CONTROL OF STABILITY AND TRANSITION IN SWEPT-WING BOUNDARY LAYERS

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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
RICH VARIETY OF STABILITY BEHAVIOR

GENERIC TO 3-D BOUNDARY LAYERS

• Streamwise vortices
• Spanwise modulations
• Secondary instabilities

3-D BOUNDARY LAYERS

- CROSSFLOW
  - Swept Wing
  - Rotating Disk
  - Rotating Cone

- ATTACHMENT LINE
  - yawed cylinder

- CORNERS AND INLETS
SWEPT WING INSTABILITY MECHANISMS

- Leading-edge contamination
- Streamwise instabilities
- Crossflow instabilities
- Curvature-induced instabilities
OBJECTIVES

• PROVIDE DESCRIPTION OF BREAKDOWN
  – IMPORTANT FREQUENCIES
  – MODE SHAPES
  – GROWTH RATES
  – SECONDARY INSTABILITY
  – ABSOLUTE INSTABILITY

• USE THESE DATA FOR:
  – PHYSICALLY CORRECT (NOT $e^N$) TRANSITION
  – GUIDANCE FOR CONTROL SYSTEM
  – FLIGHT INSTRUMENTATION
  – WHAT DO HOT FILMS SHOW?
  – MEASURING TRANSITION
SWEPT-WING STUDIES AT ASU

• BASIC CROSSFLOW EXPERIMENT
  with Ray Dagenhart 1988, 1989
  isolate crossflow mechanism from T-S flow visualization transition
  measurement $\lambda_{CF}$ measurements

• SECONDARY INSTABILITY LEADING TO TRANSITION
  with Yasu Kohama 1990
  high-frequency breakdown mechanism

• MICRO-THIN HOT FILM DEVELOPMENT
  with Siva Mangalam 1991
  flight test instrumentation development
SWEPT-WING STUDIES AT ASU CONTINUED

• MICRON-SIZED ROUGHNESS NEAR ATTACHMENT LINE
  with Ronald Radeztsky, Mark Reibert 1992, 1993
  sensitivity of stationary crossflow to roughness

• DETAILED DATA BASE FOR CROSSFLOW INSTABILITY
  with Ronald Radeztsky, Mark Reibert 1993, 1994
  attempt to find linear range at $\alpha = 0^\circ$ measure at 5% chord data base for computations
SWEPT-WING STUDIES AT ASU CONTINUED

• NONLINEAR PSE MODELLING AND COMPUTATIONS
  Helen Reed and Tim Haynes, 1996
  developed a validated code

• MODELLING TRANSITION WITH POD
  with Keith Chapman, Mark Glauser, 1997
  interpretation of hot film measurements

• MODELLING COMPRESSIBLE WITH CROSSFLOW $Re$
  Helen Reed, 1997
  Explains Rudy King data
SWEPT-WING STUDIES AT ASU CONTINUED

• CONTROL OF TRANSITION WITH DISTRIBUTED ROUGHNESS
  with Ruben Carrillo 1998
  subcritical wavelength of roughness delays transition

• SECONDARY INSTABILITY AND TRANSITION PREDICTION
  with Edward White 2000
  Details confirm theory of Malik; no absolute instability
SWEPT-WING STUDIES AT ASU CONTINUED

• EFFECTS OF FREESTREAM TURBULENCE AND RANDOM BACKGROUND ROUGHNESS
  with Robert Gladden and Pierre Gabet - in progress

• EFFECTS OF FREESTREAM SOUND
  with Edward White - Receptivity exps of leading edge 1999
  Helen Reed & David Fuciarelli 2000: DNS of leading Edge
Streamlines Over a Swept Wing
Swept-Wing Boundary Layer
CROSSFLOW INSTABILITY

- Inviscid instability
- Requires wing swept + 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
CROSSFLOW

- INSENSITIVE TO SOUND

- SENSITIVE TO FREESTREAM TURBULENCE

- INSENSITIVE TO 2-D ROUGHNESS

- SENSITIVE TO 3-D ROUGHNESS
GOALS

• linear methods do not work for crossflow induced transition

• need to provide data base for nonlinear PSE code validation for transition correlation

