Overview of Fundamental High-Lift Research for Transport Aircraft at NASA

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Berlin, Germany

Presentation Outline

NASA Aeronautics Overview

History

Configurations

Current Technology

- *Devices and Technology concepts*

CFD Status

Concluding Remarks

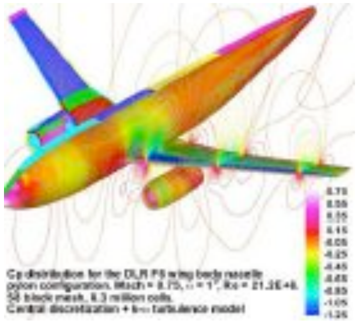
NASA's New Aeronautics Research Program

Our Three Principles

- We will dedicate ourselves to the mastery and intellectual stewardship of the core competencies of Aeronautics for the Nation in all flight regimes
- We will focus our research in areas that are appropriate to NASA's unique capabilities
- We will directly address the fundamental research needs of the Next Generation Air Transportation System (Next Gen) in partnership with the member agencies of the Joint Planning and Development Office (JPDO)

NASA's New Aeronautics Research Program

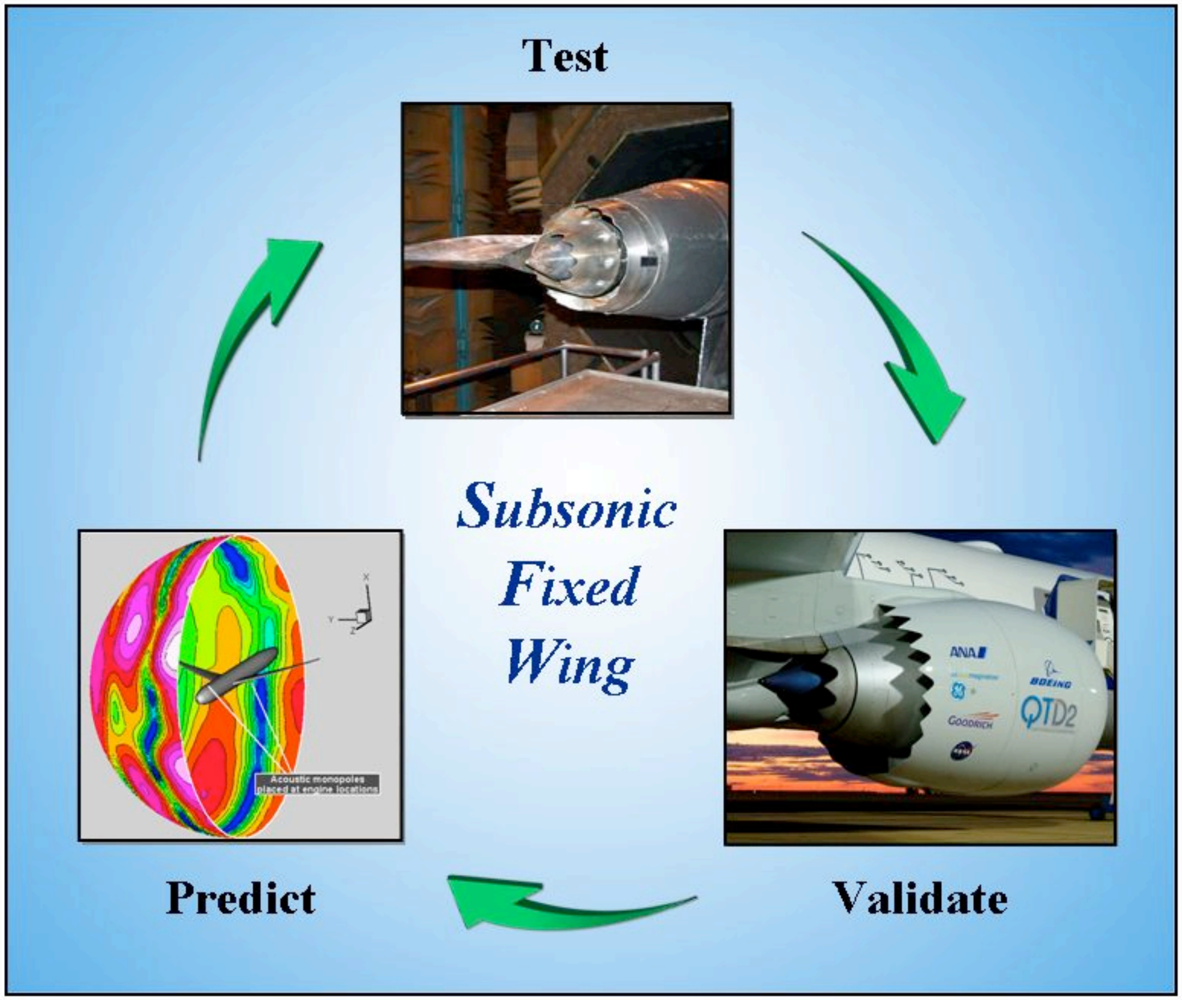
- **Fundamental Aeronautics Program**
  - Subsonics: Fixed Wing
  - Subsonics: Rotary Wing
  - Supersonics
  - Hypersonics



- **Aviation Safety Program**
  - Integrated Vehicle Health Management
  - Integrated Resilient Aircraft Control
  - Integrated Intelligent Flight Deck
  - Aircraft Aging & Durability
- **Airspace Systems Program**
  - NGATS Air Traffic Management: Airspace
  - NGATS Air Traffic Management: Airportal

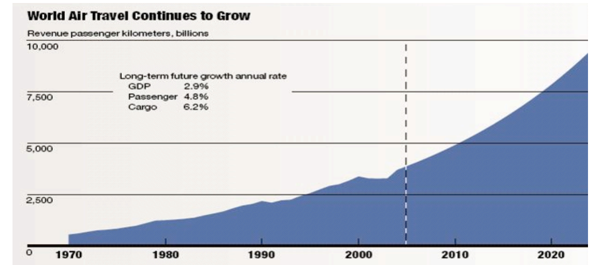
- **Aeronautics Test Program**
  - Ensure the strategic availability and accessibility of a critical suite of aeronautics test facilities that are deemed necessary to meet aeronautics, agency, and national needs

Fundamental Aeronautics Program
Subsonic Fixed Wing Project



Fay Collier, Principal Investigator
June 2007

SFW Aerodynamics - CE STOL Emphasis

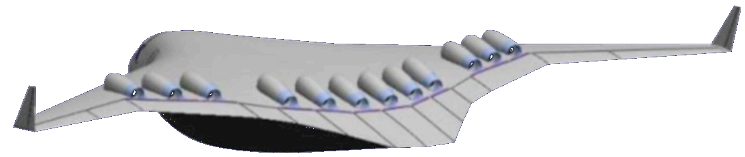


NextGen Challenge - Accommodate 2-3X Growth in Air Travel by 2025

- Barriers include capacity/congestion, noise, emissions
- Fuel Efficiency remains a vehicle constraint - becoming more important

Key Aircraft Capability

- **STOL (field length ≤ 3000 ft) with low noise and efficient high-speed cruise (Mach 0.8+)**
- Specific design trades left to end-user

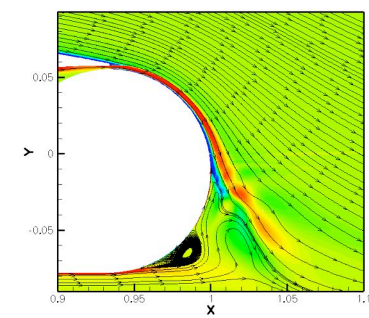


Key Aircraft Technology

- Powered Lift/Flow Control Concepts for Reduced Field Length
- Efficient Cruise Configuration/Component Concepts for Reduced Fuel Burn

Key Tools

- **3D Powered Lift/Flow Control Prediction/Design Tools (CFD - separation onset/progression)**
- **3D Powered Lift/Flow Control Test/Validation Capability (WT - relevant Mach and Rn)**



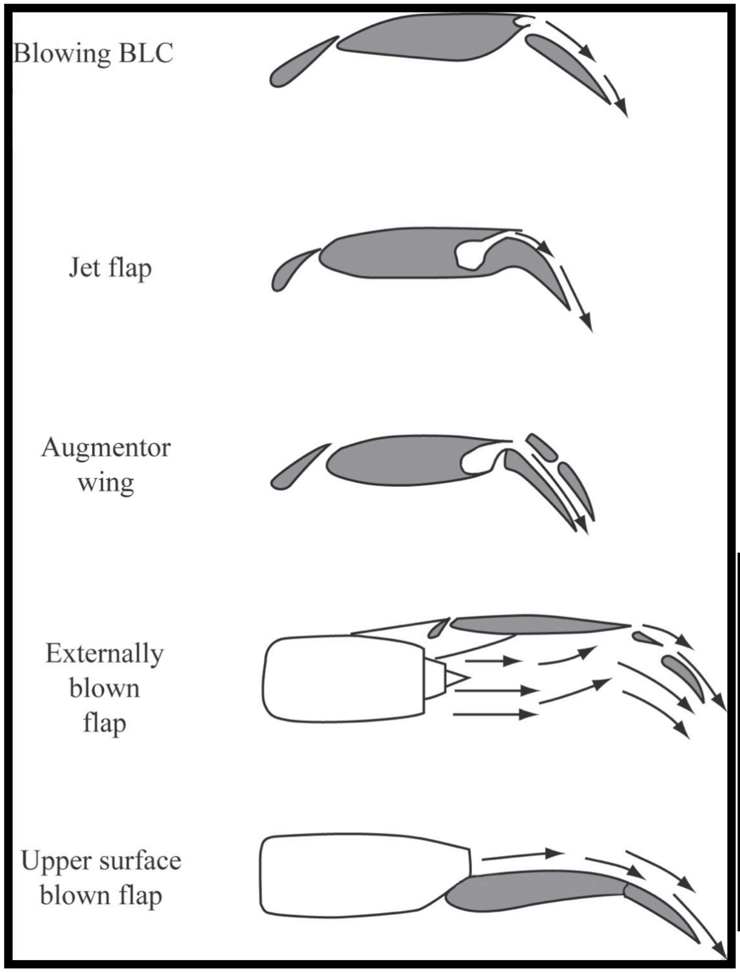
Key Partnerships for Tool & Technology Development/Validation

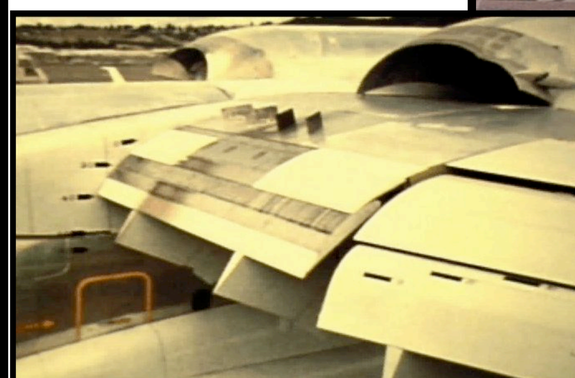
- NRA PI's at Level 1/2
- NASA/AFRL/Industry at Level 3/4

