Overview of the NASA Juncture Flow Project

Chris Rumsey

AIAA SciTech
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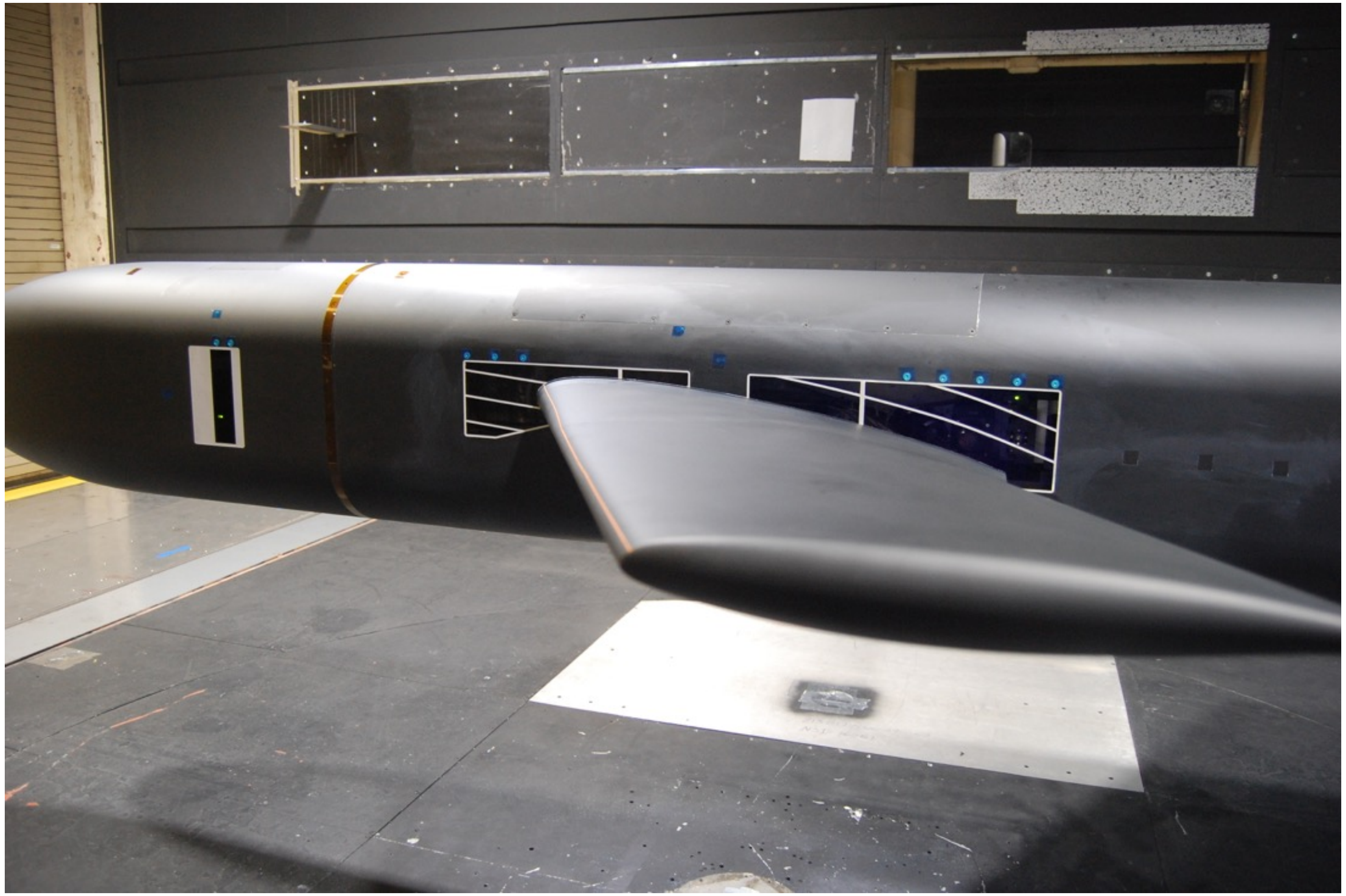
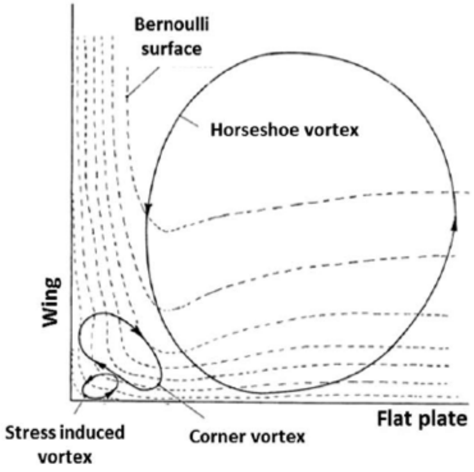
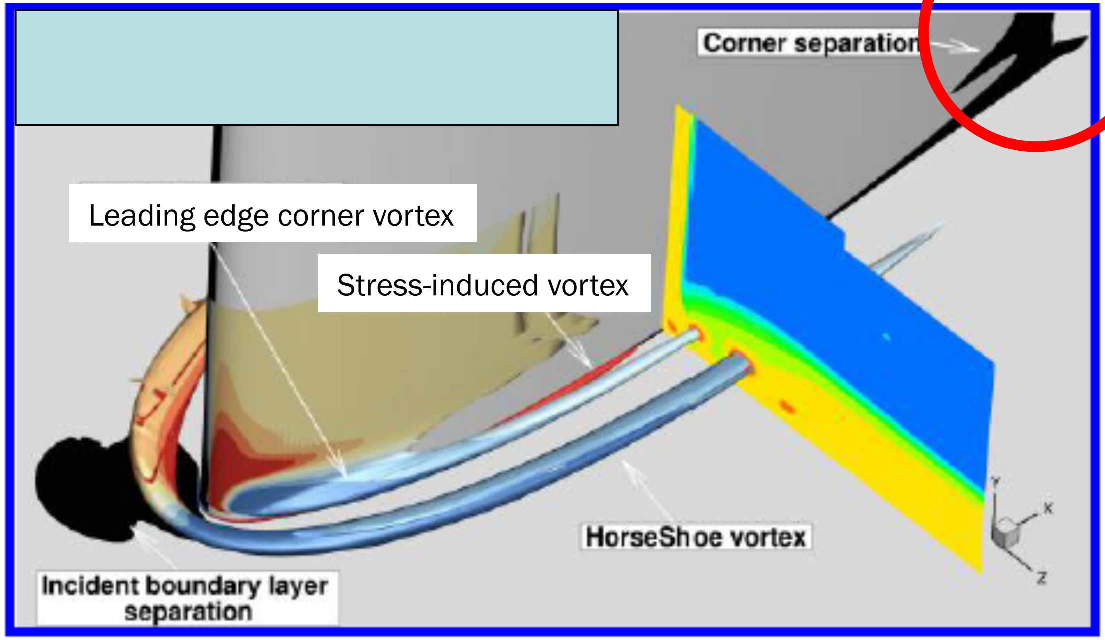
Oral presentation – no paper



The physics of juncture flow

- We are interested in **CORNER SEPARATION** in a wing-body juncture flow
- Flow physics of wing-body 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
  - There is consensus (emerging over recent years) that more accurate modeling of the Reynolds stresses is a minimum requirement for predicting separated juncture flows
    - Because these stresses control the development of the near-corner stress-induced vortex
    - This stress-induced vortex can contribute to the delay in the initiation of corner separation





From AIAA J 54(2), 386-398, 2016 (Bordji et al) with typo corrections

The physics of juncture flow, cont'd

Mean streamwise (x-direction) vorticity equation (from Perkins, JFM 44(4), 721-740, 1970):