• need to understand role of micron-sized roughness on transition
ACCOMPLISHMENTS

• outstanding agreement between CFD and experiments

• obtained revolutionary new results on controlling transition with roughness
EXPERIMENT

NLF (2)-0415 AIRFOIL AT 45 DEG SWEEP

HOT-WIRES FOR UNSTABLE REGION

VISUALIZATION FOR QUALITATIVE RESULTS

HOT-FILM ARRAYS TO GIVE REAL-TIME TRANSITION LOCATION
KEY FEATURES

• Low-turbulence tunnel
• Subcritical to T-S
• Crossflow-dominated transition
• Concentrate on distributed roughness
• Infinite swept-wing flow
  – Test-section wall liners match inviscid streamlines
  – Flowfield measurements match CFD design
TEST CONDITIONS

Test section = 1.4 × 1.4 × 5 m

\( c = 1.83 \text{ m} \)
\( \alpha = -4^\circ \)
\( \wedge = 45^\circ \)
\( U_\infty = 15-34 \text{ m/s} \)
\( Re_c = 1.5 \times 10^6 - 3.2 \times 10^6 \)
\( \delta < 5 \text{ mm} \)
Swept-Wing Model with Wall Liners
Stationary Streamwise Profiles

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 1.6 \times 10^6$, $x/c = 0.20$

No Artificial Roughness
100 Profiles, $\Delta_{\text{span}} = 1$ mm
Measured and Theoretical Pressure Coefficient

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 3.2 \times 10^6$
CROSSFLOW INSTABILITY

- Eigenvalue Problem

\[ F(\alpha, \beta, \omega, R) = 0 \quad \alpha, \beta \text{ complex} \]
solve for \( \alpha \)

\[ \alpha = f(\beta, \omega, R) \quad 2 \text{ equations} \]

fix \( \beta_r \)

choose \((\alpha_r, \beta_r)\) pair for: \( d\alpha/d\beta \) real
N-factor

$\sigma$: spatial growth rate

$\frac{A}{A_0}$: amplitude ratio between two spatial positions

$$\frac{A}{A_0} = \exp \int_{x_0}^{x} \sigma dx = e^N$$

$$N = \int_{x_0}^{x} \sigma dx = 2 \int_{R_0}^{R} \sigma dR = \ln \frac{A}{A_0}$$
Unstable Crossflow Frequency Range

35° swept wing at R = 301 and k = 0.52
Mack (1984)
VISUALIZE WALL STREAKS
WITH NAPTHALENE
TRICHLOROETHANE SPRAY
Unsteady Wind Tunnel

40%

50%

Re_c = 2.6 x 10^6, PAINTED
Crossflow Vortices

Görtler Vortices

\( \lambda_z \)
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
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

Streamwise Velocity Contours

$u/U_0$ 0.00 0.25 0.50 0.75 1.00
Stationary Crossflow Profiles

**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
NLF(2)-0415 Roughness Measurement - Paint
Filtered 20\(\mu\text{m}-1500\mu\text{m}, \text{rms}=3.30\mu\text{m} \)
NLF(2)-0415 Roughness Measurement - First Polish

Filtered 20µm-1500µm, rms=0.509µm

\[ y(\mu m) \]
\[ z(\mu m) \]
NLF(2)-0415 Roughness Measurement - Hand Polish
Filtered 20\(\mu\)m-1500\(\mu\)m, rms=0.121\(\mu\)m
Transition Location vs. Dot Diameter

- $Re_c = 3.4 \times 10^6$
- $Re_c = 3.0 \times 10^6$
- $Re_c = 2.6 \times 10^6$
Variation of Transition Wedge Location with Roughness Size

Stationary Crossflow $\lambda_{x} = 8\text{mm}$
Roughness at $\kappa / \kappa = 0.03$
$Re_{x} = 2.0 \times 10^{5}$

