TICKLE
COLLEGE OF ENGINEERING

DEPARTMENT OF
MECHANICAL, AEROSPACE &
BIOMEDICAL ENGINEERING

volAIR

revolutionary
Aerodynamics
Innovation and
Research

University Leadership Initiative (ULI)
ULI Technical Interchange

Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles

ARMD Strategic Thrust: Ultra-Efficient Commercial Vehicles (Thrust 3A)

Dr. Jim Coder, PI
Department of Mechanical, Aerospace & Biomedical Engineering

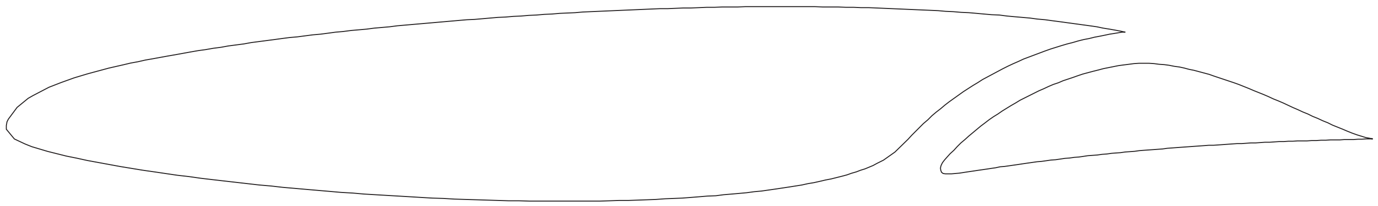
Technical Challenges

- Research targeted to address ARMD Strategic Thrust 3 – Ultra-Efficient Commercial Vehicles

- Target: Demonstrate a viable aerodynamic wing-design concept enabling 70% reduction in fuel/energy burn compared to 2005 baseline

Our Solution: Revolutionary Airfoil Design

- Slotted, natural-laminar-flow (SNLF) airfoil



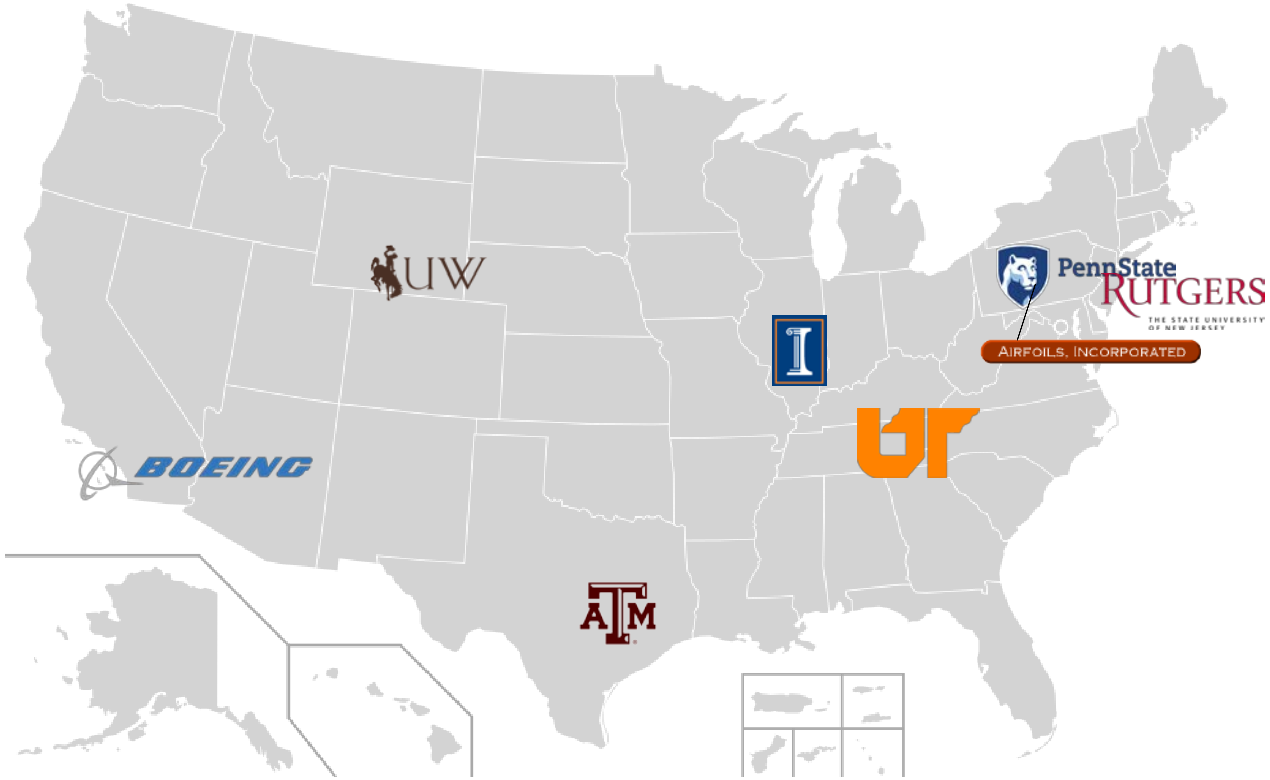
Somers S204, SNLF airfoil

- Low-speed tests show simultaneous decrease in cruise drag coefficient and increase in static maximum lift coefficient
- Slotted airfoils also have known benefits for transonic wave drag
- **Changes the rules for airfoil design and affords extra degrees of freedom**

Transformative Technology:
Non-experts will be able to see the difference

Research Team

- Multidisciplinary team of researchers covering all areas of aeronautics
- Primarily academic partners (UTK + 5 others)
- Two industrial partners



UT Knoxville Leadership Team

Mechanical, Aerospace and Biomedical Engineering

Jim Coder
Principal Investigator

Stephanie TerMaath
Co-I, Educational Outreach

Hans Goertz
Program Administrator

Joint Institute for Computational Sciences

Ryan Glasby

Academic Partners

Wyoming

Dimitri Mavriplis

Illinois

Phil Ansell

Rutgers

Onur Bilgen

Texas A&M

Helen Reed

Ed White

Penn State

Ken Brentner

Mark Maughmer

Sven Schmitz

Rob Campbell

Mike Jonson

Industry Partners

Airfoils, Incorporated

Dan Somers

Boeing Research & Technology

Abdi Khodadoust

Neal Harrison

Non-Advocate Peer Review Panel

Last	First	Institution	Type	Expertise	Email
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Cesnik	Carlos	University of Michigan	Academia	Structures	cesnik@umich.edu
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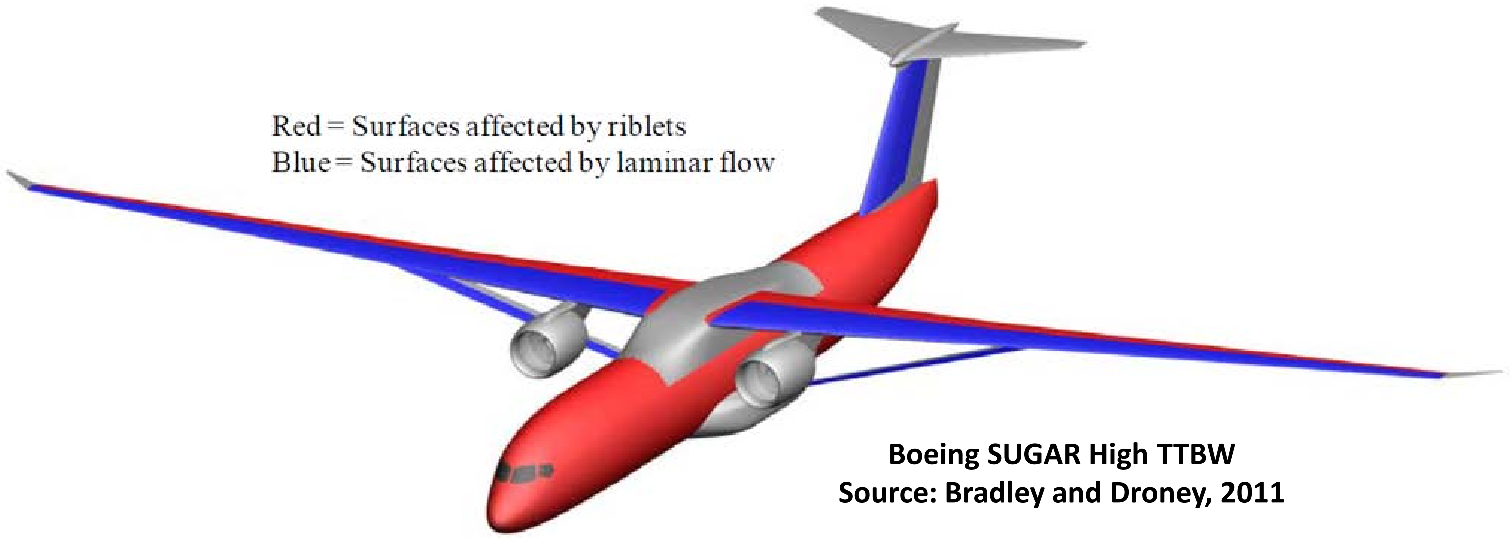
Research Objectives and Strategy

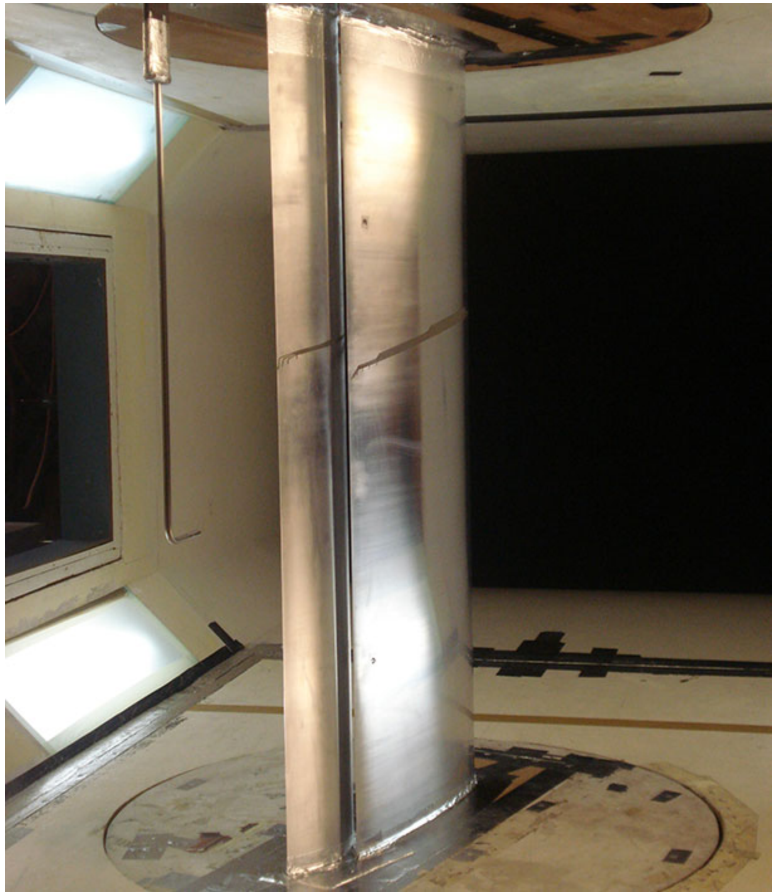
- Build upon recent N+3 concept studies by Boeing and MIT where natural laminar flow is an enabling technology for performance goals
  - Downselection to Boeing TTBW configuration



Boeing SUGAR High TTBW
Source: Bradley and Droney, 2011

Research Objectives and Strategy

- Leverage existing expertise in SNLF technology, including design and operating behavior
  - Previous NASA-funded projects
  - Army rotorcraft project
- Leverage advanced CFD analysis methods for laminar-flow wing designs
  - Advanced laminar-turbulent transition prediction modules



S414 installed in the Penn State Low-Speed, Low-Turbulence Wind Tunnel

Research Objectives and Strategy

Technology Development
Enabling technologies and design capabilities will be developed, verified, and validated

↓

Technology Integration
Broader, aircraft-level impact of enabling technologies on vehicle performance

↓

Technology Demonstration
Validate design and analysis methodologies with risk-reduction and capstone experiments

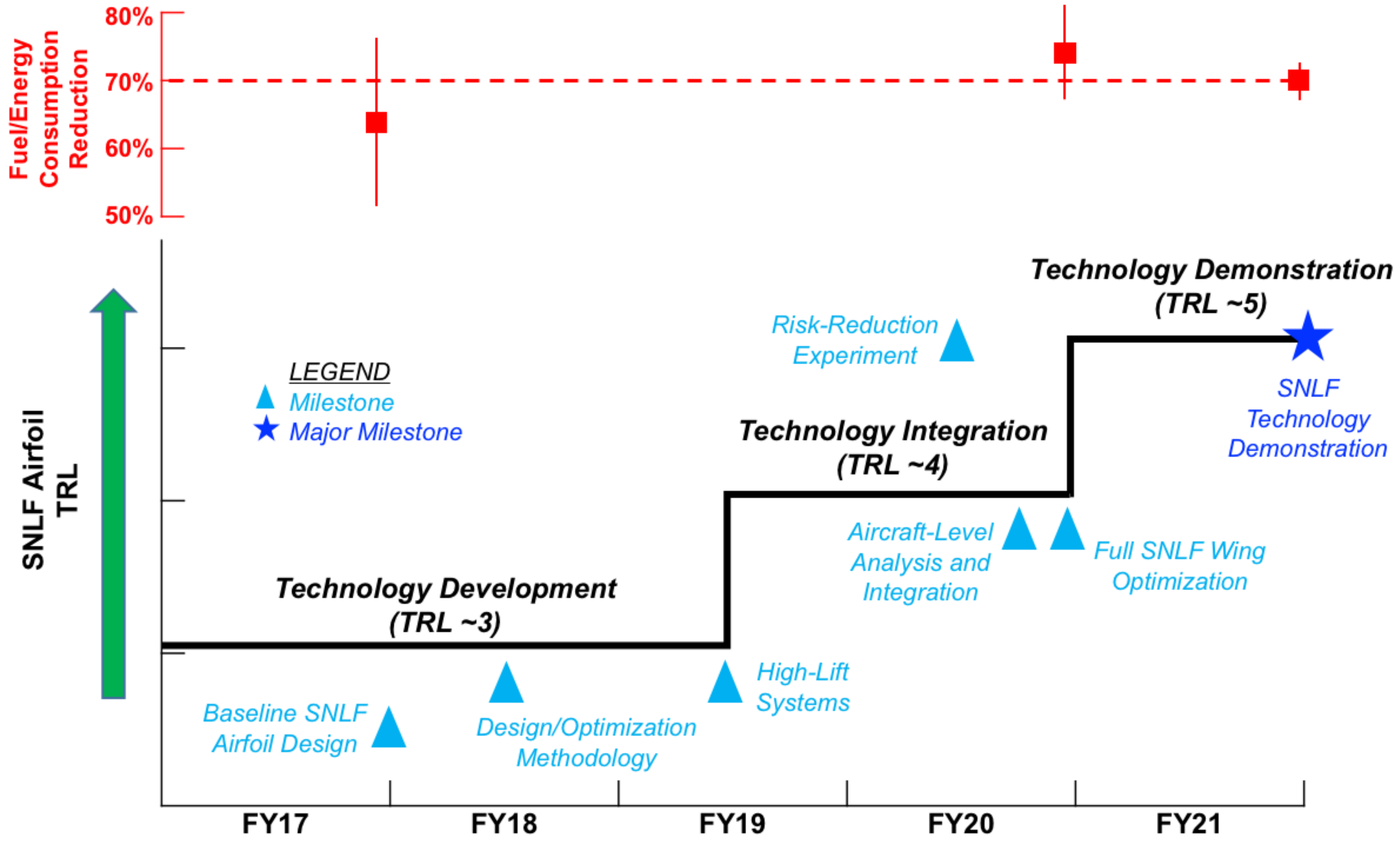
Research Areas of Interest

Baseline SNLF Airfoil Design
Aero-Structural-Acoustic Optimization of SNLF Wing
Active Flow Control for SNLF High-Lift
Boundary-Layer Stability and Transition Prediction/Control
Structural Topology Optimization and Material Selection
Piezocomposite Trailing-Edge Development
Advanced Propulsion/Airframe Integration
Aeroelastic Behavior and Flutter Mitigation
Aeroacoustic Predictions at Low-Speed Flight Conditions
Application of Winglets to SNLF Wing
Theoretical Drag Decomposition of High-Efficiency Aircraft

Aircraft-Level Integration of SNLF Technology
Complete Design of an SNLF Wing

Low-Speed Risk Reduction Experiment
Capstone Technology Demonstration

Milestones

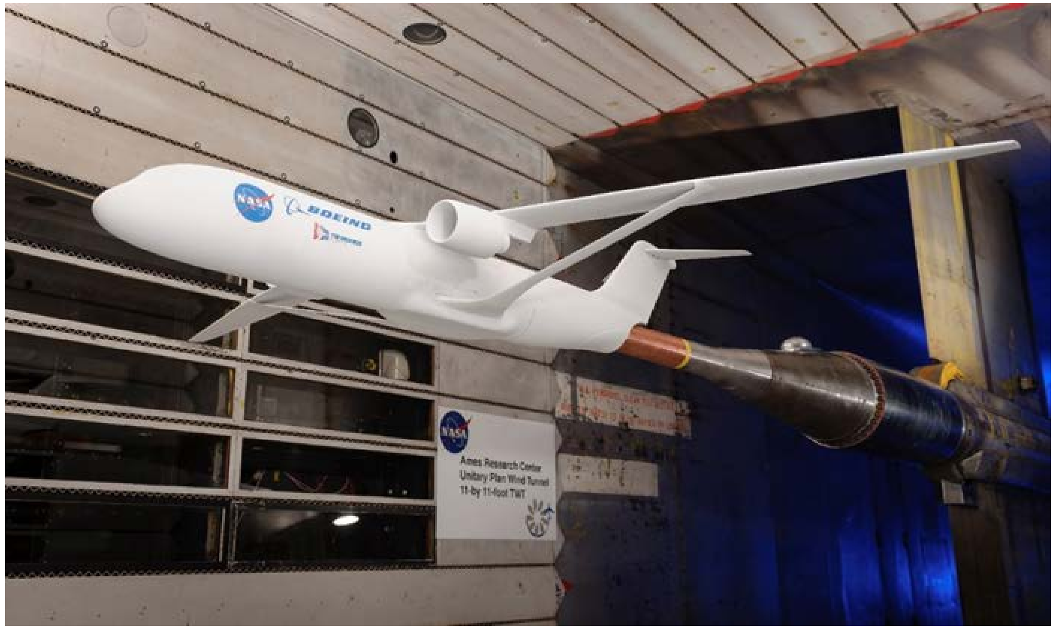


Fuel/Energy Consumption Reduction
80%
70%
60%
50%
SNLF Airfoil TRL
LEGEND
Milestone
Major Milestone
Technology Demonstration (TRL ~5)
Risk-Reduction Experiment
SNLF Technology Demonstration
Technology Integration (TRL ~4)
Aircraft-Level Analysis and Integration
Full SNLF Wing Optimization
Technology Development (TRL ~3)
High-Lift Systems
Baseline SNLF Airfoil Design
Design/Optimization Methodology
FY17
FY18
FY19
FY20
FY21

Capstone Technology Demonstration (2022)

- Targeting entry into NASA Ames Unitary Plan 11-ft Transonic Wind Tunnel

- Applying an SNLF wing to existing Boeing transonic, truss-braced model



Our Vision: Impacting Aircraft *and* Students

Aircraft Technology Impact

- Opportunity for technology revolution → changing how airplanes look
- Right combination of ideas, expertise, and experience
- Design tools, wing shapes, and test data to be made publicly available

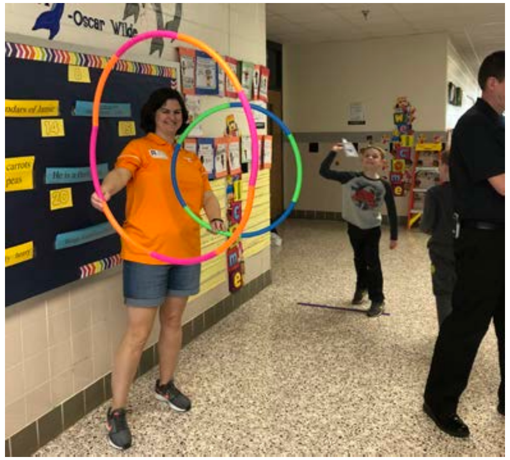
Educational Impact

- Annual Workforce Development Symposium at UT Knoxville
- Undergraduate student research opportunities and experiential learning
- Boeing summer internship for one student from partner schools

