National Aeronautics and Space Administration

Drag Reduction Status and Plans – Laminar Flow and AFC

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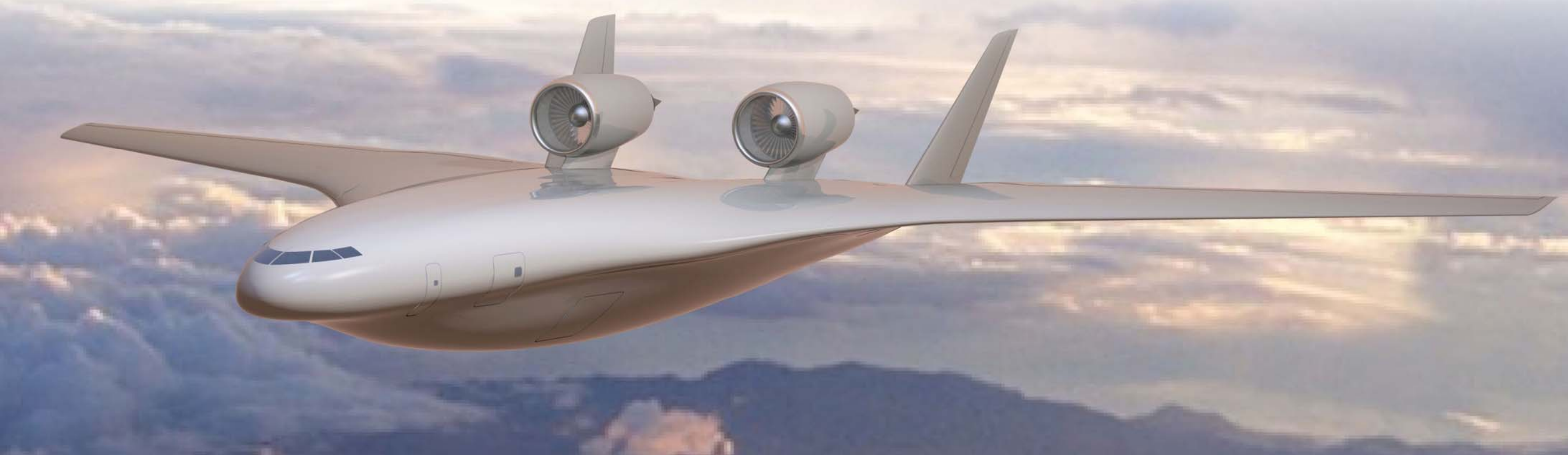
Environmentally Responsible Aviation
Integrated Systems Research Program

Main Contributors – Richard Campbell, William Saric, Israel Wygnanski, Ethan Baumann, Rudolph King



AIAA Aero Sciences Meeting
January 4-7, 2011

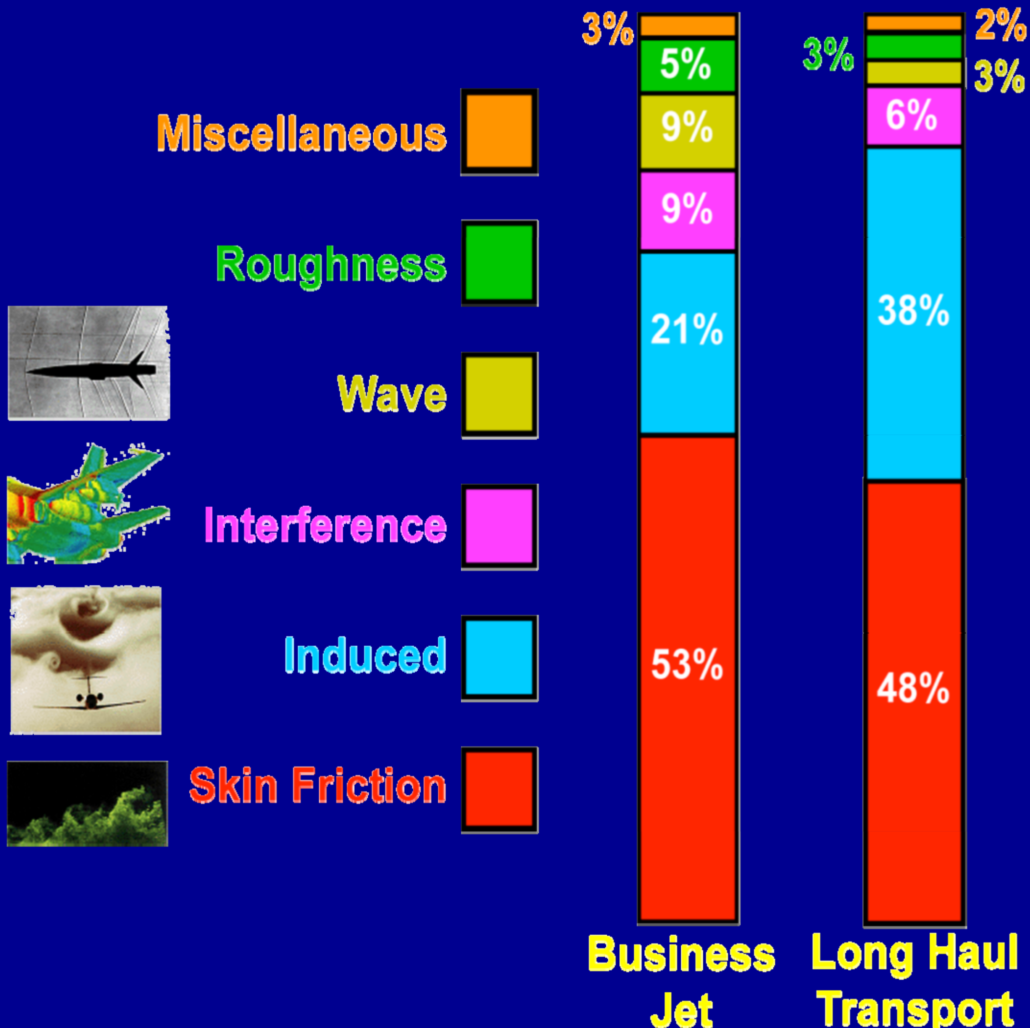
Agenda

- Comments on ERA Project and Drag Reduction
- Active Flow Control Activity
  - Active Flow Control Applied to Rudder
- Laminar Flow Activities
  - Laminar Flow Ground Testing
  - Laminar Flow Design Tools
  - Demonstration of Discrete Roughness for Hybrid Laminar Flow Control
- Concluding Remarks

ERA Technology Portfolio

- Environmentally Responsible Aviation (ERA)
  - o Focused on National Subsonic Transport System Level metrics for N + 2 timeframe
  - o System research bridging the gap between fundamental (TRL 1-4) and product prototyping (TRL 7) in relevant environments
  - o Innovative technologies for TRL 6 by 2020; critical technologies by 2015
- ERA is two phase project
  - o 2010 – 2012 (Phase 1)
    - Investments in broadly applicable technology development
    - Identify vehicle concepts with potential to meet national goals
    - High fidelity systems analysis for concept and technology trades and feasibility
  - o 2013 – 2015 (Phase 2)
    - Investments in a few large-scale demonstrations with partners