<table>
<thead>
<tr>
<th>$H$ (μm)</th>
<th>$H/\delta_{99}$</th>
<th>$H/\delta_{0.1}$</th>
<th>$r_{k}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6μm</td>
<td>0.0088</td>
<td>0.0222</td>
<td>.12</td>
</tr>
<tr>
<td>12μm</td>
<td>0.014</td>
<td>0.045</td>
<td>.50</td>
</tr>
<tr>
<td>18μm</td>
<td>0.020</td>
<td>0.084</td>
<td>1.1</td>
</tr>
<tr>
<td>24μm</td>
<td>0.027</td>
<td>0.085</td>
<td>2.0</td>
</tr>
<tr>
<td>30μm</td>
<td>0.034</td>
<td>0.11</td>
<td>3.1</td>
</tr>
<tr>
<td>36μm</td>
<td>0.041</td>
<td>0.13</td>
<td>4.5</td>
</tr>
</tbody>
</table>
3. Single and multiple-mode saturation at $\alpha = -4^\circ$
Stationary Crossflow Waves

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 3.0 \times 10^6$, $x/c = 0.45$

No Artificial Roughness
• MOST AMPLIFIED MODE $\lambda \approx 12$ mm

• FORCE AT THIS WAVELENGTH WITH ROUGHNESS $k = 6 \mu m$ $Re_k = 0.1$
Roughness Reynolds No.

\[ U_\infty = 25 \text{ m/s} \]
\[ \delta^* \text{ at roughness } = 250 \mu m \]
\[ k = 6 \mu m \quad \text{Re}_k = 0.1 \]
\[ k = 18 \mu m \quad \text{Re}_k = 1.0 \]
\[ k = 48 \mu m \quad \text{Re}_k = 7.0 \]

Background
\[ k = 0.2 \mu m \quad \text{Re}_k < 0.01 \]
SUMMARY

• Revisit $\alpha = -4^\circ \Rightarrow$ naturally occurring stationary crossflow
• Use small (6 $\mu$m) roughness to fix wavelength but avoid excessive initial amplitudes
• Multiple wavelengths from spectral decomposition
• Early Nonlinear Mode Interaction
• Data Base for Nonlinear PSE
• Look at all of the disturbance motion over $2 \lambda_z$ (24mm)

• Look at spectra - spanwise scans over $20 \lambda_z$ (240 mm)

• Look at all of disturbance motion over $20 \lambda_z$ (240 mm)
  
  » (10,000 pts at each x / c ) — Typical approach —
Stationary Crossflow Waves

NLFl2-0415 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
Stationary Crossflow Profiles

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

6 µm roughness at $x/c = 0.023$, 12 mm spacing
Stationary Crossflow Disturbance Profiles

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
RMS Crossflow Disturbance Velocity

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
RMS Crossflow Disturbance Velocity

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$
6 $\mu$m roughness at $x/c = 0.023$, 12 mm spacing
N-factor

\[ \sigma : \text{spatial growth rate} \]

\[ \frac{A}{A_0} : \text{amplitude ratio between two spatial positions} \]

\[ \frac{A}{A_0} = \exp \int_{x_0}^{x} \sigma dx = e^N \]

\[ N = \int_{x_0}^{x} \sigma dx = 2 \int_{R_0}^{R} \sigma dR = \ln \frac{A}{A_0} \]
Stationary Crossflow Amplitude and \( N \)-Factor

Amplitude computed from mode-shape profiles
NLF(2)-0415 at \( \alpha = -4^\circ \), \( Re_c = 2.4 \times 10^6 \)

6 \( \mu \)m roughness at \( x/c = 0.023 \), 12 mm spacing
NONLINEAR PARABOLIZED STABILITY EQUATIONS

- Reduced set of Navier-Stokes equations
- Low CPU and memory
- Perturb around structural vibration computations
- Physics of free-shear-layer behavior
  - high Reynolds numbers
  - nonlinear and nonparallel
  - effects of shear-layer curvature
- Obtain spatial and temporal scales
- Optimize frequencies
PARABOLIZED STABILITY EQUATIONS