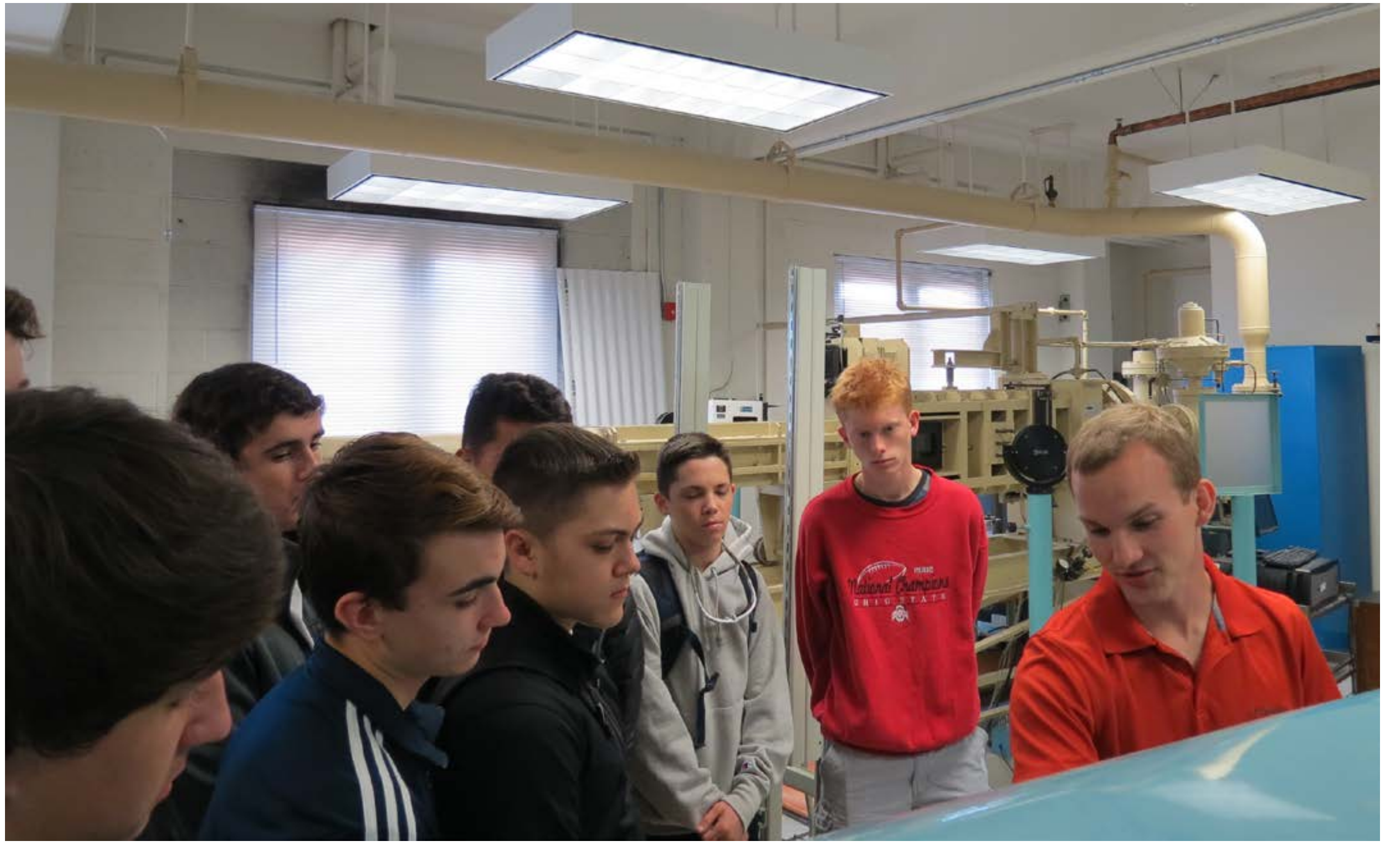
Student with test article in Texas A&M Oran W. Nicks Low-Speed Wind Tunnel

Educational Outreach

Covering the entire workforce development pipeline, from elementary through graduate school



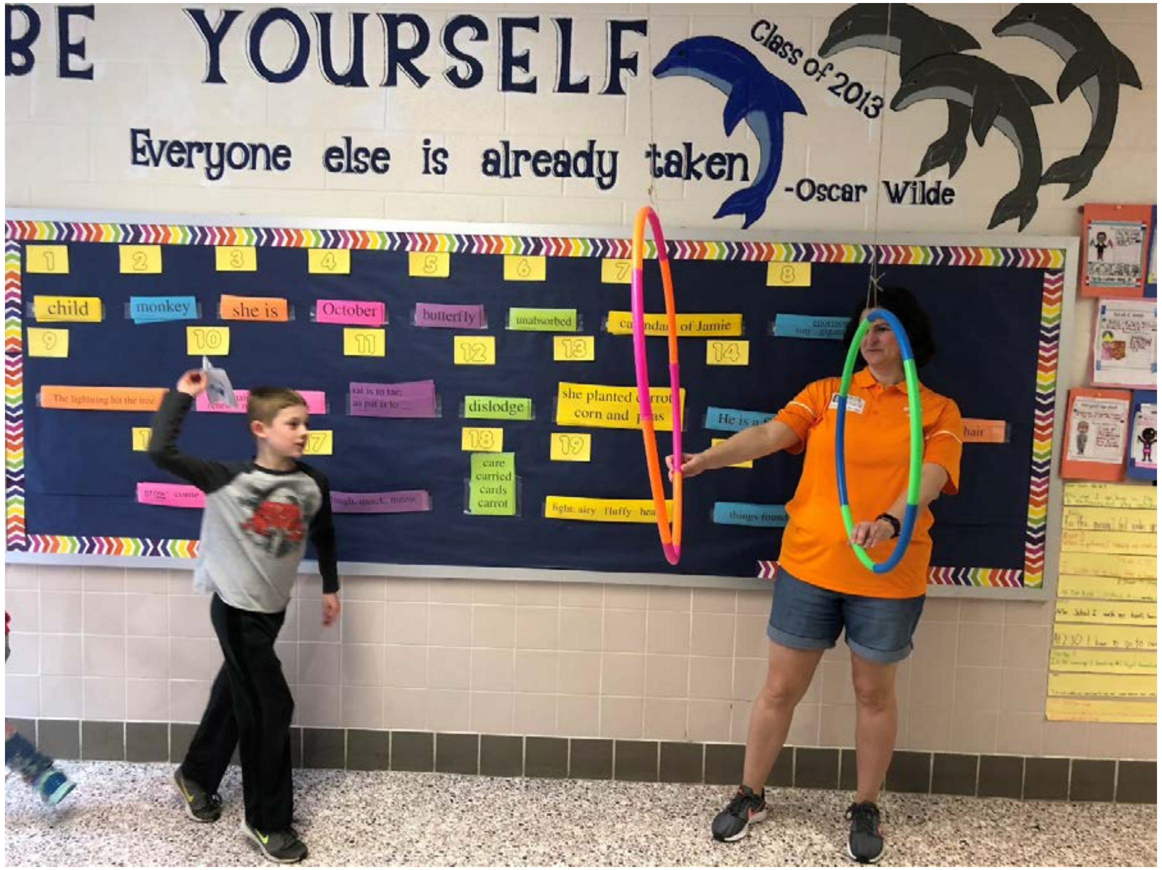
Outreach Events: Engineers Day 2017, Knoxville, TN



UT/ULI student, David Palmer, demonstrates the operation of a low-speed wind tunnel during Engineers Day 2017. Photo credit: Williams, 2017

The UT-led ULI center was awarded 2nd Place for its exhibit for Engineers Day. Photo credit: Goertz, 2017

Outreach Events: Classroom Visit, Ashburn, Virginia



Sanders Corner Primary School students participate in an obstacle course designed to teach aerodynamic concepts at a ULI outreach event. Photo credit: TerMaath 2018

Outreach Events: SWE Tomorrow's Engineers Today, Knoxville, TN

ULI student Sam Golter demonstrates principles of flight design to middle school students.
Photo credit: IACMI 2018

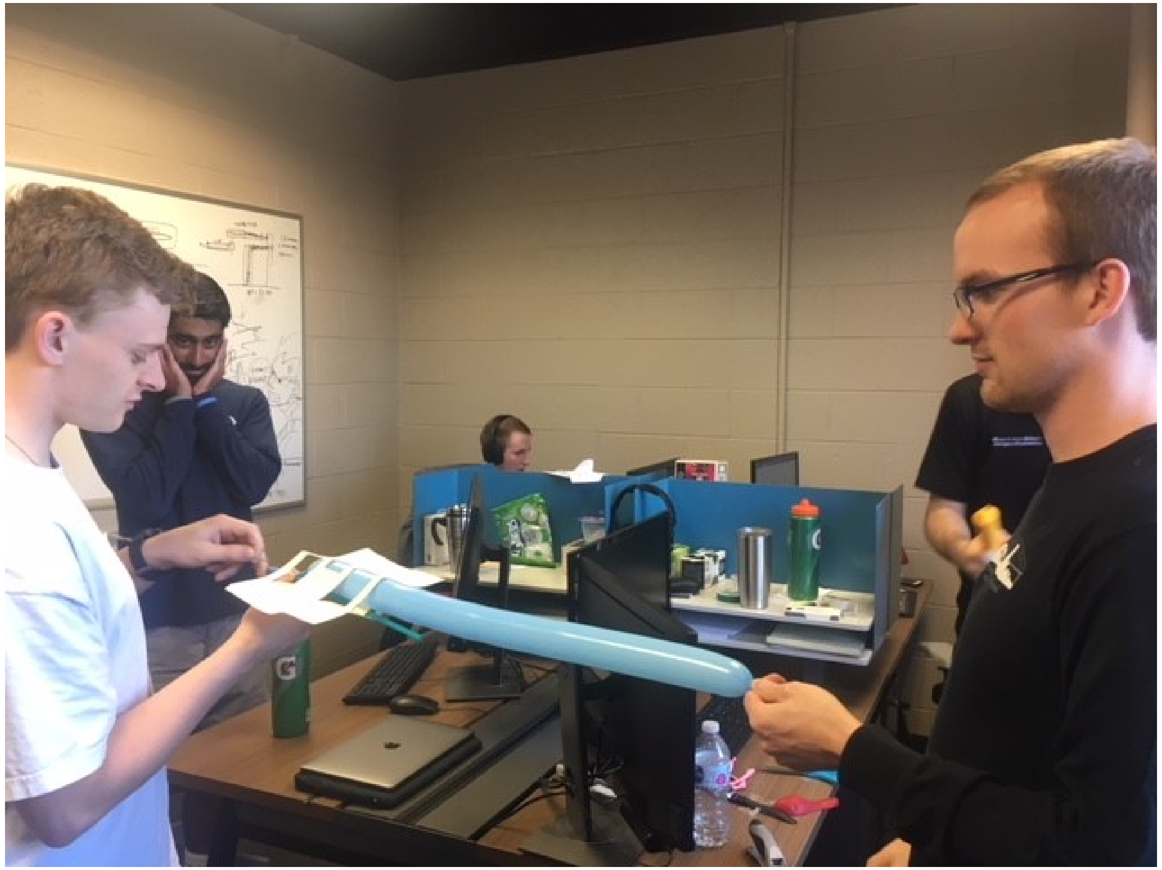
Outreach Events: SWE Tomorrow's Engineers Today, Knoxville, TN

A student holds up her completed paper airplane during Tomorrow's Engineers Today at the University of Tennessee Knoxville. Photo credit: IACMI 2018

Outreach Events: USA Science Engineering Festival Expo, Washington, DC

The Tau Beta Pi booth leads students thru learning activities designed by UT/ULI students . Photo credit: Lane, 2018

Education Modules



UT students prepare to launch a prototype rocket as part of an education module on propulsion. Photo Credit: Goertz, 2018

- Students developing teaching modules based on core aeronautic concepts
- Modules adapted for different age groups and audiences in K-12 range
- Currently beta-testing modules
- Completed modules to be disseminated thru Tau Beta Pi's MindSET and ULI partner universities

Workforce Development: Research Internships

- Funds reallocated from Year 1 budget to enroll 3 students in Summer Undergraduate Research Experience (SURE) program at U Tennessee
- Students ‘matched’ with topics contributing to ULI research tasks
- 1 ULI/UT student assigned to Boeing Huntington Beach for summer semester

Hector D. Ortiz-Melendez chosen as first intern under this agreement

- Plan to continue internships in years 2-5

Summer Undergraduate Research Experience

- Three rising seniors (2 from UTK, 1 from PSU) identified for summer program at UT Knoxville
- Working with Drs. Coder and TerMaath on aero-structural optimization

Graduate Student Involvement

Institution	UG	MS	PhD
University of Tennessee	7	2	3
Penn State University	1	1	1
Rutgers University	-	-	1
Texas A&M University	-	3	1
University of Illinois at U-C	1	2	1
University of Wyoming	-	-	3 + 1 post doc
Total	**9**	**8**	**11**

First Year Technical Progress

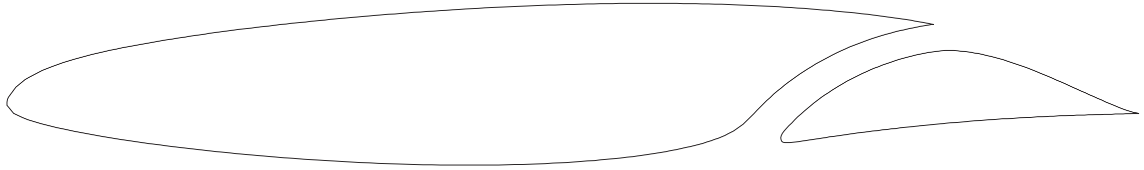
Technical Subgroups

Configuration

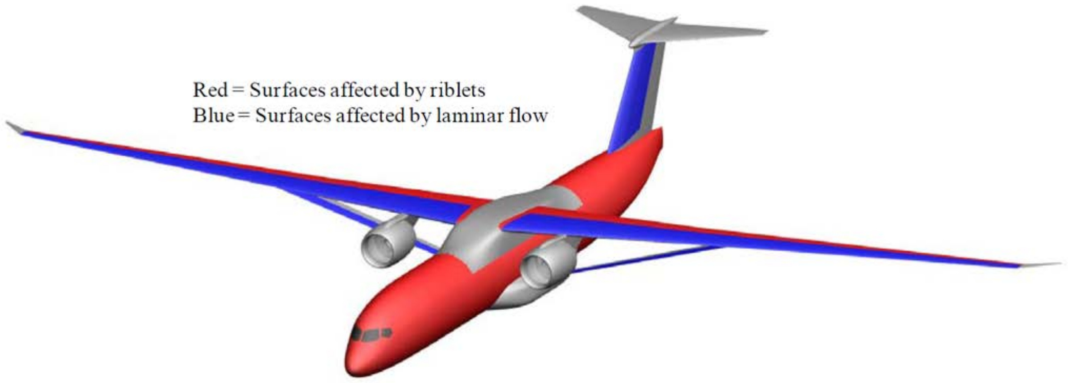
Low-Speed Flight Performance

Methods and Analysis

Combination of student-led and investigator-led meetings for coordination of research efforts



Selection of S204 and S414 for baseline studies (Licensing agreements between Airfoils, Incorporated and ULI partners)

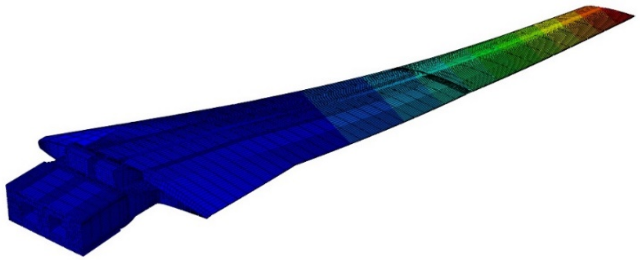


M = 0.745 TTBW configuration chosen as starting point

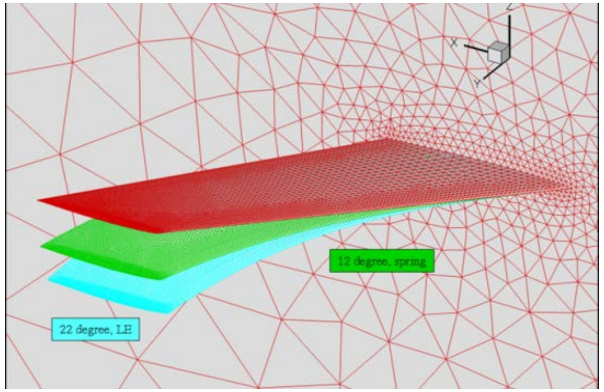
Task 1.02: Structural Optimization

PI: Dimitri Mavriplis, Professor of Mechanical Engineering, University of Wyoming

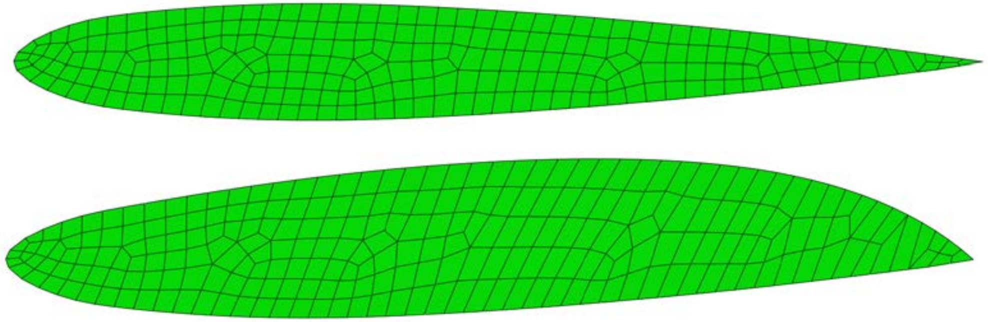
- In-house capability for structural FEA modeling and gradient-based optimization (AStrO)
  - Exact discrete adjoint
- Couples with NSU3D CFD flow solver with fluid-structure interface
  - Fully coupled discrete adjoint
- Validated in numerous tests, including HIRENASD wind tunnel experiment (AePW) and composite layup optimization of wind turbine blade
- Includes structural mesh deformation in response to OML design changes
- Target application: Aerostructural optimization for NLF with transition model



FEA model of HIRENASD wind tunnel section

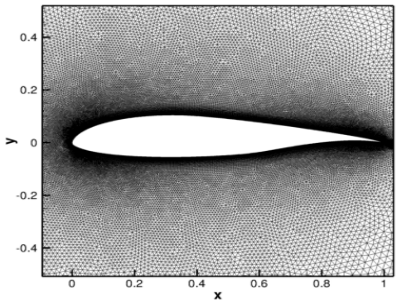


Mesh-adaptive fluid-structure interface



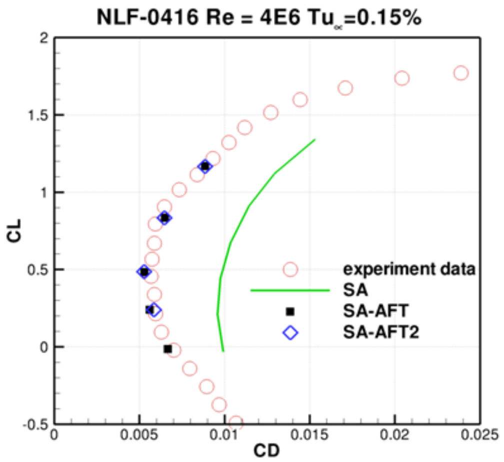
NACA 0012 airfoil cross-section before and after internal mesh deformation responding to morphing outer mold line