Potential Fuel Burn Improvements
Typical Contributions to Drag



System Assessments

325 Passenger, 4,000 nm

	Fuel Savings
Airframe Wt (-10%)	-7%
SFC (-10%)	-14%
L/D Cruise (+10%)	-13%
Skin Friction (-10%)	-9%
Induced Drag (-10%)	-6%

Merac (ONERA, 2000) and Bushnell & Hefner (AGARD 654)

Potential Drag Reduction Targets

- **Skin Friction Drag** – Laminar Flow (LF) Technologies, Active Flow Control (AFC) for wetted area reduction, turbulent drag reduction
- **Induced Drag** – configuration dominated, increased aspect ratio, wing tip devices, adaptive trailing edges, active load alleviation, *enabled by lightweight/multi-functional structures*
- **Interference Drag** – configuration dominated, propulsion/airframe integration, trim characteristics
- **Wave Drag** – configuration dominated, shock/boundary layer interactions, adaptive trailing edges/compliant structures
- **Roughness Drag** – joints, fasteners, manufacturing, operations

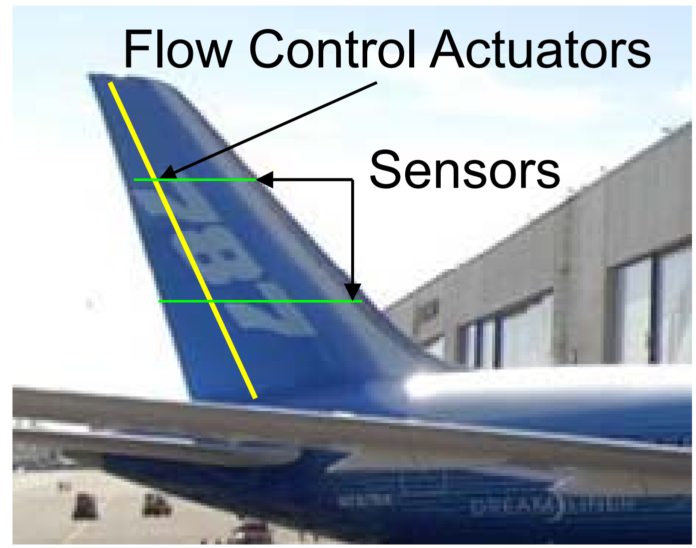
Active and Passive Concepts

Overcome practical barriers to 50% fuel burn goal through demonstration of cruise drag reduction by integrated technologies

Active Flow Control (AFC) Applied to Rudder

PI – Israel Wygnanski/Edward Whalen

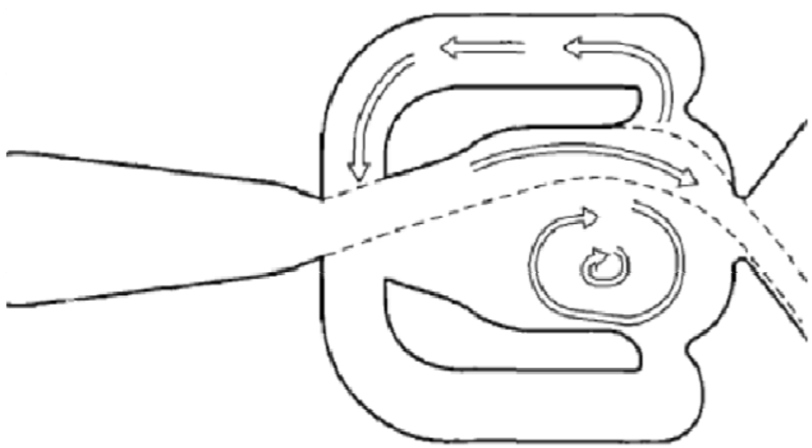
- Use AFC on vertical tail to increase on-demand rudder effectiveness
- Most Critical Condition: Vertical tail sized for engine-out on takeoff
  - High thrust engines increase required tail size
  - Large tail increases weight and cruise drag
- Target: Increase rudder effectiveness with AFC
  - AFC used to increase circulation at rudder deflection angles with natural separation
  - More effective rudder yields smaller tail
  - AFC operates only during take-off and landing
  - Critical conditions - 100-150 knots, sideslip ±15°, rudder ±30°



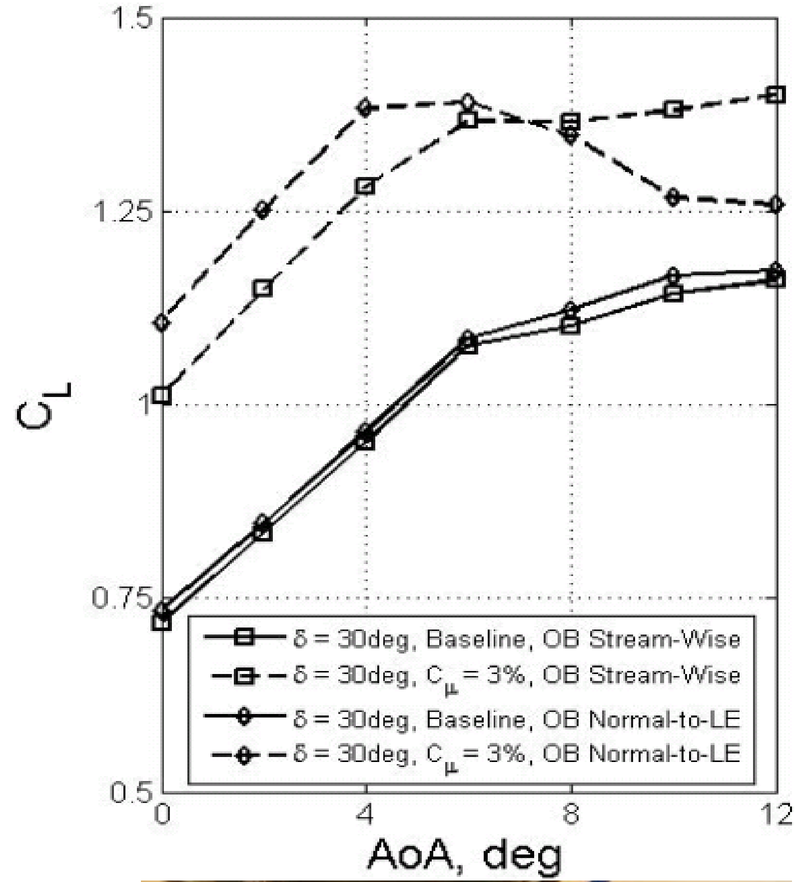
Notional AFC Approach

AFC Technology Maturation

- AFC previously demonstrated to enhance circulation around lifting surfaces
  - Numerous lab/wind tunnel demonstrations
  - XV-15 Flight Demonstration
- Use pulsed or periodic actuation to increase efficiency



