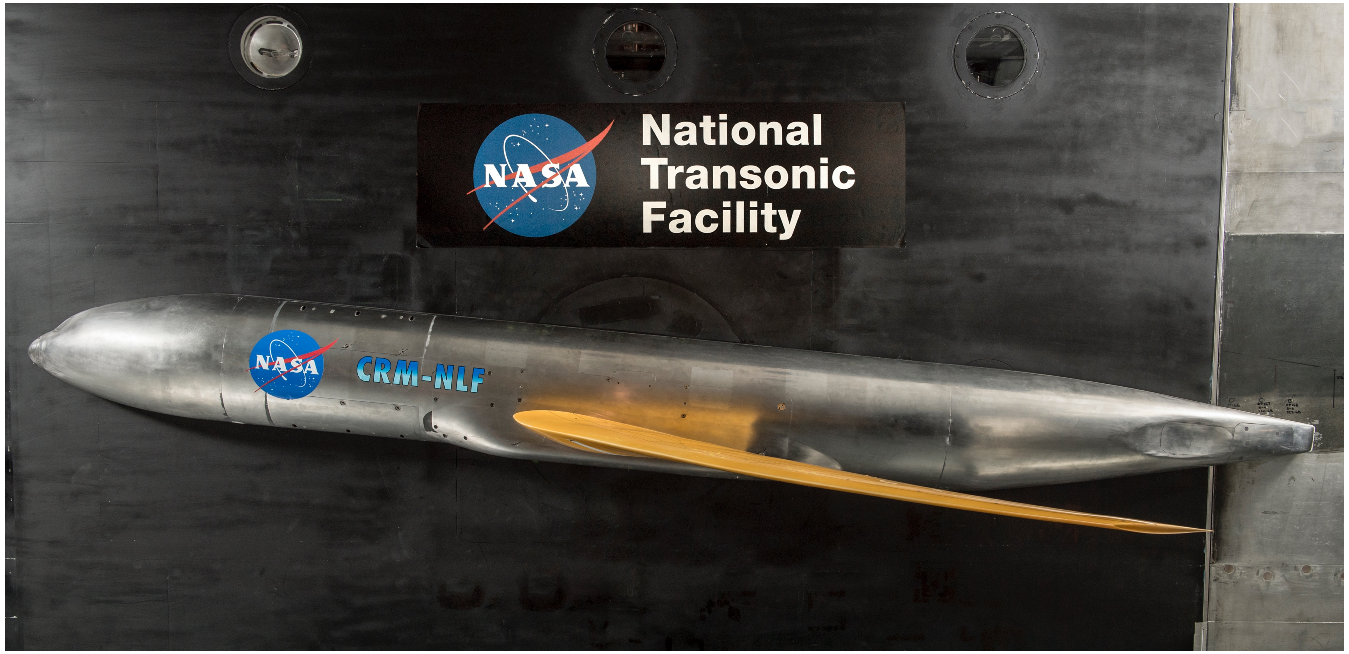
Crossflow Attenuated Natural Laminar Flow for Transport Wings



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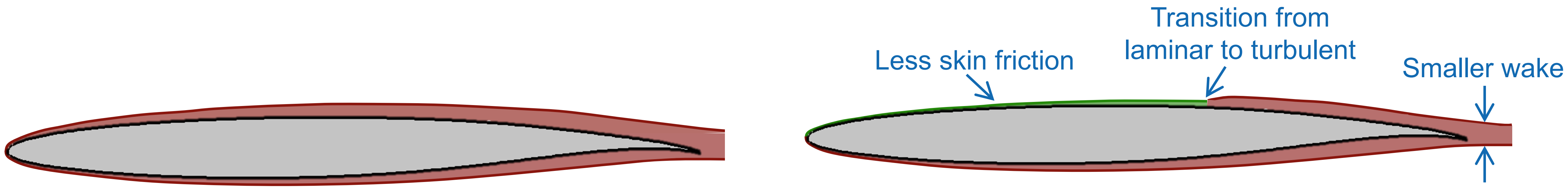
NASA Langley Research Center

7th UTIAS International Workshop on Aviation and Climate Change • May 19 – 21, 2021

Outline

- Introduction
- CATNLF Design Method
- Wind Tunnel Test
- Current Work
- Concluding Remarks

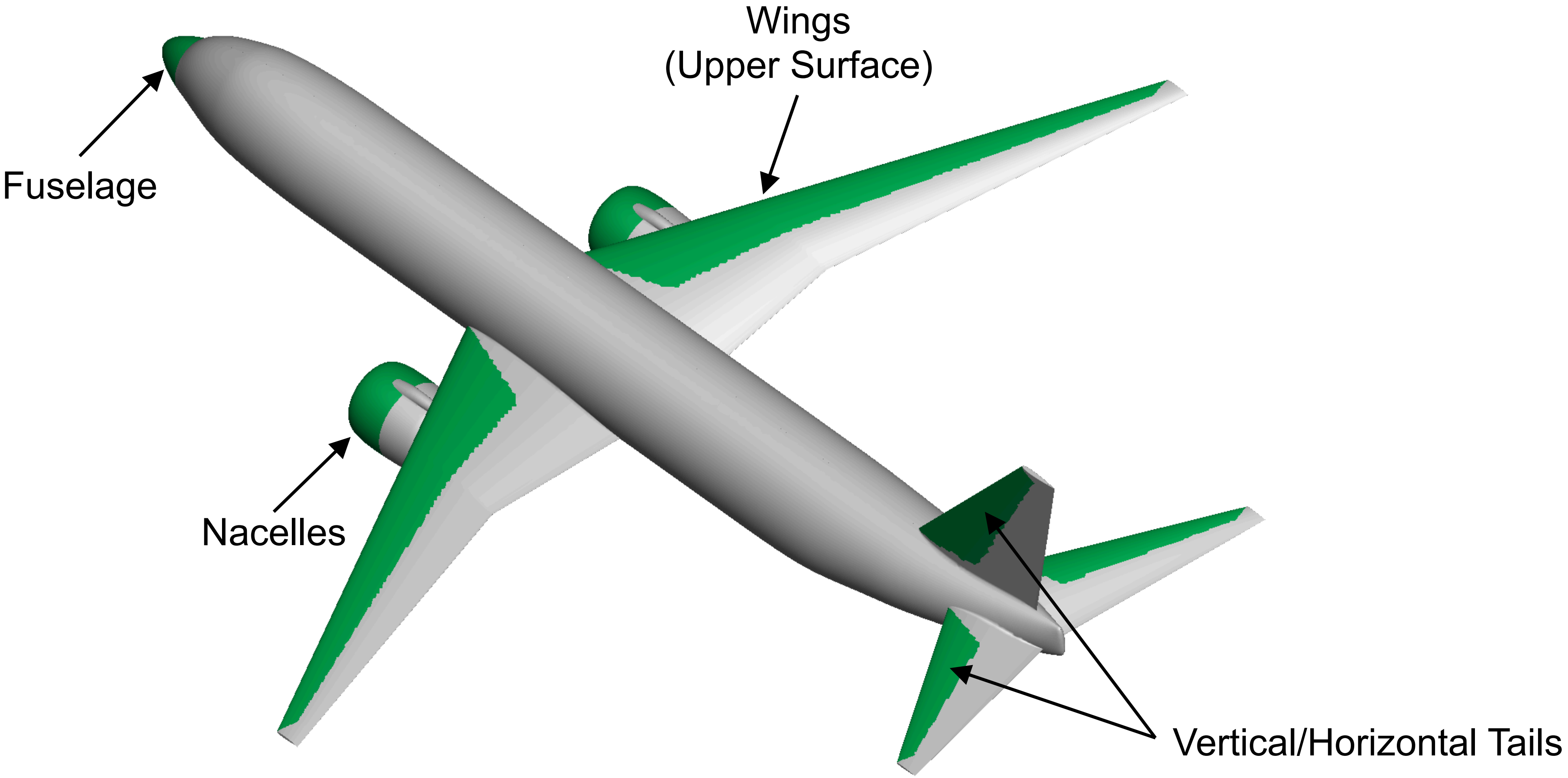
Why Laminar Flow?



Fully-Turbulent Airfoil | **Airfoil with Laminar Flow**

- "Laminar" and "turbulent" describes the state of the boundary layer (fluid very near the surface)
- Laminar flow significantly improves vehicle performance by reducing skin friction and profile drag
- For 777-class aircraft with laminar flow on 60% of the wings upper surface, the potential fuel burn savings per aircraft per year is 5-10%
  - 390,000 gallons of fuel savings
  - $1.8 million in fuel cost savings
  - 8.2 million pounds of CO_2 emissions reduced

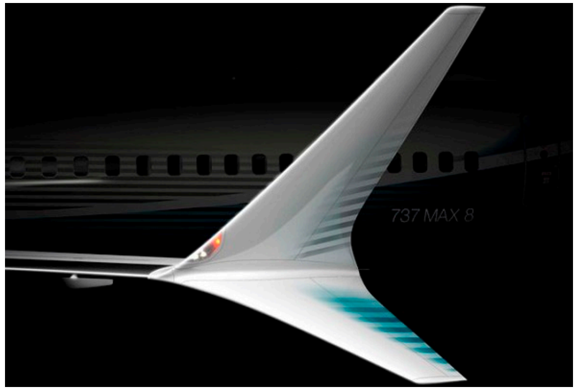
Potential for Laminar Flow on Commercial Transports



Does Industry Care About Laminar Flow?

- Currently flying on components with low sweep and/or low Reynolds numbers
- European industry heavily investing in laminar flow flight tests on transport wings
- Many next-generation configurations include laminar flow on wings to reach performance goals
- Boeing Chief Aerodynamicist claims laminar flow on transport wings is the **“remaining Grand Challenge”**

NLF Wing / Fuselage
Honda Jet

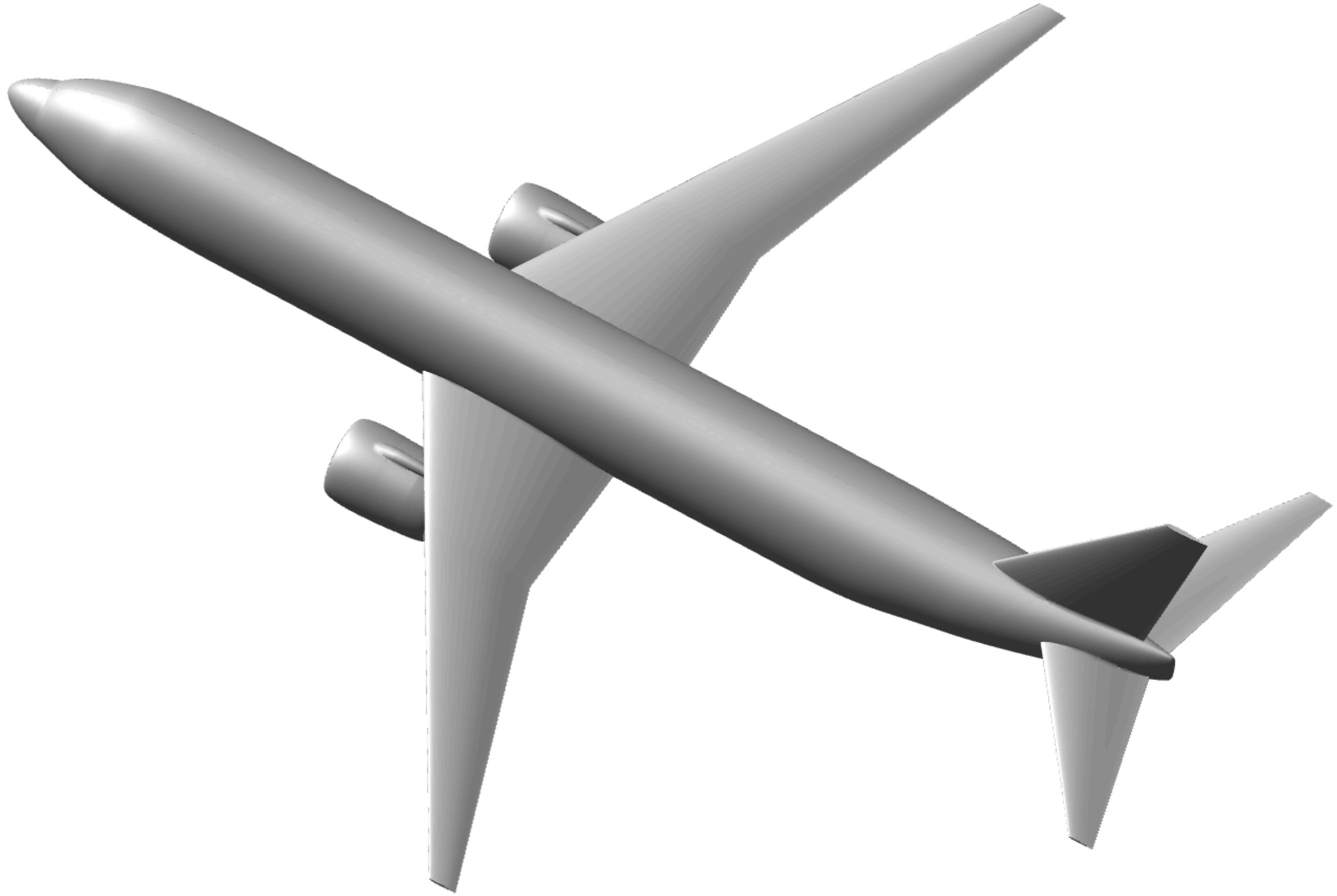


NLF Winglet
Boeing 737 MAX

NLF Nacelle
Boeing 787

Challenge with Laminar Flow on Transport Wings

Transport aircraft require swept wings to reach desired cruise speeds, which leads to 4 primary mechanisms of transition



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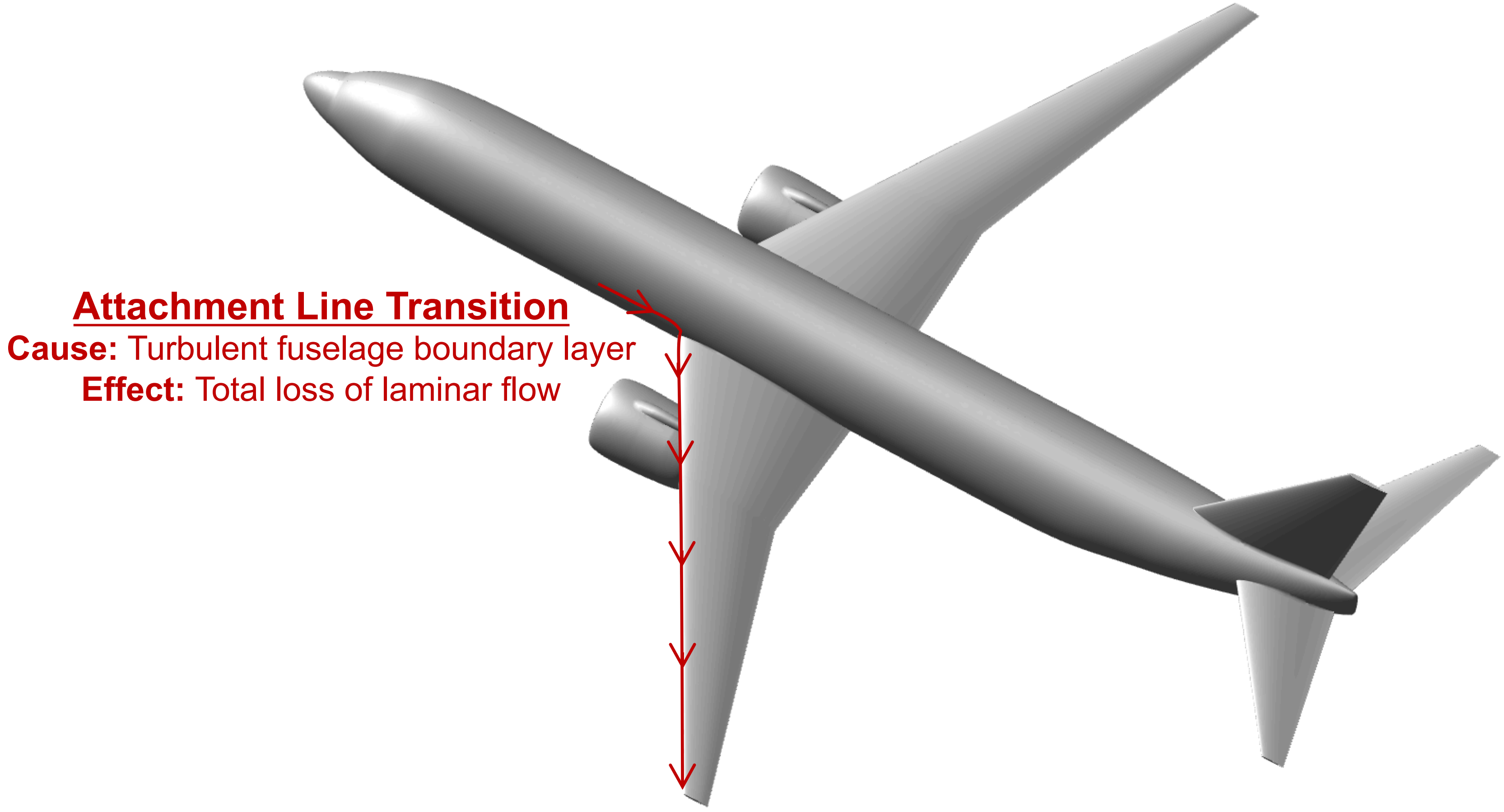