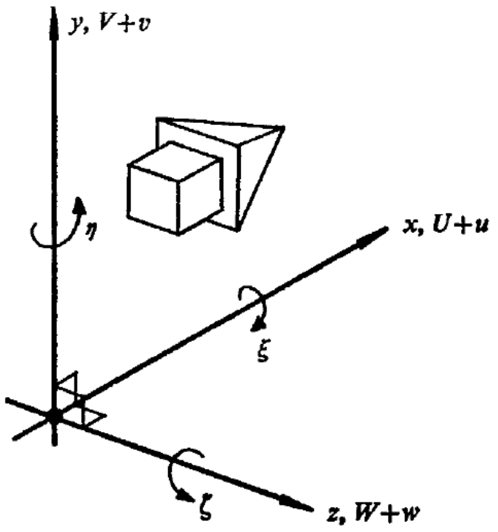
$$U\frac{\partial \xi}{\partial x}+V\frac{\partial \xi}{\partial y}+W\frac{\partial \xi}{\partial z}=\nu\nabla^2\xi+\xi\frac{\partial U}{\partial x}+\underbrace{\eta\frac{\partial U}{\partial y}+\zeta\frac{\partial U}{\partial z}}_{P_1}+\underbrace{\frac{\partial}{\partial x}\left(\frac{\partial \overline{uv}}{\partial z}-\frac{\partial \overline{uw}}{\partial y}\right)}_{P_2}$$

$$+\underbrace{\frac{\partial^2}{\partial y\,\partial z}(\overline{v^2}-\overline{w^2})}_{P_3}+\underbrace{\left(\frac{\partial^2}{\partial z^2}-\frac{\partial^2}{\partial y^2}\right)\overline{vw}}_{P_4},$$

in which $\xi=\partial W/\partial y-\partial V/\partial z,$

$\eta=\partial U/\partial z-\partial W/\partial x,$

and $\zeta=\partial V/\partial x-\partial U/\partial y,$



From Perkins, 1970

- P_1 generates vorticity via transverse pressure gradient or body force = Prandtl's secondary flow of the first kind
  - HSV and leading edge corner vortex are examples of this
- $P_2+P_3+P_4$ are responsible for maintaining secondary currents of Prandtl's second kind (present only in the turbulent boundary layer)
  - The stress-induced vortex is created/supported by these terms

Previous juncture flow work

- Some earlier experiments
  - Gessner (e.g., JFM 58(1), 1-25, 1973)
    - Square duct
  - Barber (AIAA J Aircraft 15(10), 676-681, 1978)
    - Unswept strut on flat plate
  - Simpson et al. (e.g., Ann. Rev. Fluid Mech. 33, 415-443, 2001)
    - Mostly focused on HSV and bi-modal unsteadiness (not so much on corner separation)
    - Many other researchers have focused on the HSV
  - Gand et al. (e.g., AIAA J 53(10), 2869-2877, 2015)
    - Unswept wing on flat plate

- Some earlier CFD
  - Square duct: e.g., Pettersson Reif & Andersson (FTC 61, 41-61, 2002)
  - Mostly focusing on HSV: e.g., Aspley & Leschziner (FTC 67, 25-55, 2001)
  - Unswept wing on flat plate: e.g., Gand et al. (Phys Fluids 22, 115111, 2010), Bordji et al. (AIAA J 54(2), 386-398, 2016)

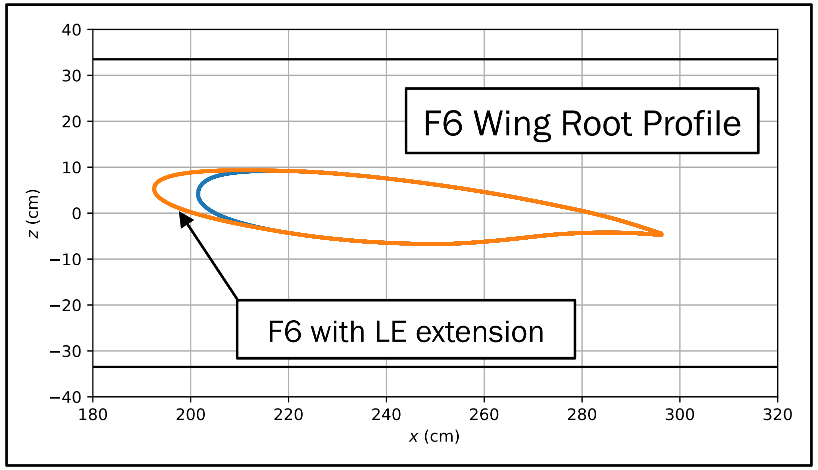
Overview of the NASA JF experiment

- Main purpose:
  – Collect data to help assess/improve the ability of existing CFD models to predict the onset and extent of the three-dimensionally separated flow near the wing juncture trailing edge region of a full-span swept wing-body configuration
- The Juncture Flow (JF) test is designed to be a "CFD Validation-Quality" experiment
  – "Experiment should include the measurements of all information necessary for a thorough and unambiguous CFD validation study, including boundary conditions, geometry information, and quantification of experimental uncertainties"
- Much time and effort was devoted to preparing this experiment
  - Precursor CFD and risk-reduction experiments helped to downselect to the final configuration
  - Developed internal LDV tools and procedures* for acquiring very-near-wall flowfield data
- Experimental campaigns in NASA's 14x22 wind tunnel:
  – **Late 2017 and Spring 2018** – F6-based wing (completed, data released)
  – **Early 2020** – F6-based wing with LE extension (resolve issues from first test, fill out dataset, include additional PIV data collection)
  – **2021** – possibly NACA 0015-based wing (incipient separation)

*AUR, Inc. and NASA Langley

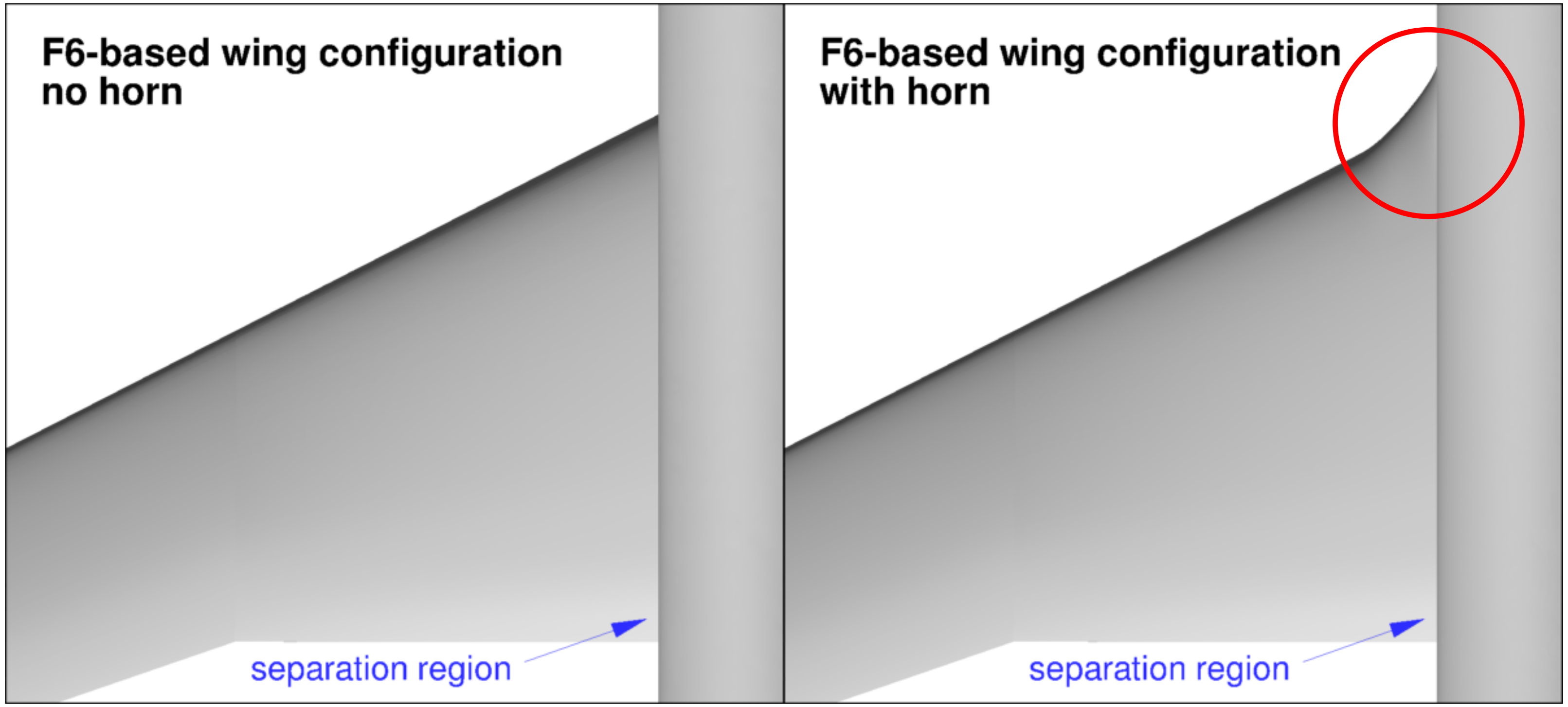
NASA JF model in NASA Langley 14- by 22-foot tunnel

Fuselage Length: 4.84 m
Wing Span: 3.4 m
Truncated DLR F6 Wings
Planform Break Chord: 0.56 m



