Technical Challenges to Reducing Subsonic Transport Drag

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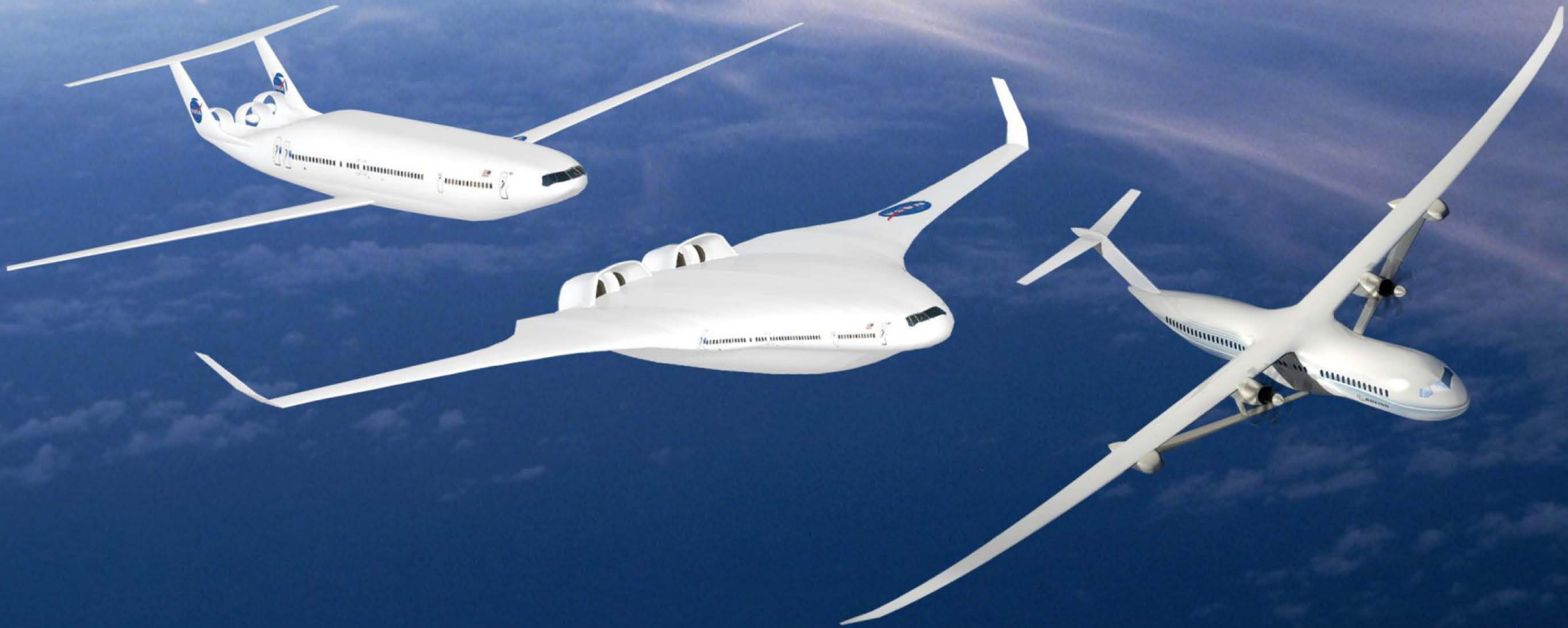
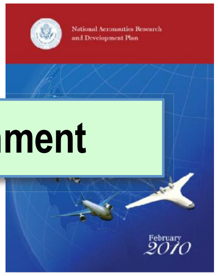


SFW Strategic Thrusts & Technical Challenges

Energy Efficiency Thrust *(with emphasis on N+3)*
Develop economically practical approaches to improve aircraft efficiency

Environmental Compatibility Thrust *(with emphasis on N+3)*
Develop economically practical approaches to minimize environmental impact


2011 NASA Strategic Plan


National Aeronautics Research and Development Plan

February 2010

Energy & Environment

Cross-Cutting Challenge *(pervasive across generations)*

TC1 - Reduce aircraft drag with minimal impact on weight (aerodynamic efficiency) — Drag

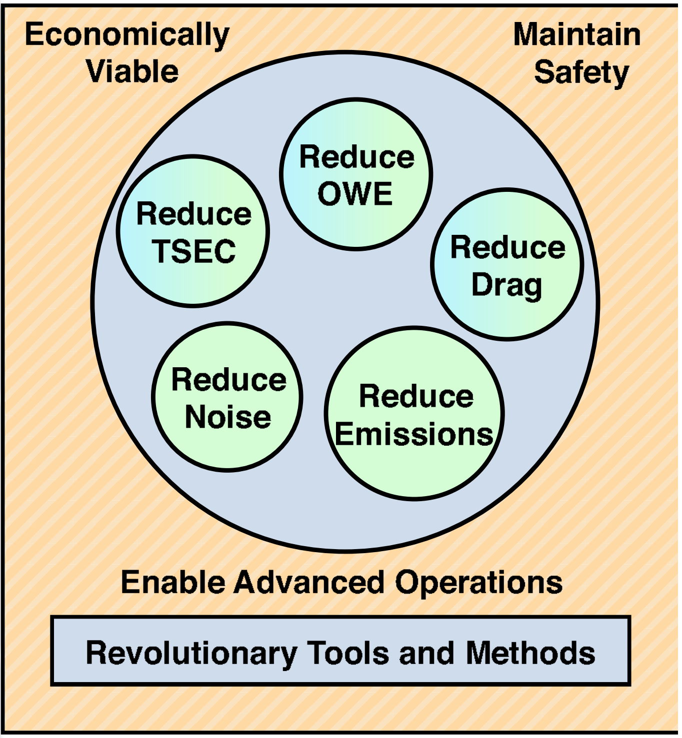
TC2 - Reduce aircraft operating empty weight with minimal impact on drag (structural efficiency) 🟦

TC3 - Reduce thrust-specific energy consumption while minimizing cross-disciplinary impacts (propulsion efficiency) 🟥

TC4 - Reduce harmful emissions attributable to aircraft energy consumption 🟧

TC5 - Reduce perceived community noise attributable to aircraft with minimal impact on weight and performance 🟫

TC6 - Revolutionary tools and methods enabling practical design, analysis, optimization, & validation of technology solutions for vehicle system energy efficiency & environmental compatibility — Tools


Economically Viable

Maintain Safety

Reduce OWE

Reduce TSEC

Reduce Drag

Reduce Noise

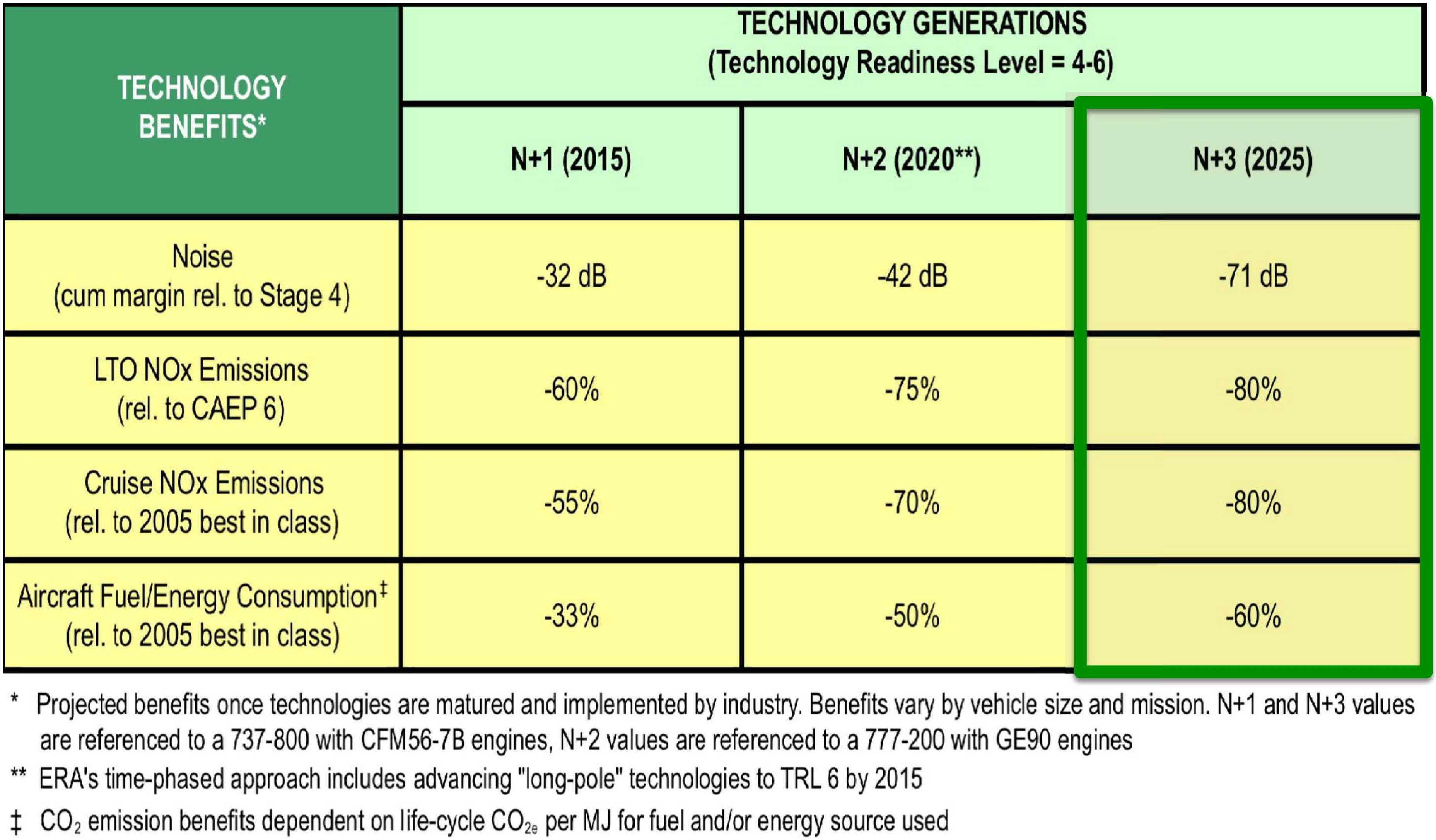
Reduce Emissions

Enable Advanced Operations

Revolutionary Tools and Methods

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance



TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	**N+2 (2020**)**	**N+3 (2025)**
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

FAA/CLEEN → **NASA/ERA** → **NASA SFW**

SFW N+3 Opportunities from Goal-Driven Advanced Concepts

broadly applicable …….

