LAMINAR FLOW CONTROL AT HIGH SPEEDS:

A work in progress

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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
- NASA-LaRC (1988-1996), AFOSR (1996-2002), DARPA (2001-2003), NASA-Dryden (2002-2003) are co-principal employers

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**

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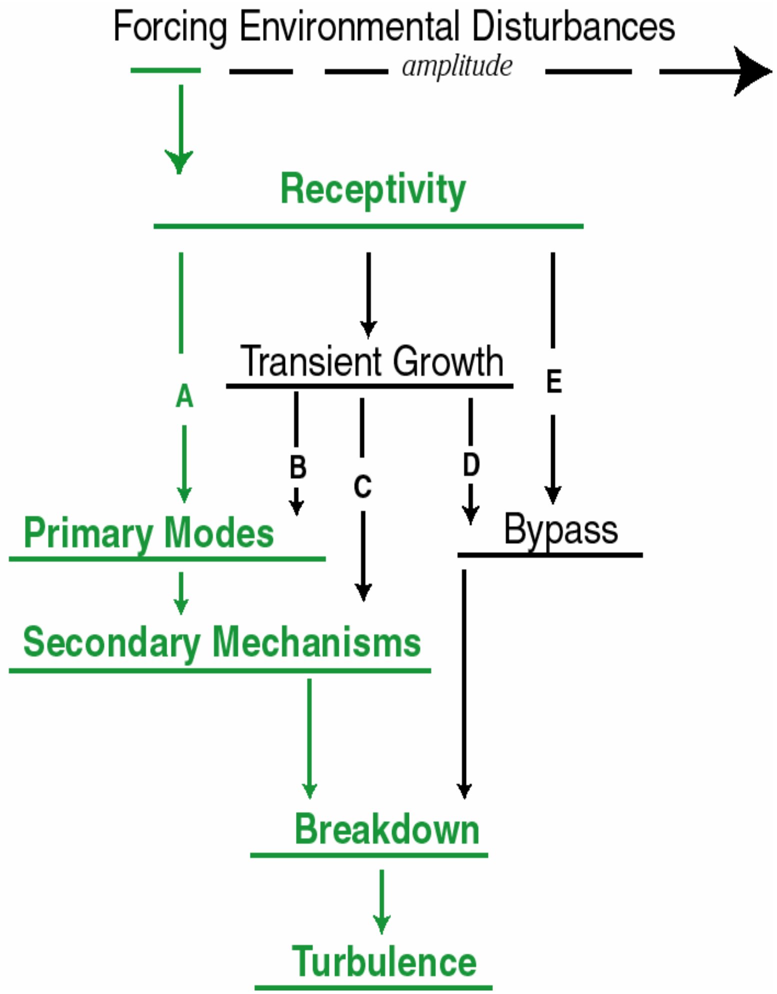
PATHS TO TURBULENCE (Reshotko et al.)



Forcing Environmental Disturbances

amplitude

Receptivity

A

Transient Growth

B

C

D

E

Primary Modes

Bypass

Secondary Mechanisms

Breakdown

Turbulence

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Control

- “NATURAL”
  - MODIFICATIONS OF Cp
- “PASSIVE”
  - FIXED WALL SUCTION
  - MEANFLOW MODIFIERS
  - WALL TEMPERATURE DISTRIBUTION
- “ACTIVE”
  - FEEDBACK SYSTEMS WITH DYNAMIC RESPONSE

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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**

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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

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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
- Details in Saric et al 2003 Ann. Rev.

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**
  - **Richard Tracy, Ilan Kroo, et al. (AIAA Reno 2002)**
  - **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**

Mean Flow Modifications
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- 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

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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)

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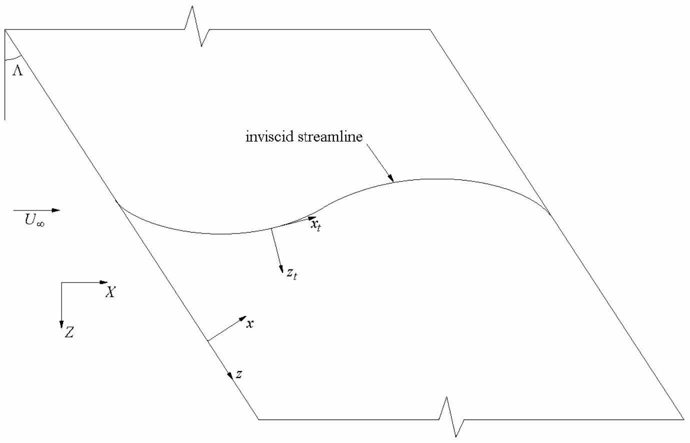
Crossflow Transition

