The NASA Juncture Flow Experiment

Final Report

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One NASA Boeing Team Meeting

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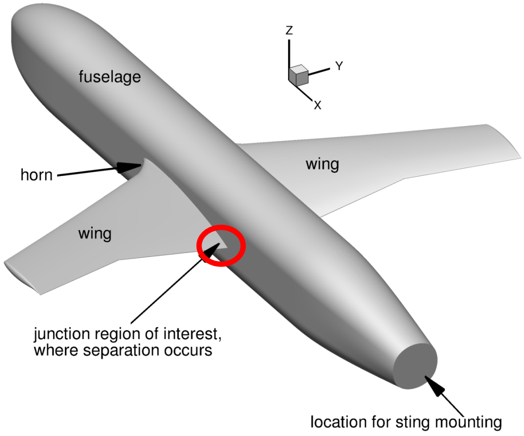
Executive Summary

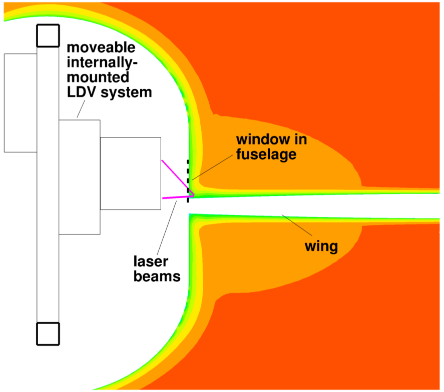
- **The NASA Juncture Flow (JF) Experiment was a long-term effort/commitment by the Transformational Tools and Technologies (TTT) Project**
  - Altogether, involved roughly 8 years of focused effort (2015-2022)
  - Goal: Perform a CFD-validation-quality experiment involving corner flow separation
    - Addresses the technical challenge of CFD's inconsistency in predicting separated flows in wing-body juncture regions. Experimental validation data is required in order to help improve the ability of turbulence models to predict this type of flow feature, which can occur at many locations on aircraft.
    - Both CFD and EXP personnel mutually connected/involved on the project throughout its life

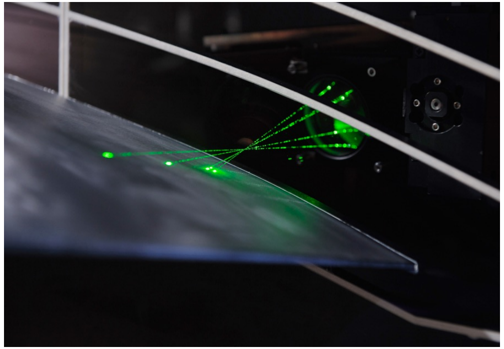
- **Outcomes:**
  - Data for 2 different wings (F6-based: larger separation vs. Symmetric: incipient separation)
  - Detailed documentation and publicly-available data on website
  - 22 NASA-coauthored papers and similar number of technical talks, including 4 archival journal articles
  - At least 18 papers written by outside researchers, using the JF data for validation
  - New Reynolds-averaged Navier-Stokes (RANS)-based turbulence model variant created, which better predicts juncture flow behavior than earlier model(s)
  - Transition data (for validation of Tollmien-Schlichting and stationary crossflow mechanisms) were obtained for the symmetric-airfoil wings

Motivation

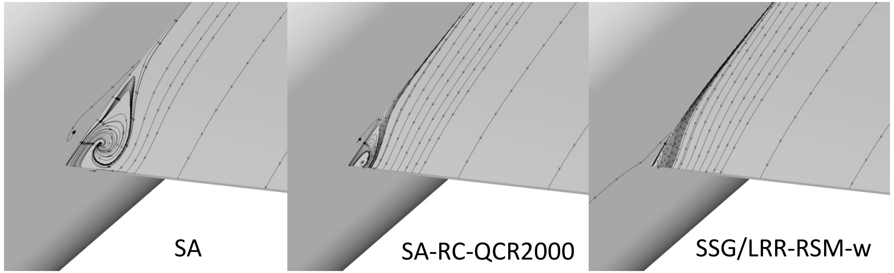
- **Original motivation came from Drag Prediction Workshop (DPW) series**
  - Huge inconsistencies in corner separation between different CFD codes and models
  - Experimental oil flow measurements were qualitative only, so not much help to CFD (other than "you missed it")
- **Internal laser-based techniques were available**
  - LDV and PIV could make use of windows in the fuselage to measure flowfield details very close to the wing-body junction (laser hardware to be housed inside)