- Nonlinear Details: Haynes and Reed (2000)
- Disturbance solved separately from basic state
- Numerical accuracy of basic state must be very high
  - Stability very sensitive to small departures of mean flow from its “exact” shape
  - Also can depend on small variations of boundary conditions for the basic state
- PSE have become popular
  - Include nonparallel and nonlinear effects
  - Relatively small resource requirements as compared with DNS
RMS Crossflow Disturbance Velocity

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
Computation includes curvature
Growth of C-F vortex: Theory and experiment for 12 mm wave.

Haynes & Reed
Crossflow Prediction

![Graph of Crossflow Prediction](Image)
Total Streamwise Velocity Contours

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.40$

48 $\mu$m roughness at $x/c = 0.023$, 12 mm spacing
Computations include curvature
NPSE SUMMARY

- Advances will come from computations and experiments working hand-in-hand on same geometries.
- Demonstrated successful precedent.
- Experiments and computations efficiently sorted out effects of curvature and nonlinearities on breakdown and together elucidated promising approach to transition delay in these flows.
NPSE SUMMARY CONT’D

• For high-speed, flight-Reynolds-number, and complex-geometry flows, collaboration even more critical:
• Because of sensitivity of transition to initial and operating conditions, computations provide validation of experiments and vice versa.
NPSE SUMMARY CONT’D

• Detailed measurements are more difficult and costly in these flow. Here, computations can guide experiments as to what effects are important and what needs to be measured.

• When computations work with experiments, explanation of mechanisms at work is easier to determine and simpler models thus developed. Each provides different level of detail and perspective.
Stationary Crossflow Amplitude and $N$-Factor

Spectral amplitude at maximum of mode shape
NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$

18 $\mu$m roughness at $x/c = 0.023$, 12 mm spacing
Measured and Theoretical Relative $N$-Factor

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

18 $\mu$m roughness at $x/c = 0.023$, 12 mm spacing
All computations include curvature
Measured and Theoretical Relative $N$-Factor

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

48 $\mu$m roughness at $x/c = 0.023$, 12 mm spacing
All computations include curvature
RMS Crossflow Disturbance Velocity

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

Roughness at $x/c = 0.023$, 12 mm spacing
Stationary Crossflow Amplitude

Computed from maximum of mode-shape profiles
NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$
Roughness at $x/c = 0.023$, 12 mm spacing
• 12 mm FORCING SHOWS $\lambda = 12, 6, 4$

• TRY 36 mm FORCING

• THEORY

$\lambda = 12$ most amplified

$\lambda = 36$ only weakly amplified
Naphthalene Flow Visualization

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.2 \times 10^6$

6 $\mu$m roughness at $x/c = 0.023$, 36 mm spacing
Naphthalene Flow Visualization

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 3.2 \times 10^6$

6 $\mu$m roughness at $x/c = 0.023$, 36 mm spacing
UNIFORMLY DISTRIBUTED ROUGHNESS

- AT MOST UNSTABLE WAVELENGTH – 12 mm
  - DESTABILIZATION
  - POOR EXCITATION OF OTHER MODES

- AT LONG WAVELENGTH DISTRIBUTION – 36 mm
  - TRANSITION MOVES FORWARD
  - RICH SPECTRUM OF OTHER MODES
Linear Theory $N$-Factors for Stationary Crossflow Disturbances

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$
Computations include curvature

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\end{figure}
## 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>18</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>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>
Linear Theory $N$-Factors for Stationary Crossflow Disturbances

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

Computations include curvature
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 $x/c = 0.023$, 8 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 $x/c = 0.023$, 8 mm spacing
Stationary Crossflow Waves

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.40$

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

NLFF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.50$

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

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

$6 \, \mu m$ roughness at $x/c = 0.023, \, 8 \, \text{mm spacing}$
Stationary Crossflow Power Spectrum

