CFD Analysis in Advance of the NASA Juncture Flow Experiment

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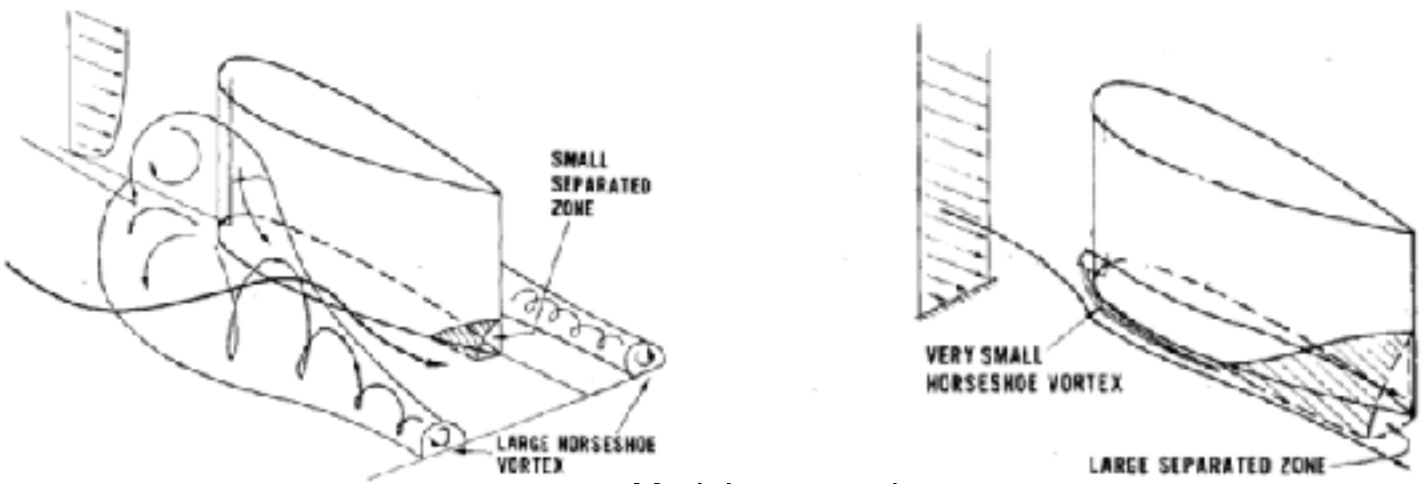
Juncture Flow

Sponsored by NASA's Transformative Aeronautics Concepts Program's Transformational Tools and Technologies (T^3) project

- Substantial effort to investigate the origin of separation bubbles found in wing-body juncture zones
- Primary goal is to gather validation level data, for future CFD code & turbulence model development
- Multi-year effort including several large-scale wind tunnel tests
- Computational Fluid Dynamics (CFD) used in both design and support of risk reduction experiment

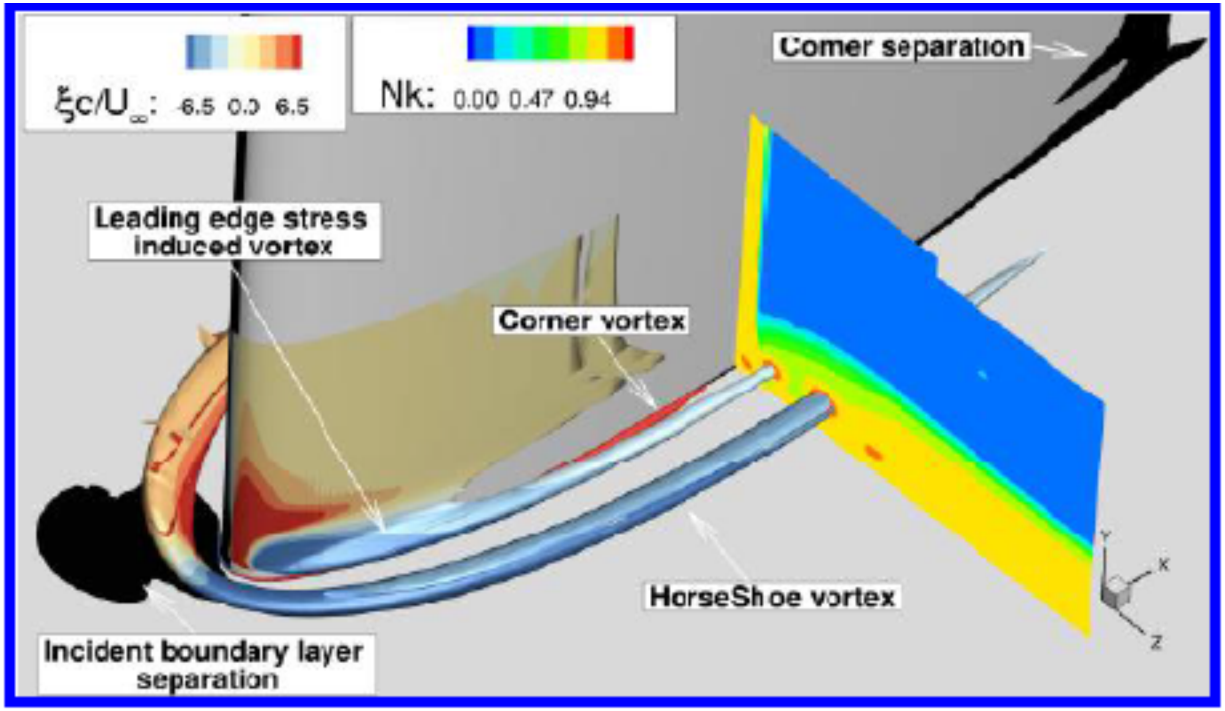


(a) thick boundary layer — Model proposed by Barber *et al.* — (b) thin boundary layer

Background

- Flow physics of juncture flows is complex
  - 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

- Previous juncture flow work:
  - Simpson et al
  - Gand et al
  - other references mentioned therein



From AIAA-2014-2690 (Bordji et al)

Background

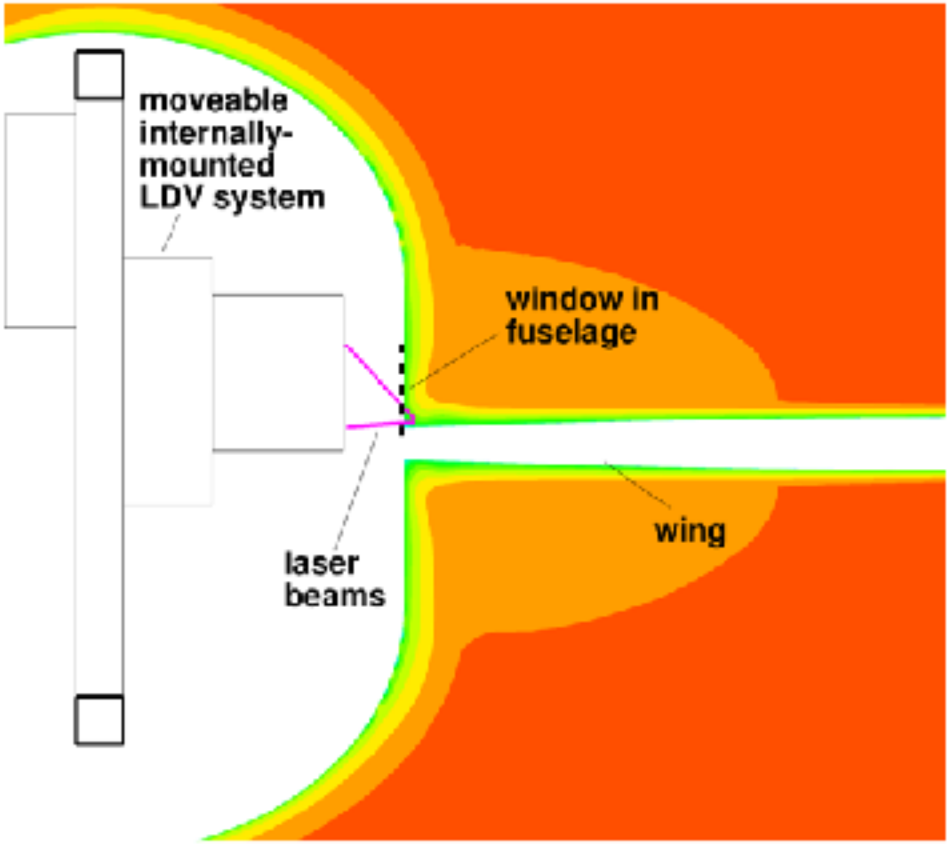
- Geometric junctures (corners) are common on aircraft
  - CFD predictive capability is currently uncertain
  - E.g. Drag Prediction Workshops, participants predicted a wide range of wing-body corner separation bubble sizes (none to very large)
- Computed juncture bubble may be influenced by: grid size, grid topology, and numerical treatments
  - Accurate modeling of the Reynolds stresses is needed
  - Non-linear turbulence modeling
- Because of the high degree of uncertainty in the CFD predictions, relevant separated corner flow experiments focused specifically on obtaining high-quality data for CFD validation are needed

Past Experiments

- Simpson et al experiments:
  - Mostly focused on HSV (not so much on corner separation)
- Gand et al experiments:
  - NACA 0012 wing (no sweep) mounted on flat plate – did not separate
  - Twisted NACA 0015 wing (no sweep) mounted on flat plate – produced corner separation at alpha=12 deg
- New NASA experiment originally conceived by members of the DPW steering committee
  - Swept wing / fuselage full-span configuration
  - To focus primarily on collecting data <u>for CFD validation</u>
  - A main objective: to obtain flow field details very near the corner

Goals and Purpose

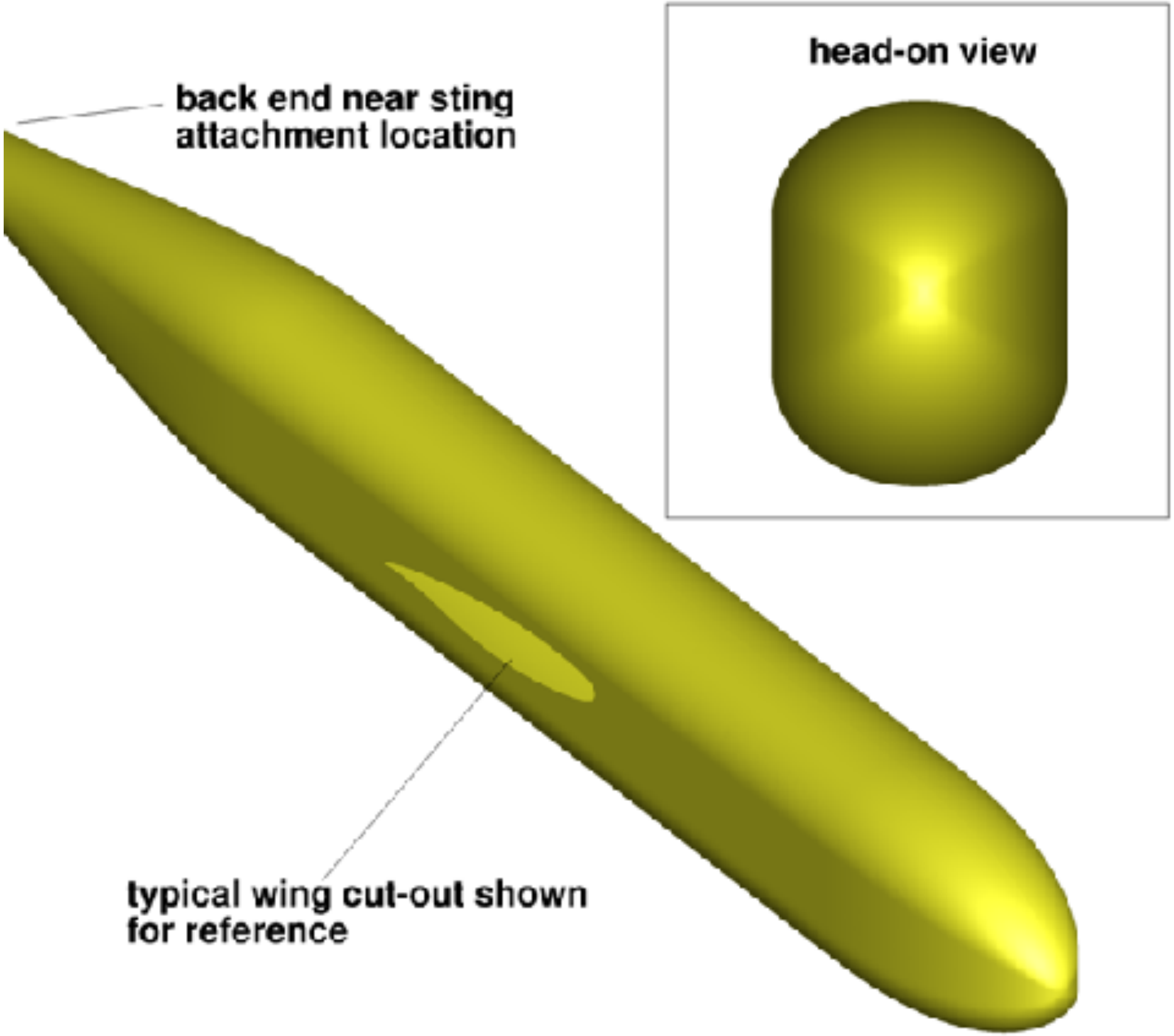
- Decision made early: to use internal Laser Doppler Velocimetry (LDV) system
  - Mounted inside of the fuselage on a movable three-axis traverse system
  - Will measure the flow field very near the wing-body juncture through window(s) in the fuselage



Goals and Purpose

- Decision made to perform a subsonic experiment
  - Subsonic testing venues of sufficient size were readily available
  - M=0.2
  - 8% model based on full scale CRM (~16 ft long, 11 ft wide)
- "CFD Validation-Quality"
  - Boundary conditions, geometry information, experimental uncertainties, etc., necessary for a thorough and unambiguous CFD validation study
  - See, e.g., Aeschliman & Oberkampf (AIAA J 36(5):733-741, 1998)
- Main purpose:
  - Assess the ability of existing models to predict the onset and extent of the three-dimensionally separated flow near the Wing Juncture Trailing Edge region of a full-span wing-body configuration, in terms of the surface topology of the flowfield structure.
  - To provide a range of prediction difficulty, a variation of low fields are required, including the onset and progression of corner separation

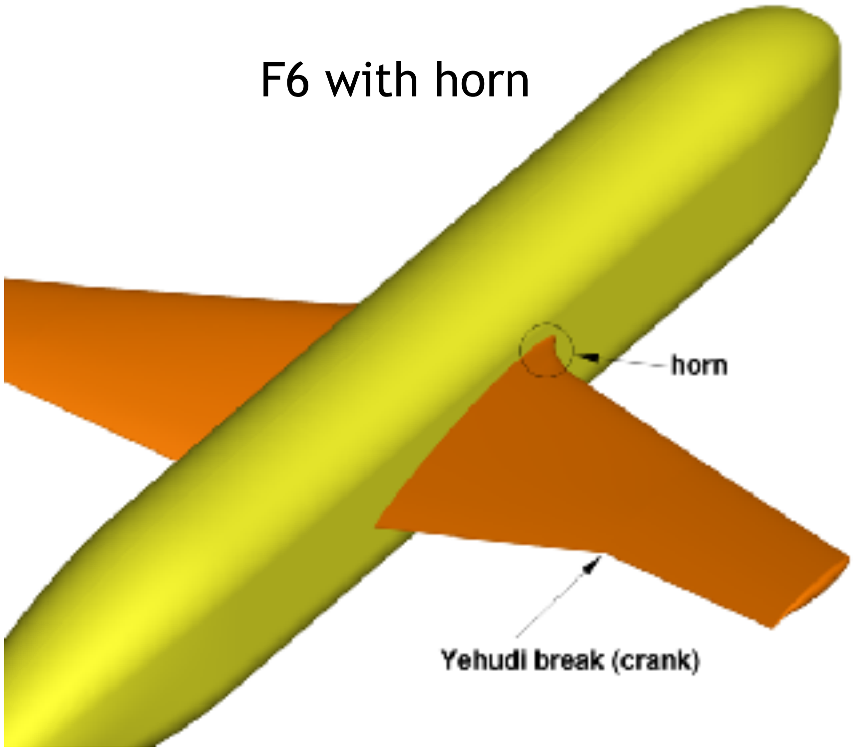
Fuselage Configuration



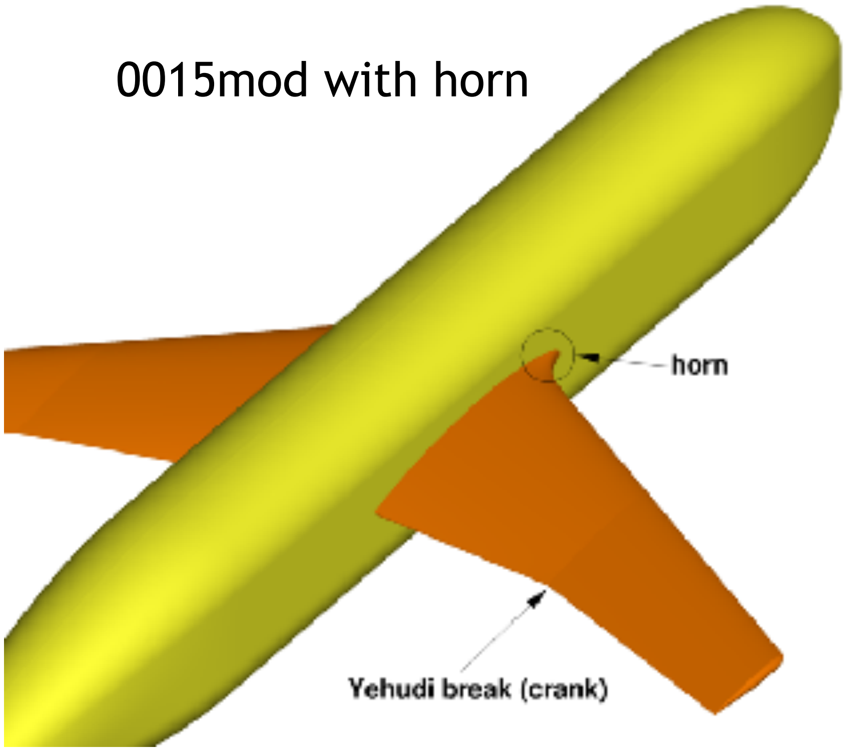
Wing Configuration

- Planforms based on truncated DLR-F6 or truncated CRM

F6 with horn

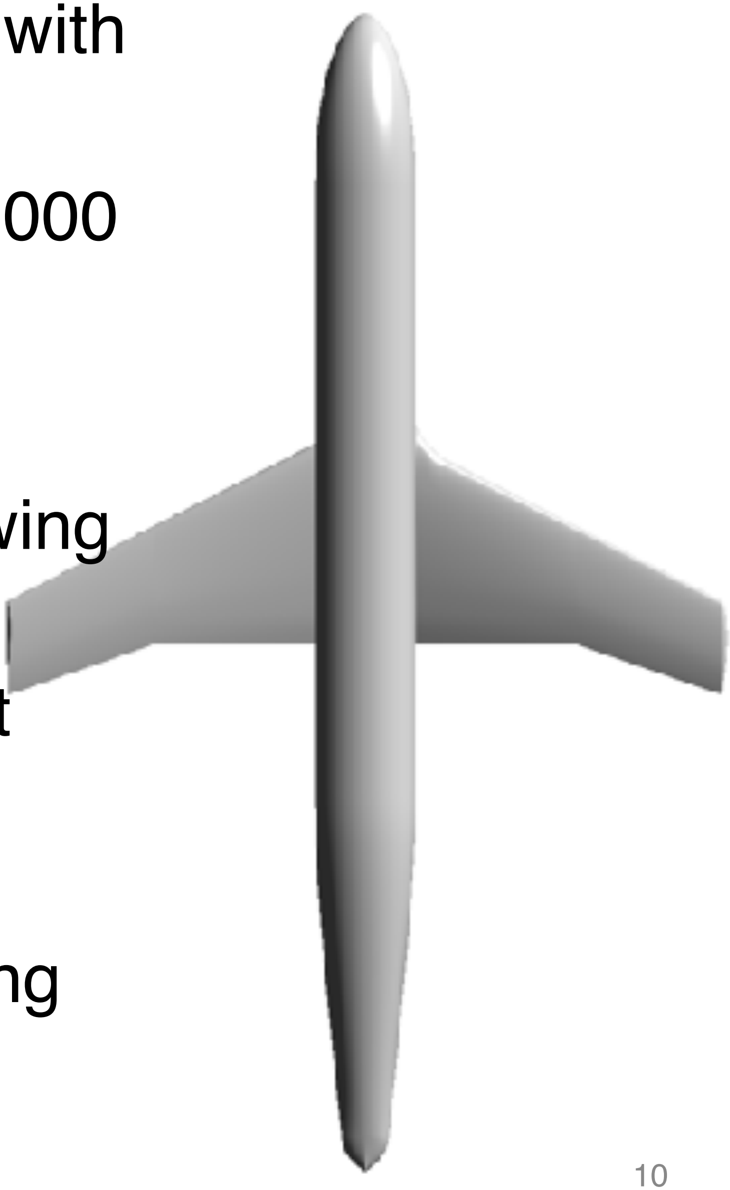


0015mod with horn

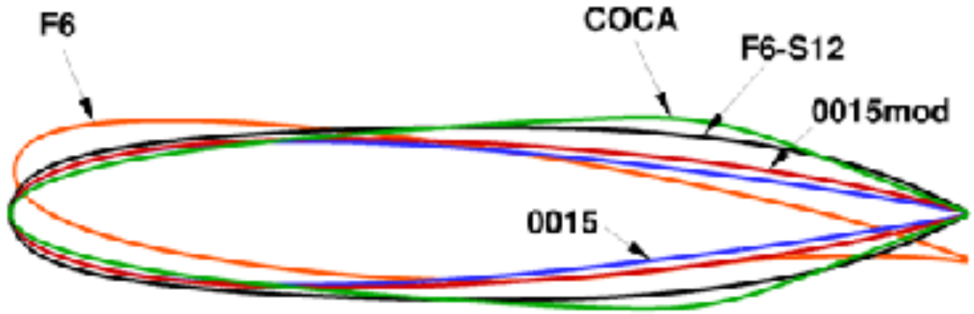


Juncture Flow Model Design

- Preliminary model design done with CFD
  - Overflow 2.2L: SARC-QCR2000
  - FUN3D: SARC-QCR2000
- Evaluated 20+ wing candidates
- Committee down-selected the wing candidates
- Selected 6 wing candidates that combined satisfied the goals
- Risk reduction experiment tests proposed: further evaluate 6 wing candidates



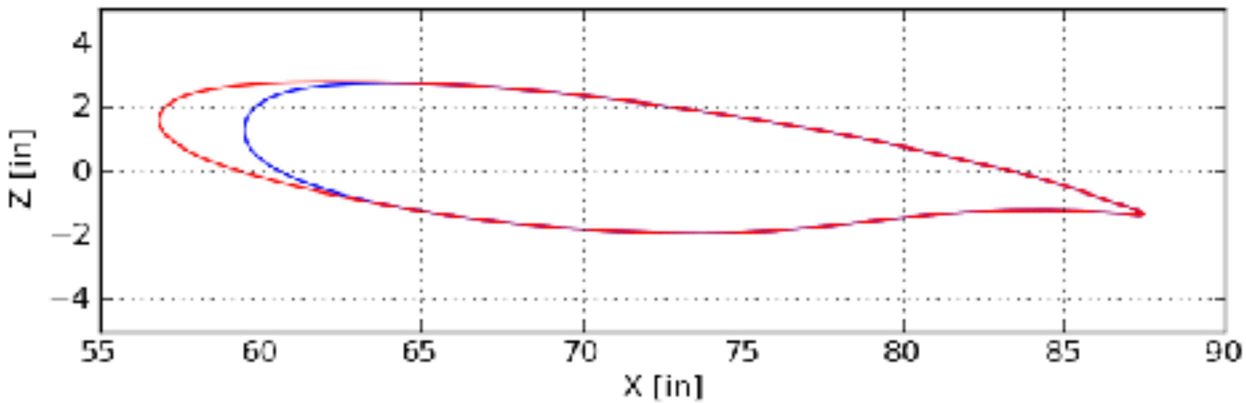
Wing Candidates



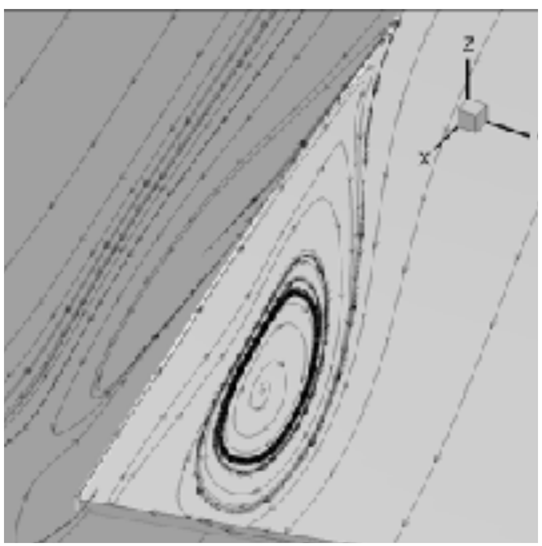
6 Wing candidates

- DLR-F6 no horn
  - Used in DPW3
  - Showed side of body separation
- DLR-F6: with LE horn
- NACA 0015 with horn: symmetric wing
- NACA 0015mod: slightly steeper pressure recovery
- F6S12: symmetric F6 variant
- COCA
  - Coder-Campbell design
  - CDISC/skin-friction constraints