Sweeping Jet Actuator Concept



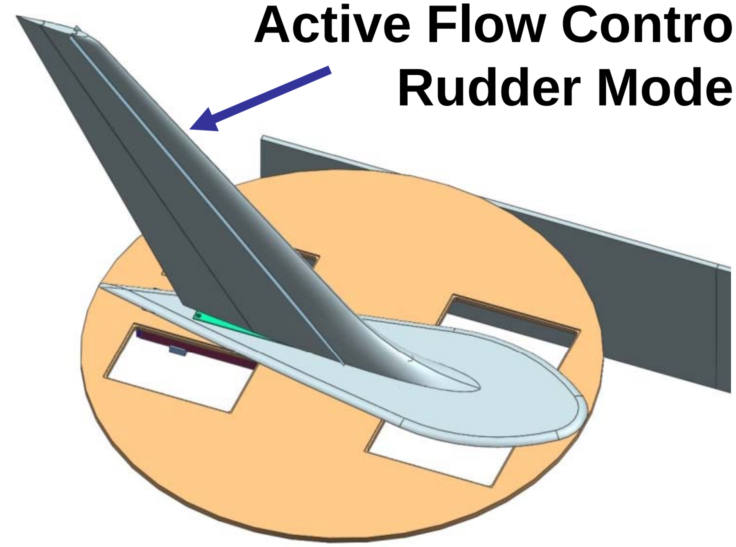
Effect of AFC on Wing

AFC Rudder System Integration Study
Increasing TRL

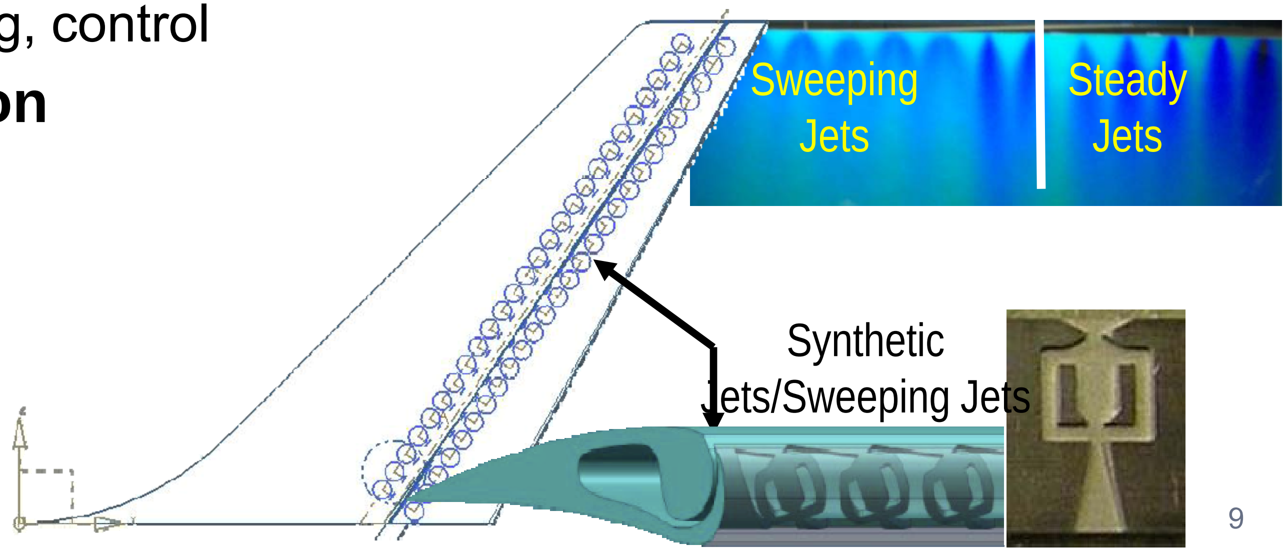
- AFC benefits applied to generic wide-body family
- Conventional planform, chord ratio, single hinged rudder
- Structural approach consistent with modern vertical tails
- Performance requirements/cost benefits for two actuation approaches evaluated
    - Synthetic jets
    - Sweeping jets
    - Comparison of preventive or corrective use of actuation
- Identify the most critical tail and rudder size constraints
- Determine limits of vertical tail size reduction
    - AFC effectiveness limit
    - Other sizing criteria (e.g. cruise stability requirements)
- Generate target size reductions based on known AFC effectiveness and sizing criteria

Drag Reduction – Active Flow Control
Increased On-Demand Rudder Effectiveness with AFC

- **AFC system development – near term**
  - NASA/Boeing partnership (RPI, Caltech)
  - Screen 2 actuators at Caltech Lucas Tunnel – Spring 2011
    - 1.2m span, 33% rudder, 50° rudder deflection
    - Modular model
    - Complimentary CFD/flow field measurements
- **AFC system development – mid term**
  - Large tunnel test in 2012 with full-scale actuators
  - Testing, simulation, modeling, control
- **AFC system demonstration**
    - Flight test in 2013



BOEING CALTECH Rensselaer

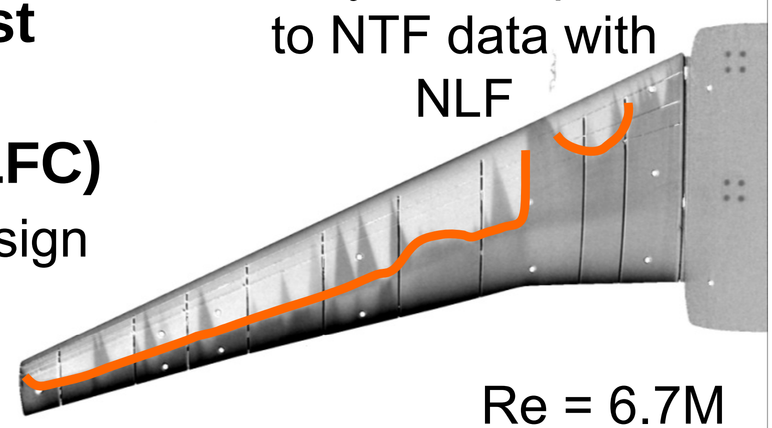


ERA Laminar Flow Technology Maturation Objectives

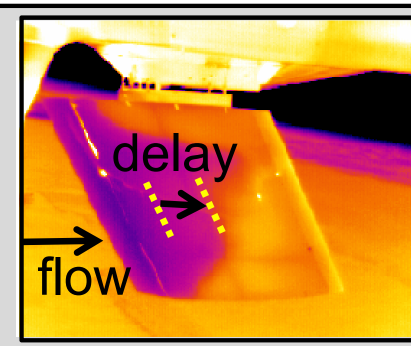
System studies require integration of laminar flow to meet fuel burn goals

– **Develop and demonstrate usable and robust aero design tools for Natural Laminar Flow (NLF) and Hybrid Laminar Flow Control (HLFC)**
  - Link transition prediction to high-fidelity aero design tools
– **Explore the limits of CF control through Discrete Roughness Elements (DRE)**
  - Practical Mach, Re demonstration at relevant C_L
  - Potential control to relax surface quality requirements
– **Seek opportunities for integration of NLF, HLFC, and/or DRE into flight weight systems**
  - Understand system trades through demonstration
– **Assess and develop high Reynolds number ground test capability**