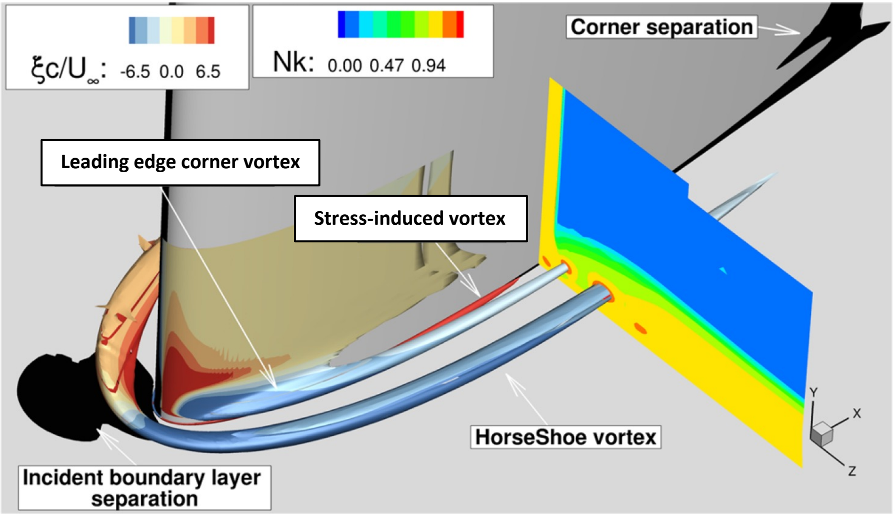


Sample corner flow computations using 3 different turbulence models



Introduction

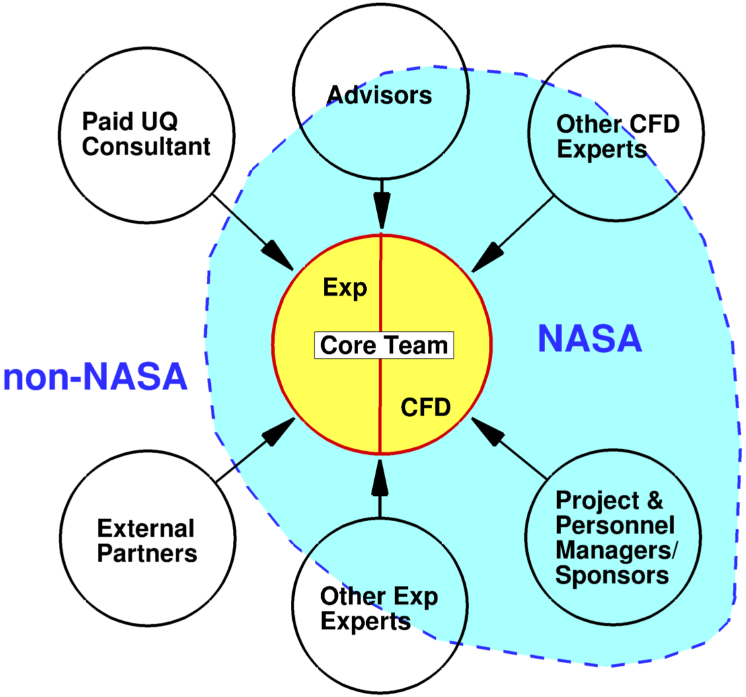
- **Flow physics of juncture flows is complex; and some aspects are not well understood**
  - Several vortical structures coexist: e.g., Horseshoe Vortex (HSV), corner vortex, stress-induced vortex
  - Many factors—such as incoming boundary layer momentum thickness, wing bluntness, and wing sweep—also play some role
- **Samples of previous juncture flow work**
  - Simpson et al. (Ann. Rev. Fluid Mech. 33:415-443, 2001)
  - Gand et al. (Phys Fluids 22:115111, 2010)
  - Bordji et al. (AIAA Journal 54(2):386-398, 2016)
- **Accurate modeling of the Reynolds stresses is required for predicting juncture flows**
  - Linear eddy viscosity models cannot capture stress-induced vortex at all
- **Both pre-test CFD and smaller-scale risk reduction experiments were performed in advance of the full JF test, to avoid surprises**
  - Investigated different wing shapes in order to attain desired separation sizes



(figure from Bordji et al., relabeled to correct typos)

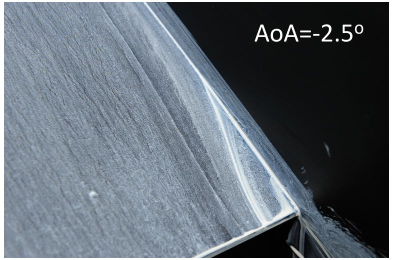
The JF Team

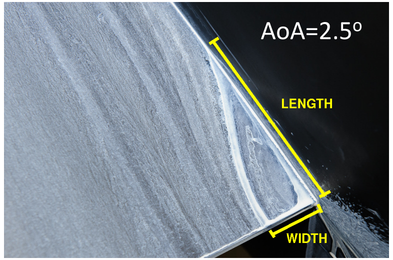
Roughly 25 total members, with about 5-6 in the core team

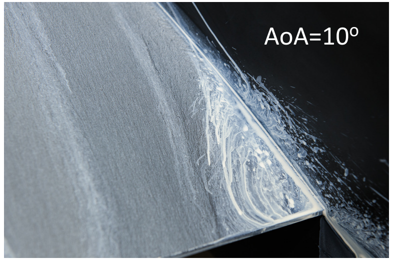


Experimental Data Acquired*

- LDV data (velocities, Reynolds stresses, velocity triple products)
- Oil-flow visualizations
- Model C_p data
- Boundary conditions (tunnel wall C_p data, tunnel wall boundary-layer rake data, tunnel inflow plane total pressures, diffuser wall pressures)
- Model geometry (high-fidelity laser scans of model and lower-resolution laser scans of model positioning in the test section)
- Digital-image correlation measurements to quantify the aeroelastic deflections of the model wings
- PIV data (velocities, Reynolds stresses) (F6-based wing only)
- Model unsteady surface pressures (F6-based wing only)
- Transition front measurements (symmetric wing only)