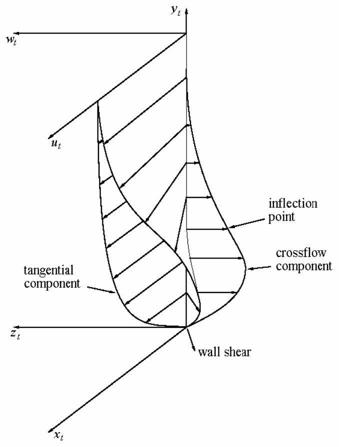
ASU Unsteady Wind Tunnel

Streamlines Over a Swept Wing



ASU Unsteady Wind Tunnel

Swept-Wing Boundary Layer



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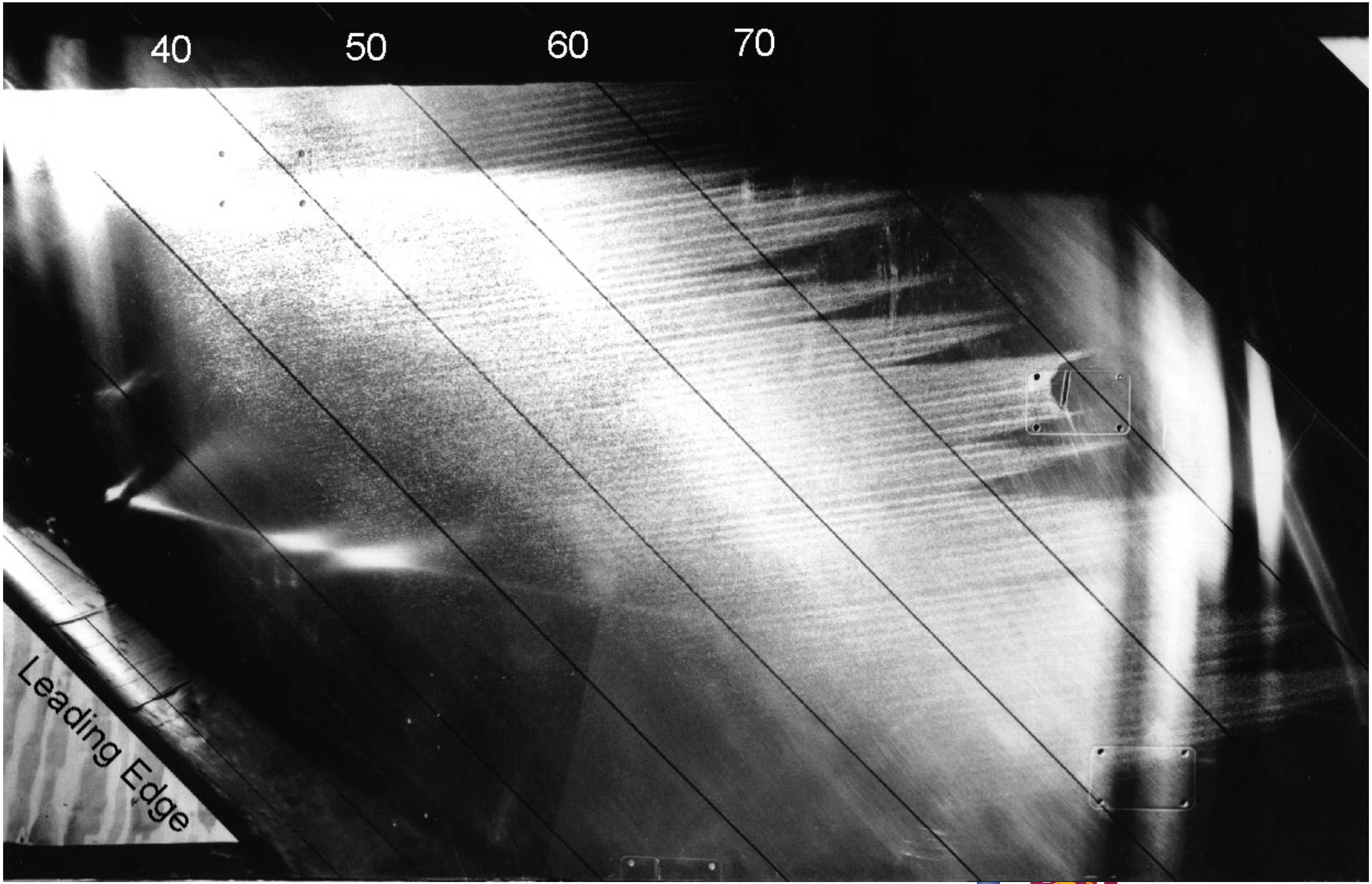
Crossflow Instability

- 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.