Task 1.02: Transition Model Implementation in NSU2D/3D

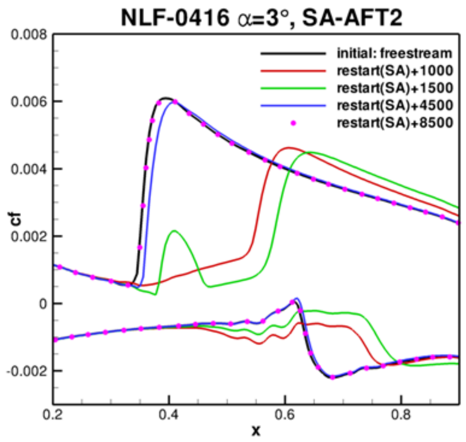


2D Validation
NLF-0416
M = 0.1, Re = 4M
Tu = 0.15%

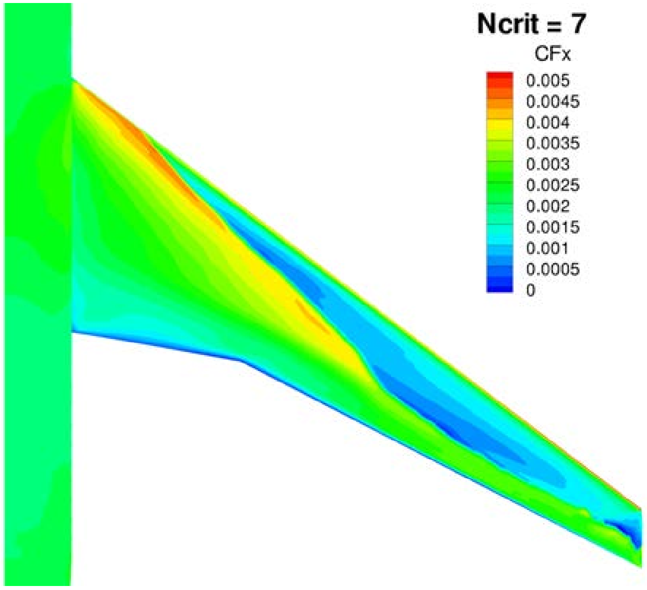
CRM @: M=0.85, Re=5M, α=1°
SA + AFT Model, Ncrit=7



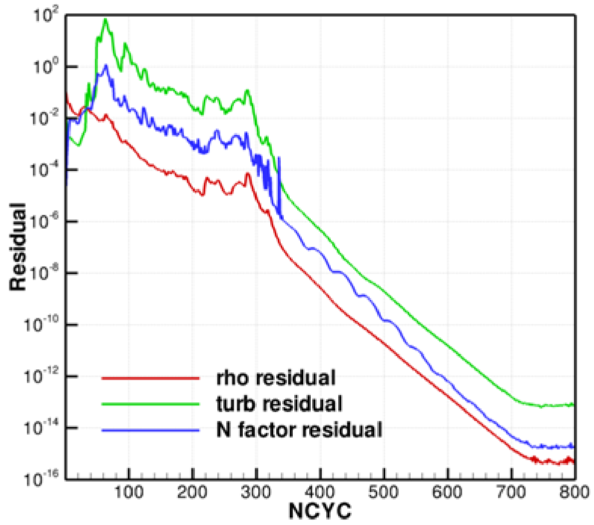
Drag polar comparison between SA, SA-AFT, SA-AFT2 and experiment data



Ensure convergence to unique (transition) solution when restarted from different initial conditions



C_F contours on wing



Convergence history

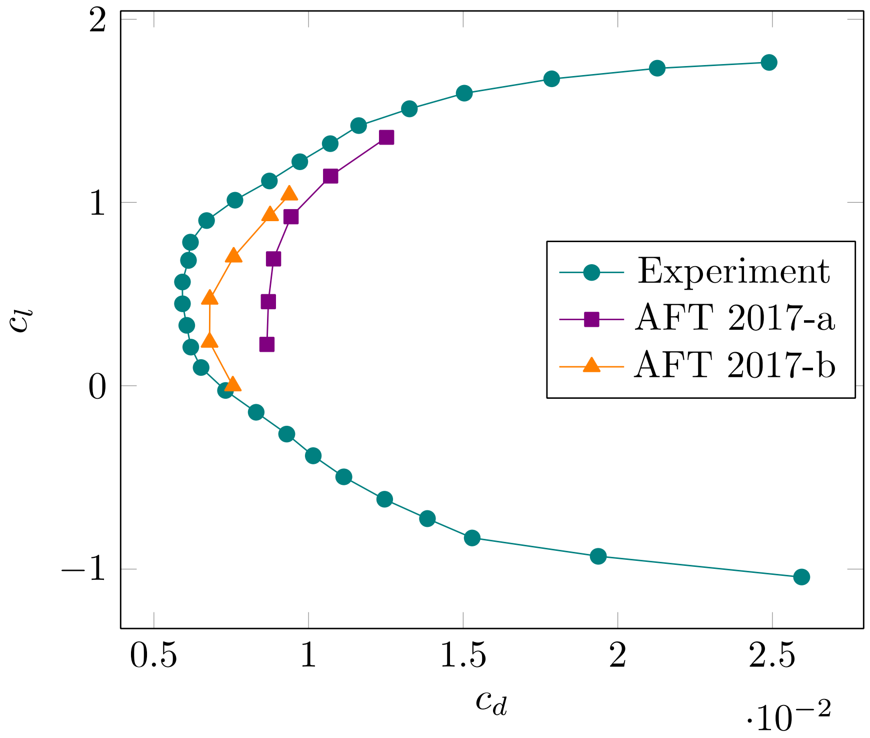
Discrete adjoint of transition model currently under development

Task 1.02: Aero-Structural-Acoustic Optimization of SNLF Wing Configuration

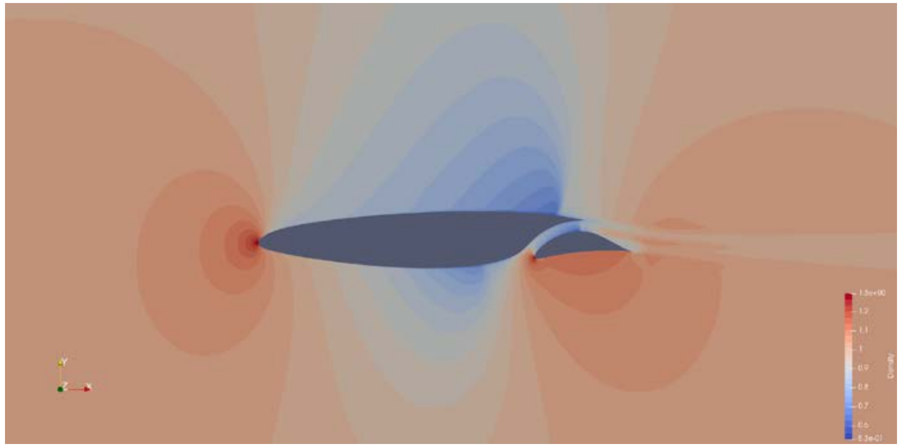
Co-I: Ryan Glasby, Research associate, Joint Institute for Computational Sciences (JICS)

- CFD-based transition prediction capability development
  - HPCMP CREATE^{TM}-AV Kestrel Component COFFE finite-element CFD solver
  - Prior work revealed deficiencies in one-equation Amplification Factor Transport Model (AFT-2017a)
  - Coupling of two-equation model (AFT-2017b) to SA-Neg turbulence model in progress
  - Goal is to enable adjoint-based design of laminar airfoils/wings
- Preliminary analysis of baseline ULI airfoil geometries (S103 and S204) under way
- Two papers planned for SciTech 2019
  - "Improvements to the Amplification Factor Transport Transition Model for Finite-Element Implementations"
  - "CFD Analysis of Slotted Natural-Laminar-Flow Concepts for Ultra-Efficient Commercial Aircraft"

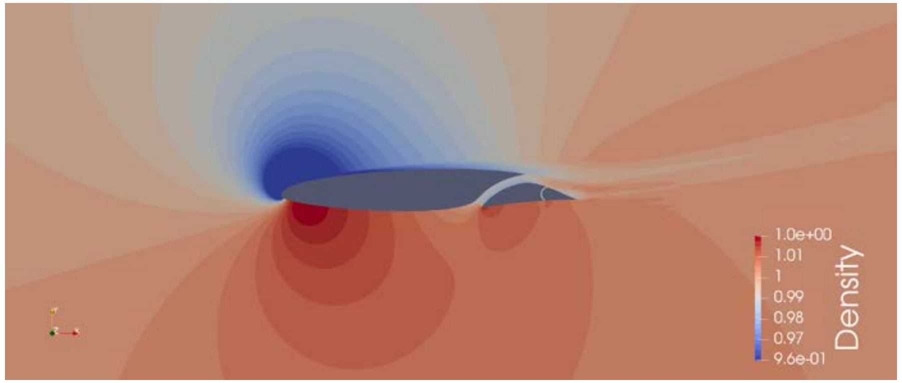
Task 1.02: Aero-Structural-Acoustic Optimization of SNLF Wing Configuration



Comparison of AFT-2017a and AFT-2017b results for the NLF-0416 benchmark case



Density contours for S103 airfoil at cruise (AFT-2017a transition model)

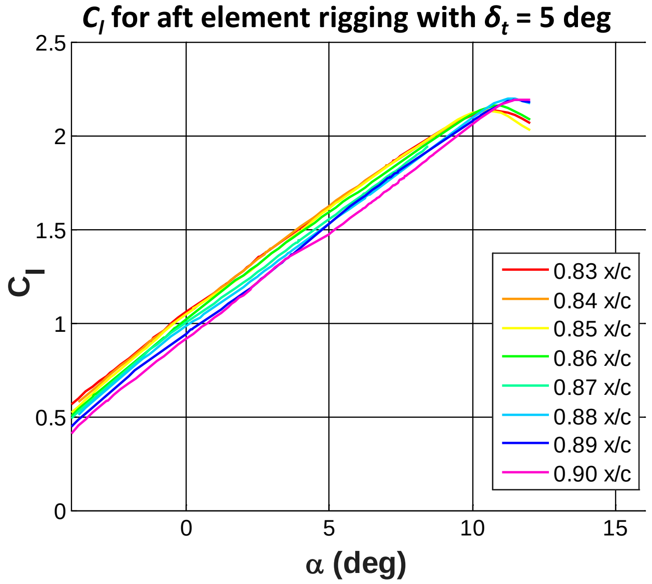


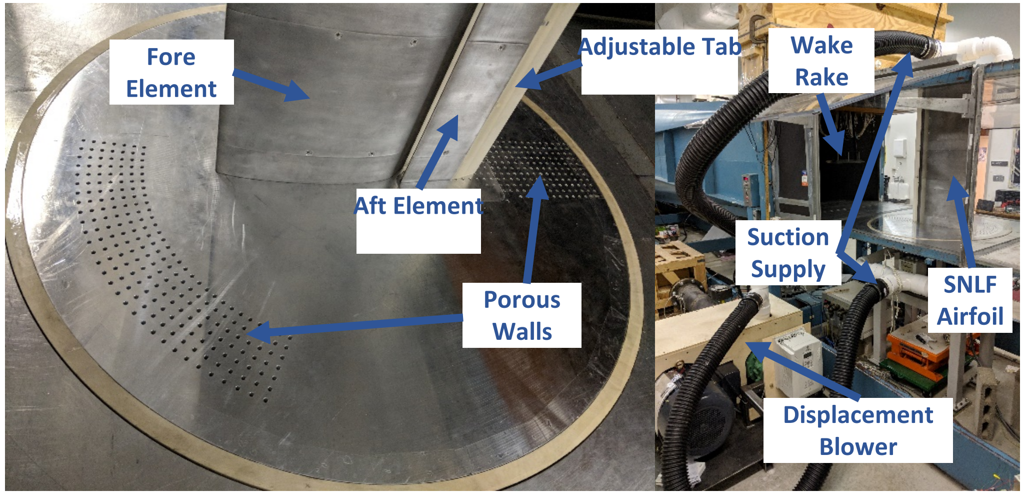
Density contours for S204 airfoil, high-lift conditions (Fully turbulent)

Task 1.03: High-Lift SNLF Airfoil Testing

PI: Phil Ansell, Assistant Professor, Aerospace Engineering, UIUC

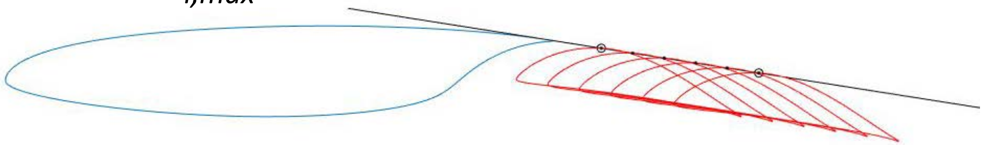
- Experiments configured for high-lift SNLF airfoil
  - Suction system required for wall flow attachment
  - Adjustable rigging, tab orientation, trailing-edge segments for AFC integration





Experimental configuration of SNLF model

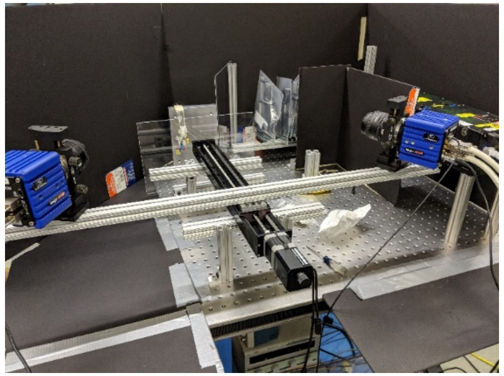
- Multi-element rigging for high lift
  - Positioning to provide surface tangency to forward-element dumping velocity
  - Aft-element separation enables further $C_{l,max}$ increases with AFC integration



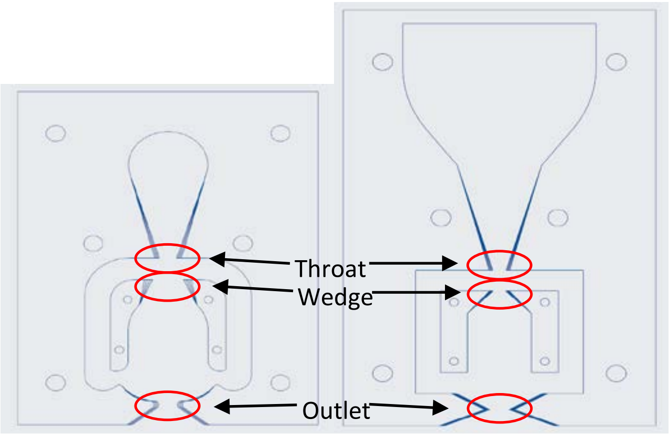
Schematic of flow tangency matching

Task 1.03: Fluidic Oscillator Scaling

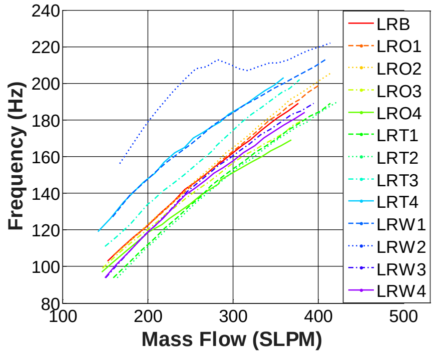
Stereo PIV configuration for jet velocity



Parametric oscillator geometry variation



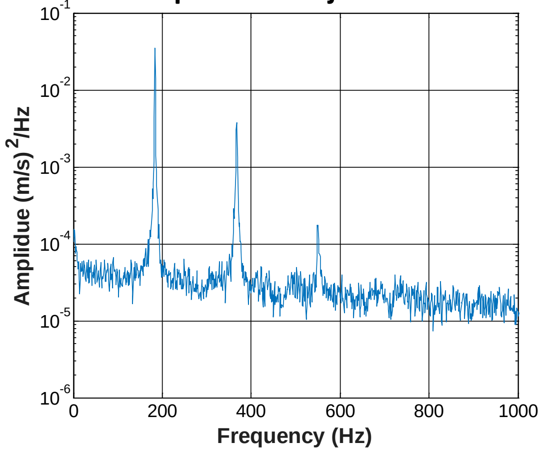
- Diagnostics of fluidic oscillator characteristics
  - Jet velocity field, internal pressure loss
  - Unsteady velocity for jet oscillation frequency
  - Coordinate with computational design

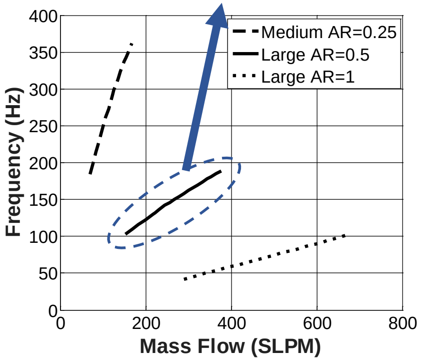


Scaling of frequency for fixed oscillator size and AR

- Frequency scaling of fluidic oscillators
  - Parametric analysis of 78 variations in oscillator geometry
  - Predictable frequency scaling permits instability resonance for AFC application
  - Nonlinear scaling of frequency with mass flow

Power spectrum of jet oscillation

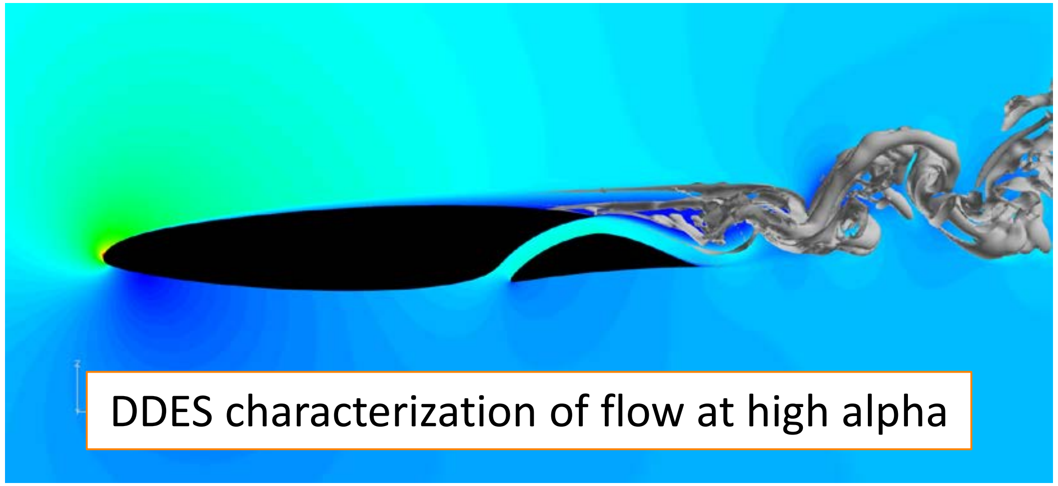




Scaling of frequency for varying oscillator size and AR

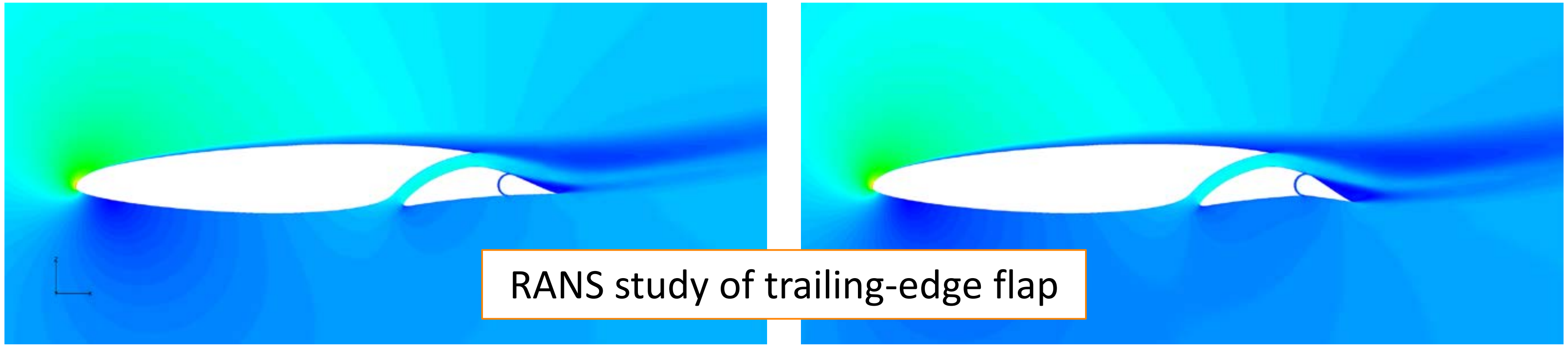
Task 1.03: High-Lift CFD Simulations

PI: Jim Coder, Assistant Professor, UT Knoxville



DDES characterization of flow at high alpha

- Numerical studies of high-lift aerodynamics using NASA OVERFLOW 2.2 solver
- Characterization of fluidic oscillators using SU2 and COFFE
  - Simulations ongoing