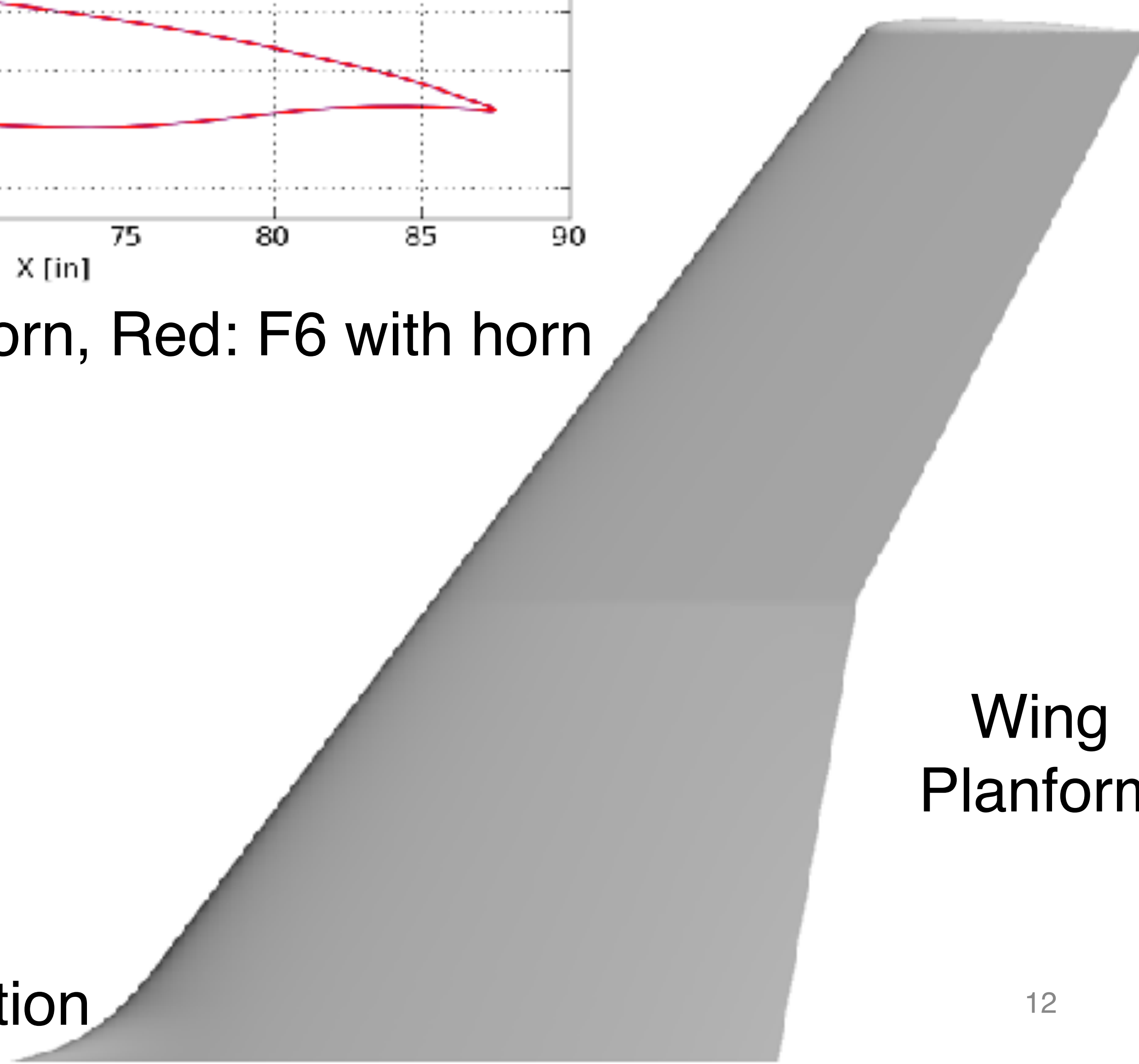
DLR-F6



Blue: F6 without horn, Red: F6 with horn

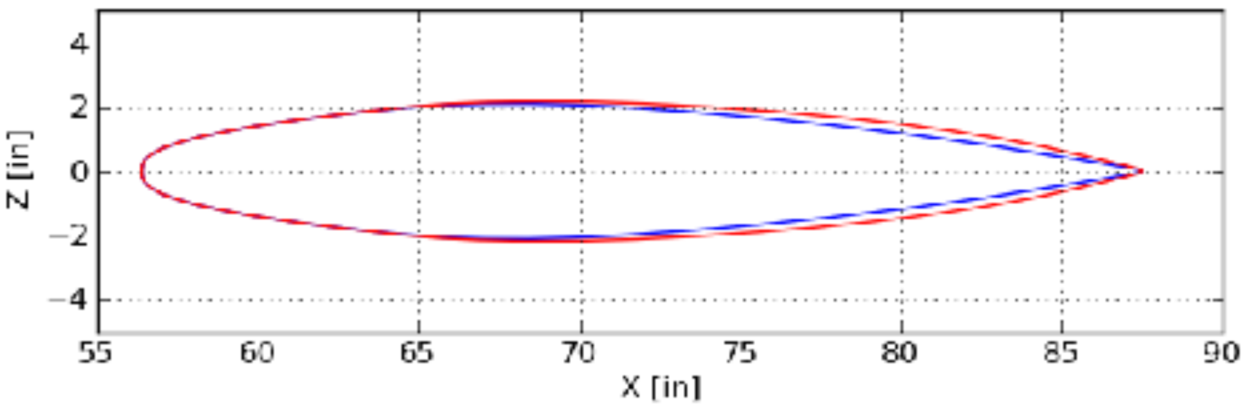


Side of Body Separation

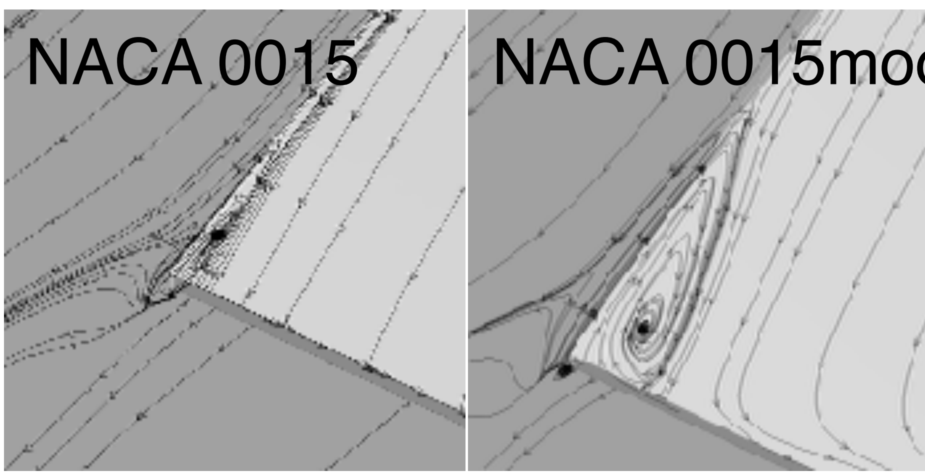


Wing Planform

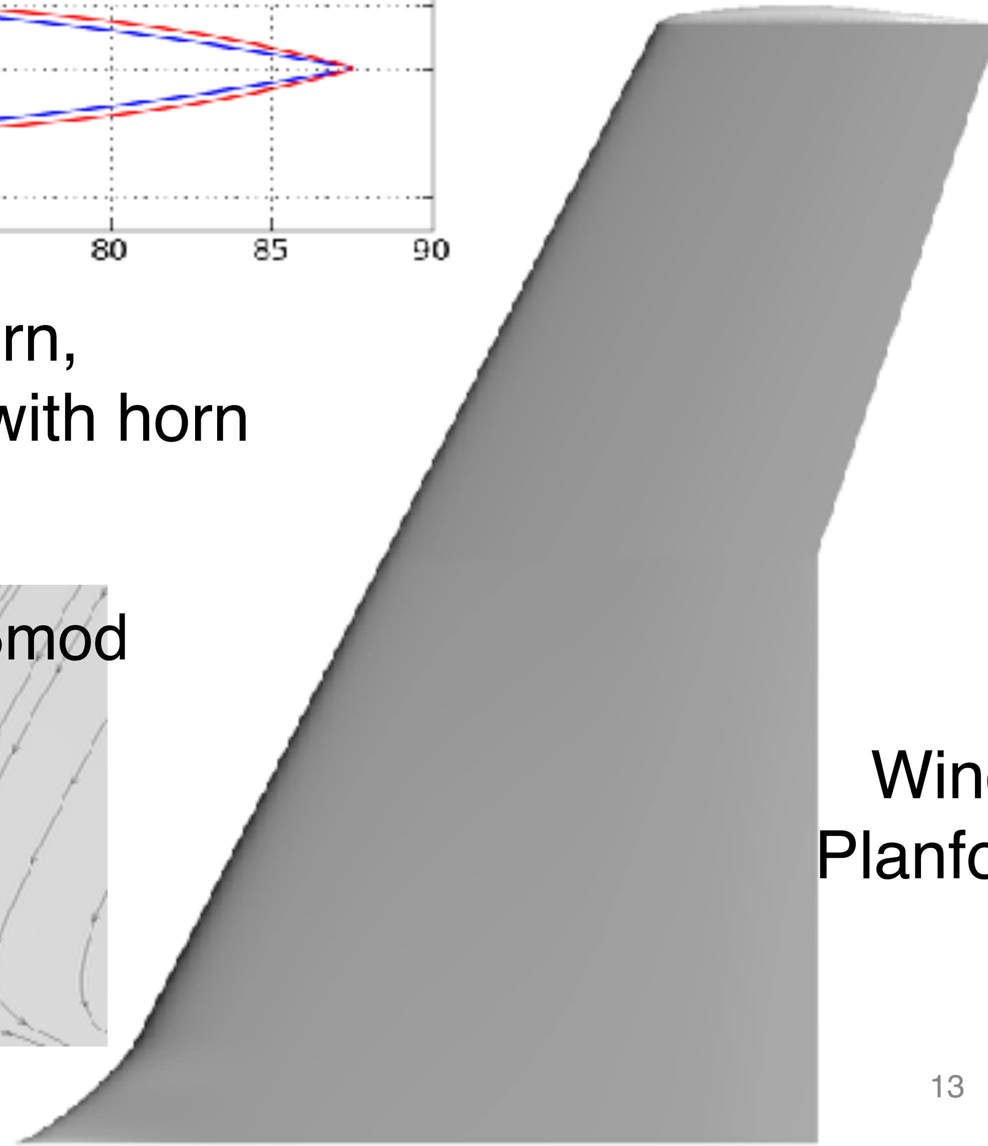
NACA 0015 — NACA 0015mod



Blue: NACA 0015 w/horn,
Red: NACA 0015mod with horn

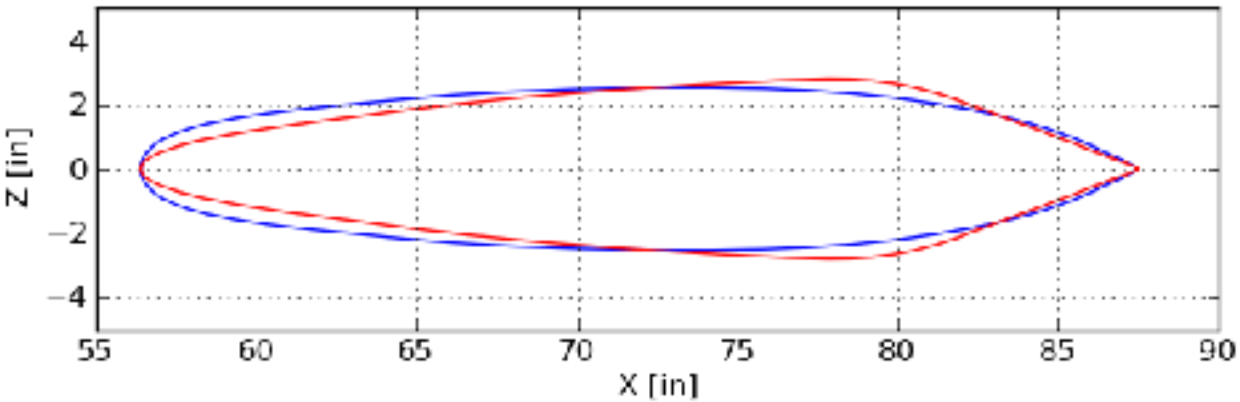


Side of Body Separation

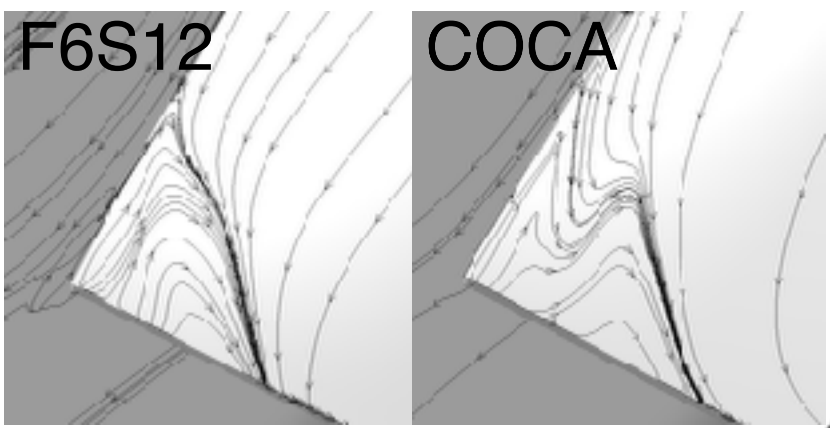


Wing Planform

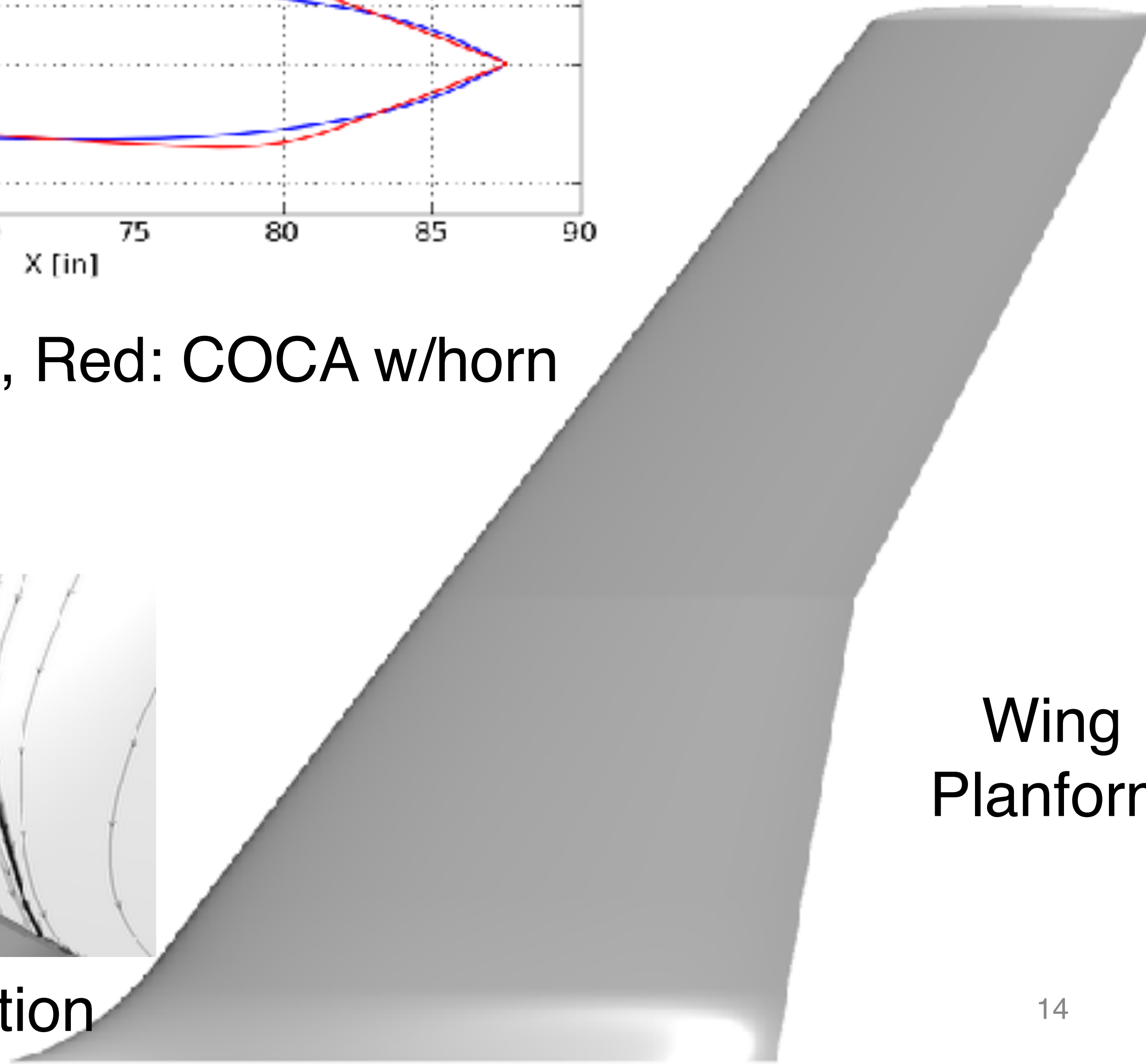
F6S12 — COCA



Blue: F6S12 w/horn, Red: COCA w/horn



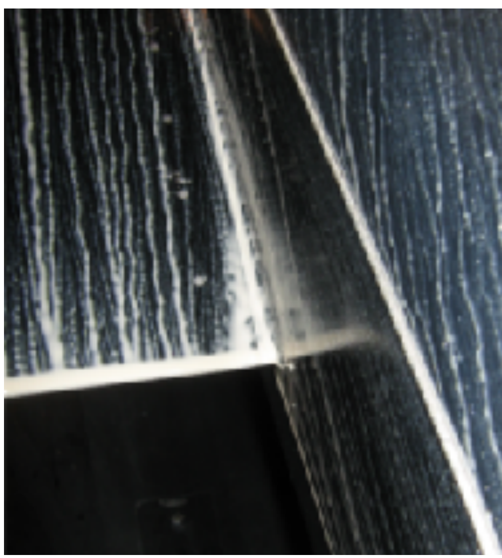
Side of Body Separation



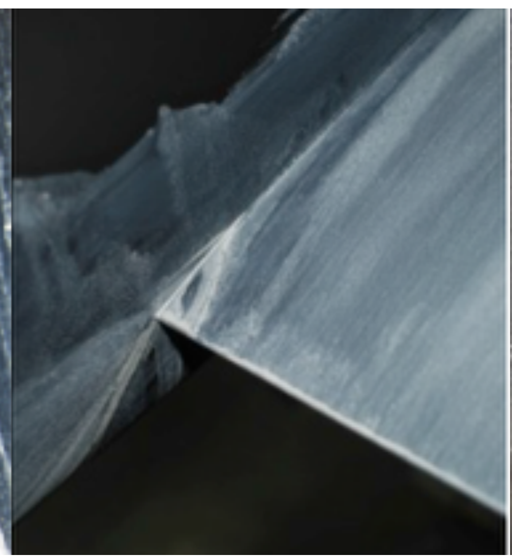
Wing Planform

Risk Reduction Tests

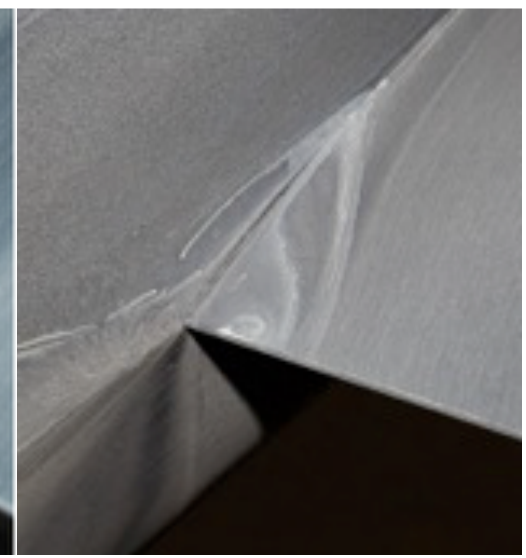
- Series of risk reduction tests
  - Ames TC2 3% wall mounted model, low RE
  - Virginia Tech 2.5% fullspan low RE
  - Langley 14x22 6% fullspan high RE
- CFD solutions were run concurrently with all tests