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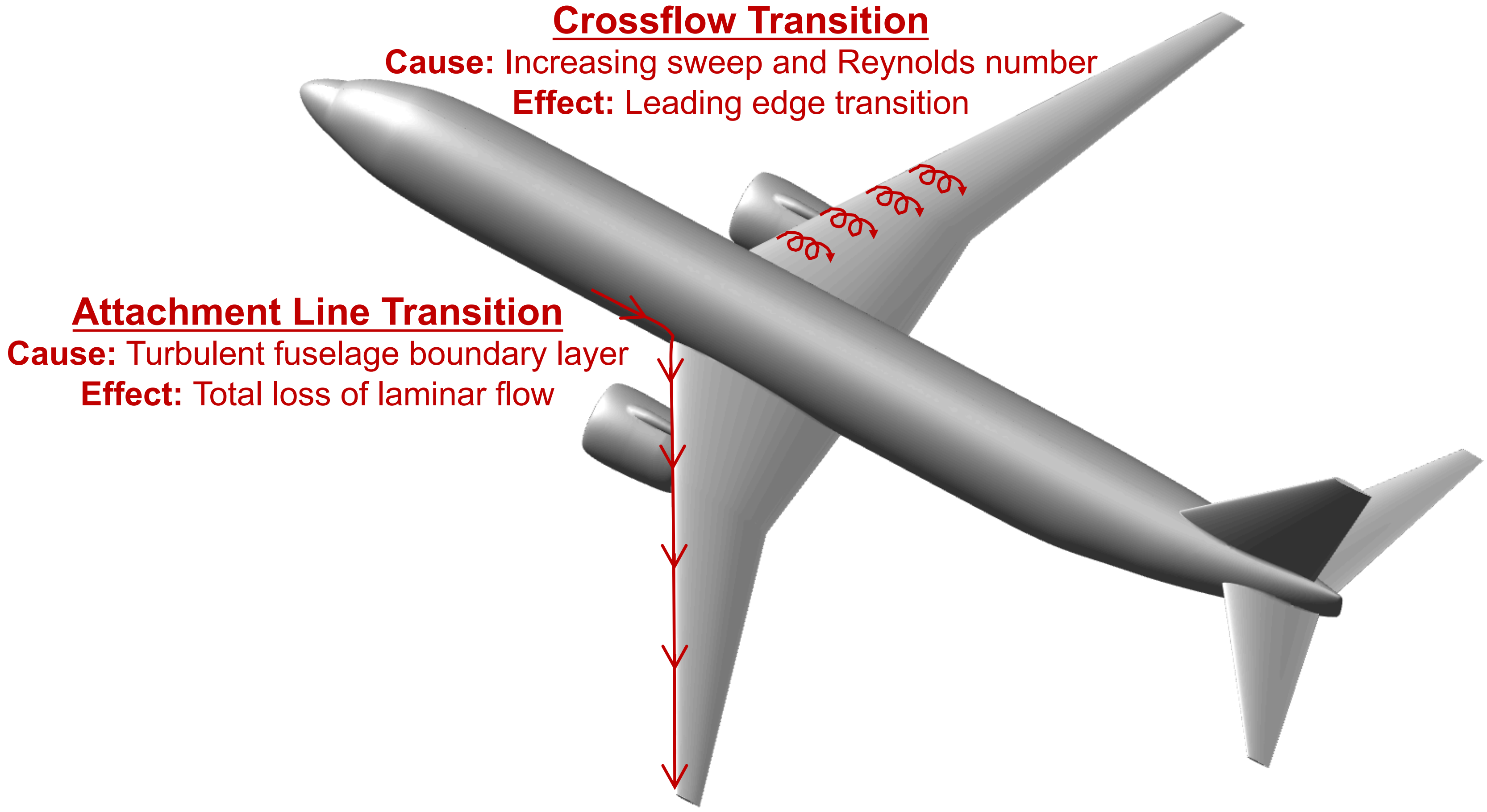

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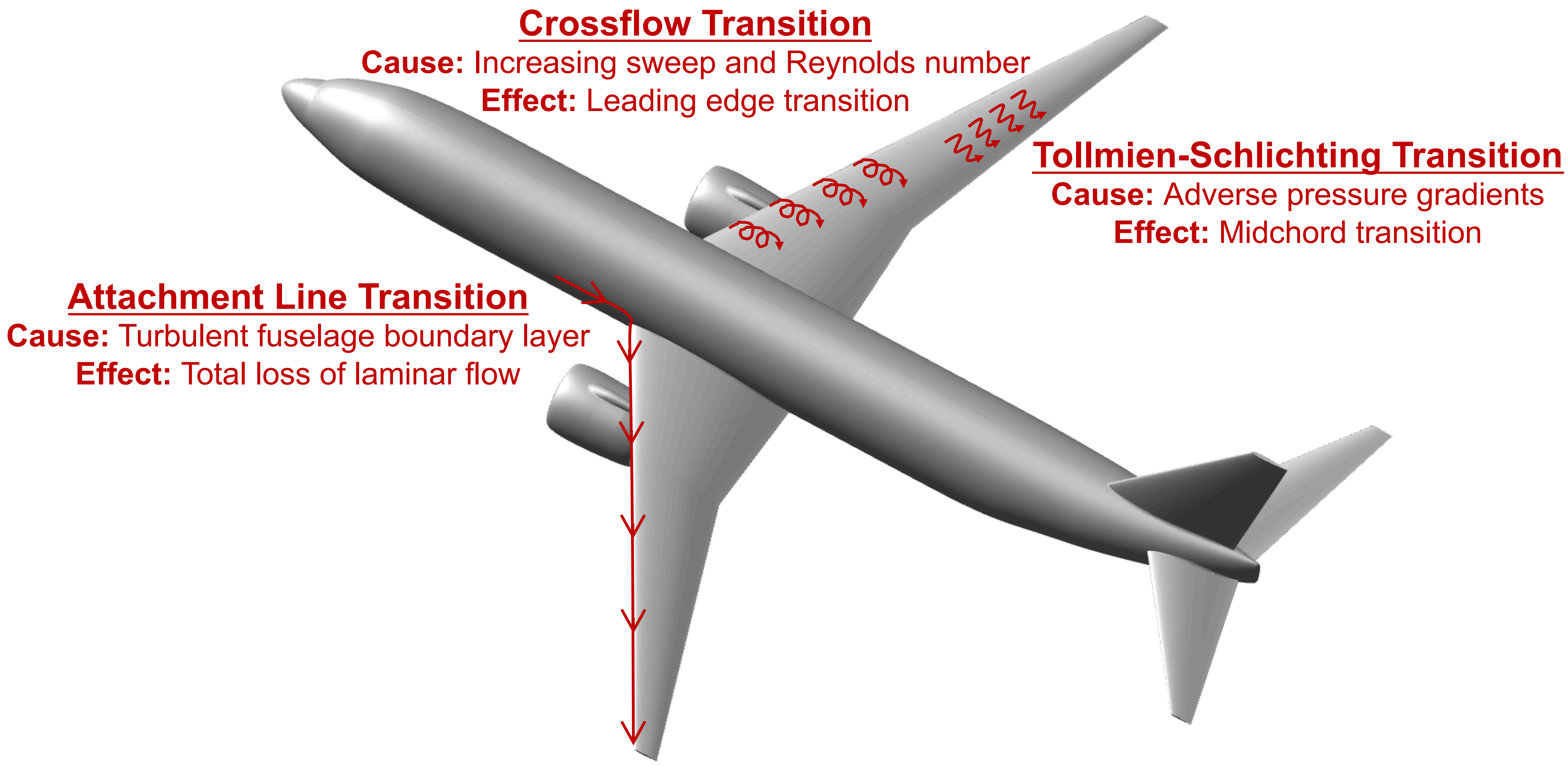

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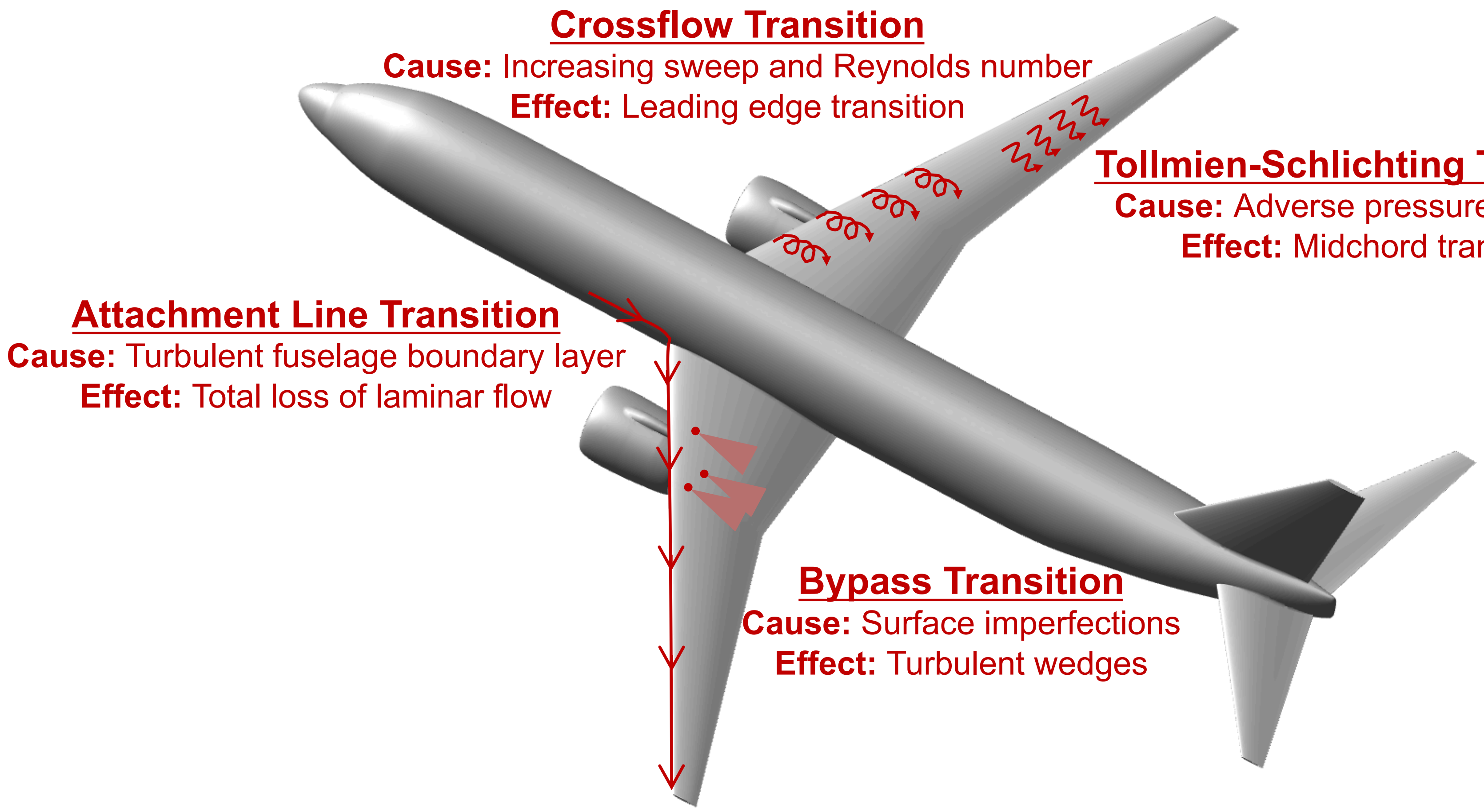


Crossflow Transition on Transport Wings

- Historic options to address crossflow transition on wings:
  1. Reduce wing sweep
     - Penalty: Requires aircraft to fly slower
  2. Introduce a flow control system, such as suction
     - Penalty: Increases weight, complexity, and cost
- Neither option has “bought its way onto” commercial transports

Research Goal

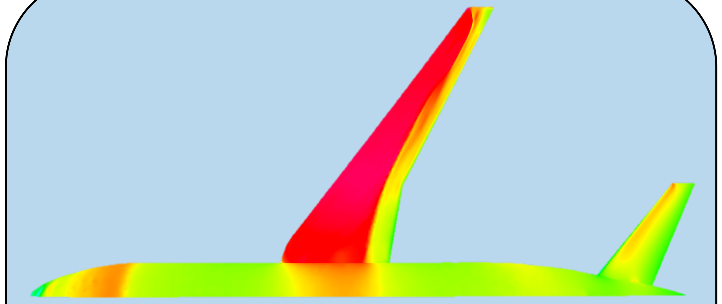
Obtain significant extents of laminar flow on typical transport wings without historic crossflow penalties

CATNLF Concept Development

New NASA Laminar Flow Design Method

Crossflow Attenuated NLF (CATNLF) design method changes the shape of the wing airfoils to obtain pressure distributions that delay transition by damping crossflow instabilities

Computational Study

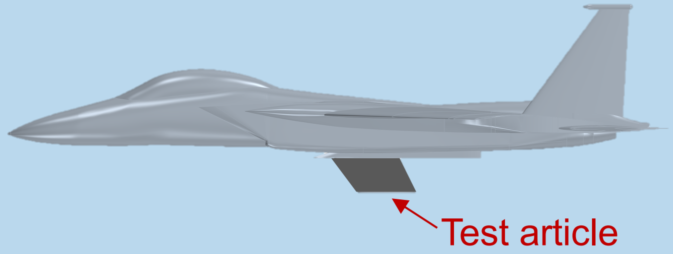


Goal: To develop technology
Reference: AIAA 2016-4326

Wind Tunnel Test

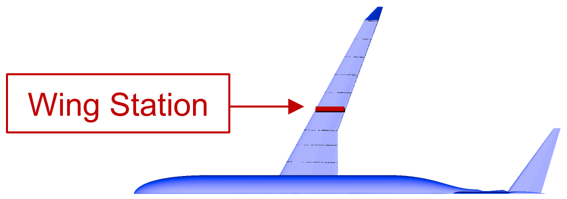
Goal: To confirm computations
References: AIAA 2017-3058, AIAA 2019-3292