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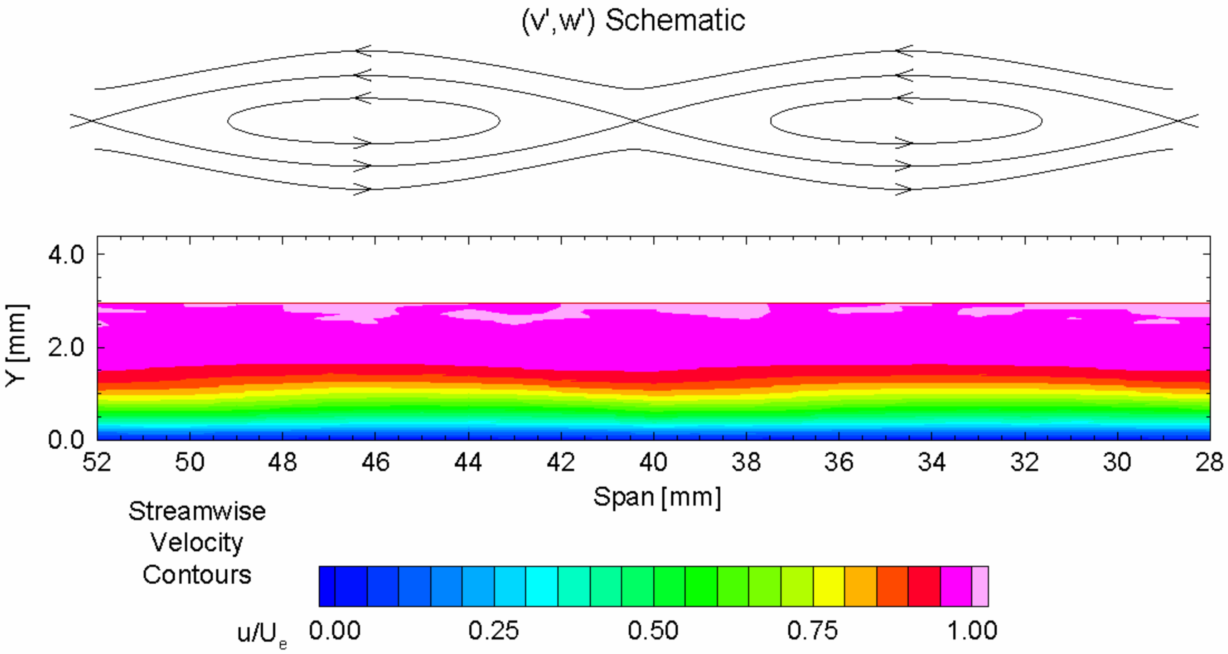
High-Speed LFC - APS Nov03

Stationary Crossflow Waves

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

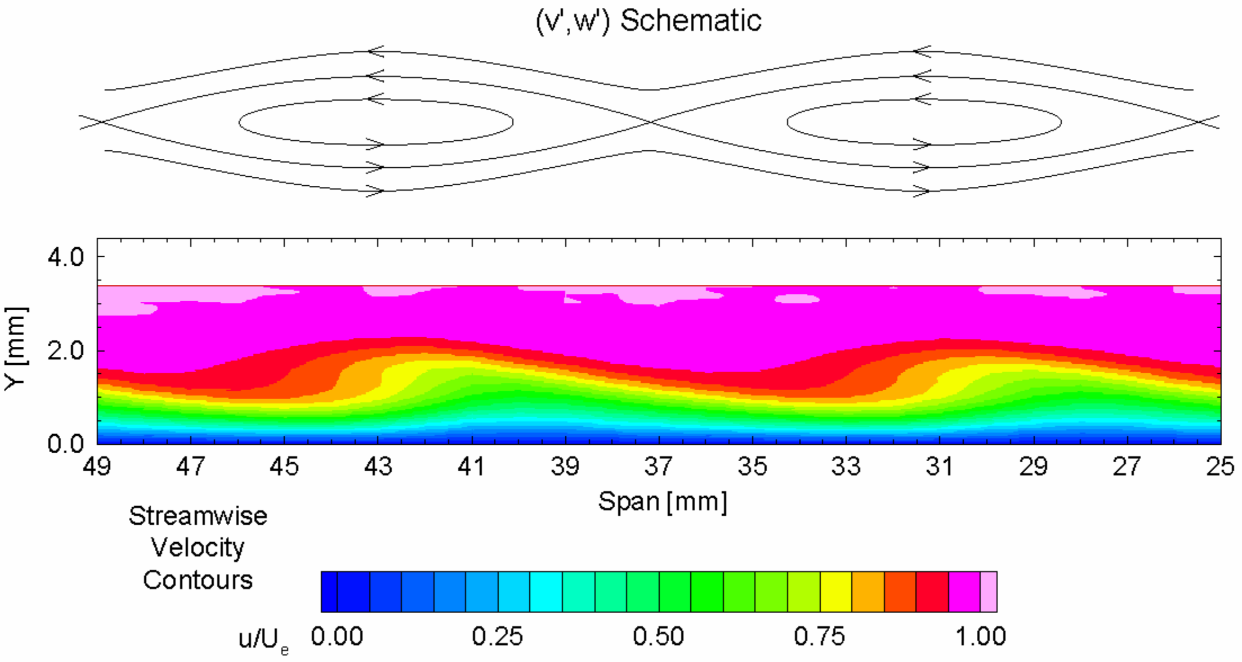
6 μm roughness at $x/c = 0.023$, 12 mm spacing