Wings and fuselage are tripped

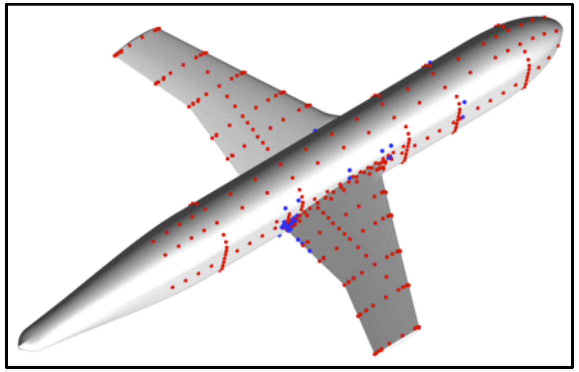
NASA JF model



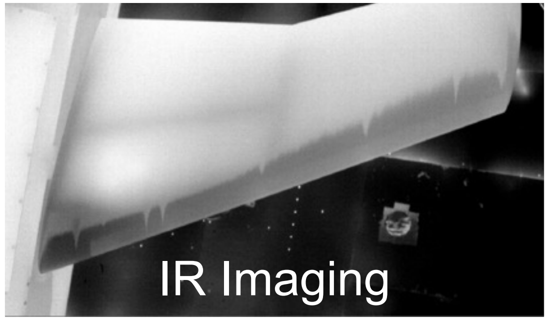
Experimental data to date have been acquired on both configurations, but primary focus of CFD has been with "horn" (leading edge extension)

- Horn mitigates size/strength of the horseshoe vortex
- Less global unsteadiness (bimodal behavior)
- More representative of today's aircraft
- More amenable to Reynolds-averaged Navier-Stokes (RANS) analysis
- Upcoming test only uses the F6 configuration with "horn"

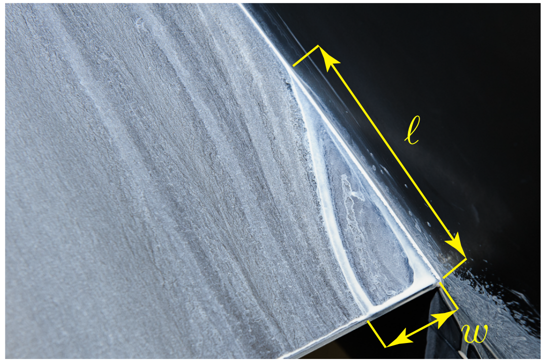
CFD validation experiment



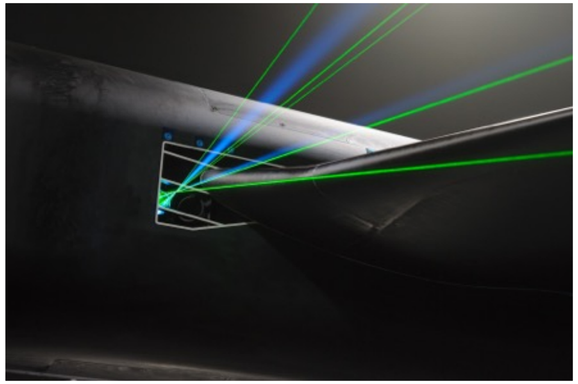
Steady/Unsteady Pressures



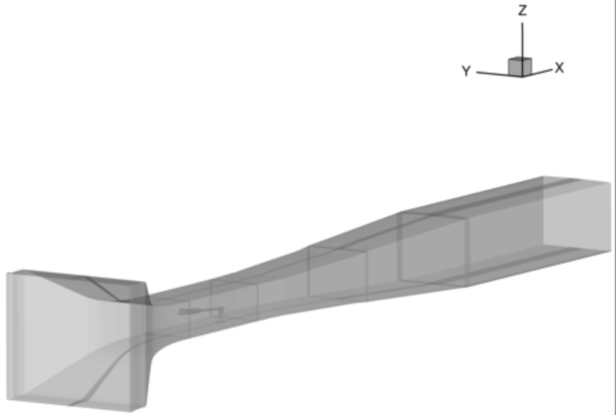
IR Imaging



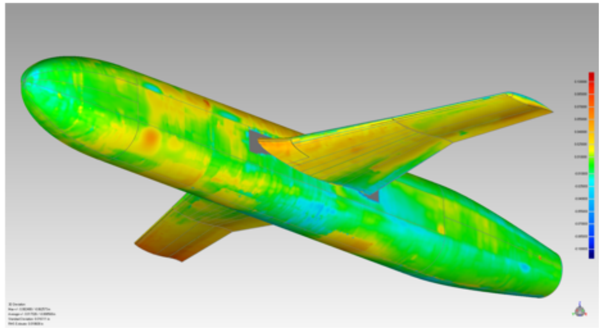
Oil-Flow Visualization



LDV Measurements



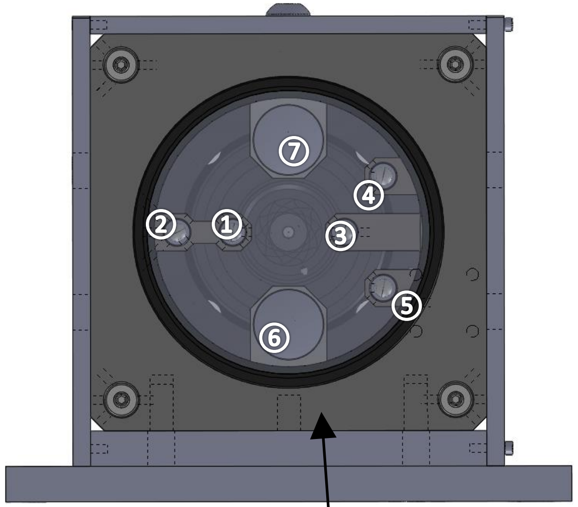
Boundary Conditions



Geometry

Dataset & details available at:
https://turbmodels.larc.nasa.gov/Other_exp_Data/junctureflow_exp.html

Laser Doppler Velocimetry (LDV)

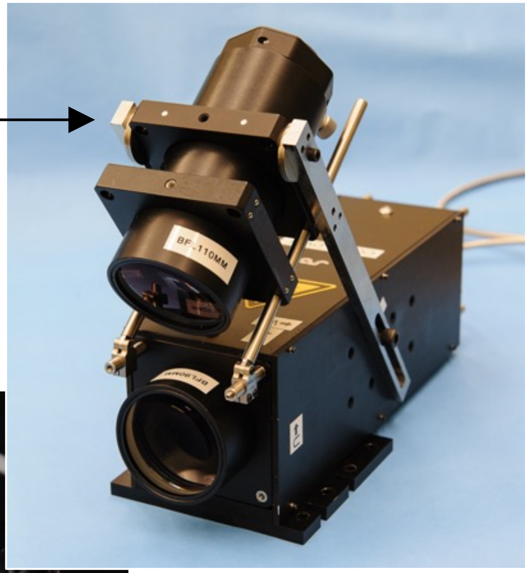


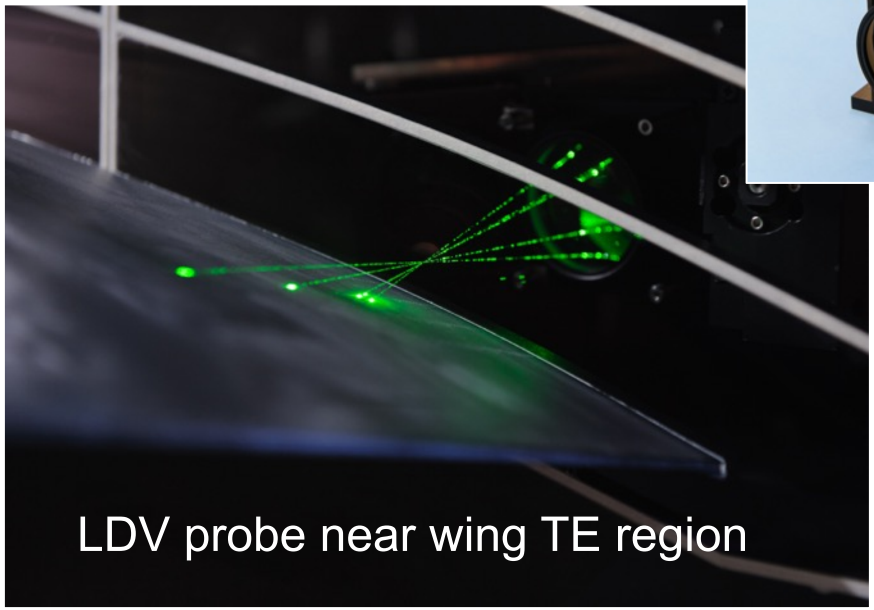
Fiber-optic based probe head

- Five green (532 nm) laser beams
- Velocity measurements in three nonorthogonal directions
- 90 mm working distance
- MV diameter of 140 μm

Off-axis receiving optics

- Reduces near-wall flare noise
- Effectively reduces MV length (180 μm)

