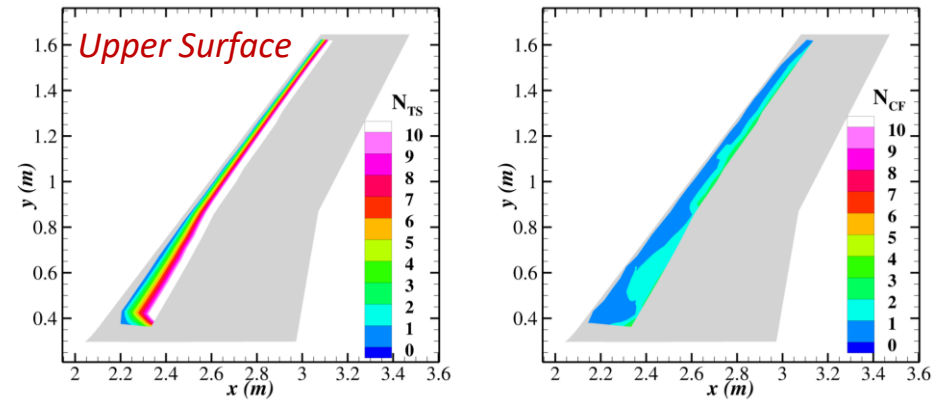
- **Upper surface:** Quick acceleration near leading edge (LE), followed by adverse pressure gradient
 - Closer to root, suction peak further downstream from LE (exception of AoA = 7.5 deg)
- **Lower surface:** LE acceleration, followed by weakly adverse/zero pressure gradient at all spanwise locations

Linear PSE – AoA = 0 deg. & 5 deg.

AoA = 0 deg.



AoA = 5 deg.



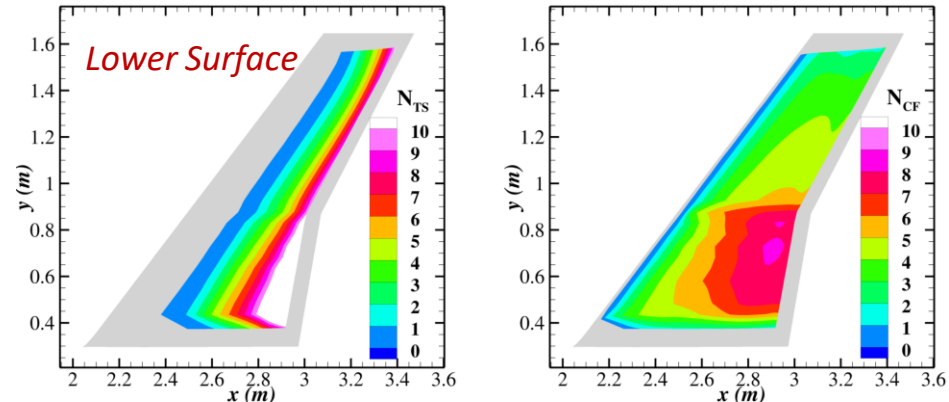
Upper surface:

- TS instability dominates at all AoA (adverse pressure gradient)
- Laminar flow region shrinks with increase in AoA

Lower surface:

- Outboard locations mostly dominated by TS waves
- Beyond 2.5 deg., CF effects become significant within inboard region with weak pressure gradient
- A small subregion in the inboard part (between root and the crank) shows comparable N-factors for both TS and CF

AoA = 5 deg.



Linear PSE – Dual N_{TS} - N_{CF} Criterion

Dual N_{TS} - N_{CF} criterion³

- Transit onset occurs when a function of N_{TS} and N_{CF} reaches a threshold

$$\left(\frac{N_{TS}}{N_{TS,c}}\right)^{a_{TS}} + \left(\frac{N_{CF}}{N_{CF,c}}\right)^{a_{CF}} = 1$$