Analysis compared to NTF data with NLF



Re = 6.7M



DRE effect, low M, low Rn

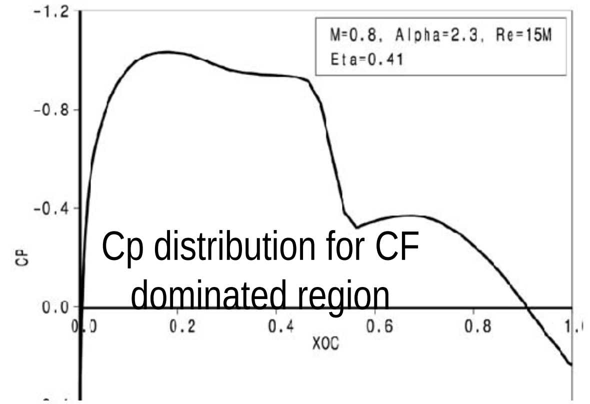
Design of Laminar Flow Wings

- **Laminar flow approach is dependent on system requirements and trades**
  - Mach/Sweep, Re, Cp distribution, high-lift system, stability and control
  - Aircraft components and laminar extent of each
  - Swept-wing laminar flow is design tradeoff between Tollmien–Schlichting and Crossflow transition modes
- **Challenges**
  - Required favorable pressure gradient and sweep limitations can increase wave drag for transonic design – counter with thinner airfoil
  - Multi-point design complicated by need to consider loss of NLF
  - Leading edge radius limit and restrictions on leading edge high-lift devices can impact low-speed performance
  - Manufacturing and maintenance tolerances tighter (surface finish, steps, gaps, design/operation affected by loss of NLF in flight (insects, ice)
  - Ground testing at flight Reynolds numbers currently not practical

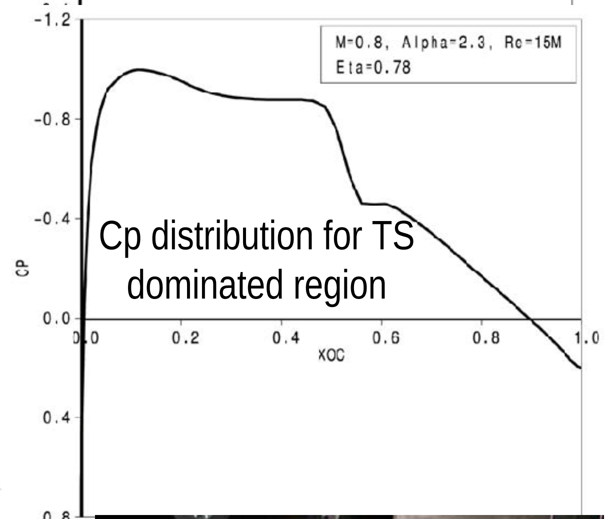
Ground Facility Capability for Laminar Flow Testing

PI – Rudolph King

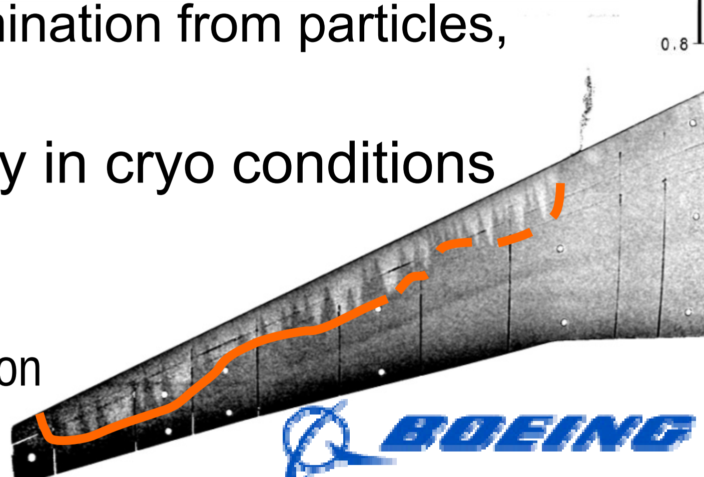
- Boeing/NASA test in NASA National Transonic Facility (NTF) at High Re (AIAA 2010-1302)
- M = 0.8, 25° leading edge sweep design for laminar flow with mix of TS and CF transition at Re between 11 – 22 million
  - Designed with non-linear full potential equations with coupled integral boundary layer code
  - Instability growth and transition prediction calculations by compressible linear stability code
- Laminar flow lost at higher Re numbers
  - Turbulent wedges emanating from leading edge of wing
  - Suspect attachment line contamination from particles, frost, and/or oil
- Spring 2011 flow quality survey in cryo conditions



Cp distribution for CF dominated region

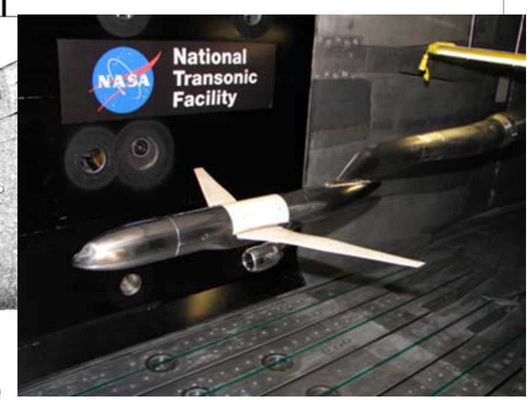


Cp distribution for TS dominated region



Analysis compared to NTF transition measurements at Re = 22 M/ft

BOEING



NLF model in NTF

Aero Design Tools for Laminar Flow
PI – Richard Campbell

- Approach to NLF Design with CFD
  - Develop multi-fidelity boundary layer transition prediction capability and couple with an advanced CFD flow solver
  - Develop a robust multipoint NLF design strategy and implement in the CDISC knowledge-based design method
  - Validate the design approach using wind tunnel test results and/or high-fidelity boundary layer stability analysis

Multi-Fidelity Transition Prediction Capability

- USM3D flow solver selected for 3-D method development
  - solves Navier-Stokes equations on unstructured grid using cell-centered, upwind method
  - Recent modifications allow specification of boundary layer transition location for Spalart-Allmaras and various 2-equation turbulence models, includes approximation to transition region to reduce abrupt changes in flow

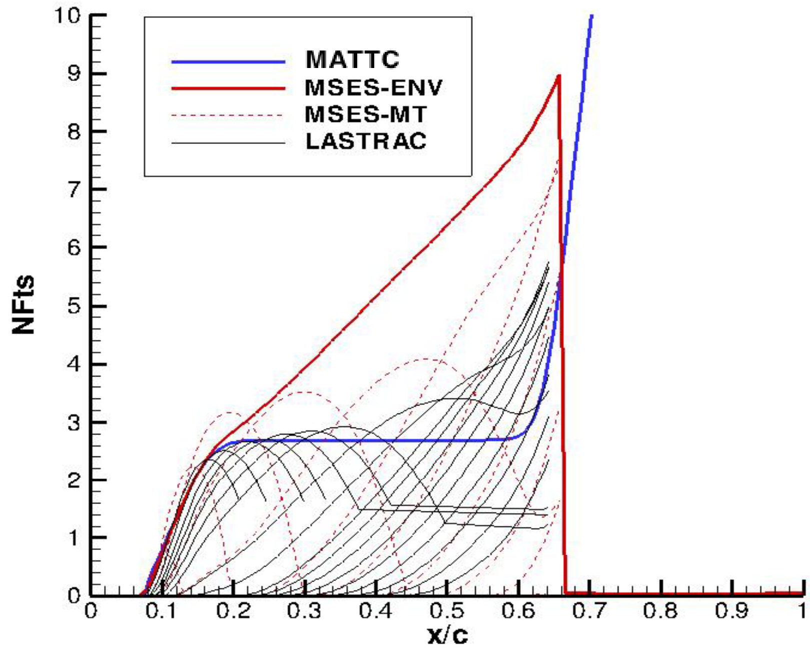
- Candidate transition prediction modules for various fidelity levels