N+3 Subsystem Concepts

🟩 1. Tailored Fuselage (turbulent Cf drag reduction)

🟩 2. High AR Elastic Wing (aerodynamic shaping and elastic aircraft flight control)

🟩 3. Quiet, Simplified High-Lift (active flow control)

4. High Efficiency Small Gas Generator

5. Hybrid Electric Propulsion

🟩 6. Propulsion Airframe Integration (aerodynamic configuration)

Near Term/Cross-cutting

7. Alternative Fuels

Tools 8. Tool Box (MDAO, Systems Modeling, Physics-Based)

Efficiency Challenge: Reduce Drag
Heilmeier Questions

What are we trying to do?

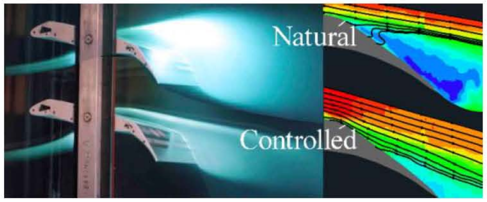
- Discover, explore, and develop technology concepts to **improve aerodynamic efficiency** for overall system-level benefit to energy efficiency and environmental compatibility

Why?

- Meet energy efficiency challenge by reducing drag

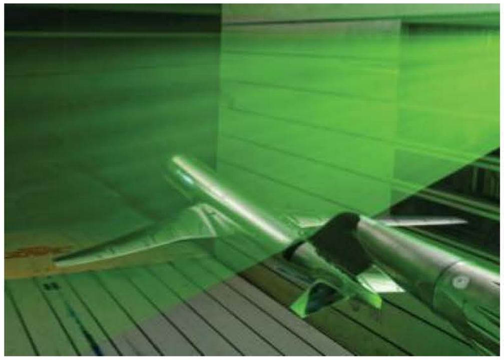
How is it done today, and what are the limits of current practice?

- Conventional, tube-and-wing designs with under-wing propulsion
- Passive, turbulent flow aerodynamics
- Induced drag reductions limited by wing weight penalties
- Lift-over-drag ratios stagnate at about 20



What is new in our approach?

- Novel configurations enabling laminar flow, reduced wetted areas, higher aspect ratio wings, and synergistic propulsion/airframe integration
- Revolutionary enabling technologies including boundary layer ingestion, active flow control, and concept enabling flight control strategies
- Improved physical understanding and physics-based high-fidelity computational design tools with broad applicability



What are the payoffs if successful?

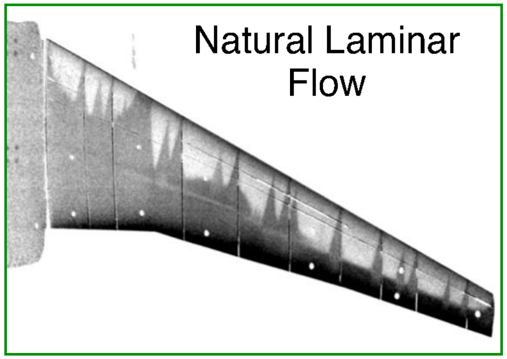
- Economical and practical approaches to improve aircraft efficiency by reducing drag with minimal impact on operating empty weight, for reduction in total aircraft energy consumption

Research Successfully Transitioned to ERA, Fall 2009

Drag Reduction

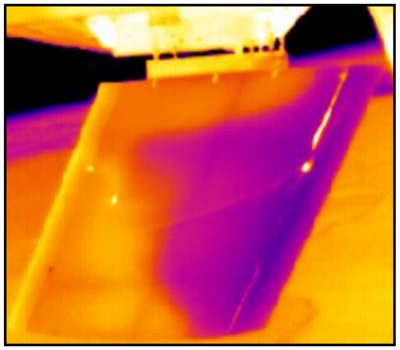
Several critical tests of laminar flow control successfully completed to improve understanding and analytical models

Natural Laminar Flow



Hybrid Laminar Flow Control

Distributed Roughness Elements



Hybrid Wing Body (HWB)

Extensive flight and wind-tunnel testing to understand flight dynamics and controls challenges and acoustic performance

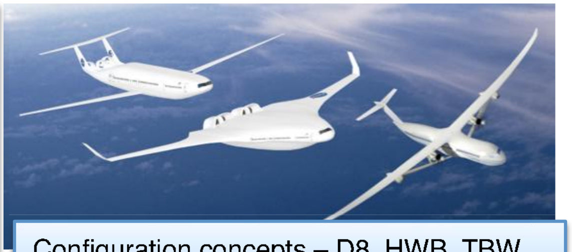
X48B Phase 1 Completed
80 Flights

BWB Wind Tunnel Database Developed

SFW TC: Reduce Drag (Aerodynamic Efficiency)
High Impact Technical Areas

- Reduce aircraft drag with minimal impact on weight

Novel Configurations/Integration
Explore the aerodynamics of innovative configuration concepts (e.g., TBW), including propulsion integration (e.g., BLI), to understand drag reduction potential and multidisciplinary (e.g., weight/loads) trades/impacts
Timeframe: far term impact

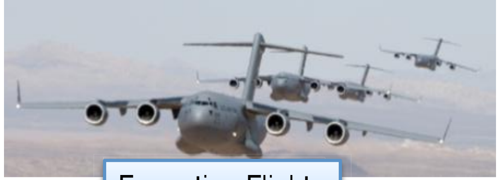


Configuration concepts – D8, HWB, TBW

Drag Reduction Technology
Explore and develop active (e.g., circulation control) and passive (e.g., cruise slotted wing) aerodynamic concepts to directly reduce friction, wave, and induced drag and/or enable multi-objective trades (e.g., for weight reduction)
Timeframe: mid to far term impact

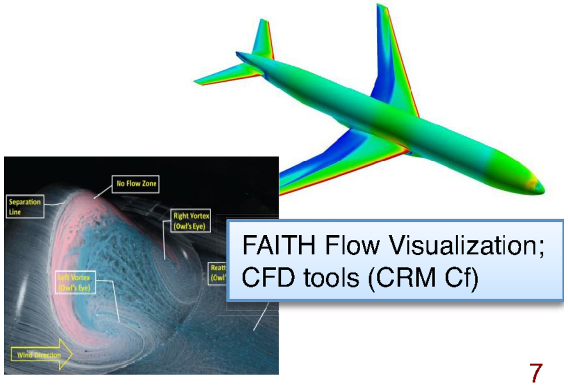
FAST-MAC Circulation Control

Advanced CONOPS
Explore and develop vehicle-centric opportunities for advanced flight operation concepts (e.g., formation flight) leveraging anticipated NextGen ATS capability (e.g., ADS-B), to enable reduced drag and/or LTO noise
Timeframe: mid to far term impact



Formation Flight

Aerodynamic Tools & Methods
Develop and validate tools and methods (e.g., turbulence model, test techniques) to study and simulate aerodynamic phenomena (e.g., separation onset/progression) to improve performance/loads prediction/design/analysis
Timeframe: near to far term impact



FAITH Flow Visualization; CFD tools (CRM Cf)

Efficient Aerodynamics

- **Novel Configurations/Integration**
  - D8 Double Bubble
  - Truss Braced Wing
  - Hybrid Wing Body (to ERA)
  - Over the Wing Nacelle
  - Active Flow Control for Simplified High Lift (FAST-MAC2, NACA0015)
  - Boundary Layer Ingestion Concepts (Goldschmied propulsor)

Inviscid Simulation of the MIT N+3 D8 Double-bubble Aircraft External Aerodynamics Completed

PROBLEM

Model and simulate the MIT D8 “double-bubble” design in an inviscid code to obtain preliminary assessment of the aircraft’s external aerodynamics in support of the aircraft design team.

OBJECTIVES

- Use accurate mesh refinement techniques to guide future (viscous) simulations.
- Study the effects of wind tunnel walls, strut, and empennage on model aerodynamic loads.
- Compare to experimental results and results from MIT’s Fluent simulations.

APPROACH

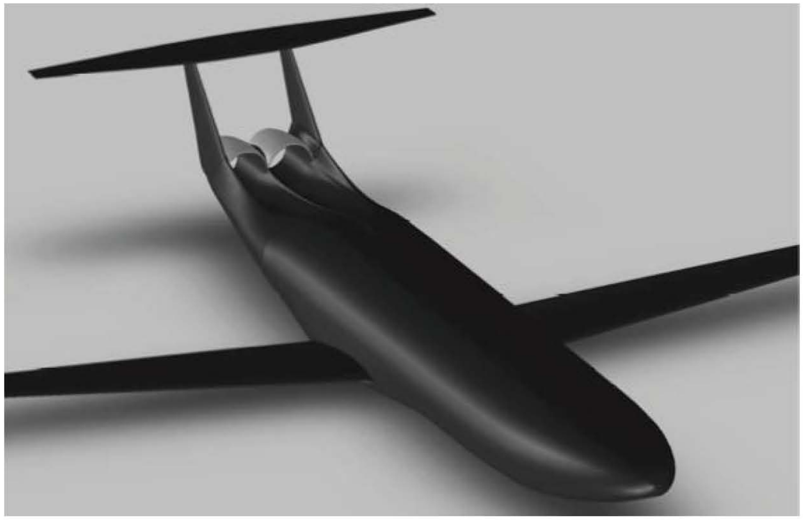
- Geometries with and without wind tunnel walls as well as strut and empennage were generated.
- The Cart3D code was used along with an adjoint-based mesh refinement method.
- Results were compared to data from the Wright Brothers wind tunnel at MIT as well as to MIT’s Fluent results.