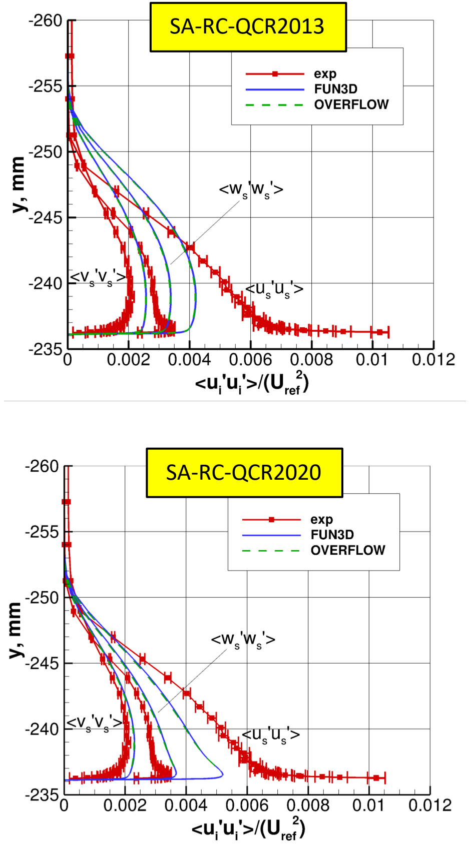


* All data acquired at Re_{crank}=2.4 million; turbulent tests included wing and fuselage trip dots

New Version of Quadratic Constitutive Relation Developed

- QCR2020
  - Developed by members of the JF team in 2020, based on JF data
  - *AIAA Journal*, Vol. 58, No. 10, 2020, pp. 4374-4384
  - Includes revised functional coefficients, C''_{cr1} and C''_{cr2}, that improve predictions of turbulent normal stresses
  - $\tau_{ij,QCR2020} = \tau^L_{ij} - C''_{cr1}[O_{ik}\tau^L_{jk} + O_{jk}\tau^L_{ik}] - C''_{cr2}\mu_t\sqrt{2W_{mn}W_{mn}}\delta_{ij}$
  - Improves results for JF configuration as well as independent cases
- Used in conjunction with Spalart-Allmaras + Rotation-Curvature correction: SA-RC-QCR2020
  - Better captures the normal stress *differences* as you move away from the wall

Reynolds normal stresses



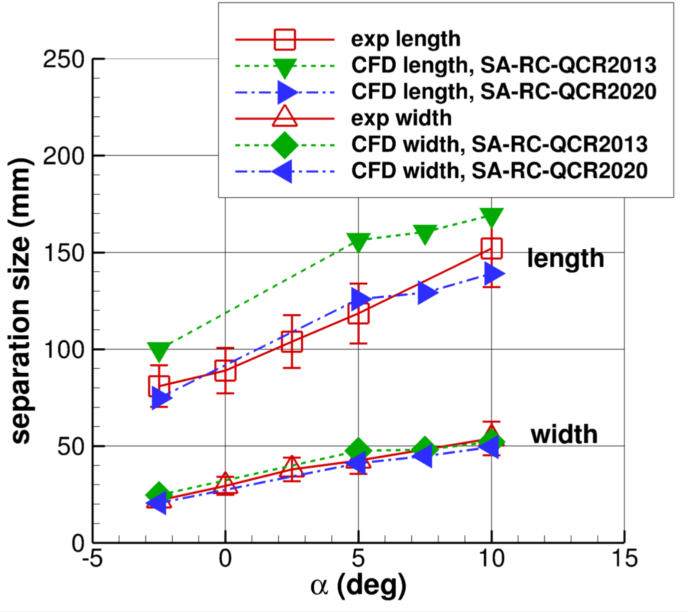
Example Comparisons for Turbulent F6-based Wing

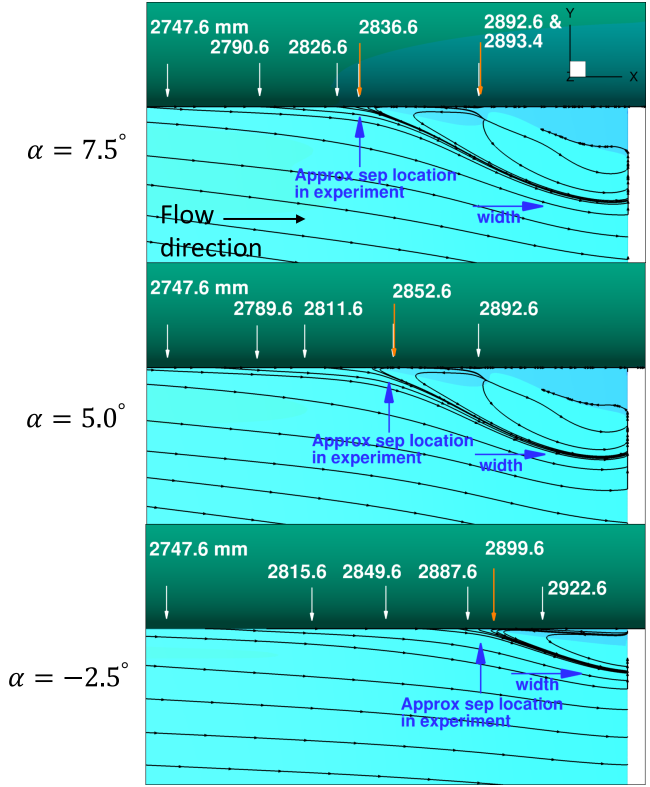
- Typical CFD Results*
  - RANS models with Boussinesq (linear) constitutive relation
    - Separation sizes predicted FAR too large (100% or more)
  - RANS models with previous nonlinear constitutive relations (including SA-RC-QCR2000 and SA-RC-QCR2013)
    - Separation sizes predicted SOMEWHAT too large (30%)
  - RANS Reynolds Stress Transport (RST) model
    - Separation sizes predicted well by SSG/LRR-RSM-w, but dependent on the particular RST model
  - Scale-resolving simulations (DDES, WMLES)
    - (Preliminary) separation sizes tend to be somewhat too small