Low	MOUSETRAP (NASA)
Medium	MATTC (NASA)
Medium	RATTraP (Lockheed/AFRL)
High	LASTRAC (NASA)

- Currently, MOUSETRAP and MATTC have been linked with USM3D using a Linux script to provide an initial automated 3-D transition prediction capability

MATTC Transition Prediction Method

- Modal Amplitude Tracking and Transition Computation
- Computes transition location based on empirical correlations
  - transition studies using 3 airfoils run in MSES and LASTRAC
  - TS: Re = 0.25 - 30 million
  - CF: Re = 10 - 30 million, sweep = 10 - 30 degrees
- x_{tr} = f(Re,dCp/dx,x), with sweep included for CF
- No boundary layer information required, provides n-factor envelope



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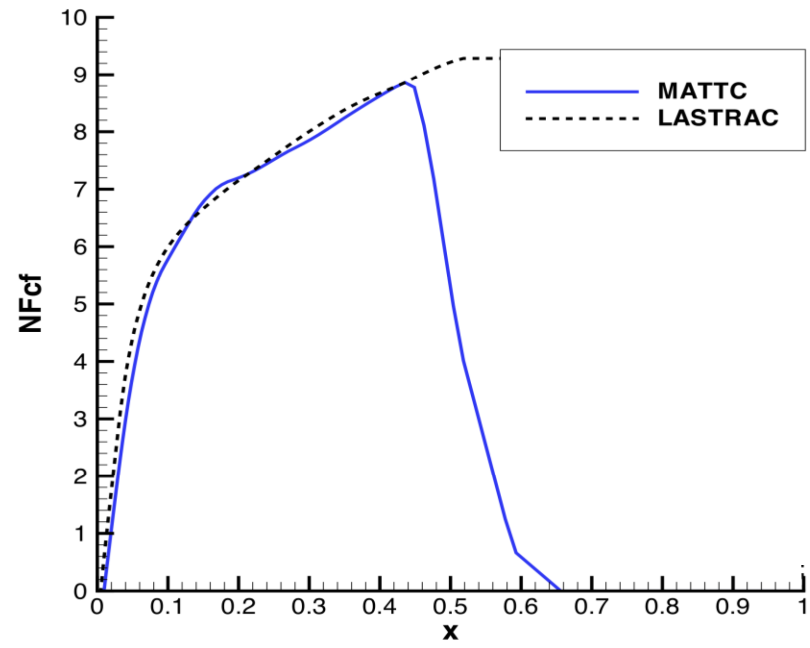
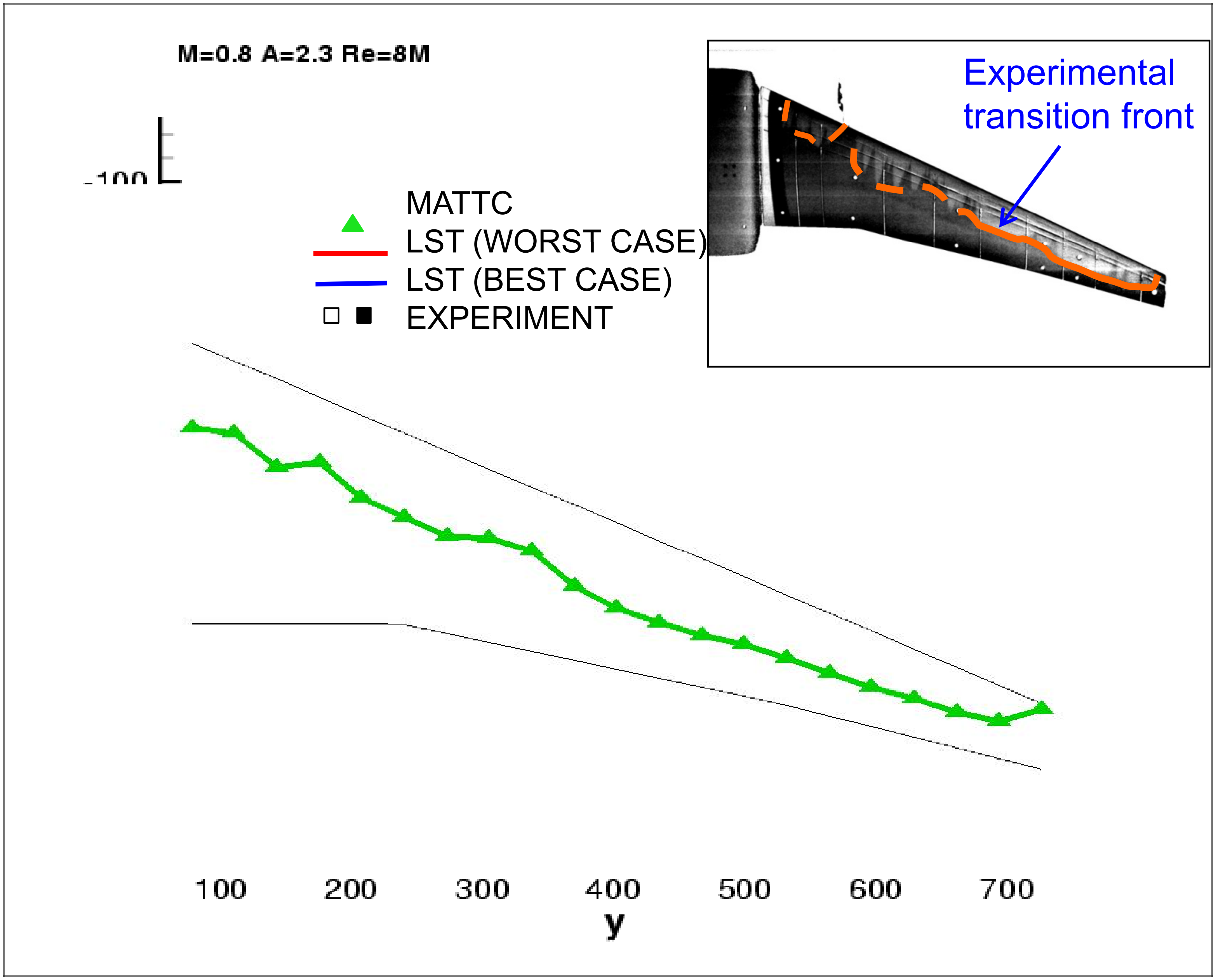
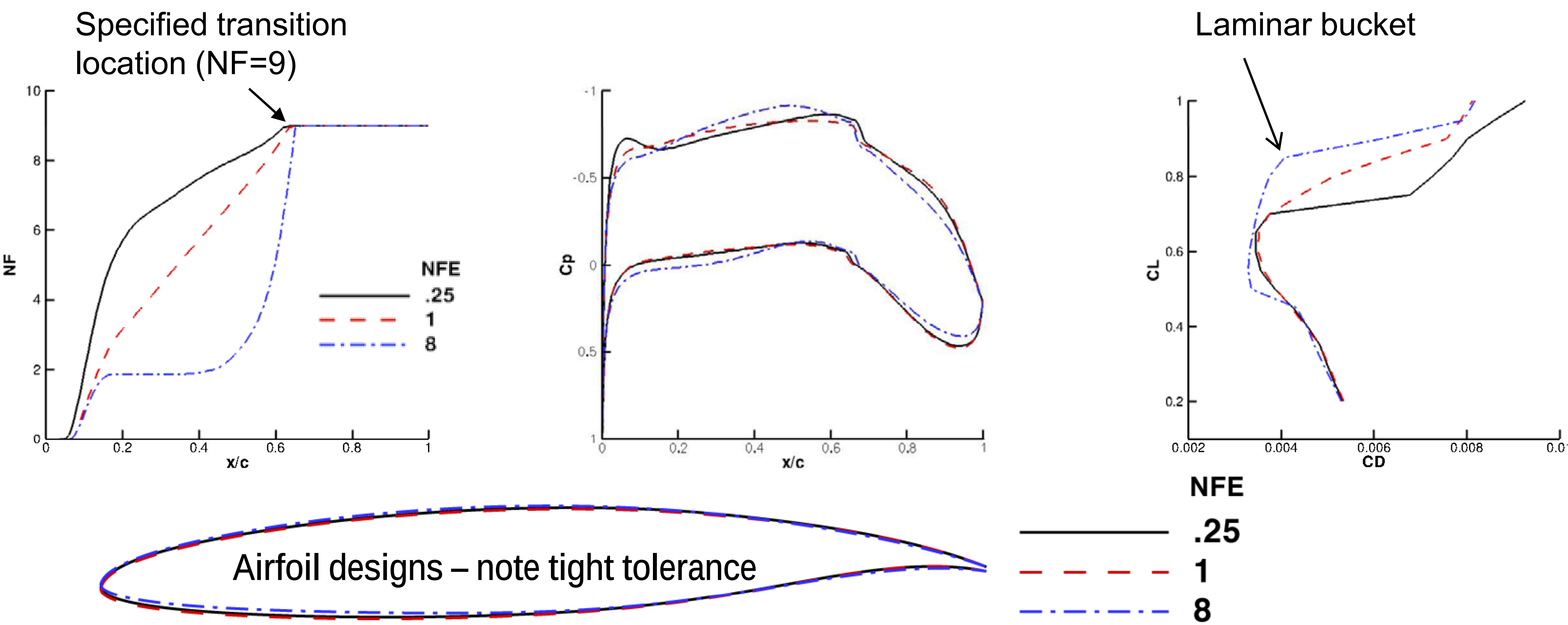