Stationary Crossflow Waves

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

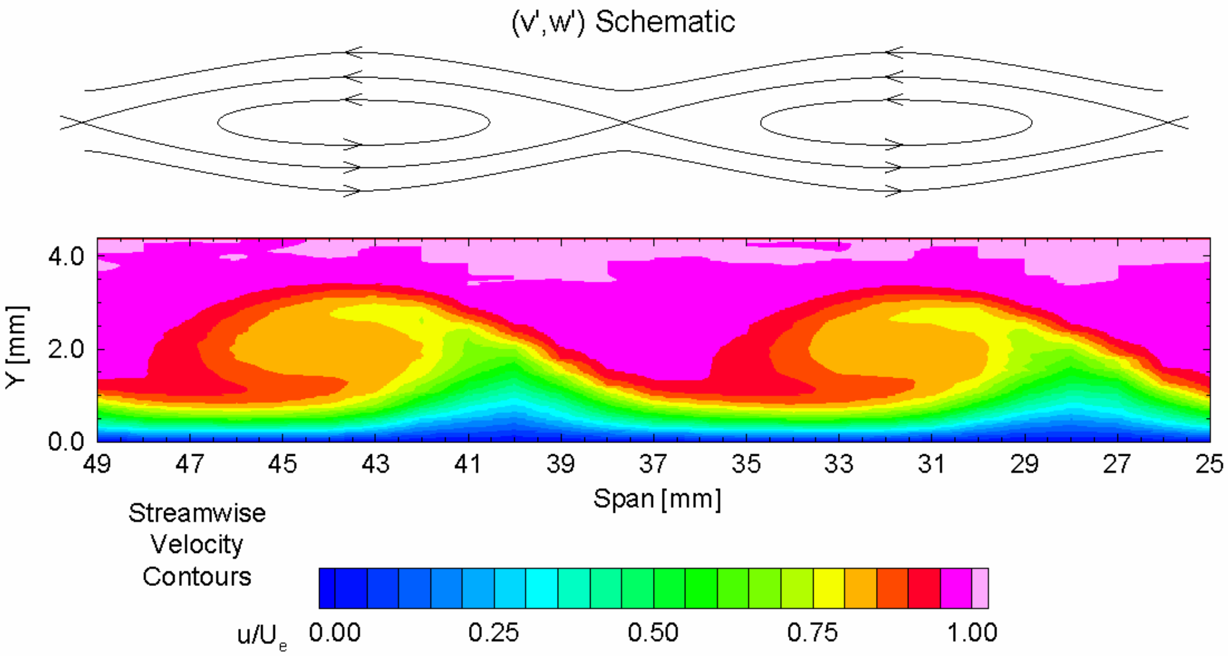
6 μm roughness at $x/c = 0.023$, 12 mm spacing



Stationary Crossflow Waves

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

6 μm roughness at $x/c = 0.023$, 12 mm spacing



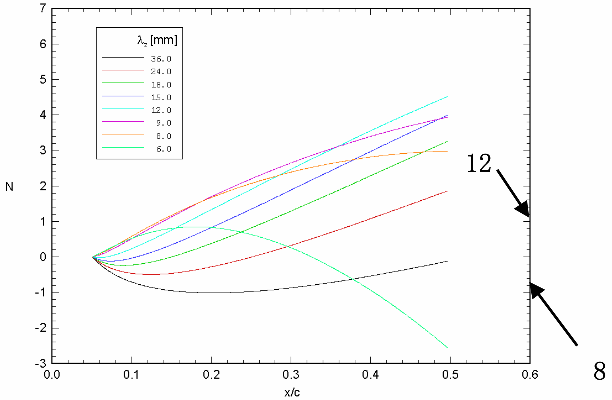
Artificial Roughness at LE of Polished Surface

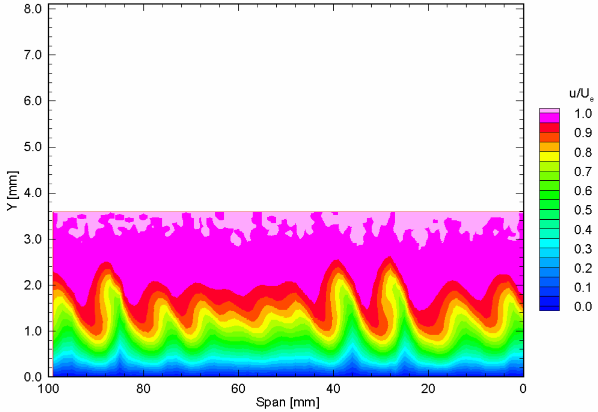
ASU Unsteady Wind Tunnel

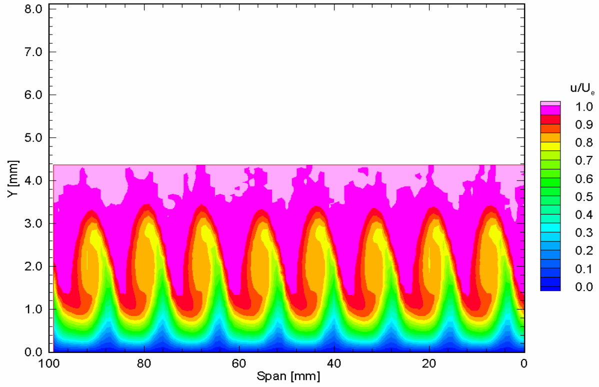
Linear Theory N-Factors for
Stationary Crossflow Disturbances