RANS study of trailing-edge flap

Task 1.04: Boundary-Layer Stability and Transition Prediction and Control

PI: Helen Reed, Professor, Aerospace Engineering, Texas A&M

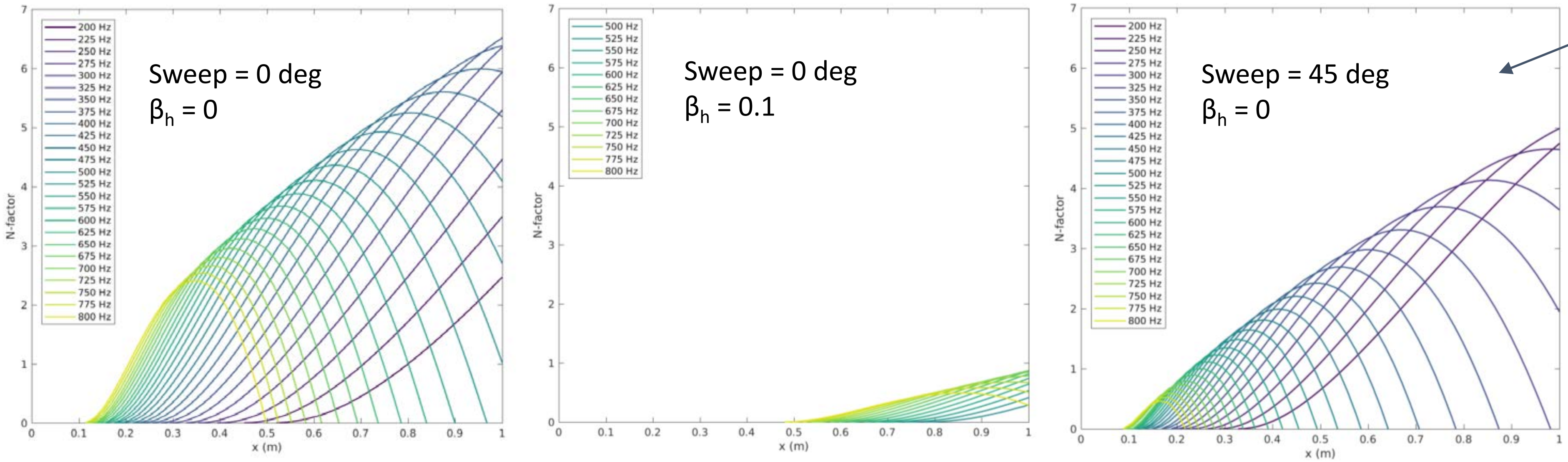
1. This quarter, the computational group at Texas A&M has focused on verifying its boundary-layer stability solver EPIC for subsonic speeds, as most prior work has been within the hypersonic flow regime.
2. Our research question is to understand the interplay between Tollmien-Schlichting waves, or T-S waves, and crossflow instabilities as sweep varies.
3. The preliminary computational geometry was flow over a wedge, described by the Falkner-Skan-Cooke equations. Flow conditions are 2.04 million unit Reynolds number per meter at sea level conditions.
4. Shown here on the chart in the three plots are the N-factor of the T-S waves vs. the leading-edge-normal coordinate, x, in meters. The leftmost plot is associated with 0 degree sweep with zero pressure gradient (aka Blasius flow), the center plot with 0 degree sweep and a favorable pressure gradient, and the rightmost plot with 45 degree sweep and zero pressure gradient. Various frequencies of the T-S instability are shown with varying colors, from 200 Hz to 800 Hz. The center plot shows the effects of favorable chordwise pressure gradients on the 2-D Tollmien-Schlichting instability: the critical Reynolds number is increased and the growth rates are damped, having a significantly stabilizing effect. The right plot shows the effect of increasing sweep with fixed freestream conditions: the critical Reynolds number is unchanged, but the growth rates are slightly damped compared to Blasius flow, moderately stabilizing the instability. These trends have been observed for decades. For example, Les Mack details these instabilities thoroughly in his 1984 report; this further verifies the results of EPIC in the subsonic regime.

Task 1.04: Boundary-Layer Stability and Transition Prediction and Control

PI: Helen Reed, Professor, Aerospace Engineering, Texas A&M

1. Year 1 Goal: Establish and verify toolset for boundary-layer stability and transition assessment.

- LPSE verification case of 2D T-S N-factors on FSC wedge flow



Increasing sweep beyond 0 deg with a constant freestream unit Reynolds number will always decrease the N-factor of 2D T-S instabilities for FSC wedge flow.*

Results suggest 2D T-S is drastically stabilized by favorable pressure gradients, and moderately stabilized by increasing sweep [1].

LPSE: Linear Parabolized Stability Equations
T-S: Tollmien-Schlichting
FSC: Falkner-Skan-Cooke

β_h: Beta-Hartree self-similar pressure gradient

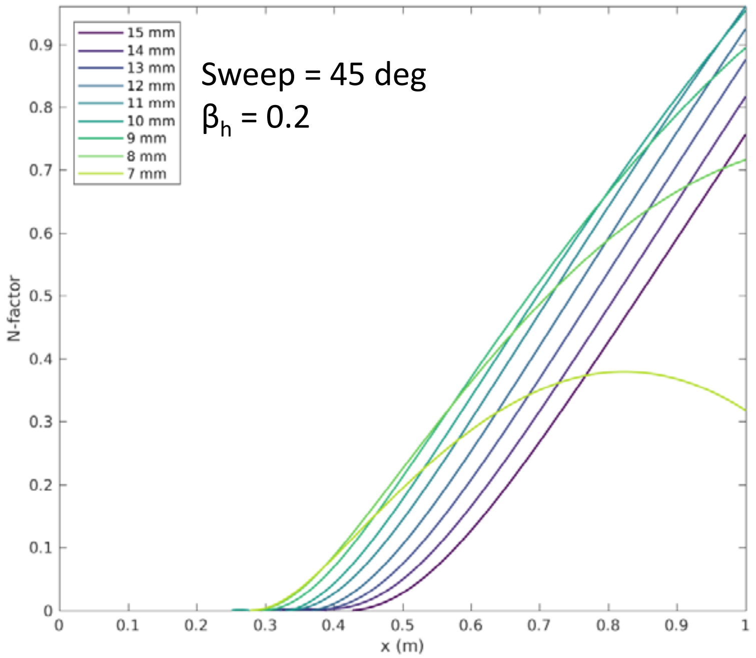
[1] Mack L. Boundary-Layer Linear Stability Theory. AGARD Report 709: Special Course on Stability and Transition of Laminar Flow, pages 3.1–3.81, 1984.

*This is a result of a smaller chordwise velocity component, and the fact that the FSC chordwise-momentum equation is decoupled from spanwise velocity.

Task 1.04: Boundary-Layer Stability and Transition Prediction and Control

1. Year 1 Goal: Establish and verify toolset for boundary-layer stability and transition assessment.

- LPSE verification case of crossflow on FSC wedge flow, swept at 45 degrees



LPSE: Linear Parabolized Stability Equations
FSC: Falkner-Skan-Cooke

β_h: Beta-Hartree self-similar pressure gradient

Crossflow instability successfully found within the subsonic regime and N-factors calculated.

- Research goal: Investigate the effects of sweep on the relative importance of Tollmien-Schlichting and crossflow instabilities.

- Next steps will include assessment of the S204 slotted, natural-laminar-flow airfoil's stability characteristics; and work to assist the design of experiments by White & Feliciano at Texas A&M.

Task 3.01: Risk-Reduction Experiment in Klebanoff-Saric LSWT

PI: Edward White, Professor, Aerospace Engineering, Texas A&M

Efforts at the Klebanoff-Saric Wind Tunnel (KSWT) are cooperatively developing validation crossflow experiments with the CSTL.

The KSWT is especially capable at performing crossflow experiments in its very-low freestream turbulence environment. Over the past XX decades, the KSWT has been the test bed for breakthrough experiments studying the turbulent transition of the boundary layer, particularly the understanding of Tollmien-Schlichting and crossflow instabilities.

From the final SNLF airfoil geometry and sweep conditions, an appropriate chord length (e.g. a Reynolds number achievable in the KSWT) will be determined computationally -- first in infinite-span configuration and second including wall-effects. In preparation, an S414 slotted, natural laminar airfoil will be used as dry-run practice of the computation and experimental-design process.

With chord and wall-liner geometry recommendations, a variable sweep and angle of attack experiment will be designed to validate experiments.

Task 3.01: Risk-Reduction Experiment in Klebanoff-Saric LSWT

PI: Edward White, Professor, Aerospace Engineering, Texas A&M

Very-low freestream turbulence, ~0.02% to match flight conditions from 1 – 25 m/s freestream velocity.

Instrumentation includes: hotwire and hotfilm anemometers, pressure taps, IR thermography

Year 1-2 Goal: *Develop a KSWT crossflow experiment to identify TS- and crossflow-dominated transition regimes of Re, sweep, and AOA.*

The experiment will:

- Accommodate variable sweep and pitch of single-element and slotted airfoils
- Operate in both parameter regimes expected to be TS and crossflow dominated
- Include wall liners to minimize spanwise flow variations for most-straightforward computational comparisons
- Be designed around the S414 with accomodations for the TBD SNLF airfoil

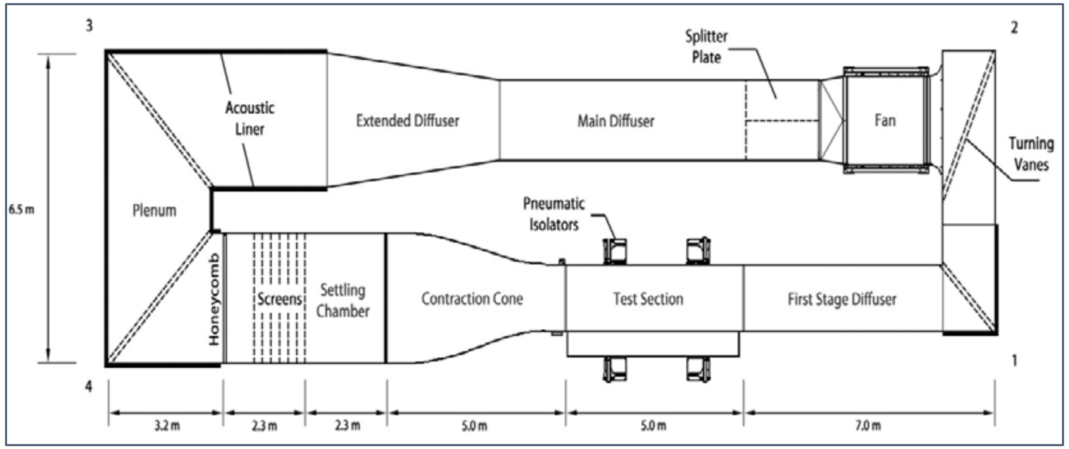


Figure 1. KSWT diagram from Hunt, et al. [1]

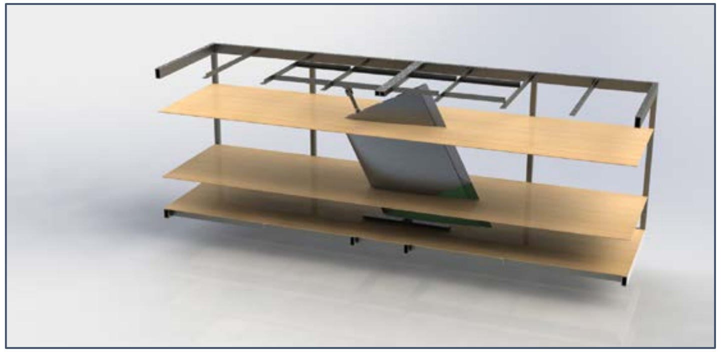


Figure 2. Conceptual rendering of crossflow experiment in the KSWT.

[1] Hunt, L., Downs, R., Kuester, M., White, E., & Saric, W. (2010). Flow quality measurements in the klebanoff-saric wind tunnel. In 27th AIAA Aerodynamic Measurement Technology and Ground Testing Conference (p. 4538).

Research Products and Technology Transfer

- AIAA Aviation 2018 Papers with ULI support
  - Coder, J. G. and Ortiz-Melendez, H. D., "Transitional Delayed Detached Eddy Simulation of Multielement High-Lift Airfoils," AIAA Paper 2018-2846
    - **Monday, 11:00 AM, Fairlie**
  - Schmitz, S., "Drag Decomposition Using Partial Pressure Fields in the Compressible Navier-Stokes Equations," AIAA Paper 2018-2908
    - **Monday, 11:00 AM, Lenox**
  - Maughmer, M. D., Coder, J. G., and Somers, D. M., "Exploration of a Slotted, Natural-Laminar-Flow Airfoil Concept," AIAA Paper 2018-3815
    - **Wednesday, 11:30 AM, Fairlie**
  - Stefanski, D. L., Glasby, R. S., Erwin, J. T., Allmaras, S. R., Coder, J. G., and Burgess, N., "A Modified k-ω Turbulence Model for Finite-Element CFD," AIAA Paper 2018-4041
    - **Wednesday, 2:30 PM, Auburn**

- **Special session for AIAA SciTech 2019 being organized**

Advanced Aerodynamic Design Center for Ultra-Efficiency Commercial Vehicles

The Pennsylvania State University

Department of Aerospace Engineering

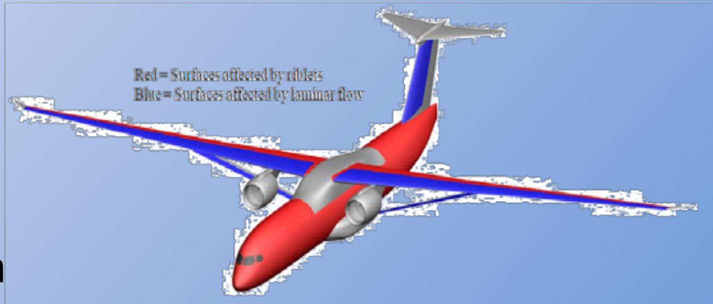
Mark D. Maughmer, Professor

Sven Schmitz, Associate Professor

Kenneth S. Brentner, Professor

Applied Research Laboratory

Robert C. Campbell, Senior Research Associate

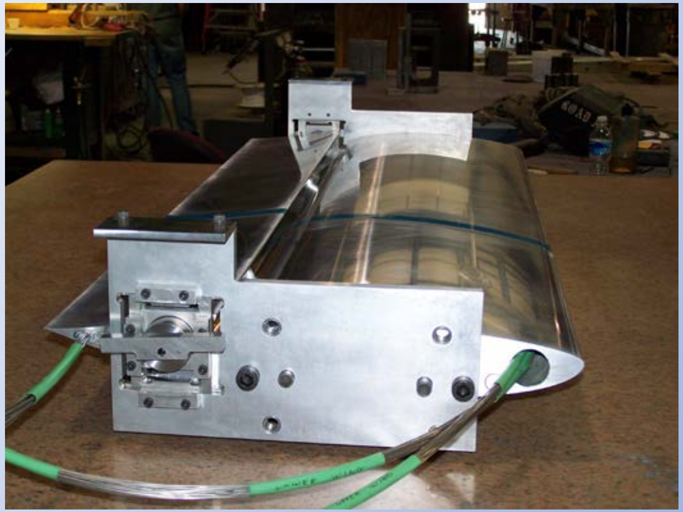


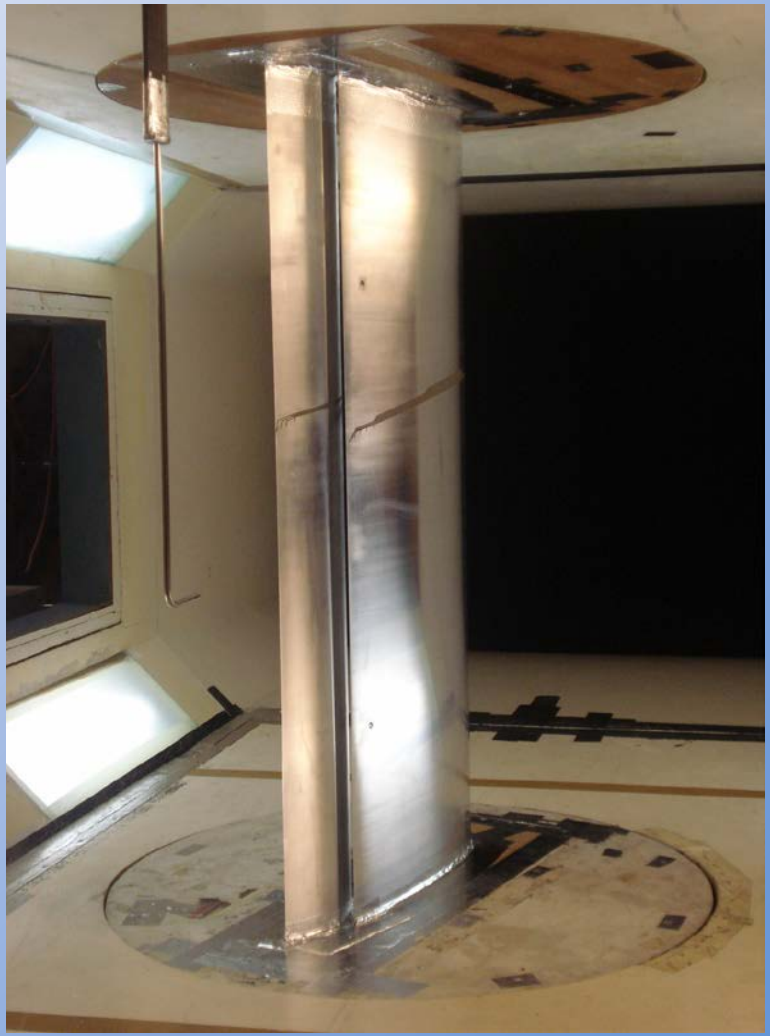
AIAA Aviation ULI Forum

S103 Airfoil, 2001. Designed for R = 3.0 × 10^6 to 9.0 × 10^6. Tested in the Low-Turbulence, Pressure Tunnel at NASA LaRC.

S414 Airfoil, 2009 (Army), 2013 (NASA Learn, Phase 1). Designed for R = 1.0 × 10^6 to 2.5 × 10^6. M = 0.7 (modified for low-speed testing). Tested in the Low-Speed, Low-Turbulence, Wind Tunnel at Penn State.