* The F6-based wing was the subject of several AIAA special sessions in 2020

Example Comparisons for Turbulent F6-based Wing

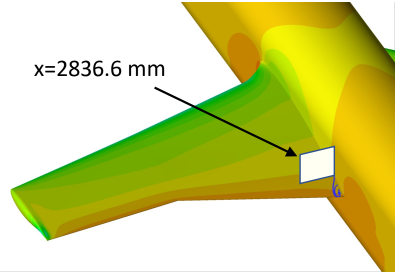
- Using **SA-RC-QCR2020**, the prediction of F6-wing separation size/shape is within experimental uncertainty



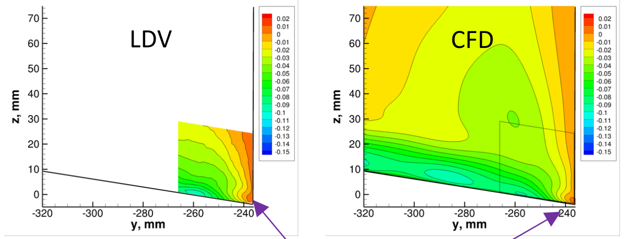


Example Comparisons for Turbulent F6-based Wing

AoA=7.5º



v/U_{ref}

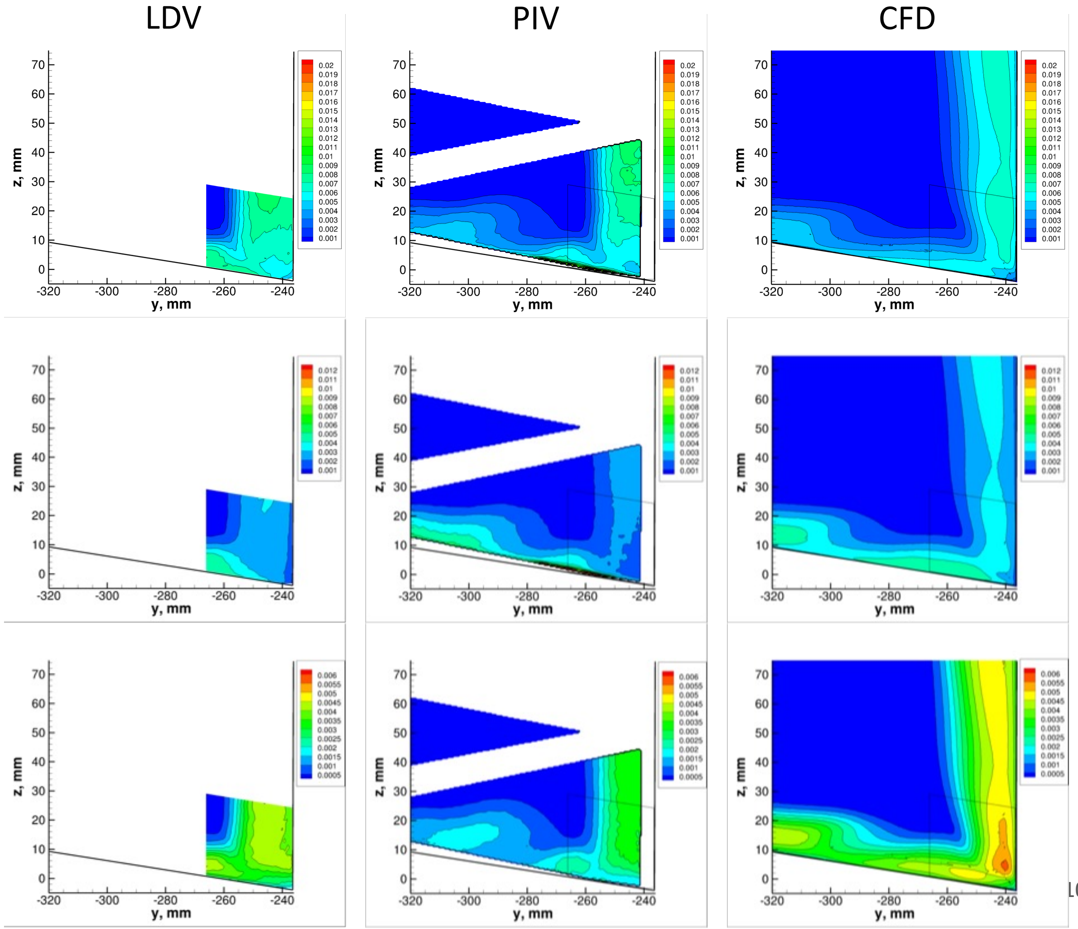


evidence of stress-induced vortex

$\langle u'u' \rangle/(U_{ref}^2)$

$\langle v'v' \rangle/(U_{ref}^2)$

$\langle w'w' \rangle/(U_{ref}^2)$



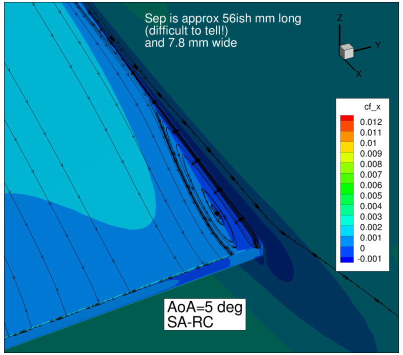
Example Comparisons for Turbulent Symmetric Wing

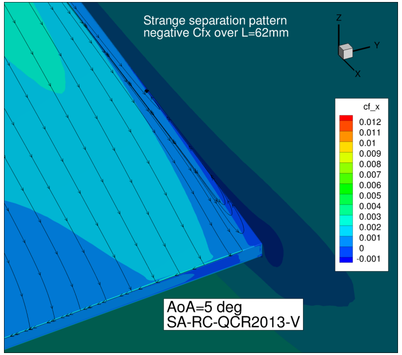
- Blind test using SA-RC, SA-RC-QCR2020, SA-RC-QCR2013, and SSG/LRR-RSM-w