Flight Test

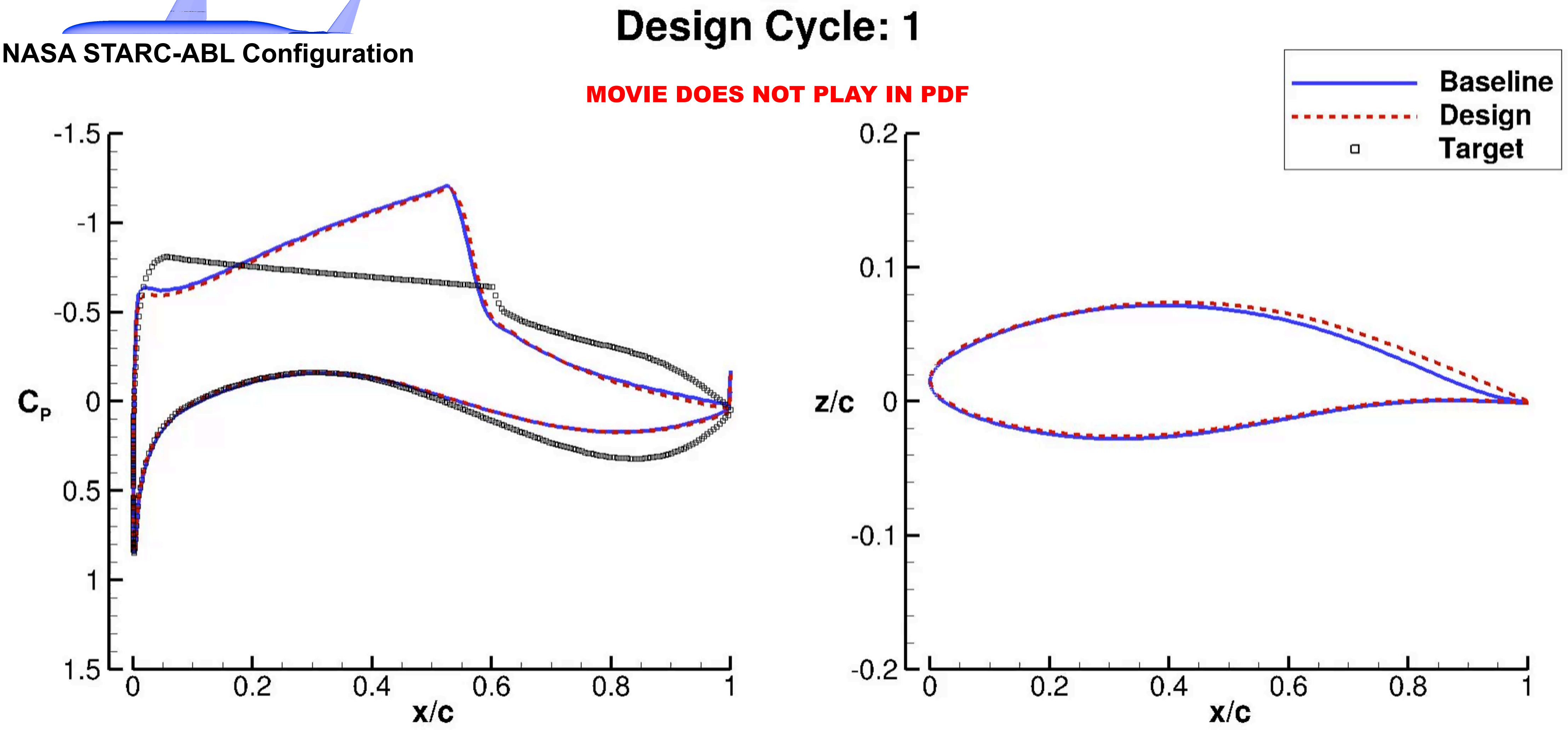


Goal: To advance technology
Reference: AIAA 2021-0173

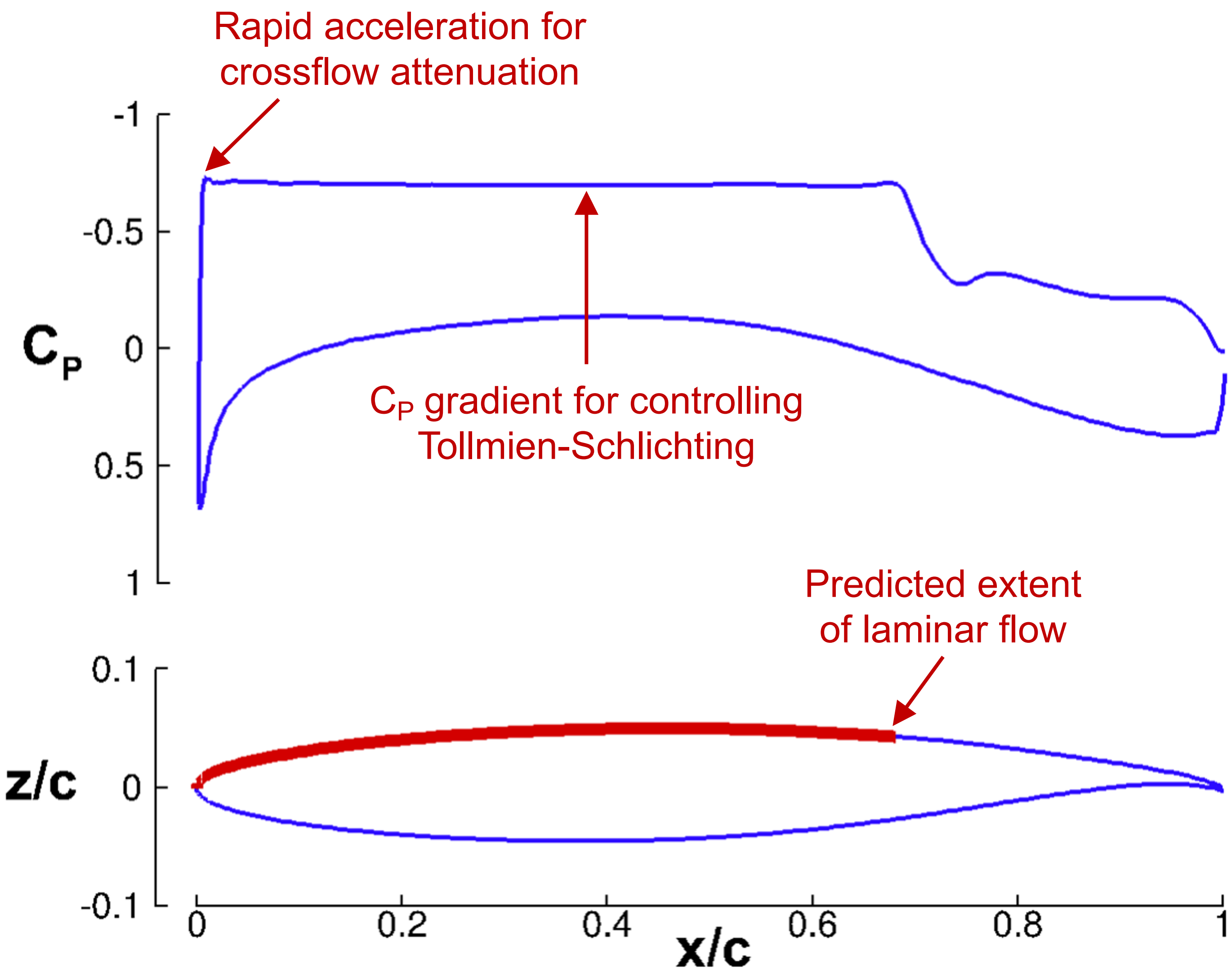
Example Turbulent Airfoil Design



NASA STARC-ABL Configuration



Example CATNLF Pressure Distribution



Wind Tunnel Test Objectives

Wind Tunnel Test

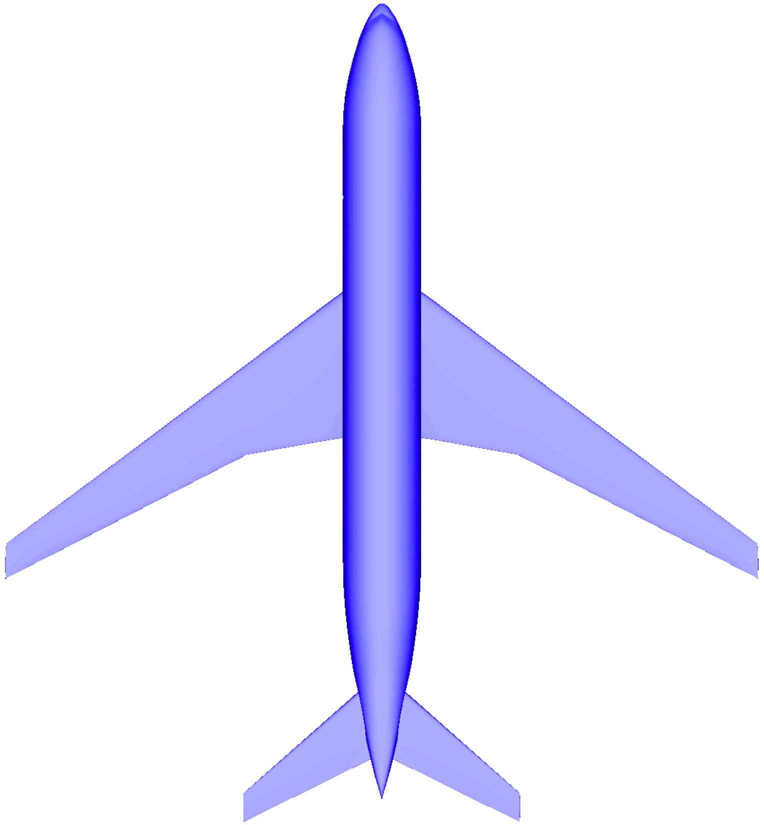
Goal: To confirm computations
References: AIAA 2017-3058, AIAA 2019-3292

Test Objectives:

1. Validate the CATNLF design methodology and analysis tools
2. Characterize the National Transonic Facility (NTF) laminar flow testing capabilities
3. Establish best practices for laminar flow wind tunnel testing

Wind Tunnel Model Design

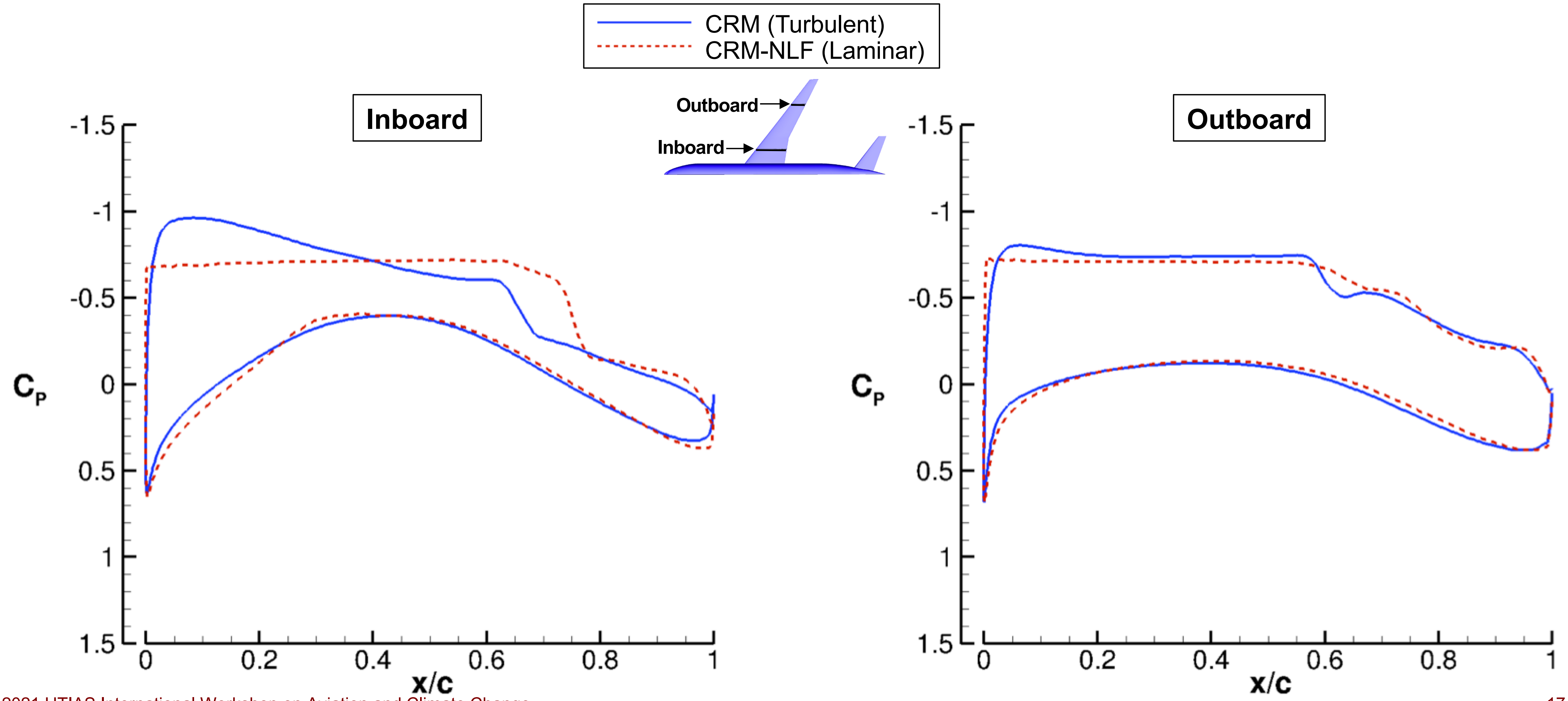
- Designed a model using the CATNLF design method
- Baseline configuration is the Common Research Model (CRM)
  - Generic open geometry of a 777-class transport
  - Used for computational and experimental studies around the world
- New model is referred to as the Common Research Model with Natural Laminar Flow (CRM-NLF)
- Design conditions:
  - Mach = 0.85
  - Re_{MAC} = 30 million
  - C_L = 0.50
  - Flight turbulence levels (Critical N-factor = 10)



Planform view of the baseline CRM

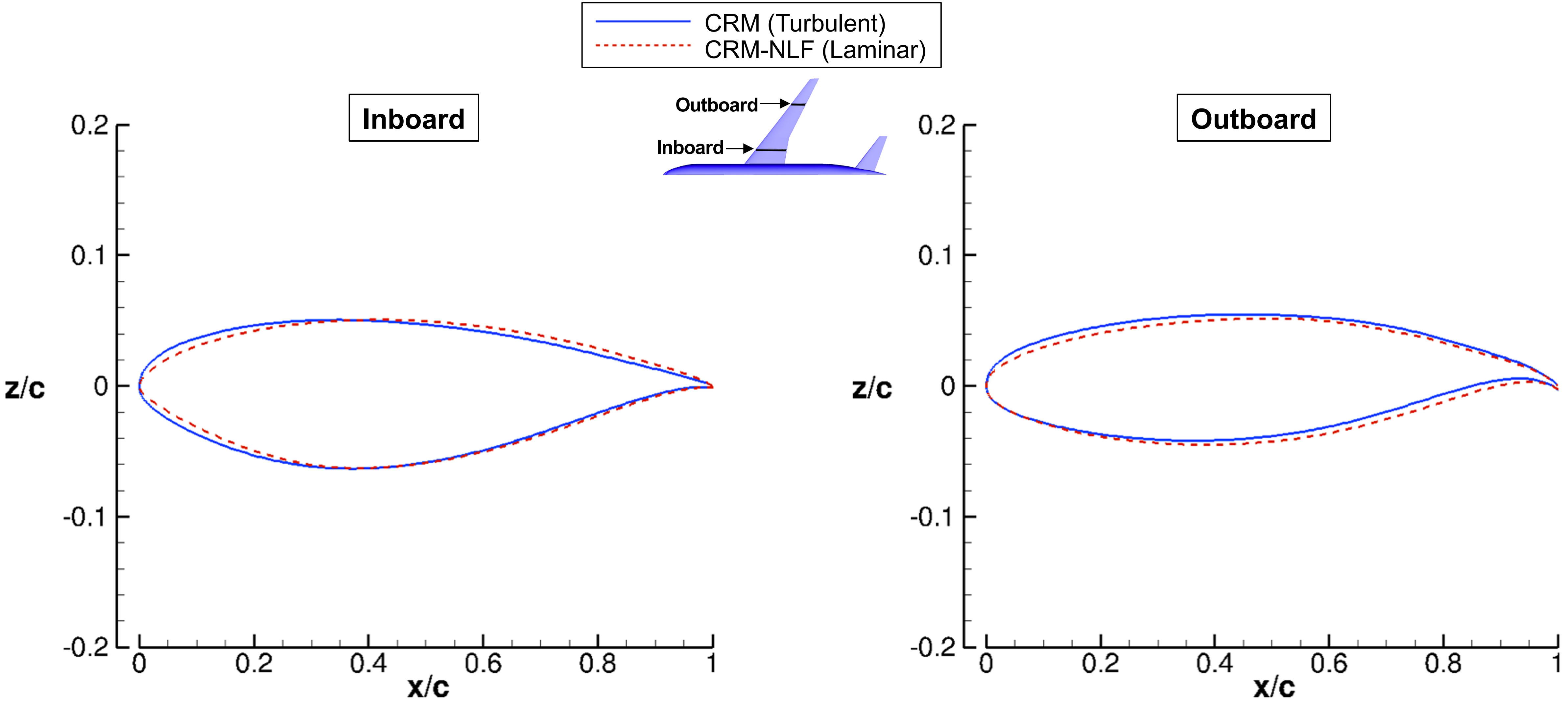
Pressure Changes Needed for CATNLF Concept