History

NASA High-Lift History

• *Powered Lift**



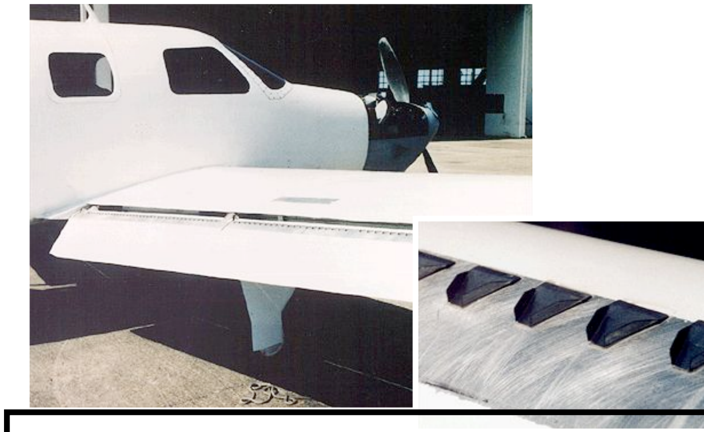


**From Chambers “Innovations in Flight, SP-2005-4539*

μVG- Streamwise Vorticity at fraction of TBL δ

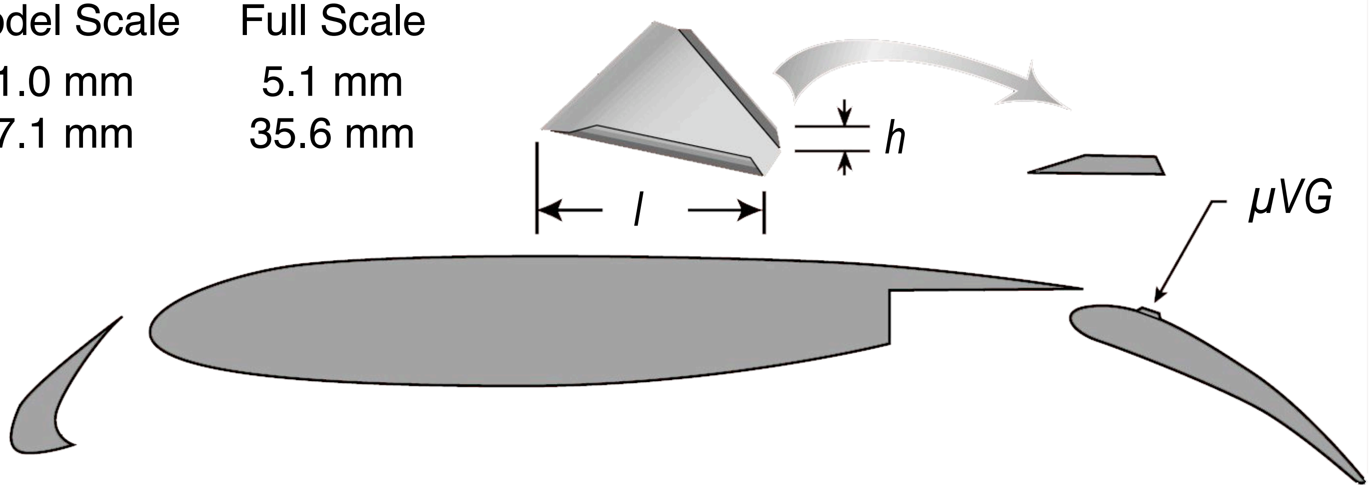
Efficient means of controlling flow separation

- *Redirects high energy flow into boundary layer*
- *Height of μVGs on the order of 0.2 h/δ*



Piper Malibu Application - enabled FAA certificaiton

	Model Scale	Full Scale
h	1.0 mm	5.1 mm
l	7.1 mm	35.6 mm



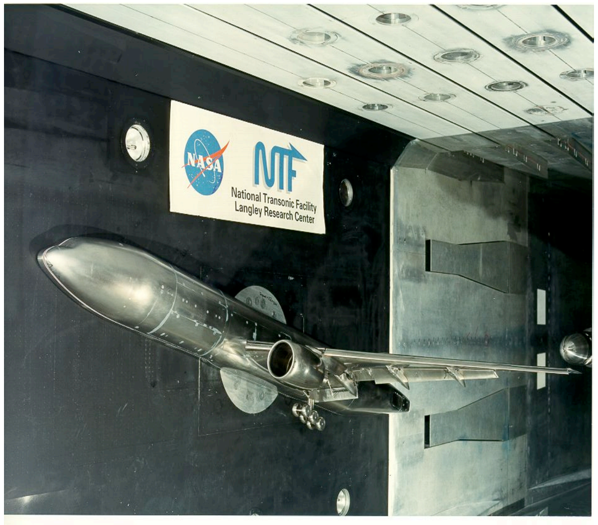
AST Program High-Lift Element (1994-2000)

- **Objective**

  Develop improved ***experimental*** and ***computational*** techniques which can provide increased 3-D high-lift system understanding and analysis and enables significant reduction in high-lift aerodynamic design cycle time.

Full-span trap wing model in the ARC 12' PWT

5.2% B777 in NTF



High Wing Transport in ARC 12' PWT

Configurations

ATT

Pneumatic Channel Wing

AFRL/NASA ESTOL Partnership

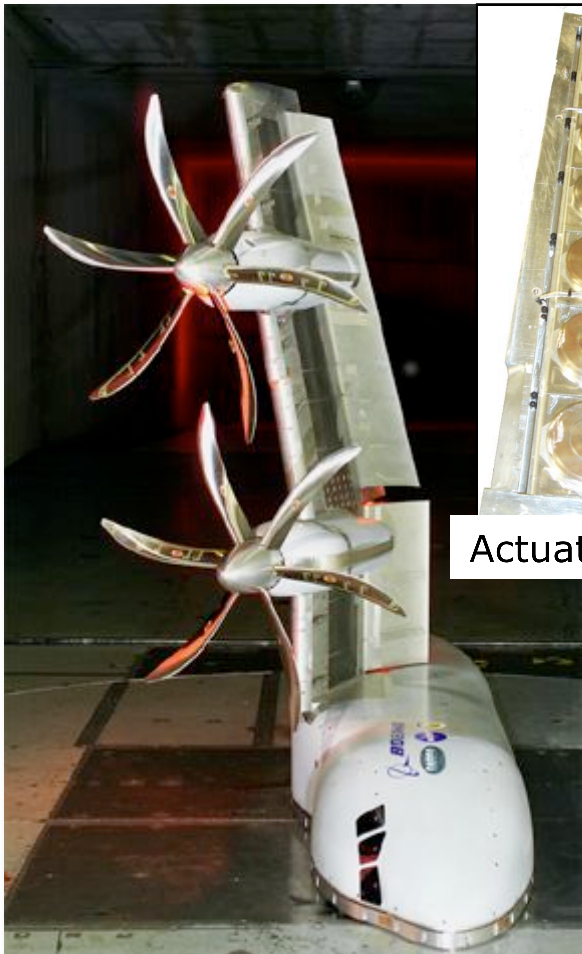
Flow Control on the Advanced Tactical Transport (ATT)

- **Boeing Advanced Theater Transport**
  - Forward-swept, tilt-wing, 4-engine turboprop
  - Deliver large payloads (80K lbs) on very short (750 ft) and unimproved landing sites
- **Requires Active Separation Control to achieve high lift goals for short takeoff and landing with simple hinged flap system**

BOEING®

Simplified High Lift – ATT/ADVINT

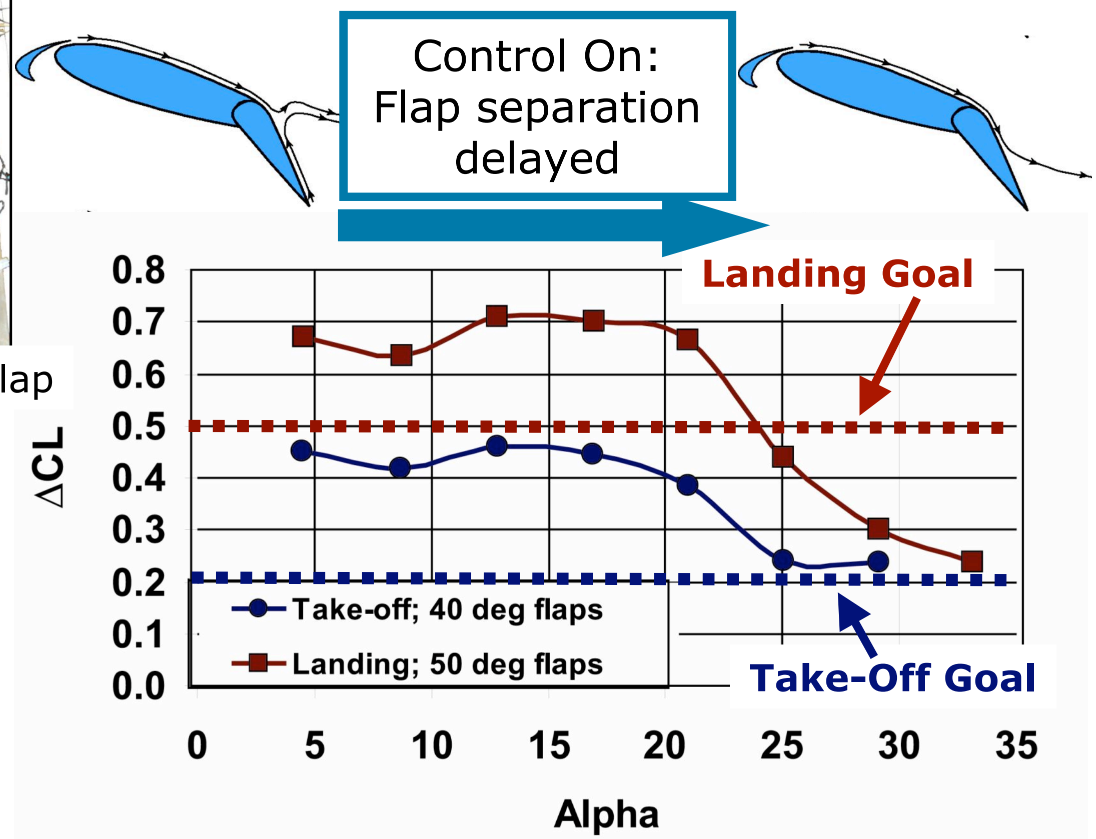
11% ATT Model in 14- by 22- Foot Tunnel



Actuators in flap

Goals for Active Flow Control (deltas from powered no-flow-control data)

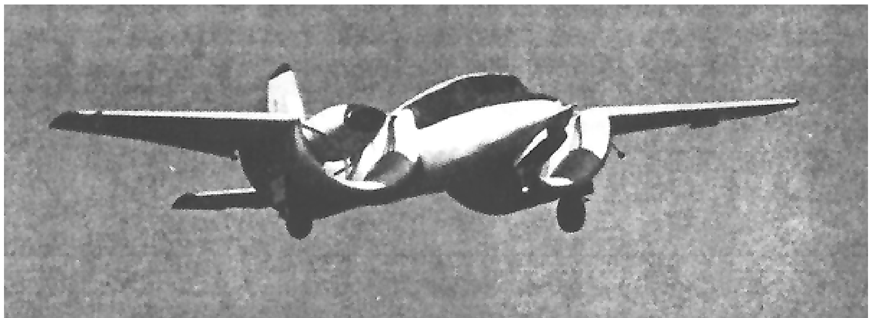
- Take-off, 40 deg flaps $\Delta CL = 0.2$ goal
- Landing, 50-60 deg flaps $\Delta CL = 0.5$ goal



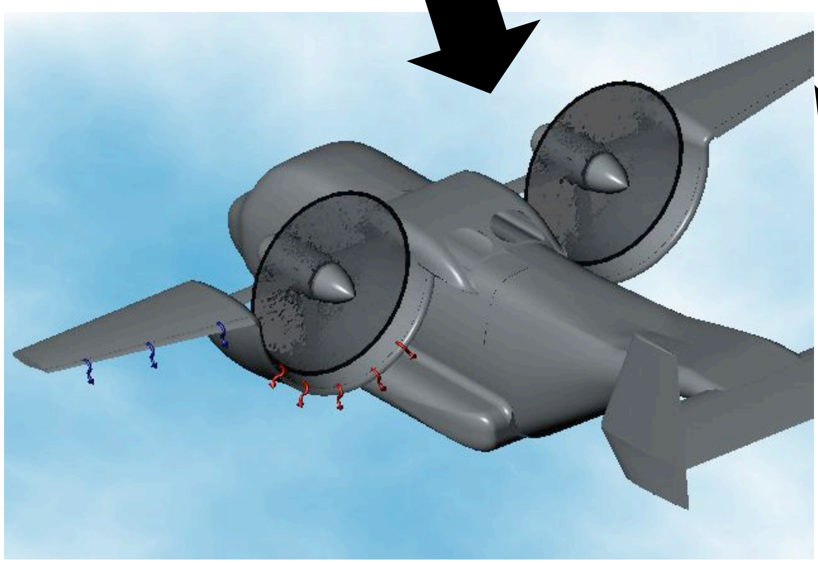
Pneumatic Channel Wing

Merging Proven Technologies

Custer Channel Wing



Circulation Control Wing (CCW)