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.30$, $y = 0.85$ mm

6 $\mu$m roughness at $x/c = 0.023$, 8 mm spacing
Stationary Crossflow Power Spectrum

NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$, $x/c = 0.60$, $y = 1.0$ mm
$6 \mu$m roughness at $x/c = 0.023$, 8 mm spacing
Stationary Crossflow Amplitude and $N$-Factor

Total and spectral amplitude at maximum of mode shape
NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$

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

![Graph showing the relationship between N Factor and Stationary Crossflow Amplitude vs x/c. The graph includes multiple lines representing different conditions and parameters.](image-url)
Theory and experiment for 8 mm wave
Naphthalene flow visualization for $Re_c = 2.4 \times 10^6$ and no artificial roughness.
Naphthalene flow visualization for $Re_c = 2.4 \times 10^6$, [6][8] roughness
Stationary Crossflow Amplitude and $N$-Factor

Total and spectral amplitude at maximum of mode shape
NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$
48 $\mu$m roughness at $x/c = 0.023$, 8 mm spacing
Stationary Crossflow Amplitude and $N$-Factor

Total and spectral amplitude at maximum of mode shape
NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$

48 $\mu$m roughness at $x/c = 0.023$, 12 mm spacing
Stationary Crossflow Amplitude

Computed from maximum of mode-shape profiles
NLF(2)-0415 at $\alpha = -4^\circ$, $Re_c = 2.4 \times 10^6$
Roughness at $x/c = 0.023$, 8 mm spacing
At a chord Reynolds number of 2.4 million

<table>
<thead>
<tr>
<th>Roughness height $\mu$m</th>
<th>Spacing mm</th>
<th>Transition x/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 random</td>
<td>65%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>12 (most unstable)</td>
<td>45%</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>&gt;80%</td>
</tr>
<tr>
<td>48</td>
<td>8</td>
<td>&gt;70%</td>
</tr>
</tbody>
</table>
MICROBUBBLES

• THIN METAL FILM ATTACHED OVER PRESSURIZED CAVITIES PROVIDES VARIABLE ROUGHNESS. USE DISTRIBUTED ARRAYS OF MICROBUBBLE ELEMENTS NEAR THE LEADING EDGE IN ORDER TO VARY THE ROUGHNESS HEIGHT AND SPACING.

• ROUGHNESS HEIGHTS VARY FROM 0 TO 50 µm ON ROWS OF ACTUATORS.

• SYSTEM IS MECHANICALLY ROBUST.

• WORKING SURFACE CAN BE MACHINED TO ANY CONTOUR.
Flow Direction

Roughness Element

Tape

Pressurized Cavity

Insert

Leading Edge
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 ≈ 6 MICRON AND RANDOM

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

USE DYNAMIC ACTUATION TO CANCEL TRAVELING WAVES
Transition Location with Roughness

- Try control strategy on painted surface
- Paint the film covering the actuator holes
- Background roughness peak-to-peak is now 11-34 microns
### Transition Location with Roughness

<table>
<thead>
<tr>
<th>Roughness height</th>
<th>Spacing</th>
<th>Transition location</th>
</tr>
</thead>
<tbody>
<tr>
<td>µm</td>
<td>random</td>
<td>65%</td>
</tr>
<tr>
<td>0.2</td>
<td>random</td>
<td>65%</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>45%</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>&gt;80%</td>
</tr>
<tr>
<td>48</td>
<td>8</td>
<td>&gt;70%</td>
</tr>
<tr>
<td>painted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>8</td>
<td>together</td>
</tr>
<tr>
<td>11-34</td>
<td>random</td>
<td>&gt;70%</td>
</tr>
<tr>
<td>airplane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>random</td>
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</tbody>
</table>
OBJECTIVES

• Subcritical Wavelength Forcing Delays Transition

• Determine the Role of Random Background Roughness on the Transition Control Scheme

• Determine the Effects of Freestream Turbulence on the Transition Control Scheme
CONCLUSIONS I

