Drag Reduction Status and Plans – Laminar Flow and AFC

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Agenda

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

• Environmentally Responsible Aviation (ERA)
  o Focused on National Subsonic Transport System Level metrics for N + 2 timeframe
  o System research bridging the gap between fundamental (TRL 1-4) and product prototyping (TRL 7) in relevant environments
  o Innovative technologies for TRL 6 by 2020; critical technologies by 2015

• ERA is two phase project
  o 2010 – 2012 (Phase 1)
    • Investments in broadly applicable technology development
    • Identify vehicle concepts with potential to meet national goals
    • High fidelity systems analysis for concept and technology trades and feasibility
  o 2013 – 2015 (Phase 2)
    • Investments in a few large-scale demonstrations with partners
Potential Fuel Burn Improvements
Typical Contributions to Drag

System Assessments
325 Passenger, 4,000 nm

<table>
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<tr>
<th>Factor</th>
<th>Business Jet</th>
<th>Long Haul Transport</th>
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<tbody>
<tr>
<td>Miscellaneous</td>
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<td>3%</td>
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<tr>
<td>Roughness</td>
<td>5%</td>
<td>2%</td>
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<tr>
<td>Wave</td>
<td>9%</td>
<td>6%</td>
</tr>
<tr>
<td>Interference</td>
<td>9%</td>
<td>3%</td>
</tr>
<tr>
<td>Induced</td>
<td>53%</td>
<td>48%</td>
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<tr>
<td>Skin Friction</td>
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Merac (ONERA, 2000) and Bushnell & Hefner (AGARD 654)
Potential Drag Reduction Targets

- **Skin Friction Drag** – Laminar Flow (LF) Technologies, Active Flow Control (AFC) for wetted area reduction, turbulent drag reduction

- **Induced Drag** – configuration dominated, increased aspect ratio, wing tip devices, adaptive trailing edges, active load alleviation, *enabled by lightweight/multi-functional structures*

- **Interference Drag** – configuration dominated, propulsion/airframe integration, trim characteristics

- **Wave Drag** – configuration dominated, shock/boundary layer interactions, adaptive trailing edges/compliant structures

- **Roughness Drag** – joints, fasteners, manufacturing, operations

Overcome practical barriers to 50% fuel burn goal through demonstration of cruise drag reduction by integrated technologies
Active Flow Control (AFC) Applied to Rudder
PI – Israel Wygnanski/Edward Whalen

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

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

Sweeping Jet Actuator Concept

Effect of AFC on Wing
AFC Rudder System Integration Study
Increasing TRL

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

- **AFC system development – near term**
  - NASA/Boeing partnership (RPI, Caltech)
  - Screen 2 actuators at Caltech Lucas Tunnel – Spring 2011
    - 1.2m span, 33% rudder, 50° rudder deflection
    - Modular model
    - Complimentary CFD/flow field measurements

- **AFC system development – mid term**
  - Large tunnel test in 2012 with full-scale actuators
  - Testing, simulation, modeling, control

- **AFC system demonstration**
  - Flight test in 2013

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**Active Flow Control Rudder Model**

**Sweeping Jets**

**Steady Jets**

**Synthetic Jets/Sweeping Jets**
ERA Laminar Flow Technology Maturation Objectives

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

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

Analysis compared to NTF data with NLF

Re = 6.7M

DRE effect, low M, low Rn
Design of Laminar Flow Wings

• Laminar flow approach is dependent on system requirements and trades
  – Mach/Sweep, Re, Cp distribution, high-lift system, stability and control
  – Aircraft components and laminar extent of each
  – Swept-wing laminar flow is design tradeoff between Tollmien–Schlichting and Crossflow transition modes

• Challenges
  – Required favorable pressure gradient and sweep limitations can increase wave drag for transonic design – counter with thinner airfoil
  – Multi-point design complicated by need to consider loss of NLF
  – Leading edge radius limit and restrictions on leading edge high-lift devices can impact low-speed performance
  – Manufacturing and maintenance tolerances tighter (surface finish, steps, gaps, design/operation affected by loss of NLF in flight (insects, ice)
  – Ground testing at flight Reynolds numbers currently not practical
Ground Facility Capability for Laminar Flow Testing
PI – Rudolph King