Comparison of MATTC/USM3D Results with Wind Tunnel and other CFD Results



“Knowledge-Based” NLF Airfoil Design with CDISC NLFCP Constraint



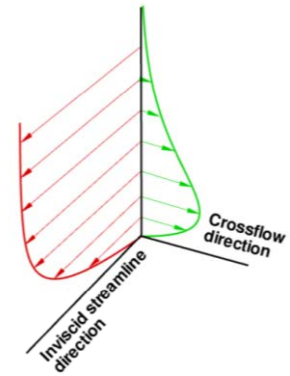
- New knowledge-based approach for design to a specified TS N-factor distribution
- Laminar “drag bucket” characteristics can be related to the N-factor family exponent (NFE)
- New approach compatible with other CDISC design method flow and geometry constraints for practical 3-D design
- Independent analysis by Streit at DLR using Schrauf’s LILO method confirmed TS results and indicated robust CF performance

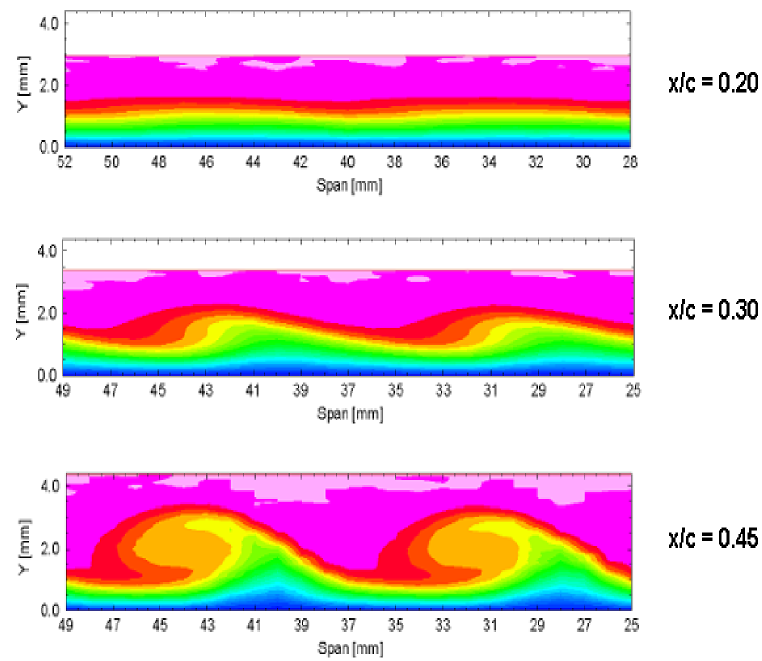
Hybrid Laminar Flow Control with Discrete Roughness

PI – William Saric

Crossflow transition delay possible on swept wing

- Judiciously designed Cp distribution
- Passive, spanwise periodic Discrete Roughness Elements (DRE) near attachment line (Saric et al. 1998)
  - controls growth of spanwise periodic crossflow instability
  - Introduces weakly growing wavelength at half most amplified wavelength through stability analysis
  - modified mean flow is stable to all greater wavelengths
  - Restricts TS waves due to more stable 3D wave