TC2

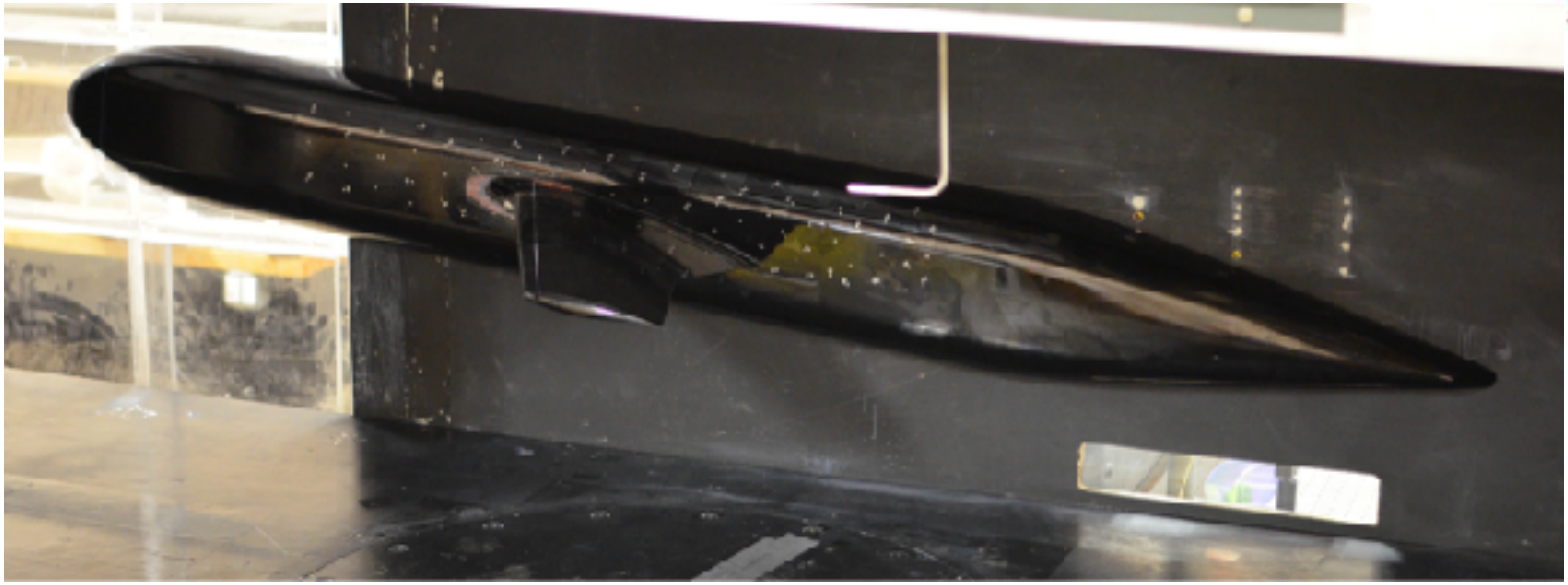


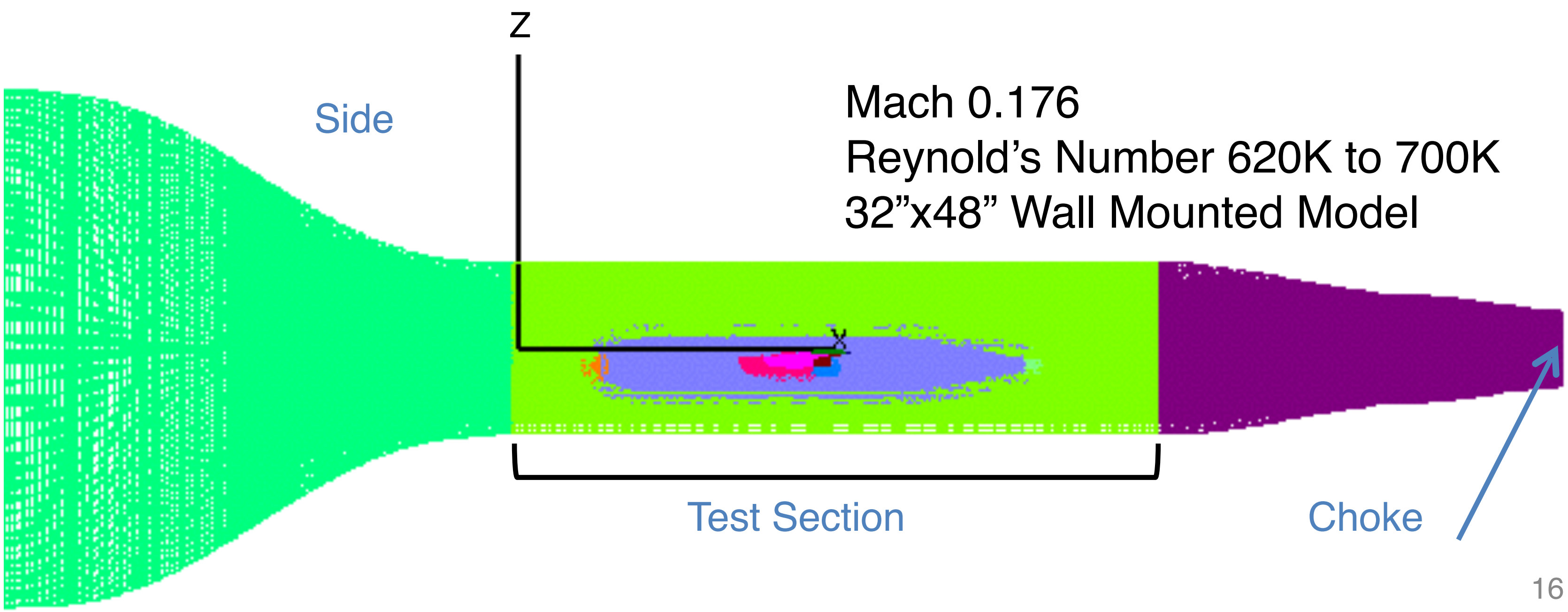
VA Tech



14x22

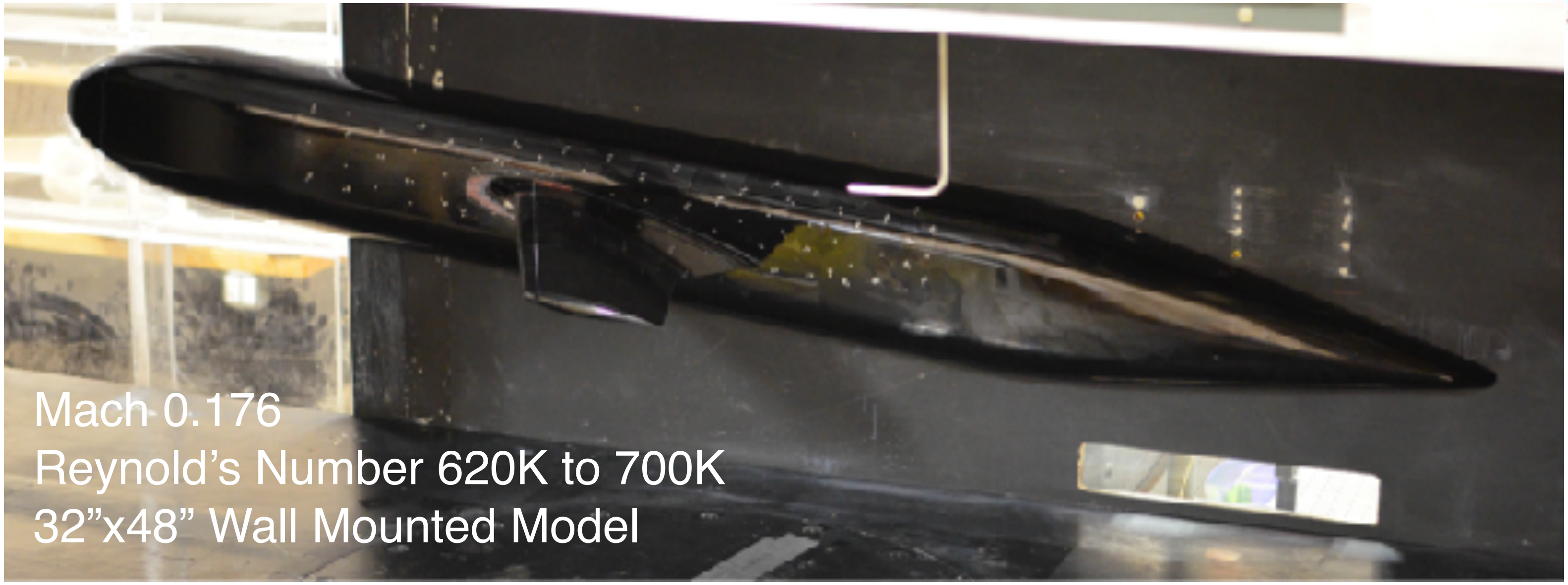
Model in TC2 and CFD Geometry

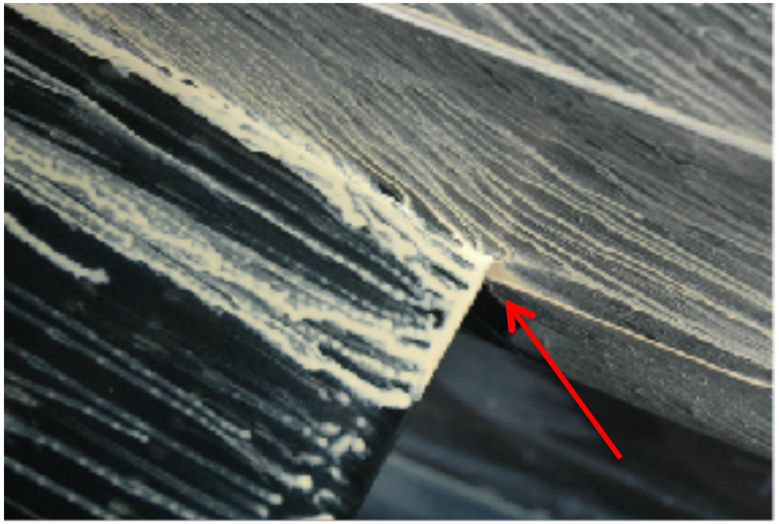




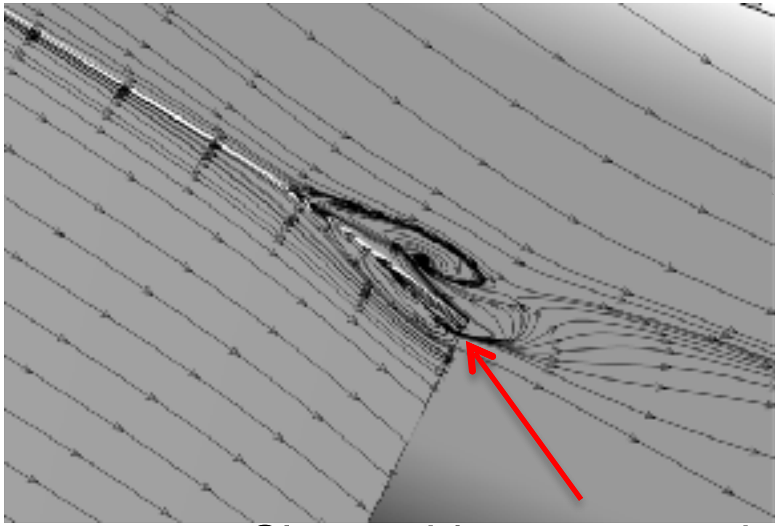
Mach 0.176
Reynold’s Number 620K to 700K
32”x48” Wall Mounted Model

TC2 Risk Reduction





Small hint of separation



Clear evidence separation

Determined Wall Mounted model is not ideal for this test

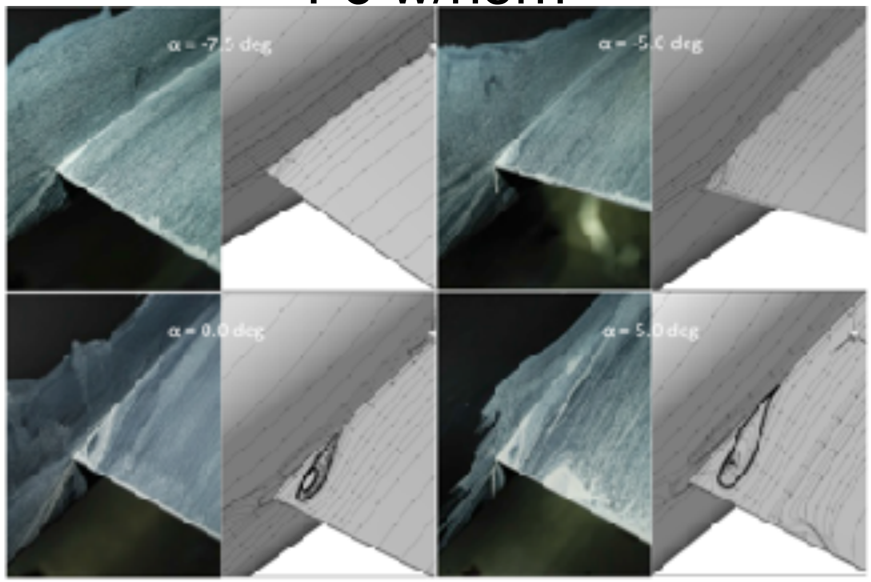
Results published in AIAA Paper 2016-1558

Virginia Tech 2.5% Full Span Test

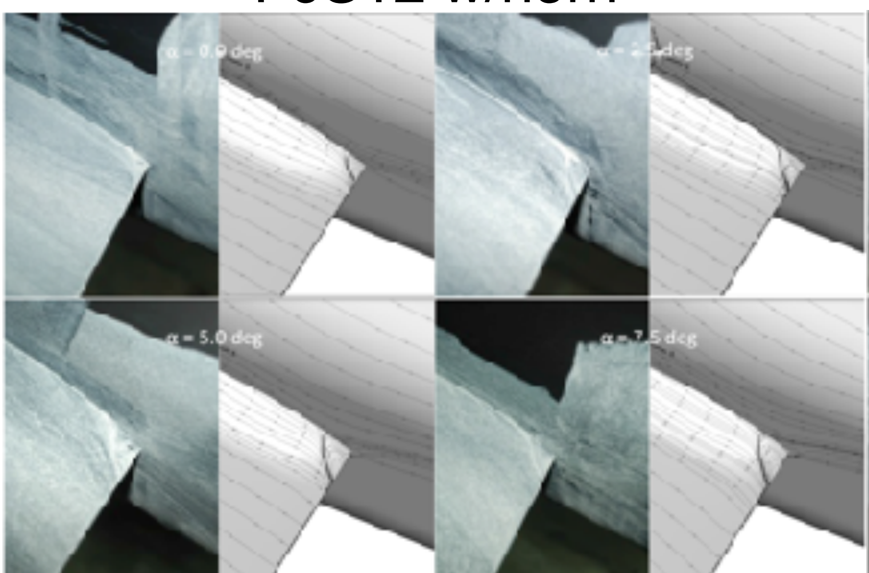
Mach 0.176, Reynolds Number of 620K, 6' Test Section

VT Tunnel Risk Reduction

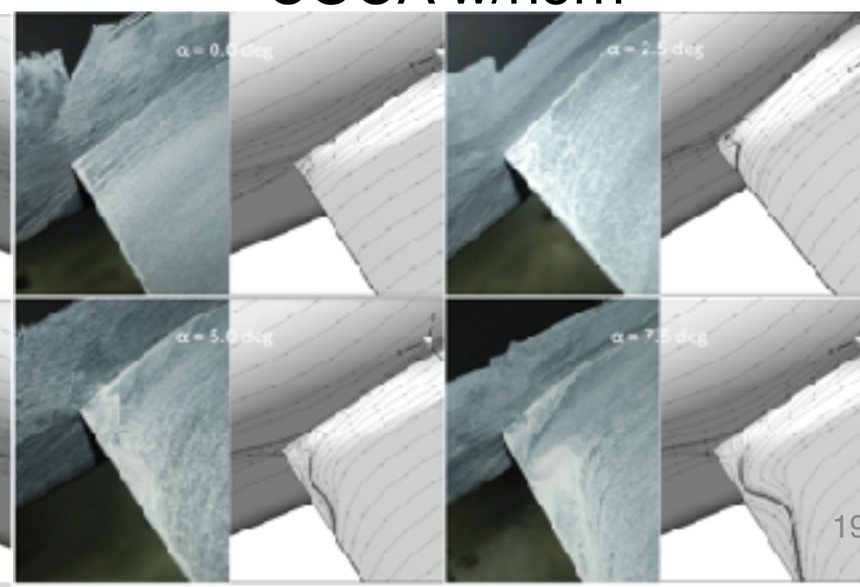
F6 w/horn



F6S12 w/horn

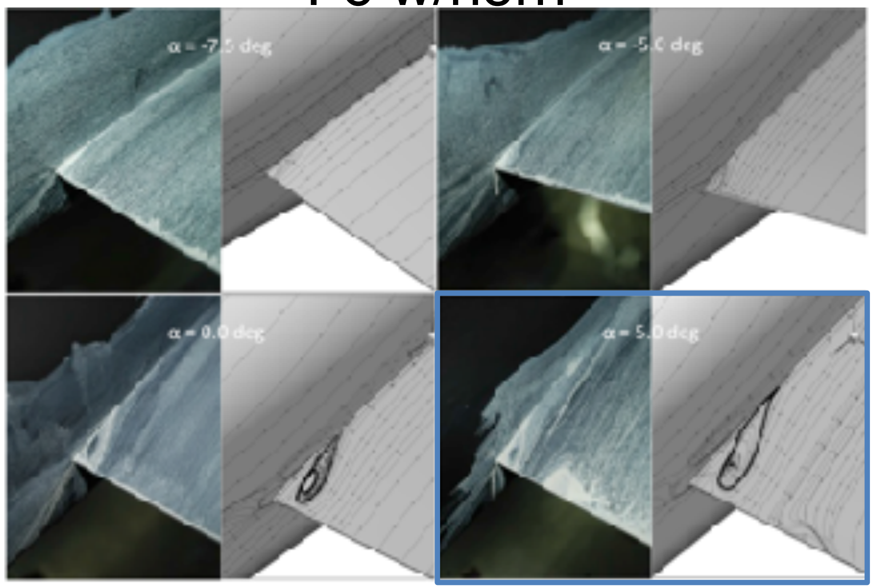


COCA w/horn

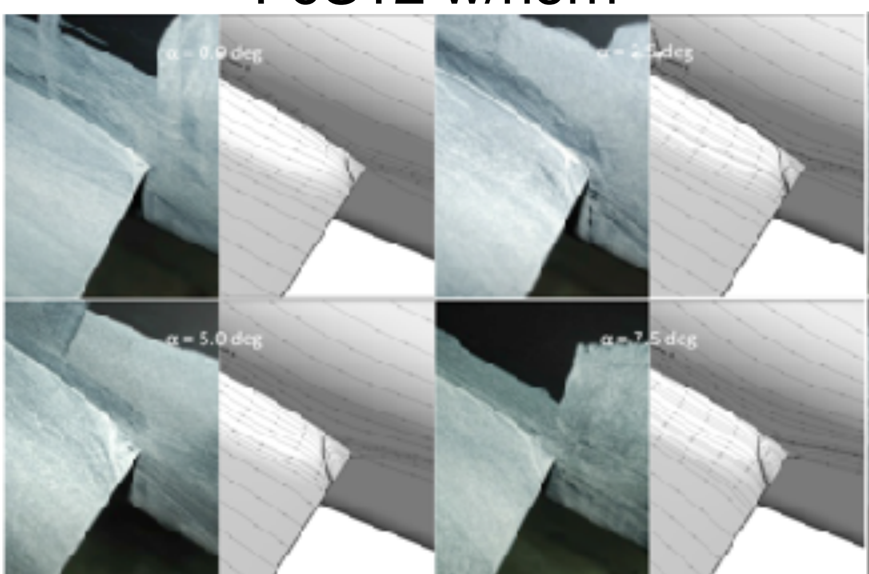


VT Tunnel Risk Reduction

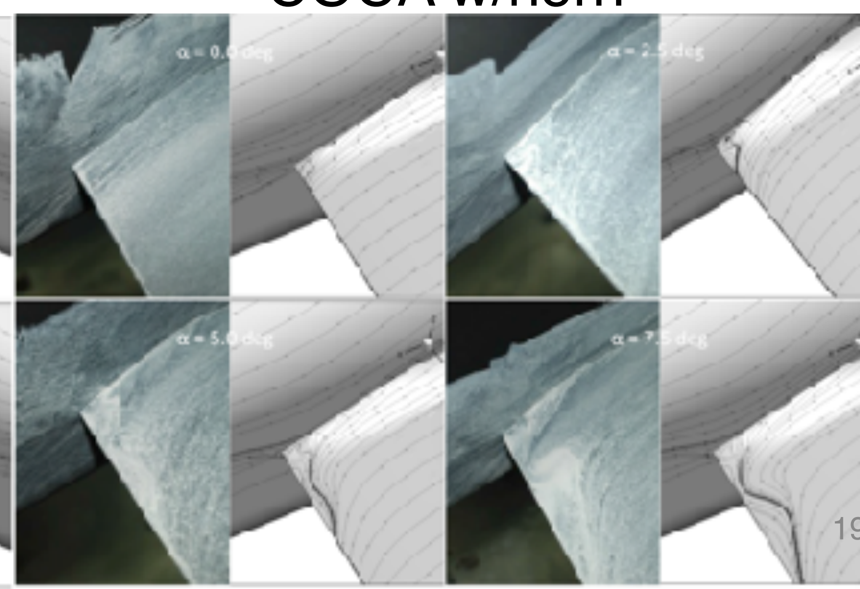
F6 w/horn



F6S12 w/horn



COCA w/horn



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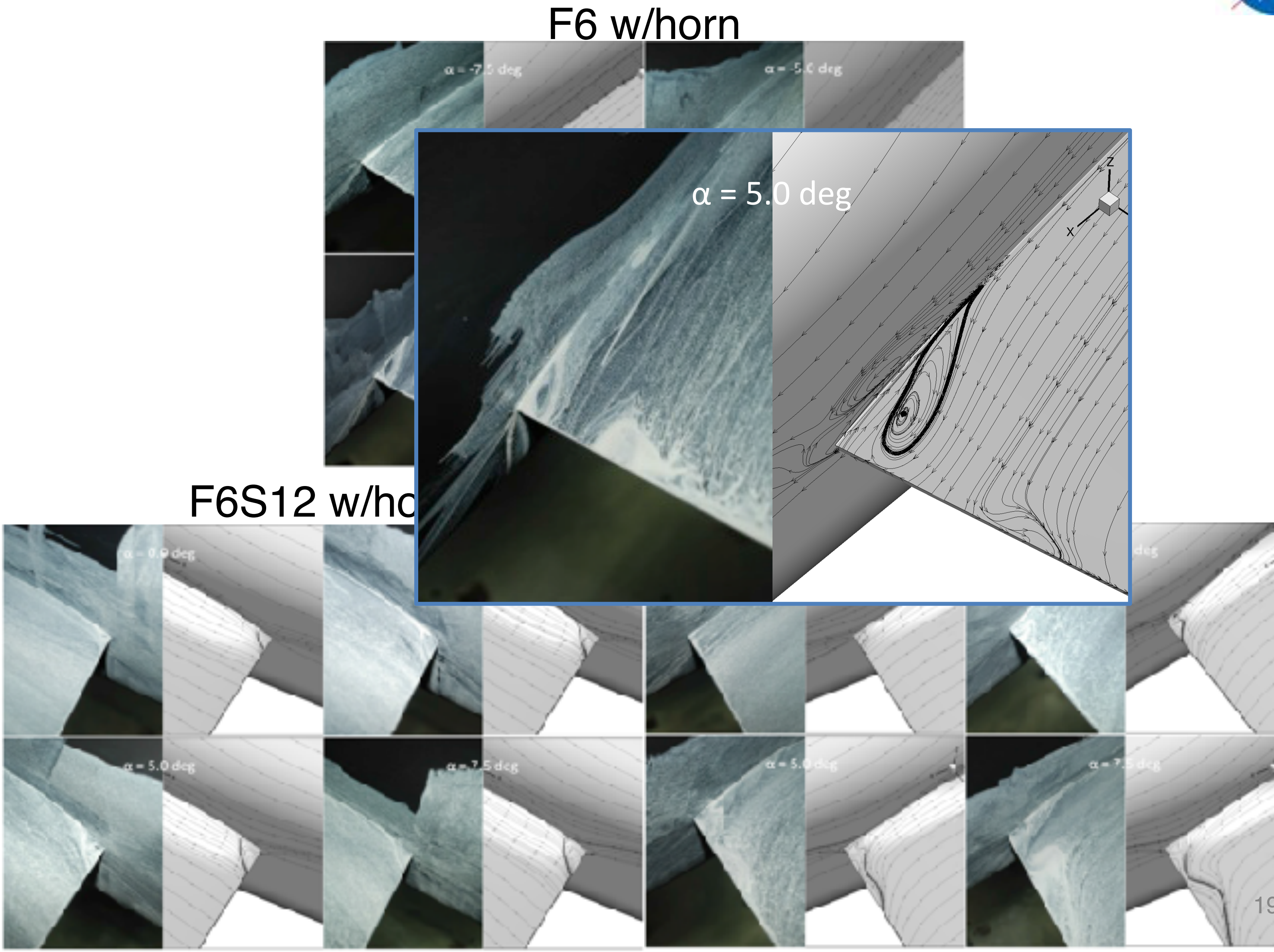
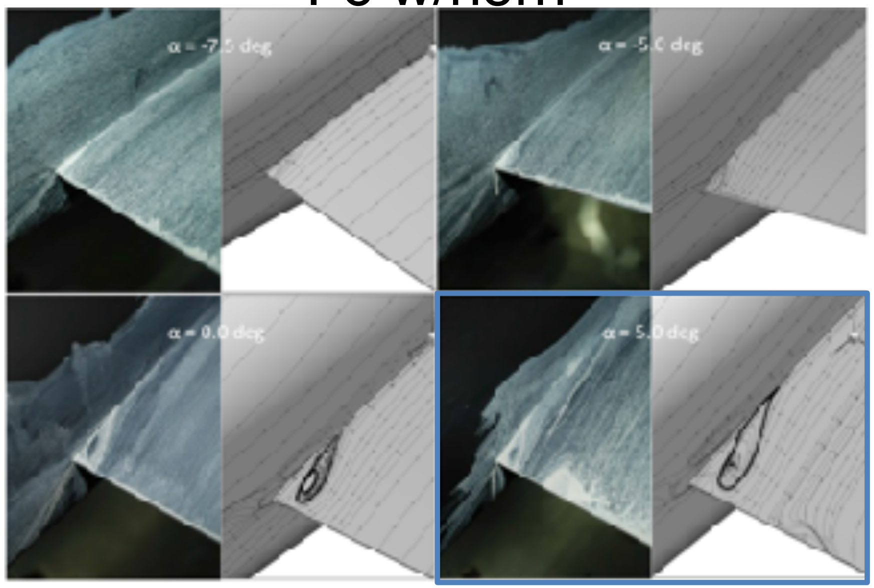
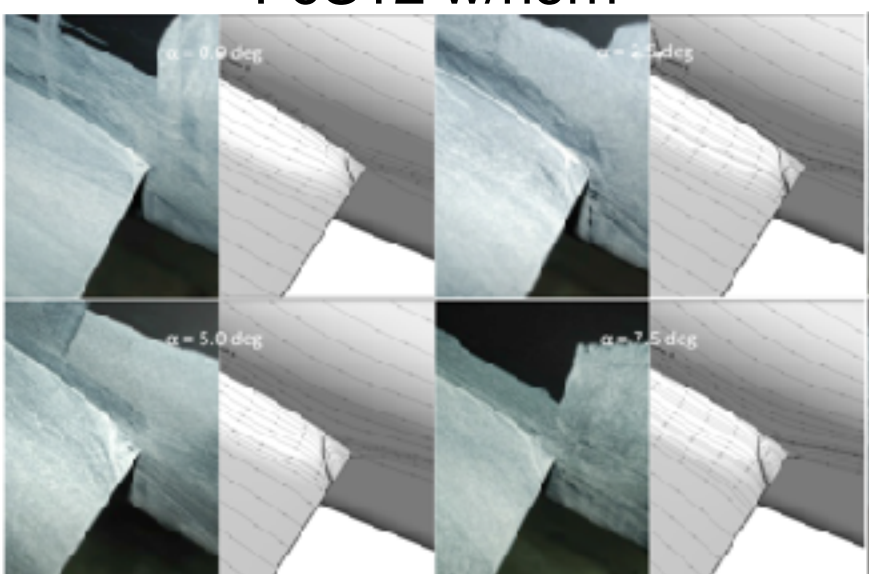