SECONDARY INSTABILITY OF DISTORTED MEAN FLOW

• Saturation amplitude independent of initial conditions

• Linear stability of distorted mean flow is enough

• Leads to transition prediction scheme
CONCLUSIONS II

DISTRIBUTED ROUGHNESS AT SUBCRITICAL WAVELENGTHS

1. INHIBIT GROWTH OF MOST UNSTABLE WAVELENGTHS

2. EVENTUALLY DECAY AND DO NOT LEAD TO TRANSITION

Laminarization is possible with roughness
CONCLUSIONS II-B

- IN LOW DISTURBANCE ENVIRONMENTS AND HIGH REYNOLDS NUMBERS
  - TRAVELLING WAVES HIGHLY AMPLIFIED
  - CONTROL WITH DISTRIBUTED ROUGHNESS LIMITS WAVELENGTHS OF TRAVELLING WAVES
  - GROWTH OF TRAVELLING WAVES MUCH LOWER FOR SUBCRITICAL WAVELENGTHS
CONCLUSIONS III

• Significant Random Background Roughness Does Not Influence Transition Control Scheme

• Increased Freestream Turbulence (0.3%) Enhances Travelling Waves and Moves Transition Forward
CONCLUSIONS IV

ISOLATED ROUGHNESS

- Affects transition like random background roughness
- Exhibits “wave-packet” behavior and excites multiple modes
- Spanwise scale of roughness is critical $D>0.1\lambda_{CF}$
- Location near attachment line is critical $x/c$
- Affects “Stability for $Re_k$ up to $Re_k\approx 150$
  - then transition at roughness-Braslov & Doenhoff criterion
CONCLUSIONS V

UNIFORMLY DISTRIBUTED ROUGHNESS

• At most unstable wavelength - 12 mm
  – minimum destabilization
  – poor excitation of other modes

• At long wavelength distribution - 36 mm
  – transition moves forward
  – rich spectrum of other modes

• Has huge affect on disturbance boundary layer
  
  \[6 \mu m \rightarrow 18 \mu m, \quad \Delta \sim 15\%, \quad x/c \sim 0.45\]
  
  \[6 \mu m \rightarrow 48 \mu m, \quad \Delta \sim 30\%,\]

  \[\delta^* \sim 280 \mu m \quad \text{at roughness}\]
ATTACHMENT-LINE
CONTAMINATION
UNSTEADY WIND TUNNEL
ATTACHMENT LINE STABILITY

However, for swept wings, disturbances produced in corners may propagate along the leading edge and affect stability elsewhere—leading-edge contamination.

Gregory, et al. 1955
Pffeninger, 1977

Poll placed trip wires normal to attachment line, diameter D

Defined length scale

\[ \eta = \left[ \frac{v}{(dU_e/dx)_{x=0}} \right]^{1/2} \]

\[ D/\eta > 1.55 \quad \text{Turbulent bursts at wire} \]
\[ 0.8 < D/\eta < 1.55 \quad \text{Wire feeds disturbances along LE until turbulent bursts occur} \]
\[ D/\eta < 0.8 \quad \text{Nothing happens} \]
Leading Edge Contamination

Pfenninger and later, Poll, defined an attachment-line Reynolds number, $R_{AL}$, based on edge velocity, $V_e$, parallel to the leading edge and using the length scale $\eta$. The critical Reynolds number is $\text{Re}_{cr} = 250$, below which, propagation of disturbances along attachment line does not occur.

$$R_{AL} = 0.404\left[Q_o r \sin^2 \Lambda/ (1 + \varepsilon) \nu \cos \Lambda\right]^{1/2}$$
ATTACHMENT LINE
REYNOLDS NUMBER

\[ R_{\theta AL} = 0.404 \left( \frac{Q_\infty r \sin^2 \Lambda}{(1+\varepsilon) \nu \cos \Lambda} \right)^{1/2} \]

- \( r \): nose radius
- \( \varepsilon \): thickness ratio of equivalent ellipse

\( R_{\theta AL} < 100 \) To avoid contamination