AoA=5°

Oil flow

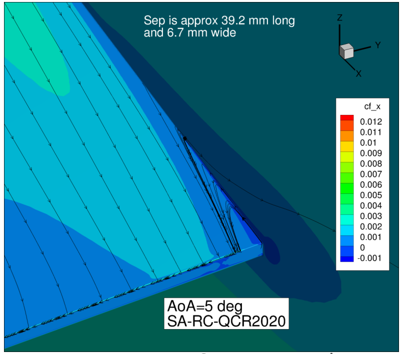
Separation region is roughly 25 mm long

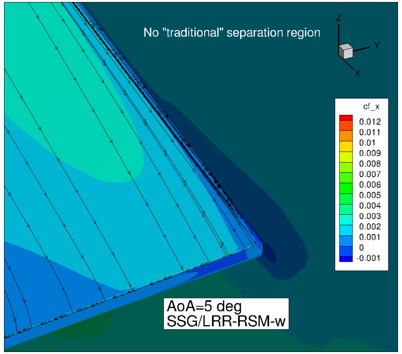




SA-RC-QCR2020 yields closest results, but overpredicts separation size somewhat

SA-RC-QCR2013 and SSG/LRR-RSM-w both produce non-traditional corner separation



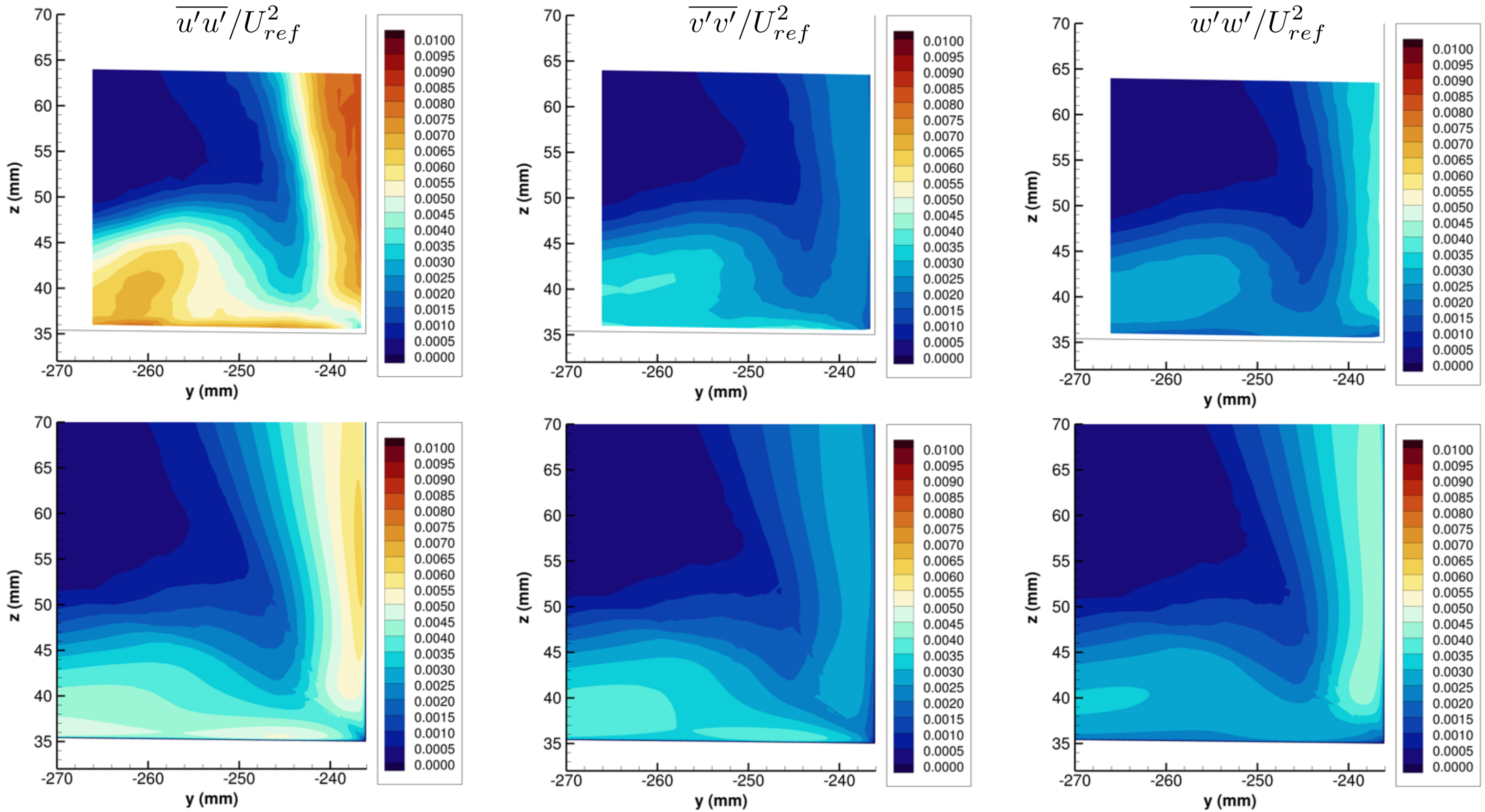


Example Comparisons for Turbulent Symmetric Wing

EXP

CFD

SA-RC-QCR2020



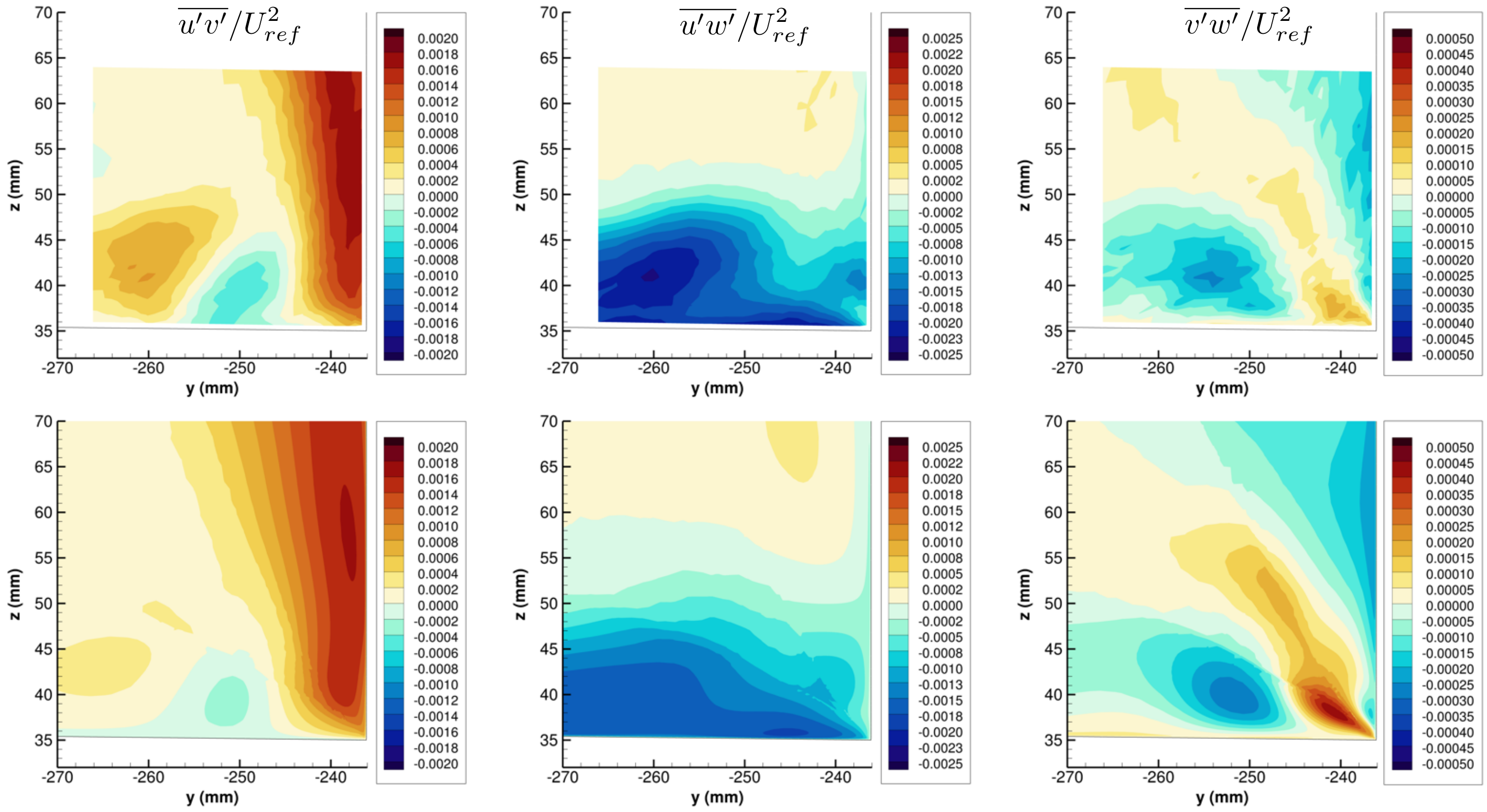
AoA=0°

Example Comparisons for Turbulent Symmetric Wing

EXP