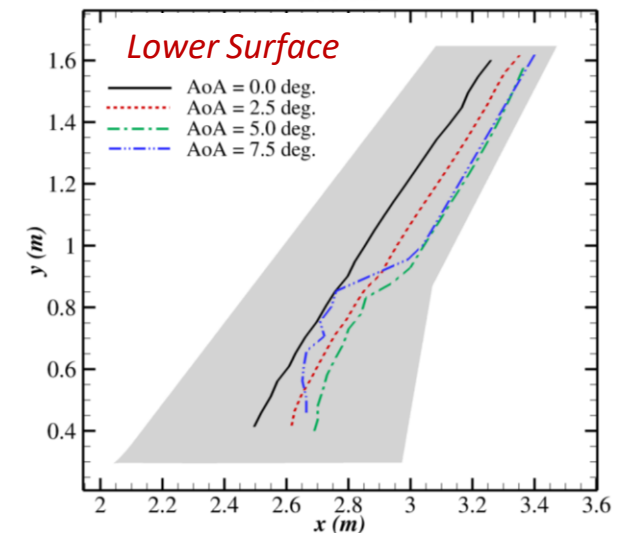
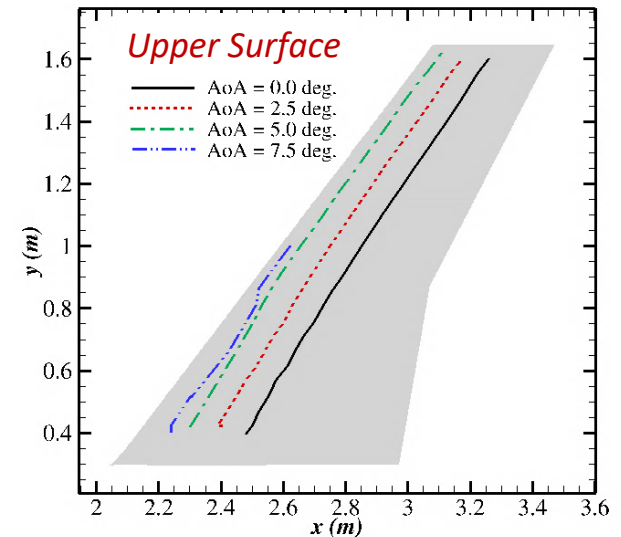
- $N_{TS,c} = 8$; $N_{CF,c} = 8$; $a_{TS} = 3$; $a_{CF} = 3$
 - Critical N based on disturbance, roughness levels
 - See Paredes et al. AIAA Paper 2021-1431

Upper surface:

- Transition front moves closer to LE with increasing AoA
- Front remains parallel to the LE

Lower surface:

- Outboard region: transition front moves downstream with increasing AoA
- Inboard portion: smaller laminar region with increase in AoA due to CF effects (at 5 deg. and greater)



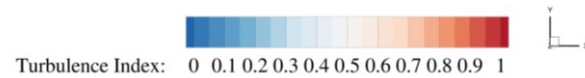
3. Arnal, D. "Boundary layer transition: Prediction based on linear theory". In: *Special course on Progress in Transition Modeling*. AGARD R-793. 1994, pp. 1–62.

RANS-based Transition Models

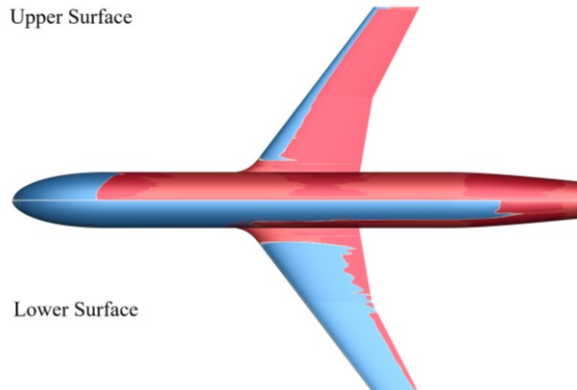


Risk-Reduction Expt.
(2016)