Rapid acceleration near the leading edge used for crossflow control



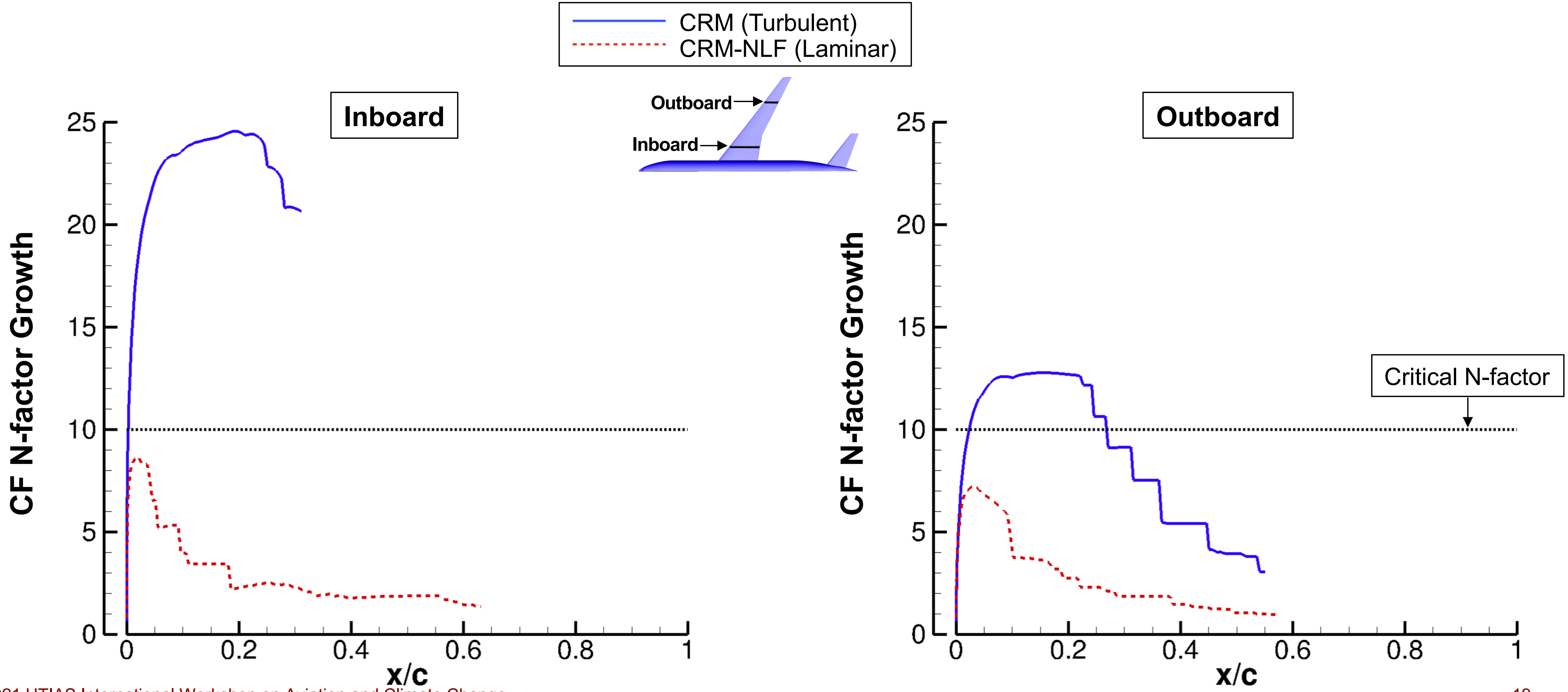
Airfoil Changes Needed for CATNLF Concept

Largest change needed near the leading edge on inboard airfoils



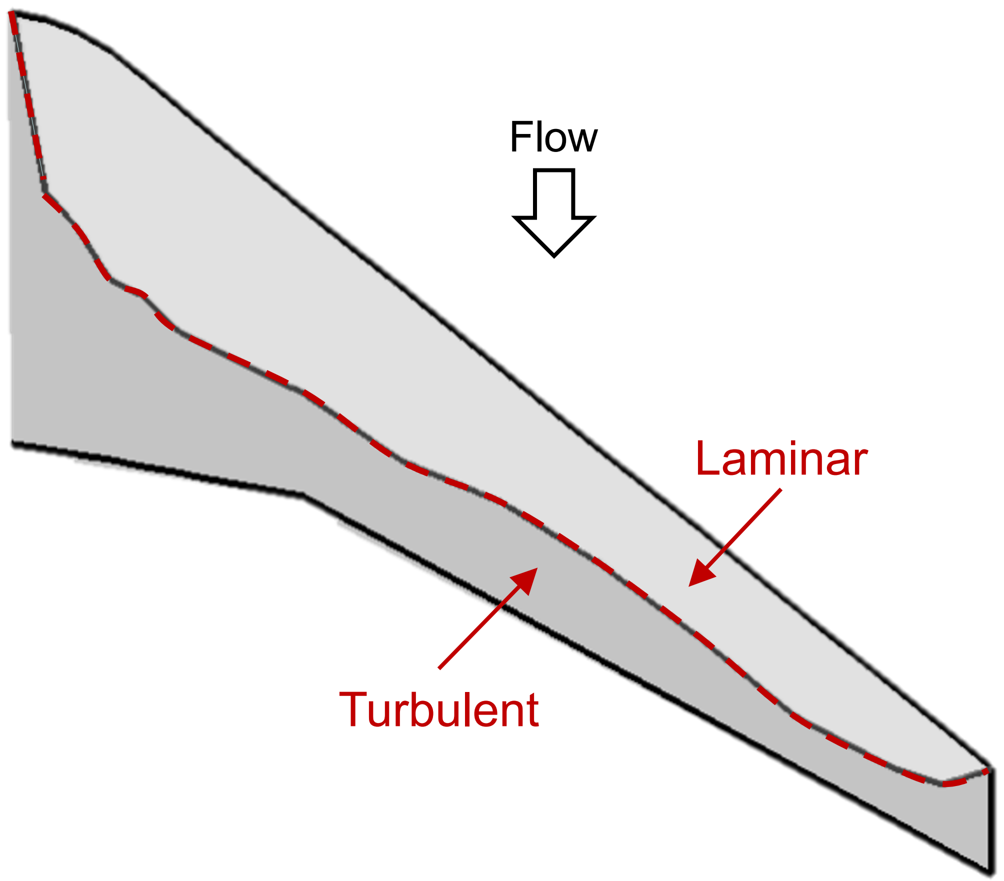
Crossflow Growth Resulting from CATNLF Concept

Crossflow (CF) growth is reduced to sub-critical level on CRM-NLF



Laminar Flow Extent on the CRM-NLF

CRM-NLF has laminar flow on 56% of the wing upper surface at the design condition, which provides a 7% drag reduction compared to the turbulent CRM



Facility Description

Aerial view of the NTF complex

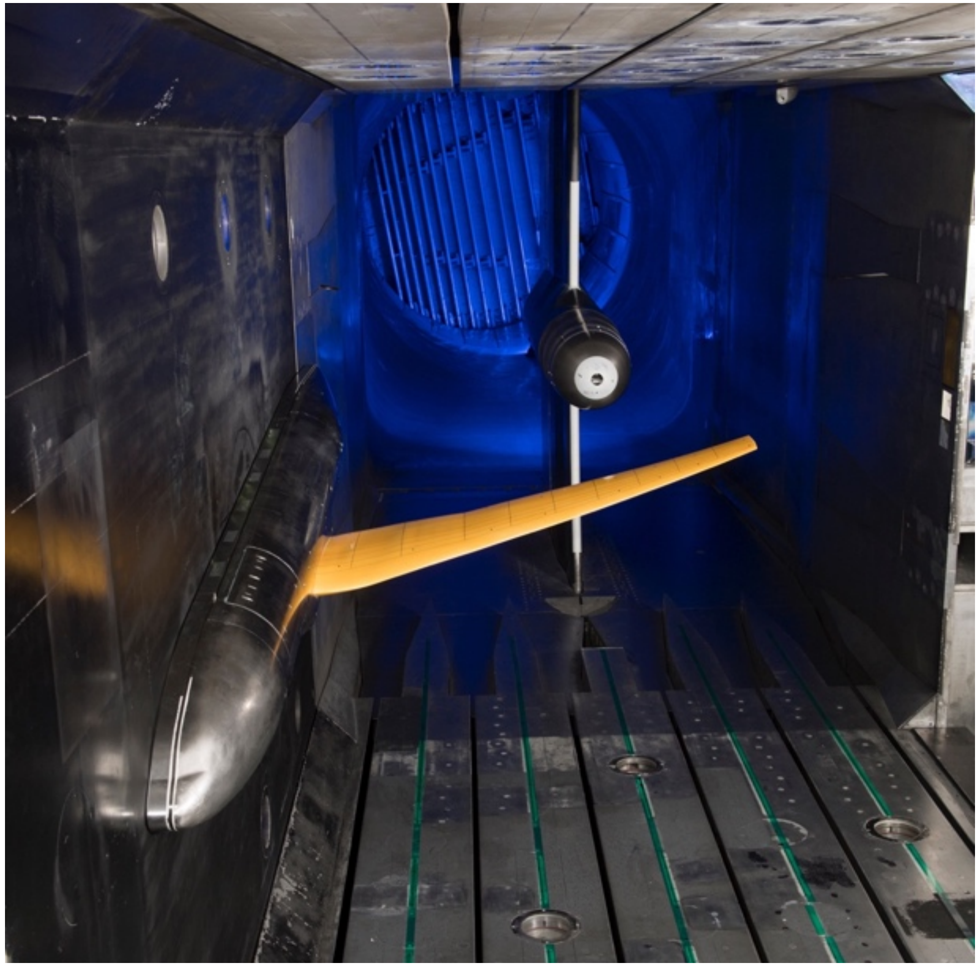
- Test completed in October 2018 in the National Transonic Facility (NTF)
- NTF is a pressurized cryogenic closed-circuit, continuous-flow, fan-driven wind tunnel
- Motivation for testing in the NTF:
  - Flight Reynolds numbers for relevant laminar flow data
  - Semispan testing capability for reducing unit Reynolds numbers
  - Acceptably low turbulence levels for laminar flow testing

Instrumentation and Measurements

- 5.2% scale semispan model
  - Semispan length = 60.2 inches
  - Reference chord = 14.3 inches
- Data acquired:
  - Surface pressure
  - Transition visualization
  - Force and moment
  - Model deformation

Primary Test Conditions

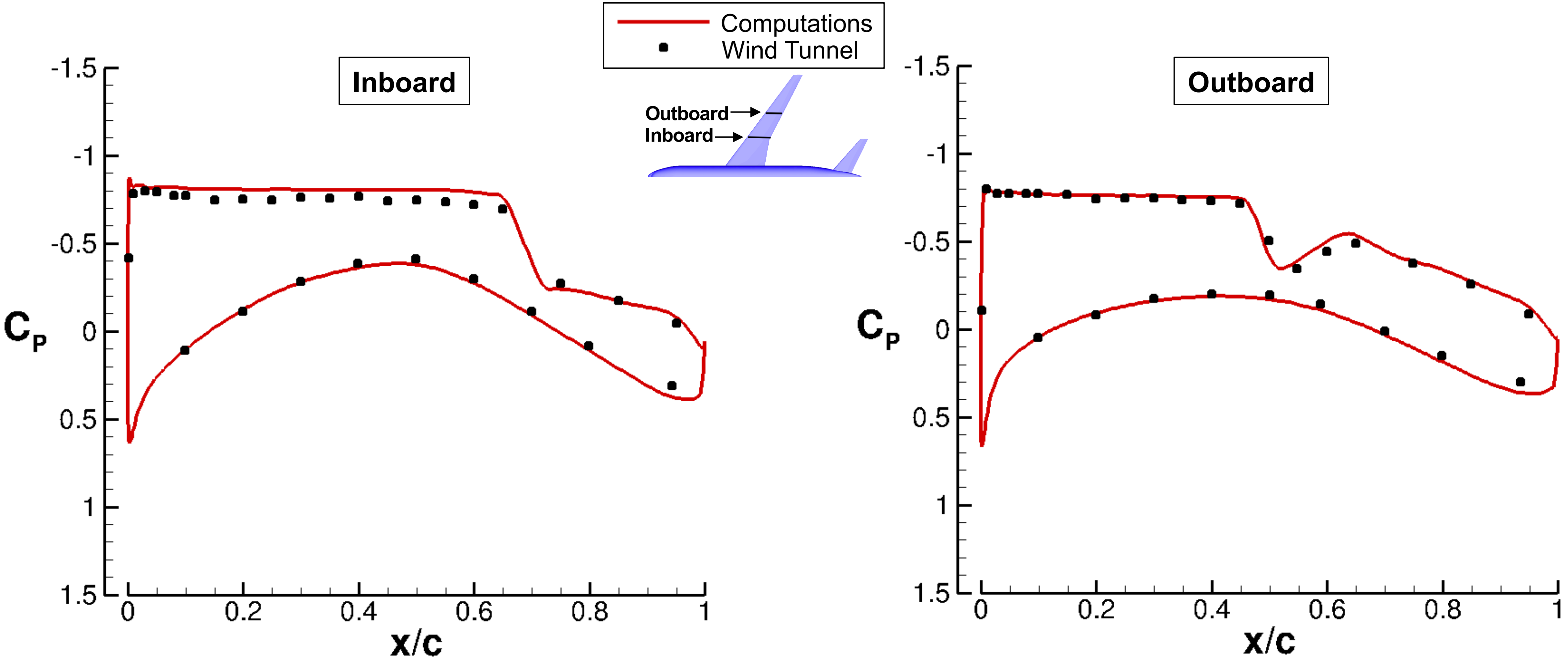
Mach	α (deg.)	T_T (°F)	Re_{MAC} (million)
0.86	1.5 to 3.0	+40	10.0 to 15.0
		-50	12.5 to 20.0
		-150	20.0 to 30.0



CRM-NLF semispan model installed in the NTF

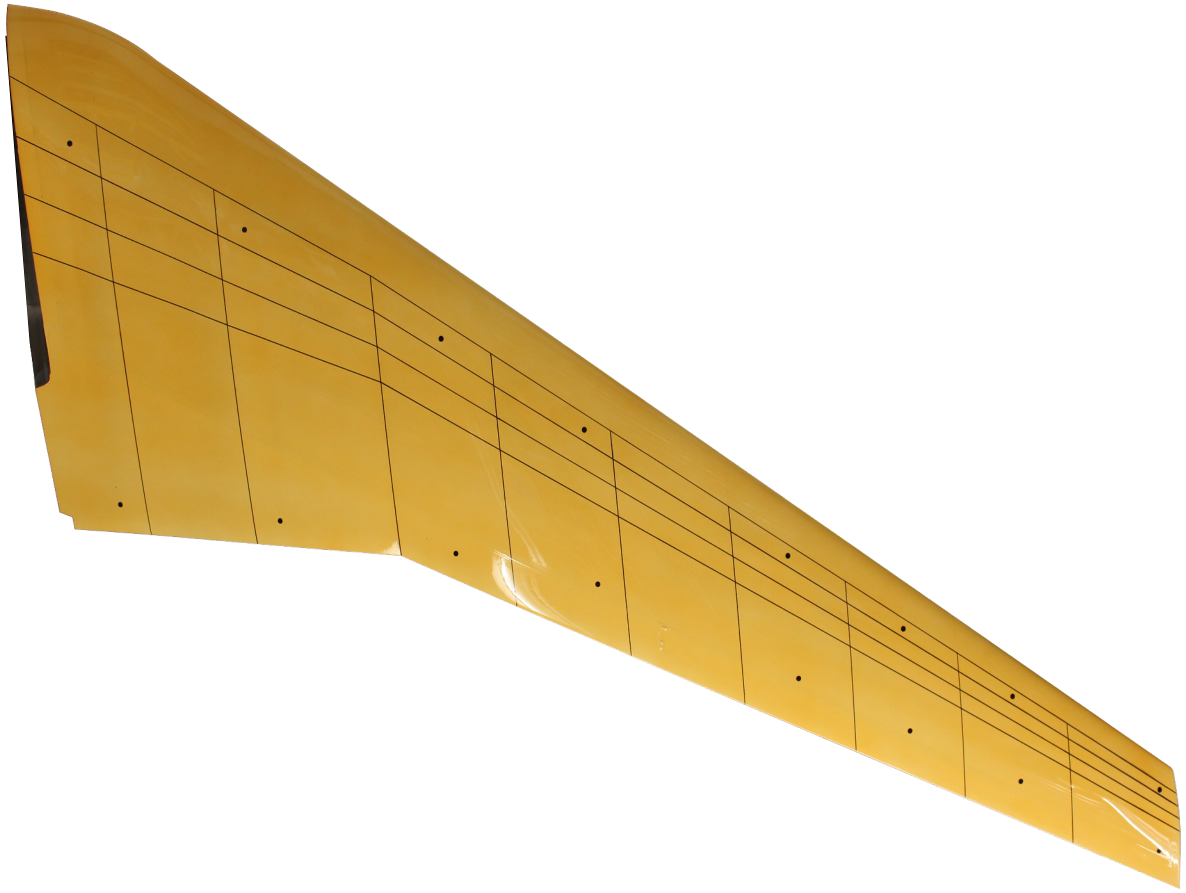
Wind Tunnel Pressure Measurements

Pressure measurements from the wind tunnel test showed CATNLF pressure distributions are obtained on the model