SNLF Airfoil Model

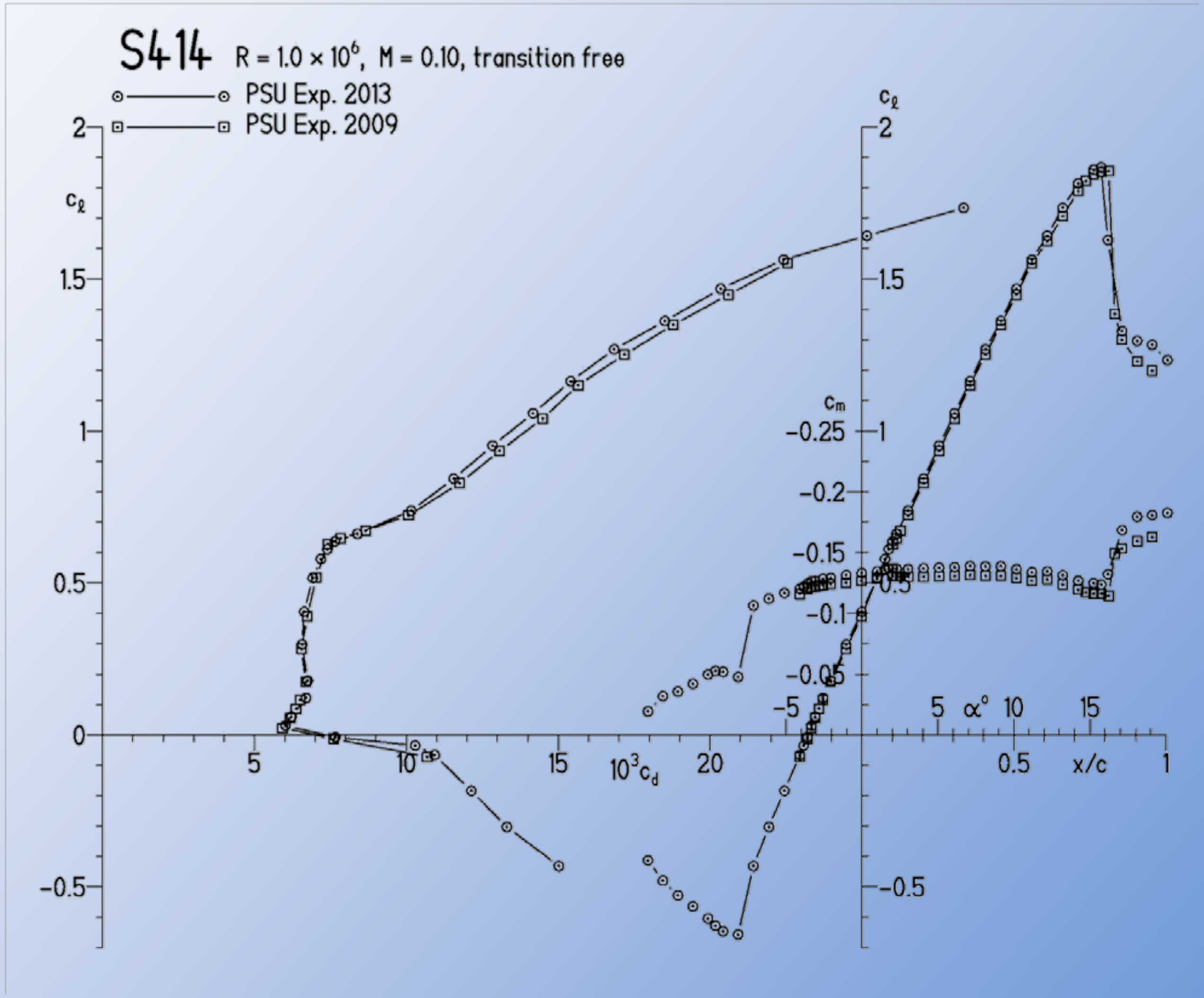




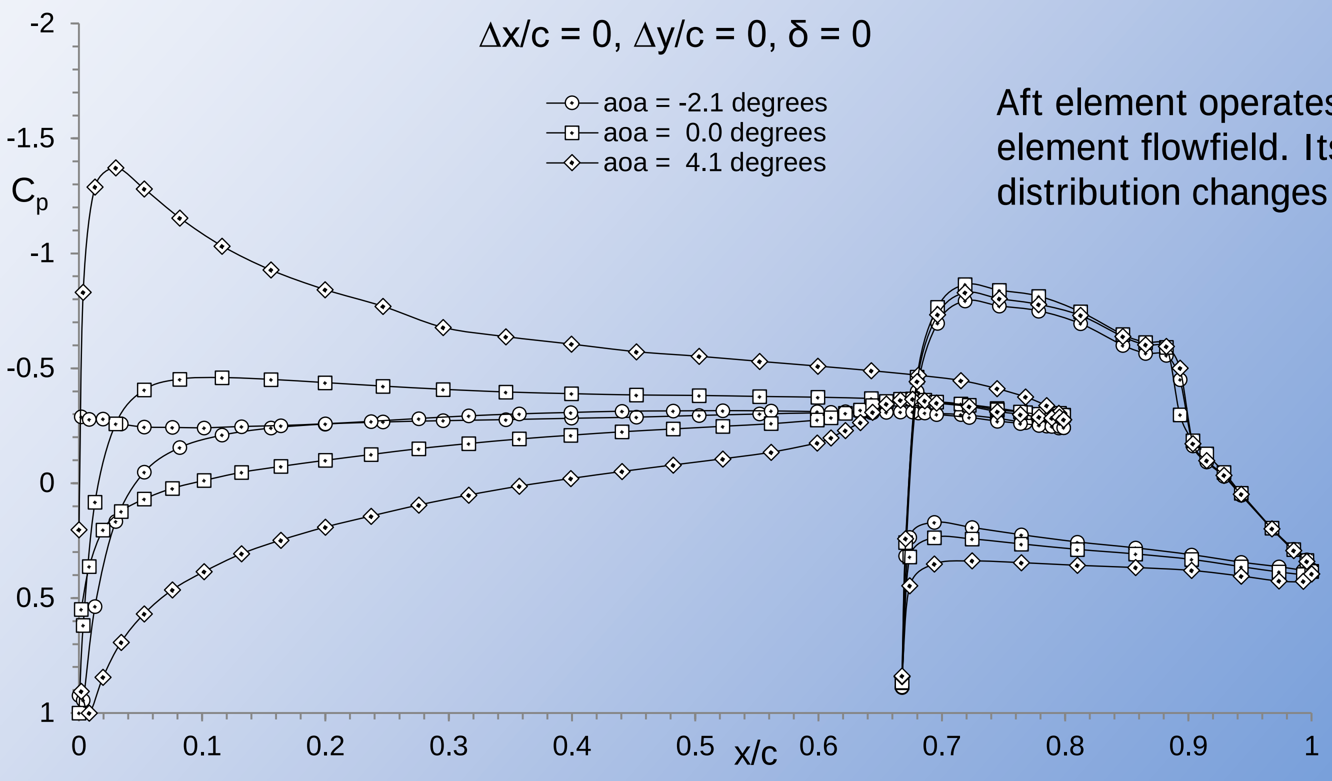
PennState College of Engineering

Baseline Aerodynamic Characteristics 2009 (Army) and 2013 (NASA Learn)

NASA University Leadership Initiative

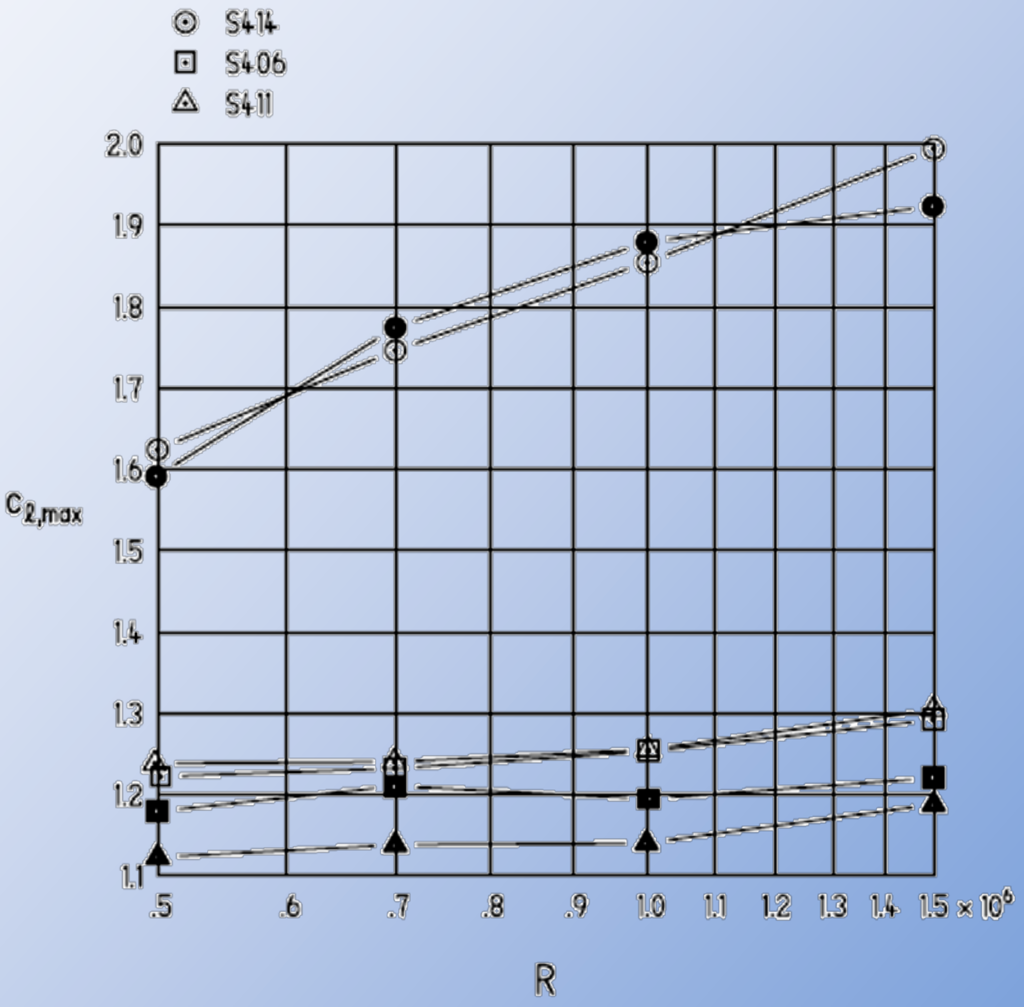


Baseline Pressure Distributions

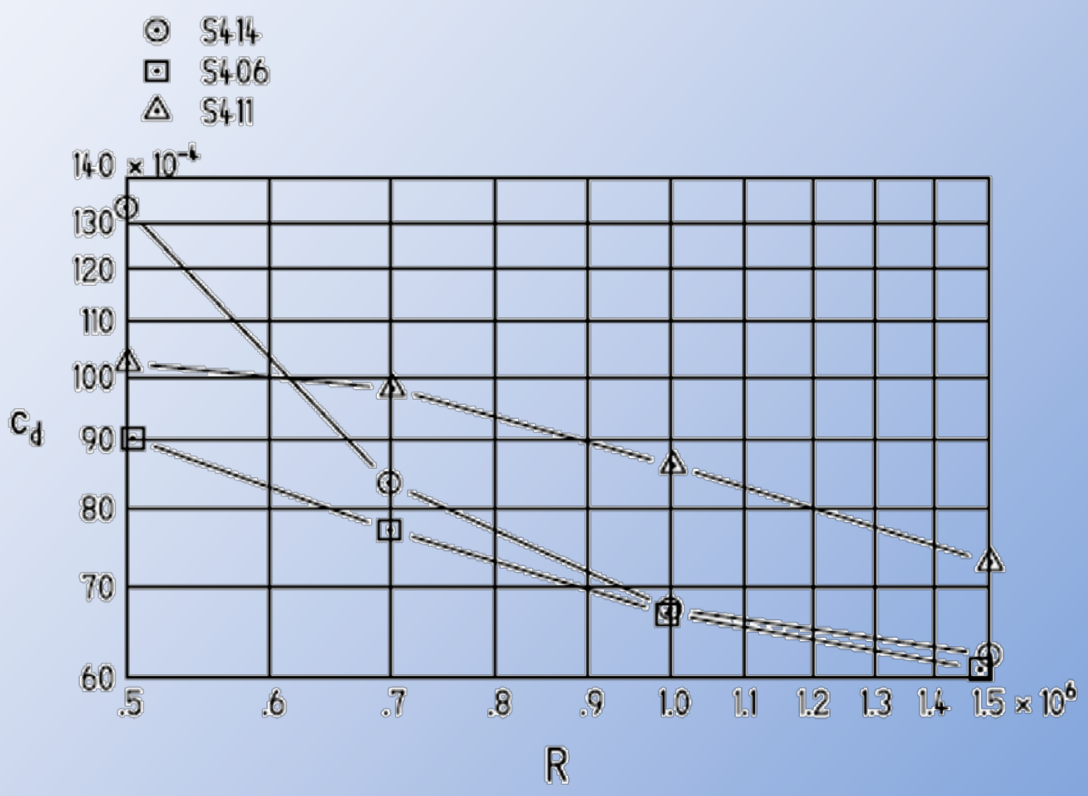


Aft element operates in fore element flowfield. Its pressure distribution changes very little.

$C_{l,max}$ vs. Reynolds Number

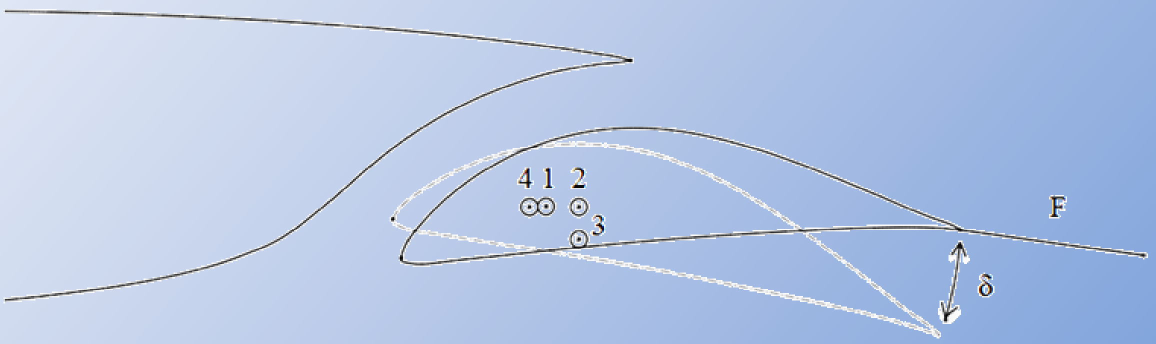


c_{dmin} vs. Reynolds Number

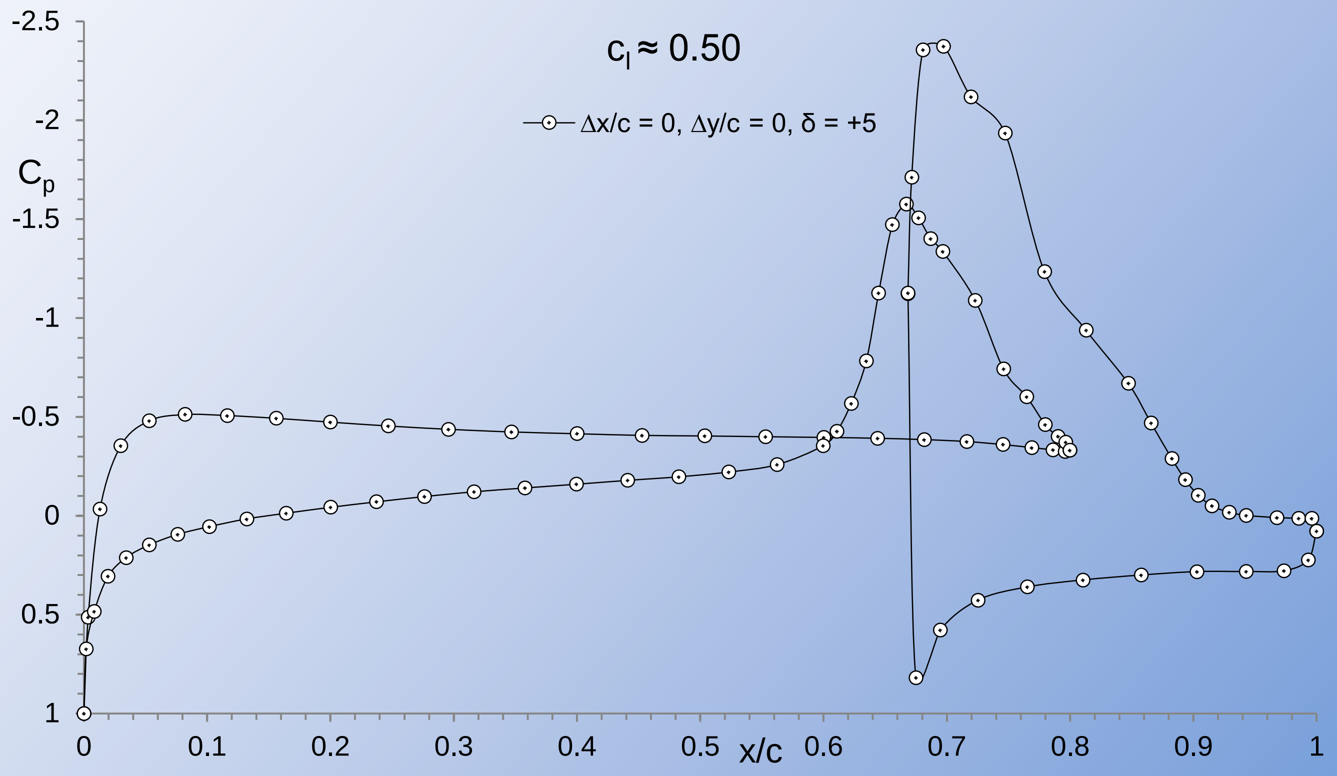


Aft Element Position and Deflection Schedule

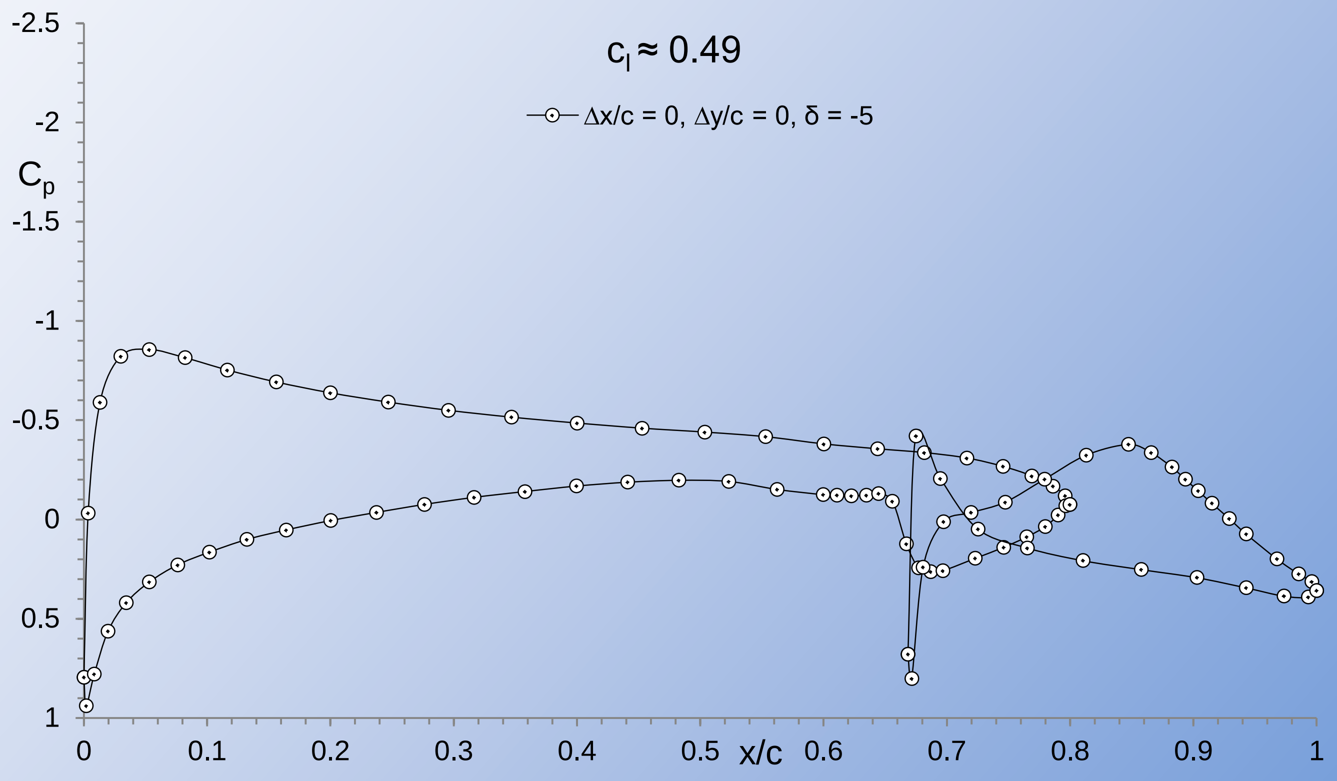
Position	δ_{ae} (aft-element incidence)							δ_t (tab deflection)		
1	0	1	5	10	-5	-10	-15			
1+F	0							3.5	22.5	-17
2	0	5	10							
3	2	5								
4	0									