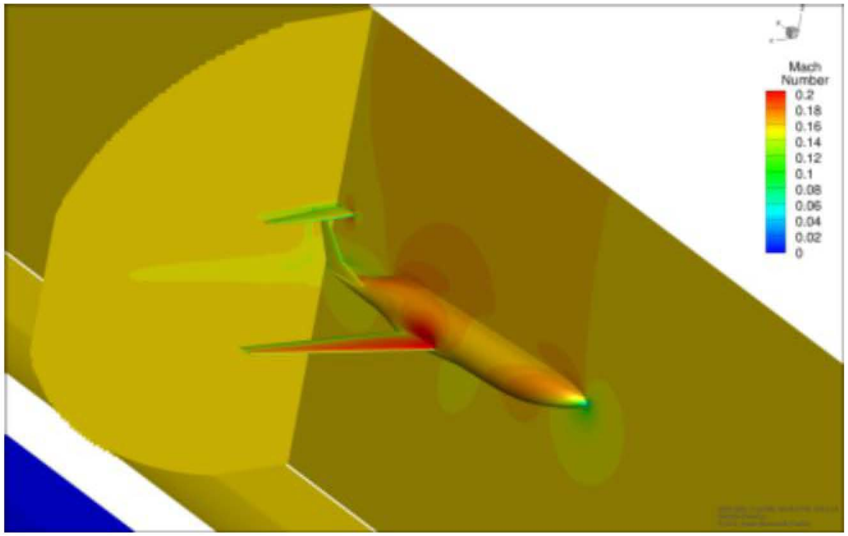
RESULTS

- Good CL agreement without WT walls, stall only predicted with WT walls, no stall in Fluent results.
- CD is over-predicted.
- Cm is good at low-α.
- Strut effects are minimal, WT wall effects are substantial.
- Empennage contributes significant loads.

SIGNIFICANCE

Loads assumptions are verified, and guidance for mesh clustering is completed. Allows the group to move on to simulations with viscous effects and propulsion system integration.

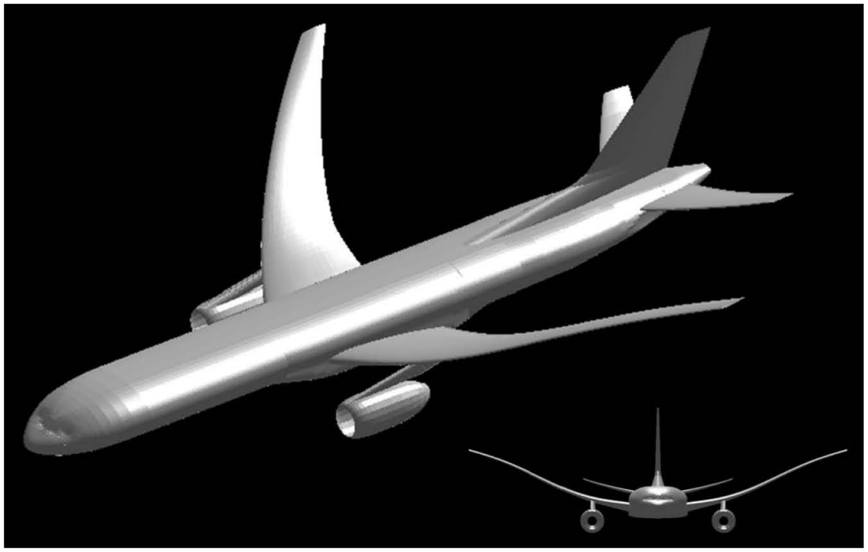




POC: Shishir A. Pandya (NASA ARC)

Efficient Aerodynamics

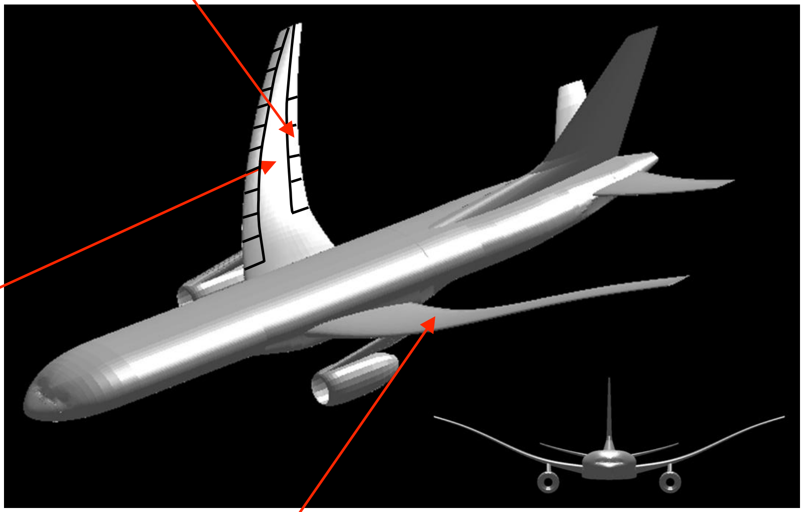
- **Drag Reduction Technology**
  - Laminar Flow (to ERA)
  - Turbulent Skin Friction Drag Reduction
  - High Aspect Ratio Wings, Elastically Shaped Aircraft Concept
  - Low Sweep Transonic Wings (FAST-MAC2, slotted wing?)



Elastically Shaped Aircraft Concept (ESAC)

- **Addressing SFW project goal of drag reduction for high-aspect ratio elastic wing configurations for current and future N+3 aircraft concepts**

- **Developing integrated MDAO solutions to drag reduction challenge**
  - Aeoelastic wing optimization for cruise drag reduction
  - Active aeroelastic wing shaping control for drag reduction
  - Integrated aeroelastic flight dynamic modeling of current and N+3 aircraft concepts
  - Aeroelastic flight control solutions to enable operation of high-aspect ratio wing
    - Gust load alleviation
    - Modal suppression
    - Load limiting control allocation
  - Low-drag variable camber continuous trailing edge (VCCTE) flap device for wing shaping control



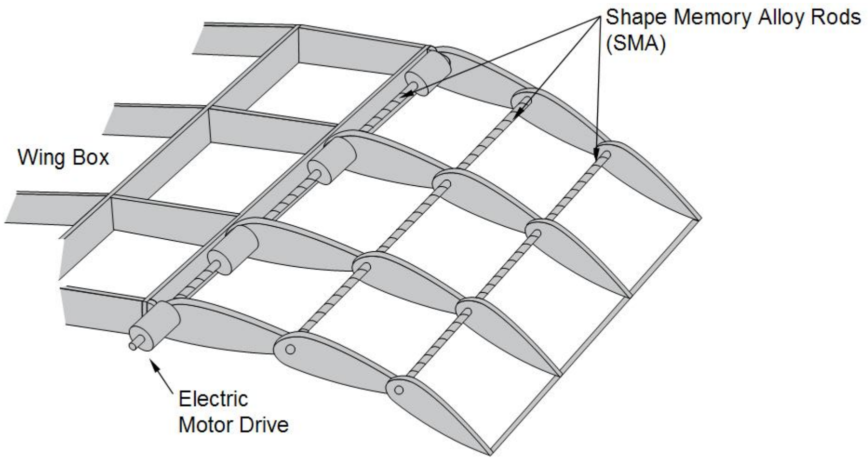
VCCTE Flap Device

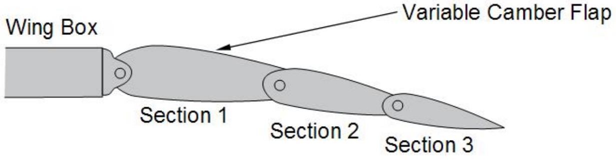
Wing Shaping Control
for Drag Reduction

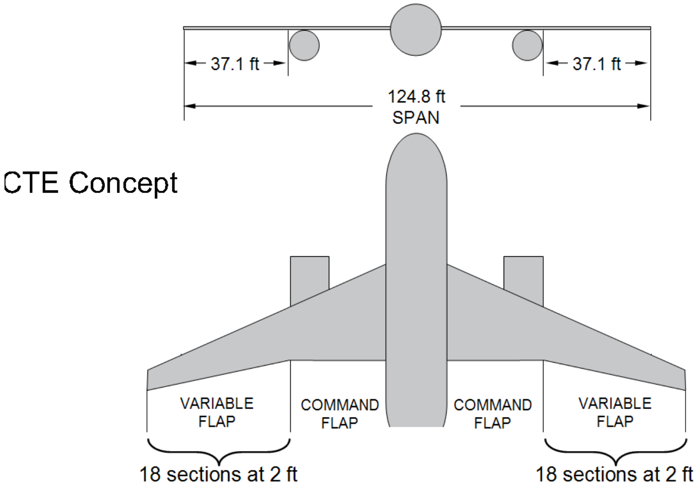
Wing Curvature and Washout Twist Optimized for Drag

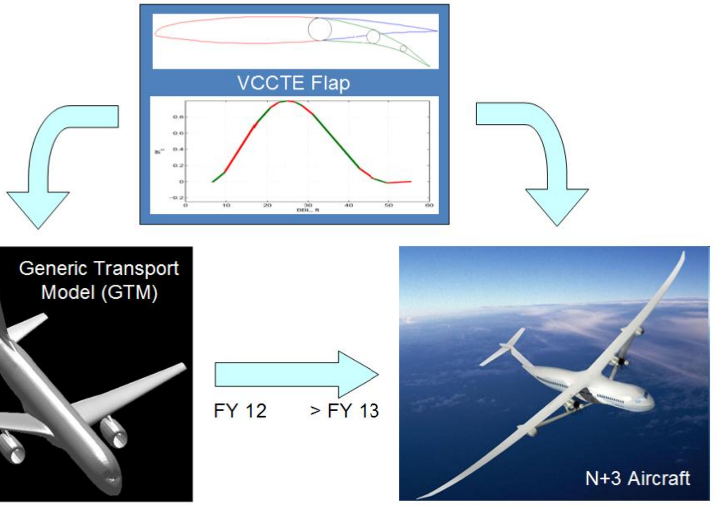
Variable Camber Continuous Trailing Edge Flap System Partnership

- **Collaboration with Boeing under SMAAART contract NNL11AD25T "Development of Variable Camber Continuous Trailing Edge Flap System"**
  - Establishes a design of a VCCTE flap system that will act as the dominant control effector to shape the wings on a transport aircraft for the purpose of achieving minimum drag
  - Addresses the goal of the SFW project to reduce drag with minimal impact on weight