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

Computations include curvature







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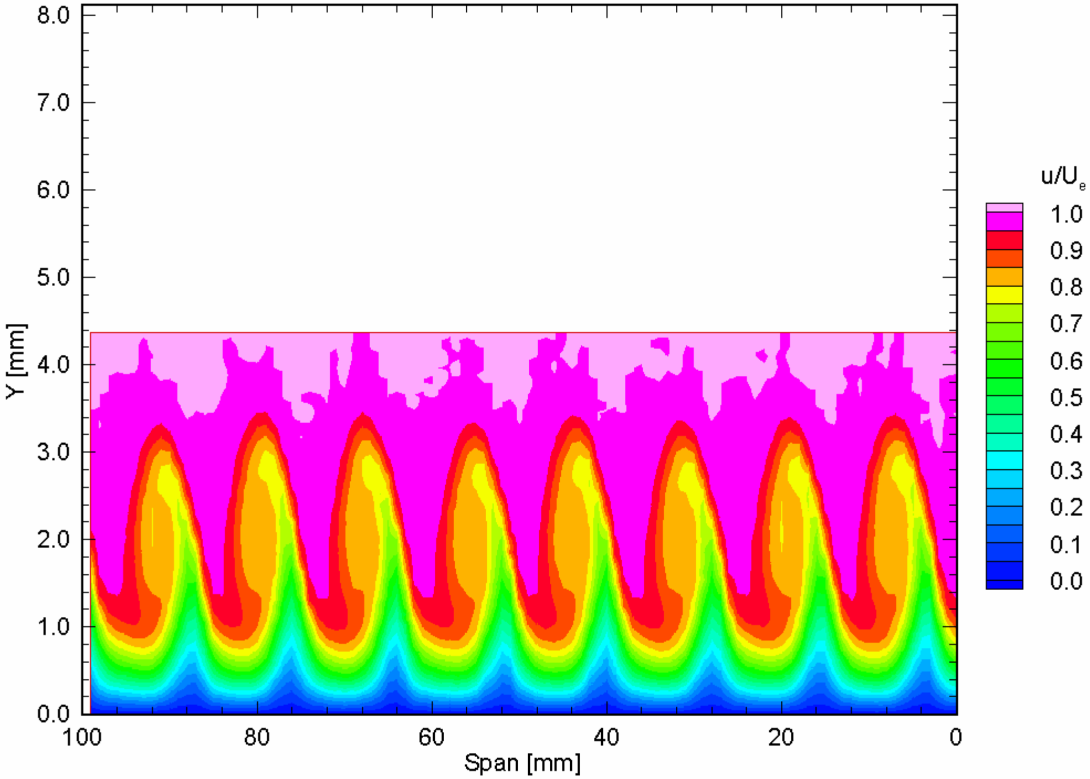
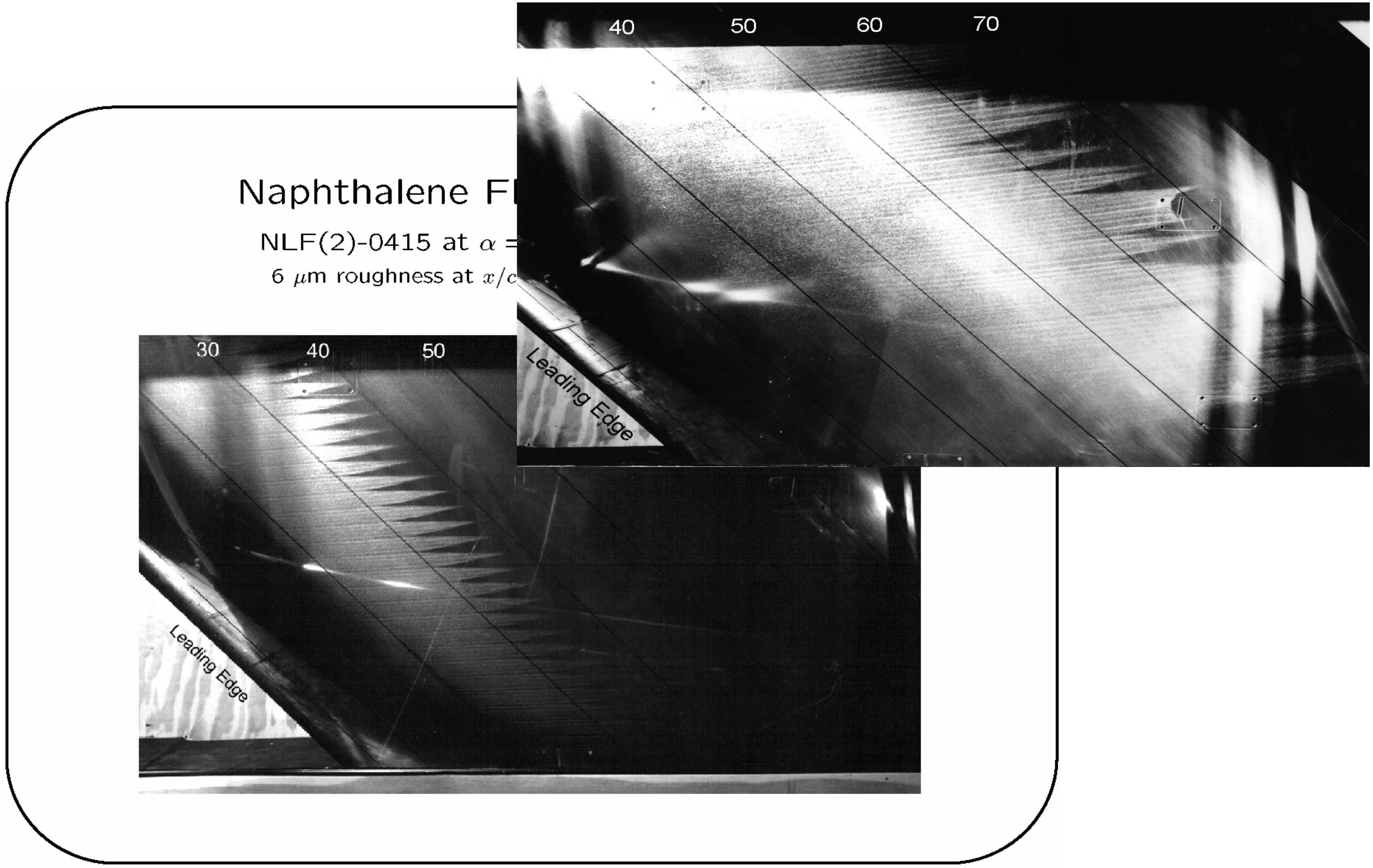
Stationary Crossflow Waves