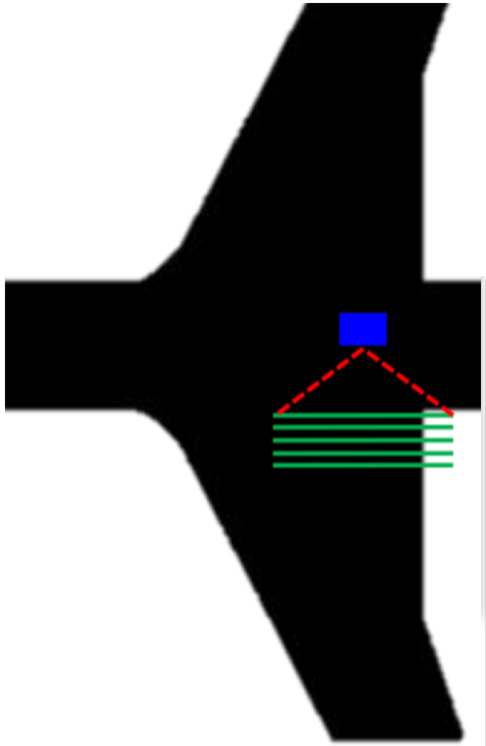


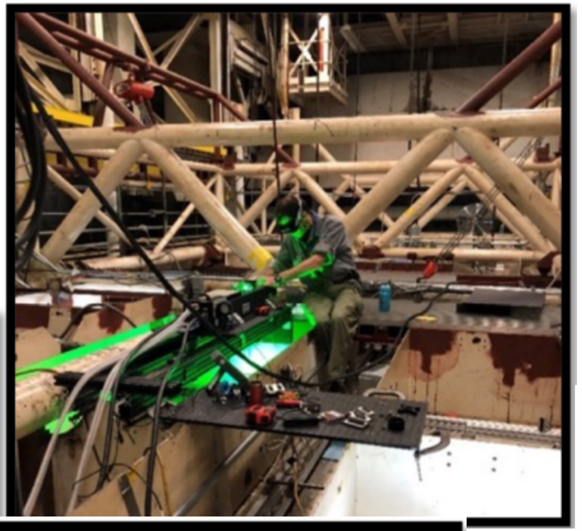


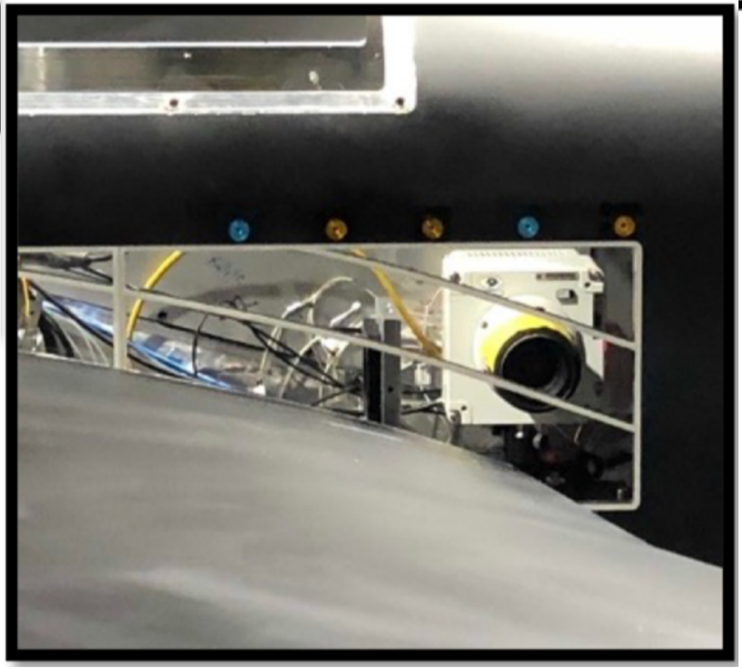
LDV probe near wing TE region

Particle Image Velocimetry (PIV)

To date, only **risk reduction** testing has been performed for PIV

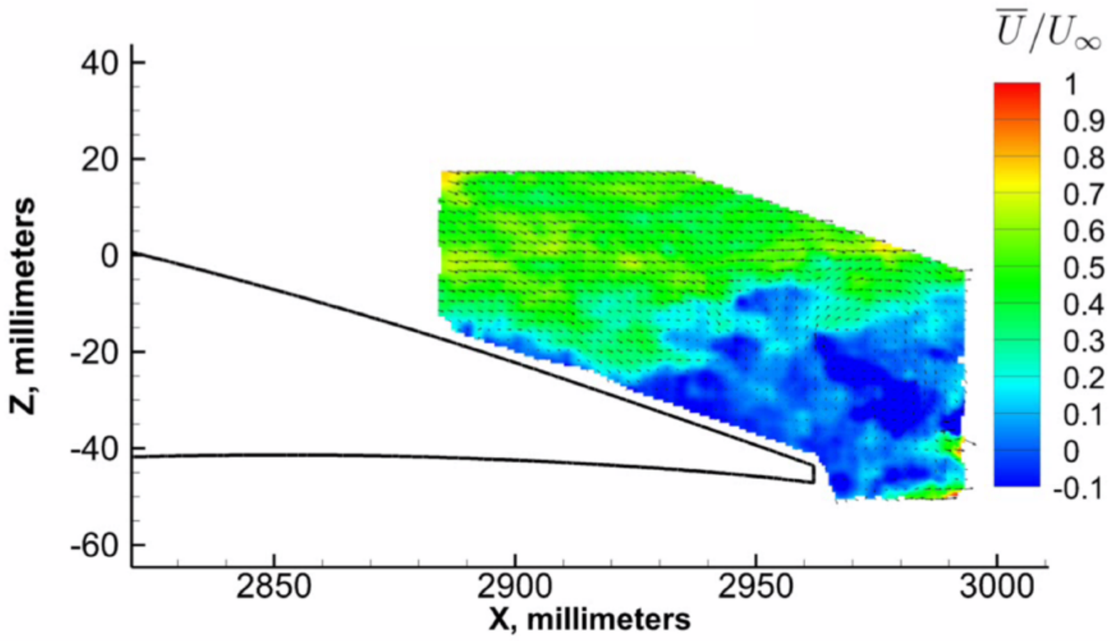






Additional PIV data will be acquired in January 2020

the separated flow is highly unsteady



Many NASA JF papers are available

- Key papers:

  - **Kegerise, M. A. and Neuhart, D. H., "An Experimental Investigation of a Wing-Fuselage Junction Model in the NASA Langley 14- by 22-Foot Subsonic Tunnel," NASA/TM-2019-220286, June 2019.** — THE EXP DATA
  - Kegerise, M. A., Neuhart, D. H., Hannon, J. A., Rumsey, C. L., "An Experimental Investigation of a Wing-Fuselage Junction Model in the NASA Langley 14- by 22-Foot Subsonic Wind Tunnel," AIAA-2019-0077, January 2019. — EXP data summary
  - Rumsey, C. L., Carlson, J.-R., Ahmad, N. N., "FUN3D Juncture Flow Computations Compared with Experimental Data," AIAA-2019-0079, January 2019. — CFD comparisons
  - Lee, H. C., Pulliam, T. H., "Overflow Juncture Flow Computations Compared with Experimental Data," AIAA-2019-0080, January 2019. — CFD comparisons
  - Rumsey, C. L., Carlson, J.-R., Hannon, J. A., Jenkins, L. N., Bartram, S. M., Pulliam, T. H., Lee, H. C., "Boundary Condition Study for the Juncture Flow Experiment in the NASA Langley 14x22-Foot Subsonic Wind Tunnel," AIAA-2017-4126, June 2017. — CFD BC study in tunnel
  - Kegerise, M. A. and Neuhart, D. H., "Wind Tunnel Test of a Risk-Reduction Wing/Fuselage Model to Examine Juncture-Flow Phenomena," NASA/TM-2019-219348, November 2016. — EXP risk reduction

(These and other papers are available on the website)