Pneumatic Channel Wing

Super-STOL

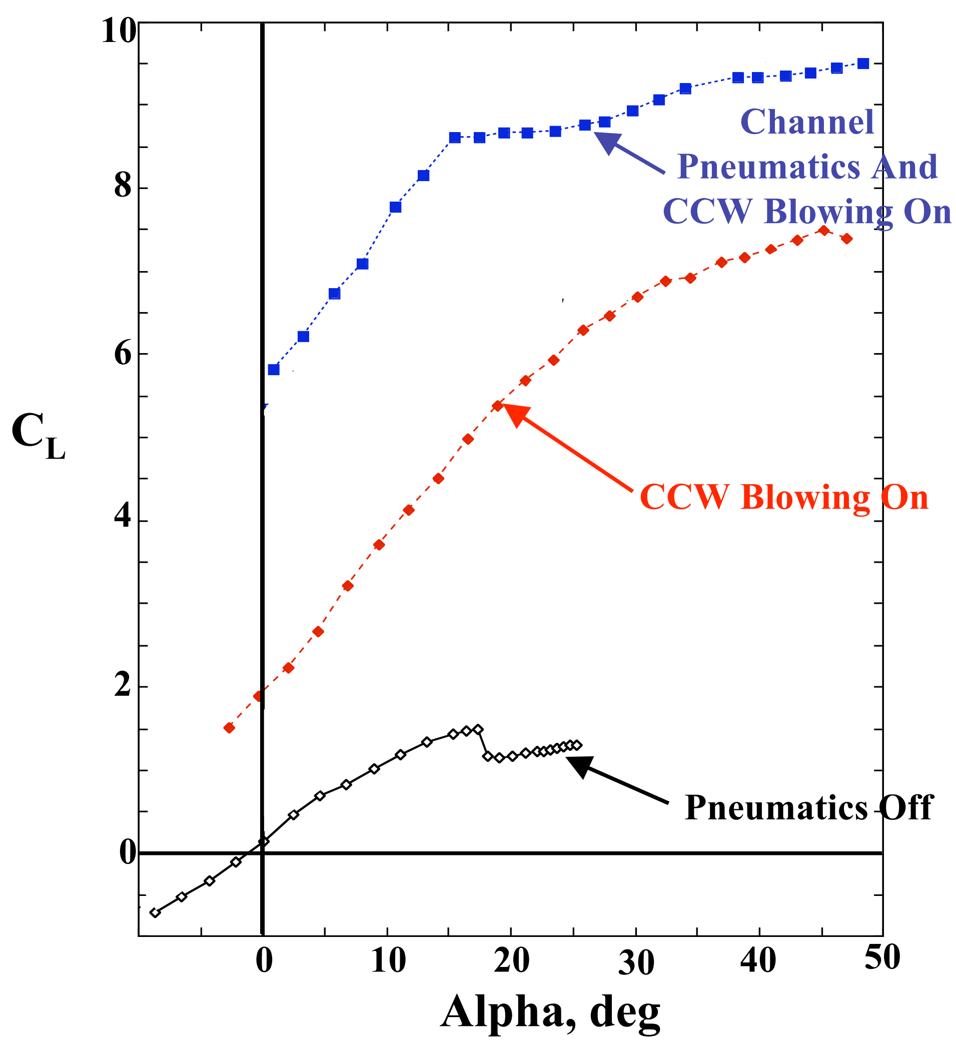
Near-VTOL

Utilizations

Remote sites
Rough Fields
Urban Environments
for
***Military**
***Personal Air Vehicles**
***Commercial**

Patented by Englar and Bushnell

Pneumatic Channel Wing



Performance Benefits

- On demand high-lift:
  - $C_L = 9$ (full wing)
  - $C_L = 10.5$ (isolated channel)
- Stall angles > 45°
- Rapid take-off
- Low-speed, steep landing approach
- Pneumatic roll/yaw maneuverability

AFRL/NASA ESTOL Partnership

FY08 New Start

Speed Agile Concept Demo

- Challenge: Achieving Efficient Flight at Low Speed / Terminal Area Conditions as well as Transonic Cruise Conditions
  - Historically STOL aircraft have had lower cruise speeds (~0.65 M) and transonic transports have required long fields

- Vision: A transport capable of carrying the Army's FCS at cruise speeds of Mach 0.8 and routinely operating from short (2,000 ft.), austere fields
- Speed Agile Concept Demo (FY08-FY10) -- Validate low speed, STOL performance and transonic performance of a common, integrated configuration (TRL goal: 5+, BAA/PRDA release fall 07)

Technologies

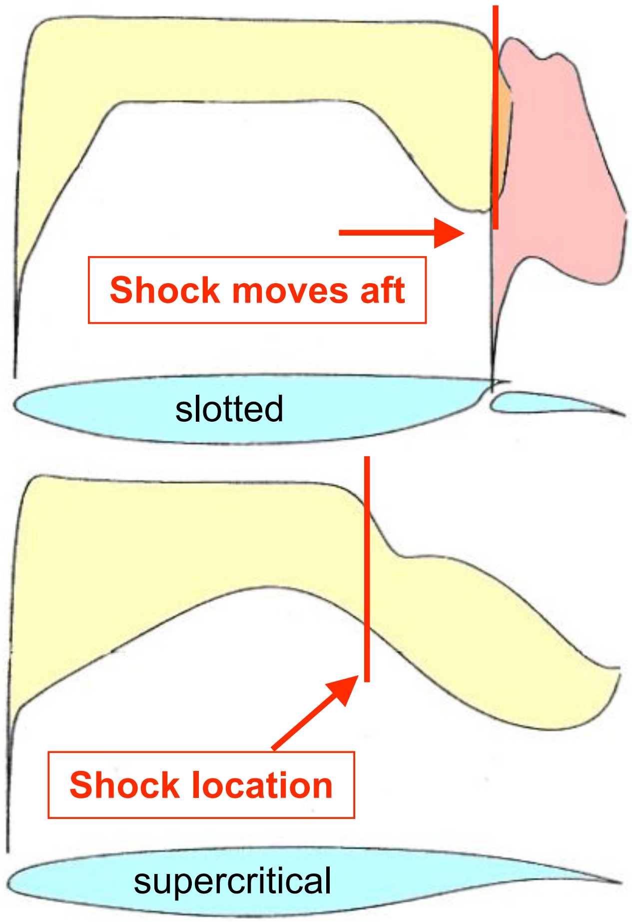
Slotted Wing (High Lift Aspects)

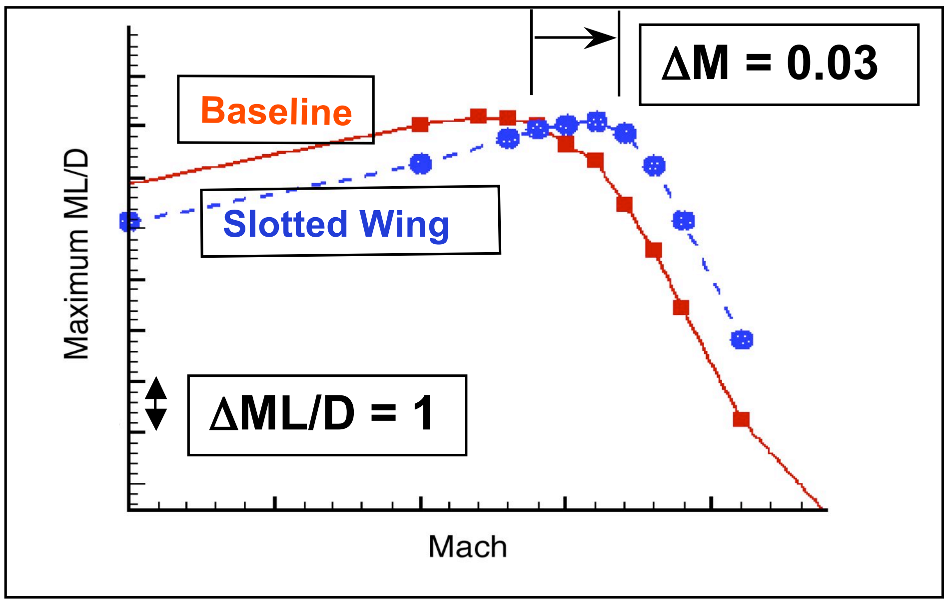
Circulation Control Wing (CCW)

Flow Control

Cruise Slotted Wing - Wave drag

- Complex viscous flow interactions
  - slot flow, wake, scale effect, shock/bl, etc
- Multidisciplinary trades and integration
  - multiple CFD cycle with experimental verification
- Key Findings
  - Performance benefit is achievable in 3D
  - CFD correlation with experiment needs improvement

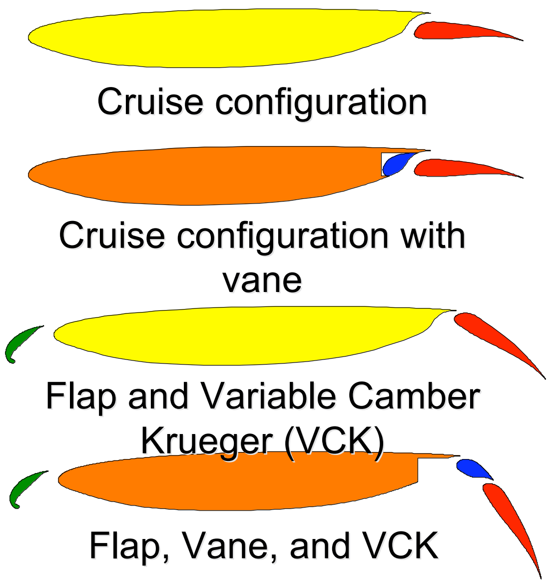




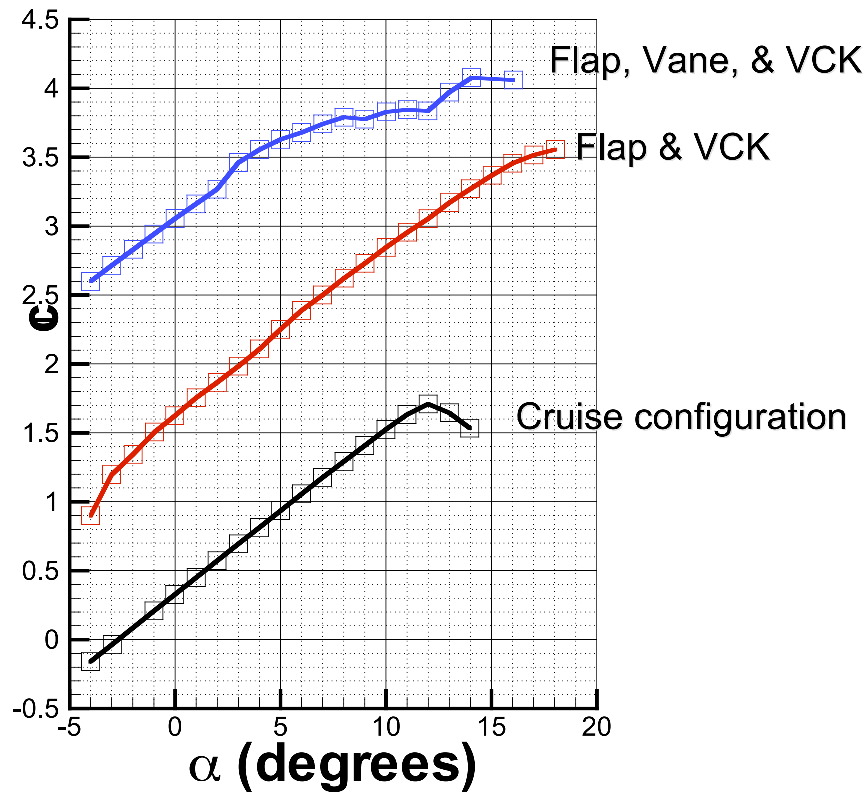
Slotted Wing Development

Technical Accomplishment

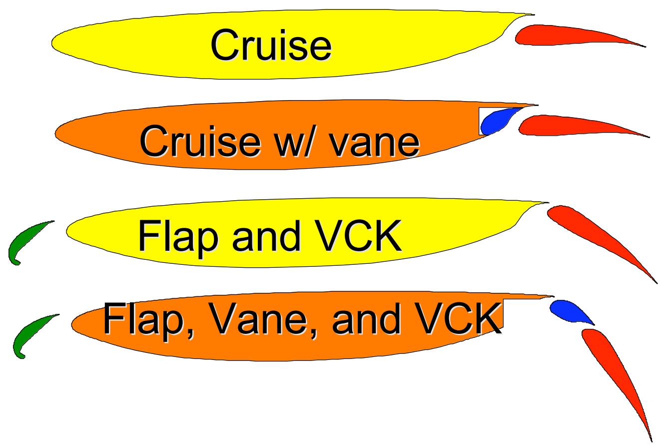
High Lift System Integration for Swept Slotted Wing Configurations