VT Tunnel Risk Reduction

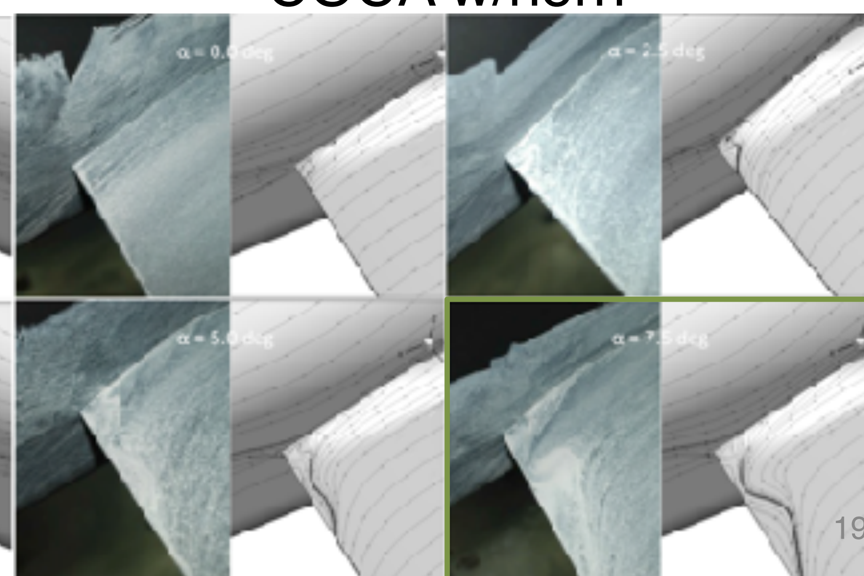
F6 w/horn



F6S12 w/horn

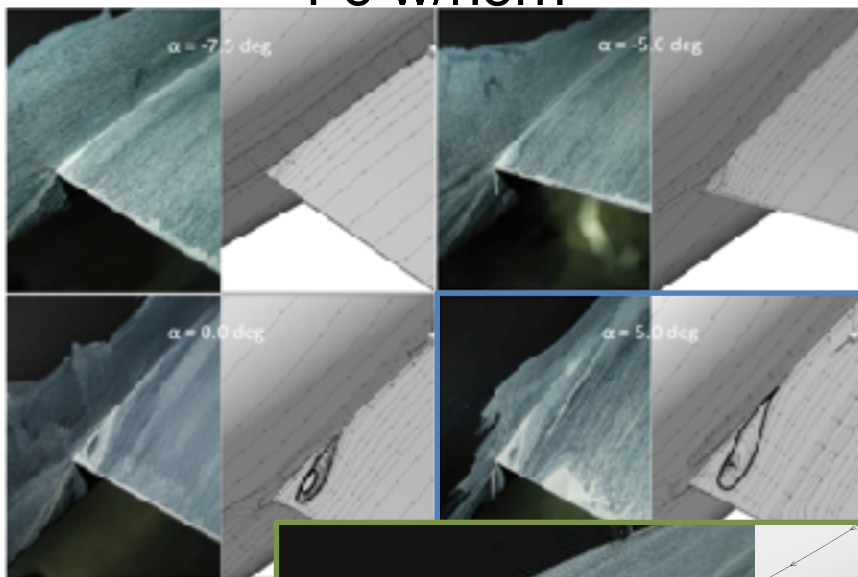


COCA w/horn

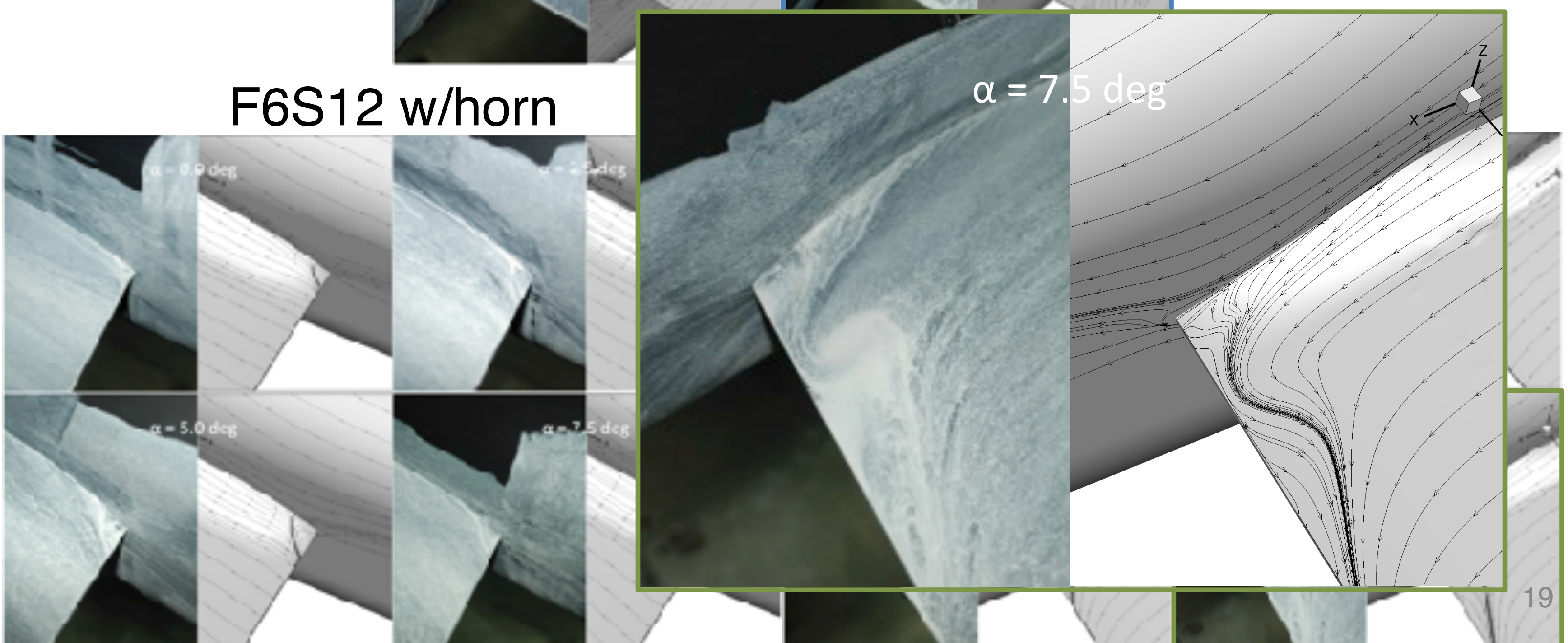


VT Tunnel Risk Reduction

F6 w/horn

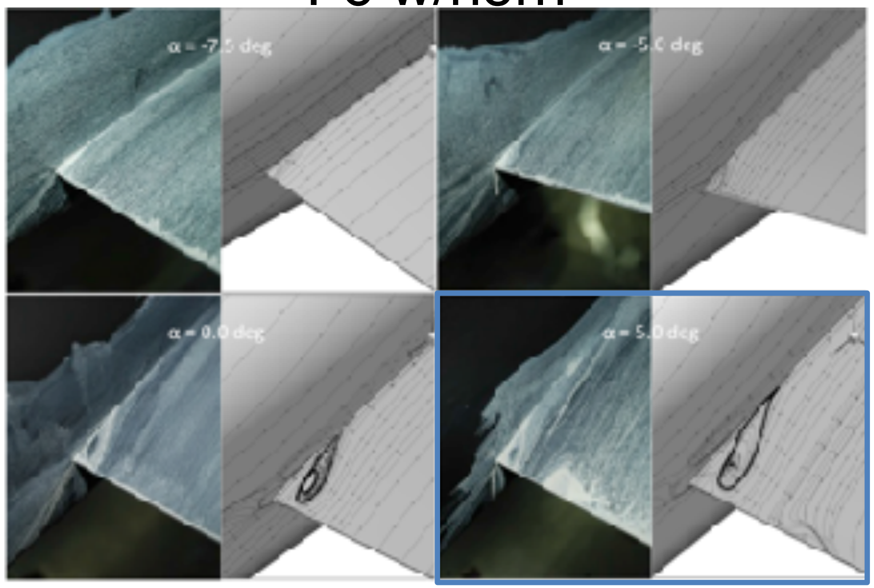


F6S12 w/horn

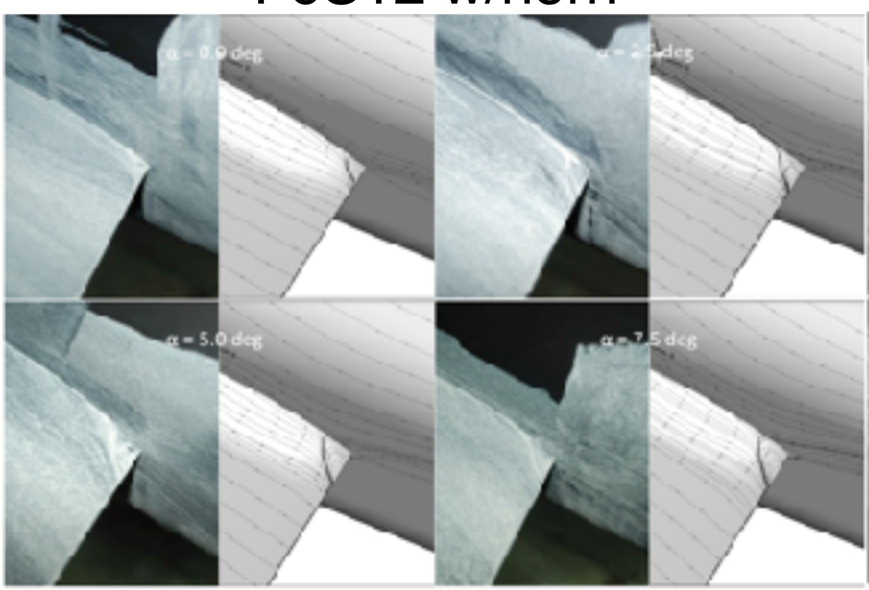


VT Tunnel Risk Reduction

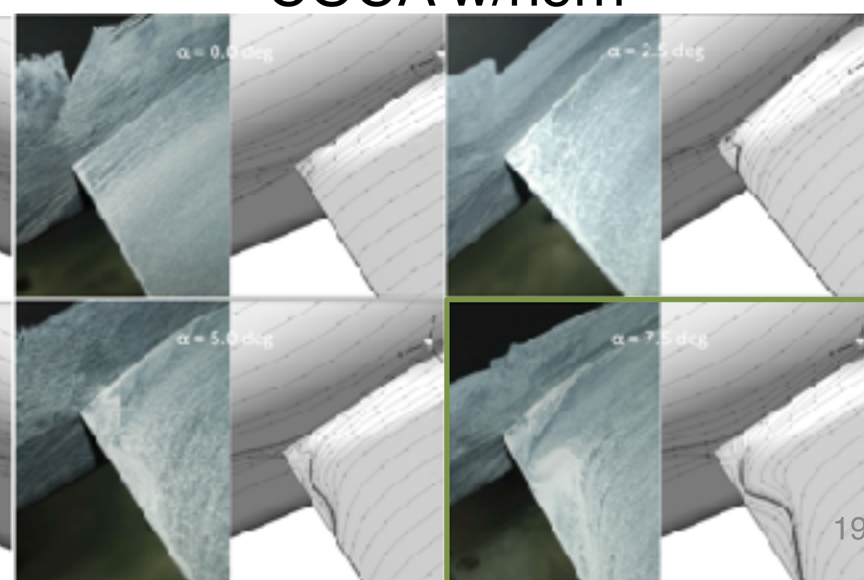
F6 w/horn



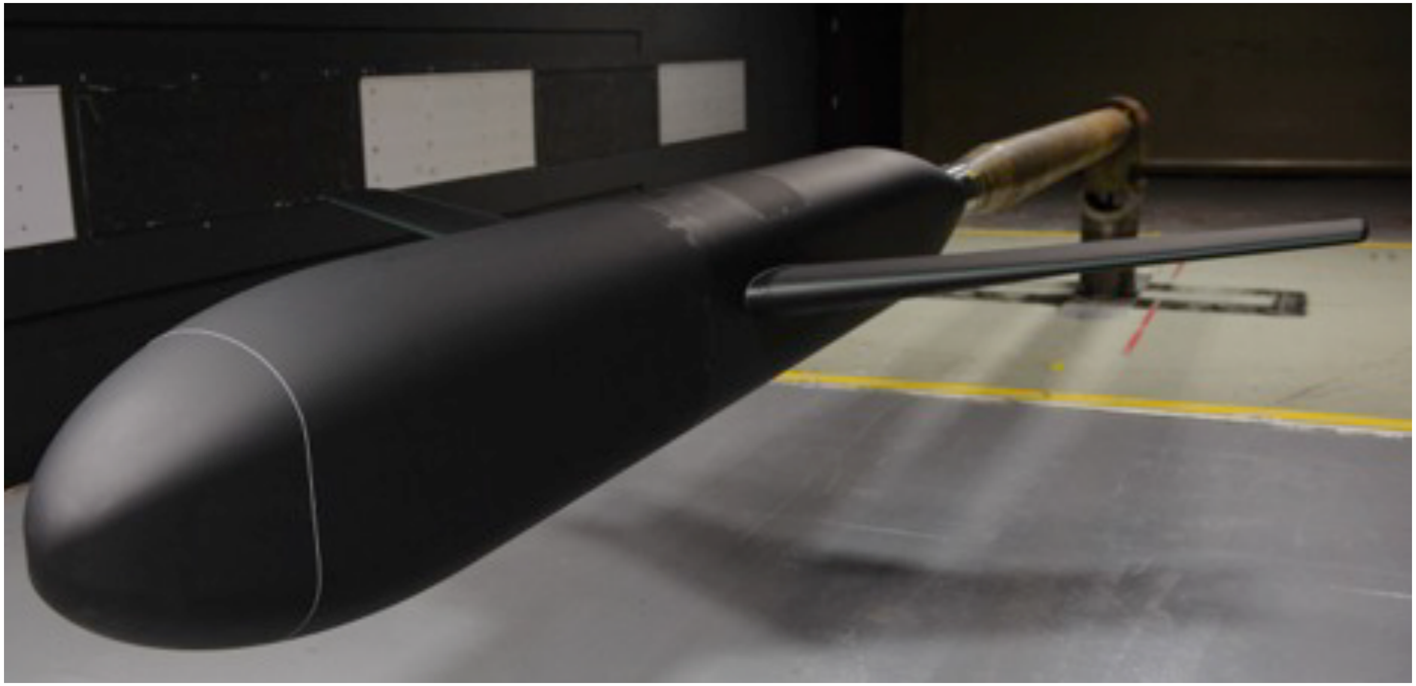
F6S12 w/horn

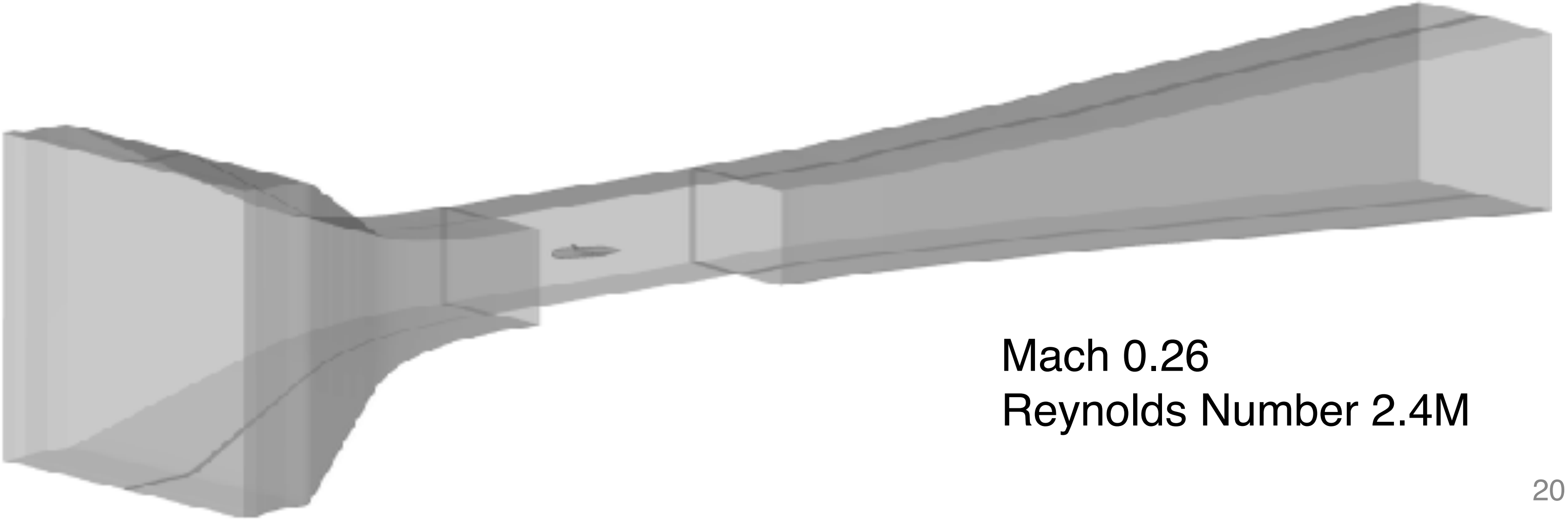


COCA w/horn



14x22 6% Risk Reduction Test





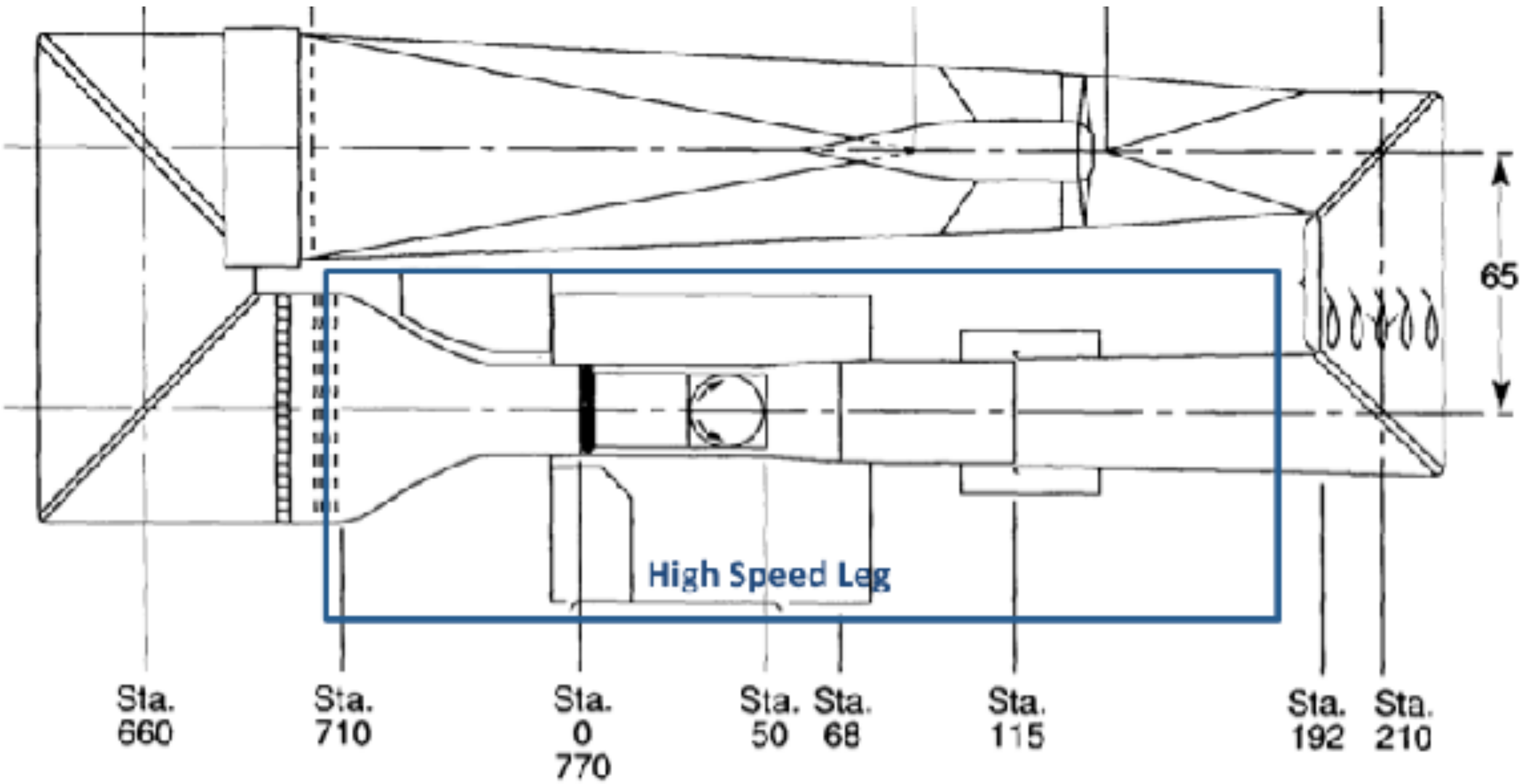
Mach 0.26
Reynolds Number 2.4M

14x22 6% Risk Reduction Setup

- Three data sources
  - Experiment
  - CFD in Free Air
  - CFD with 14x22 wind tunnel walls
- Comparisons: oil flow vs streamlines
- Additional results for $\alpha =$ -10.0 — 10.0 degrees in paper
- Additional experimental results in NASA TM–219348

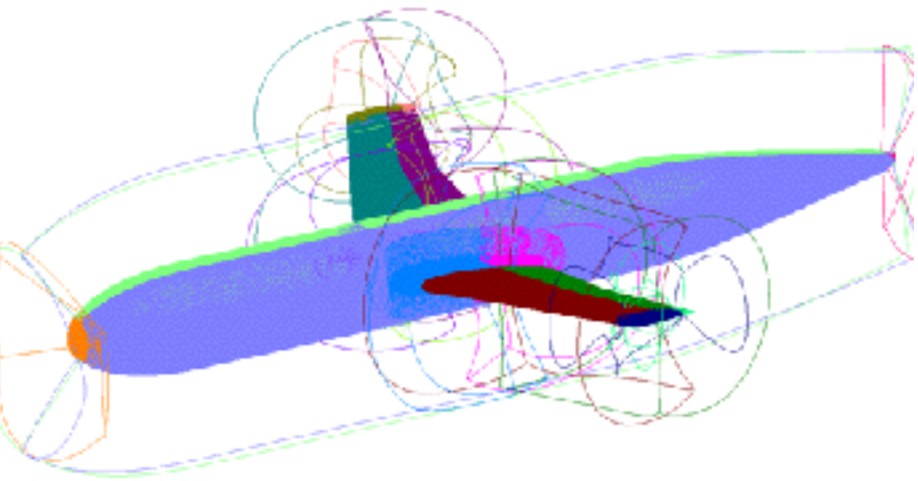
NASA Langley 14- by 22-Foot Subsonic Tunnel

- 14.5 ft high by 21.75 ft wide test section
- Closed-circuit wind tunnel
- Blue box represents high speed leg
- RE = 2.4 million, Mach 0.26

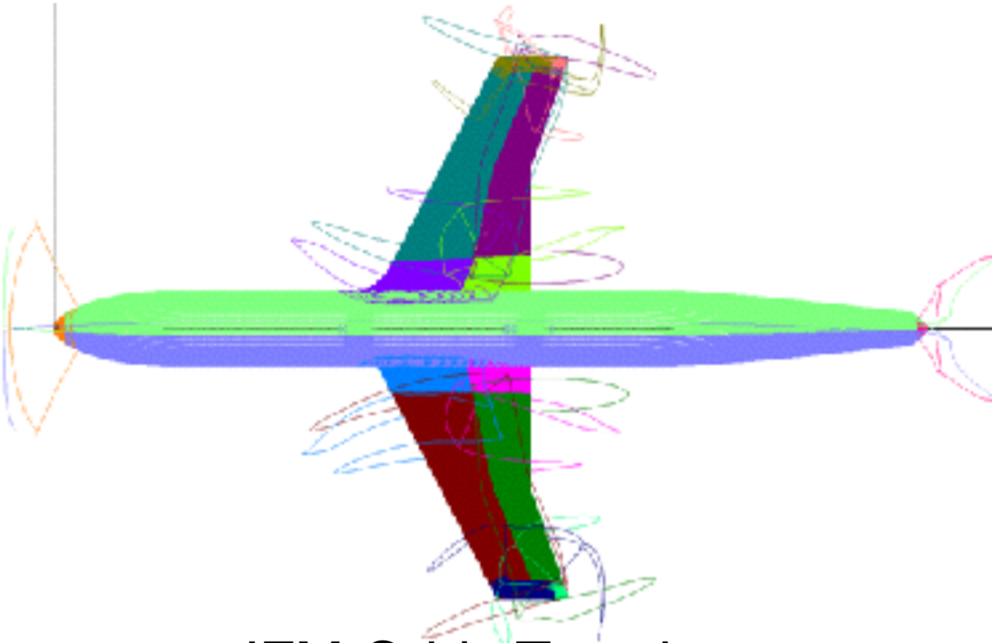


Juncture Flow Model Grids

- Grids created based on best practices, as defined by AIAA workshops (DPW, HiLift, etc)
- Grid resolution study was performed early on to establish grid guidelines for all cases