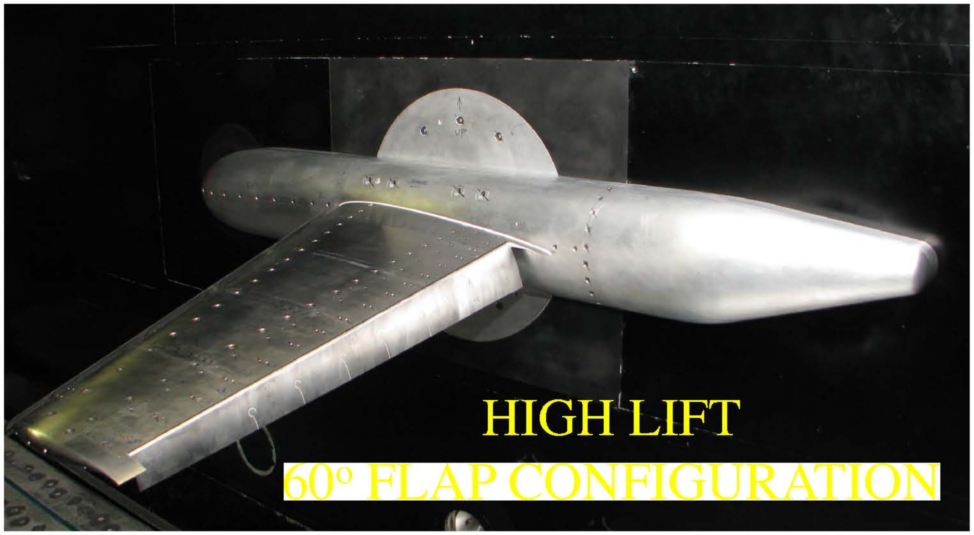


- **Ultimate goal is to develop wing shaping control technology for N+3 aircraft design**

FAST-MAC Circulation Control Research

Fundamental Aerodynamics Subsonic Transonic - Modular Active Control

- Low-speed high-lift & transonic cruise
- State-of-the-art aerodynamic design, open geometry
- Modular research model for future flow control concepts
- High-pressure air capability added to NTF with separate feeds for flow control and propulsion simulation (can be added)
- Can be shared with industry for cooperative research


HIGH LIFT
60° FLAP CONFIGURATION

FAST-MAC Circulation Control Research

PROBLEM

Can circulation control (CC) be used to reduce drag at cruise? How much lift augmentation for takeoff and landing can be achieved with the same CC system?

OBJECTIVES

- Explore drag reduction with blown flap in stowed cruise position at transonic speeds and flight Reynolds numbers.
- Evaluate a blown short-chord hinged flap high-lift system at takeoff and landing conditions.
- Develop a non-proprietary CFD validation database for CC at realistic flight Reynolds numbers.

APPROACH

Upgrade National Transonic Facility (NTF) by adding a new high-pressure air delivery station and new balance to enable blown semi-span testing. Obtain surface pressure distributions using pressure taps and cryogenic Pressure Sensitive Paint (PSP).

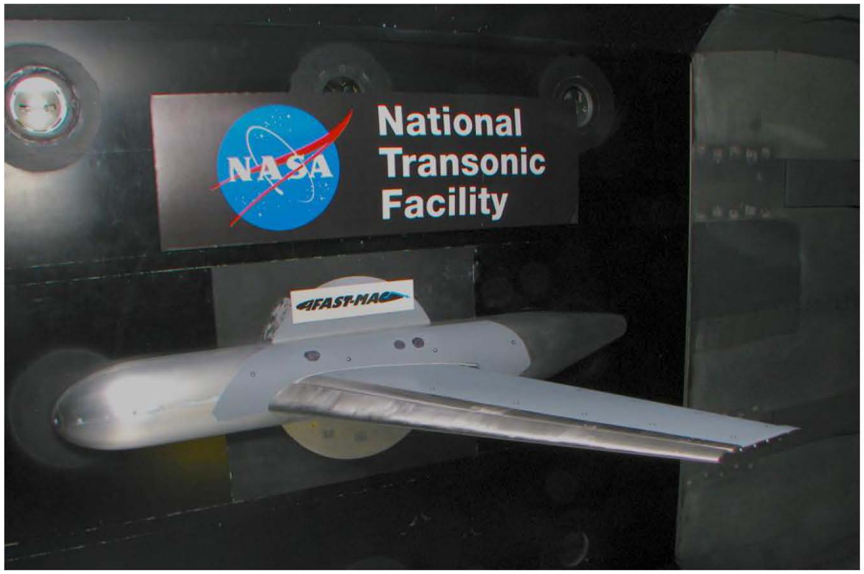


Photo by Scott Goodliff @ NTF

FAST-MAC Model in the NTF

RESULTS

At transonic speeds CC altered the shock pattern on the upper wing surface and affected flow separation. Application of CC to the outboard portion of the wing demonstrated the feasibility of pneumatic-based maneuver control. CC increased the low-speed maximum lift coefficient by 40%. Prior difficulties with cryogenic PSP were successfully overcome. Post-test data analysis is required to remove the thrust contribution and document the drag reduction potential.

SIGNIFICANCE

The ability to modify the shock location on the wing surface indicates that CC has the potential to reduce cruise drag and fuel burn. Further analysis of the data followed by a second FAST-MAC test will quantify this benefit.

POCs: William E. Milholen, II, Gregory S. Jones, and David T. Chan (NASA/LaRC)

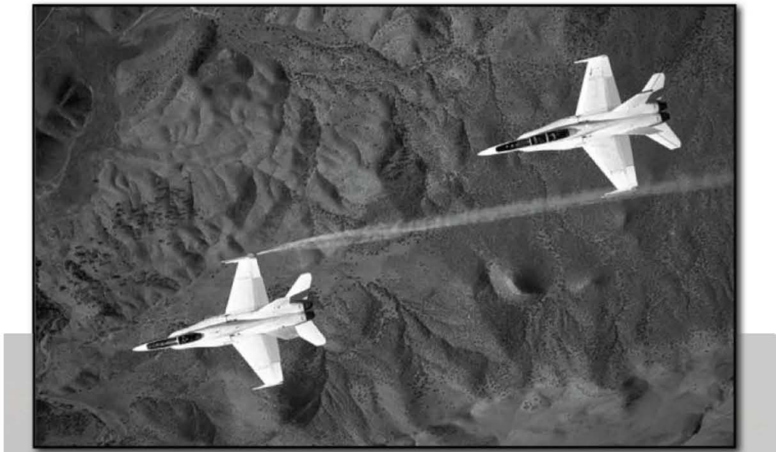
FAST-MAC

Fundamental Aerodynamics Subsonic/Transonic-Modular Active Control

Efficient Aerodynamics

- **Advanced CONOPS**
  - Formation Flight

14% reduction in heart rate when in formation
(Weimerskirch et al., 2001)



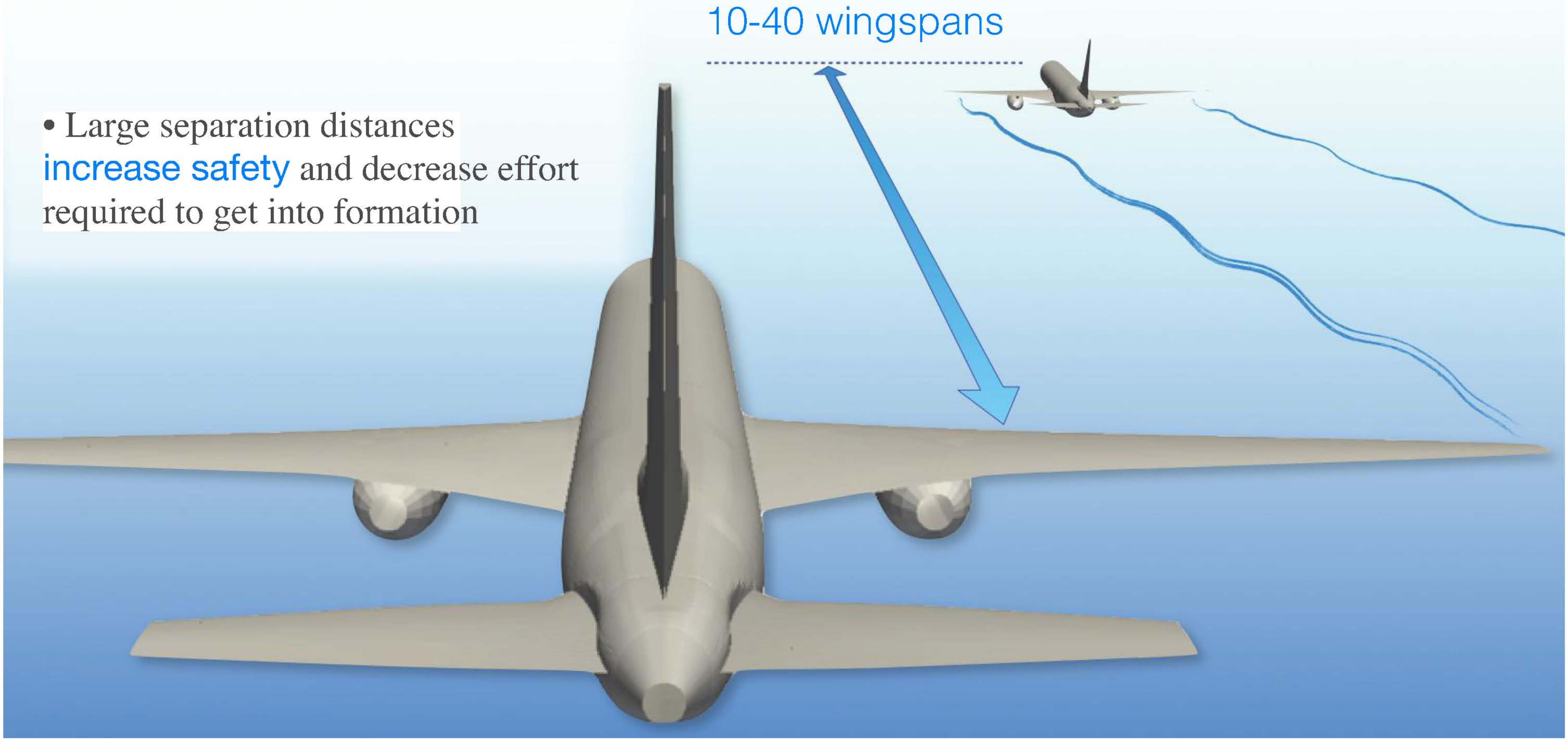
Over 20% drag reduction and 18% fuel flow reduction for trailing aircraft
(NASA, 2002)

10-15% drag reduction and 8-12% fuel flow reduction for transport aircraft in extended formation (NASA, 2010)