Wind tunnel data from LTPT
M=0.2, Re=9x10^6



High Lift Integration with Cruise Slotted Wing Concept



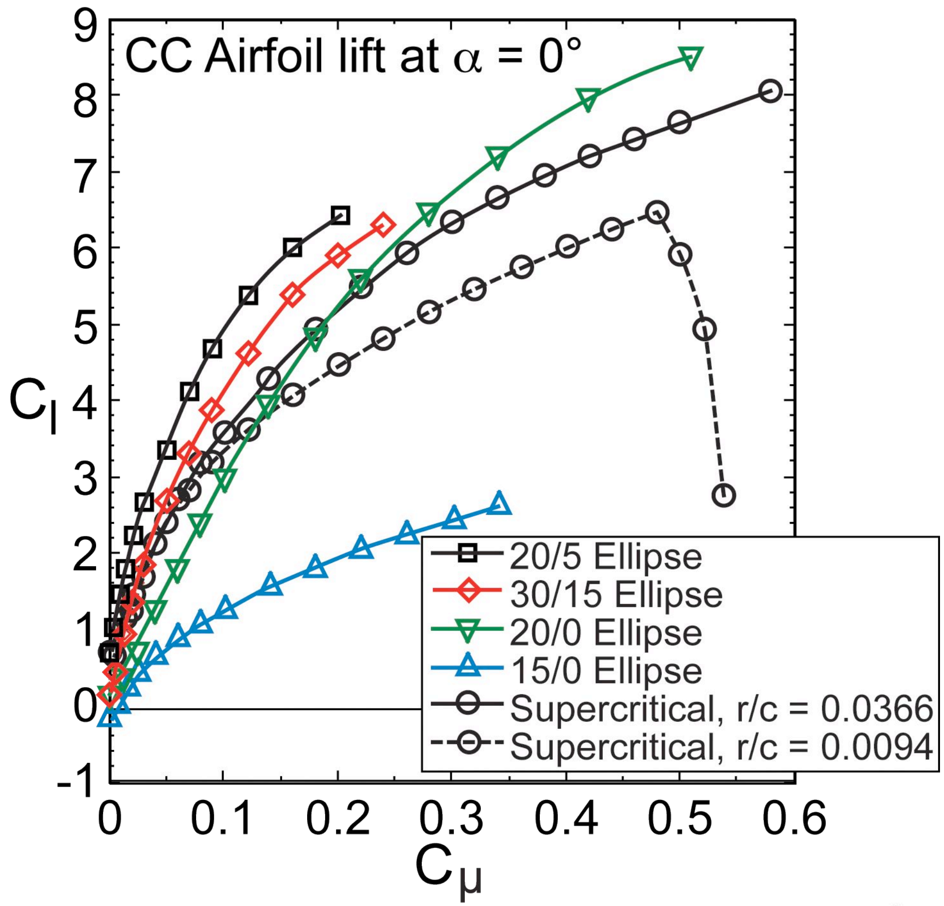
Integration concepts
TE: Single/Multi-element (vane)
LE: Variable Camber Krueger

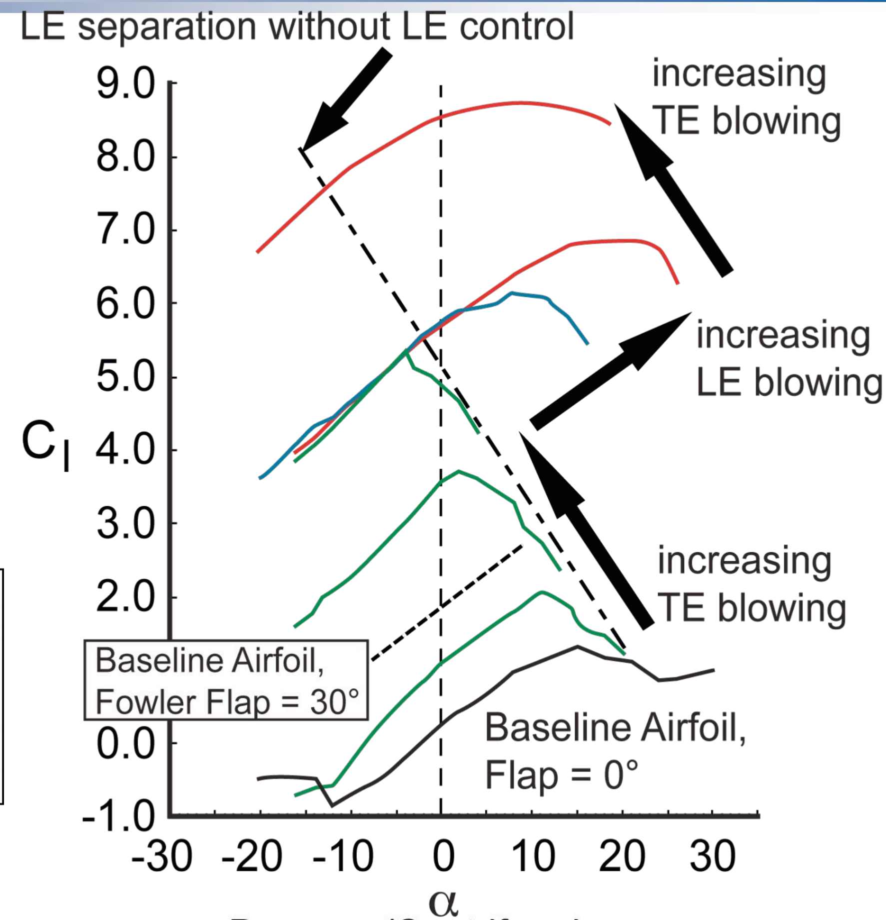
- Many benefits, few issues
  - Approach CL: many options available
  - Landing CLmax: short chord flaps may reduce CLmax, but flight Rn may help
  - Low Speed L/D : continuous span flaps provide large benefits

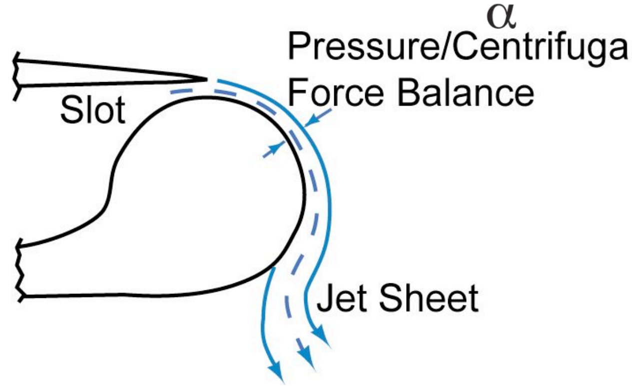
NASA NRA with Bob Englar, Georgia Tech RI

- Objective: Create a new, more complete database to systematically quantify effects of slot height, mass flow, jet velocity. Provide physical understanding.
- Collaborative effort in two facilities
  - Parametric studies at GTRI MRF
  - Limited condition flow field measurements at NASA LaRC
- 3 year effort
  - Year 1: test hardware fabricated, parametric F&M and Cp data, complete QA of model, LaRC facility mods, CFD calculations
  - Year 2: detailed flowfield measurements @LaRC BART, LE blowing F&M and Cp data, CFD calculations
  - Year 3: transonic data acquired