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

6 μm roughness at $x/c = 0.023$, 12 mm spacing





Naphthalene Fl

NLF(2)-0415 at α =

6 μm roughness at x/c

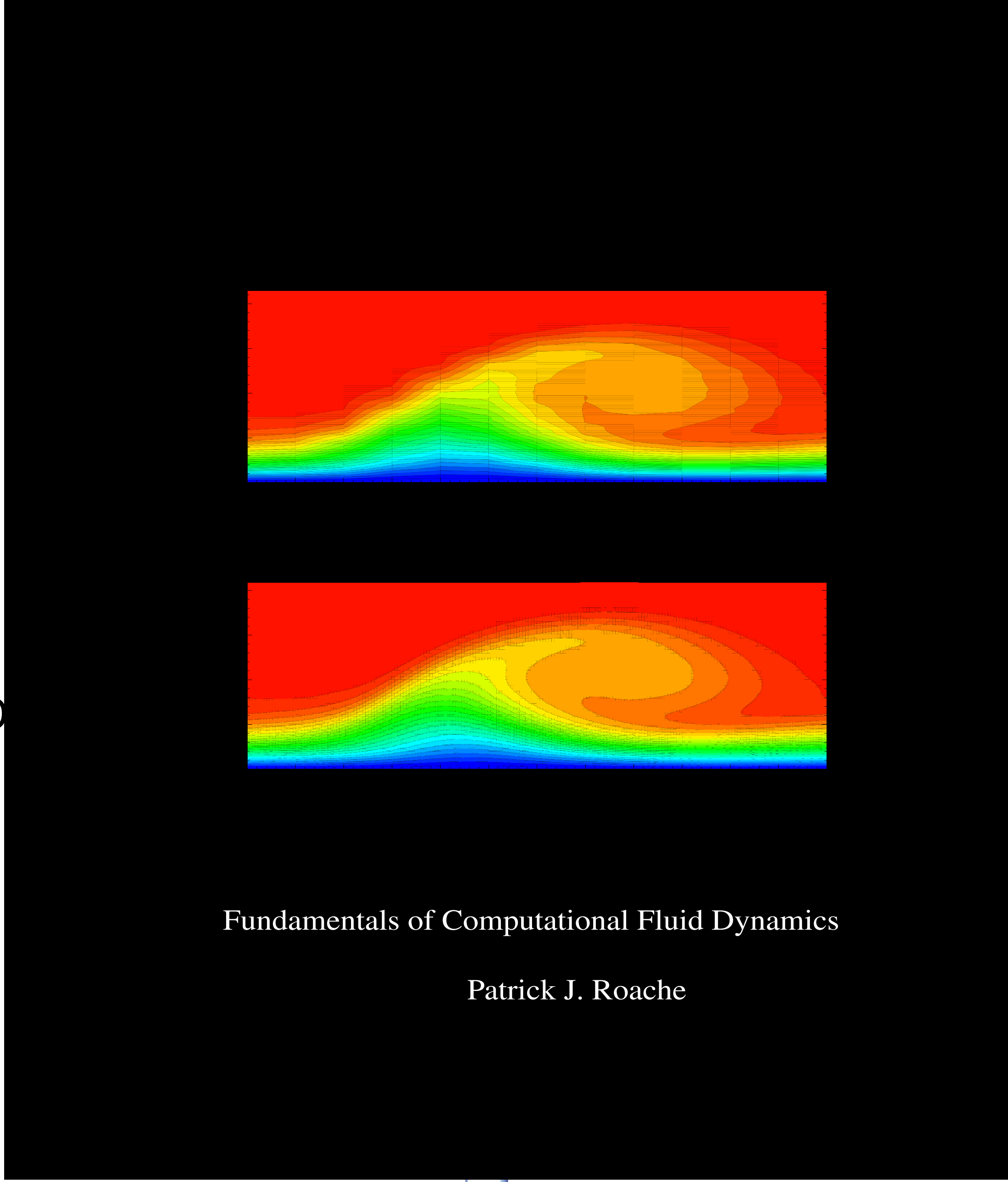
Naphthalene flow visualization for $Re_c = 2.4 \times 10^6$ and no artificial roughness.