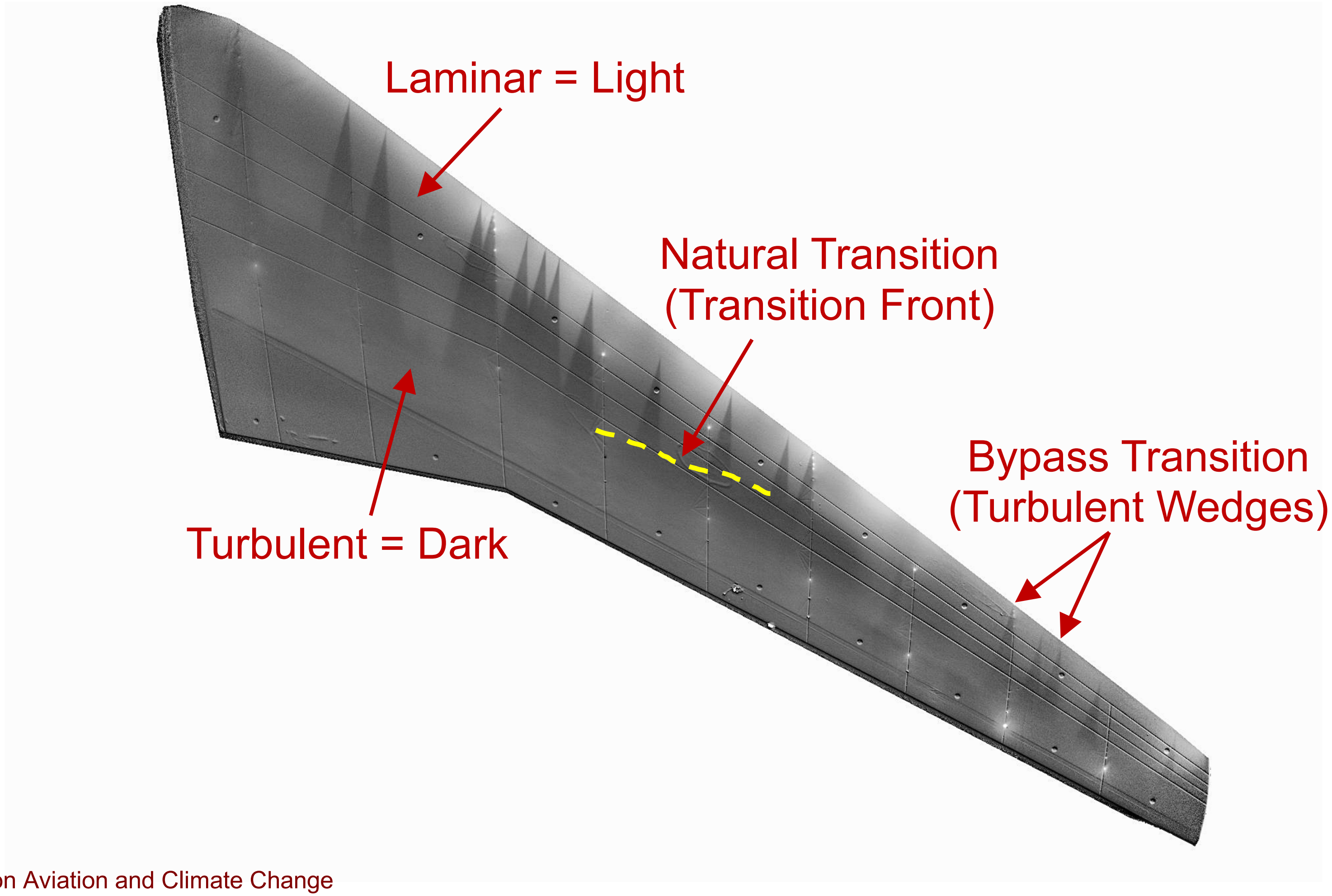
Transition Visualization in the NTF

Wing painted with Temperature Sensitive Paint (TSP) and new resistive heating layer to visualize extents of laminar flow



Transition Visualization in the NTF

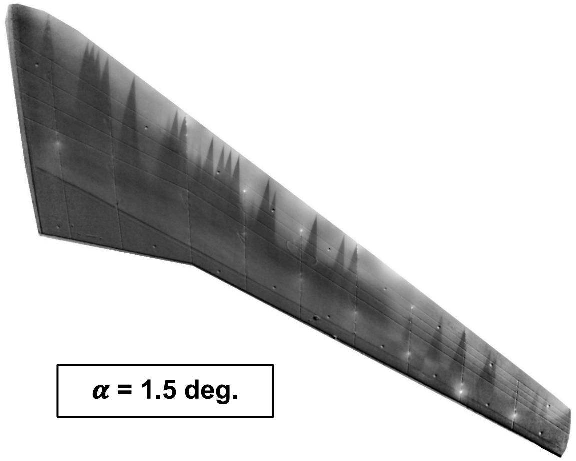
TSP images show regions of laminar flow on the wing upper surface



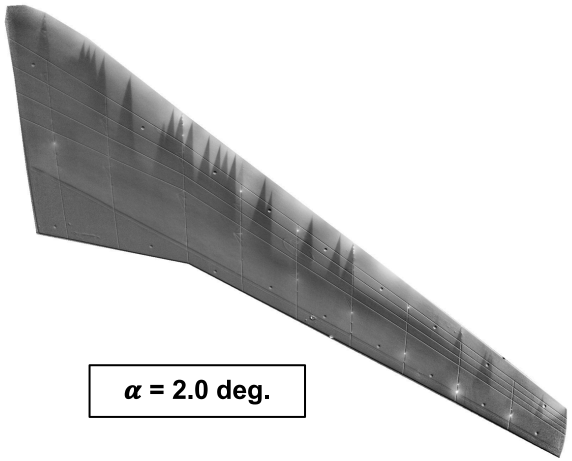
Sample TSP Images for an Alpha Sweep

Tunnel Conditions: M = 0.86, Re_{MAC} = 15x10^6

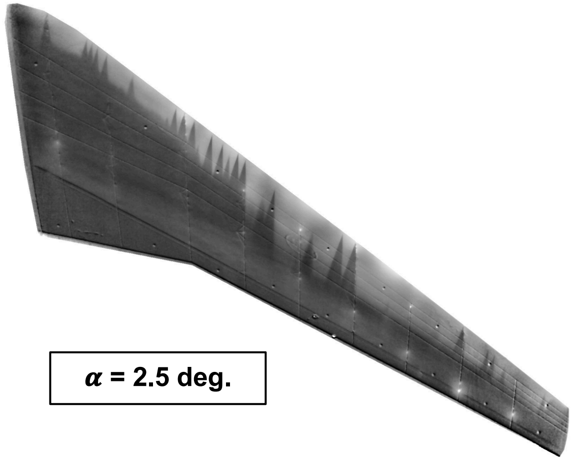
Laminar flow maintained across alpha sweep



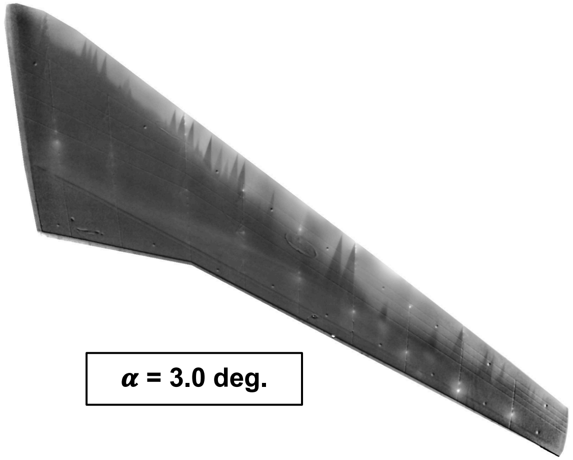
α = 1.5 deg.



α = 2.0 deg.



α = 2.5 deg.

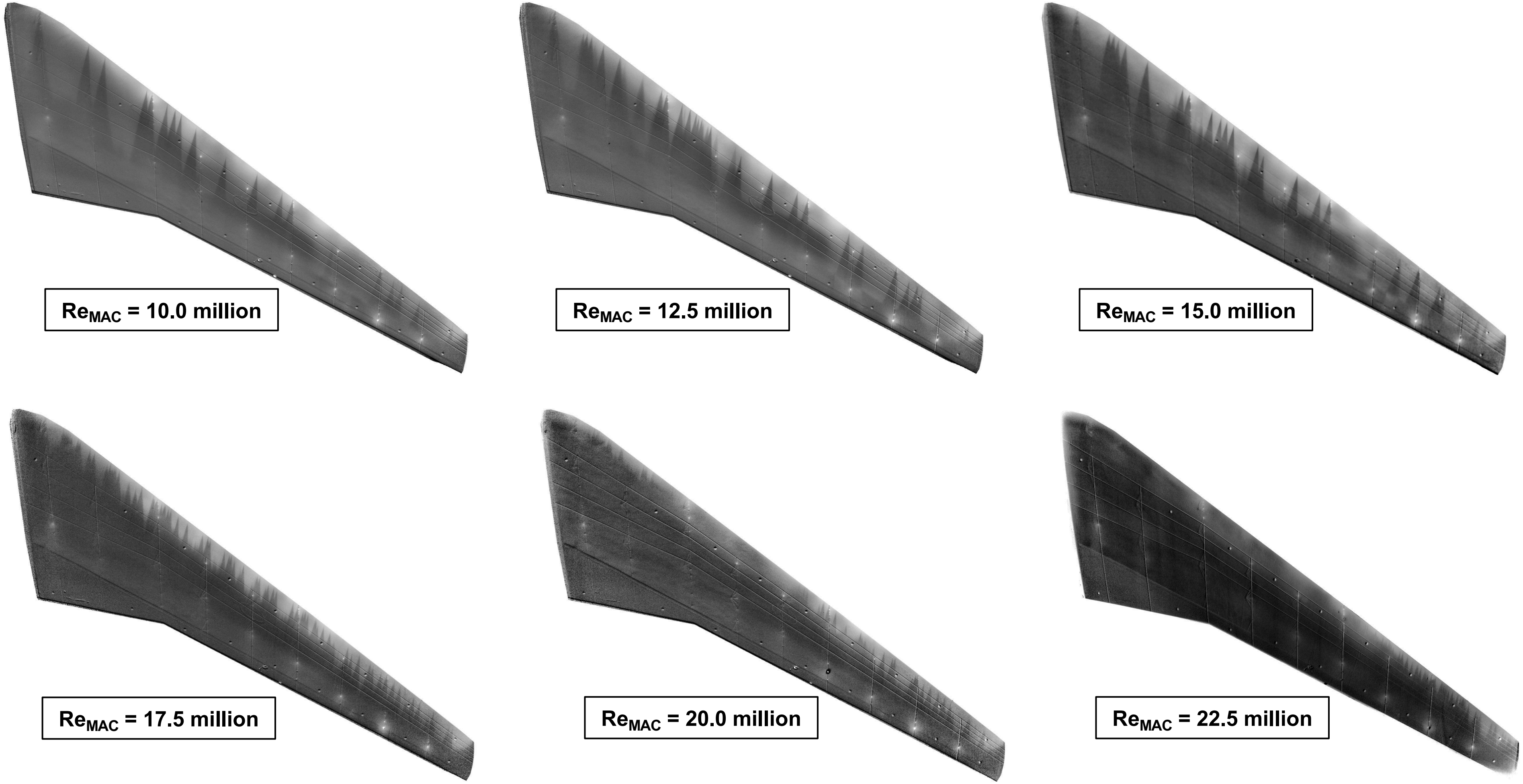


α = 3.0 deg.

Sample TSP Images for a Reynolds Number Sweep

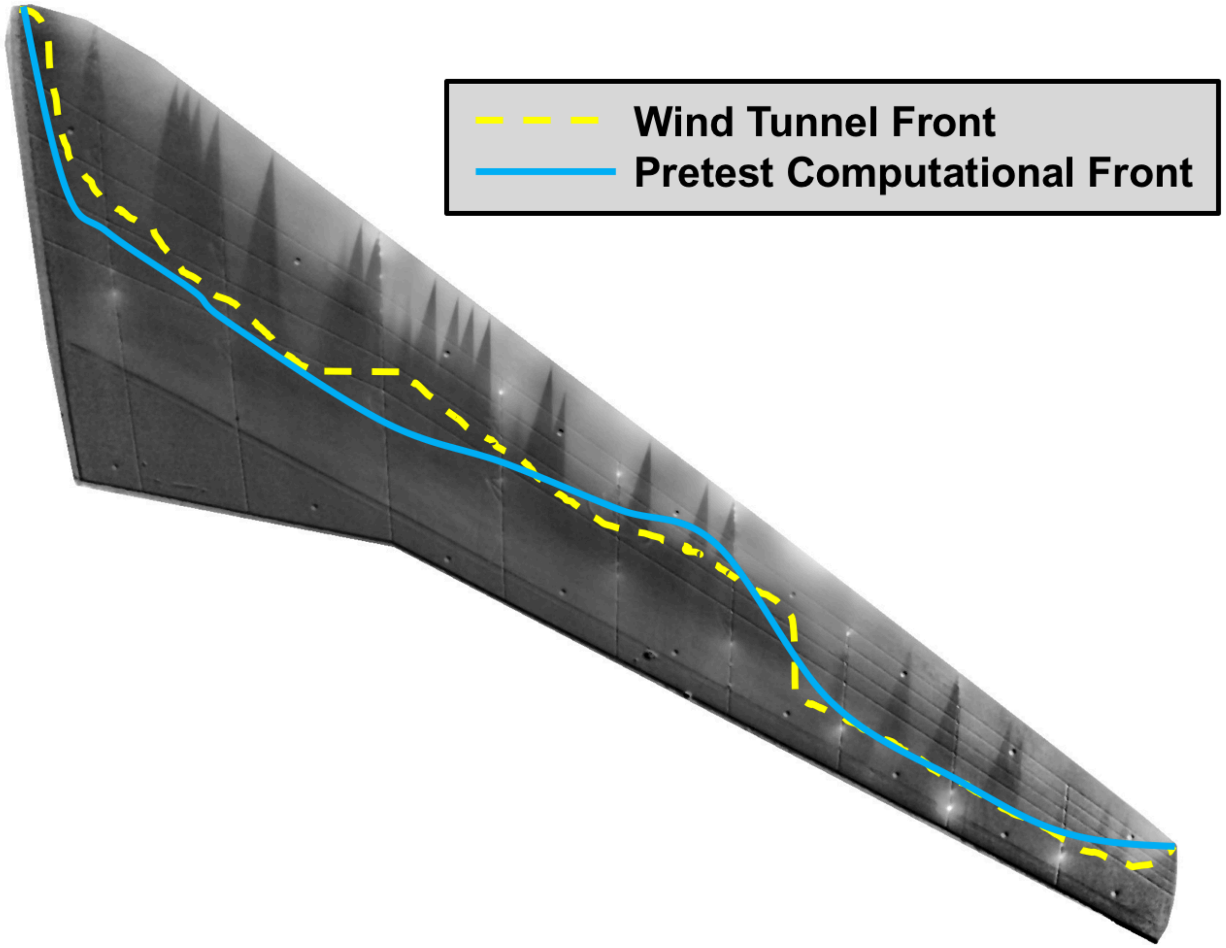
Tunnel Conditions: M = 0.86, α = 1.5 deg.