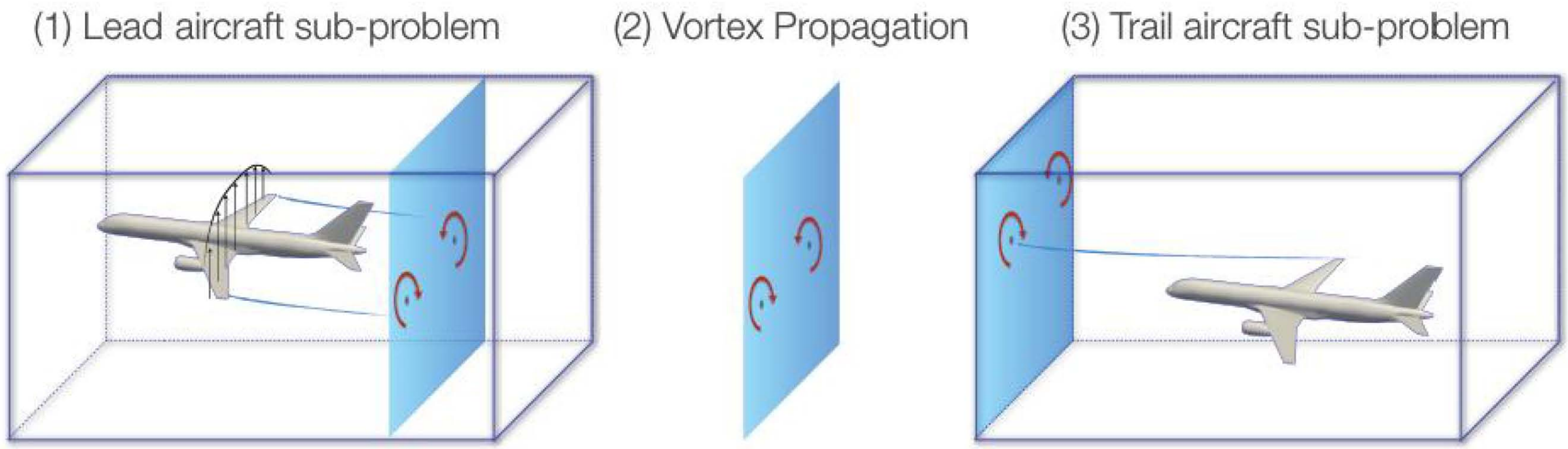
Extended Formation Flight

- The wingtip vortex structure behind an aircraft decays slowly, making extended formations possible

- Large separation distances increase safety and decrease effort required to get into formation



Computational Approach


(1) Lead aircraft sub-problem

(2) Vortex Propagation

(3) Trail aircraft sub-problem

Extract lift distribution
~150 CPU-hrs

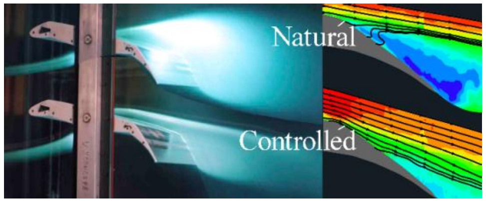
Impose vortex boundary-condition on CFD domain

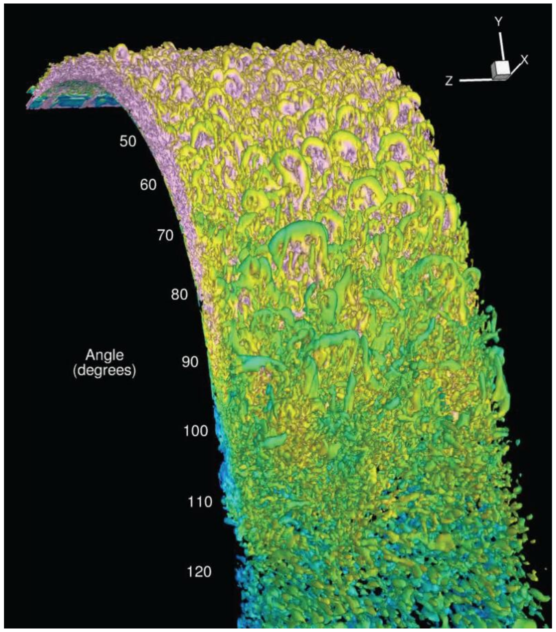
~150 CPU-hrs (untrimmed)
~600 CPU-hrs (trimmed)

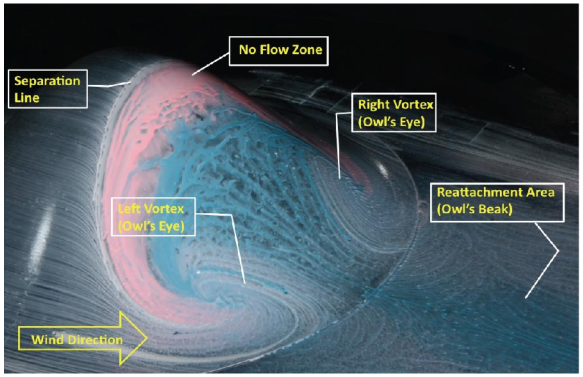
- While good performance estimates are possible using lower-order methods, high fidelity simulation makes it possible to include effects of
- Compressibility
- Control surface deflection required to trim the trailing aircraft for steady-level-flight
- Long vortex propagation distances, and the requirement to essentially compute improvement in lift-induced drag makes problem computationally intensive

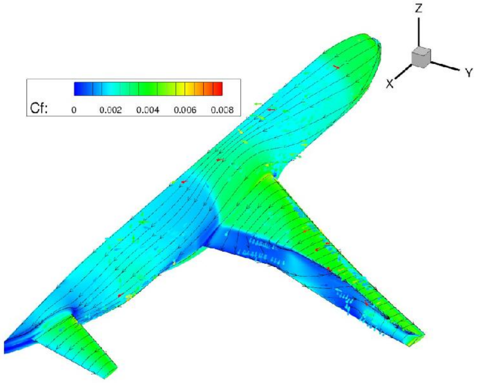
Efficient Aerodynamics

- **Aerodynamics Tools and Methods**
  - CFD Prediction Workshops and Validation Exercises
  - Validation Experiments and Novel Experimental Techniques (Juncture Flow, Englar airfoil, FAITH, COMSAC)
  - Transition Prediction and Modeling
  - Turbulence Modeling
  - Numerical Methods and Algorithms (Unstructured Grids, High-Order Methods)
  - Error Estimation and Uncertainty Quantification
  - Flow Control Physics
  - Learn To Fly (self-learning vehicle)









4th (and 5th) AIAA CFD Drag Prediction Workshop NASA Common Research Model (CRM)

PROBLEM

Disagreement among state-of-the-art CFD tools with respect to the prediction of drag and the prediction of the location and extent of separated flow regions (with associated variation in pitching moment prediction) on commercial transports.

OBJECTIVE

Identify the reasons for this discrepancy and improve CFD tool capability. Utilize high-quality experimental data from two separate wind tunnels to guide interpretation of CFD results.

APPROACH

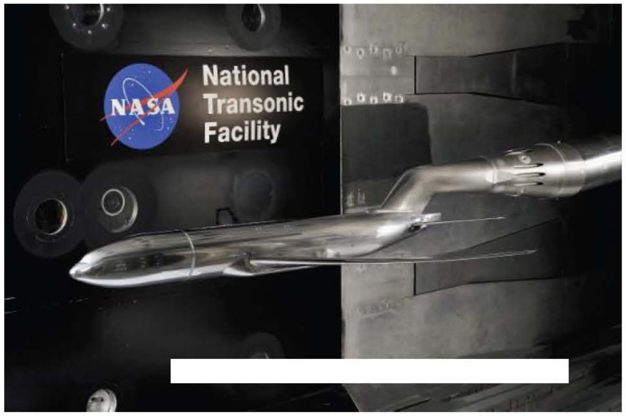
International Workshop with participants from industry, government, universities, and CFD vendor companies using a variety of state-of-the-art Reynolds-Averaged Navier-Stokes (RANS) solvers and different turbulence models to predict forces, moments, and regions of flow separation on a single open geometry configuration, the NASA Common Research Model (CRM), on standardized common grid families (both structured and unstructured) with experimental validation data gathered after the workshop in both the LaRC National Transonic Facility (NTF) 13 Jan 2010 to 16 Feb 2010 and the ARC 11-foot Transonic Wind Tunnel 16 Mar 2010 to 2 Apr 2010.

RESULTS

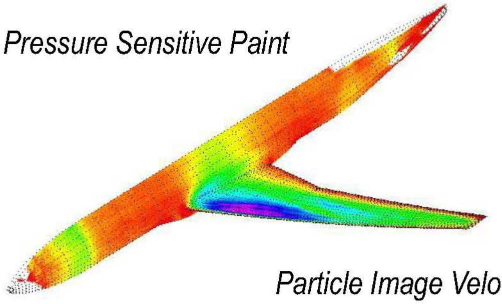
- CFD drag prediction still showing spread of up to 40 counts
- Large scatter in CFD prediction of separated zones and pitching moments
- Pressure Sensitive Paint (PSP) data gathered in both tunnels
- Oil Fringe Interferometry (OFI) skin friction measurements taken in ARC 11-foot
- Particle Image Velocimetry (PIV) off-body velocity measurements taken in ARC 11-foot
- Reynolds number effects and static aeroelastic effects assessed in LaRC NTF
- Configuration effect data (tail, nacelle/pylon) data acquired
- Demonstrated ability of new active damper system to acquire data at higher AOA

SIGNIFICANCE

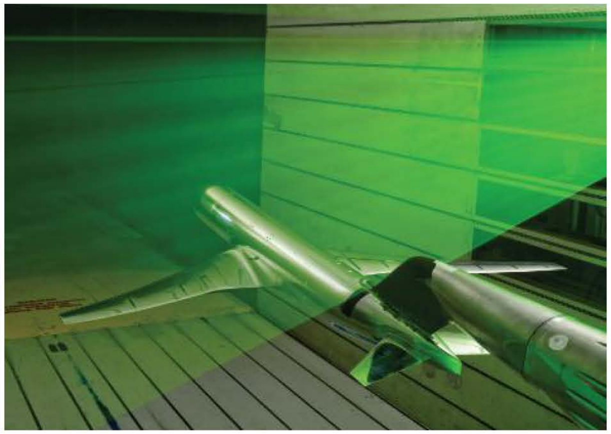
Broadly available, extensive computational and experimental database that is enabling progress in CFD predictive capability. Higher confidence in CFD predictions will enable designs with less margin, less weight, less wetted area, and less drag.