FLIGHT RESEARCH LABORATORY

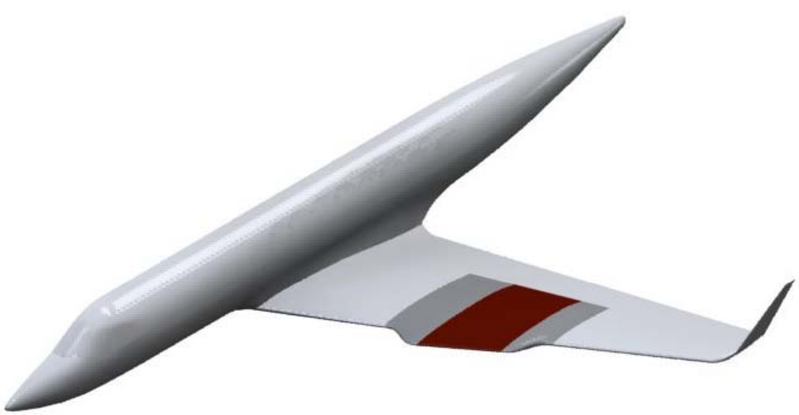
Texas A&M University

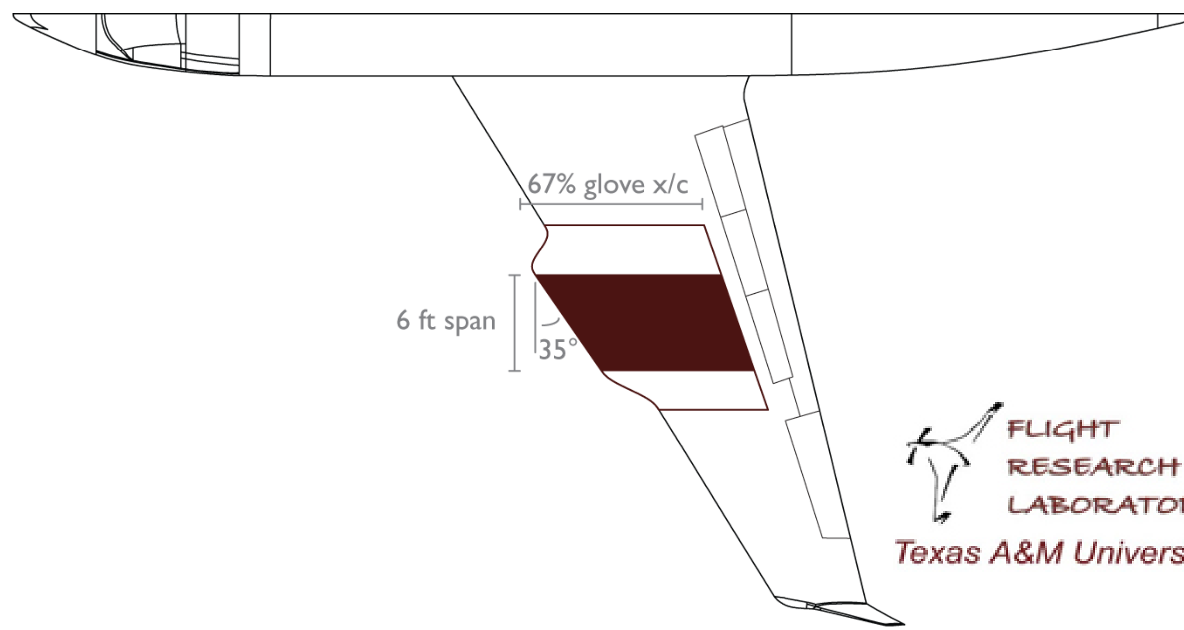
Flight Demonstration of DRE

- DRE technology previously demonstrated in flight (Saric et al. 2010; Rhodes et al. 2010)
  - chord Re_c = 7.5M
  - 30° swept wing
- ERA Goal: Demonstrate DRE on NASA DFRC G-III SubsoniC Research AircrafT (SCRAT)
  - Re_c characteristic of transport aircraft (up to 30 million)
  - Relevant wing loading (section $C_l \geq 0.5$)
  - Mach range from 0.66 to 0.76
  - Nominal cruise for host aircraft (around 3.5° - 4.0°)

SARGE Wing Glove Layout and Objectives

- SARGE is an instrumented wing glove designed to demonstrate hybrid laminar flow control on both the pressure and suction sides of the glove
- Primary Goal:
  – At Re_c up to 22 million, SARGE will demonstrate natural laminar flow (NLF) to 60% x/c (glove chord) on the suction side and 50% x/c on the pressure side
  – At $Re_c \geq 22$ million, DREs will be used to increase laminar flow on the suction side by at least 50% (e.g. if natural transition occurs at 40% x/c, DREs will be used to delay transition to 60% x/c)
- Secondary Goal: Demonstrate ability of DRE overcome surface quality on leading edge by textured paint finishes





FLIGHT RESEARCH LABORATORY
Texas A&M University

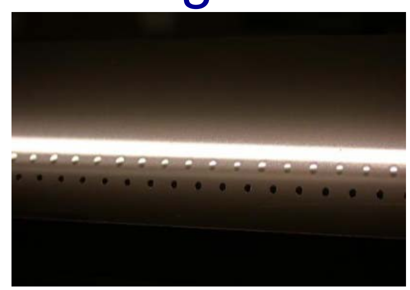
SARGE Glove Design Cycle

Design philosophy

- *t/c* and C_L are design points
- Design pressure minimum as far aft as possible
  - Subcritical to TS instability
  - Restrict leading edge radius to R_θ <100 for subcritical attachment line
- Iterate *Cp* distribution with stability calculations for crossflow control
  - Euler and Navier-Stokes for Cp and BL
  - Orr-Sommerfeld for stability
  - Parabolized Navier-Stokes for final assessment

- DRE appliqué with with diameter of 1.5 mm, height of 6-12 microns, wavelength of ~ 4 mm along *x/c* = 1%
- Demonstrate validity at Mach, CL, and Re before addressing *potential* need for reconfigurable actuators