Turbulent wedges at high Reynolds numbers make analysis challenging

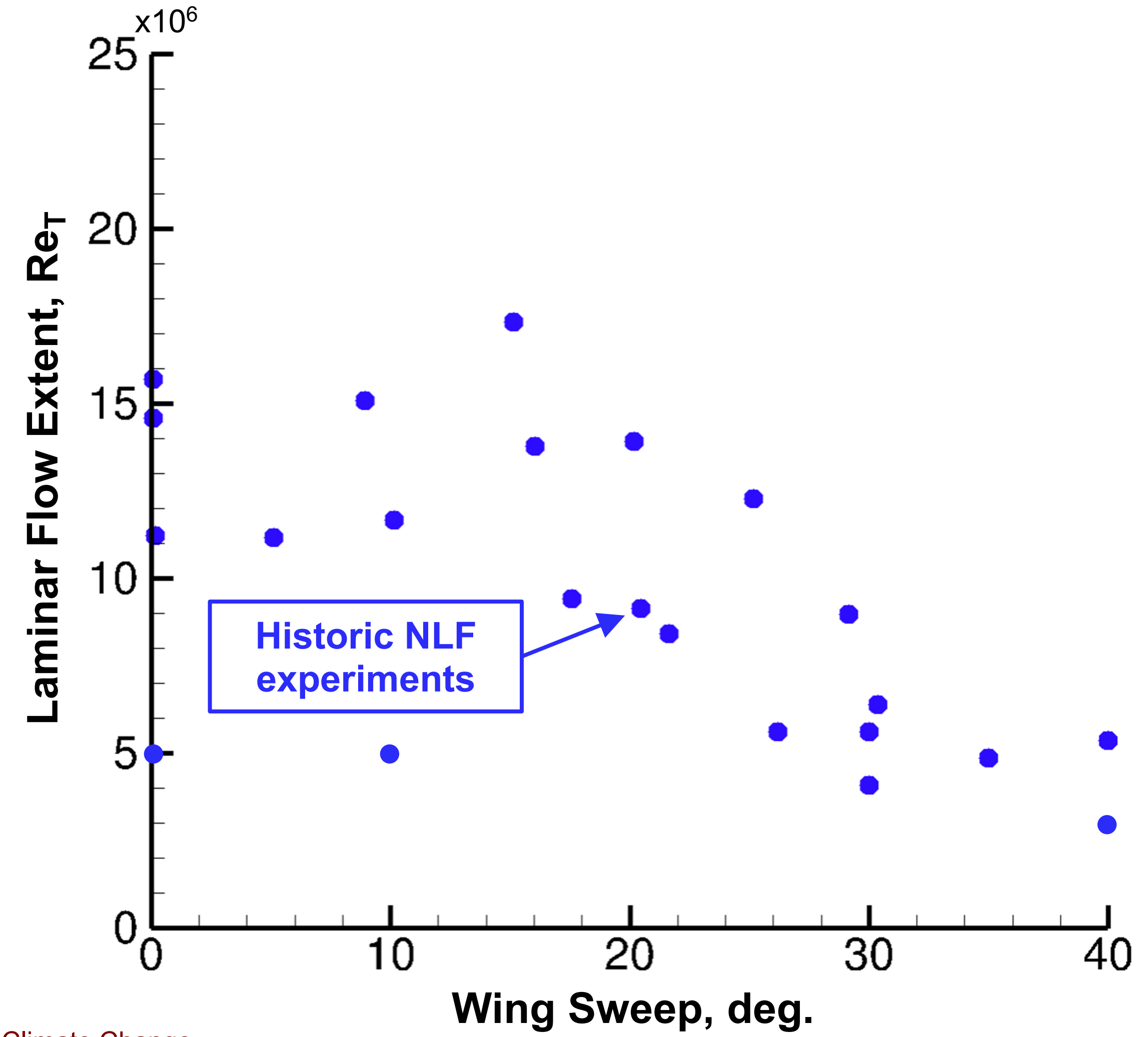


Wind Tunnel Results Relative to Computational Predictions

Good agreement between pretest predictions and experimental extents of laminar flow suggest CATNLF assumptions, tools, and design method are valid

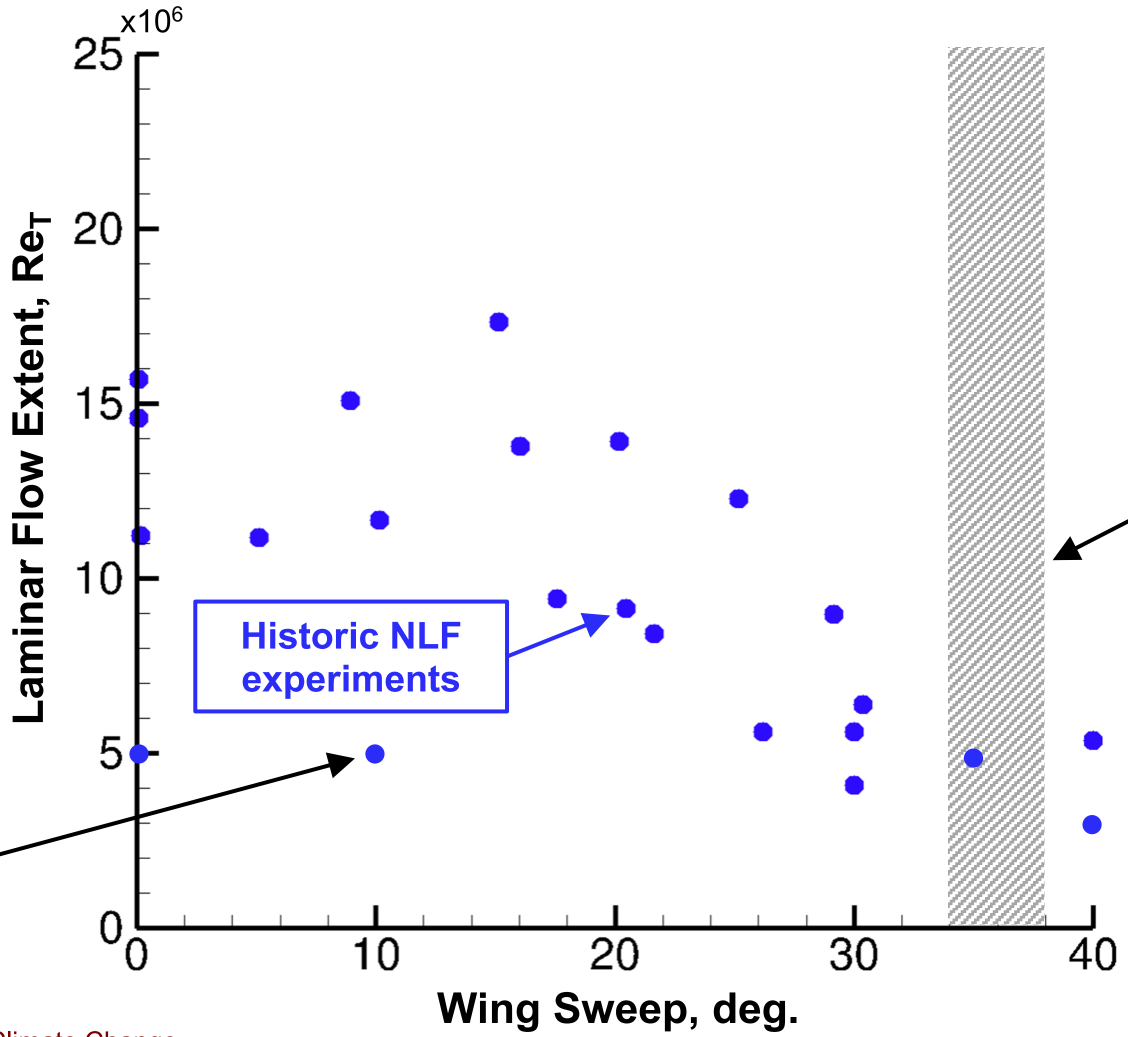


Wind Tunnel Results Relative to Past NLF Experiments



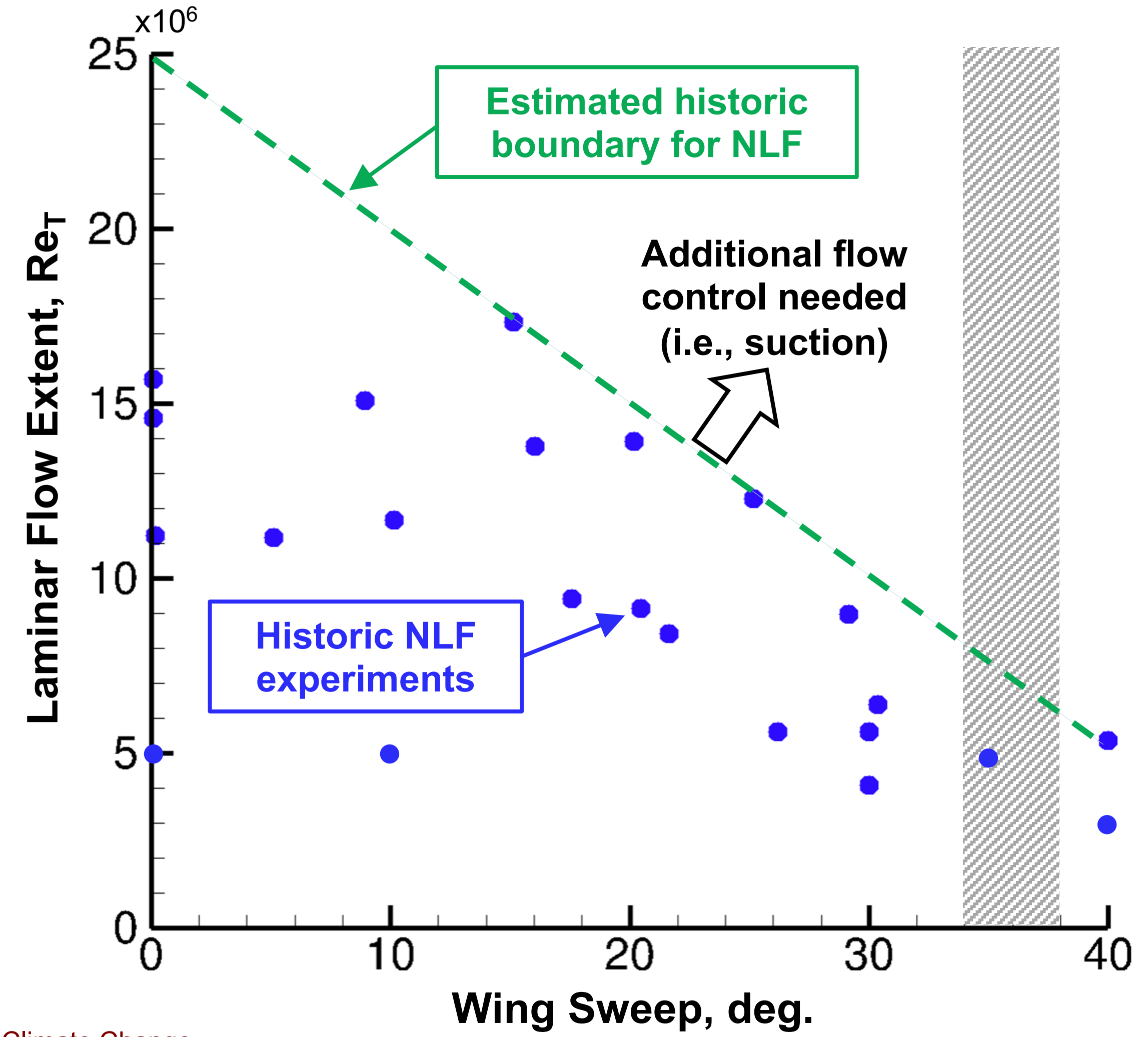
Wind Tunnel Results Relative to Past NLF Experiments

NLF Wing on Honda Jet
Speed = Mach 0.72
Wing Sweep = 10 deg.



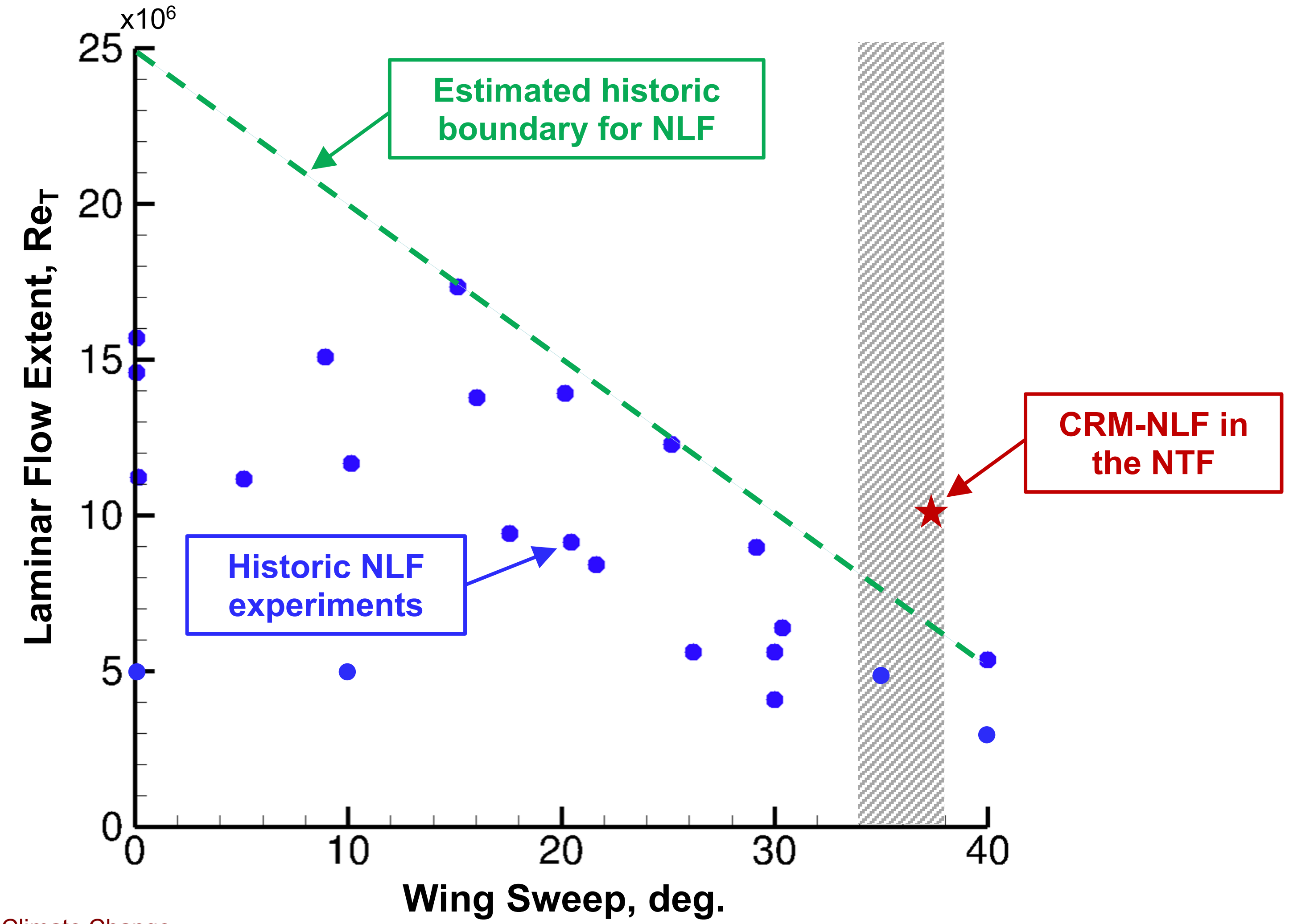
Typical 777-Class Aircraft
Speed ≈ Mach 0.85
Wing Sweep ≈ 34 – 38 deg.

