LAMINAR FLOW CONTROL
AT HIGH SPEEDS:
*A work in progress*

WILLIAM SARIC

MECHANICAL AND AEROSPACE ENGINEERING
ARIZONA STATE UNIVERSITY

---

*High-Speed LFC – APS Nov03*
Acknowledgements

• Helen Reed has participated from the beginning with LST, PSE, NPSE, DNS, Euler, and N-S computations as well as airfoil design for LFC

Boundary-Layer Transition

• Receptivity
  – External disturbances enter the boundary layer, creating the initial conditions for instability
  – Acoustic and vortical disturbances, roughness, geometry, vibration

• Typical Linear Stability
  – Unsteady, linearized Navier-Stokes
  – Basic-state distortions are ignored

• Breakdown
  – Nonlinear interactions
  – Basic-state distortions lead to secondary instabilities
PATHS TO TURBULENCE  (Reshotko et al.)

Forcing Environmental Disturbances

Receptivity

Primary Modes

Secondary Mechanisms

Breakdown

Turbulence

High-Speed LFC – APS Nov03

Copyright William Saric, 2003
Control

• “NATURAL”
  – MODIFICATIONS OF Cp

• “PASSIVE”
  – FIXED WALL SUCTION
  – MEANFLOW MODIFIERS
  – WALL TEMPERATURE DISTRIBUTION

• “ACTIVE”
  – FEEDBACK SYSTEMS WITH DYNAMIC RESPONSE
Transition Control

- Basic idea *has always been* to control the initial instability before it grows large enough to cause transition
- Re-laminarization of turbulent boundary not economical
Transition Control

• Physics of the linear mechanisms are known
  – THIS IS THE REGIME WITHIN WHICH LAMINAR FLOW
    CONTROL OPERATES
  – AN ABSOLUTE TRANSITION PREDICTION IS NOT
    NECESSARY

• Certain instabilities exhibit early nonlinearities and saturation – this suggests
  the need and the opportunity for a different type of control
Boundary-Layer Instabilities

- Attachment Line
- Curvature Induced
- Streamwise (T-S waves)
- Crossflow
Streamwise Instabilities (T-S Waves)

- Important for both swept and unswept wings
- Breakdown usually in pressure recovery region
- Subsonic: primarily 2-D
- Supersonic: primarily 3-D approximately $M < 4.5$
- Supersonic: 2-D *Mack Modes* for $M > 4.5$
  - Control strategy is very much different in this case
- Very sensitive to freestream sound
- Very sensitive to 2-D roughness
  - $M < 1$ normal roughness
  - $M > 1$ oblique roughness
Crossflow Instabilities

• Important only for swept wings
• Stationary and traveling modes
• No new physics up to approx $M = 3$
• Very sensitive to freestream turbulence
• Very sensitive to very small 3-D roughness
• Insensitive to sound and small 2-D roughness

High-Speed LFC – APS Nov03

Copyright William Saric, 2003
Control Mechanisms

• Wave superposition and cancellation
• Modification of instability amplifiers
• Meanflow modifications
Control Mechanisms

• Wave superposition and cancellation
• Modification of instability amplifiers
• Meanflow modifications
Stability Modifiers

- **Parametric resonance - Mathieu equation**
  - Stabilize unstable modes/De-stabilize stable modes
    - Typical response through subharmonic
  - Not exploited in bounded shear flows

- **Change the instability forcing function**
  - pressure gradient, suction, heating/cooling for control
  - useful for streamwise instabilities (T-S waves)
Control Mechanisms

- Wave superposition and cancellation
- Modification of instability amplifiers
- Meanflow modifications
Meanflow modifications

• Large amplitude sound
  – Acoustic streaming due to quadratic nonlinearity
    » Affects the profile curvature
    » May be useful for separation control
  – Not practical for control of instabilities

• Excite stationary instabilities
  – Stationary waves (crossflow or Görtler vortices) distort meanflow. Stability of distorted meanflow is changed.
High-Speed Applications

- Weak Boundary-Layer Suction
- Natural Laminar Flow
- Modified Mean Flow
Boundary-Layer Suction (see Joslin 1998)

- Transonic experiments in NASA-LaRC TPT
- NASA-LaRC Jetstar flight tests
- F-16XL supersonic flight tests: Boeing, NASA
- It works
  - Economic trade-offs and reliability are unclear
Natural Laminar Flow

• Reno Air, DTI, Desk-Top Aero Concept
  – Very low sweep angle, long run of accelerated flow