Reasonable Match

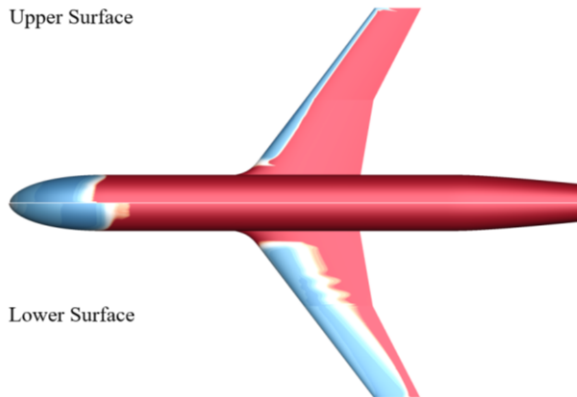


Upper Surface



Lower Surface

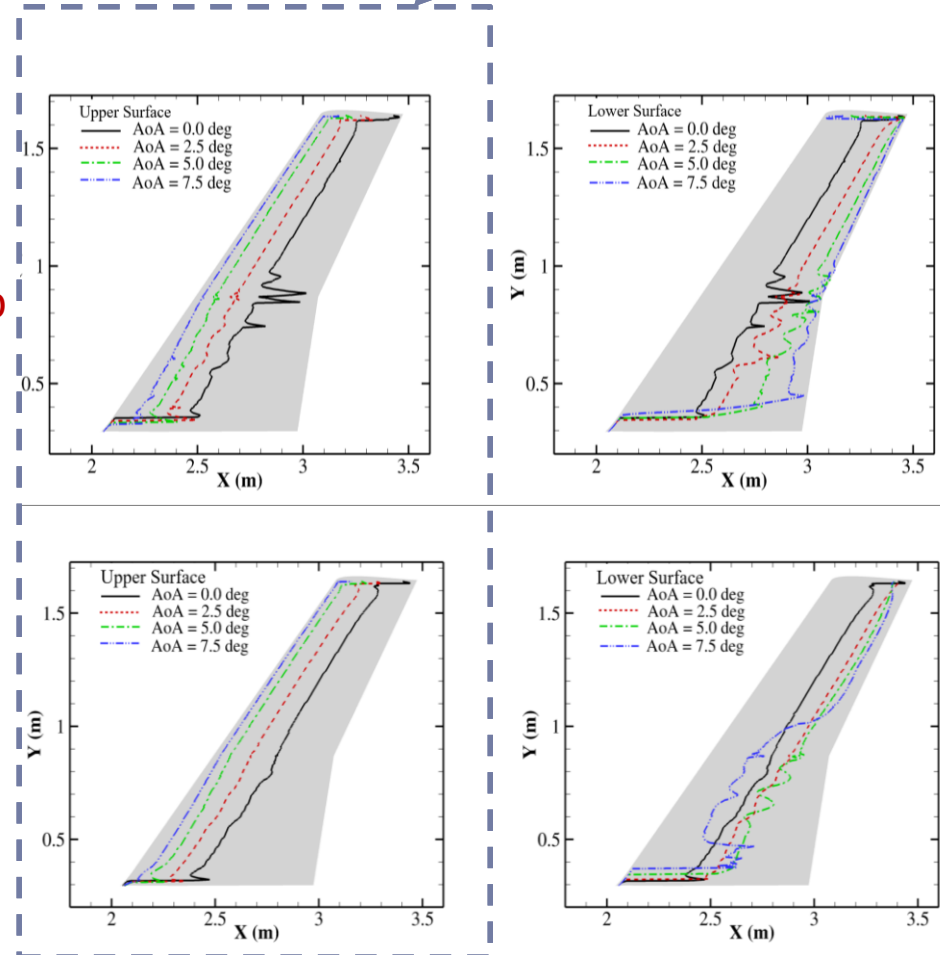
Upper Surface



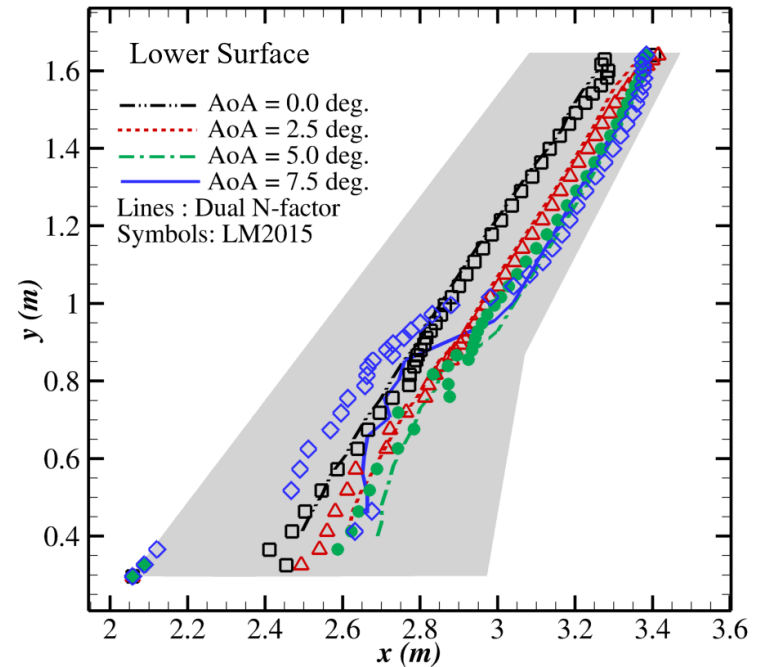
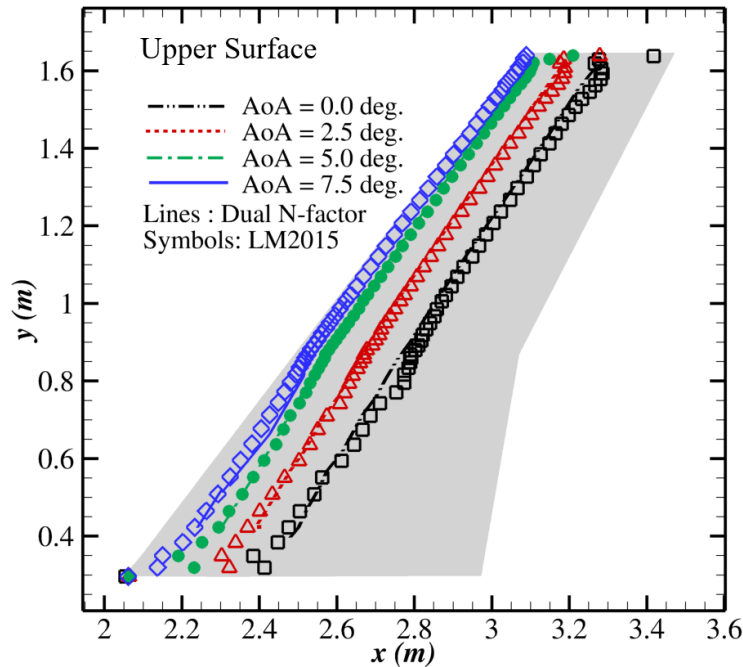
Lower Surface