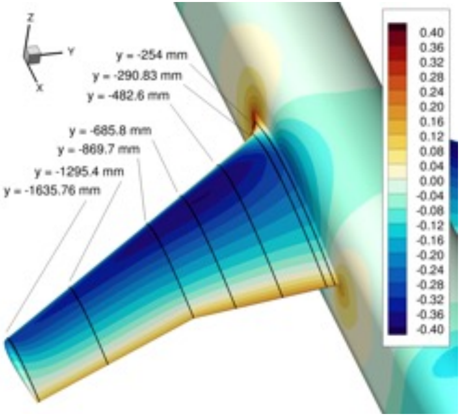
CFD

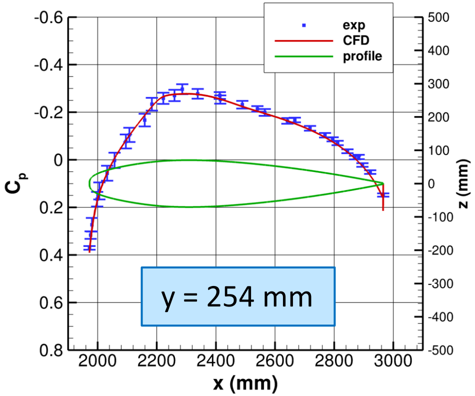
SA-RC-QCR2020

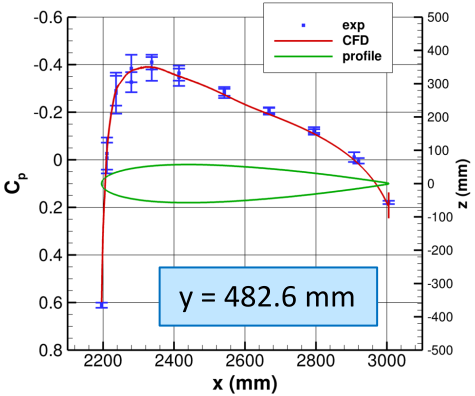


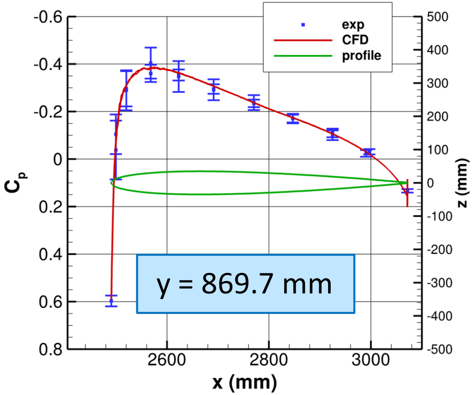
AoA=0°

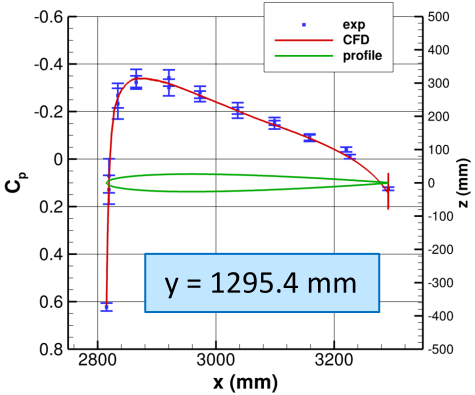
Example Comparisons for Turbulent Symmetric Wing