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

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

NLF model in NTF
Aero Design Tools for Laminar Flow
PI – Richard Campbell

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


Multi-Fidelity Transition Prediction Capability

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

- **Candidate transition prediction modules for various fidelity levels**
  
<table>
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<th>Level</th>
<th>Module</th>
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<tbody>
<tr>
<td>Low</td>
<td>MOUSETRAP (NASA)</td>
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<tr>
<td>Medium</td>
<td>MATTC (NASA)</td>
</tr>
<tr>
<td>Medium</td>
<td>RATTraP (Lockheed/AFRL)</td>
</tr>
<tr>
<td>High</td>
<td>LASTRAC (NASA)</td>
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- **Currently, MOUSETRAP and MATTC have been linked with USM3D using a Linux script to provide an initial automated 3-D transition prediction capability**
MATTC Transition Prediction Method

- **Modal Amplitude Tracking and Transition Computation**
- Computes transition location based on empirical correlations
  - transition studies using 3 airfoils run in MSES and LASTRAC
  - TS: Re = 0.25 - 30 million
  - CF: Re = 10 - 30 million, sweep = 10 - 30 degrees
- \( x_{tr} = f(Re, dCp/dx, x) \), with sweep included for CF
- No boundary layer information required, provides n-factor envelope
Comparison of MATTSC/USM3D Results with Wind Tunnel and other CFD Results

M=0.8 A=2.3 Re=8M

MATTC
LST (WORST CASE)
LST (BEST CASE)
EXPERIMENT

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

Specified transition location (NF=9)

Laminar bucket

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

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

- DRE technology previously demonstrated in flight (Saric et al. 2010; Rhodes et al. 2010)
  - chord $Re_c = 7.5M$
  - $30^\circ$ swept wing

- ERA Goal: Demonstrate DRE on NASA DFRC G-III Subsonic Research Aircraft (SCRAT)
  - $Re_c$ characteristic of transport aircraft (up to 30 million)
  - Relevant wing loading (section $C_l \geq 0.5$)
  - Mach range from 0.66 to 0.76
  - Nominal cruise for host aircraft (around 3.5° - 4.0°)
SARGE Wing Glove Layout and Objectives

• SARGE is an instrumented wing glove designed to demonstrate hybrid laminar flow control on both the pressure and suction sides of the glove

• Primary Goal:
  – At $Re_c$ up to 22 million, SARGE will demonstrate natural laminar flow (NLF) to 60% x/c (glove chord) on the suction side and 50% x/c on the pressure side
  – At $Re_c \geq 22$ million, DREs will be used to increase laminar flow on the suction side by at least 50% (e.g. if natural transition occurs at 40% x/c, DREs will be used to delay transition to 60% x/c)

• Secondary Goal: Demonstrate ability of DRE overcome surface quality on leading edge by textured paint finishes
SARGE Glove Design Cycle

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

• DRE appliqué with diameter of 1.5 mm, height of 6-12 microns, wavelength of $\sim 4$ mm along $x/c = 1\%$
• Demonstrate validity at Mach, CL, and Re before addressing potential need for reconfigurable actuators
SARGE Glove Design Status

Pressure distribution near $C_l$ of 0.5, $M = 0.75$, $H = 41300$ ft, $AoA = 3.3^\circ$
SARGE Flight Envelope

• Experiment will demonstrate hybrid laminar flow control over a wide range of Mach and $Re_c$
  – mid-span $Re_c = 17 – 22M$ for NLF, and $Re_c = 22 – 27.5M$ for DRE control
Partners in ERA Drag Reduction Activities

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

Relevant Papers at 2011 AIAA Applied Aero Conference

- Design of the Subsonic Aircraft Roughness Glove Experiment (SARGE), M.J. Belisle, M.W. Roberts, M.W. Tufts, A.A. Tucker, T. Williams, W.S. Saric, H.L. Reed
- Computational Analysis of the G-III Laminar Flow Glove, M. Malik, W. Liao, E. Lee-Rausch, F. Li, M. Choudhari, C-L Chang
Concluding Remarks

• ERA Project Drag Reduction Investments
  – Phase 1 - broadly applicable viscous drag reduction technologies
  – Phase 2 – Select a few large scale demonstrations including drag reduction technologies

• Address critical barriers to practical laminar flow
  – Design and Integration
  – Surface tolerances, steps, and gaps
  – Maintenance and operations – ice, insects, etc.

• Demonstrate feasibility of Discrete Roughness Elements (DRE) as form of hybrid laminar flow control for swept wings