Circulation Control Wing (CCW) Technology

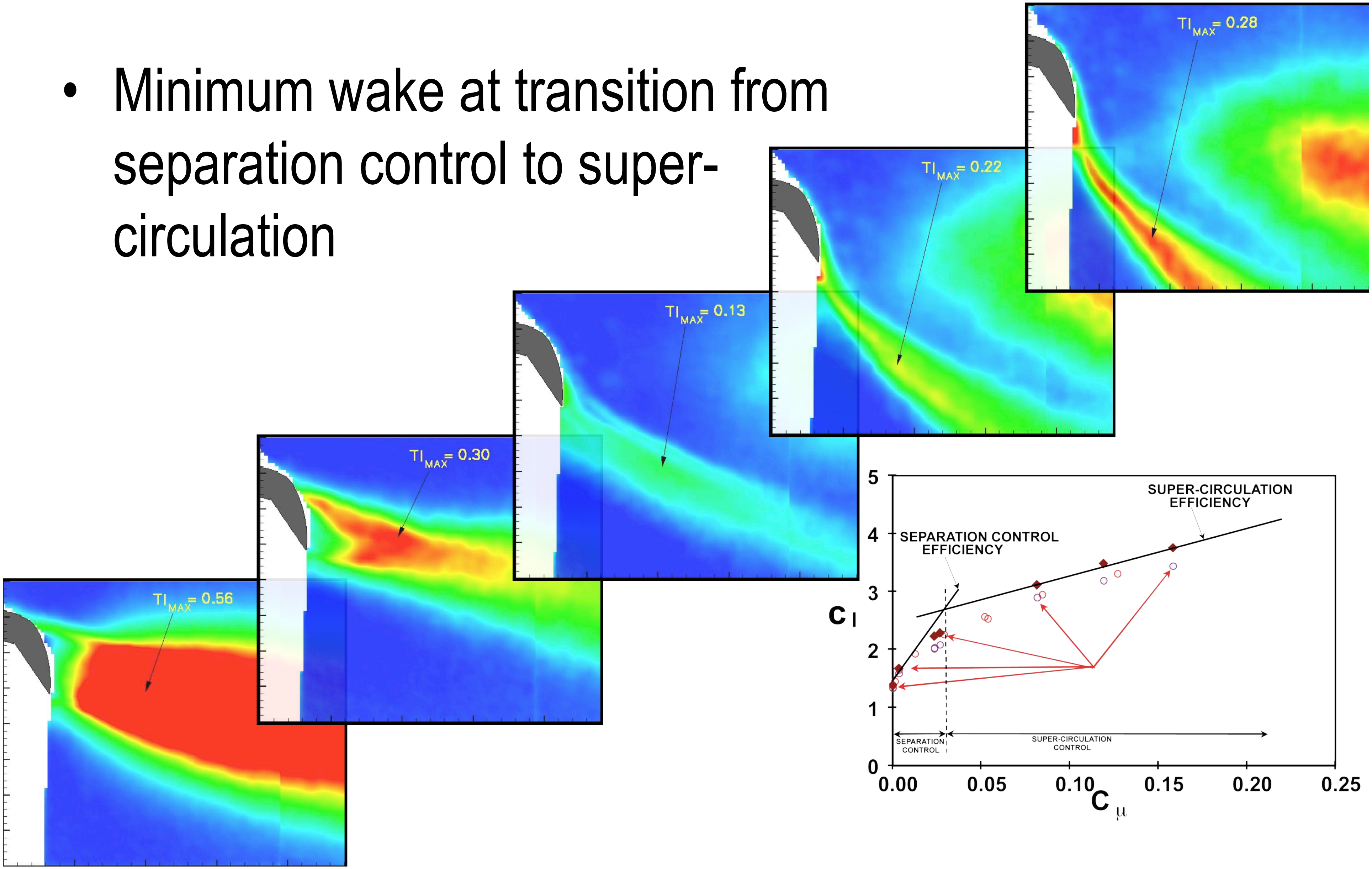






Wake turbulence as function of Cµ

- Minimum wake at transition from separation control to super-circulation



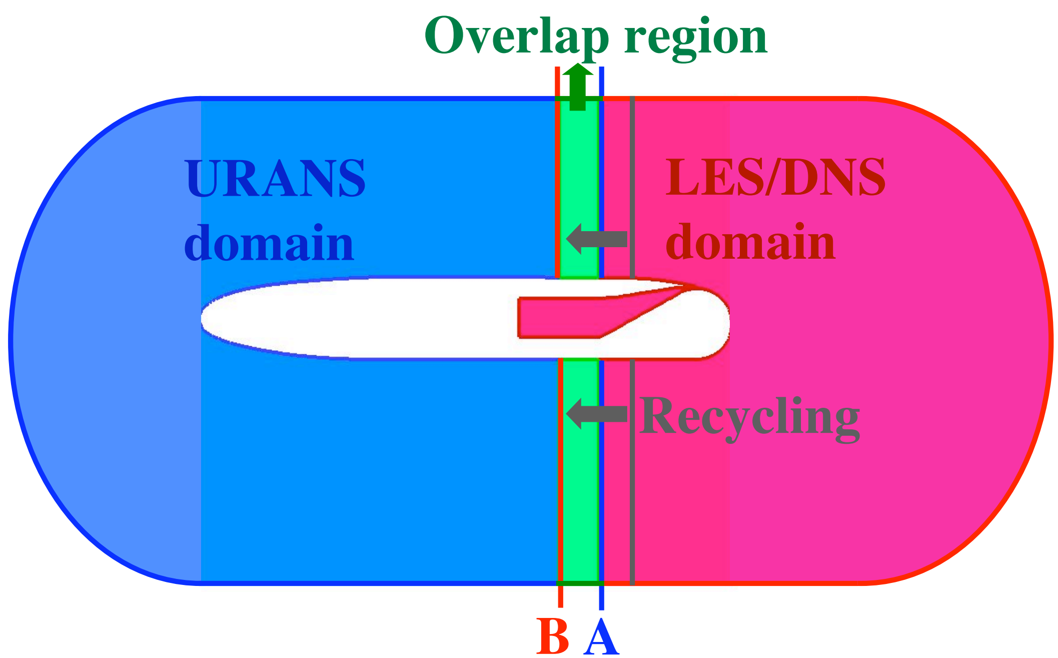
Current CFD status for 2-D CCW Predictions

- Many isolated successes using RANS have been reported, depending on case
  - But usually only for lower blowing rates
  - At higher blowing rates, CFD tends to predict separation too late (flow wraps around trailing edge too far)
  - Most successful turbulence model (NASA LaRC experience) has been SARC (Spalart-Allmaras with rotation-curvature correction), ***but inconsistent!***
- Other methods (DES/LES) too preliminary to draw firm conclusions
- Some issues:
  - Strong sensitivity of results to numerical parameters for these cases
  - Potential sensitivity to transition within the jet
  - Some conditions will require time-accurate computations
  - Uncertainties in boundary conditions used to match experiment
  - Loss of two-dimensionality in the experiment at higher blowing conditions
  - Most experiments very old – new experiments needed
  - Separation sensitive to turbulent kinetic energy, k
  - Limited effort on RANS modeling for transition implies k starts off incorrectly
  - Shear and streamline curvature shut off/change sign of production of k, models do not or at best badly represent

Rumsey (LaRC), Shariff et.al.(ARC)

Coupled URANS + LES/DNS Simulation at ARC

Novak Airfoil



A: Mean velocity from time-averaged LES/DNS solution;
Convective outflow condition for turbulence variables.

B: Mean velocity from RANS;
Velocity fluctuations from the recycling procedure (Lund 1998)

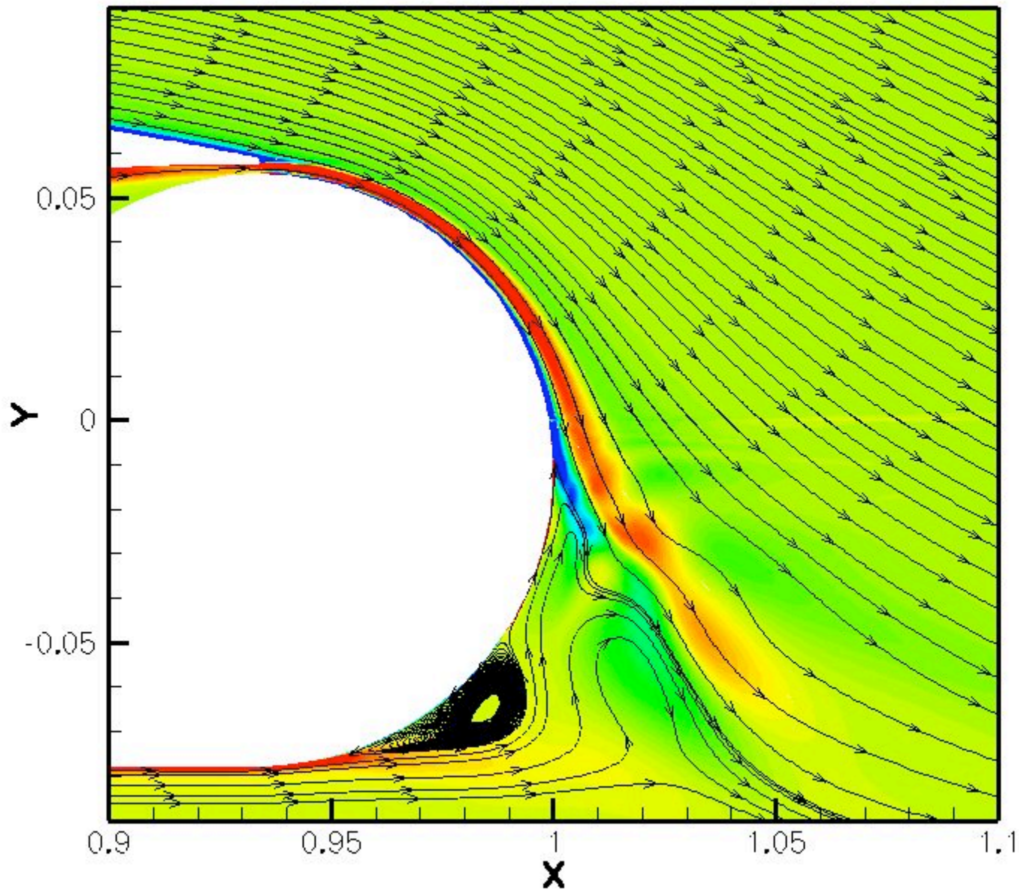
Currently using two codes : OVERFLOW and CDP

(Shariff, et.al. NASA ARC)

Preliminary CDP RANS Simulation (v2-f model)

Novak Airfoil, M= .12, Cμ = 0.03

Vorticity contours + Streamlines (α = −2.46 deg)



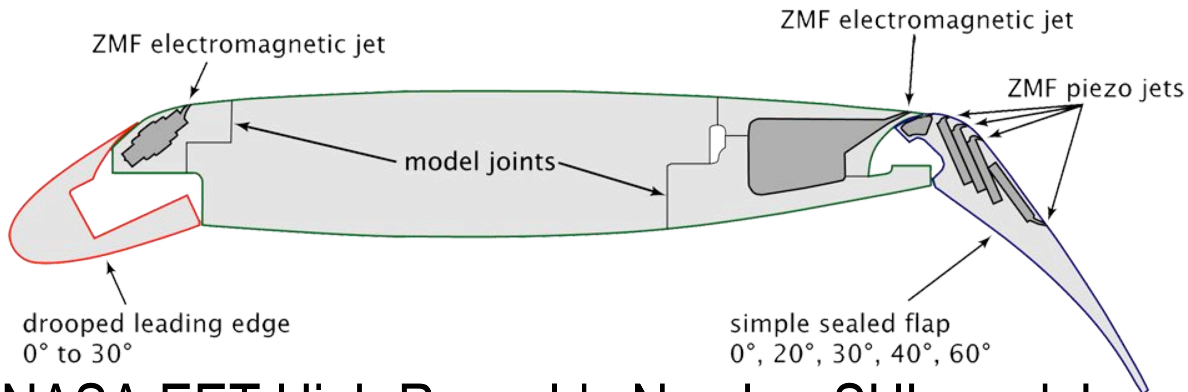
α = -2.46 deg. C_L = 1.5 (Exp); 1.42 (CDP v2-f model)

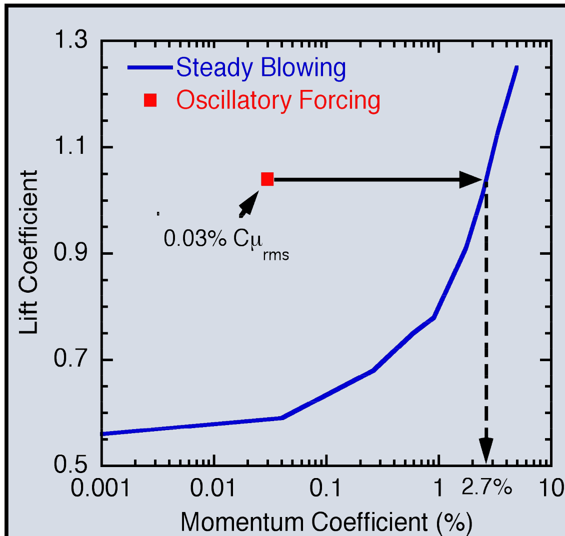
LES currently running.

AFC for Simplified High Lift

Motivated by study(s)[1] indicating benefits of simplified high lift systems

- Large Benefit of AFC on 2D NACA 0015 with flap at High Re
- ZMF actuation effective, no compressed air source required?
- Evaluate potential for active separation control to enable similar performance to conventional 3-element systems



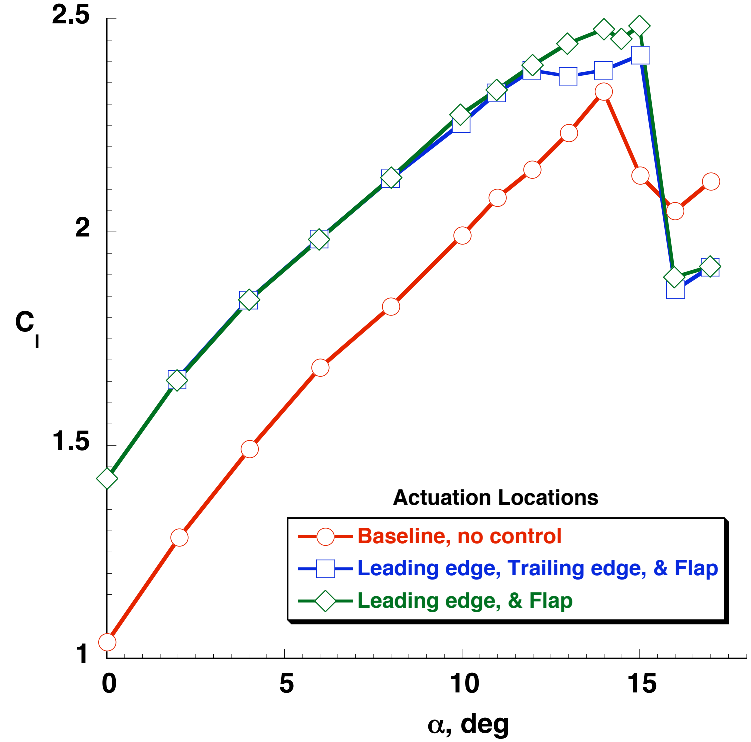


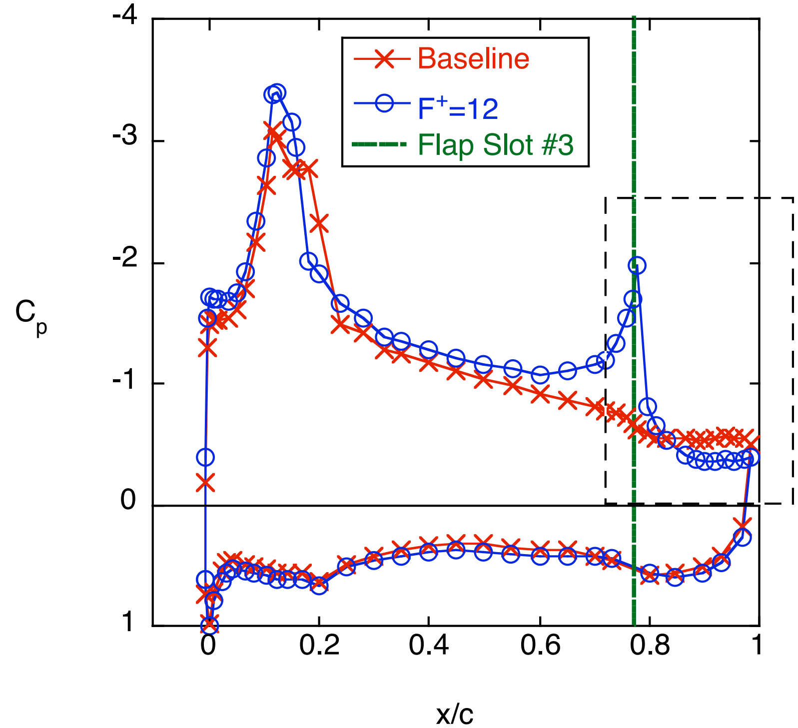
Efficiency of ZMF on NACA 0015 at High Re