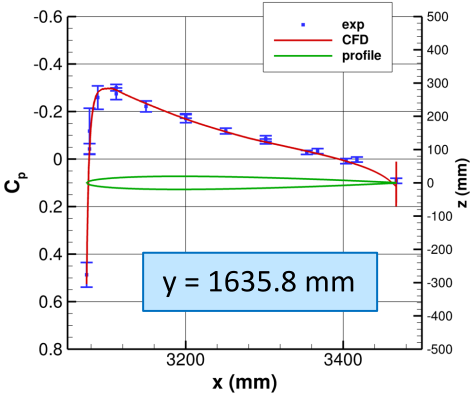










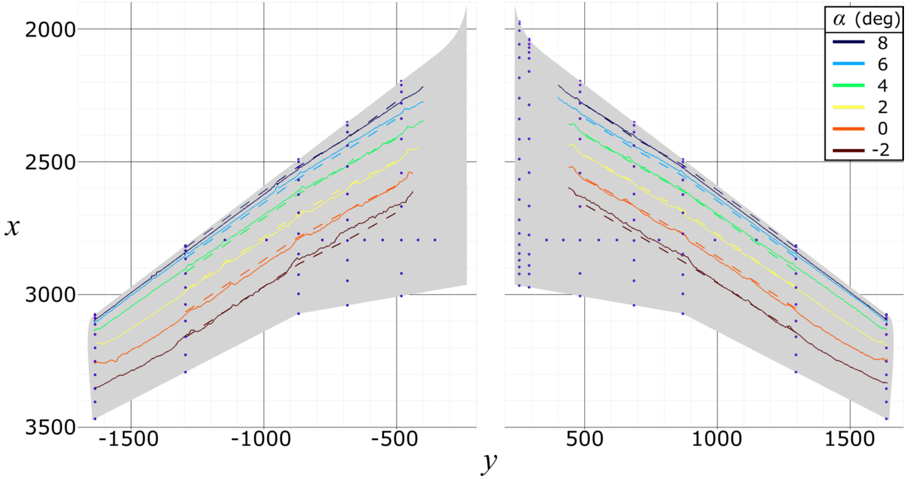


AoA=0°

SA-RC-QCR2020

Transitional Symmetric Wing

- Test conducted without wing trip dots
  - Transition dominated by Tollmien-Schlichting (TS) for positive α and (increasingly) stationary crossflow (CF) for more negative α
- Transition fronts were determined both by infrared (IR) and by surface pressure analysis
- CFD results used both stability analysis tool and three different RANS-based transition models

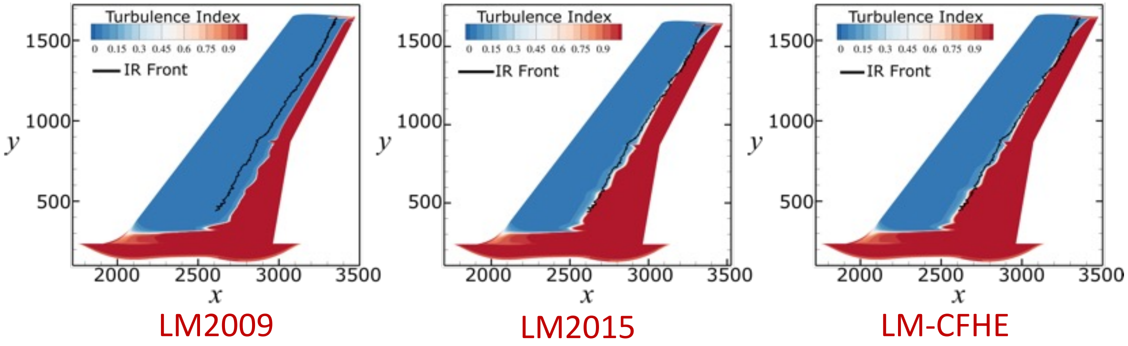


Transition front comparison between methods of determination.
IR-based fronts are solid lines, while pressure-based fronts are dashed lines.

Example Comparisons for Transitional Symmetric Wing

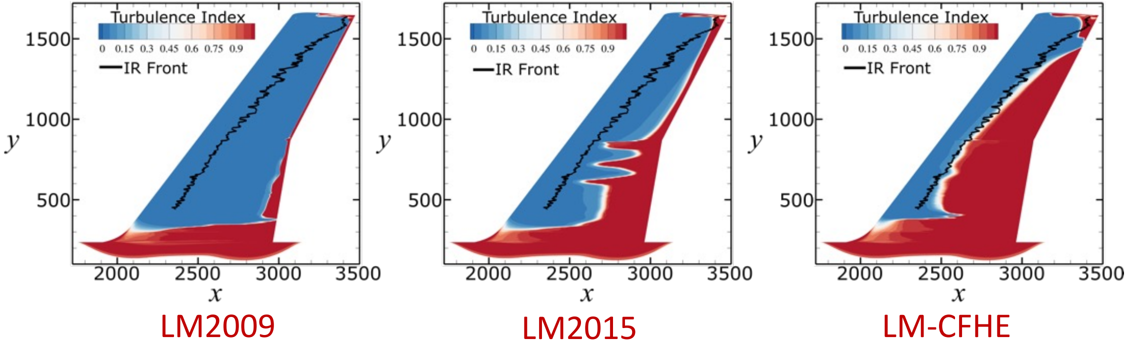
- All three RANS-based transition models perform well for α > -2.5°
- The helicity-based LM-CFHE model gives the best results for all conditions where CF is important, even though it doesn't account for roughness

α = -2°



Turbulence index contours using different transition models for α = -2°

α = -6°



Turbulence index contours using different transition models for α = -6°

Conclusion

- **Performing a thorough CFD validation experiment requires a serious commitment of resources (people, money, time)**
  - Ongoing dialog and interaction between EXP and CFD personnel is crucial to success
  - The TTT leadership made this commitment, and stuck with it
  - End result is a world-class set of experimental data that has already helped to refine a widely-used RANS turbulence model, and should be useful for separated corner flow CFD validation for many years
  - Further improvements for both RANS and SRS can still be made

- **The JF team won a NASA Group Achievement Award in May 2022: "For outstanding collaboration in ground-breaking instrumentation development and measurements that have led to significantly improved predictions of turbulent separated juncture flows."**

End