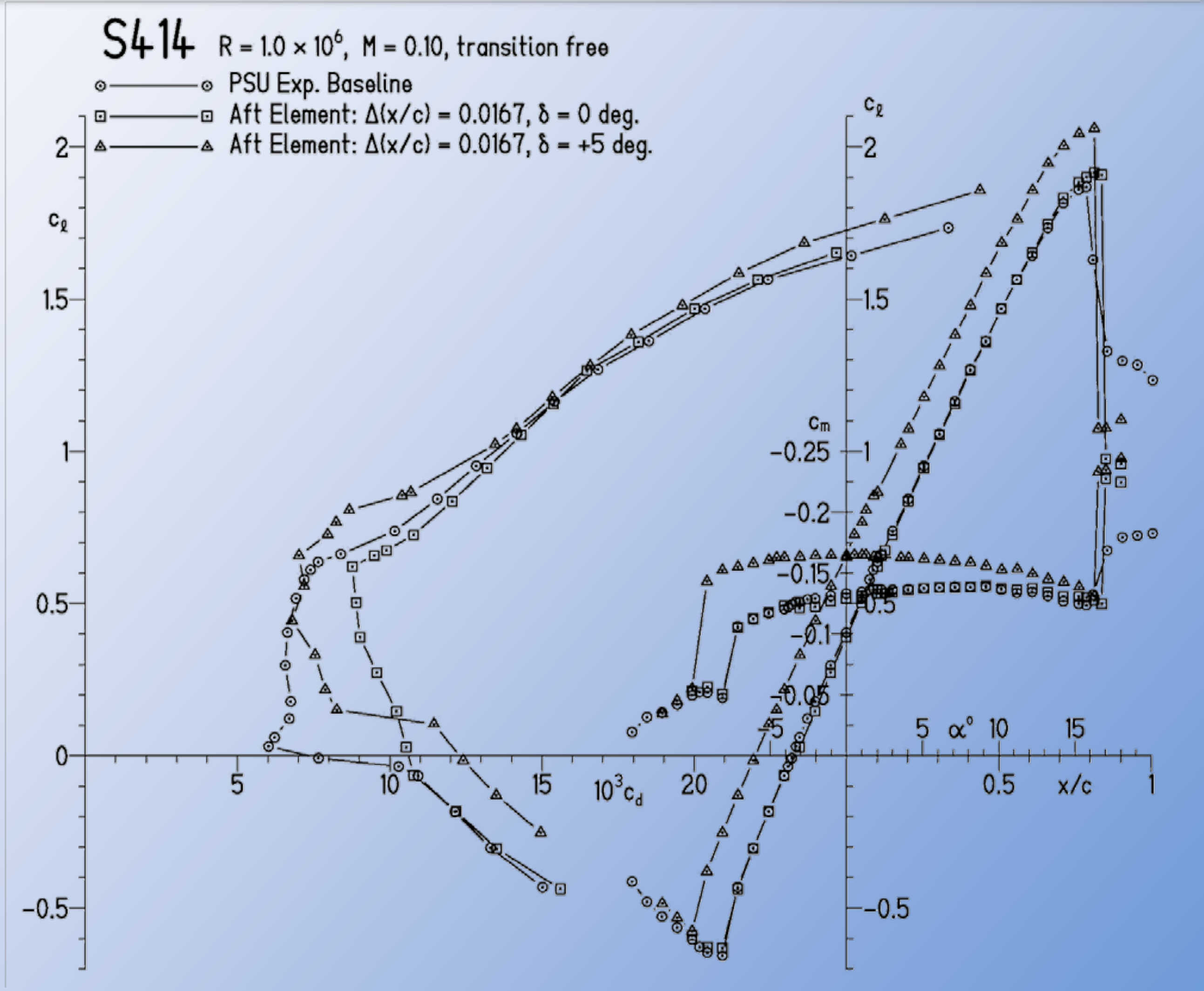
Pressure Distributions



Pressure Distributions



Aft-Element Schedules



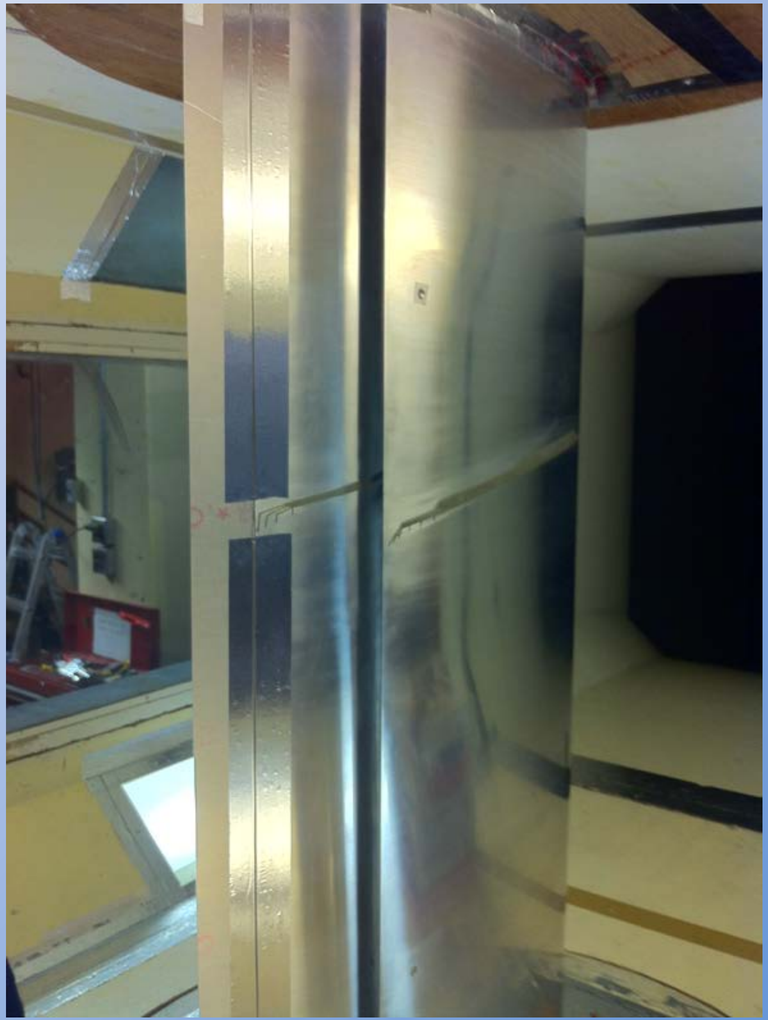
Tab Simulating a Simple Flap

Tab was taped on aft element.

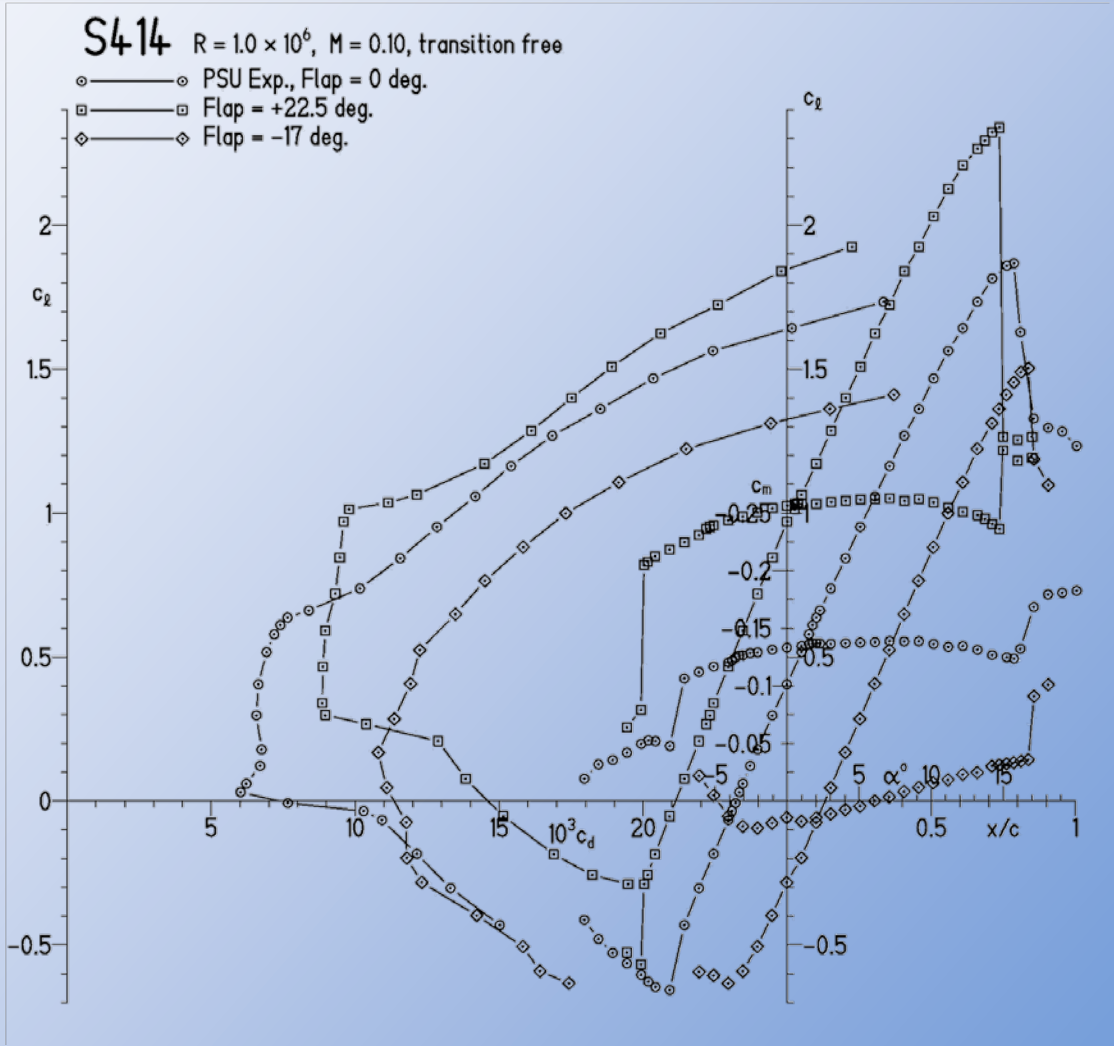
Tab chord was 10% of total airfoil chord, 30% of aft-element chord.

Deflections of -17, 0, 3.5, 22 degrees.

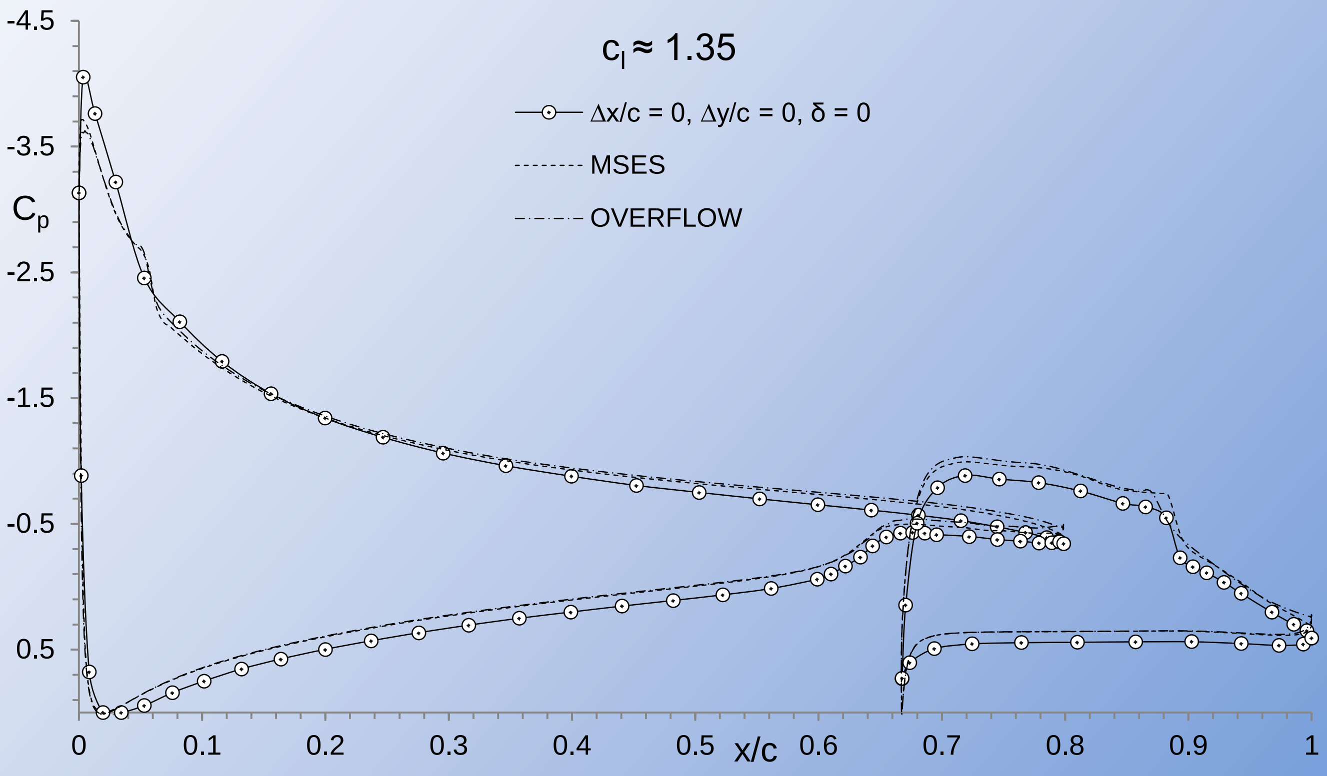
No pressure orifices on tab.



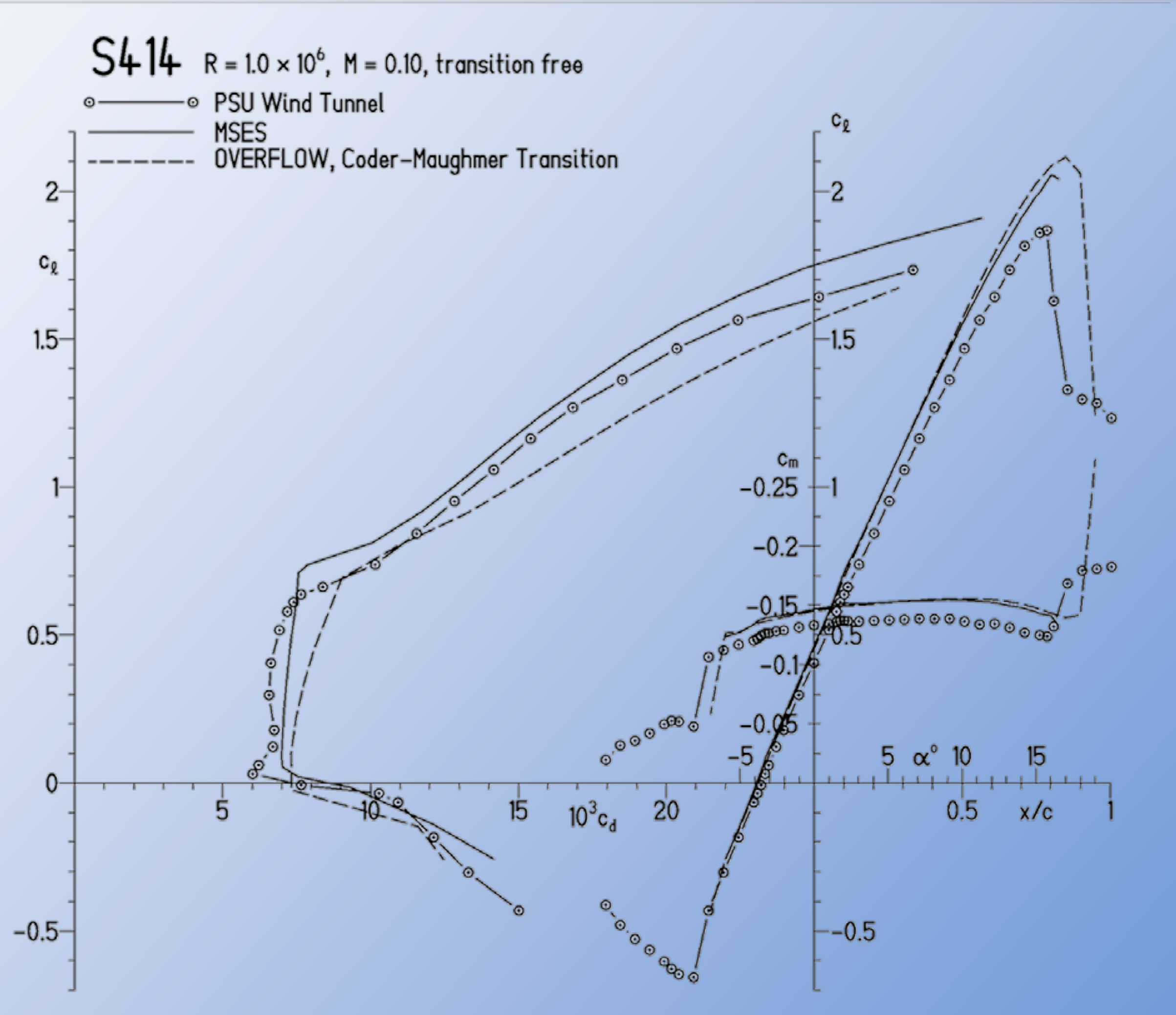
Aerodynamic Characteristics- Tab Simulating a Simple Flap



Baseline Pressure Distributions
Theory vs. Experiment



Aerodynamic Characteristics Theory vs. Experiment



Conclusions - NASA Learn Project

SNLF concept works

Theory is reliable except for maximum lift and stall characteristics

While scheduling of aft element for ailerons/flaps is possible, a simple flap/aileron on aft element seems more suitable

Aft element mounting bracket drag is not excessive

S414 stall characteristics are undesirable

Relevant Publications

Somers, D.M., "Laminar-Flow Airfoil, U.S. Patent 6,905,092 B2, June 2005.

Maughmer, M.D., "Benefits of Using a Slotted, Natural-Laminar-Flow Airfoil to Business-Jet, Cruise Performance," Airfoils, Inc., July 2004.

Somers, D.M. and Maughmer, M.D., "Design and Experimental Results for the S414 Airfoil," U.S. Army Research, Development and Engineering Command, RDECOM TR 10-D-112, August 2010.

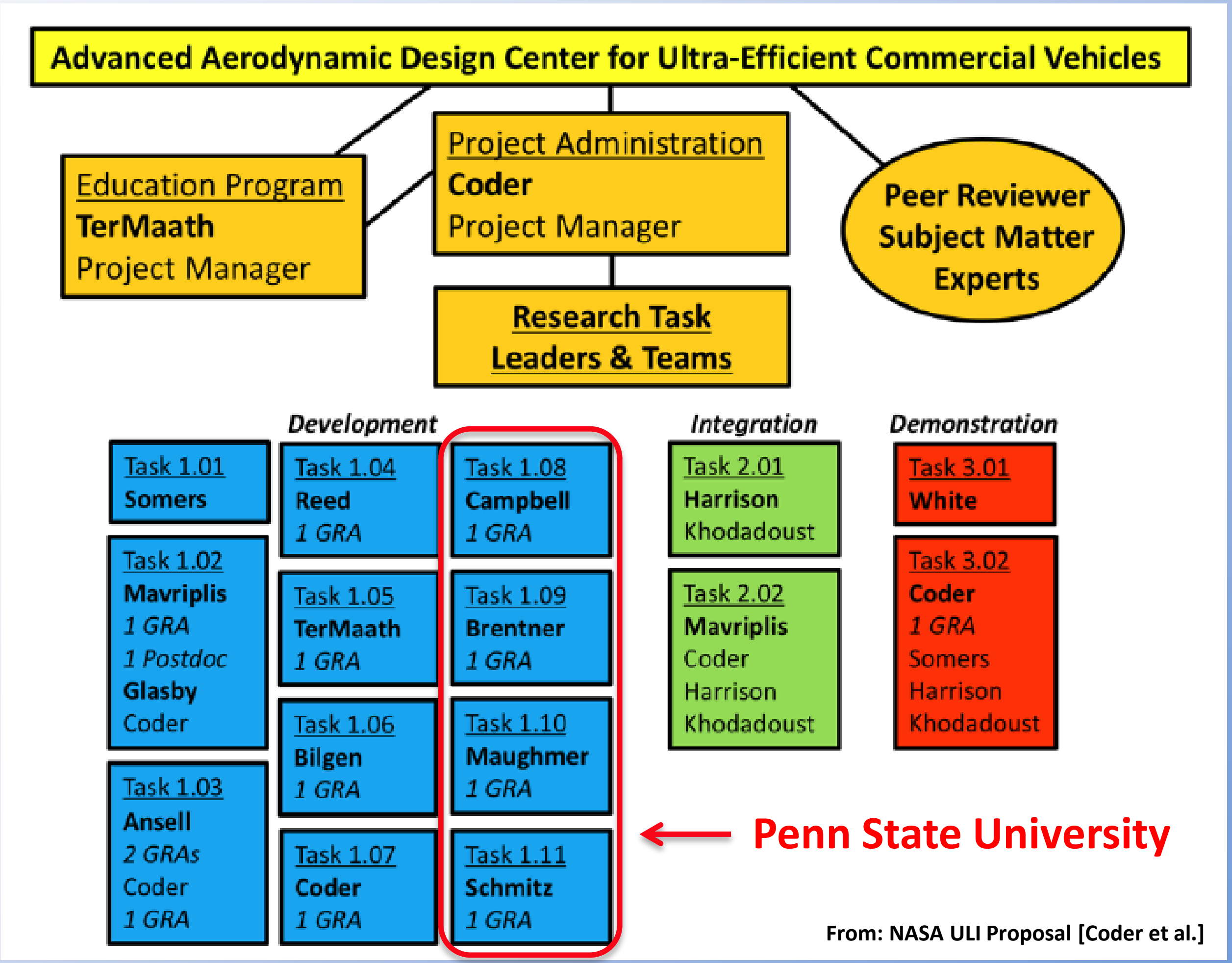
Somers, D. M., "An Exploratory Investigation of a Slotted, Natural-Laminar-Flow Airfoil," NASA/CR-2012-217560, April, 2012.