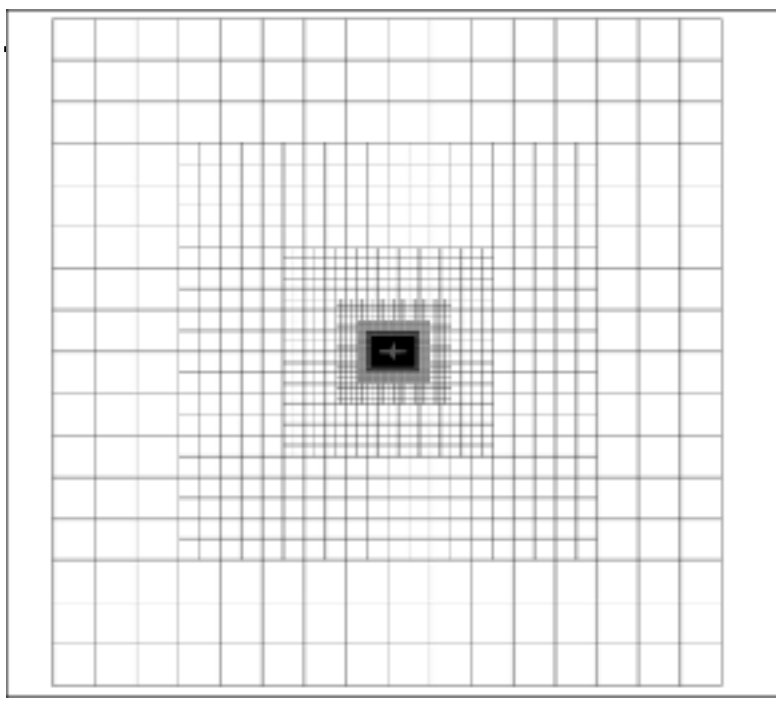
JFM Grids ISO-view

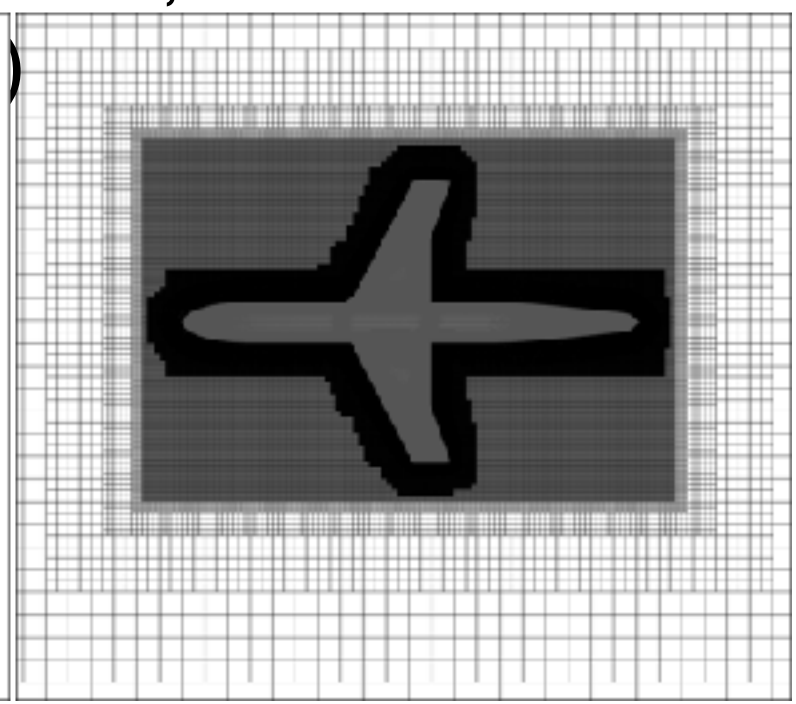


JFM Grids Top-view

JFM Free Air Cases

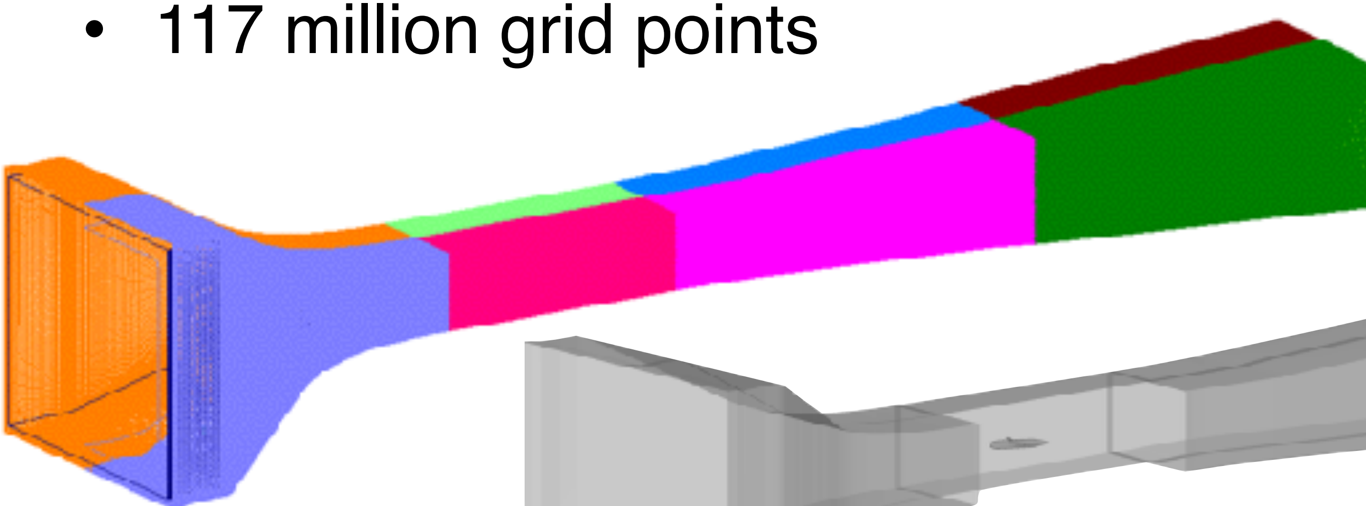
- JFM grids, imbedded in Overflow's off body grids
- Fairfield at 100 chord lengths away
- 108 Million grid points
- 420 Intel Broadwell cores, 12 hours wall



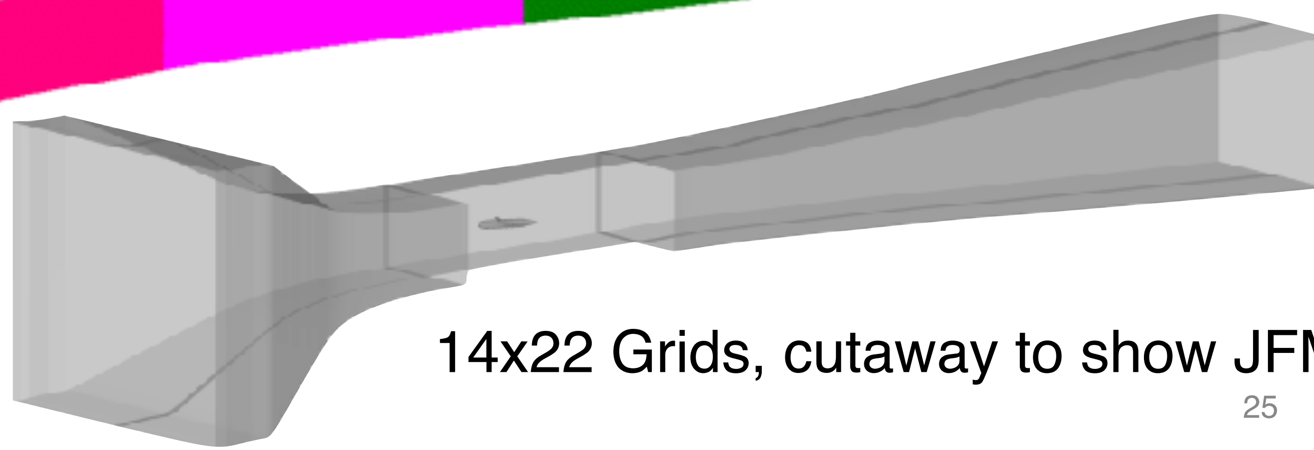


JFM Wind Tunnel Cases

- JFM grids, installed in the 14x22 wind tunnel grids
- Inflow BC: Stagnation pressure/temperature
- Outflow BC: Back pressure iterated to match tunnel speed.
- 1200 Intel Ivy Bridge cores, 60-120 hours wall time (NASA Pleiades)
- 117 million grid points



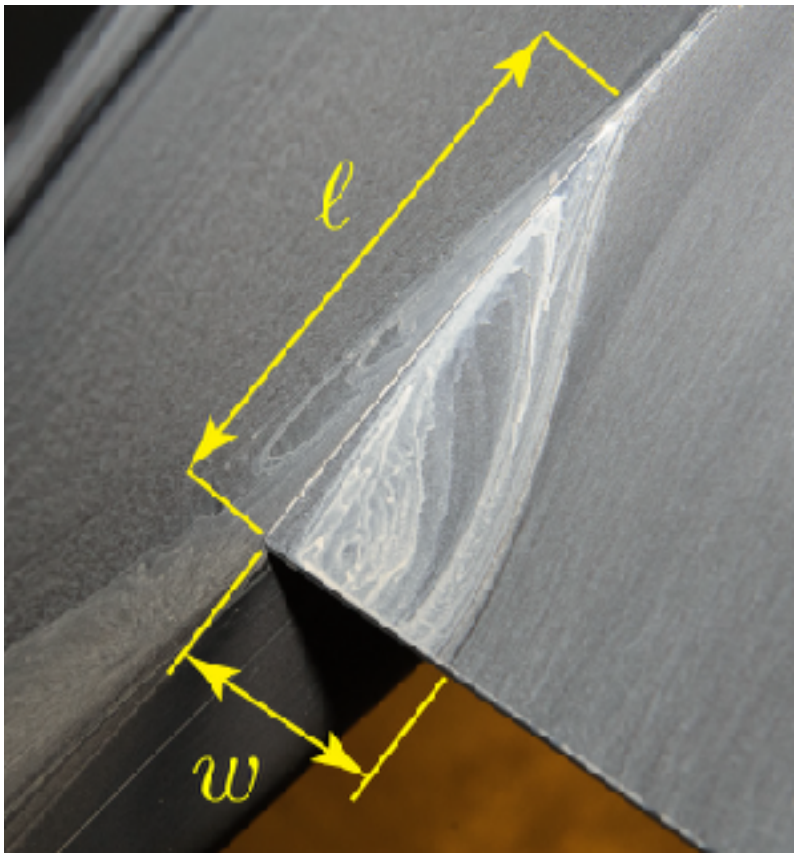
14x22 Grid



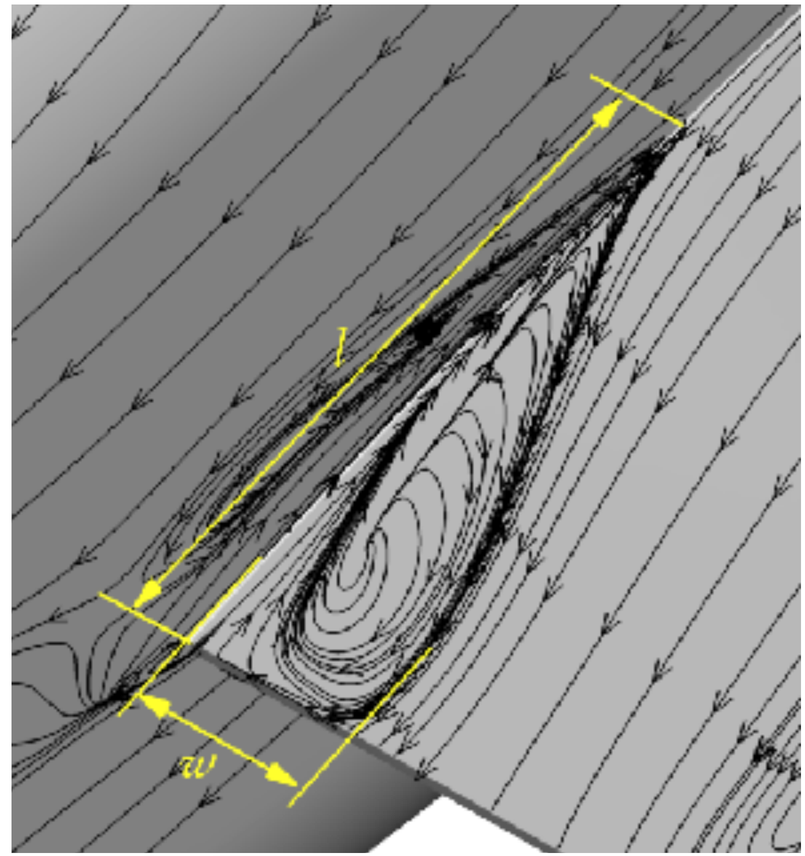
14x22 Grids, cutaway to show JFM

SOB Bubble Size Definitions

Experiment Oil Flow



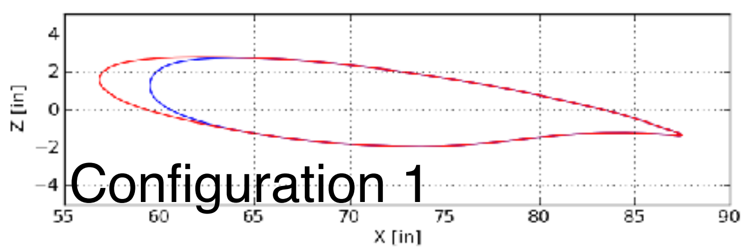
CFD Surface Streamlines

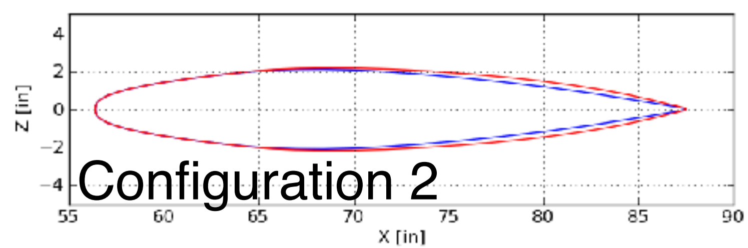


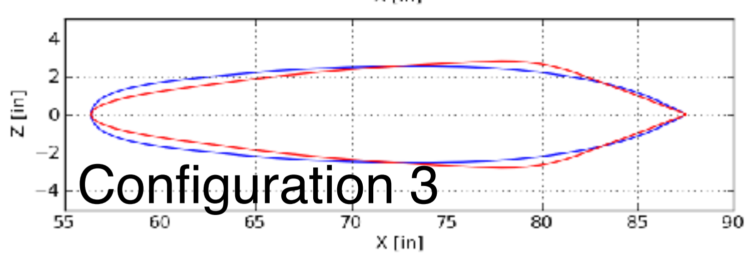
length ***l*** and width ***w*** bubble size definitions

Wing Configurations

Configuration	Port Wing	Starboard Wing	Data
1	F6 no horn	F6 w/horn	Exp, CFD Free Air, CFD WT
2	NACA 0015 w/horn	NACA 0015mod w/horn	Exp, CFD Free Air, CFD WT
3	F6S12 w/horn	COCA w/horn	Exp, CFD Free Air



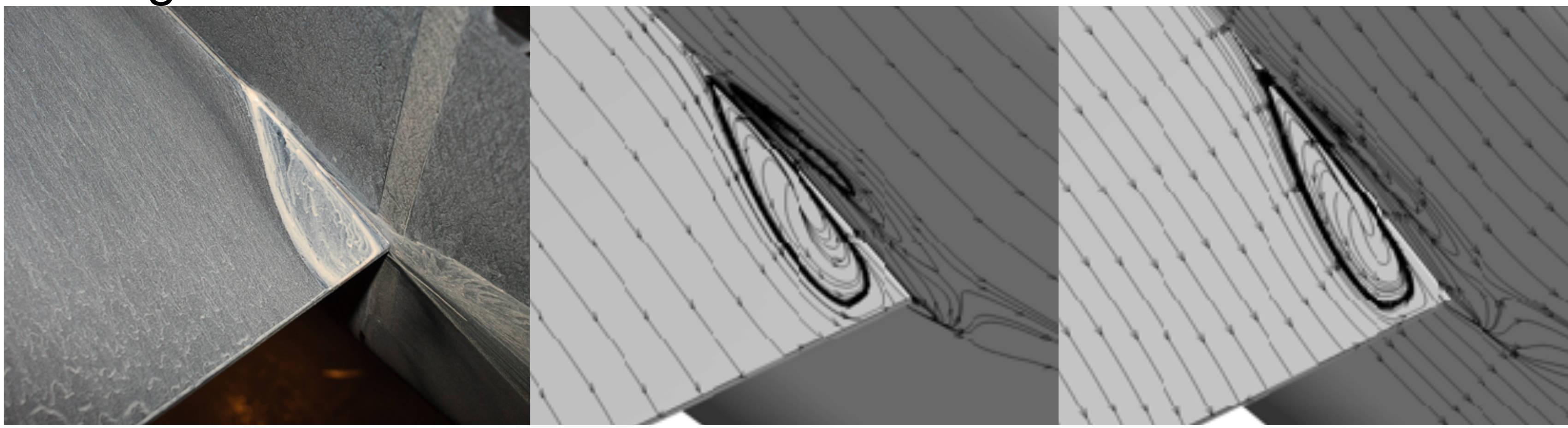




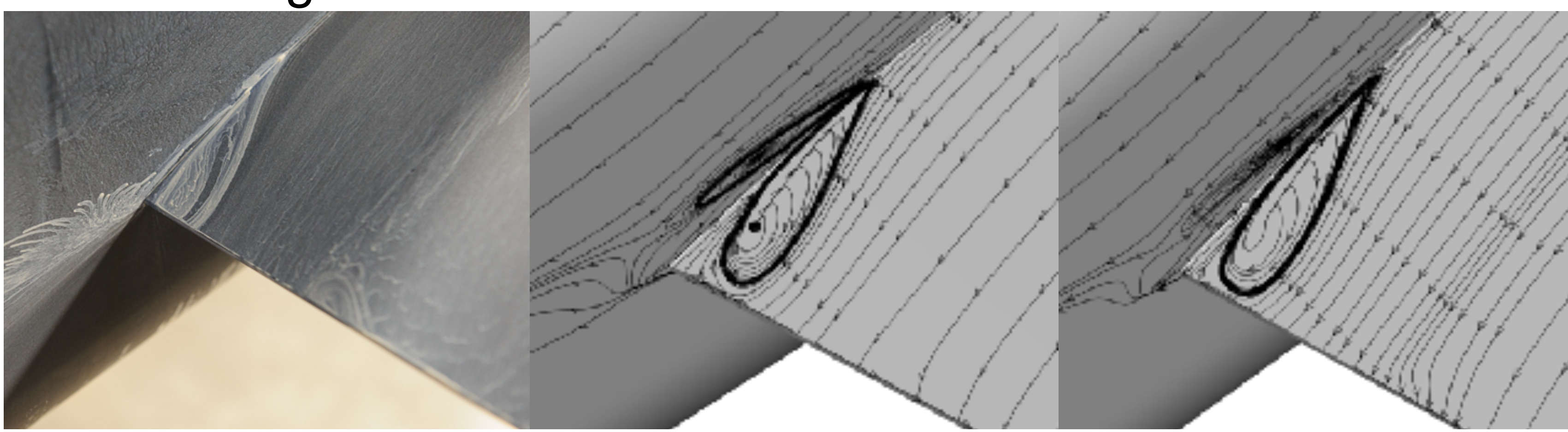
— Port Wing (blue)
— Starboard Wing (red)

Configuration 1: F6 no horn—F6 w/horn, $\alpha=5.0^{o}$

Port Wing: F6 no horn

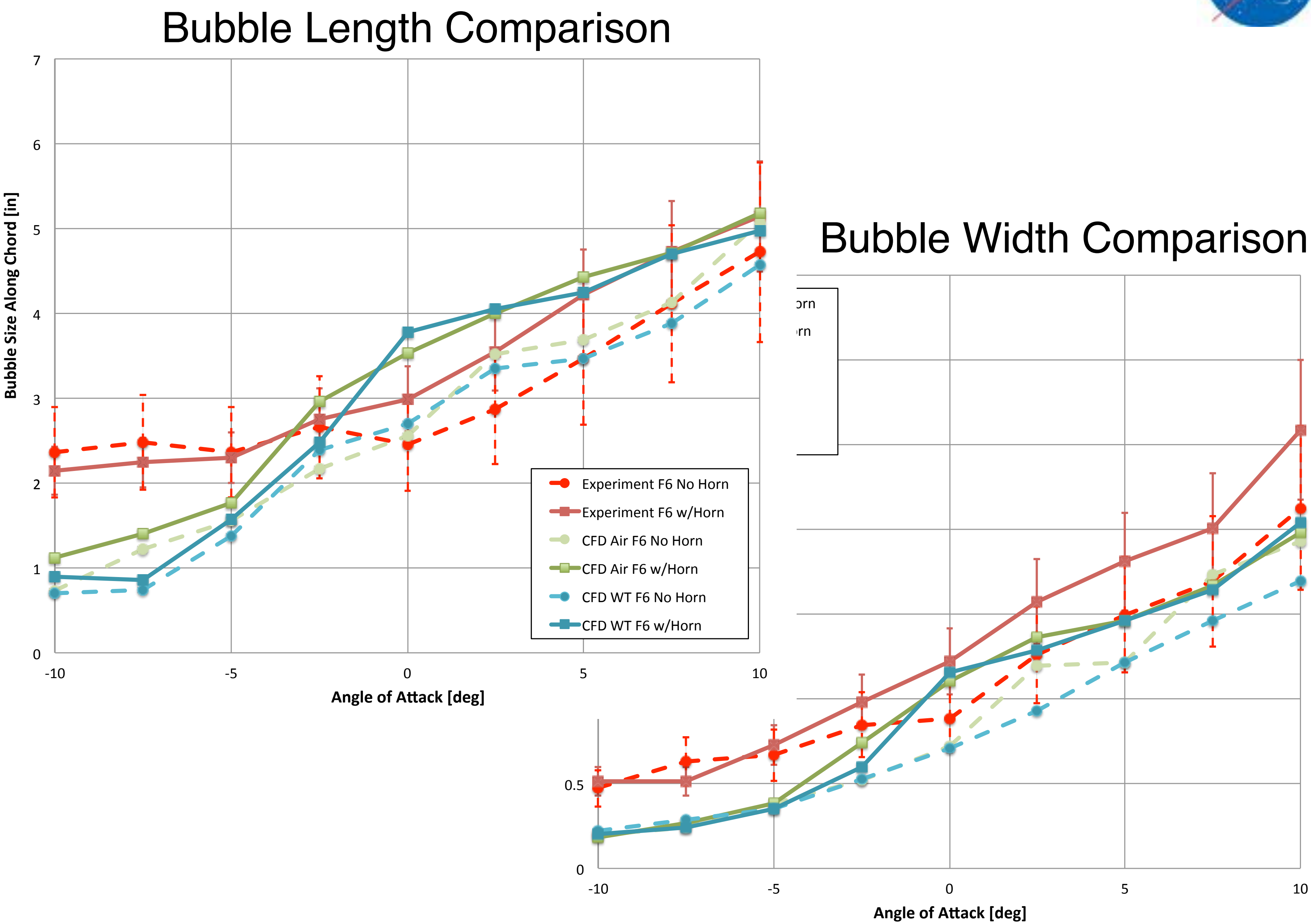


Starboard Wing: F6 w/horn



Experiment | CFD Free Air | CFD WT

Configuration 1: F6 no horn—F6 w/horn



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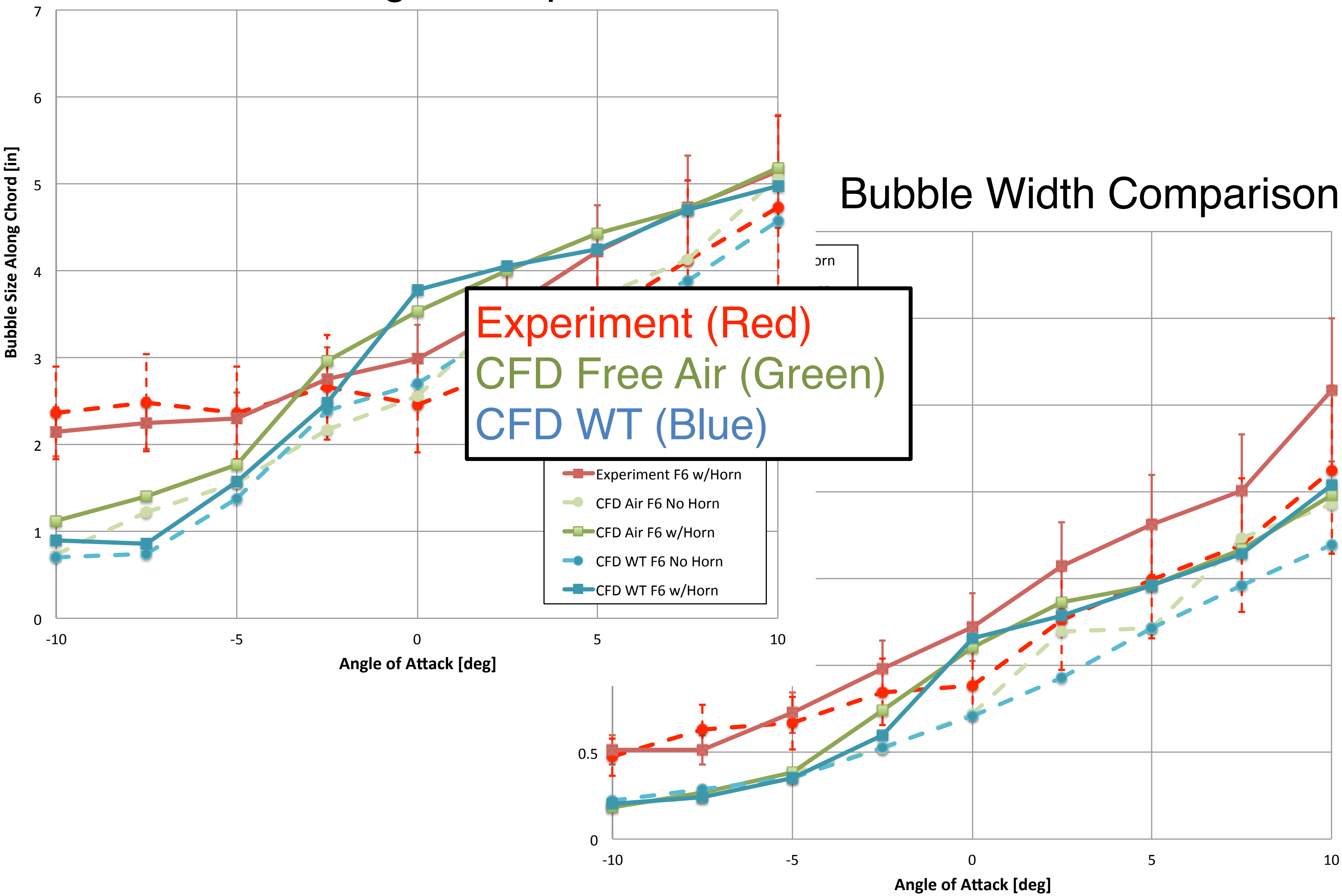
Bubble Length Comparison