• NAL, Japan Concept (AIAA St Louis 2002)
  – Very rapid crossflow acceleration, then flat Cp

• Don’t be marginal with T-S
  – Wind tunnel tests are difficult
  – High Re is difficult

Copyright William Saric, 2003
Mean Flow Modifications
ASU Concept

- Sweep wing beyond Mach angle (subsonic L.E.)
- Accelerate the flow to $x/c = 80$
  - Amplifies crossflow but subcritical to T-S
- Use distributed roughness to excite subcritical wavelengths that:
  - Grow early
  - Modify meanflow
  - Prevent critical wavelengths from growing
  - Decay before causing transition
High Speed Swept-Wing Studies at ASU

- **Quiet Supersonic Platform (QSP) - ongoing**
  - With Simone Zuccher, Lloyd McNeil, Jarmo Monttinen

- **Computations**
  - LST, NPSE development and computations
  - Airfoil design for LFC in ASU experiments, flight tests, LaRC experiment, LMCO system and experiment

- **Experiments**
  - ASU SWT at M=2.4; F-15 at M=1.9; LaRC 4x4 UPWT at M=2.17; ARC 9x7 at M = 2.4 (2004); Draken at M =1.8 (2005)
Crossflow Transition

Streamlines Over a Swept Wing

Swept-Wing Boundary Layer

Copyright William Saric, 2003

High-Speed LFC – APS Nov03
Crossflow Instability

• Inviscid instability
• Requires wing sweep + streamwise pressure gradient
• Linear eigenvalue problem
• Stationary ($\omega=0$) and traveling unstable waves
• Co-rotating vortices aligned with potential flow direction
• Early development of nonlinear effects
Naphthalene flow visualization for $Re_c = 2.4 \times 10^6$ and no artificial roughness.

*High-Speed LFC – APS Nov03*
Stationary Crossflow Waves

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.20$

6 $\mu$m roughness at $x/c = 0.023$, 12 mm spacing
Stationary Crossflow Waves

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.30$

6 $\mu$m roughness at $x/c = 0.023$, 12 mm spacing

(y',w') Schematic

Streamwise Velocity Contours
Stationary Crossflow Waves

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.45$

$6 \mu m$ roughness at $x/c = 0.023$, 12 mm spacing

(V', w') Schematic
Artificial Roughness at LE of Polished Surface
Stationary Crossflow Waves

NL(F(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.45$

6 $\mu m$ roughness at $x/c = 0.023$, 12 mm spacing
Naphthalene flow visualization for $Re_c = 2.4 \times 10^6$ and no artificial roughness.

*High-Speed LFC – APS Nov03*
Parabolized Stability Equations (PSE)

Review: Herbert (1997)

PSE popular
- Include nonparallel and nonlinear effects
- Successfully model variety of convective flows
- Relatively small resource requirements compared with DNS
MOST UNSTABLE MODE AT $\lambda = 12$ mm

<table>
<thead>
<tr>
<th>EXCITATION</th>
<th>RESPONSE</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 mm</td>
<td>12 mm</td>
<td>No 24 mm</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>No 36</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>36 mm</td>
<td>36 mm</td>
<td>Transition moves forward slightly</td>
</tr>
<tr>
<td></td>
<td>18, 12, 9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.2, 6, 5.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5, 4</td>
<td></td>
</tr>
<tr>
<td>18 mm</td>
<td>18 mm</td>
<td>No 12 mm</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>No 36 mm</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>8 mm</td>
<td>8 mm</td>
<td>No 12 mm</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

High-Speed LFC – APS Nov03

Copyright William Saric, 2003
Stationary Crossflow Waves

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.60$

6 $\mu$m roughness at $x/c = 0.023$, 8 mm spacing
ROUGHNESS

• NONLINEAR RESPONSE OF STREAMWISE VORTICES CREATES HARMONICS IN WAVENUMBER SPACE, NOT SUBHARMONICS

• INTRODUCE HIGHER WAVENUMBER DISTURBANCES THAT INITIALLY GROW AND INHIBIT THE GROWTH OF LOWER WAVENUMBER DISTURBANCES. THE HIGHER WAVENUMBER DISTURBANCES THEN DECAY, LEAVING NOTHING
CONTROL STRATEGY