Parabolized

Review: Herbert (1997)

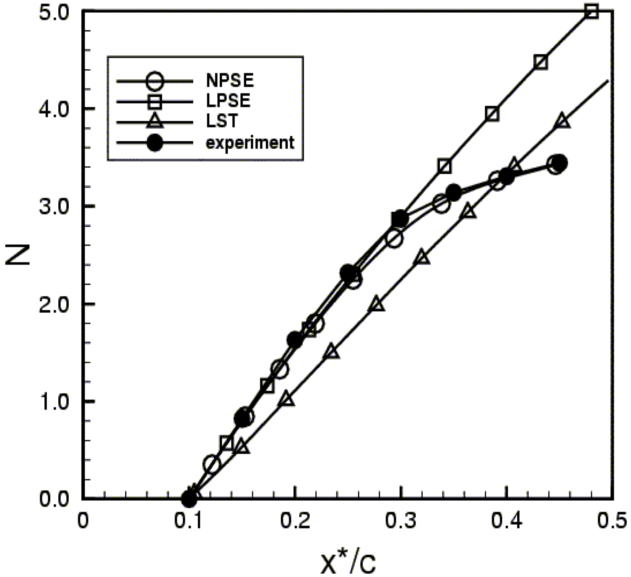
PSE popular

- Include nonparallel and nonlinear effects
- Successfully model variety of convective flows
- Relatively small resource requirements compared with D



Fundamentals of Computational Fluid Dynamics

Patrick J. Roache



MOST UNSTABLE MODE AT λ = 12 mm

EXCITATION	RESPONSE	COMMENT
• 12 mm	12 mm	No 24 mm
	6	No 36
	4	
• 36 mm	36 mm	Transition moves forward slightly
	18, 12, 9	
	7.2, 6, 5.1	
	4.5, 4	
• 18 mm	18 mm	No 12 mm
	9	No 36 mm
	6	
	4.5	
• 8 mm	8 mm	No 12 mm
	4	