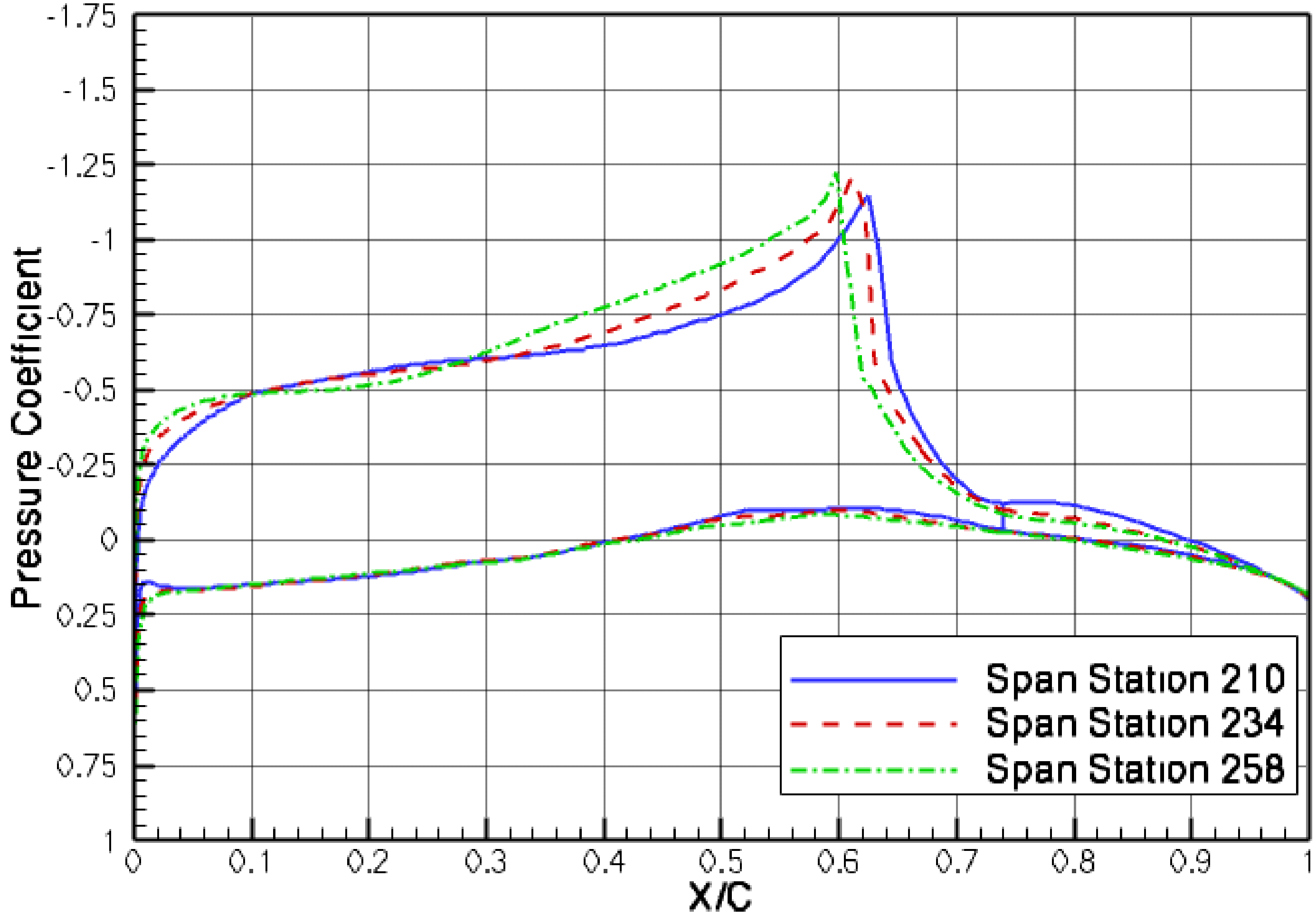
Wing



Discrete Roughness Elements

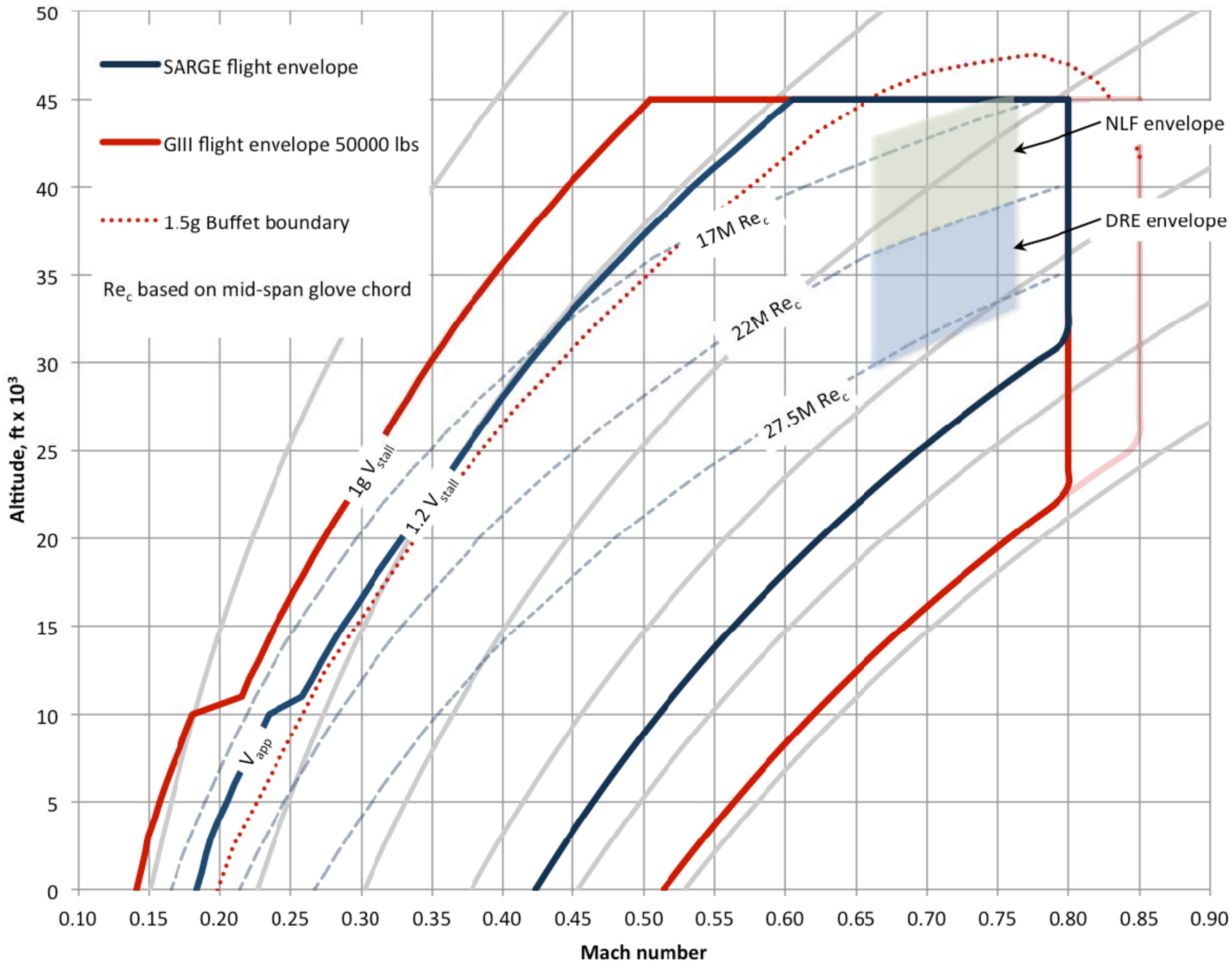
SARGE Glove Design Status

Pressure distribution near C_l of 0.5, M = 0.75, H = 41300 ft, AoA = 3.3°



SARGE Flight Envelope

- Experiment will demonstrate hybrid laminar flow control over a wide range of Mach and Re_c
  - mid-span Re_c = 17 – 22M for NLF, and Re_c = 22 – 27.5M for DRE control



Partners in ERA Drag Reduction Activities

- Texas A&M University - William Saric, Helen Reed, Joseph Kuehl, Michael Belisle, Matthew Roberts, Aaron Tucker, Matthew Tufts, Thomas Williams
- Boeing Research and Technology - Edward Whalen, Arvin Smilovich
- Boeing Commercial Airplanes - Doug Lacy, Mary Sutanto, Jeffrey Crouch
- Rensselaer Polytechnic Institute - Miki Amitay, Helen Mooney, Sarah Zaremski and Glenn Saunders
- California Institute of Technology - Mory Gharib, Roman Seele
- Iowa State - Richard Wlezien
- Air Force Research Lab - Gary Dale

- Relevant Papers at 2011 AIAA Applied Aero Conference
  - *Progress Toward Efficient Laminar Flow Analysis and Design*, R. L. Campbell, M. L. Campbell, T. Streit
  - *Design of the Subsonic Aircraft Roughness Glove Experiment (SARGE)*, M.J. Belisle, M.W. Roberts, M.W. Tufts, A.A. Tucker, T. Williams, W.S. Saric, H.L. Reed
  - *Computational Analysis of the G-III Laminar Flow Glove*, M. Malik, W. Liao, E. Lee-Rausch, F. Li, M. Choudhari, C-L Chang

Concluding Remarks

- ERA Project Drag Reduction Investments
  - Phase 1 - broadly applicable viscous drag reduction technologies
  - Phase 2 – Select a few large scale demonstrations including drag reduction technologies
- Address critical barriers to practical laminar flow
  - Design and Integration
  - Surface tolerances, steps, and gaps
  - Maintenance and operations – ice, insects, etc.
- Demonstrate feasibility of Discrete Roughness Elements (DRE) as form of hybrid laminar flow control for swept wings