ASSUME BACKGROUND ROUGHNESS $\approx 2$ MICRON AND RANDOM

BIAS THIS DISTRIBUTION WITH SUBCRITICAL SPACING TO INHIBIT GROWTH OF CRITICAL WAVELENGTHS AND DELAY TRANSITION

High Speed LFC

• F-15B Flight Tests
• ASU Wind Tunnel Tests
• High-Reynolds-Number Wind Tunnel Tests
Outline

• F-15B Flight Tests
  – Basic ideas
  – Flowfield Computations of ASU side
  – Recent Flights

• ASU Wind Tunnel Tests

• High-Reynolds-Number Wind Tunnel Tests
Flight Trajectory

Altitude (kft)

Level Accel from M 0.8-1.85
M = 1.8 descent: 1200 psf qbar max

Level Cruise 10 sec: <1200 psf, ~35kft

Subsonic Descent

Normal T.O.

Time

Normal Landing

High-Speed LFC – APS Nov03

Copyright William Saric, 2003
NASA-DFRC  F-15B

High-Speed LFC – APS Nov03

Copyright William Saric, 2003
ASU side of test article, $\Lambda = 30^\circ$
6\text{µm} \text{ roughness spaced at 4 mm, 2}\%C
F-15B Flight Tests Cont.

• **F-15B limited to Mach 1.5 by Eglin AFB on 14 May 02**

• **Delays pushed testing back**
  – e.g. 3 aborts during March 03
  – Low priority and equipment problems

• **Flight tests resumed July 03**
  – 1. Improved landing technique minimized oil splashes
  – 2. Pressure tests conducted first (4 channels at a time)
  – 3. Distributed roughness with periodic roughness elements
  – 4. Obtain data at M = 1.85 and M = 0.9
$M = 1.85$ @ 40k ft altitude

Overshoot on $C_p$ nullifies control inboard

$Re_c$ approx 9 million

- control 4 mm
- maintains laminar boundary layer
- not susceptible to random LE disturbances

Copyright William Saric, 2003
F-15 Subsonic IRT Results

- $M = 0.9$
- $\Lambda = 30^\circ$
- $H = 36,000\ ft$
- $Re' = 2.5 \times 10^6/ft$
- mid-span chord = 2.5 ft
- $Rec = 6.25 \times 10^6$
- Baseline, 80% chord, pressure minimum
- With 4 mm control,
  full chord laminar flow

Copyright William Saric, 2003
Outline

• F-15B Flight Tests

• **ASU Wind Tunnel Tests**
  – *Hotfilms, hotwires, glow discharge, and PWM CTA*
  – *IR Thermography (Zuccher et al APS 03)*

• **High-Reynolds-Number Wind Tunnel Tests**
Outline

• F-15B Flight Tests

• ASU Wind Tunnel Tests

• High Reynolds Number Wind Tunnel Tests
  – Model design
  – Stability analysis and tunnel conditions
  – Status
NASA-LaRC Test

- **Test campaign Dec 02/Jan 03**
  - Confirmed leading-edge contamination
  - Leading-edge radius twice the design value

- **Test campaign May 03**
  - ASU redesign of airfoil – Model #2, re-fabricated at Tri Models
  - Suction peak near leading edge caused separation bubble and premature transition
  - Leading-edge flow field in tunnel remarkably different than free-air calculation – subsonic leading edges

*High-Speed LFC – APS Nov03*
Symmetric, 3.5% thick
LE sweep 68°, TE sweep 66.5°
Unit $Re = 7$ million/foot, $q = 1600$ psf, $M = 2.16$
Streamwise chord = 7 feet, Span = 4 feet
Normal-to-LE radius = 1/16 inches
Attachment line $Re_{\theta} \approx 100$
LaRC Experiments

- Leading-edge radius was twice as large as originally designed.
- Attachment line contamination at Re’ = 2.7x10^6/ft
- Corresponds to Re_{θAL} = 100
- Model Machined with new leading edge and improved dp/dx
LaRC Experiments – part 2

- Tunnel Entry May 2003
- Leading-edge separation bubble
  - Less laminar flow than before
  - Rex (transition) = 700,000
- Confirmed with ASU and LMCO Navier-Stokes
- Need to re-machine model and possibly change angle of attack

*High-Speed LFC – APS Nov03*
CONCLUSIONS

• Periodic roughness technique works for modest Re
• F-15 flight tests are very encouraging
• ASU SWT tests seem affected by leading-edge separation, freestream turbulence, and model scale
• Demonstrated laminar flow at Langley 4x4. With proper redesign, await the high Re tests