Coder, J.G., Maughmer, M.D., and Somers, D.M., "Theoretical and Experimental Results for the S414, Slotted, Natural-Laminar-Flow Airfoil," *Journal of Aircraft*, Vol. 51, No. 6, Nov.-Dec. 2014, pp. 1883-1890.

Coder, J.G., Maughmer, M.D., and Somers, D.M., "Theoretical and Experimental Results for the S414, Slotted, Natural-Laminar-Flow Airfoil," AIAA Paper 2013-2655, 31st AIAA Applied Aerodynamics Conference, San Diego, CA, June 24-27, 2013.

Maughmer, M.D., "The Theoretical and Experimental Exploration of a Slotted, Natural-Laminar-Flow Airfoil Concept," Symposium for Sailplane Development, Technical University Braunschweig, Nov. 21 -22, 2013.

Organizational Chart



Tasks

- **Application of Winglets to SNLF Transport Wing**
  PI: Mark D. Maughmer (+1 Graduate Student)

- **Theoretical Drag Decomposition of High-Efficiency Aircraft**
  PI: Sven Schmitz (+1 Graduate Student)

- **Aeroacoustic Predictions at Low-Speed Flight Conditions**
  PI: Kenneth S. Brentner (+1 Graduate Student)

- **Aeroelastic Behavior of Flutter Mitigation of Multielement Wings**
  PI: Robert C. Campbell (+1 Graduate Student)

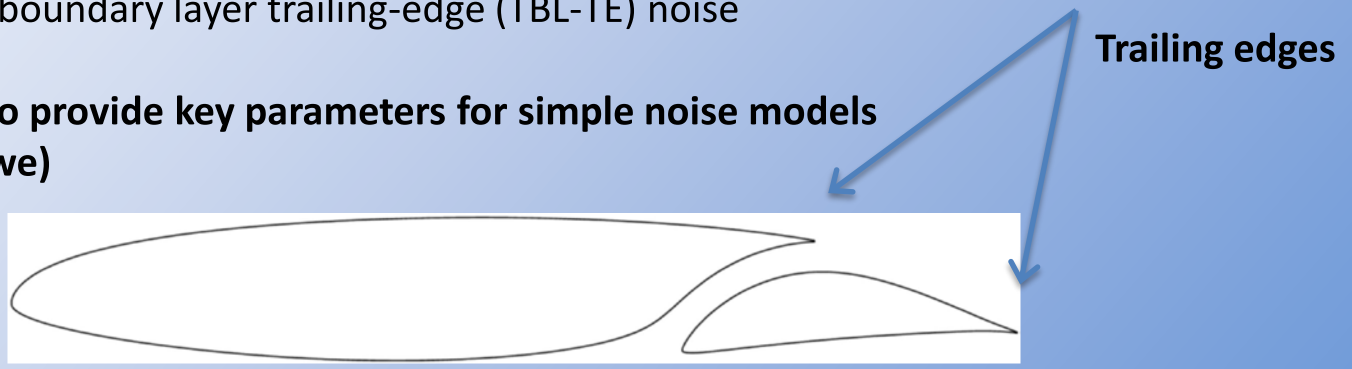
Task 1.09: Aeroacoustic Predictions at Low-Speed Flight Conditions

PI: Dr. Kenneth S. Brentner, Professor of Aerospace Engineering

Approach to SNLF wing noise prediction:

- **Trailing-edge noise focus (two main types)**
  - Laminar-boundary layer – vortex shedding (LBL-VS) noise
  - Turbulent-boundary layer trailing-edge (TBL-TE) noise

- **Steady RANS to provide key parameters for simple noise models (FW-Hall / Howe)**



- **Scale-resolving hybrid RANS/LES couple with Ffowcs Williams-Hawkings (FW-H) solver (PSU-WOPWOP) for higher fidelity predictions**
  - More demanding computations
  - In principle, can account for unsteady flow interactions, active flow control, coupling between main element and aft element, etc.

Task 1.09: Aeroacoustic Predictions at Low-Speed Flight Conditions

PI: Dr. Kenneth S. Brentner, Professor of Aerospace Engineering

Anticipated approach to take-off noise:

- SNLF configuration should result in noise reduction due to smaller engines (due to improved configuration efficiency)
- Use ANOPP/ANOPP2 for system noise prediction
  - Predict SNLF configuration noise based on improved efficiency
    - Resized engines
    - Quantify noise reduction
    - Evaluate sensitivity of noise reduction to efficiency improvements
  - Predict baseline noise configuration for take off (baseline aircraft TBD)

Task 1.10 Configuration Development Support and Winglet Design

PI: Dr. Mark D. Maughmer, Professor of Aerospace Engineering

Statement of Work

1. Support the determination of the most appropriate airframe configuration for the application of the SNLF airfoil design through traditional drag build-up and performance analyses methods, Year 1 (PI + 1 Ph.D. student). Preliminary results obtained with CRM and S103 airfoils.
2. Explore the winglet design space, considering such questions as to whether or not overall performance would benefit from the use of an SNLF airfoil on the winglet, Year 2 (PI + 1 Ph.D. student).
3. Develop a finalized winglet design, including a detailed performance analysis using traditional approaches. Compare the drag build-up and performance results with those obtained using the CFD drag decomposition approach, Years 3 (PI + 1 Ph.D. student).

Deliverables

- Annual reports of progress.
- Publication of findings and design studies in the AIAA Journal of Aircraft; presentations at AIAA Aviation and/or SciTech conferences.
- Final SNLF transport configuration, including wing/winglet design. Predicted aerodynamics and performance.

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NASA University Leadership Initiative

Task 1.11 Theoretical Drag Decomposition of High-Efficiency Aircraft

PI: Dr. Sven Schmitz, Associate Professor of Aerospace Engineering

Consistent methodology for aircraft drag decomposition is important for design process.

$p = p_E + p_\mu$ = **Static pressure**

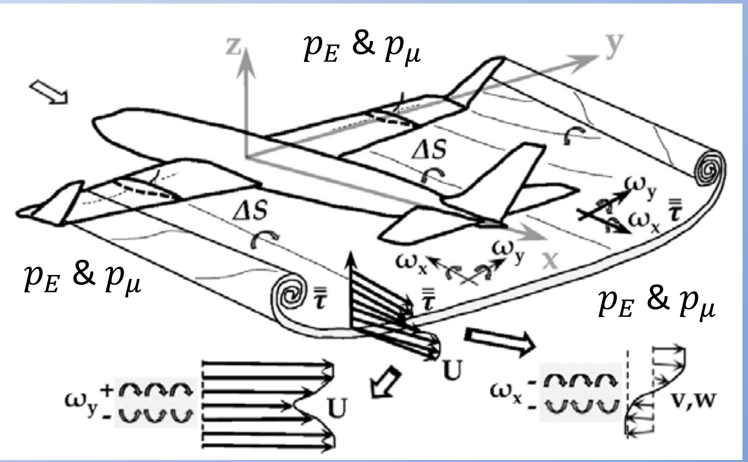
p_E = **Euler pressure**

=> Lift & Vortex-Induced Drag

p_μ = **Dissipative pressure**

=> Lift perturbation & Form Drag

Paper presented in *Fundamental Fluids I*



AIAA-2018-2908

Concept of 'Partial-Pressure Fields' eliminates difficulties of classical far-field methods :

i. Co-processing of partial pressure fields vs. post-processing of wake/volume flow data
ii. Detailed surface pressure fields vs. single integrated value sensitive to wake surface
iii. Applicable to general lifting body vs. assumptions of lightly-loaded wake etc.

Task 1.11 Theoretical Drag Decomposition of High-Efficiency Aircraft

PI: Dr. Sven Schmitz, Associate Professor of Aerospace Engineering

Conceptual Idea : **Quantify 'viscous-inviscid interaction' co-processed with viscous flow solution.**

Momentum Equation : $\rho(\boldsymbol{q}\cdot\nabla)\boldsymbol{q} = -\nabla p + \nabla\cdot\boldsymbol{\tau} \qquad ;\ p = p_E + p_\mu$

Pressure Decomposition : $\nabla p_E + \rho\nabla\left(\frac{1}{2}\boldsymbol{q}\cdot\boldsymbol{q}\right) - \rho\boldsymbol{q}\times\boldsymbol{\omega} = -\nabla p_\mu + \nabla\cdot\boldsymbol{\tau}$

Transport Equations : $(\boldsymbol{q}\cdot\boldsymbol{\nabla})p_E = -\rho\boldsymbol{q}\cdot\boldsymbol{\nabla}\left(\frac{1}{2}\boldsymbol{q}\cdot\boldsymbol{q}\right)$ $\qquad (\boldsymbol{q}\cdot\nabla)p_\mu = \boldsymbol{q}\cdot(\nabla\cdot\boldsymbol{\tau})$

Euler pressure p_E integrates to compressible vortex-induced drag

Approach & Activities :

Year 1: Theoretical Drag Decomposition Using Partial-Pressure Fields (PI only). AIAA-2018-2908

Years 2-3: Implementation of Partial-Pressure Transport Equations in CFD codes. (PI + 1 Ph.D. student)

Years 3-4: Drag Decomposition Using Partial-Pressure Fields and Far-Field Methods. (PI + 1 Ph.D. student)

Years 4-5: Drag Decomposition of Final Configuration – Design Improvements. (PI + 1 Ph.D. student)

Education Program

- **Freshman Seminar: Aerospace Explorer**
  - Engage early engineering students into the Advanced Aerodynamic Design Center
- **Undergraduate Education**
  - Research Experience for Undergraduates (REU)
    - Partner w/ Penn State branch campuses and NASA ULI partners
  - Integrate lesson material in Aerospace courses
    - Aerodynamics I/II (Schmitz, Brentner), Flight Vehicle Design & Fabrication (Maughmer)
- **Diversity & Inclusion**
  - Partner w/ the CoE Office of Engineering Diversity for the *Women in Engineering Program Orientation* (WEPO)
- **Technology Transfer**
  - Collaborate w/ Boeing (Tasks 2.01 & 2.02) and NASA (Task 3.02)
  - Student Internships at Boeing & NASA

Advanced Aerodynamic Design Center for Ultra-Efficient Commercial Vehicles

University Leadership Initiative (ULI) Program
Boeing's Role

ULI Session at Aviation **June 25, 2018**

Abdi Khodadoust
Sr. Manager, Advanced Aerodynamic Design
Boeing Research & Technology
abdollah.Khodadoust@Boeing.com

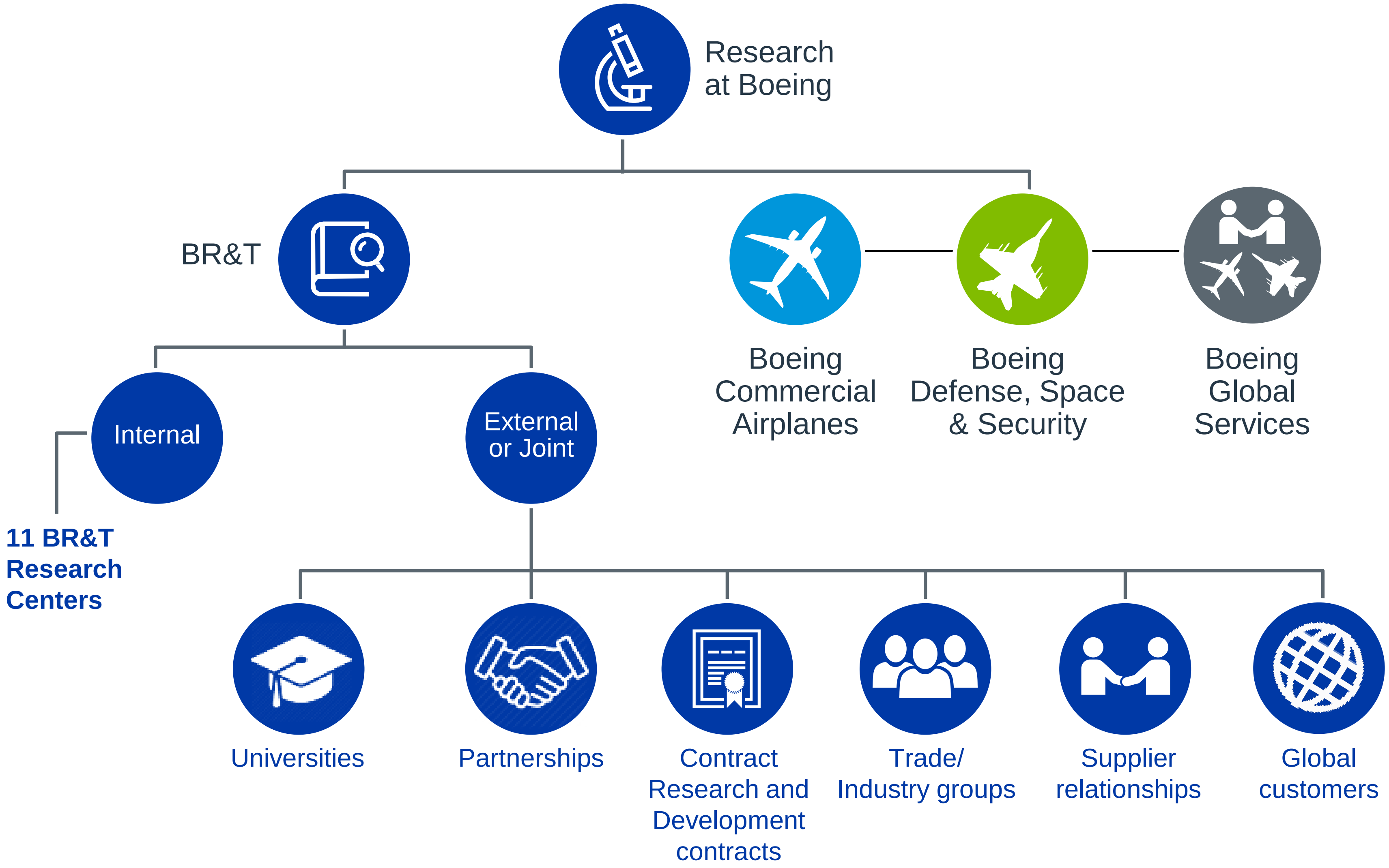
Why we are interested in this NASA ULI study?

The Boeing Company continually seeks to advance knowledge and understanding of flight vehicle concepts that show or hold a significant promise for improved aerodynamic performance.

- The Transonic Truss Braced Wing concept seeks to take advantage of high aspect ratio wings to reduce the aircraft's induced drag
- Significant challenges exist in developing a 737-class vehicle.
- Questions of interest – does implementation of Slotted Natural Laminar Flow (SNLF) wing technology further enable the TTBW concept to enjoy even longer range or lower fuel burn? If so, by how much?

Boeing is actively involved in the development of the future aerospace workforce, and in providing high-quality educational opportunities for students in STEM disciplines

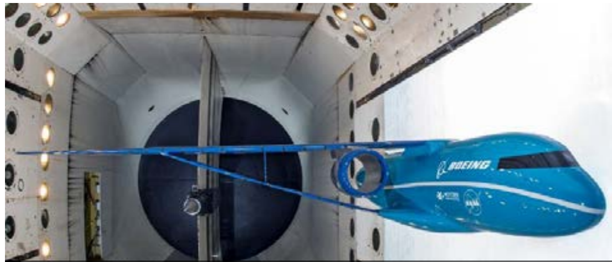
Research & Development at Boeing
Robust and widespread



NASA/Boeing Transonic Truss-Braced Wing (TTBW)

Boeing currently under contract with NASA to mature and develop the TTBW Concept. This is a continuation of previously-funded NASA Projects:

- SUGAR Phase I – TTBW Conceptual design and technology roadmap
- SUGAR Phase II – TTBW Aeroelastic development (FEM and TDT test)
- SUGAR Phase III – High-speed design and test of a TTBW for M_{cruise}=0.745
- SUGAR Phase IV (in progress)
  - Development of high-speed lines for M_{cruise}=0.8
  - High-speed wind tunnel test
  - Low-speed (high-lift) system development
  - Low-speed (high-lift) wind tunnel test



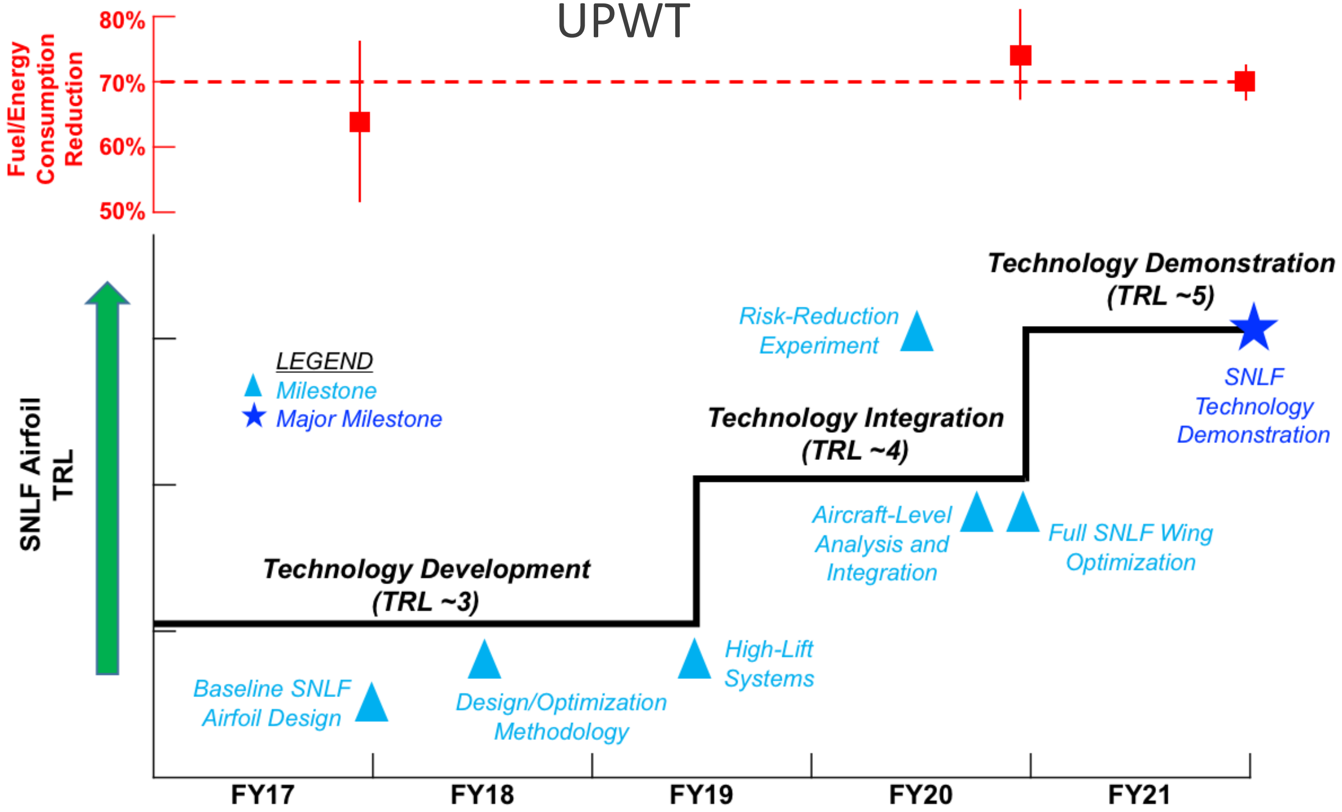
SUGAR Phase II
Aeroelastic Testing at NASA TDT

SUGAR Phase III
Transonic wind tunnel test at NASA Ames 11' UPWT

Project Plan

Boeing's Role by Phase

- Technology Development – Design Consultation
- Technology Integration – Aircraft-level Aerodynamic Performance Analysis
- Technology Demonstration – Active participation in the planning and execution of the SNLF wind tunnel test in the NASA Ames 11' UPWT