Bubble Width Comparison



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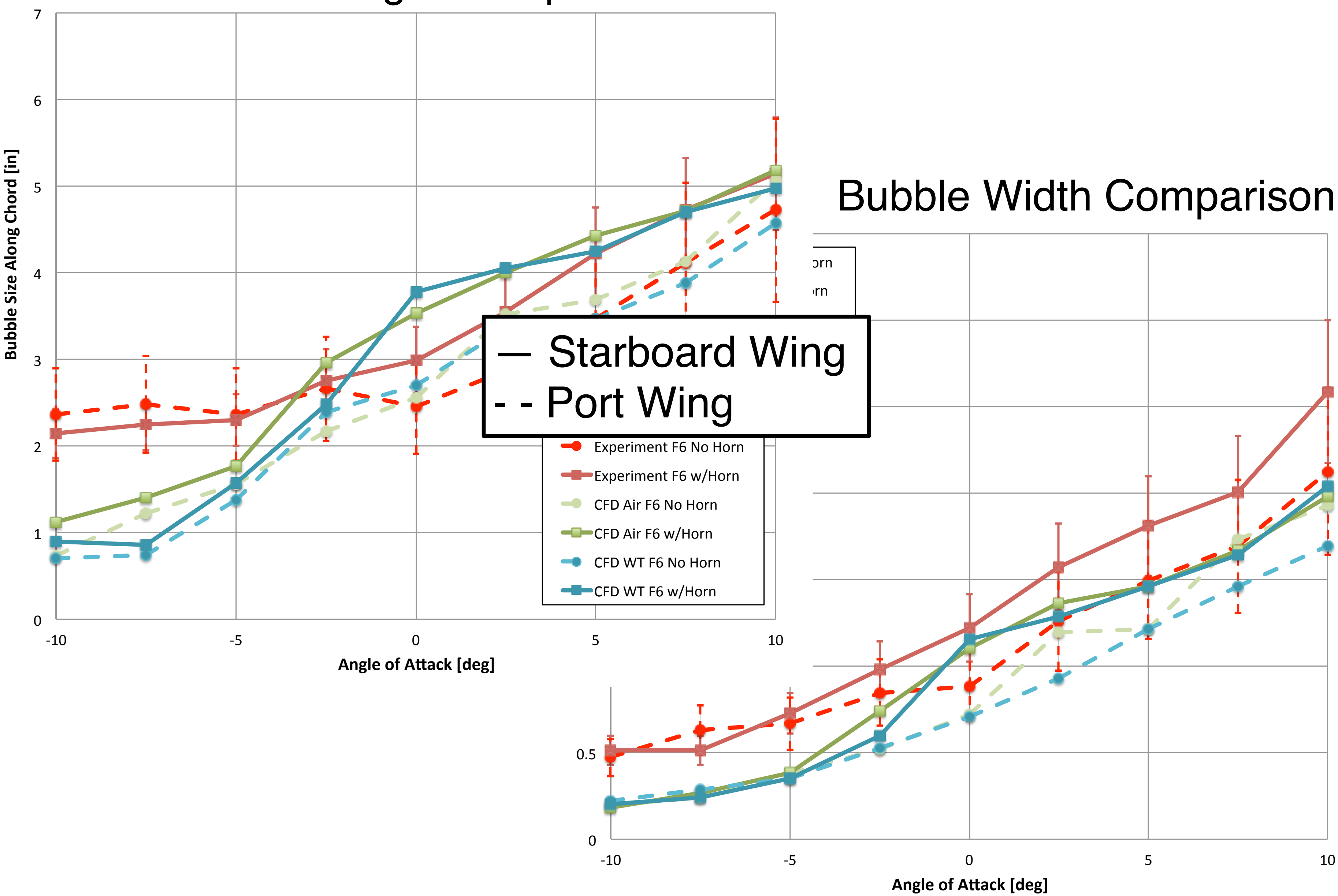

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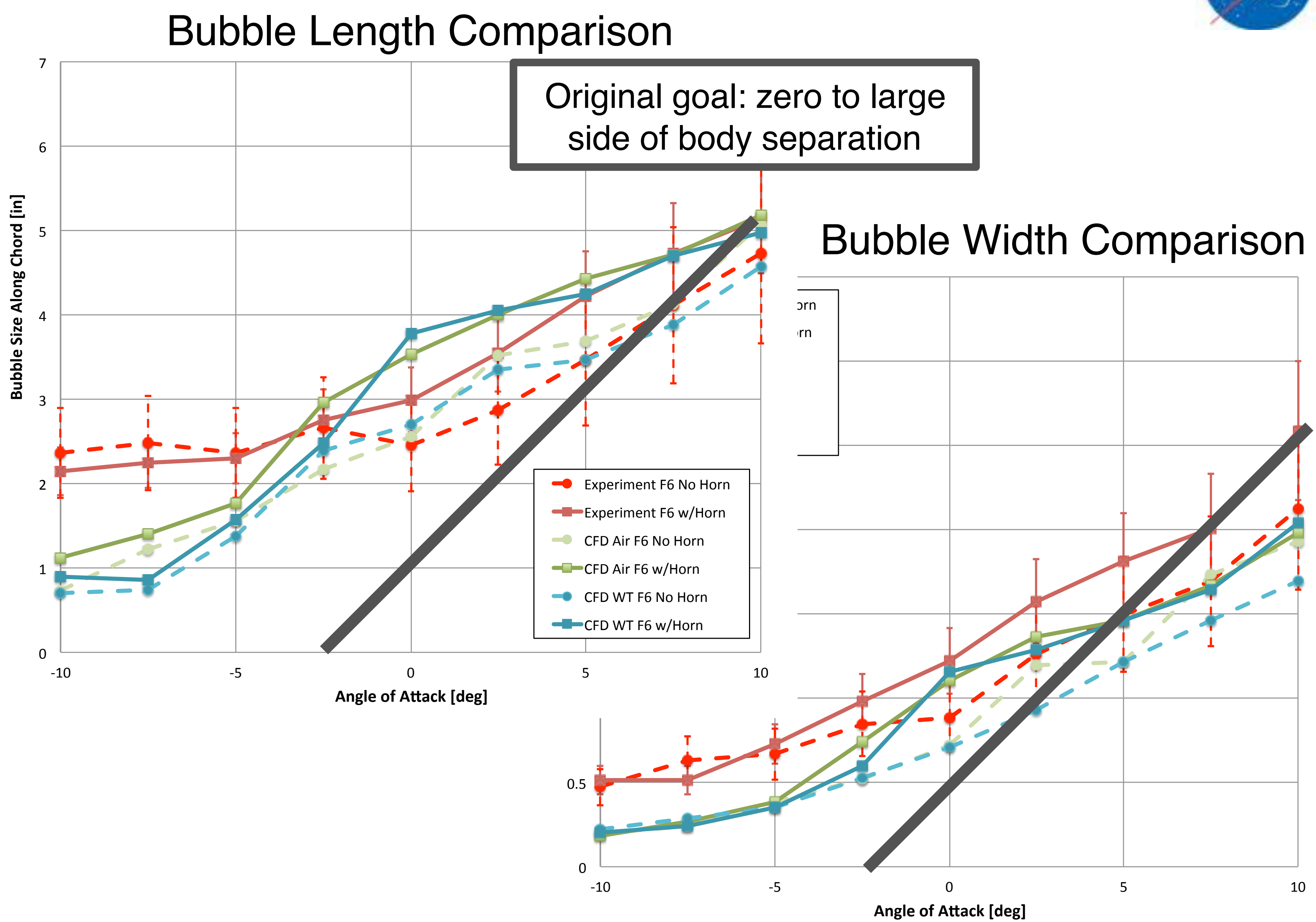

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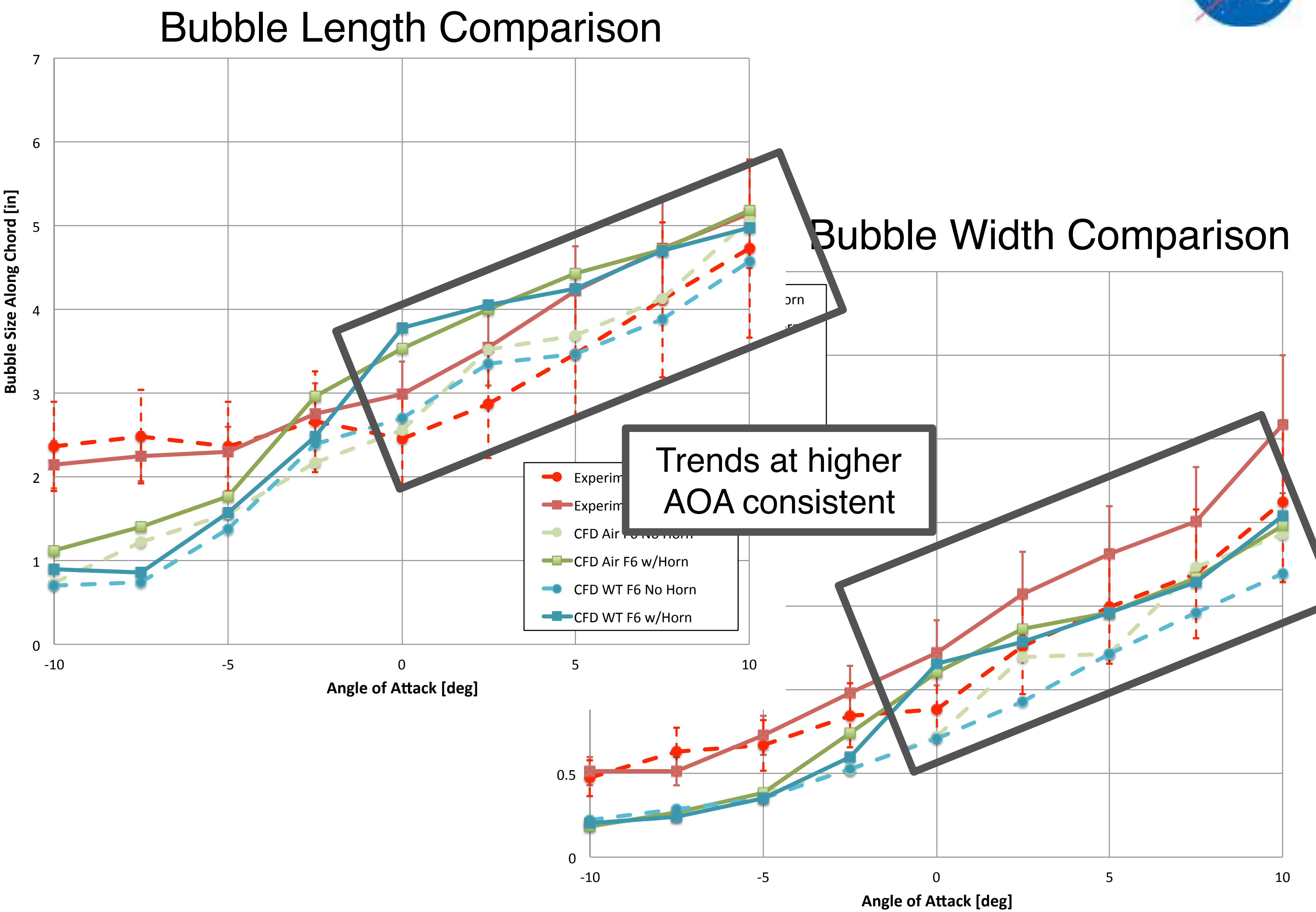

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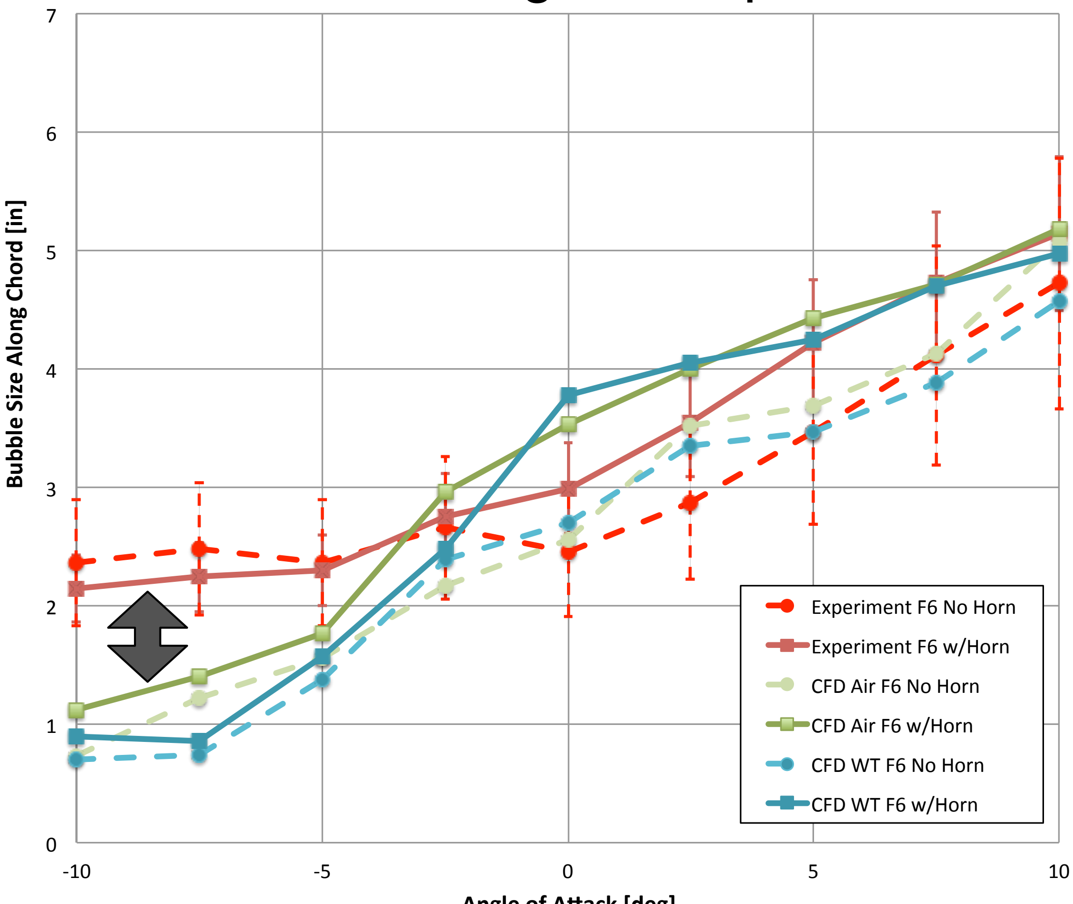

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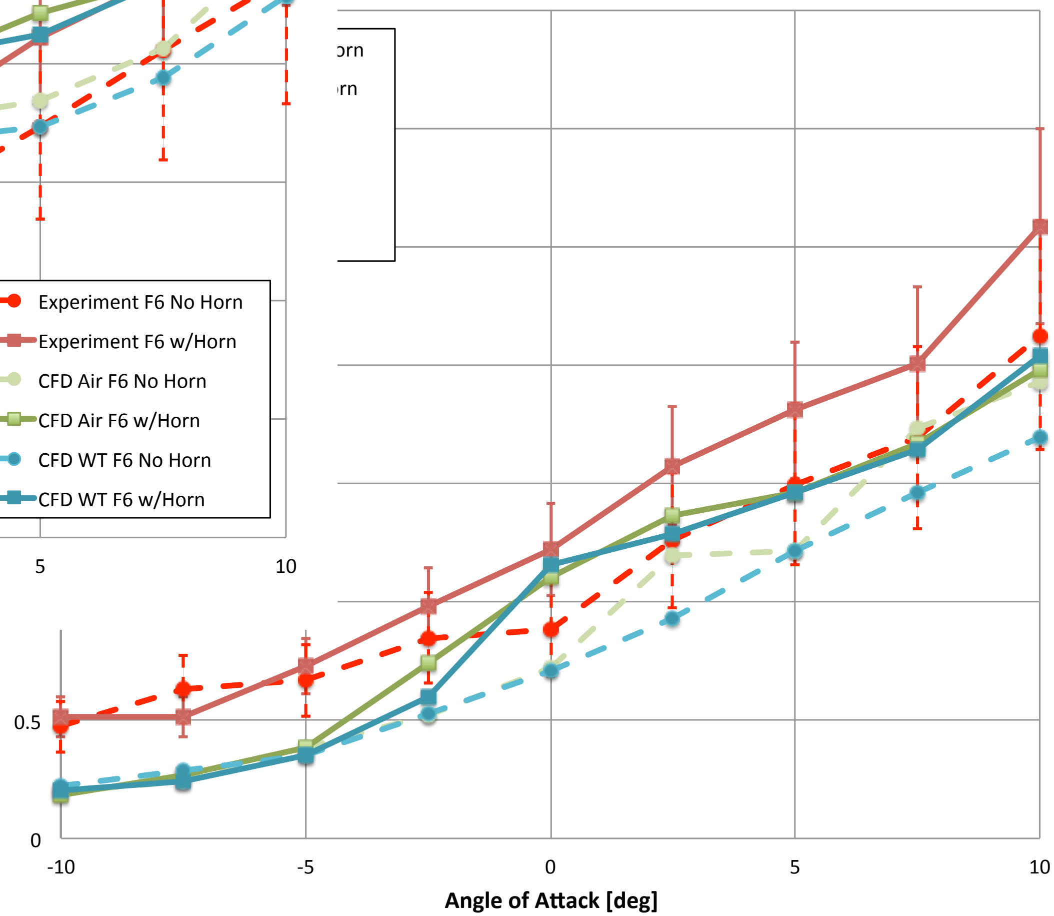
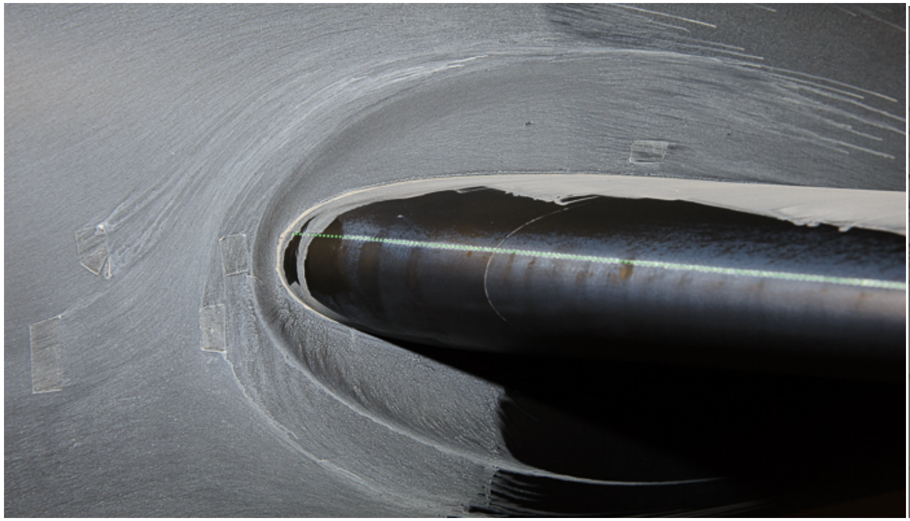
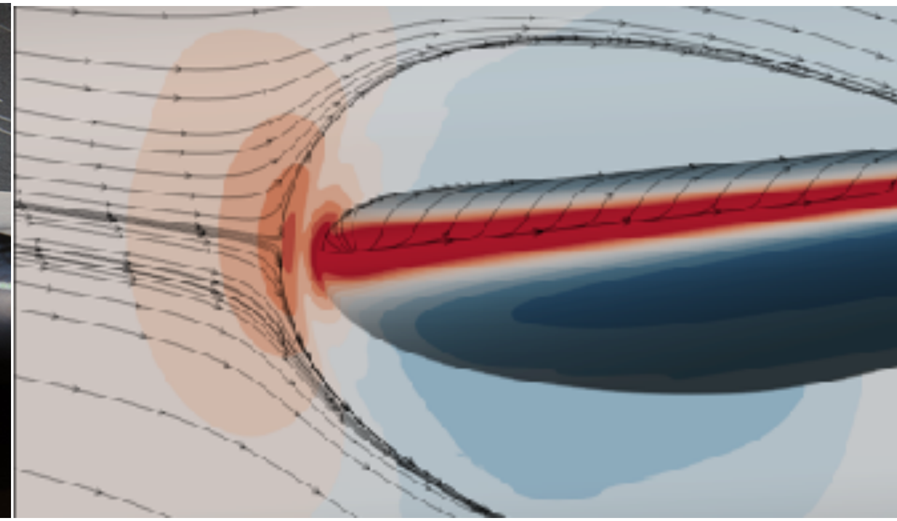


Larger difference between CFD and WT Data at lower AOA. Bubble size doesn't go to zero

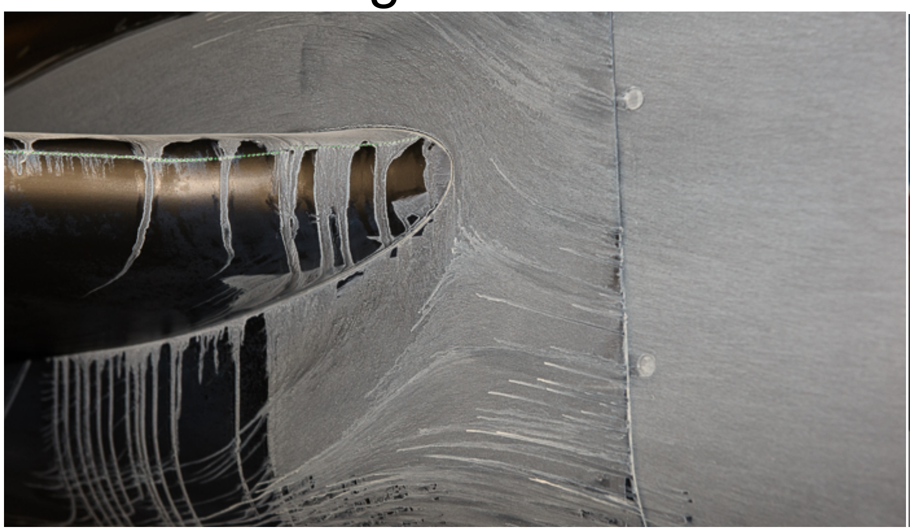
Configuration 1: F6 no horn—F6 w/horn, $\alpha=5.0^o$ LE

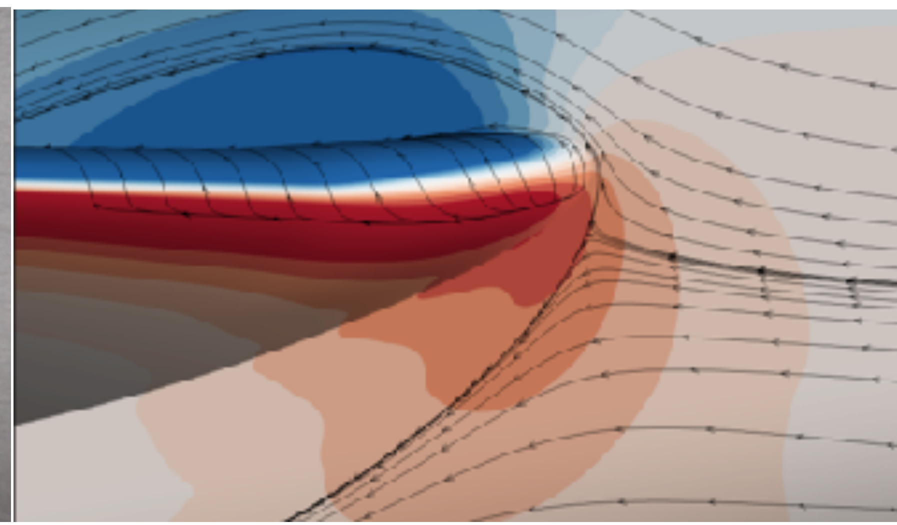
Port Wing: F6 no horn





Starboard Wing: F6 w/horn



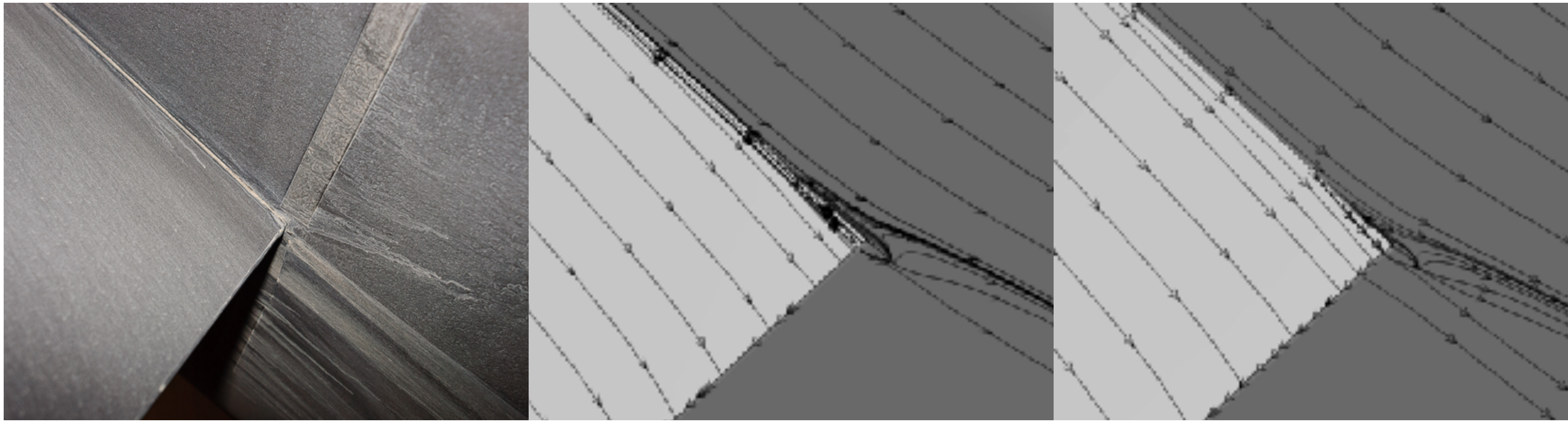


Experiment

CFD WT

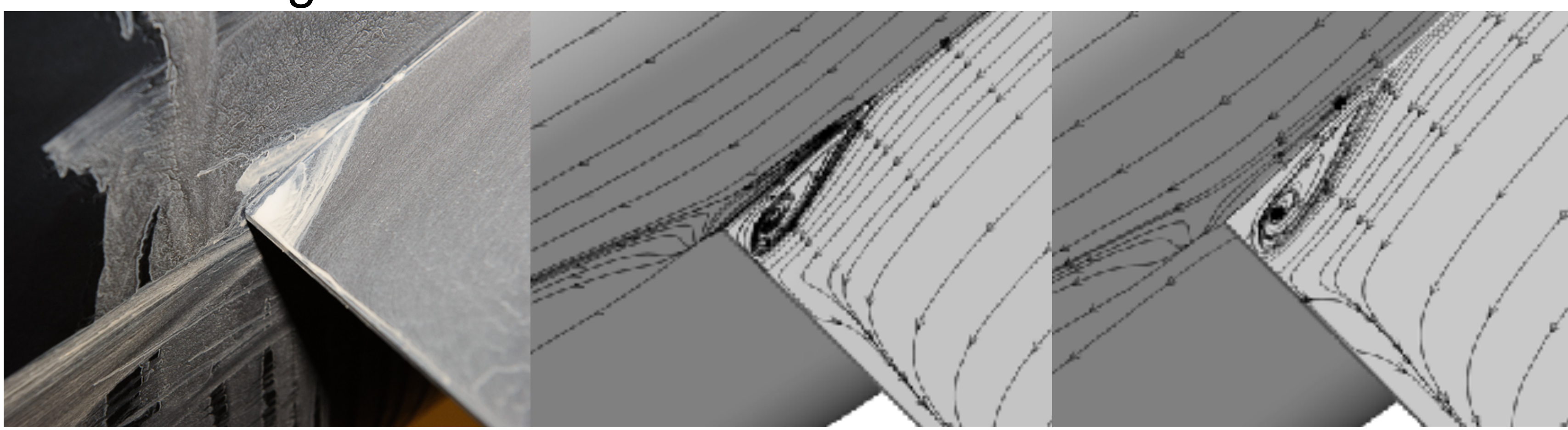
Configuration 2: NACA 0015—NACA 0015mod, $\alpha=5.0^o$