- NASA EET High Reynolds Number SHL model
  - Drooped leading edge is 15% of chord and simple hinged flap is 25% of chord
  - 12% thick supercritical airfoil
  - Internal and external actuation for LaRC Low Turbulence Pressure Tunnel

1. McLean et al., NASA/CR-1999-209338, June 1999

Previous Work on SHL

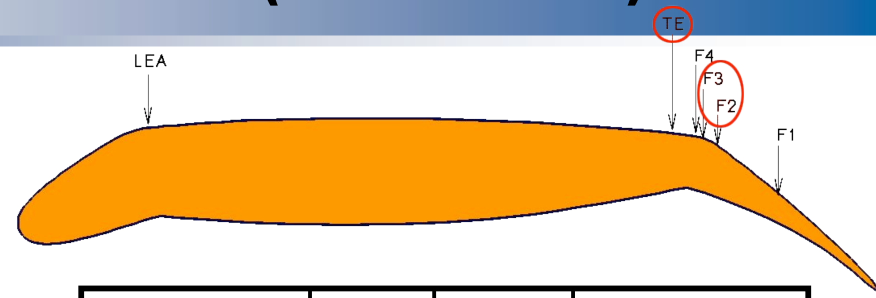




- Low Re (0.75×10^6), small model (0.4 m chord), δ_f =30°
- Using actuator combinations, studied effects of
  - Excitation waveform (Sine, AM, PM)
  - Excitation phase angle (TE and Flap)
  - Duty cycle

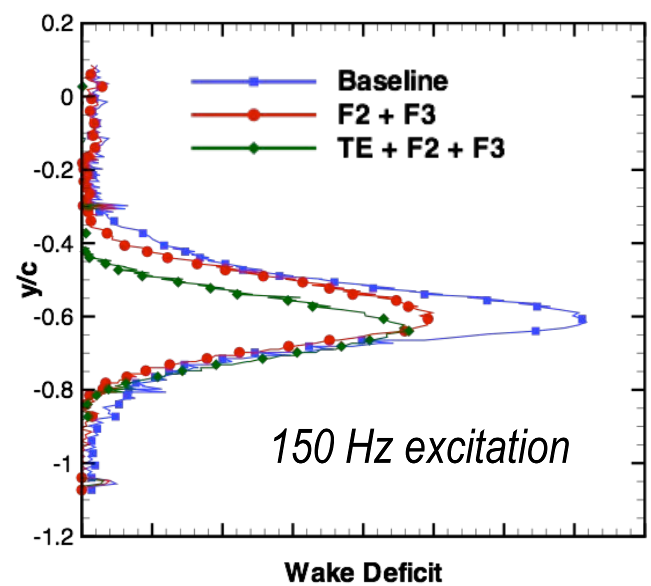
- Using LE, TE, and Flap actuation improved the lift performance
  - 25% at approach angles of attack
  - 6% in C_{lmax}
  - Control sensitive to actuation location and phase angle
- Interaction at C_{lmax} is very complex

SHL at High Re in LTPT (to 9 x 10^6)



- Electromagnetic and piezo ZMF actuators
  - Actuator performance degraded at large Re due to pressure
  - Actuators did not have sufficient authority to attach flap at required flap deflections
    - Multiple excitation locations improve performance
- Based on calibrated actuator authority, results consistent with low Re data
  - Re plays a key role in base flow but not in AFC physics
    - Location of actuation determined by base flow
  - Circulation controlled better at low frequencies, separation at higher frequencies
  - Scaling parameters for AFC and actuators are critical

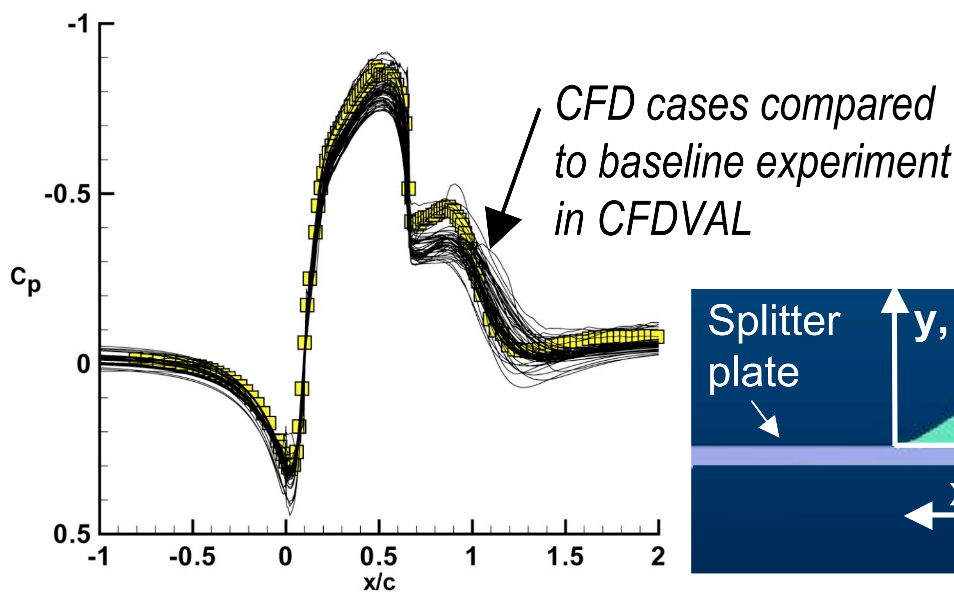
Actuators	ΔC_l	ΔC_{dp}	Frequency
F2,F3	+6%	+5%	75 Hz
TE, F2, F3	+6%	-3%	75 Hz
F2, F3	+0%	-10%	150 Hz
TE, F2, F3	+3%	-7.5%	150 Hz

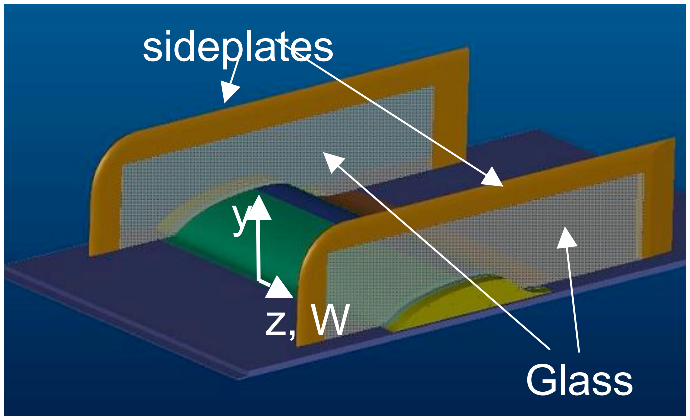


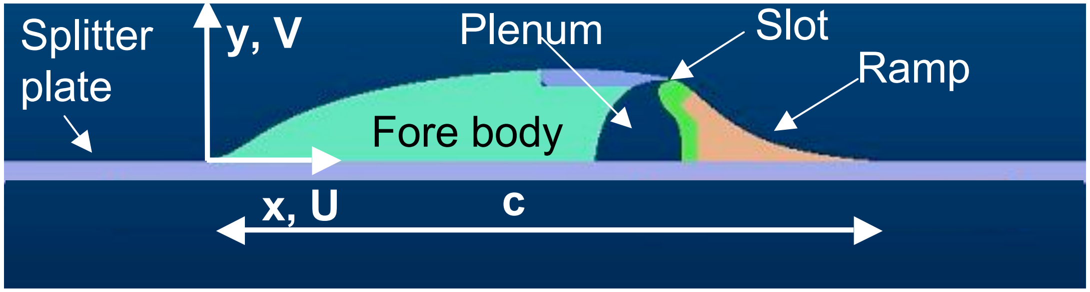
AIAA 2007-0707, Pack-Melton et al (NASA)
AIAA 2007-4424, Khodadoust & Washburn (Boeing)

CFD Validation of Unsteady Flows

- Turbulent Separation Control of Flow over Wall-mounted Hump Model (AIAA 2004-2220 Greenblatt and others)
  - Case 3 of CFDVAL workshop. Includes baseline flow, steady suction, ZMF oscillatory control
  - Systematic evaluation of capability of URANS