Taste of (RANS) CFD results to date

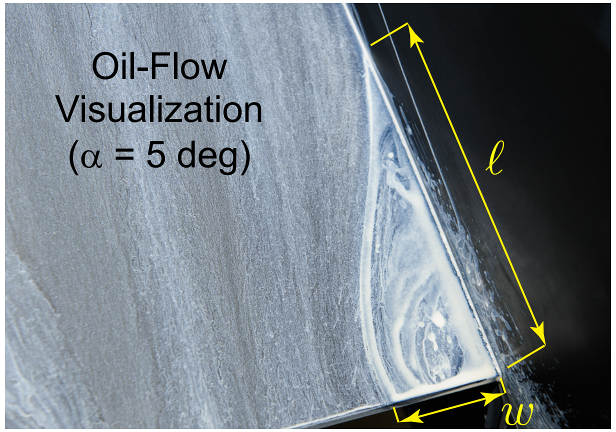
- Initial RANS results and comparisons with experiment (F6 wing with LE extension) have been made with FUN3D and OVERFLOW
  - AIAA-2019-0079 and 0080
  - Included grid density studies and exploration of free-air vs. in-tunnel computations (more to be shown today, putting results from the 2 codes together)
- Running CFD with wind tunnel walls
  - Is do-able with RANS, but includes some challenges:
    - Properly matching the wind tunnel's calibration procedure (see, e.g., NASA/TM-2018-219812)
    - Difficulty attaining perfectly consistent BCs between different codes and different grids when iterating the back pressure (esp. if there is separation present in the diffuser)
  - Will be more difficult for scale-resolving simulations
- Running CFD in free air is a viable option to investigate turbulence model effectiveness in juncture region
  - The wind tunnel walls, mast, and sting have relatively minor influence* (see AIAA-2020-1304)
- Effect of as-built shape, aeroelasticity, and tripping has not yet been explored with CFD, but their effects are currently assumed to be relatively small*
- However, characterizations of the wind tunnel, as-built geometry, etc. are still a major part of our study, and are considered crucial knowledge when comparing with CFD

* On the main quantities of interest in the junction region

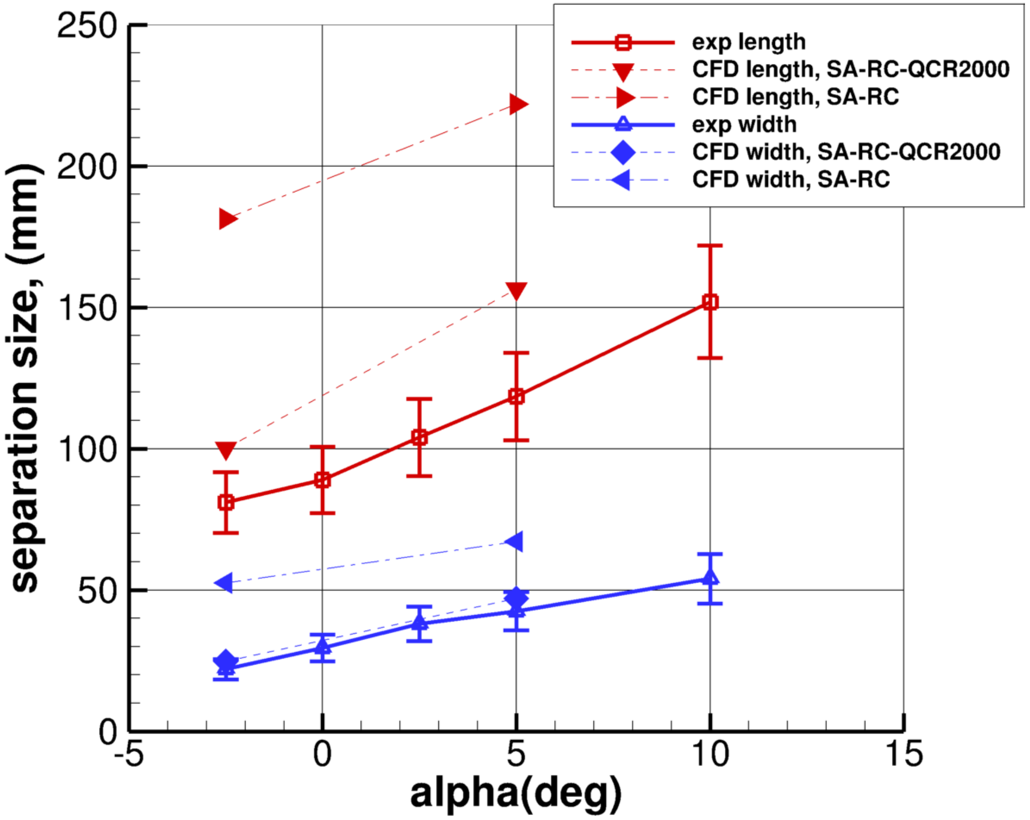
Flow conditions

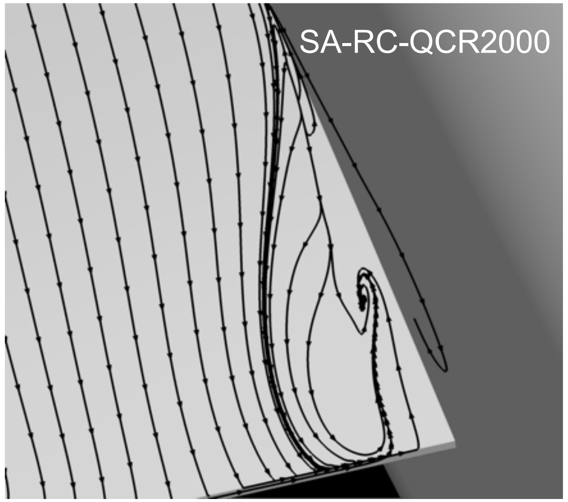
- Reynolds number based on crank chord = 2.4 million (+-0.3%)
  - Crank chord = 557.17 mm (the crank is the location of the break in the wing)
- Alpha, nominal uncorrected model incidence angles in tunnel (for the LDV data) ranged from -2.54 to -2.48 (nominally -2.5) and +4.97 to +5.04 (nominally +5.0) deg.
- Mach number ranged from about 0.175 to 0.205 (nominally 0.189)
- Velocity ranged from about 58 to 72 m/sec (nominally 64.36 m/s)
- Temperature ranged from about 275 to 308 K (nominally 288.84 K)
- Dynamic pressure ranged from about Q = 2107 to 2921 Pa (nominally 2476 Pa)

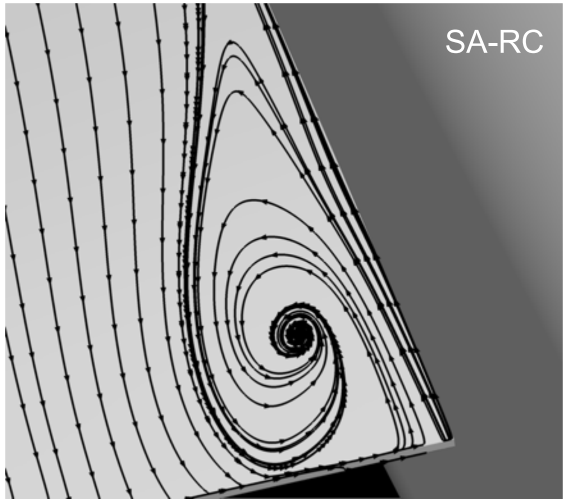
Corner flow separation, example comparisons with RANS