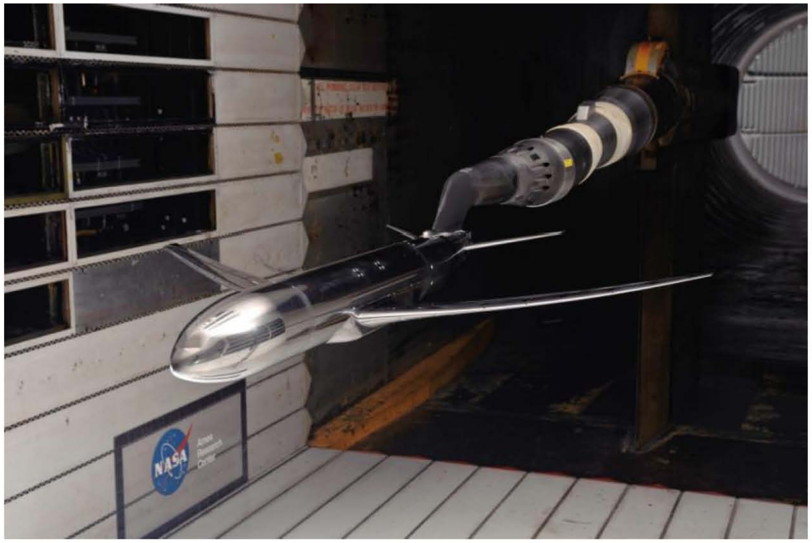
Pressure Sensitive Paint



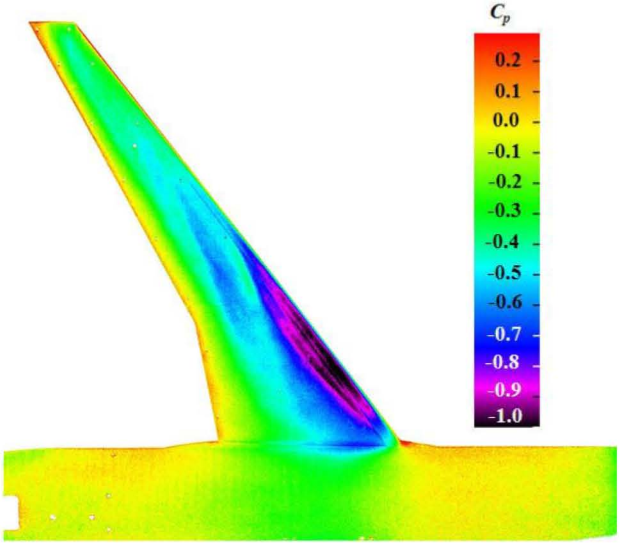
Particle Image Velocimetry in 11-foot



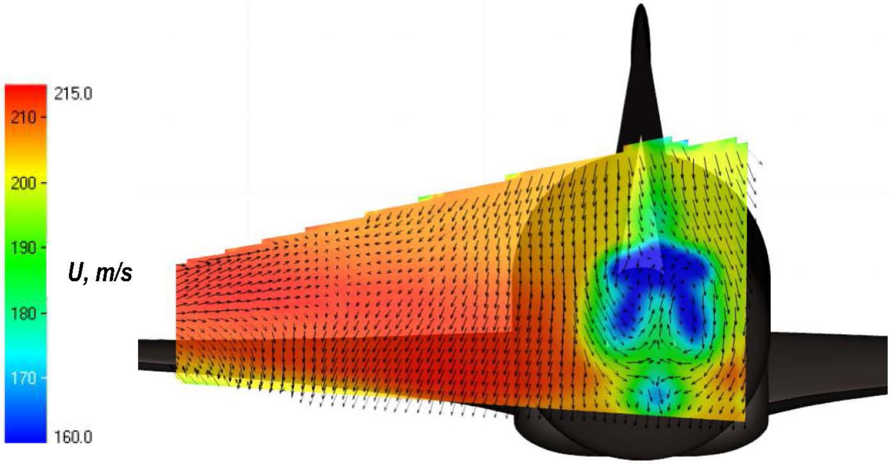
NASA Common Research Model Measurements



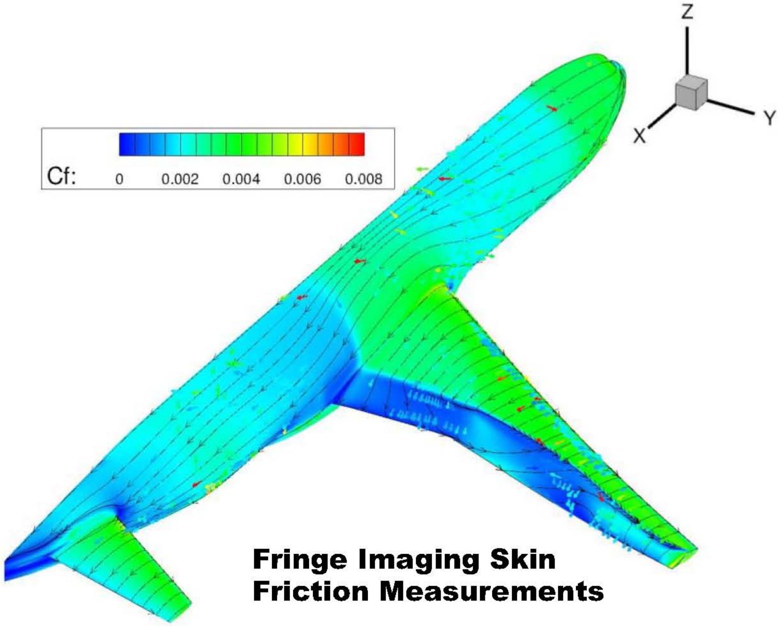
Common Research Model in the Ames 11-foot Wind Tunnel



Pressure Sensitive Paint Measurements



Particle Image Velocimetry Measurements



Fringe Imaging Skin Friction Measurements

POCs: James Bell, J.T. Heineck, Greg Zilliac

Low-Noise HWB CESTOL Aircraft Research

PROBLEM

Lack of aerodynamic and acoustic validation data for active flow control CESTOL configurations.

OBJECTIVE

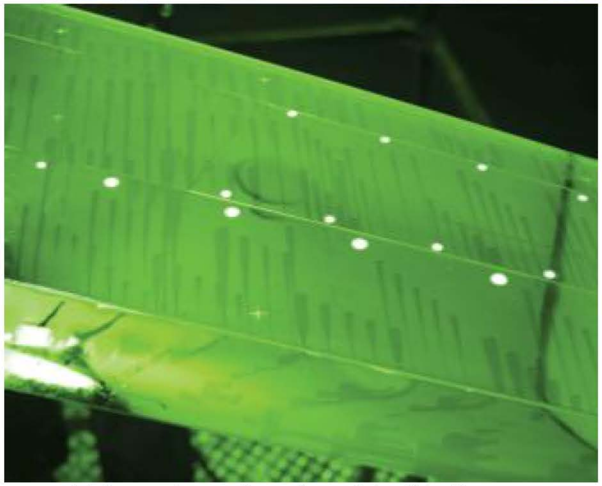
Acquire aerodynamic and acoustic validation data for a low-noise HWB CESTOL configuration developed by Cal Poly through an NRA.

APPROACH

- Conceptual studies identified HWB configurations capable of meeting NASA's noise, fuel burn, emissions, and field length goals.
- Large-scale wind tunnel model tests in the NASA Ames 40x80 Wind Tunnel to examine:
  - Low-speed, high-lift aerodynamic performance for take-off and landing
  - Transition to high-speed cruise
  - Acoustic characteristics of jet-blown systems for powered lift
  - Multiple flow visualization techniques

RESULTS

- Model fabrication completed. Model has 10-foot wing span, incorporates two high-pressure, air-powered Turbine Powered Simulators (TPS), and has a circulation control wing with a leading and trailing edge slot blown high-lift system.
- Wind tunnel test currently underway in NFAC 40'x80' wind tunnel.
- Results will be correlated with CFD predictions.



Fringe imaging for skin friction

SIGNIFICANCE

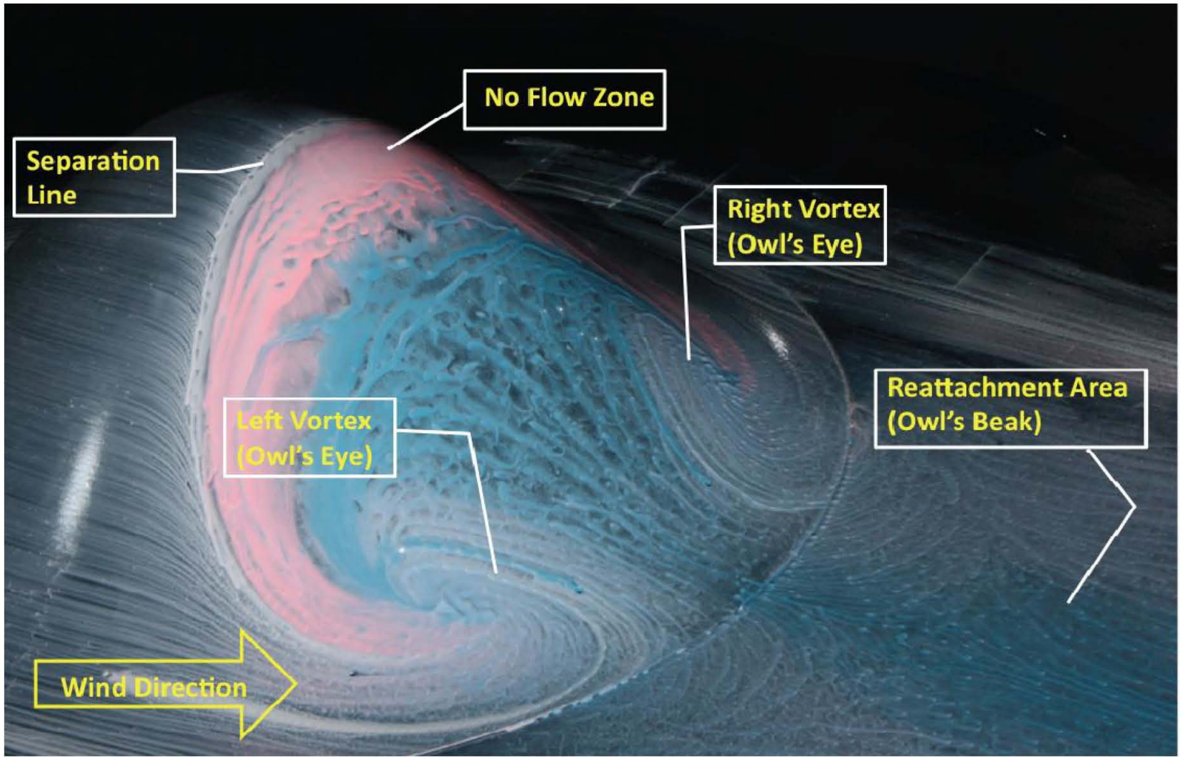
Experimental data will be used to develop tools that address the aerodynamic and acoustic design challenges associated with HWB configurations and blown high-lift systems. Circulation control can enable lighter high-lift systems and reduced field length capability. Alternatively, lift benefits can be traded for reduced weight and drag aircraft.