Wind Tunnel Results Relative to Past NLF Experiments



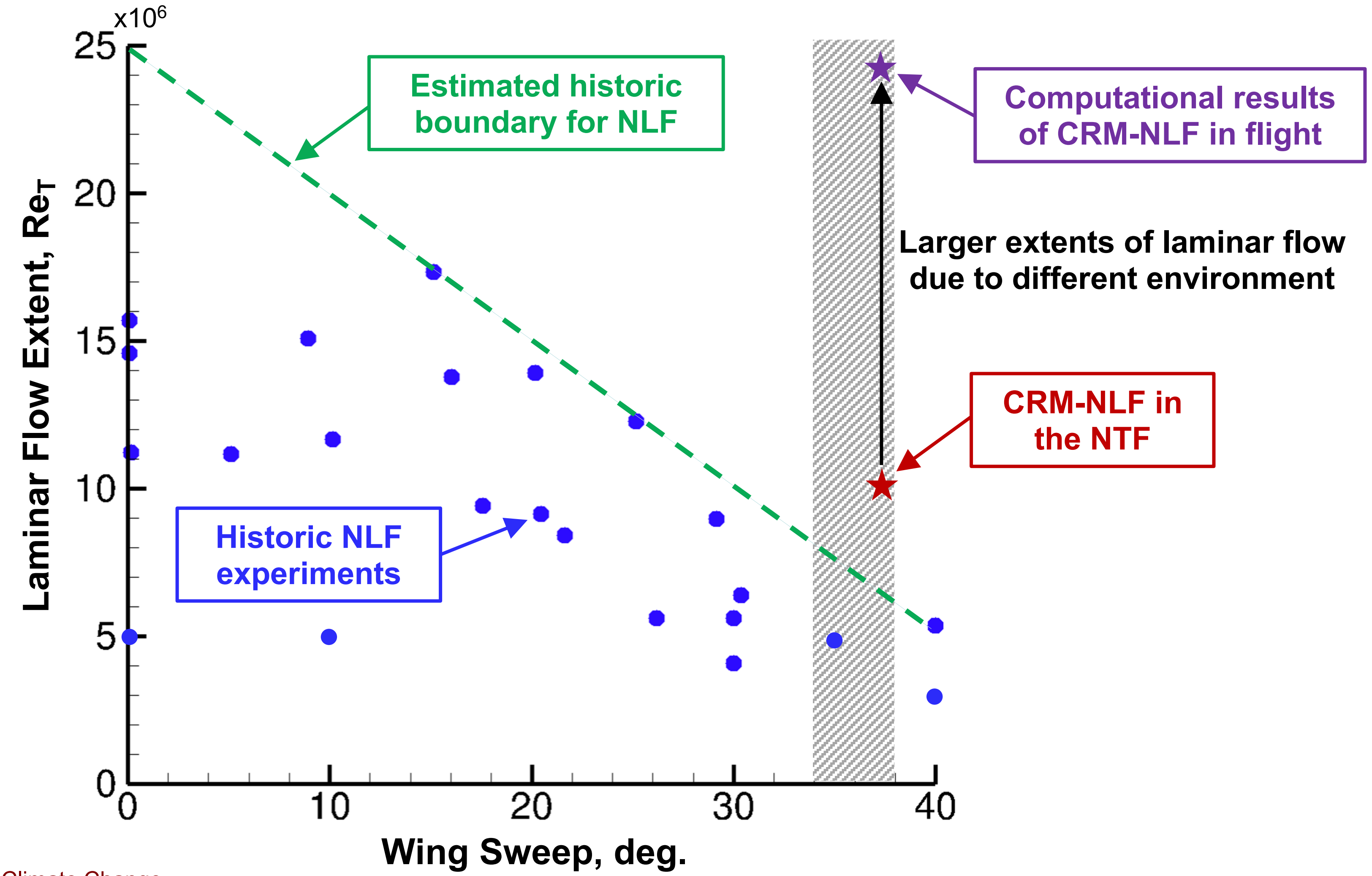
Wind Tunnel Results Relative to Past NLF Experiments

CRM-NLF in the NTF showed extents of laminar flow that nearly double the historic maximum seen at comparable wing sweep

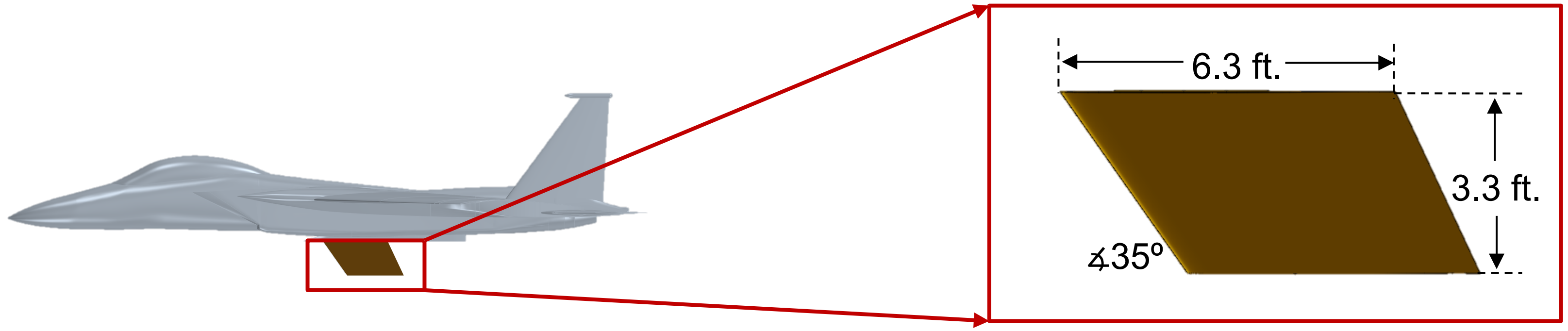


Wind Tunnel Results Relative to Past NLF Experiments

Computational predictions of the CRM-NLF in a flight environment significantly expand the historic boundary for NLF technology



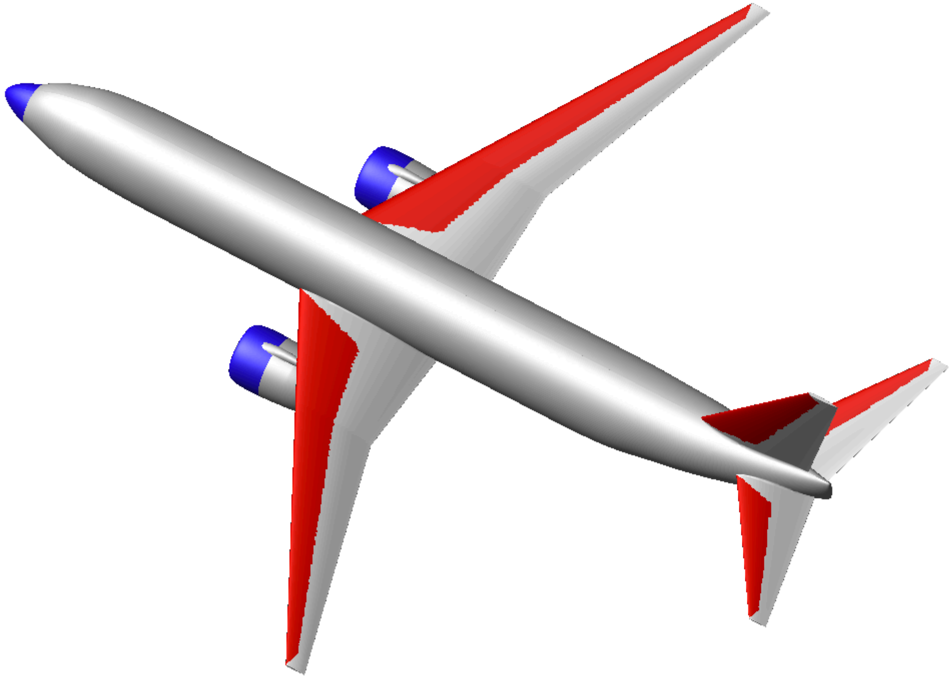
Current Work: CATNLF Flight Test



- Flight testing the CATNLF concept provides a relevant environment (i.e., turbulence levels and model size) and higher Reynolds numbers
- Series of 3 flight tests underneath the F-15 in collaboration with Armstrong Flight Research Center
  - Resistive heating layer experiment for laminar flow detection (2020/2021, AIAA 2020-3089)
  - Flow rake experiment to quantify the flow environment under the F-15 (Summer 2022)
  - CATNLF “stub wing” test article to advance technology (Fall 2022)
- Plans to also test the CATNLF “stub wing” test article in a wind tunnel to provide direct comparison of laminar flow in two environments

Impact of CATNLF and Wind Tunnel Test

- CATNLF offers a practical means to the known NLF performance benefit without historic penalties
  - Speed maintained without adding suction system
  - Compatible with goals for next-generation aircraft
  - CATNLF design method is available to US citizens
- Wind tunnel test data to be used to promote advancement of computational tools
  - CRM-NLF has been released as an open-geometry, similar to baseline CRM
  - Data was used in the recent AIAA Transition Prediction Workshop in January 2021
- Lessons learned during wind tunnel test contribute to establishing best practices for laminar flow testing



CATNLF enables NLF on additional components that have previously been outside the historic NLF boundary

Concluding Remarks

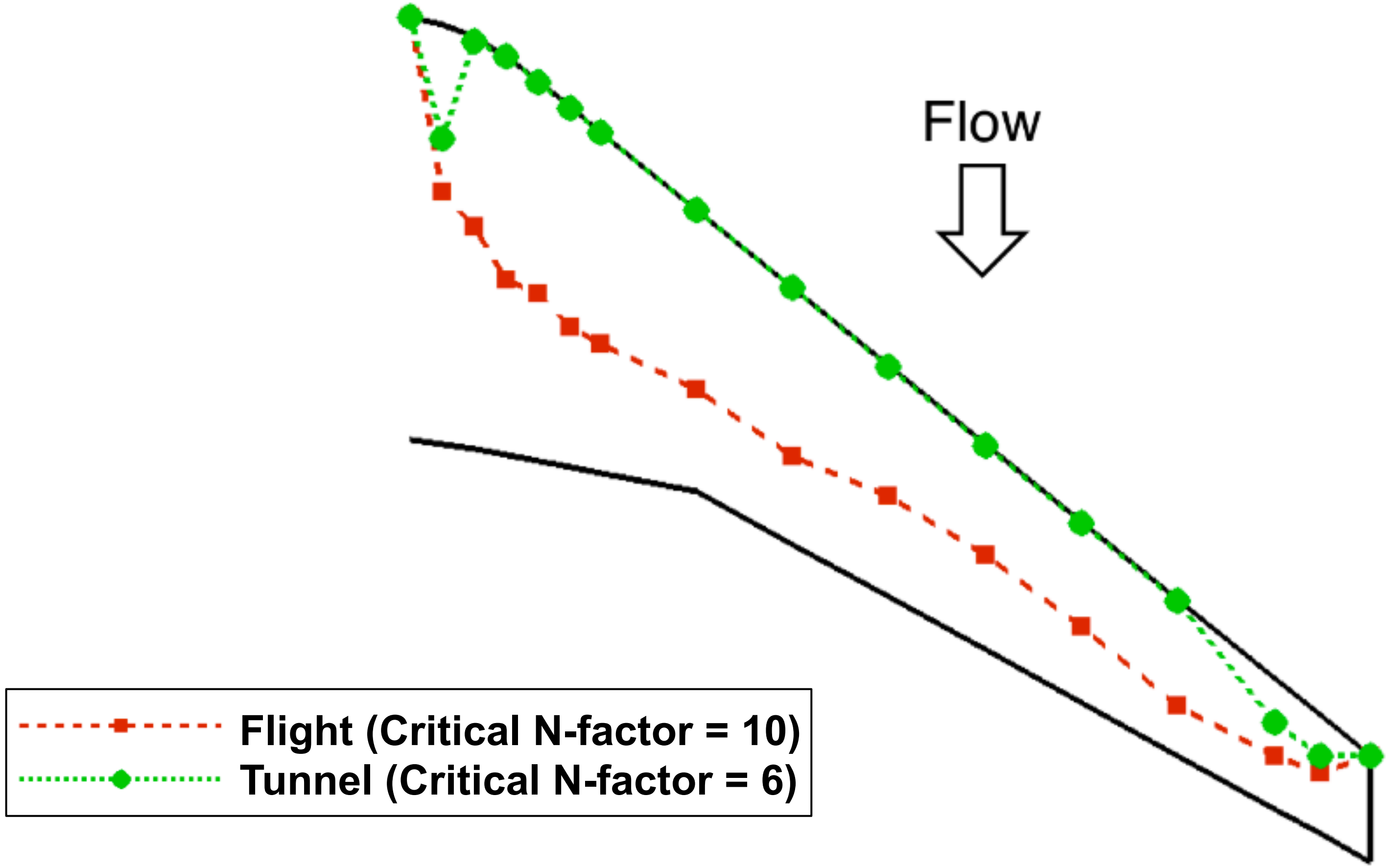
- Laminar flow on transport wings has the potential to reduce fuel burn by 5-10%, but has been limited in practical application due to the challenge of crossflow growth on swept wings
- A new NASA laminar flow design method, CATNLF, has been developed to provide the known NLF performance benefit without historic penalties
- CATNLF design method has been experimentally investigated with a wind tunnel test in the NTF
  - Experimental laminar flow extents agree well with pretest computational predictions
  - Extents of laminar flow nearly doubled any previous NLF experiment at comparable sweeps
  - Results will be used to advance computational tools for the worldwide laminar flow community
- A CATNLF flight test is being developed to experimentally investigate the design method in a flight-relevant environment and advance the technology

Thank You!

Back Up Slides

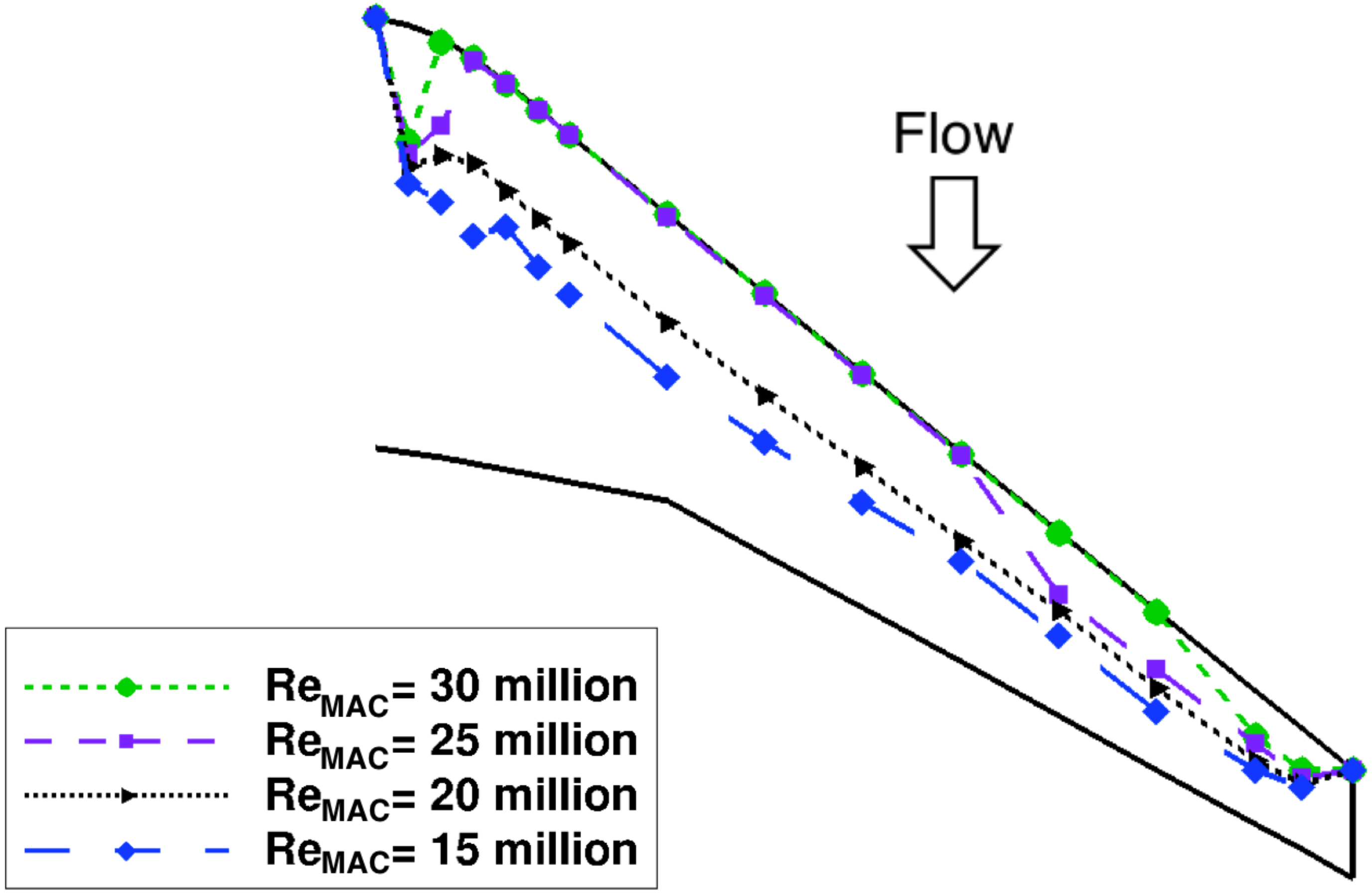
Laminar Flow Extents in Flight vs. Wind Tunnel