Phase II: Technology Integration

Task	Description	Key Personnel	Boeing Role
2.01	Aircraft-Level Integration of SNLF Technology	Harrison, Vijgen	CASES assessment of aerodynamic, structural weight and control effectives
2.02	Complete Design of an SNLF Wing	Coder, Mavriplis, Harrison, Vijgen	Wing Design and analysis consultation

Boeing will utilize an in-house conceptual analysis tool (CASES) to perform aircraft-level performance analysis

Computer-Aided Sizing and Evaluation System (CASES)

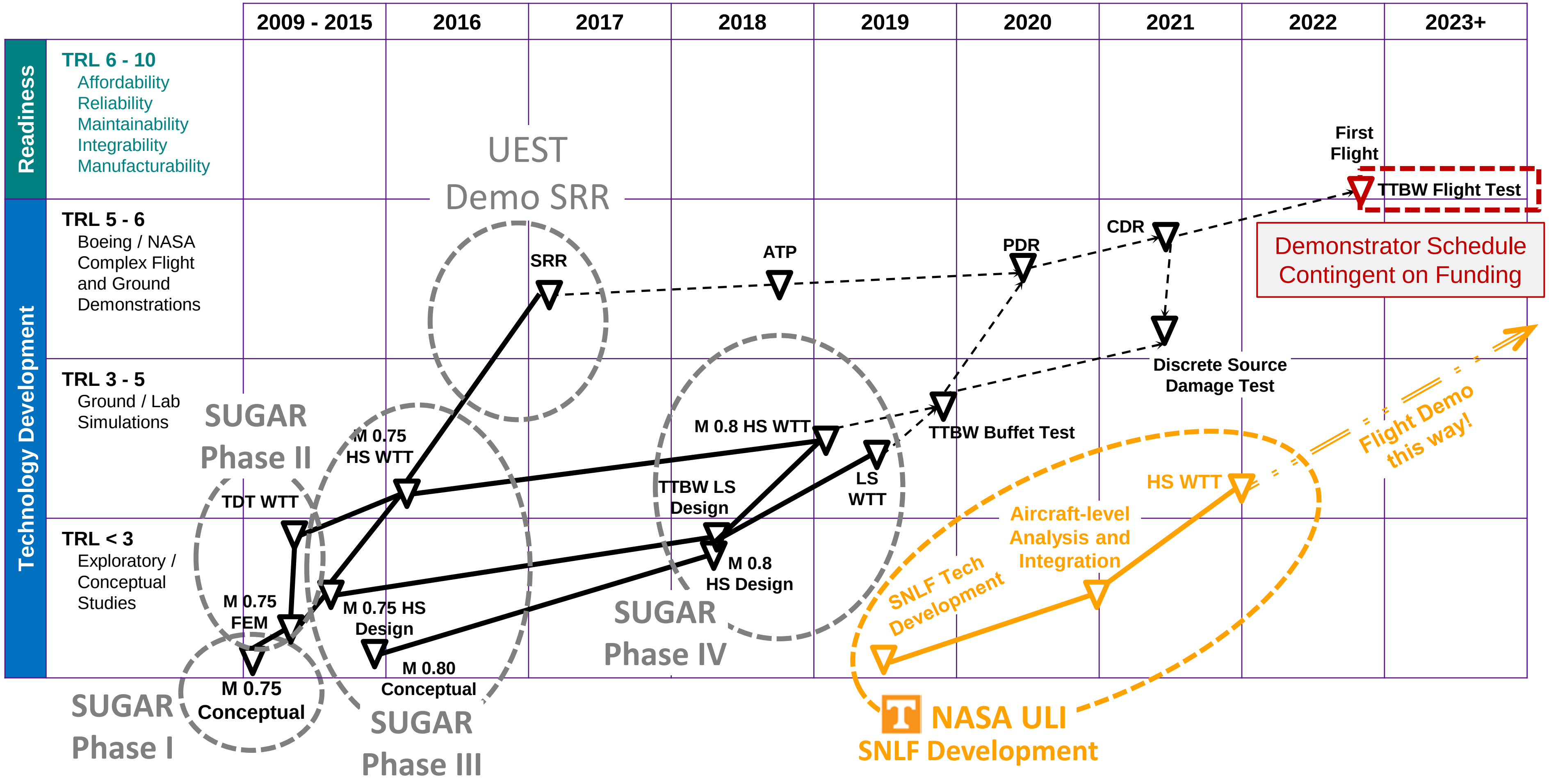
- Heritage tool used for performing aircraft sizing and performance analysis
- Integrated, modular, inter-disciplinary analysis system for the rapid synthesis and assessment of new or derivative air vehicles at the conceptual design level (or higher)
  - Discipline modules represent the best practices of the Boeing Co.
  - Multi-level design tools used for military and commercial advanced design activities
  - Common configuration database

Phase III: Technology Demonstration

Task	Description	Key Personnel	Boeing Role
3.01	Risk-Reduction Experiment in TAMU LSWT	White	Observer + Consultant
3.02	Capstone Technology Demonstration in NASA Ames 11-ft WT	Coder, Somers, Harrison, Vijgen + student	Experience with WT testing of the baseline TTBW at the same facility.

Boeing will actively participate in the SNLF High-speed Wind Tunnel test, providing test planning, test support, analysis and guidance.

NASA/Boeing Transonic Truss-Braced Wing (TTBW) Technology and Development Roadmap
with NASA ULI Overlay



Projected Outcomes

Aircraft concept that shows distinct benefits, beyond those offered by the baseline Transonic Truss Braced Wing concept, would be of tremendous interest.

- Family of aircraft with strong potential for significant fuel savings.

Cadre of future work-force engineers and scientists that can become hire candidates at The Boeing Company.

- Summer internships at Boeing for students

Build on the strong relationship already in place between Boeing and academic partners Tennessee, Penn State, Illinois, Wyoming, Texas A&M and Rutgers

Connect, Protect, Explore & Inspire the World

EXTRA SLIDES

–

FOR Q&A

Slotted, Natural-Laminar-Flow Airfoils

Figure 1. S204 SNLF airfoil

Maughmer, M. D., Premi, A., and Somers, D. M., “Exploration of a Slotted Laminar-Flow-Control Airfoil Concept,” Final Technical Report, NASA Grant No. NNX13AB86A, Nov. 2013.

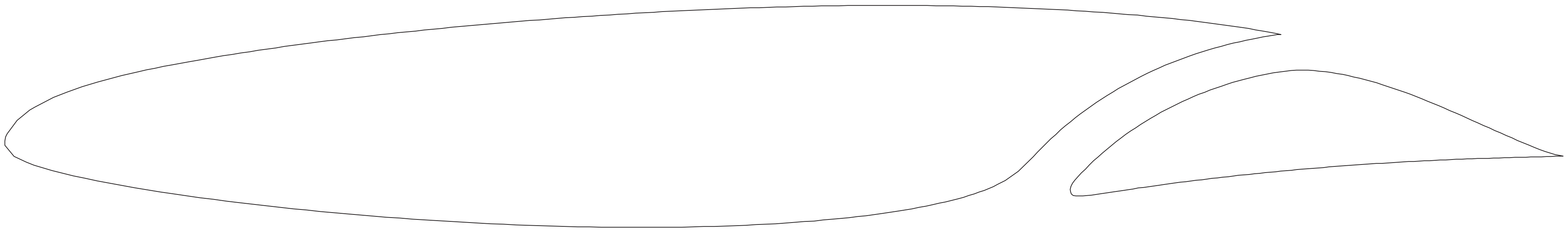
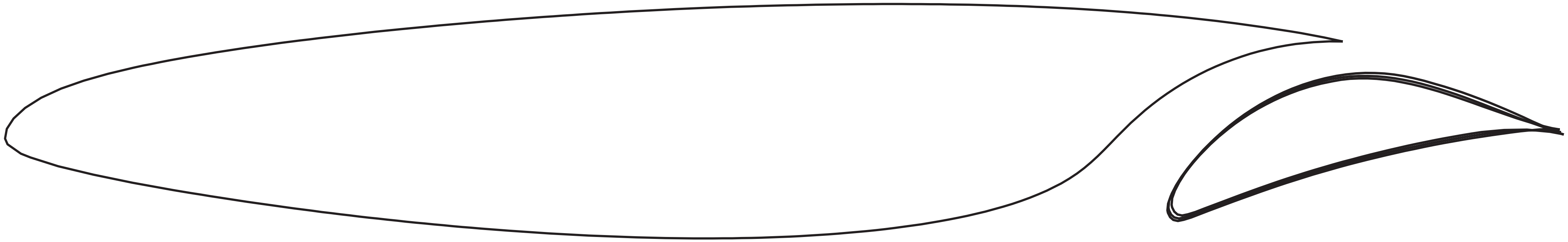
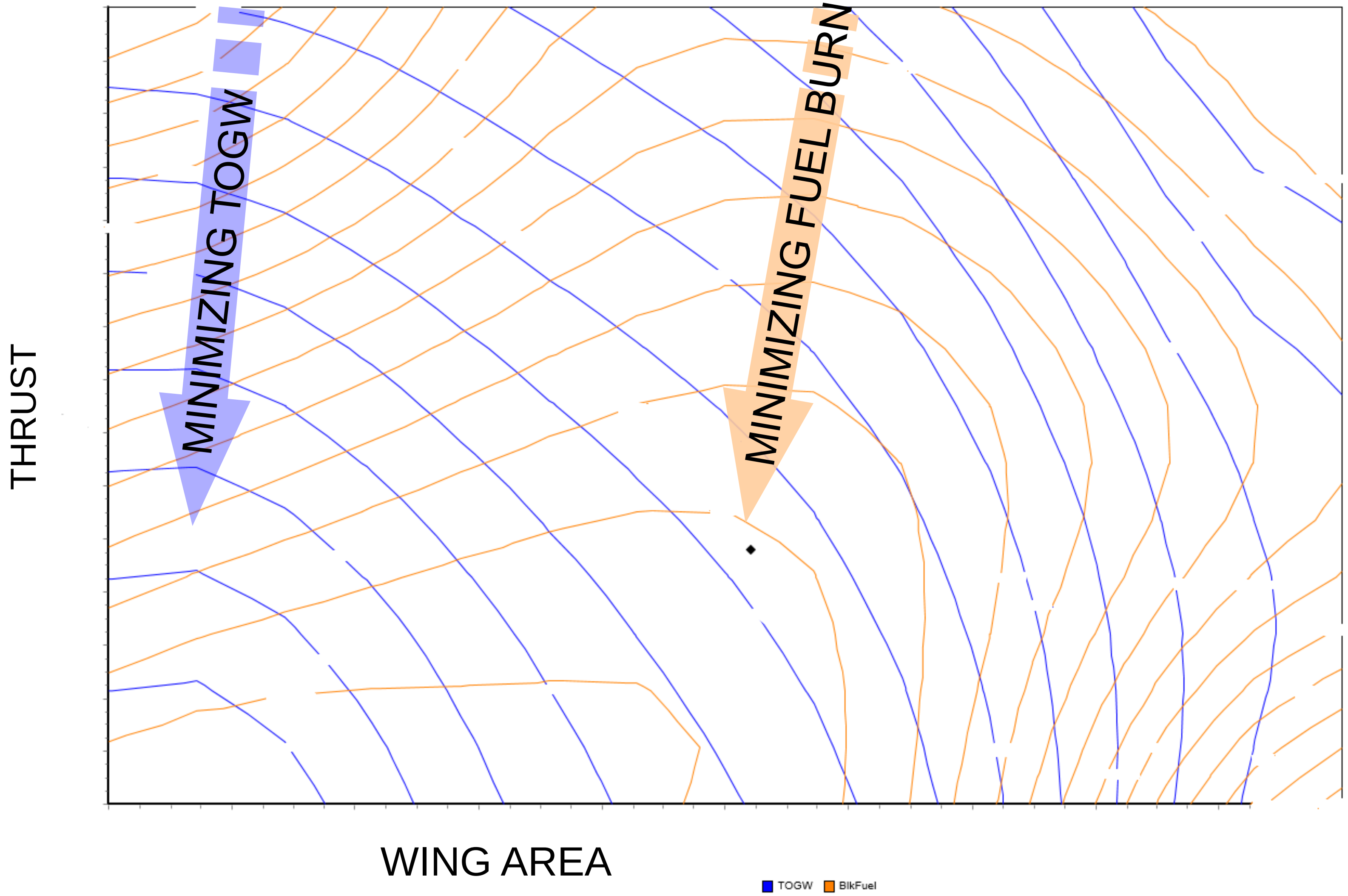


Figure 2. S103 SNLF airfoil

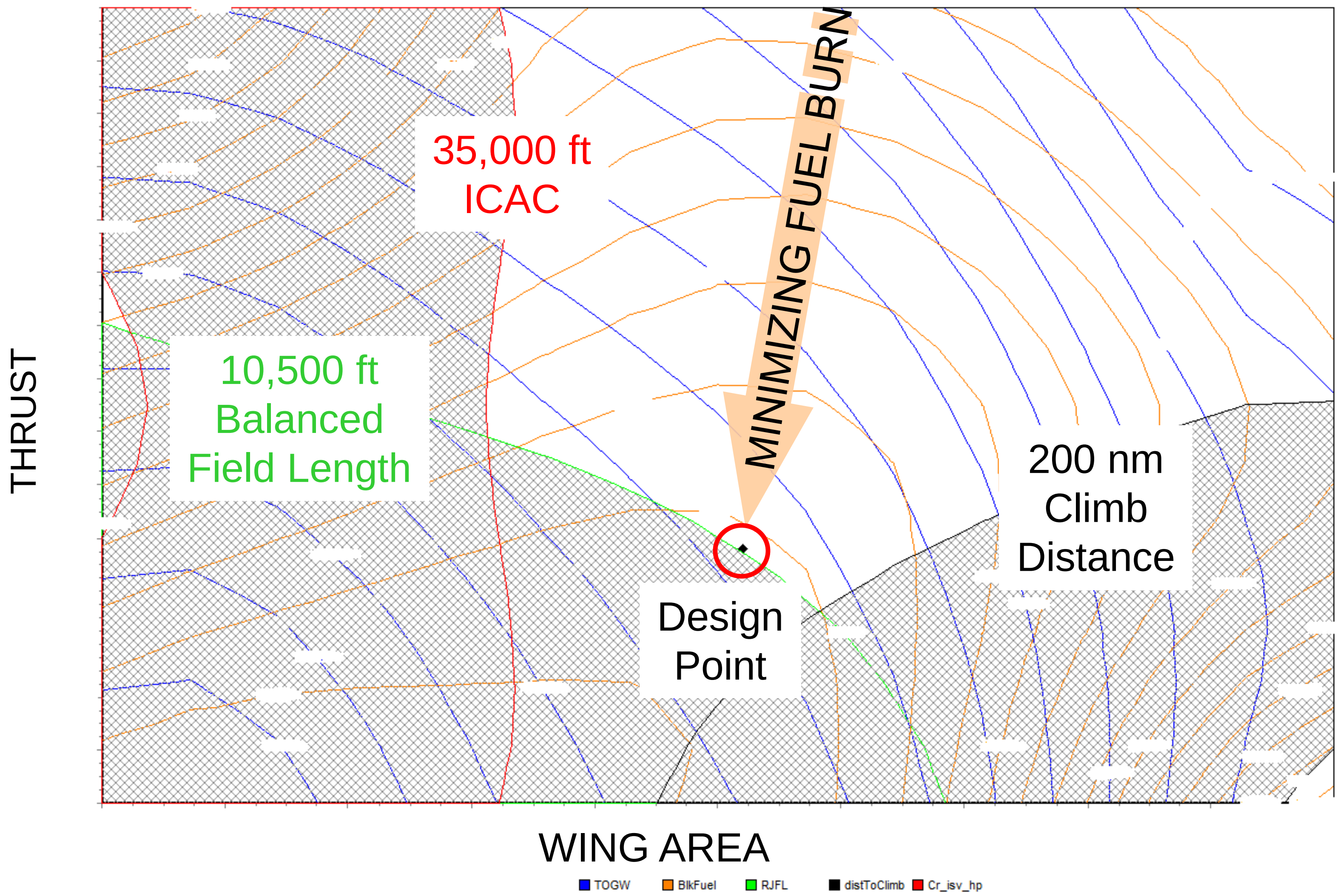
Somers, D. M., “An Exploratory Investigation of a Slotted, Natural-Laminar-Flow Airfoil,” NASA/CR-2012/217560, 2012.



Example Sizing Plot (Tube & Wing)

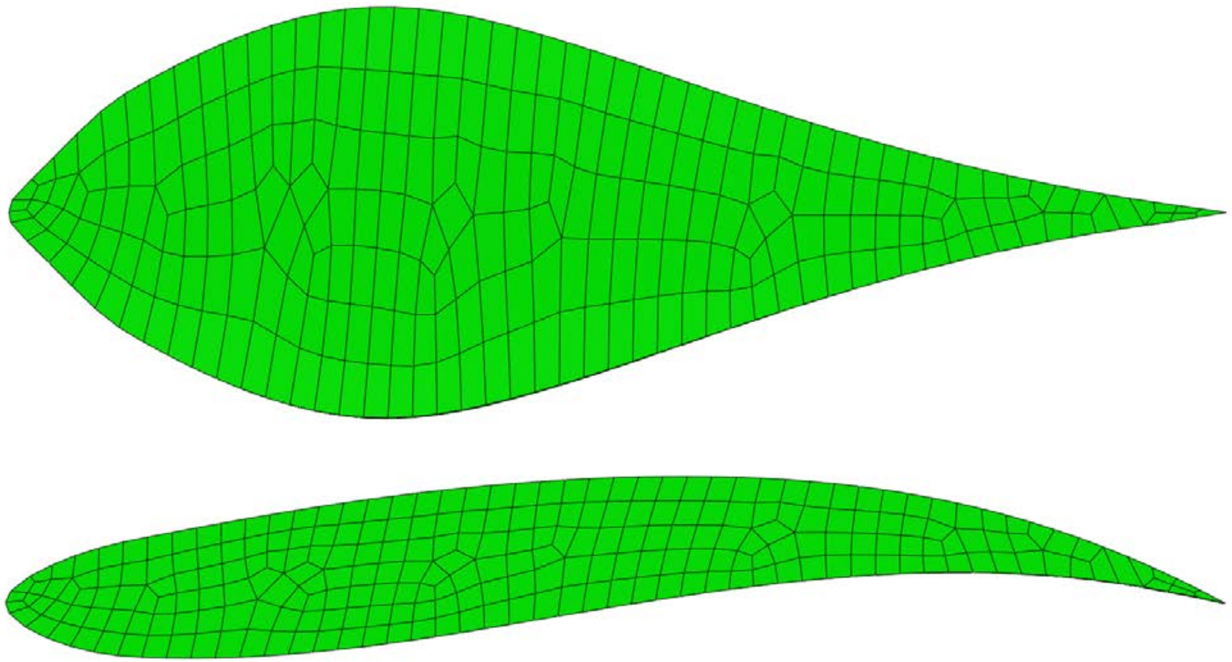


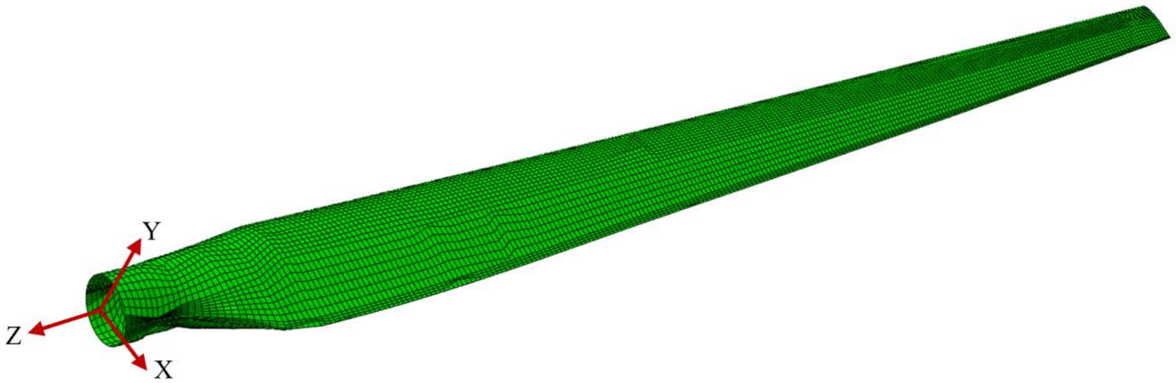
Example Sizing Plot (Tube & Wing)



Task 1.02: Structural Optimization

PI: Dimitri Mavriplis, Professor of Mechanical Engineering, University of Wyoming





(Backup figures)