Port Wing: NACA 0015 w/horn



*Was run without horn

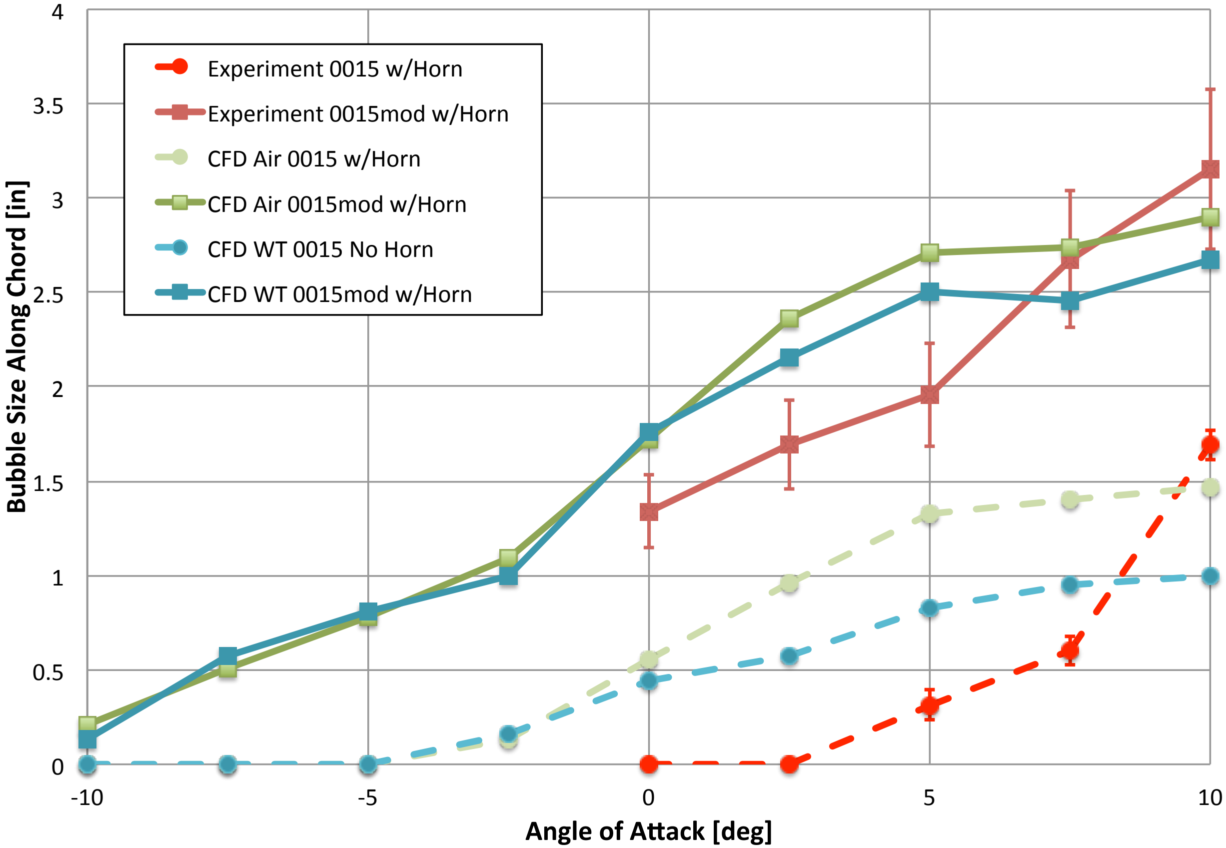
Starboard Wing: NACA 0015mod w/horn



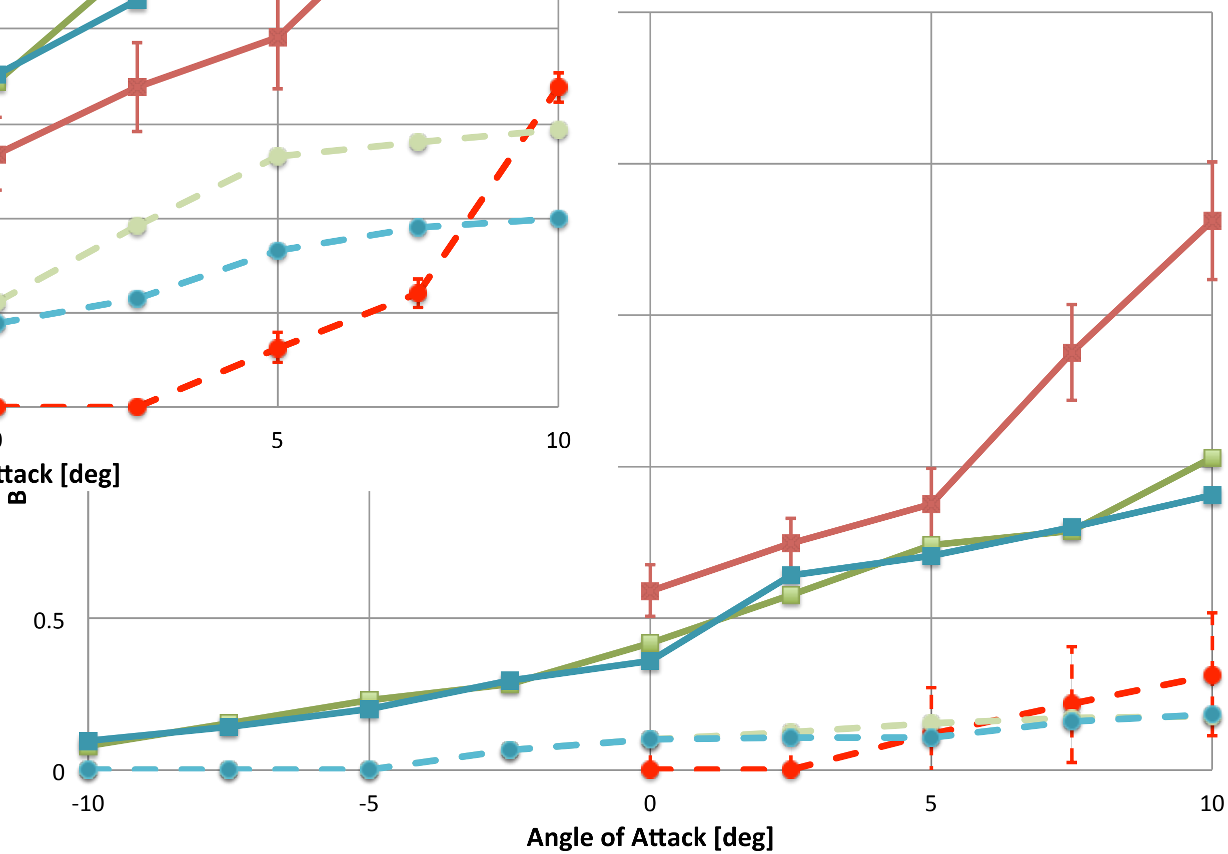
Experiment | CFD Free Air | CFD WT

Configuration 2: NACA0015—NACA0015mod

Bubble Length Comparison



Bubble Width Comparison



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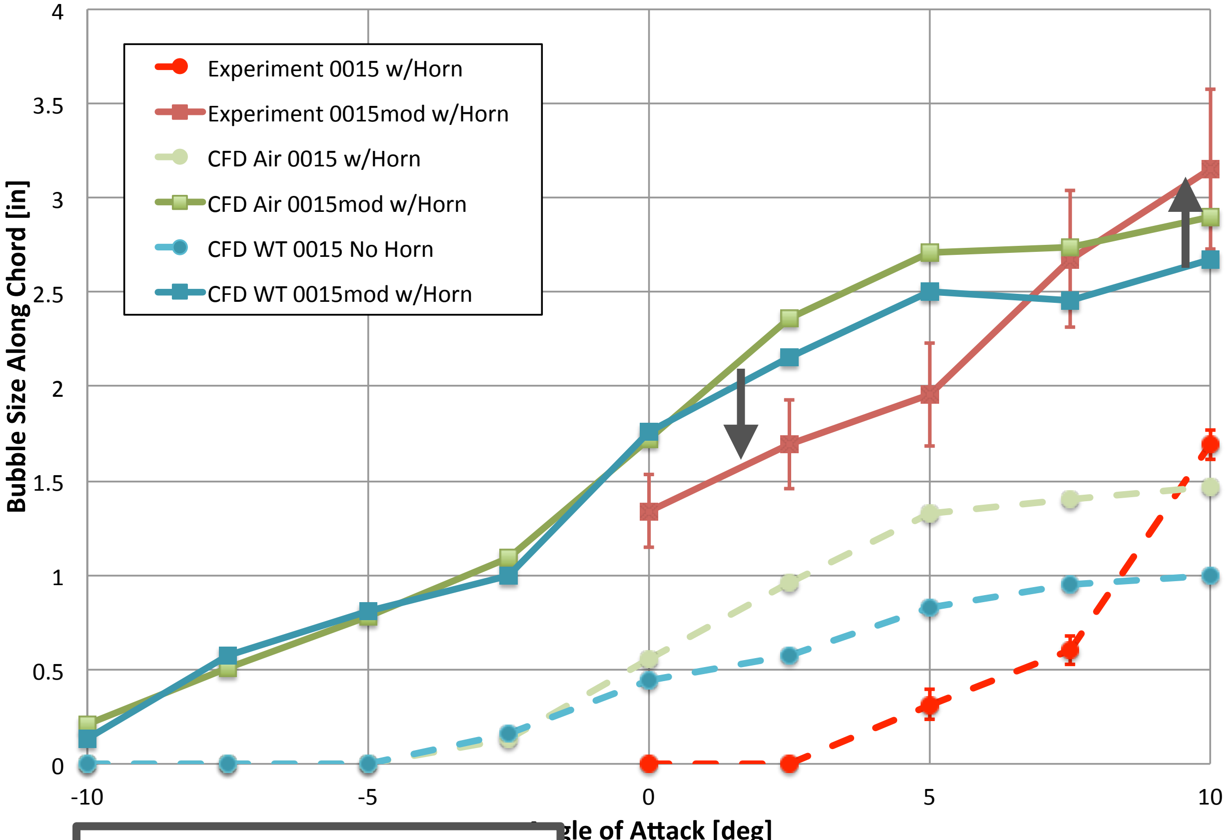
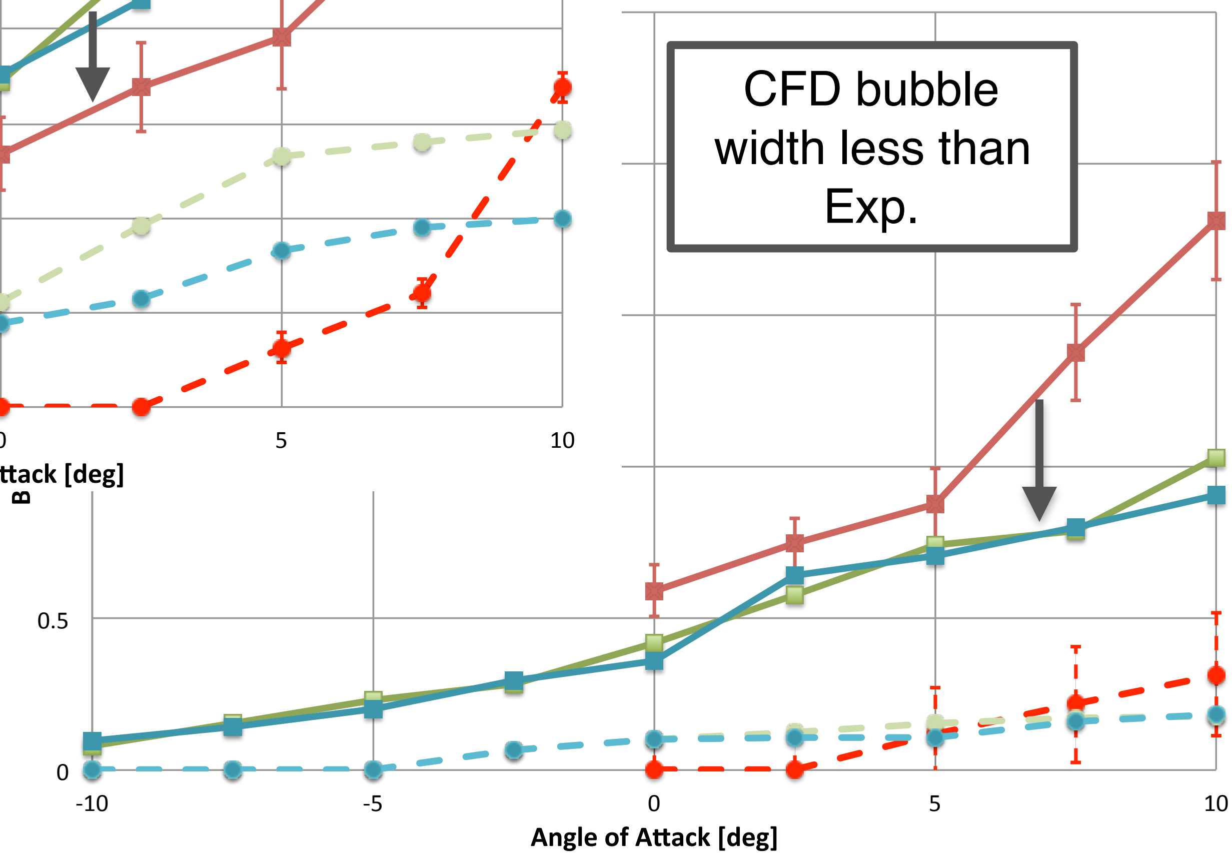


CFD Bubble Length slightly longer than Exp. at lower alpha, under predicts at high alpha

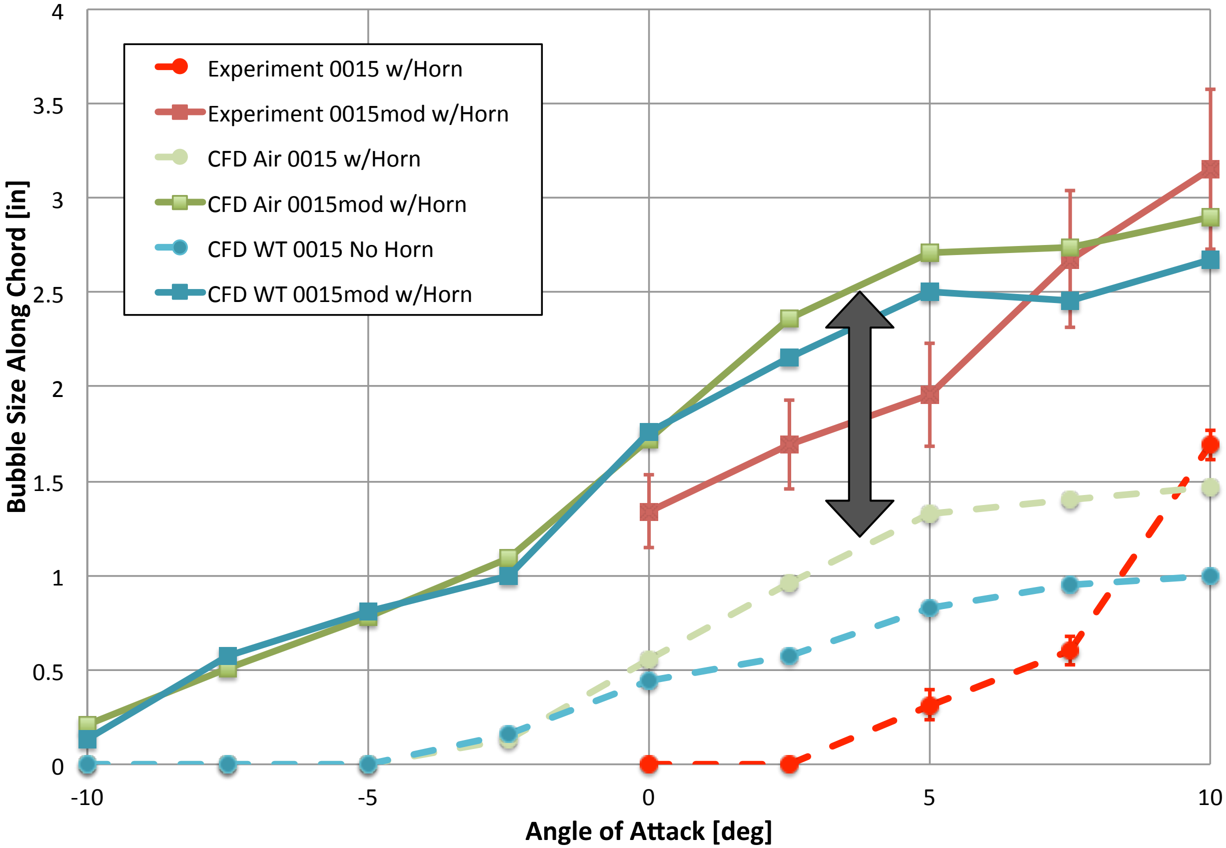
Bubble Width Comparison



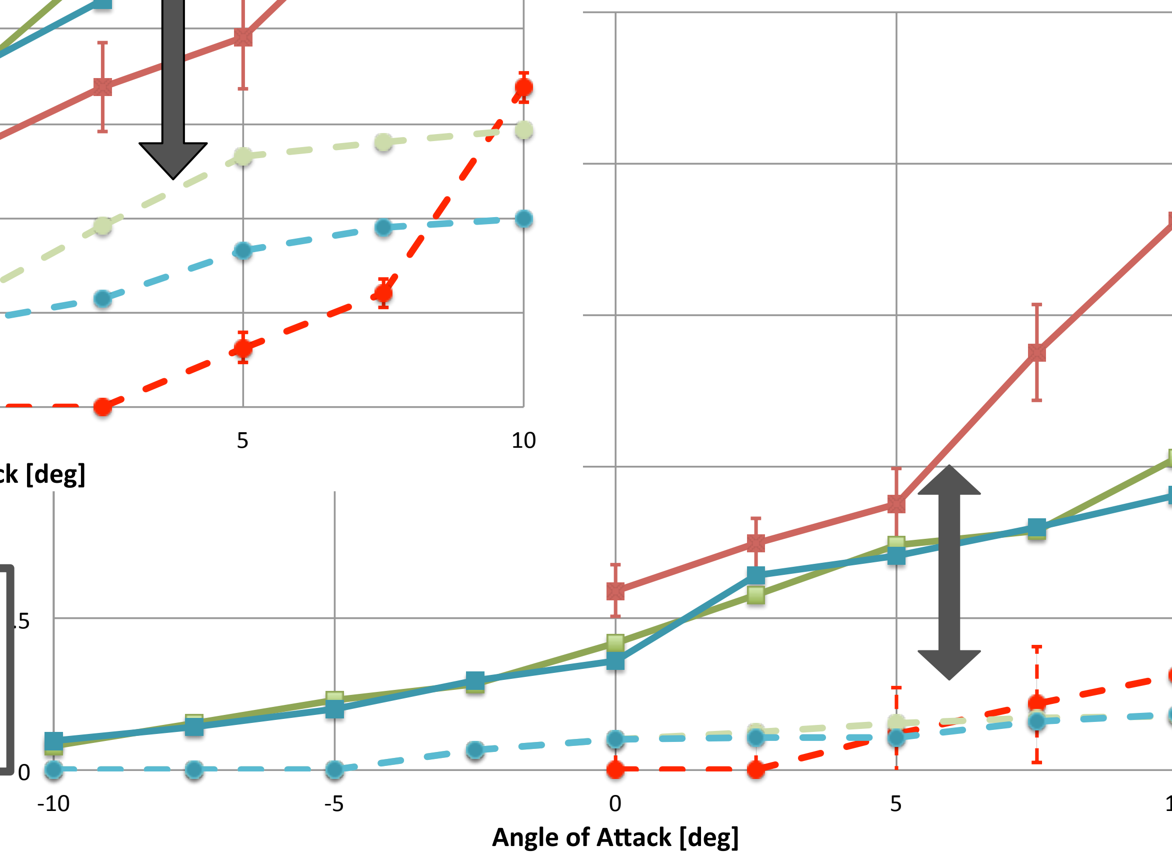
CFD bubble width less than Exp.

Configuration 2: NACA0015—NACA0015mod

Bubble Length Comparison



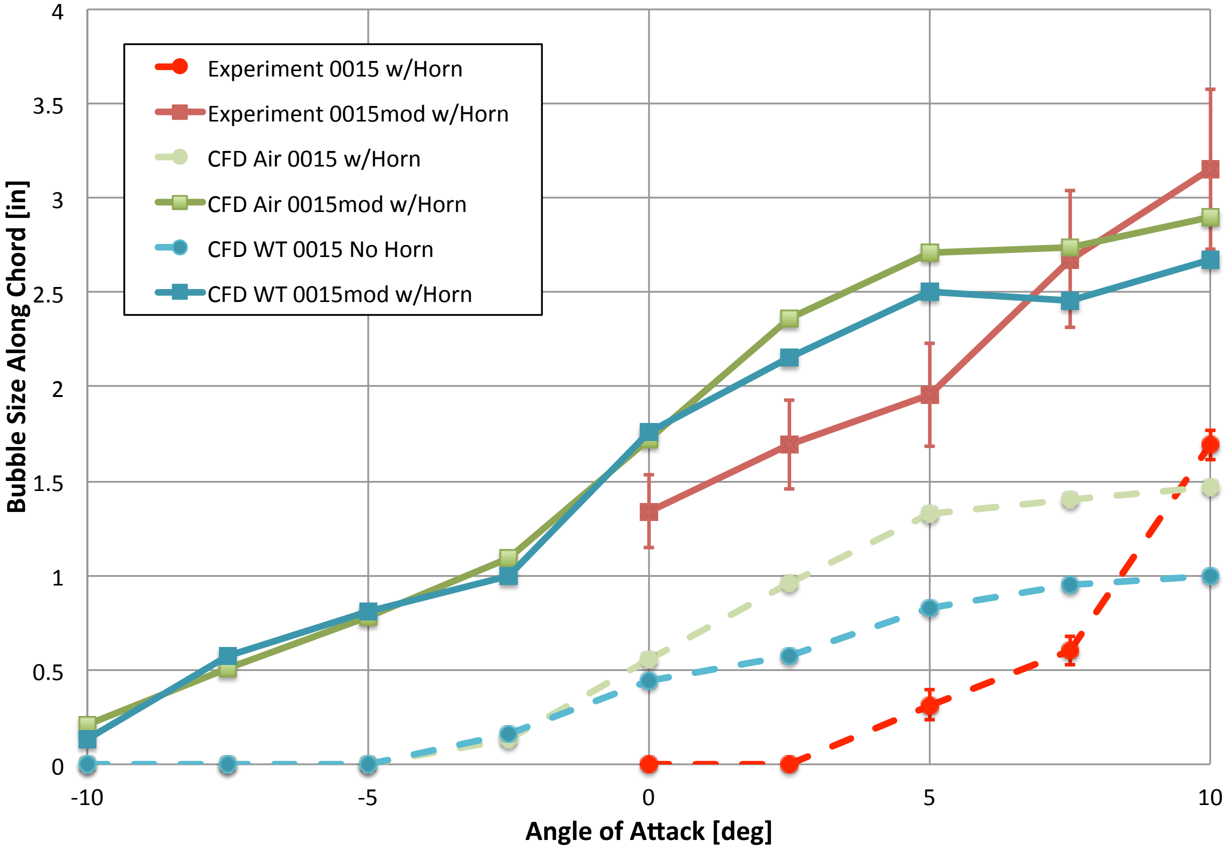
Bubble Width Comparison



Increment between 0015 vs 0015mod wing consistent

Configuration 2: NACA0015—NACA0015mod

Bubble Length Comparison



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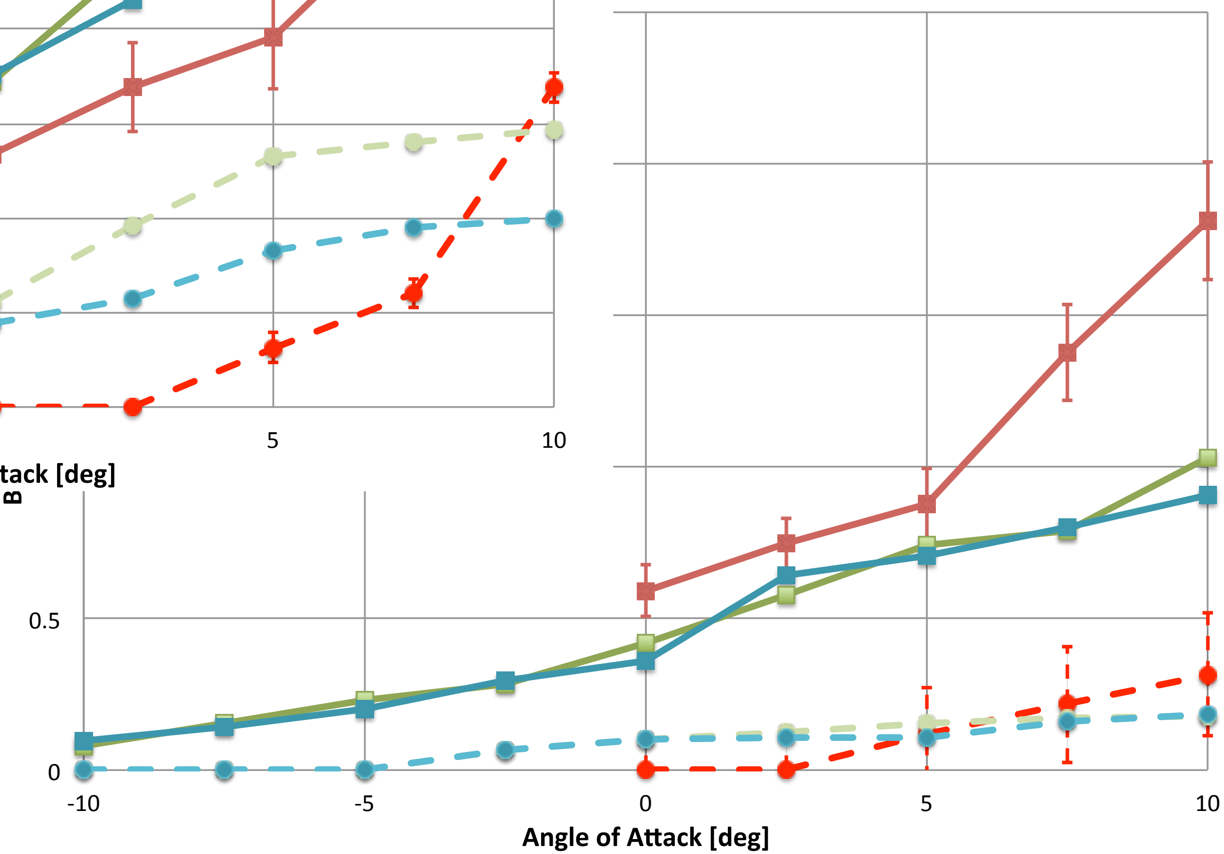