AFT 2017b

LM2015



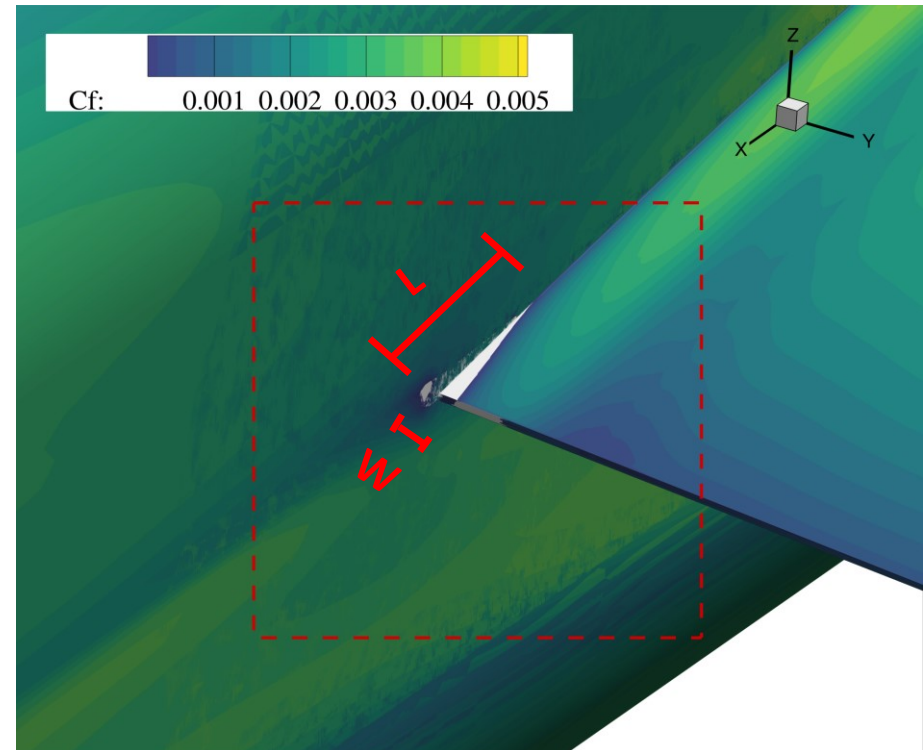
RANS-based Transition Models



- **Upper surface:** TS domination $\Rightarrow$ good comparison with RANS-based models
- **Lower surface:** LM2015 matches linear PSE in outboard region
- When crossflow effects dominate,
 - AFT2017b based transition front is inaccurate
 - LM2015 predicts the trend correctly but transitions earlier transition than stability theory
- Need to explore effects of potentially mixed mode transition (inboard region on the lower surface)

Flow Separation

- Did not encounter laminar separation
 - BL naturally transitioned upstream of where a nominally laminar BL would have separated
- Small flow separation near wing-root juncture region near the TE at all AoA (on the upper surface)
- Bubble size increased with increasing AoA
 - Bubble at AoA = 0 deg.: L = 54 mm; W = 5 mm.
 - At AoA = 7.5 deg., L was 24% larger and W was 60% larger compared to AoA = 0 deg.
- Comparison of bubble size with computations based on fully turbulent BL will help assess the impact of transition on juncture flow separation



Contours of skin friction (cut-off applied for values below 0) on the model surface to indicate regions of separated flow for an angle of attack equal to +7.5 degrees.