POCs: D. Marshall, T. Jameson (Cal Poly); C. Hange, C. Horne (NASA ARC)

3D FAITH Hill Experiment

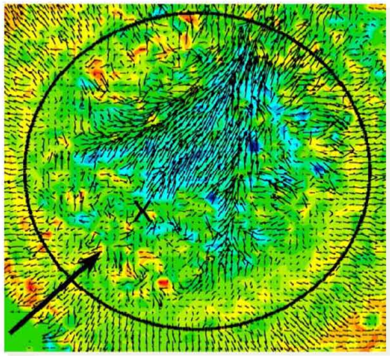
…. database for turbulence modeling assessment and development

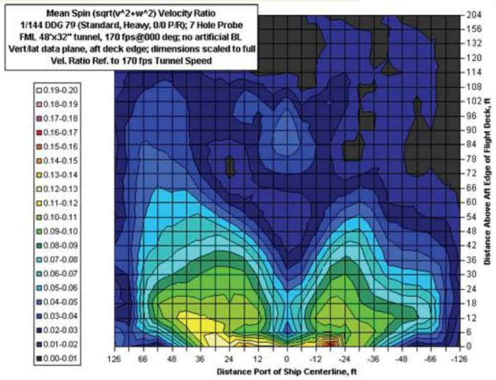
- Used as challenge for turbulence model related NRA solicitations
  - Well-documented flow field and boundary conditions
  - Several tunnel test entries; PIV data recently acquired



FAITH Measurement Techniques

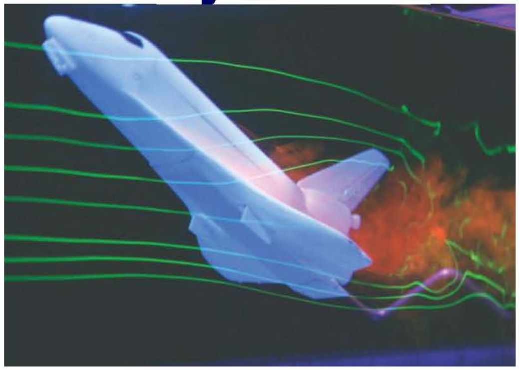
PIV

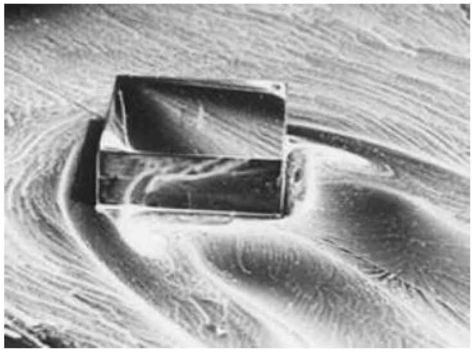




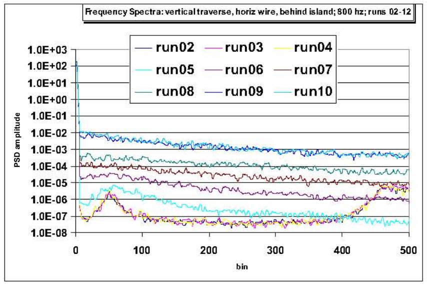
Mini Tufts

Dye Flow

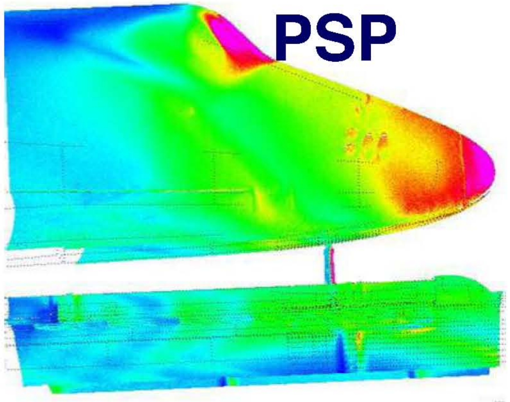




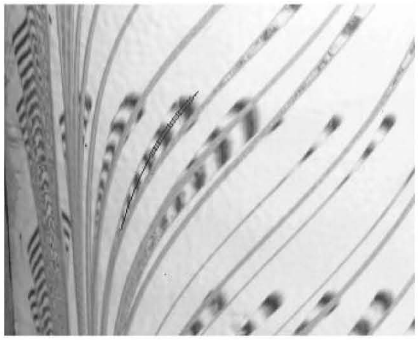
Cobra Probe



PSP



Oil Flow

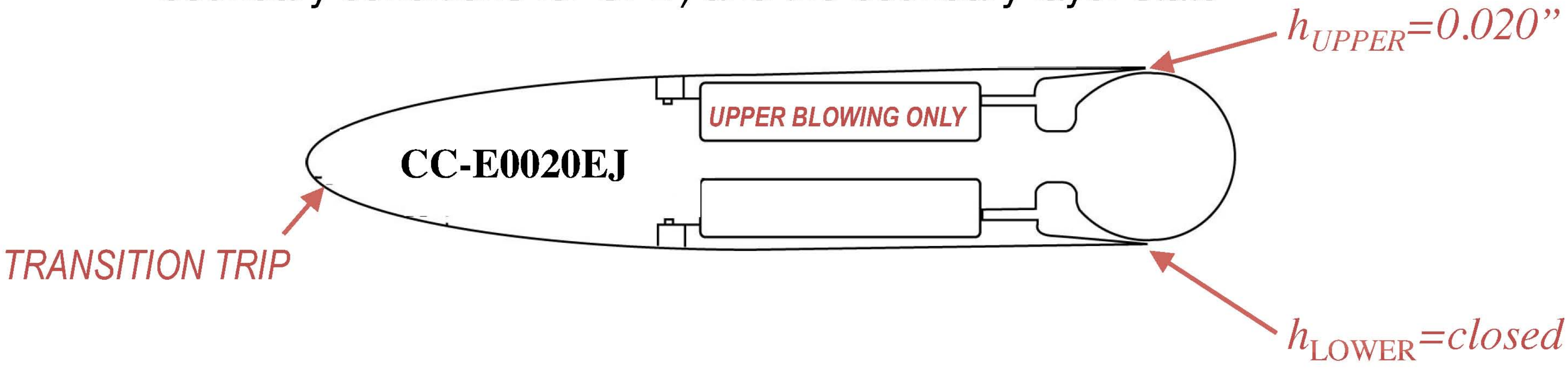


FISF

2D Circulation Control Airfoil Experiment

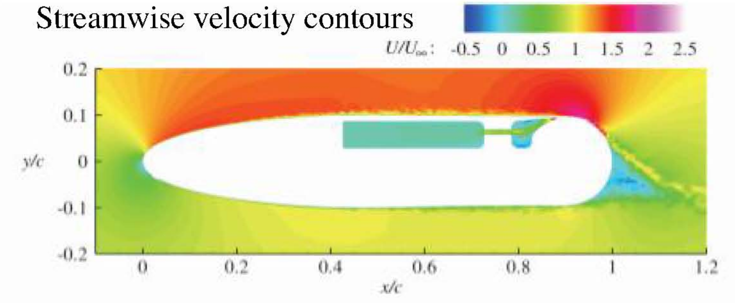
…. database for turbulence modeling assessment and development

- Details given in AIAA Paper 2009-902
- Georgia Tech experimental data
  - Primary focus on performance
- NASA experimental data
  - Primary focus on CFD validation
  - Testing is on-going
  - Current testing focusing on use of PIV to acquire near-body jet data
  - Of particular interest are conditions at the jet exit (these will define the boundary conditions for CFD) and the boundary layer state

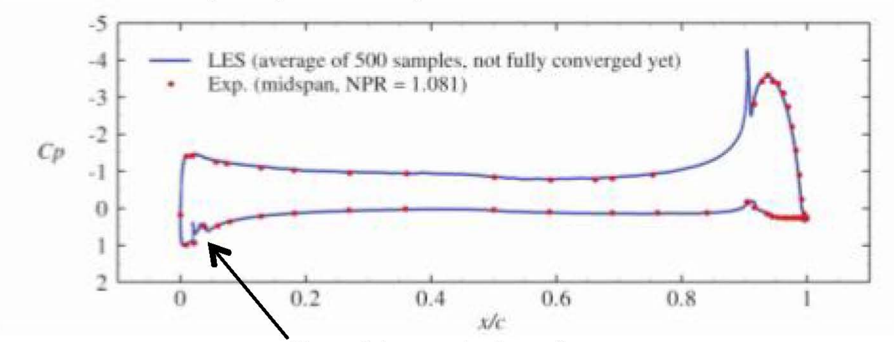


Large Eddy Simulation (LES) of the 2D Englar Circulation Control (CC) Airfoil

- **Objective:** Current CFD is incapable of reliably predicting the separation location on CC airfoils and therefore cannot predict lift. Improved turbulence models that correctly predict separation and lift are needed.
- **Approach:** Use Large Eddy Simulation to create a database to guide turbulence model development. Validate LES against experimental data acquired for the same configuration.
- **Results and Impact:** Statistics from LES show good agreement with experimental data. Extraction of statistics for turbulence model development and LES of higher blowing case underway.


Streamwise velocity contours

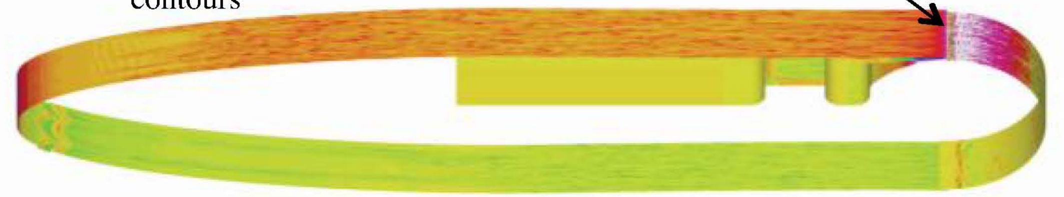
Pressure distribution



Transition strip location

Skin friction contours

CC blowing slot



Research team: Karim Shariff (LES Lead), Takafumi Nishino (ORAU postdoc), Seonghyeon Hahn (Center for Turbulence Research) in collaboration with Bob Englar (GTRI) and LaRC experimentalists (Greg Jones, John Lin) and RANS modelers (Brian Allan, William Milholen, Chris Rumsey).