Environment (represented by critical N-factor) effects extent of laminar flow



Laminar Flow Extents with Varying Reynolds Number

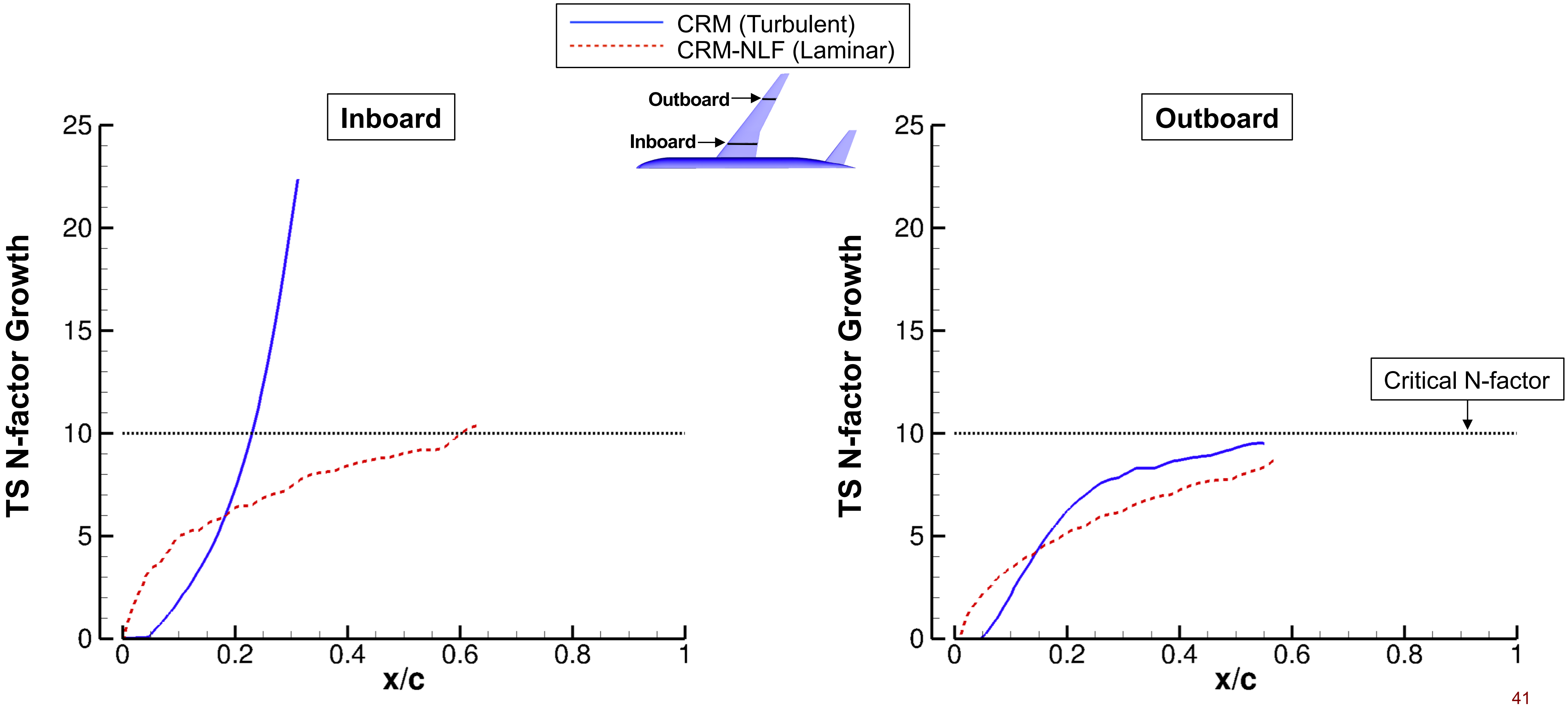
Reducing Re_{MAC} in wind tunnel environment will extend laminar flow



Tunnel Environment (Critical N-factor = 6)

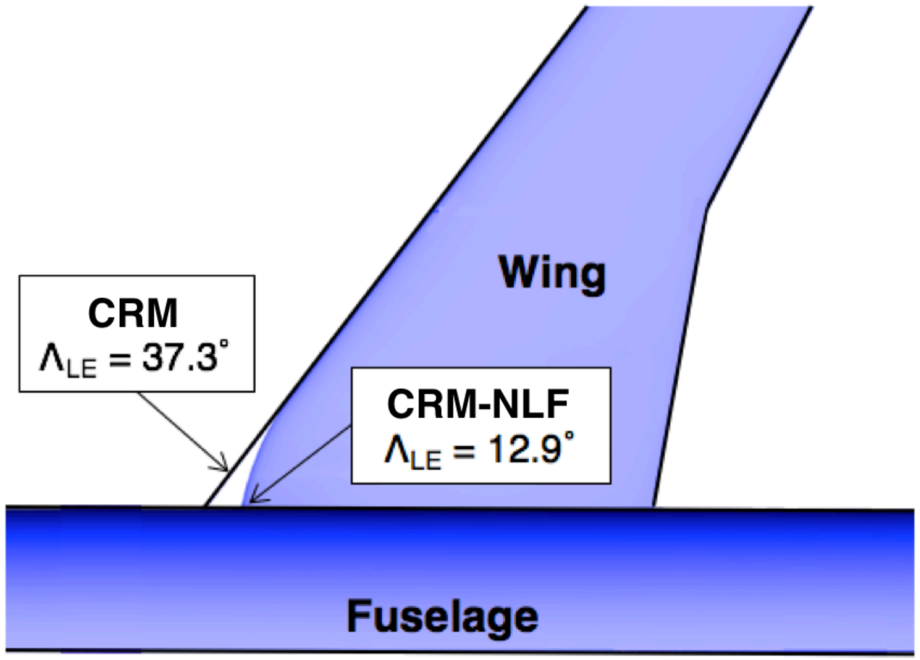
Tollmien-Schlichting Growth Resulting from CATNLF Concept

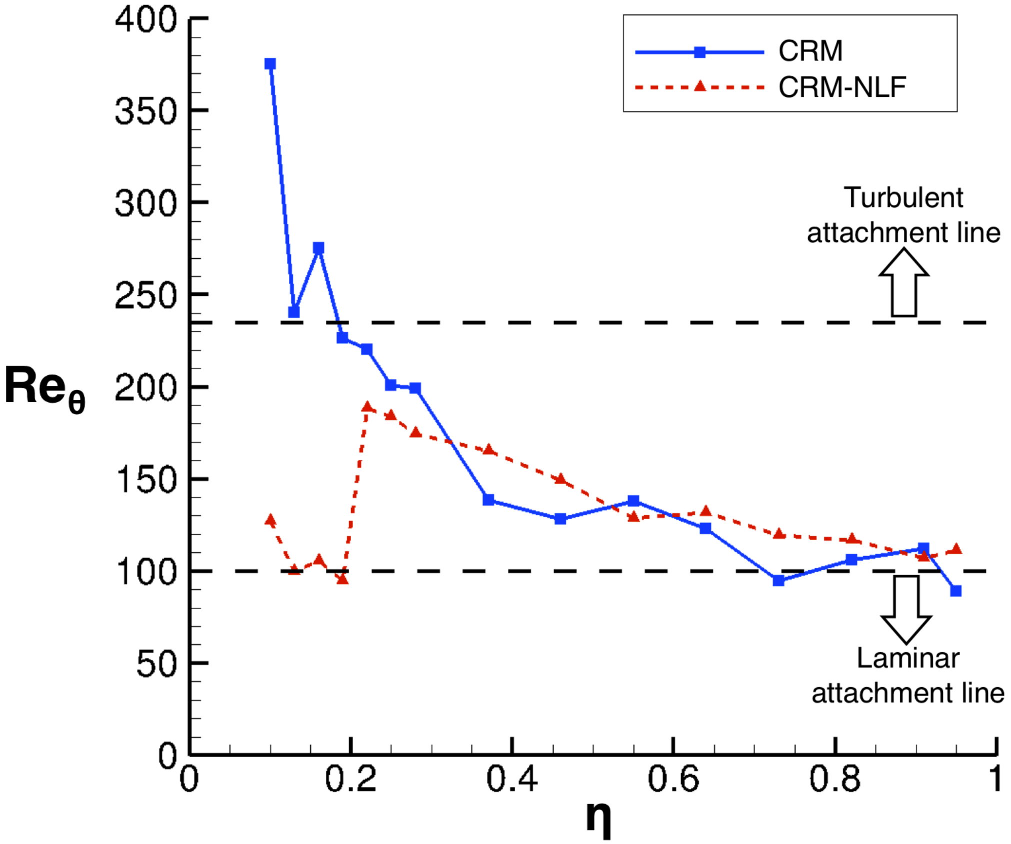
Tollmien-Schlichting (TS) grows gradually to transition location on CRM-NLF



Attachment Line Control on CRM-NLF

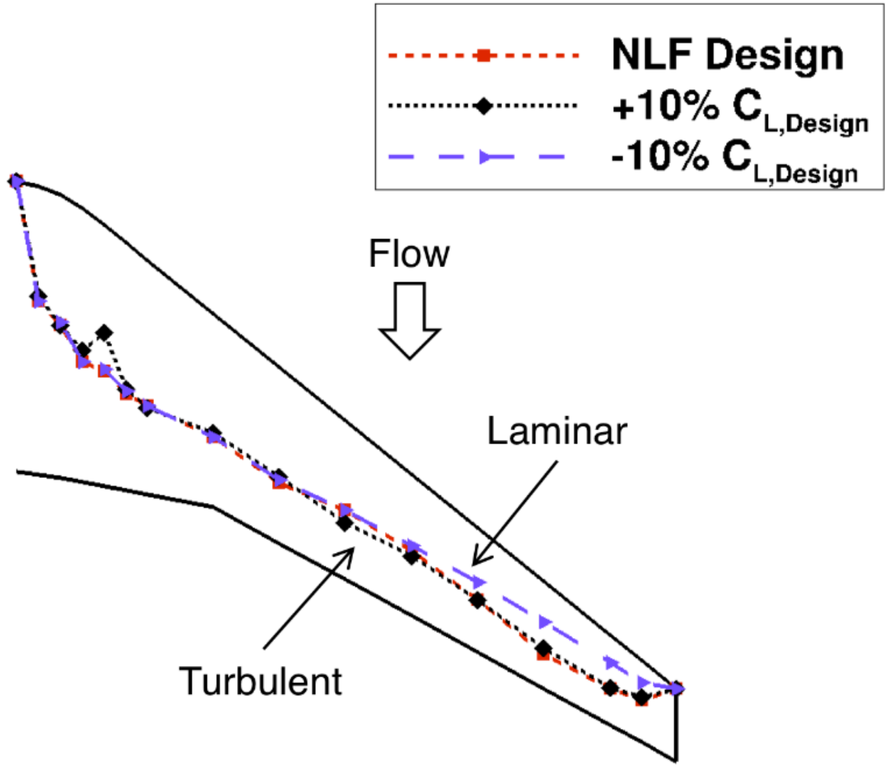
Attachment line contamination is addressed with reduced sweep inboard

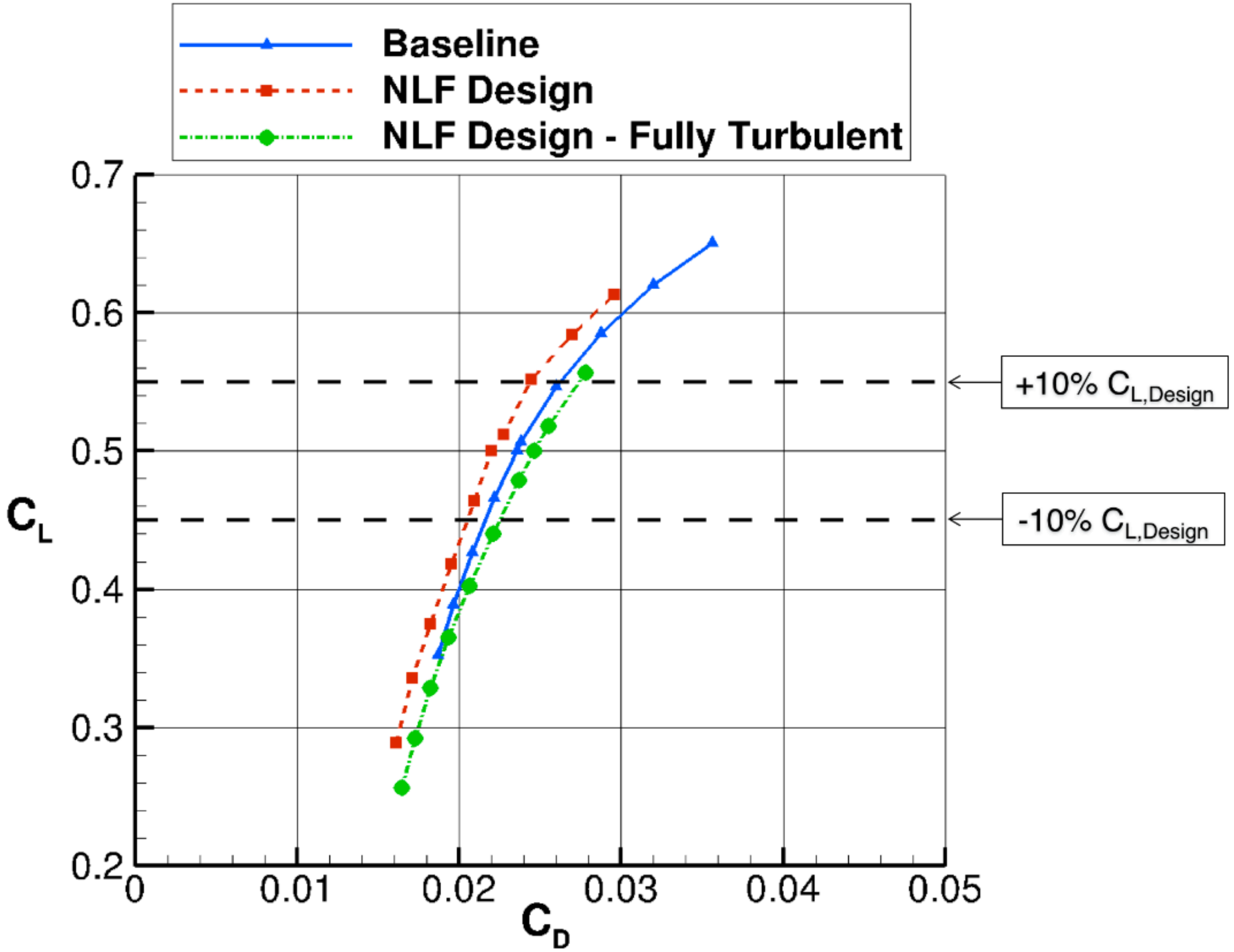




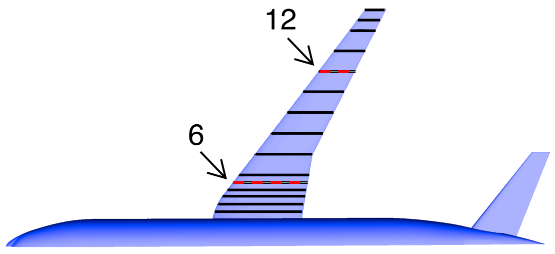
Off-Design Results for CRM-NLF

CRM-NLF shows sustained laminar flow and drag reduction at near-cruise conditions





Changes with Total Loss of Laminar Flow on CRM-NLF



Configuration	C_L	C_D	ΔC_D (from Baseline)
Baseline	0.500	0.0236	
NLF Design	0.500	0.0220	-16 counts (7% savings)
NLF Design (Fully Turbulent)	0.500	0.0246	+10 counts (4% penalty)