Summary

NASA juncture flow model with NACA 0015-based wing - Pretest computational assessment of BL transition was completed for a selected set of flow conditions via both Linear PSE and RANS-based transition models

- **Upper surface of the wing:**
 - **Dominated by TS-instability; AFT2017b and LM2015 model predictions compare well with linear PSE results**
 - Laminar flow extent decreases from 50% chord with increase in AoA
- **Lower surface of the wing:**
 - TS-instability most dominant mechanism on the outboard region
 - Laminar flow extent increases with AoA
 - **CF effects begin to dominate within inboard region at higher AoA (≥ 5 deg.)**
 - **Small subset of inboard region also displays mixed TS-CF instability.**
 - **LM2015 predicts reasonably the overall trend seen from linear PSE stability results**
 - Earlier transition predicted at AoA = 5.0 & 7.5 deg
 - AFT2017b does not perform as well on pressure side, as it does not account for CF effects
- Valuable guidance for the planned experiment. In return, the measurements will help improve these models

Future work:

- Explore alternative crossflow models that don't rely on input parameters related to surface roughness amplitude
- Impact of assumed surface roughness levels on LM2015 predictions
- Influence of Re on predicted transition behavior and also, identify when laminar separation is likely to occur

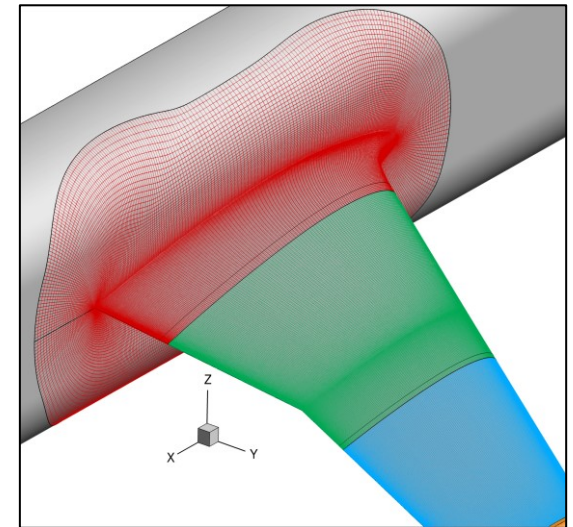
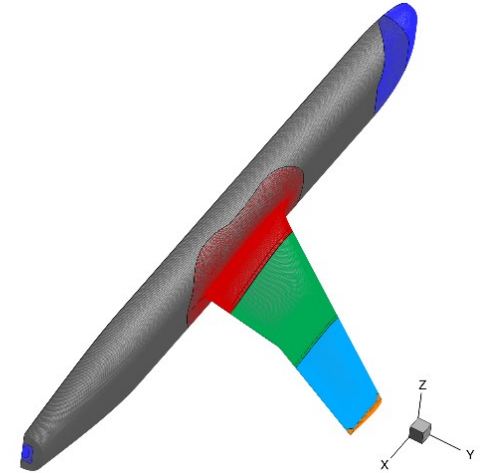
Back up slides

Flow Conditions and Computation Details

- **Re based on crank chord = 2.4 Million**
- **Mach = 0.189 ; Tref = 288.84 K;**
- **Angle of Attack (AoA) = 0, 2.5, 5.0, and 7.5 deg.**
- Freestream Turbulence Intensity (FSTI) = 0.08% (tunnel characterization);
- Surface roughness = 3.3 μm (assumption based on painted surface)

CFD Computation Details

- Computation performed under semi-span assumption
- In-house generated grids (see paper for additional details)
 - Baseline grid: 140 million near-body grid points ($y^+ \sim 0.5$)
- Steady-State computations
- SST-2003 model with option to sustain turbulence was used to enforce appropriate FSTI (*Spalart & Rumsey, 2007*)



Future Work

- Attachment line instabilities
- Explore alternate crossflow models that don't rely on input parameters related to surface roughness amplitude
- Impact of assumed surface roughness levels on LM2015 predictions
- Influence of Re on predicted transition behavior, especially for RANS based transition models (also, identify when laminar separation is likely to occur)

Additional Details In the Paper

- Details about mesh and grid convergence of results
- Integrated force and moment coefficients for the different flow conditions
- Detailed discussion of the results at all the flow conditions considered