F6-based wing with LE extension

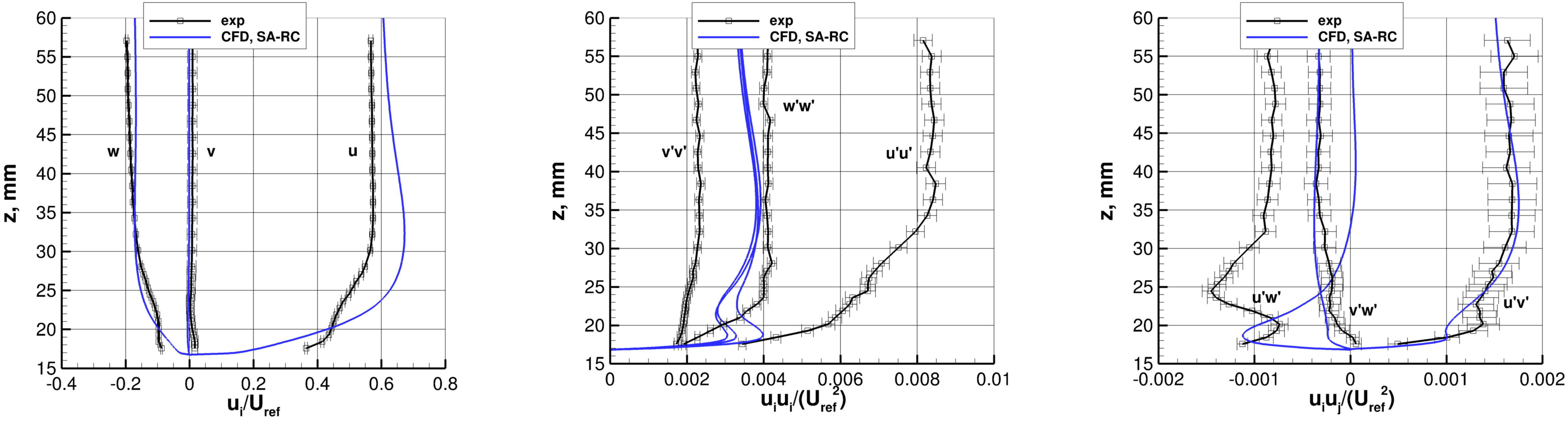




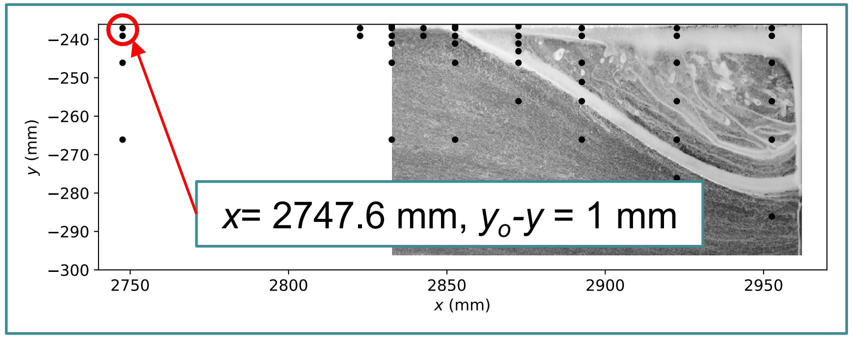


Mean velocity and Reynolds stress profiles, example comparisons

SA-RC

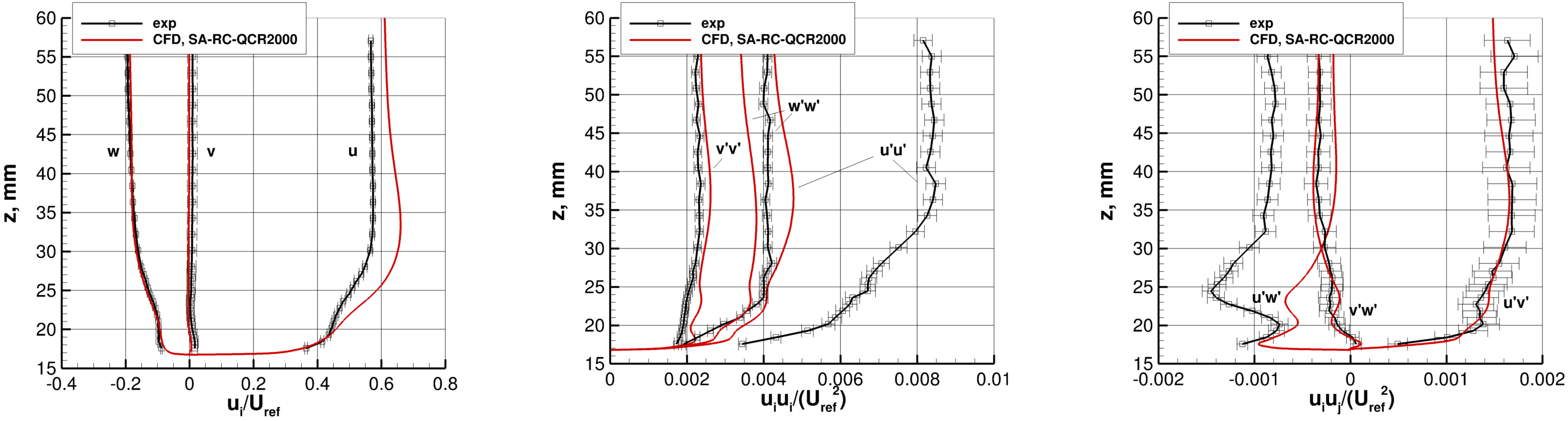


F6-based wing with LE extension

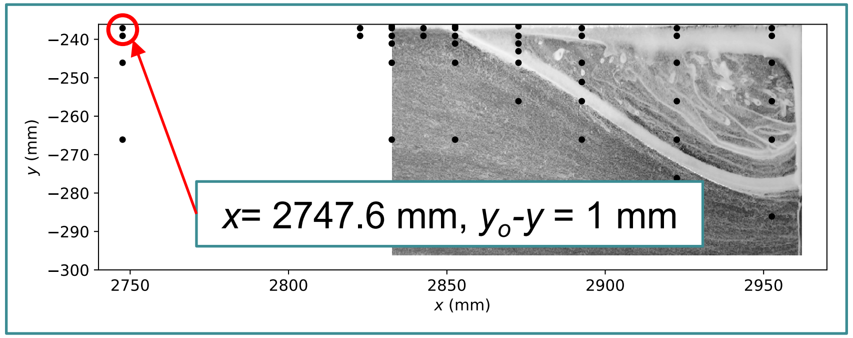


Mean velocity and Reynolds stress profiles, example comparisons

SA-RC-QCR2000



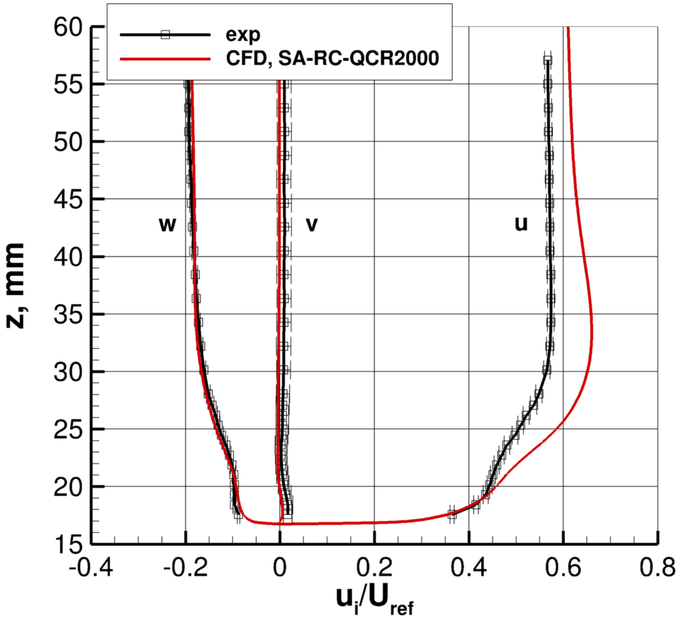
F6-based wing with LE extension

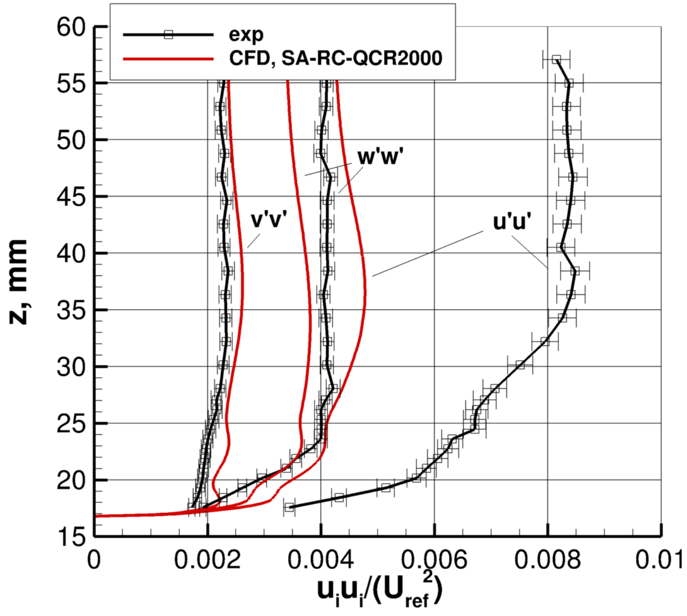


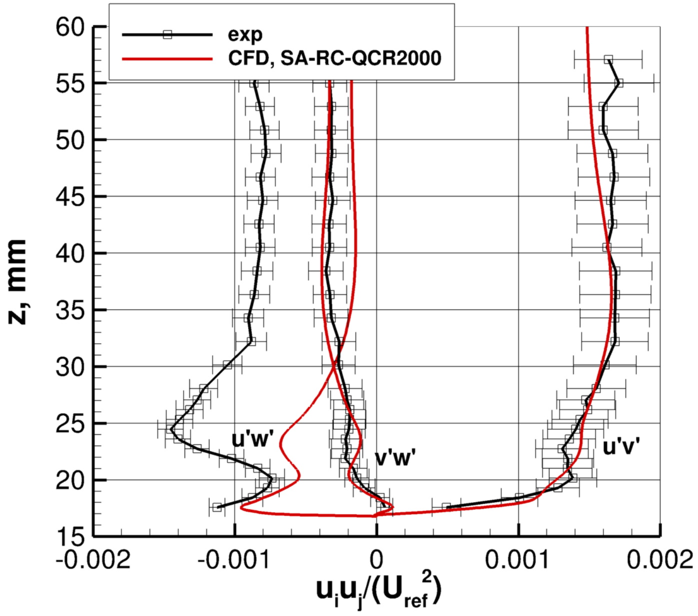
Key factor influencing improved separation prediction with QCR appears to be the difference between the turbulent normal stresses (upstream of separation)