Increasing Focus on Turbulence Modeling

- Improved CFD tools enable aircraft designs with
  - Reduced drag
  - Reduced design margins, leading to further reductions in drag and weight
- SFW process to develop improved turbulence models
  - Turbulence model assessments
    - Workshops, other studies
  - Generation, development, and documentation of validation databases
    - Experimental and Computational
  - Turbulence model development
    - In-house efforts and via NRA
- Includes RANS, LES, and hybrid RANS-LES models
- Primary research focus is on prediction capability for complex aerodynamic flow fields that include separation
- Need for additional foundational research
- **“Focused Research in Turbulence Modeling and Advanced CFD”**

Revolutionary Computational Aerosciences

- “Focused Research in Turbulence Modeling and Advanced CFD” effort
  - bring additional resources (FTE, NRA) to this research area
  - managed as a new sub-project of SFW
  - work initiated in FY12
  - Revolutionary Computational Aerosciences (RCA)
- Cross-project Fundamental Aeronautics effort
  - SFW, SRW, SUP, HYP stakeholders
  - RCA coordinated with ongoing related turbulence research efforts in all four projects
  - A test case for better cross-project integration in specific areas
- Technical Lead: Mujeeb Malik

Round 5 Turbulence Modeling NRA Awards
June 2011

- Gianluca Iaccarino – "Structure Based Modeling of 3D Separated Flows" Stanford University

- Hassan Hassan – "Development of Turbulence/Transitional Model and Assessment of Complex Aerodynamic Flows" North Carolina State University

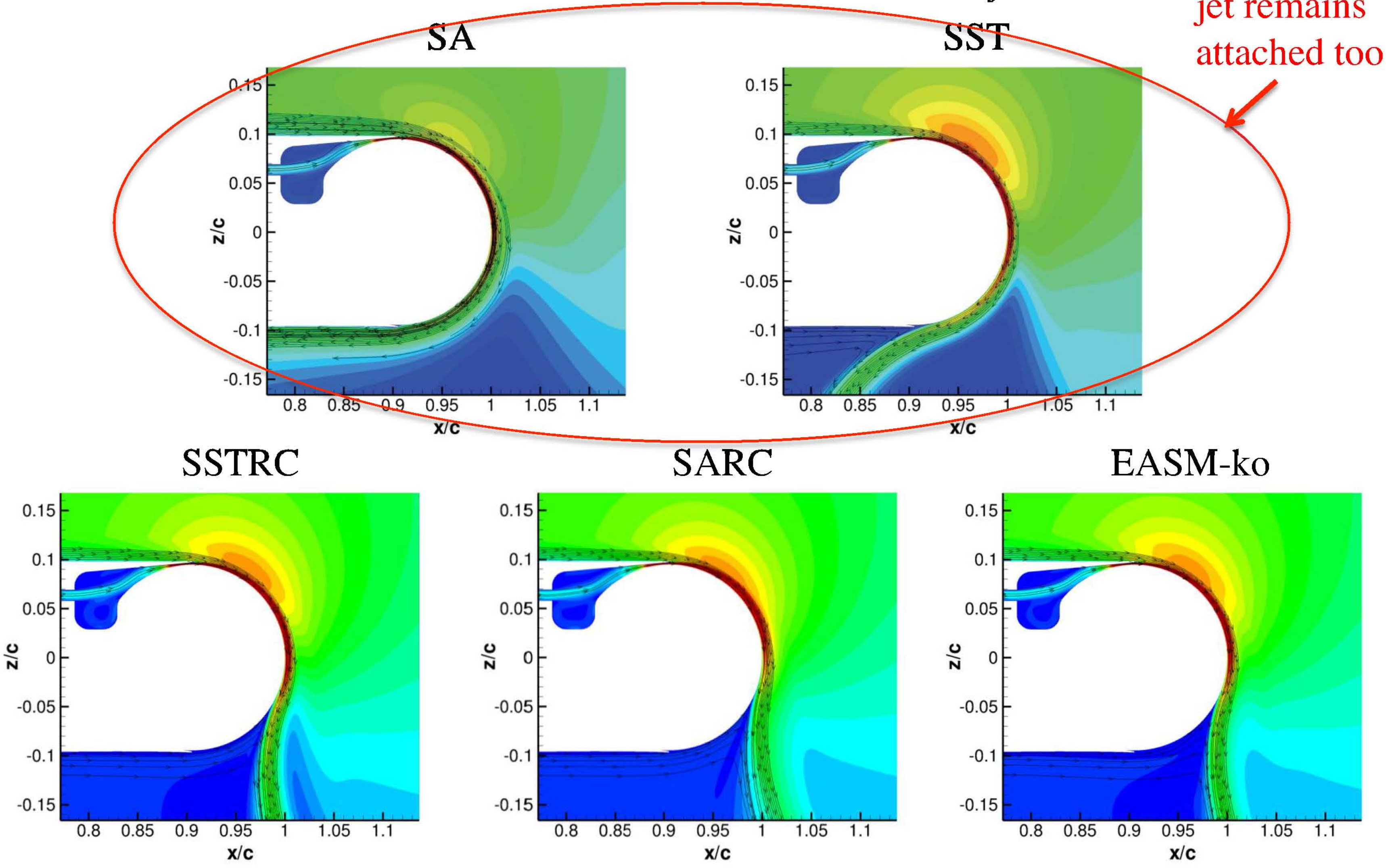
- Sharath Girimaji – "High Fidelity Multi-Resolution Turbulence Computations of Highly Separated Aerodynamic Flows" Texas A&M University

- Parviz Moin – "Large Eddy Simulation with Near-Wall Modeling of Multi-Component Airfoils at Flight Reynolds Numbers" Stanford University

Circulation Control RANS Simulations

…. assessment of models for prediction of challenging flow physics

RANS results at high blowing rate, M_j=0.90



SA

SST

SSTRC

SARC

EASM-ko

Non-physical;
jet remains
attached too long

RANS and LES Comparison of the Englar Circulation Control Airfoil

PROBLEM

Existing turbulence models cannot accurately predict circulation control (CC) airfoil flows, particularly for high jet-blowing conditions.

OBJECTIVE

Compare flowfield details from large eddy simulation (LES) with various Reynolds-averaged Navier-Stokes (RANS) approaches to determine where RANS turbulence models are inadequate.

APPROACH

- Compare simulations from LES (CDP), structured-grid RANS (CFL3D), and unstructured-grid RANS (FUN3D) codes.
- Assess five different RANS turbulence models, three of which include the effects of curvature, for mild to strong blowing.

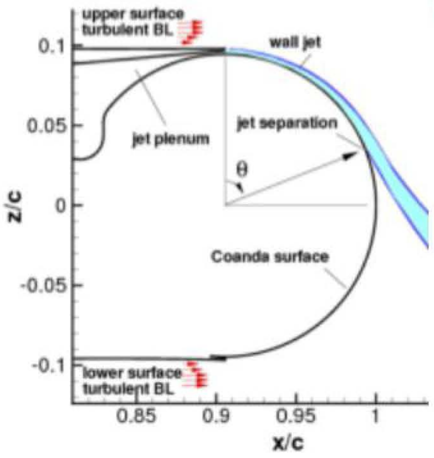
RESULTS

- At high blowing rates, models without curvature corrections (SA and SST) yielded unphysical solutions in which the jet separated too late.
- Of the three models tested that account for curvature, SARC agreed best with LES near the Coanda surface, but was worse downstream.
- All three models agreed with LES jet separation location, but yielded slightly different jet sheet positions downstream and over-predicted circulation.
- It is important to capture not only details near the surface – including jet separation location – but also to properly model the jet sheet behavior after separation.

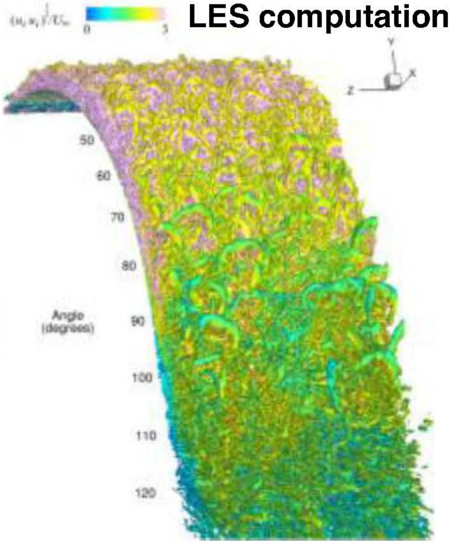
SIGNIFICANCE

LES provides a means of assessing and developing RANS turbulence models for smooth surface flow separation.

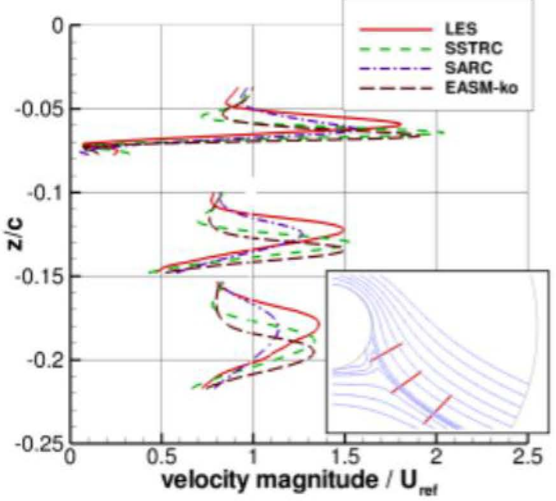
Illustration of CC airfoil trailing edge region



LES computation

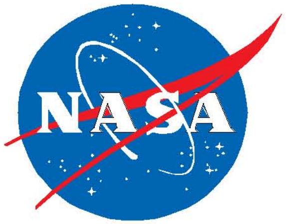


Wake contours across jet sheet comparing RANS models with LES



Fundamental Aeronautics Program
Subsonic Fixed Wing Project

POCs: Christopher L. Rumsey (NASA LaRC), Takafumi Nishino (NASA Ames postdoctoral fellow)


NASA