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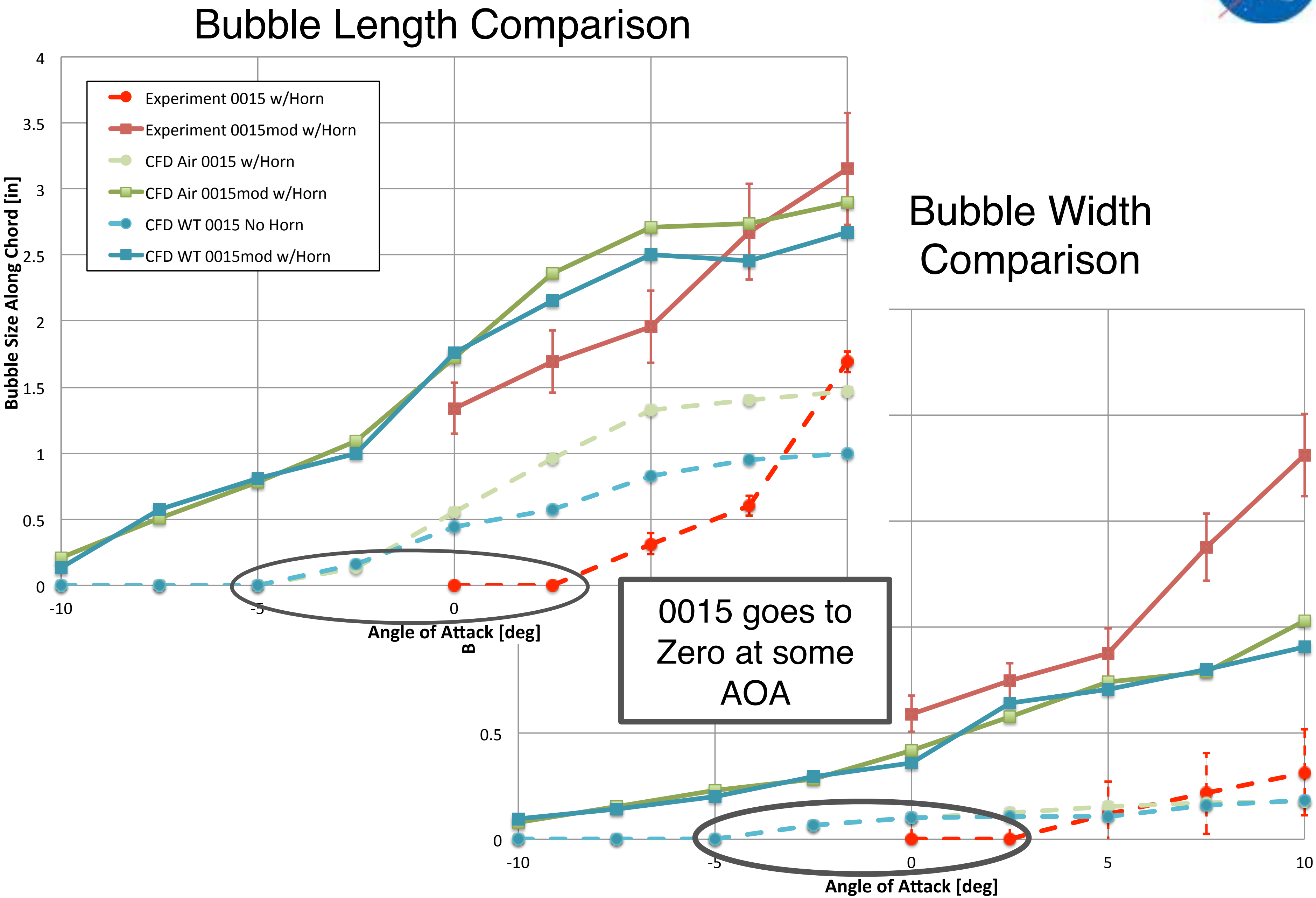
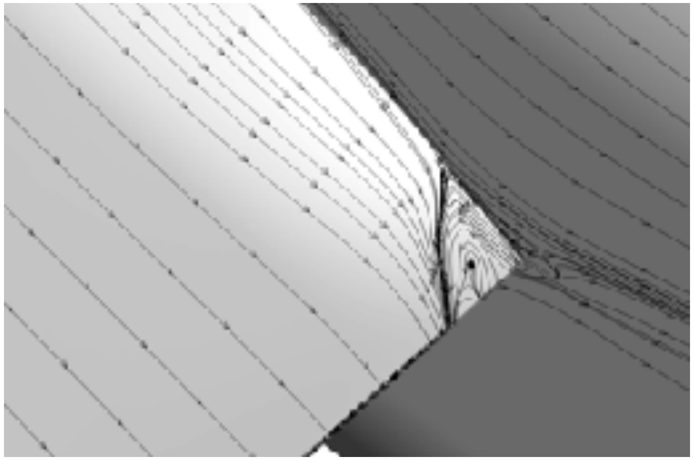
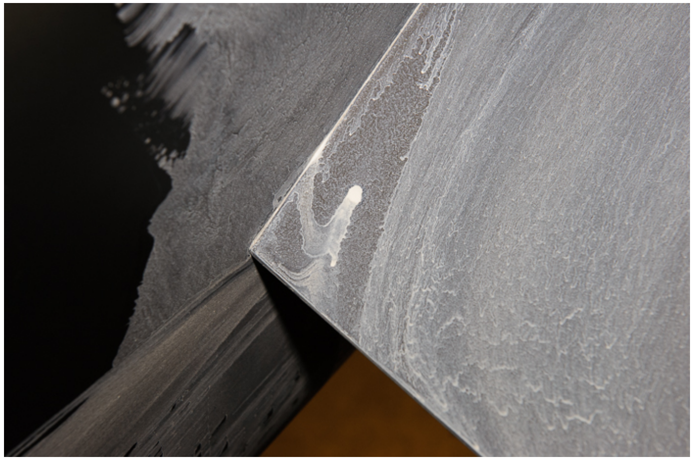
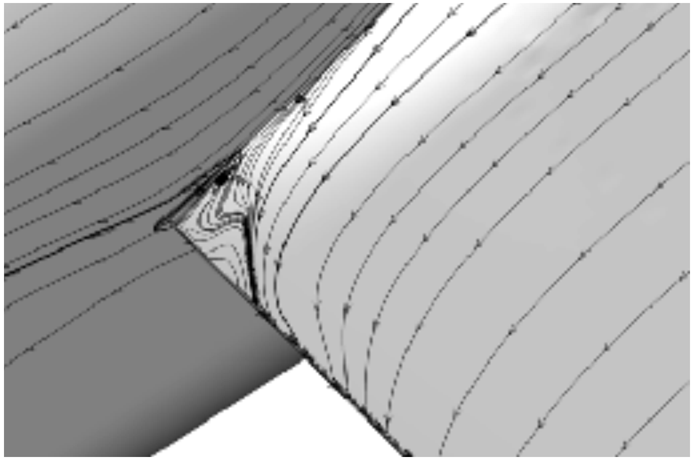


Configuration 3: F6S12—COCA, α=5.0°

Port Wing: F6S12 w/horn

Starboard Wing: COCA w/horn

Experiment CFD Free Air

Wing Evaluations

- Trends between CFD and Experiment are very good

- F6 showed medium to large side of body separations
- NACA 0015 showed none to small separation
- NACA 0015mod showed small to medium separation
- COCA wing and F6S12 ruled out
- LE-horn indicates smaller LE horseshoe vortex

Conclusions and Upcoming

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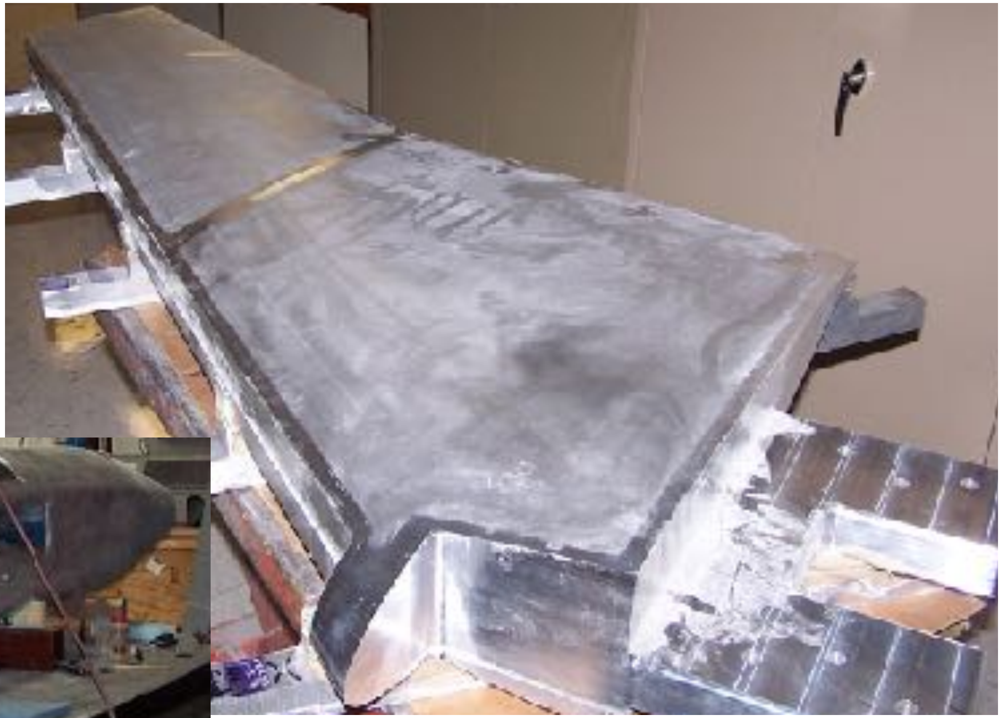

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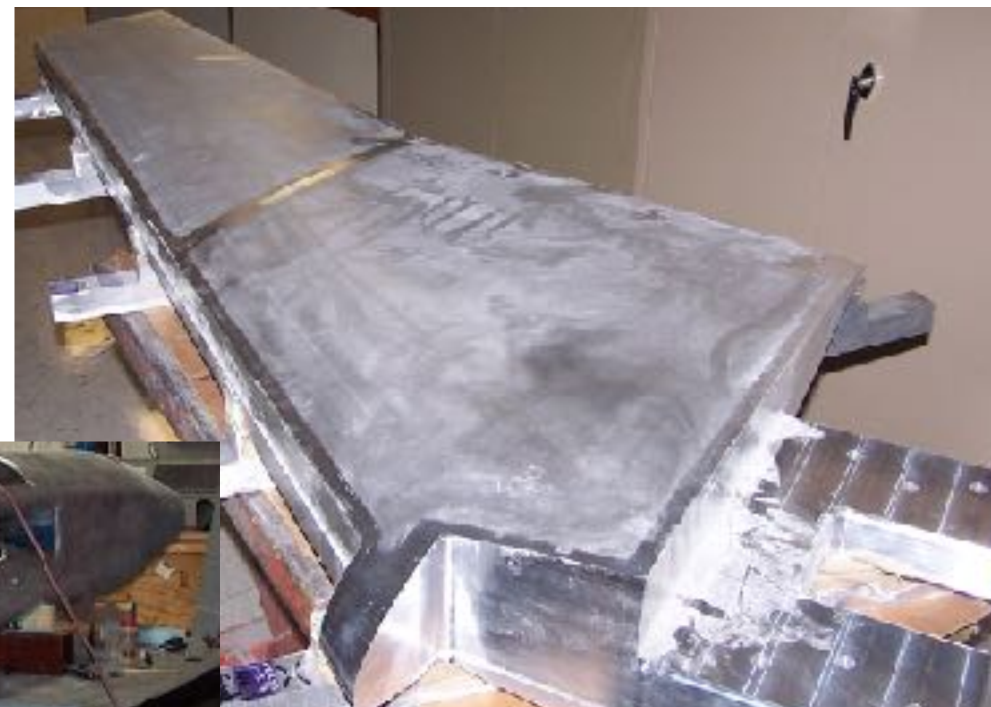

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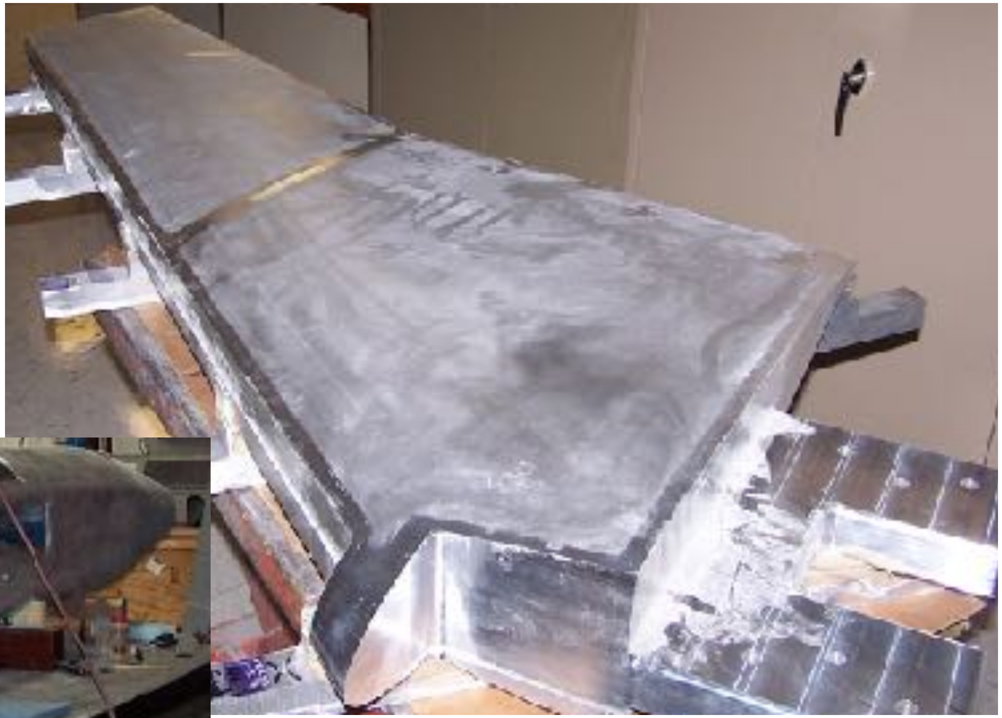
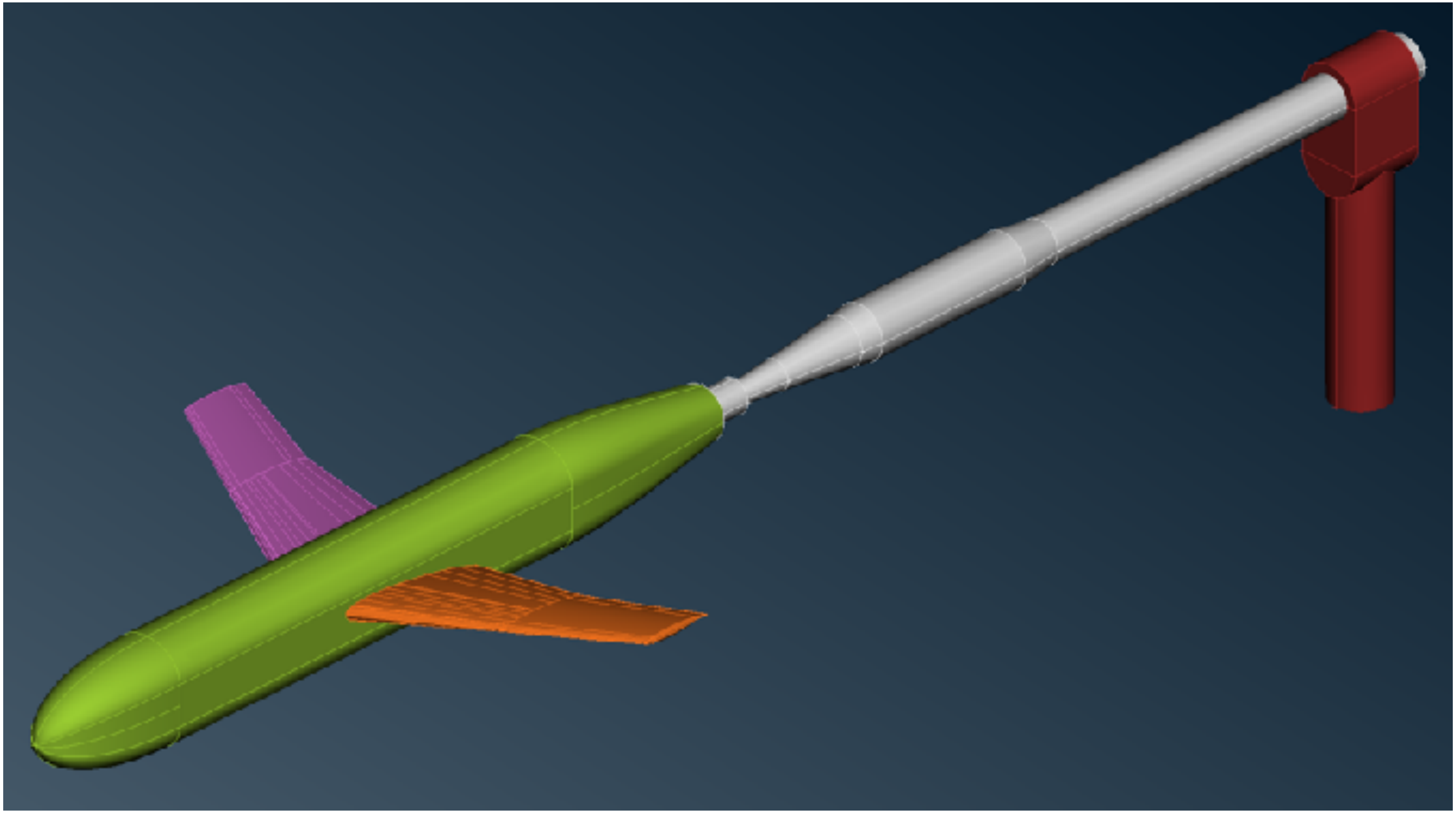


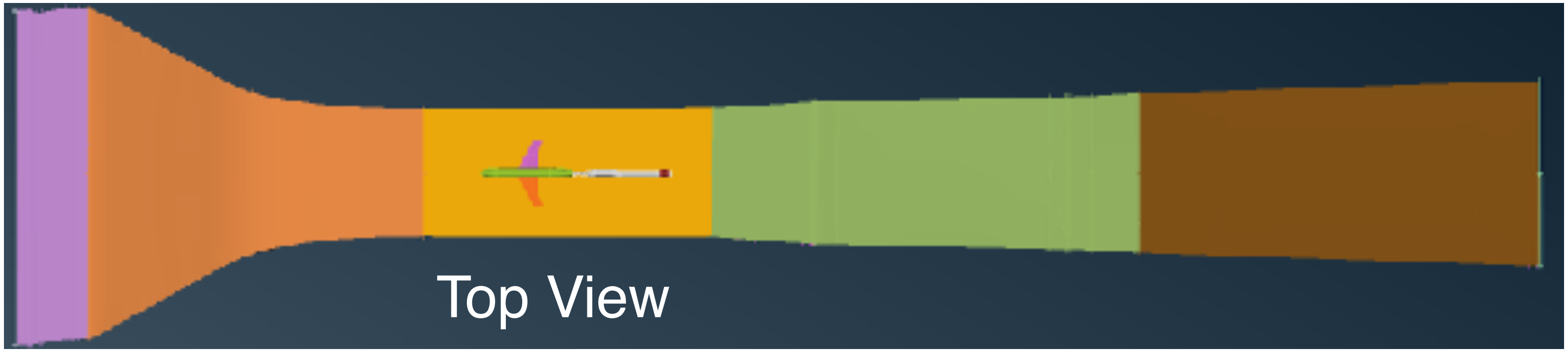
Upcoming CFD



Mock up of the JFM 8% model with roll sting and mast

Upcoming CFD

- Run with Overflow & Fun3D
- Incremental buildup
  - Free air: JFM, JFM + Sting, JFM + Sting + Mast
  - 14x22 WT: JFM, JFM + Sting, JFM + Sting + Mast



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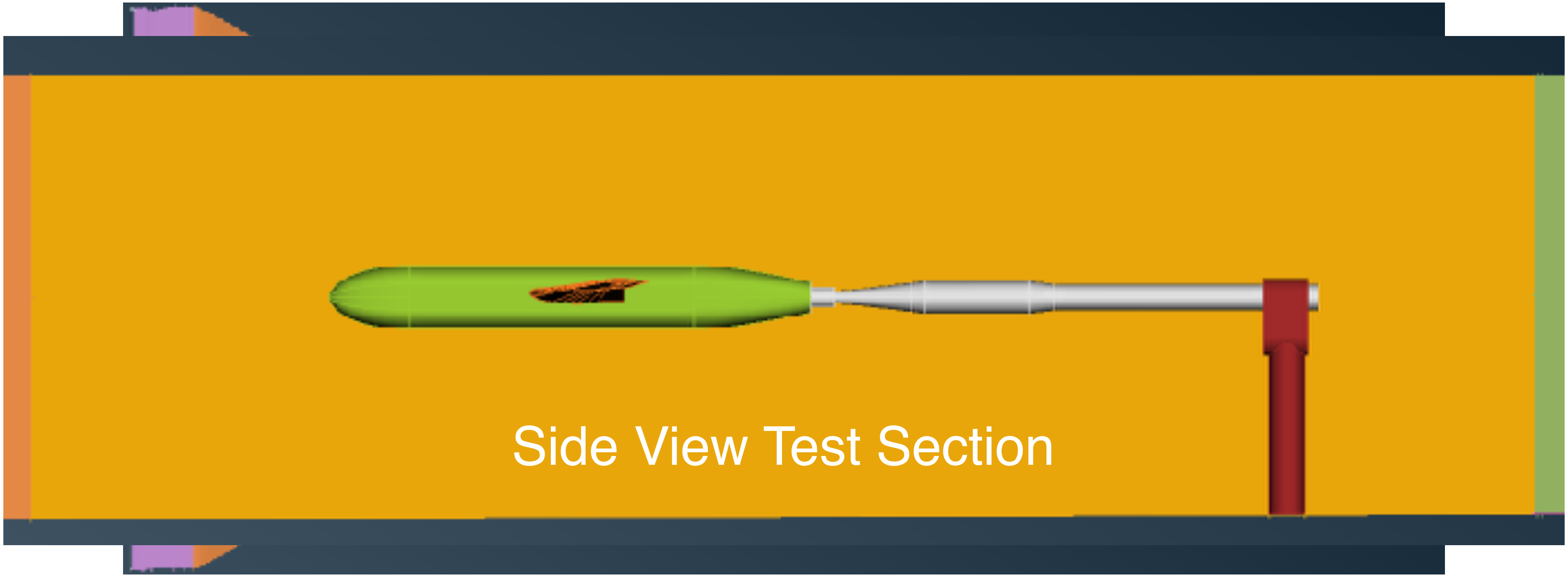

Acknowledgements

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