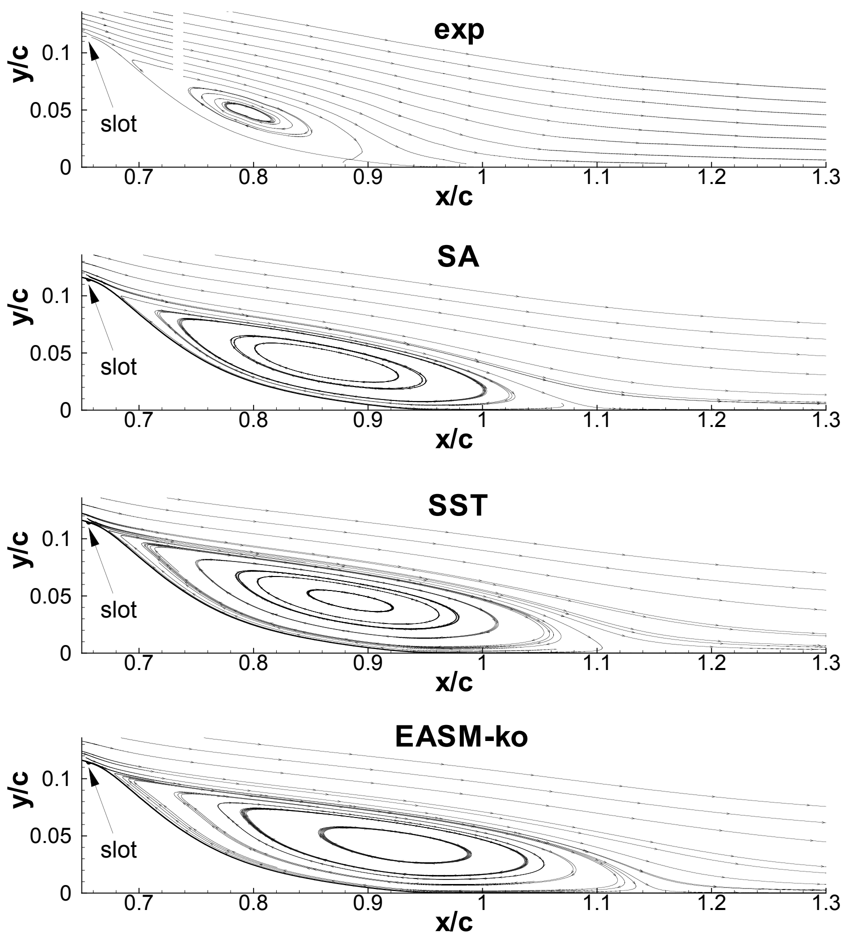




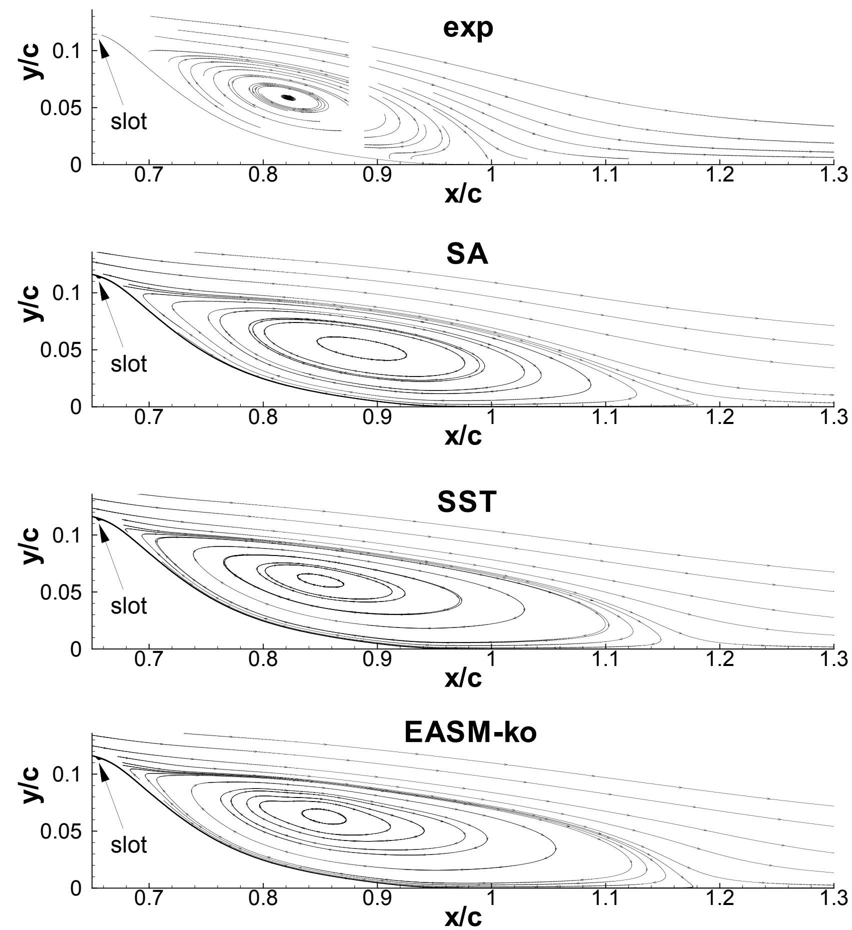


Streamlines (workshop cases)

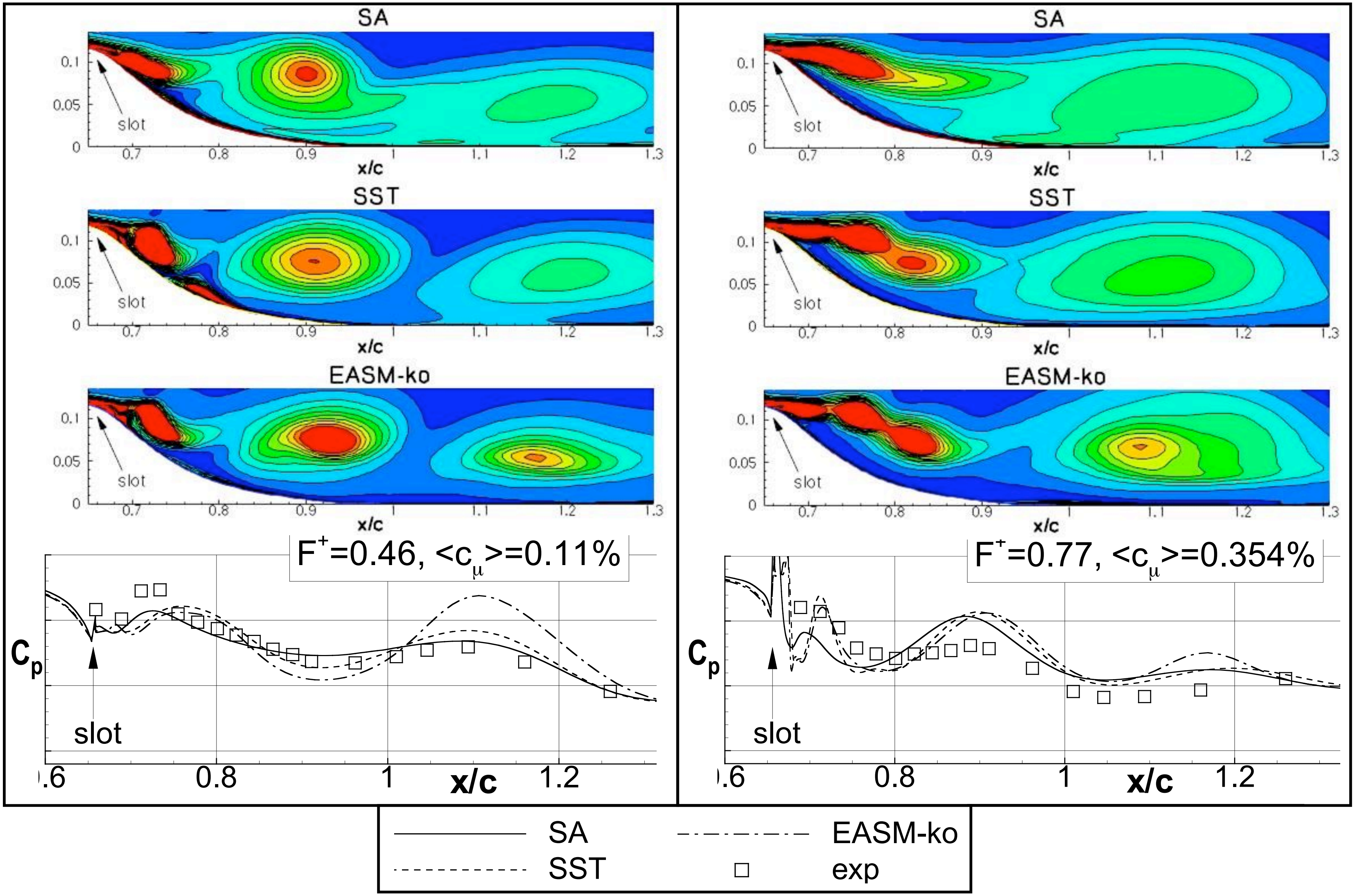
Steady suction



Oscillatory control



Phase Averaged Vorticity and Cp



Use of RANS/URANS to Predict Trends

This was an investigations into the effects of Reynolds number, control magnitude, and control frequency

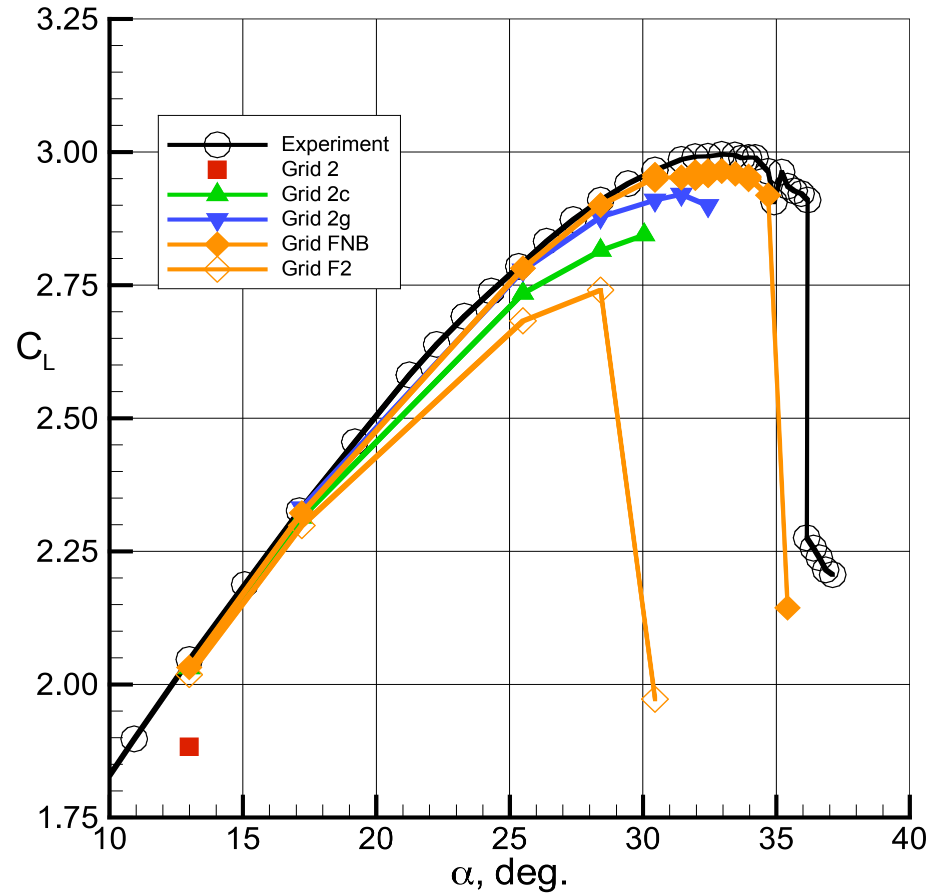
- 3 turbulence models similar, but SA model tended to agree with experiment the best
- Steady suction: RANS capable of predicting the trends due to $C\mu$ (but not absolute levels)
- Oscillatory control: URANS does not predict trends due to $C\mu$ and F+ in the mean very well, but some phase-averaged trends were qualitatively captured
- It is apparent that LES will be required to improve the prediction of the vortex strength/magnitude

3D Viscous CFD

3D CFD Viscous Prediction

Enabling Objective:

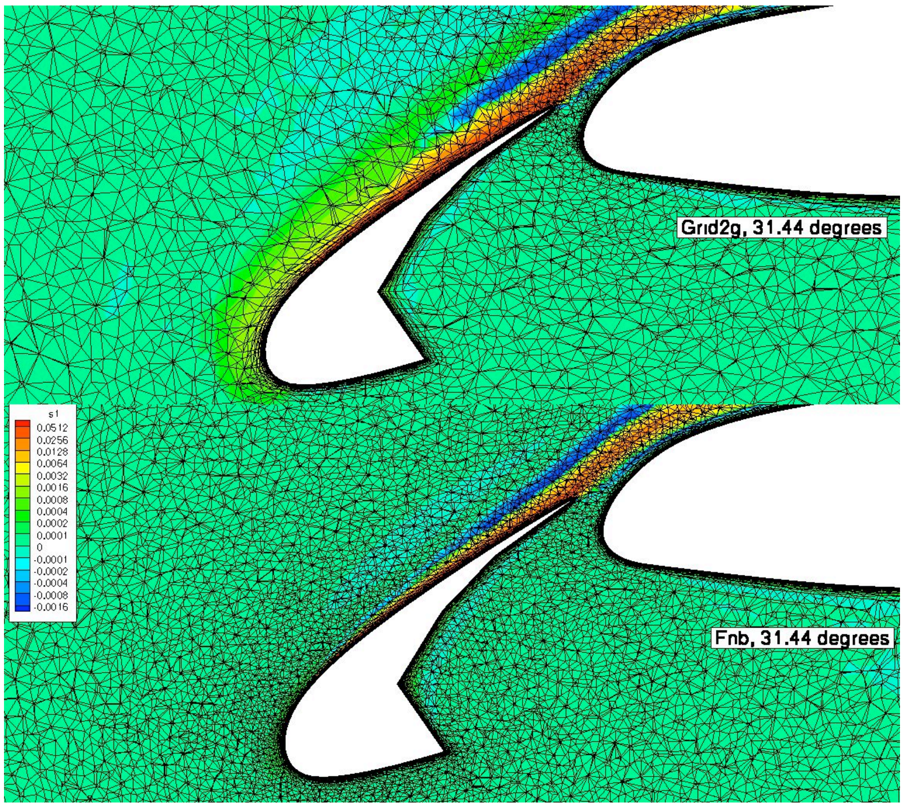
Establish 3D viscous prediction capability for high-lift systems through CLmax