Mean velocity and Reynolds stress profiles, example comparisons

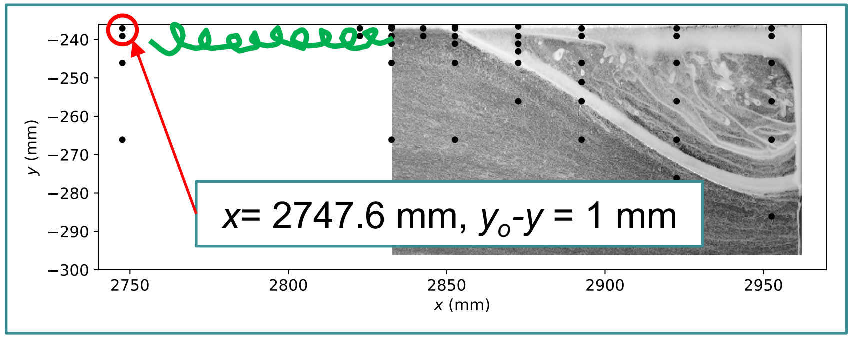
SA-RC-QCR2000







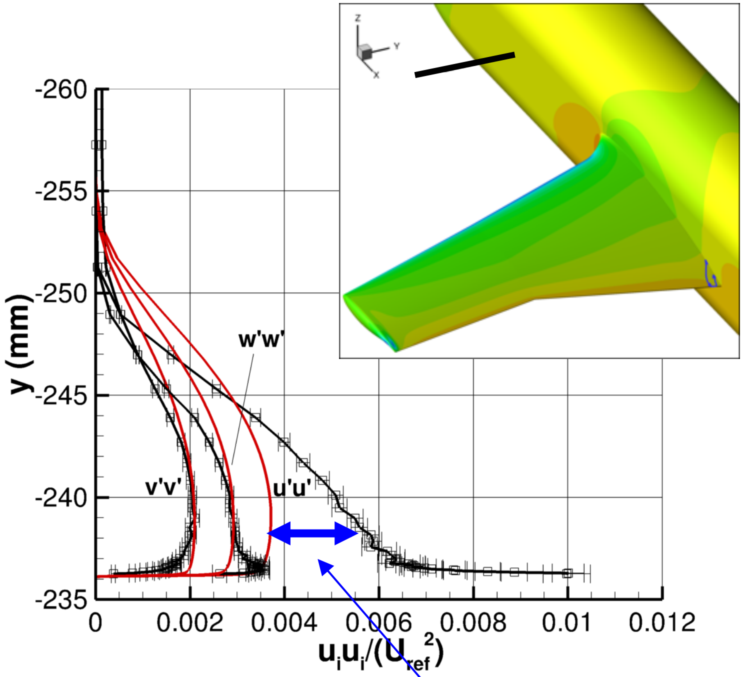
F6-based wing with LE extension

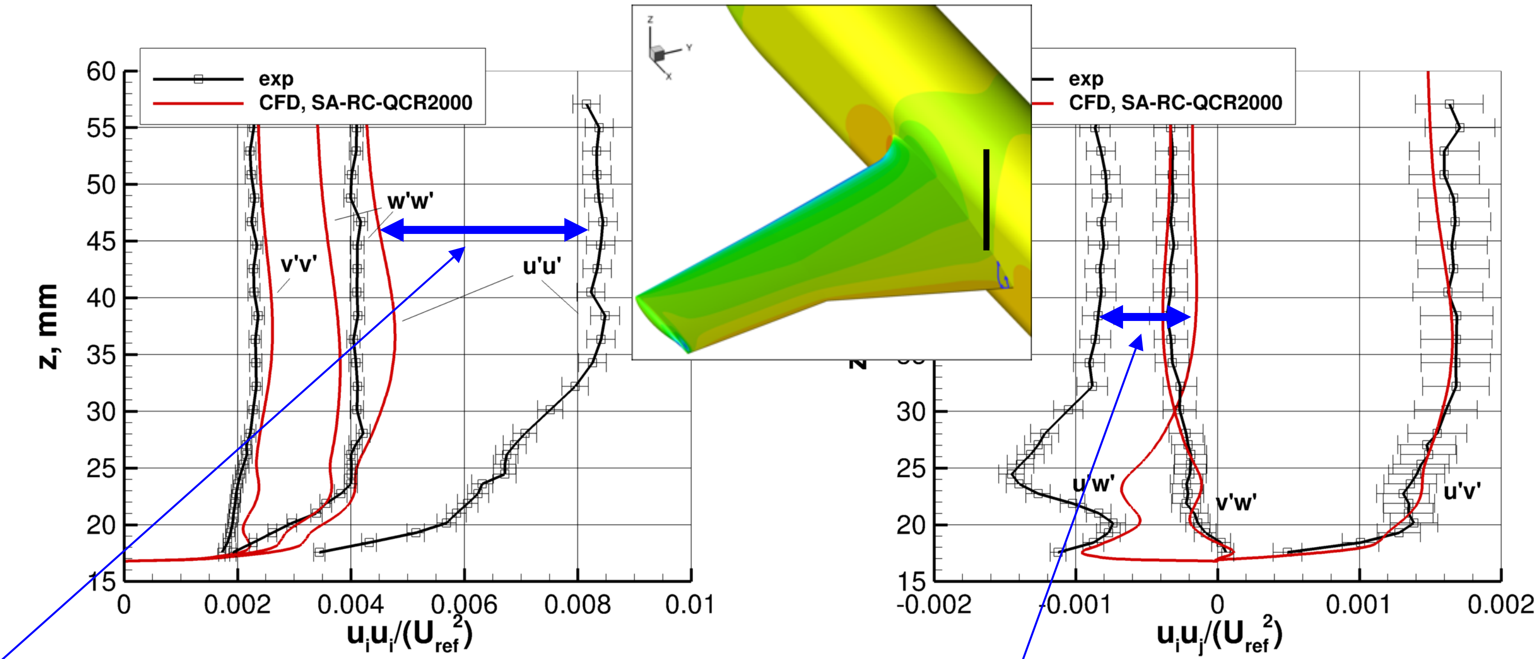


May encourage/promote stress-induced vortex deep in the corner, which helps to delay onset of separation