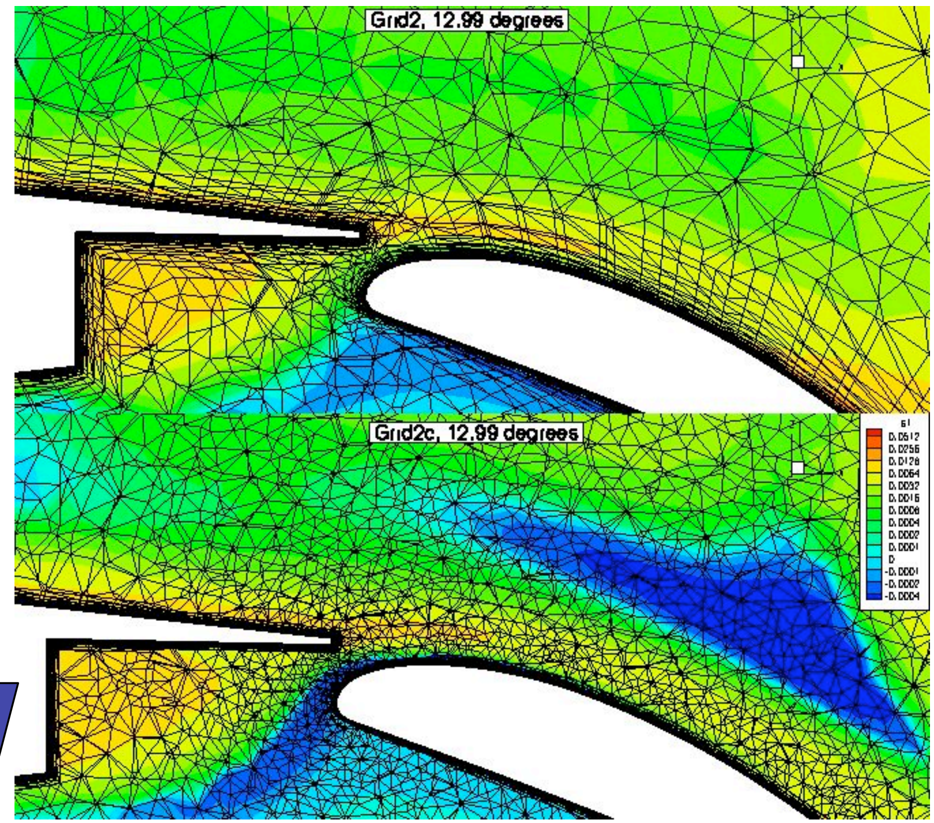
Chaffin, NASA LaRC

Focus on Grid/Physics

Near Clmax
slat wake becomes more important



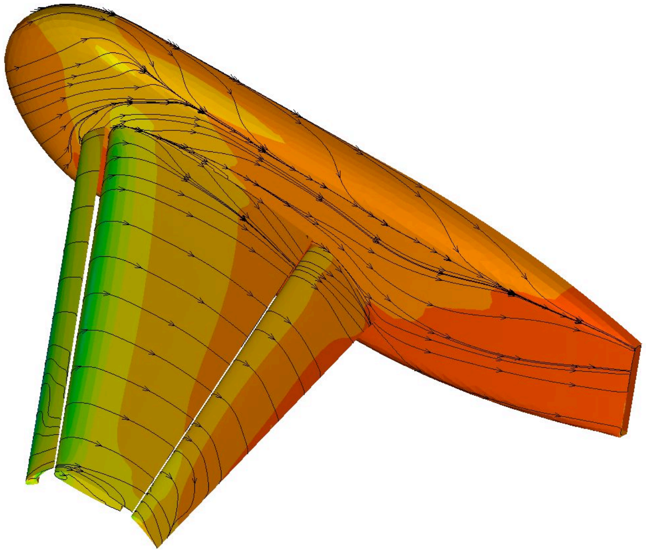
In the linear region
main wake is more important



increasing grid resolution

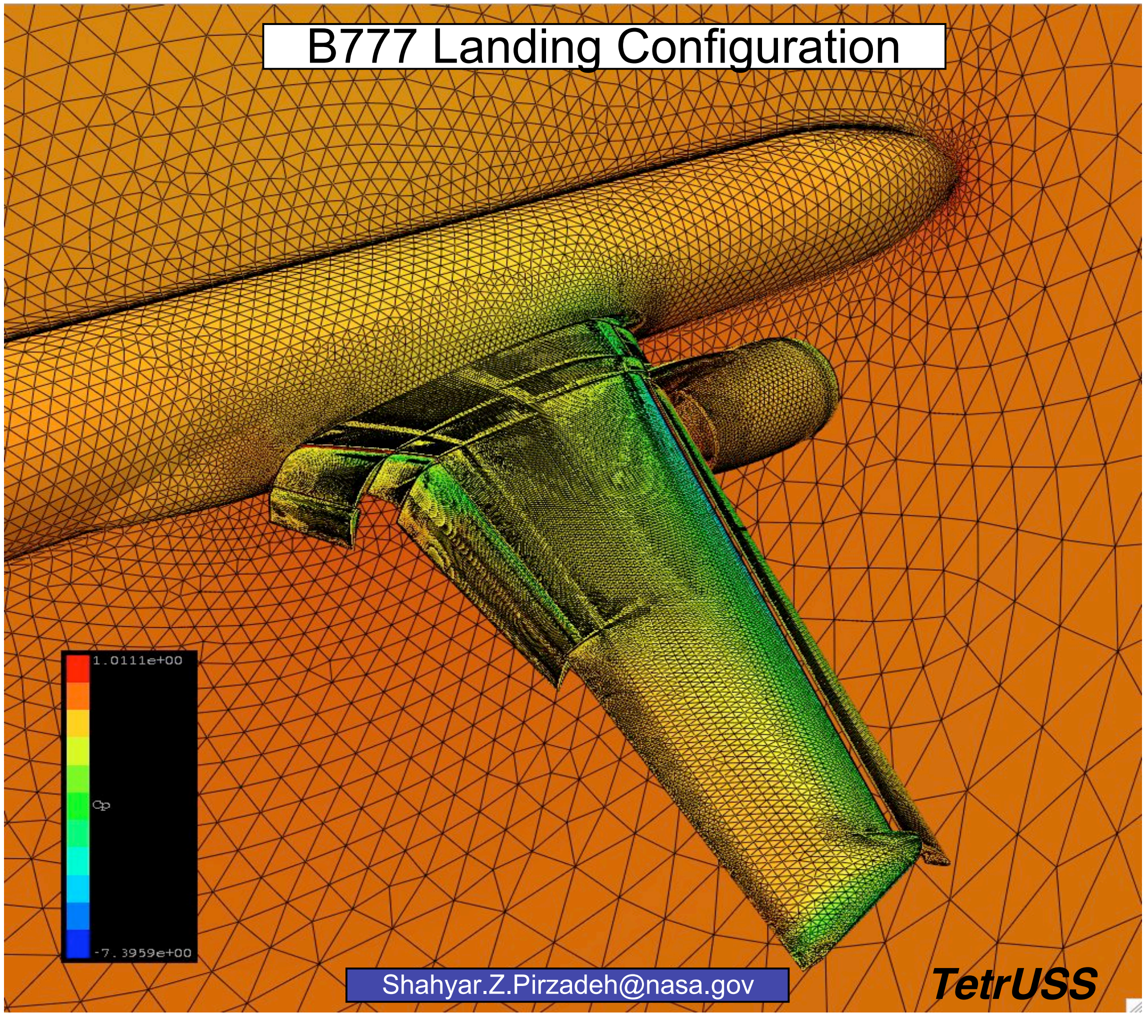
Lessons/Status

- **Lessons:**
  - **Wake resolution is critical- CFD tends to overpredict the velocity deficit**
  - **Surface grid refinement is not enough**
  - **Grid resolution around the slat is important**
  - **It's not always the turbulence model**
  - **Grid needs to be better resolved to capture bracket effects**
  - **Grid generation is tedious, but could probably be automated**



If certain guidelines regarding grid, transition, and turbulence model are followed, then Cp, Cf, Cl, and Cd can be predicted with reasonable accuracy at angles of attack below stall. Clmax still an issue.

Current Technical Challenges
massively large-scale problem sizes



- 107 million tetrahedra
  - NAS Columbia for grid generation
  - Months of run time
  - Still not able to predict $C_{L,max}$
- Needs for grid gen.
  - Parallelize VGRID
  - Solution adaptive grids
- Needs for flow solvers
  - More processors
  - Faster algorithms
  - Better turbulence models
  - Quantification of uncertainty

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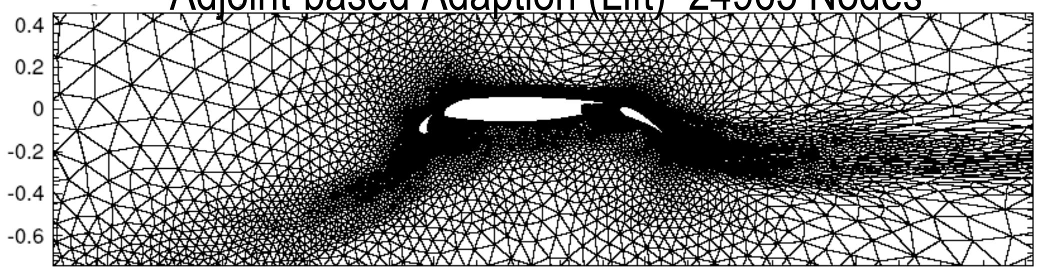
Self-Adaptive analysis with known error bounds

Adjoint recognizes importance of "smooth" flow regions

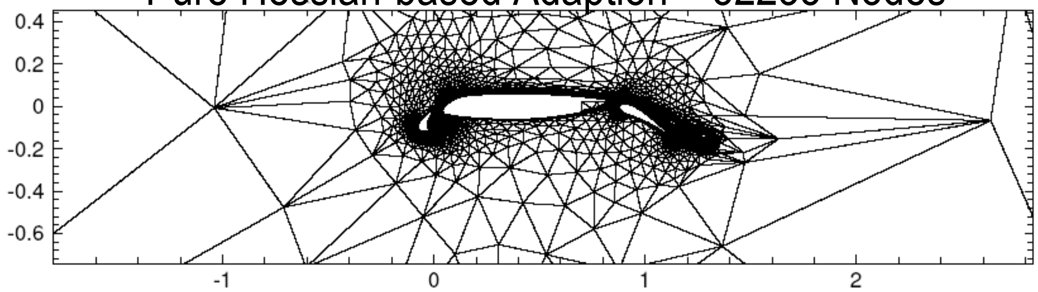
Adjoint technique is clearly superior to traditional ad hoc or feature based approach

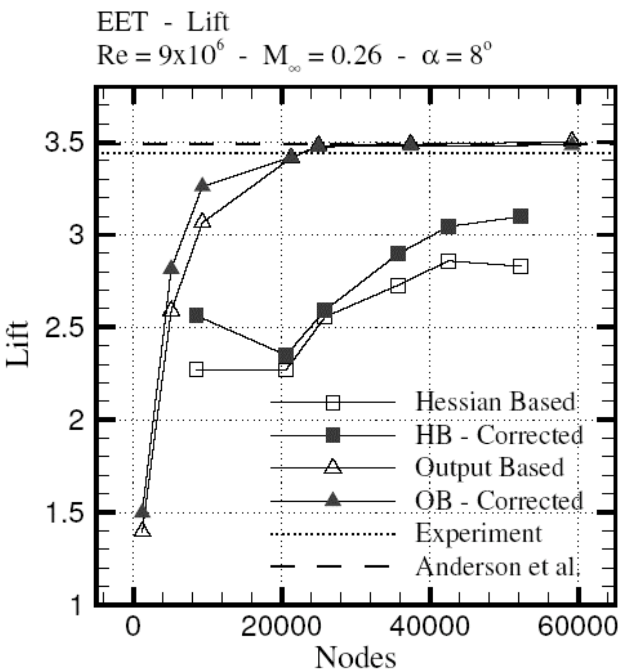
2D High-Lift Example

Adjoint-based Adaption (Lift) 24965 Nodes



Pure Hessian-based Adaption 52235 Nodes





Courtesy Venditti & Darmofal at MIT (using FUN2D)

Concluding Remarks

- *NASA has had a long history in fundamental and applied high lift research*

- *Current programs provide a focus on the validation of technologies and tools that will enable extremely short take off and landing* ***coupled*** *with efficient cruise performance*

    - *simple flaps with flow control for improved effectiveness*

    - *circulation control wing concepts*

    - *some exploration in to new aircraft concepts*

    - *partnership with Air Force Research Lab in mobility*

- *Transport high-lift development testing will shift more toward mid and high Rn facilities at least until the question: "How much Rn is required" is answered (Frank Payne, AIAA 2007-0751)*