Mean velocity and Reynolds stress profiles, example comparisons

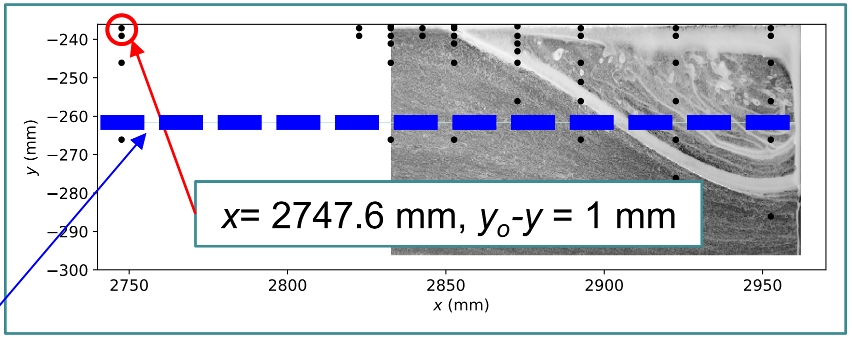
SA-RC-QCR2000





Missing u'u' near the wall here means missing it everywhere here

F6-based wing with LE extension

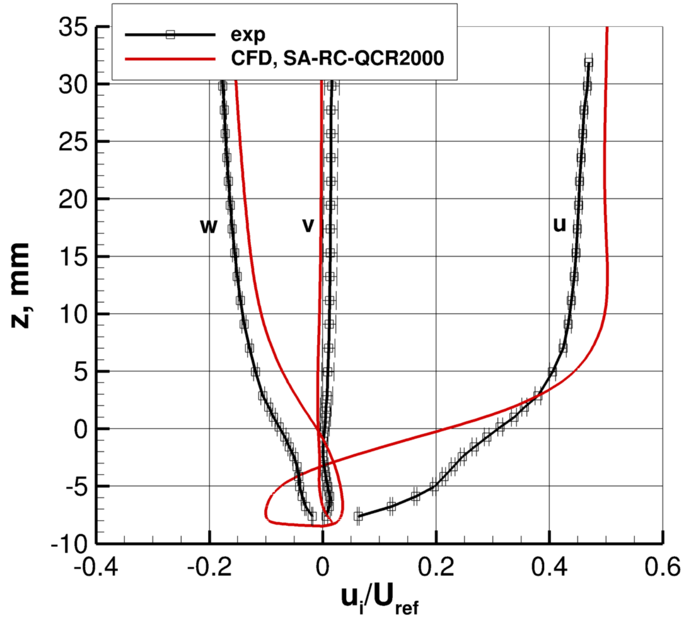


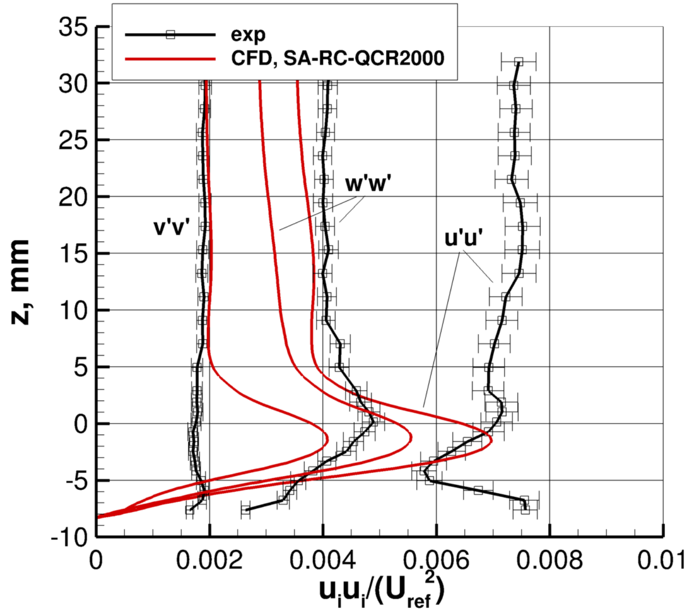
Approx BL thickness on fuselage

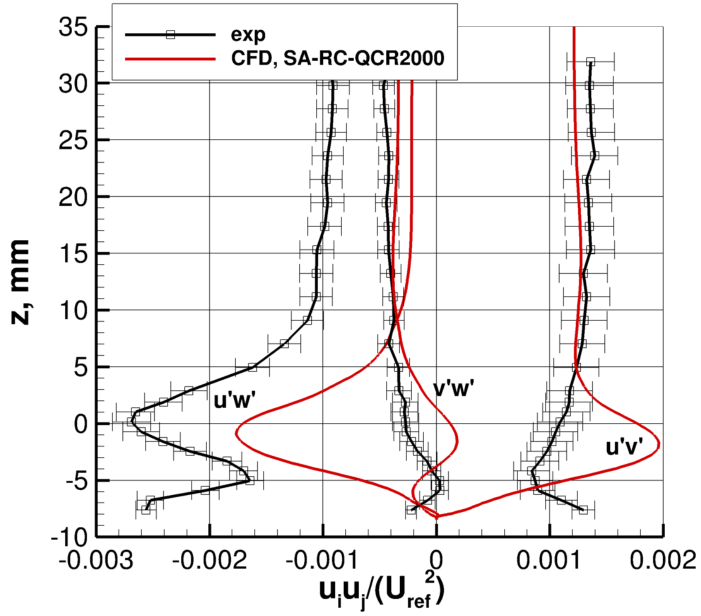
For the purpose of improving turbulence models, it also may help to perform analysis in the local body-surface axis system, because in the global fuselage-based axis system, errors in u_{local}' will appear to influence other components

Mean velocity and Reynolds stress profiles, example comparisons

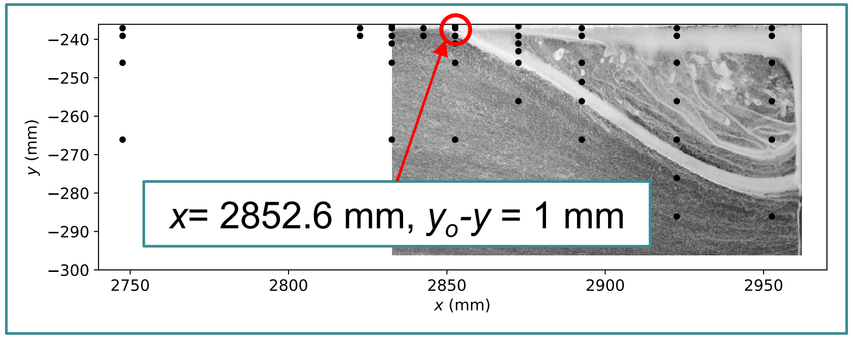
SA-RC-QCR2000







F6-based wing with LE extension



Once you reach separation location of the experiment, RANS CFD is already off, and agreement is very poor here and downstream

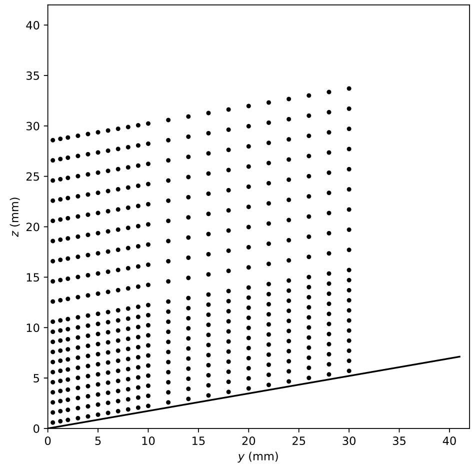
Current status, experiment

- High-quality flowfield and surface data has been acquired and released, toward goal of CFD validation of juncture flow
- Breakthrough use of on-board LDV and PIV laser measurement systems in a major NASA production wind tunnel
- Data for F6-based wing with and without LE extension:
  - Oil flow, surface pressures, unsteady pressures
  - LDV: mean velocity, Reynolds stresses, and velocity triple products in three areas
  - PIV: risk-reduction so far; data expected from the 2020 test
- Improving the input data for the purpose of CFD validation:
  - Laser scans of as-built shape
  - Laser scans of mast/sting configurations relative to tunnel walls
  - Photogrammetry to determine wing shapes under load
  - Pressures along diffuser floor
  - Wall rakes on walls and ceiling to record BL thicknesses and growth
  - IR thermography to verify trip effectiveness
  - On the model itself, flow measured well upstream on the fuselage nose
  - Attempts made to measure details of tunnel's incoming freestream
  - Test section pressures along walls and ceiling (TBD)

Next steps

- CFD:
  - Collate learnings from the current special sessions
  - Additional Special Sessions to be held on “Separated Juncture Flow” at AIAA Aviation 2020
  - JF test case will be included in a future workshop on “High Fidelity CFD” in January 2021 (focus on SA-QCR verification)
  - Other CFD workshop possibilities?
  - Research to improve RANS CFD (specifically SA-based QCR) is being pursued, by making use of the JF LDV data

- Experiment:
  - **6-week test in early 2020** – resolve issues from first test, fill out dataset, include additional PIV
    - Configuration: F6 wing with LE fillet
    - Unusual surface pressures seen on parts of the fuselage
    - Fill in gaps upstream of separation
    - Acquire several LDV planar surveys →
    - Additional repeat runs
    - Include a third angle of incidence with more separation (planned: 7.5 deg)
    - Acquire PIV planar data for direct comparisons with LDV
  - **Tentative 8-week test in 2021** – incipient separation



CFD Special Sessions at AIAA SciTech 2020

- **RANS** update using FUN3D and OVERFLOW (Rumsey, Lee, Pulliam, NASA LaRC & Ames)
- **RANS** using k-kL-based models (Abdol-Hamid, Ahmad, Carlson, NASA LaRC)
- **RANS** using RSM (Eisfeld et al, DLR)
- **WMLES** (Iyer and Malik, NASA LaRC)

- **WMLES** (Lozano-Duran, Moin, Bose, Stanford & Cascade)
- **Hybrid LES-RANS** (Jansen et al, U Colorado Boulder)
- **LB** (Duda and Laskowski, Dassault)

LES = large eddy simulation
WMLES = wall-modeled LES
LB = Lattice-Boltzmann

Some things to look for in these JF special sessions

- How well/poorly do the various RANS models perform?
- What aspects can they capture well? Where are they most lacking?
- Do the RANS models need to be improved? How?
- Would it be "good enough" for RANS to predict the mean corner separation size, but none of the unsteadiness or details in & downstream of the separation region? What happens downstream of separation?
- Are the RANS codes consistent?
- Is grid generation still a bottleneck? Can automatic grid adaption help?

- Are the hybrid scale-resolving methods capable of tackling this type of flow yet? In the mean? Regarding separation dynamics?
- Is wall-resolved LES going to be necessary?
- What are the biggest hurdles to overcome for the hybrid scale-resolving methods?
- Which methods work best?
- How much time and expertise is required to compute this flow?
- Are the hybrid scale-resolving codes consistent?

- How dependent are the solutions on the grid? On the numerics?

Tomorrow's special session ends with a ½ hour general discussion time

Please join us!