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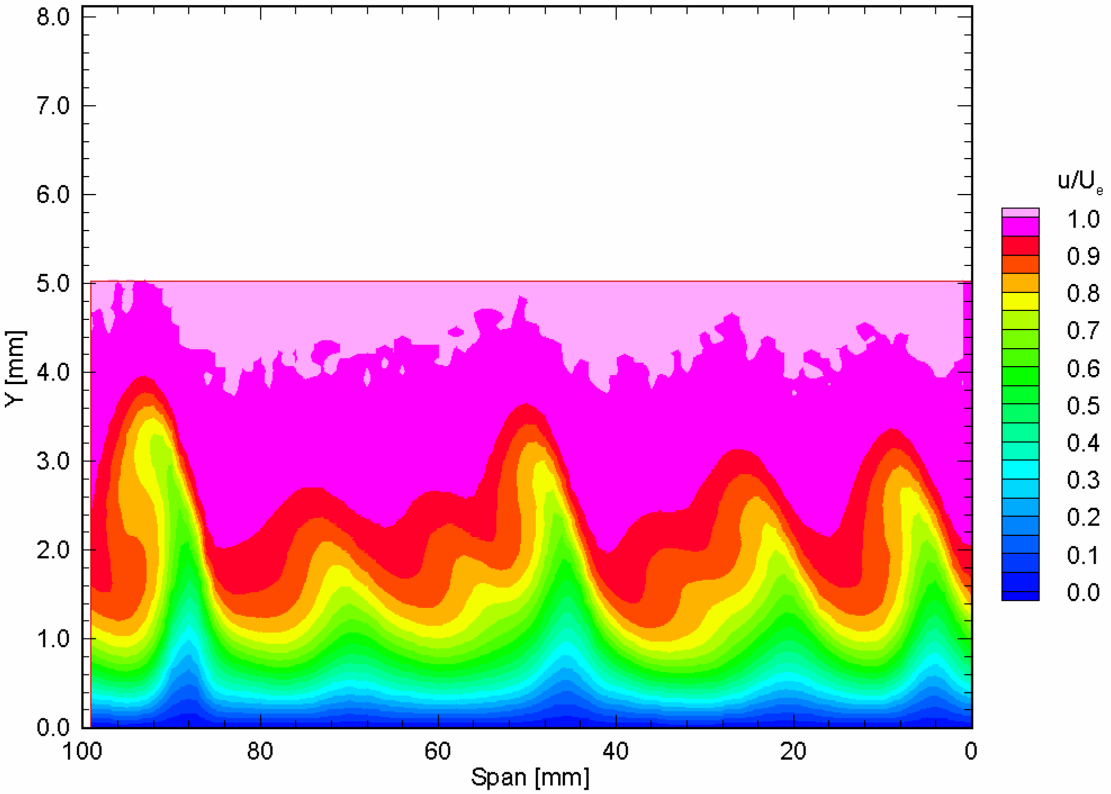
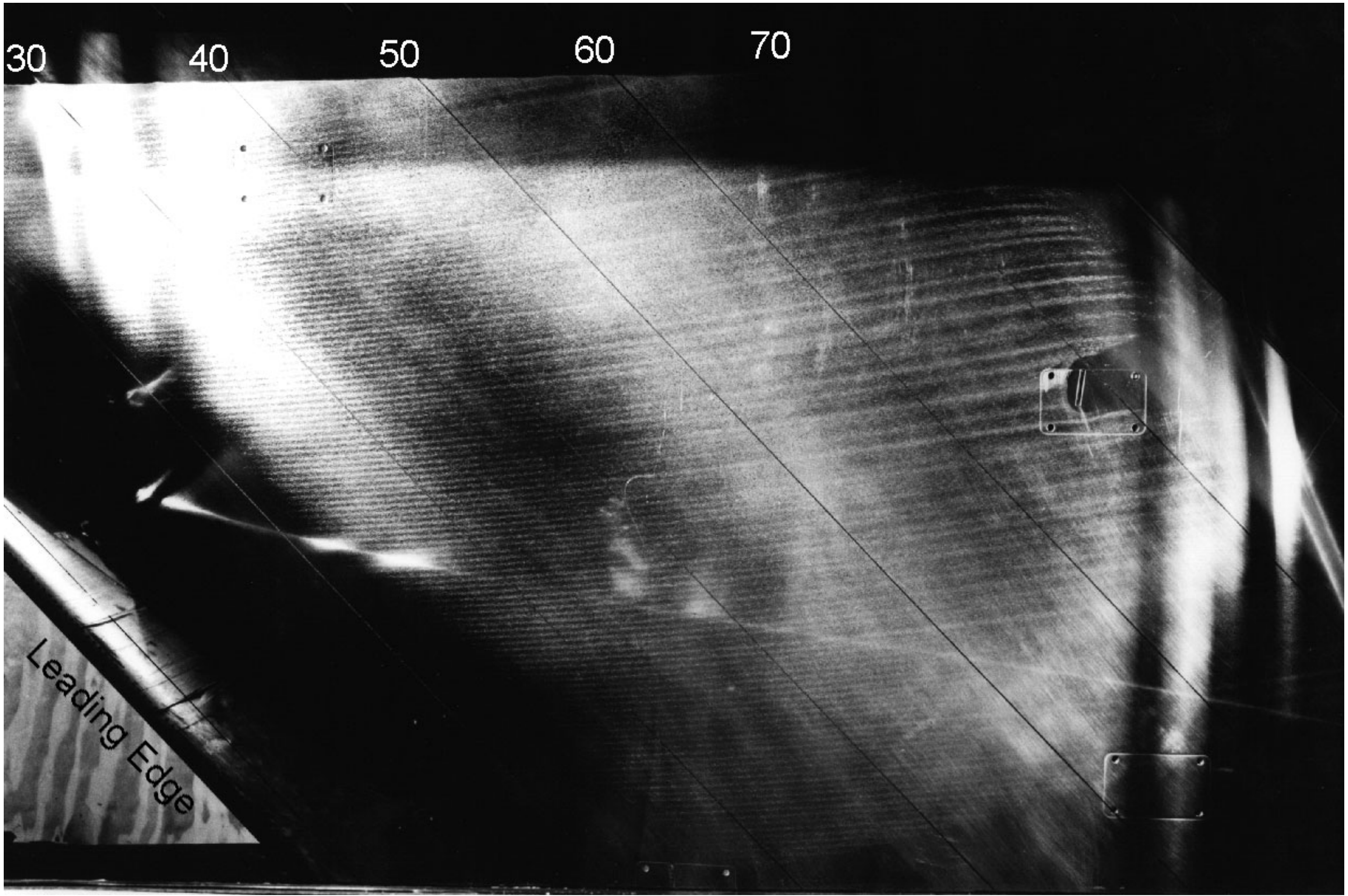
Stationary Crossflow Waves

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

6 μm roughness at $x/c = 0.023$, 8 mm spacing





Control
roughness

High-Speed LFC - APS Nov03

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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 ≈ 2 MICRON AND RANDOM

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

CONFIRMED WITH NPSE OF HAYNES & REED (2000) AND DNS OF WASSERMANN & KLOKER (2002)

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

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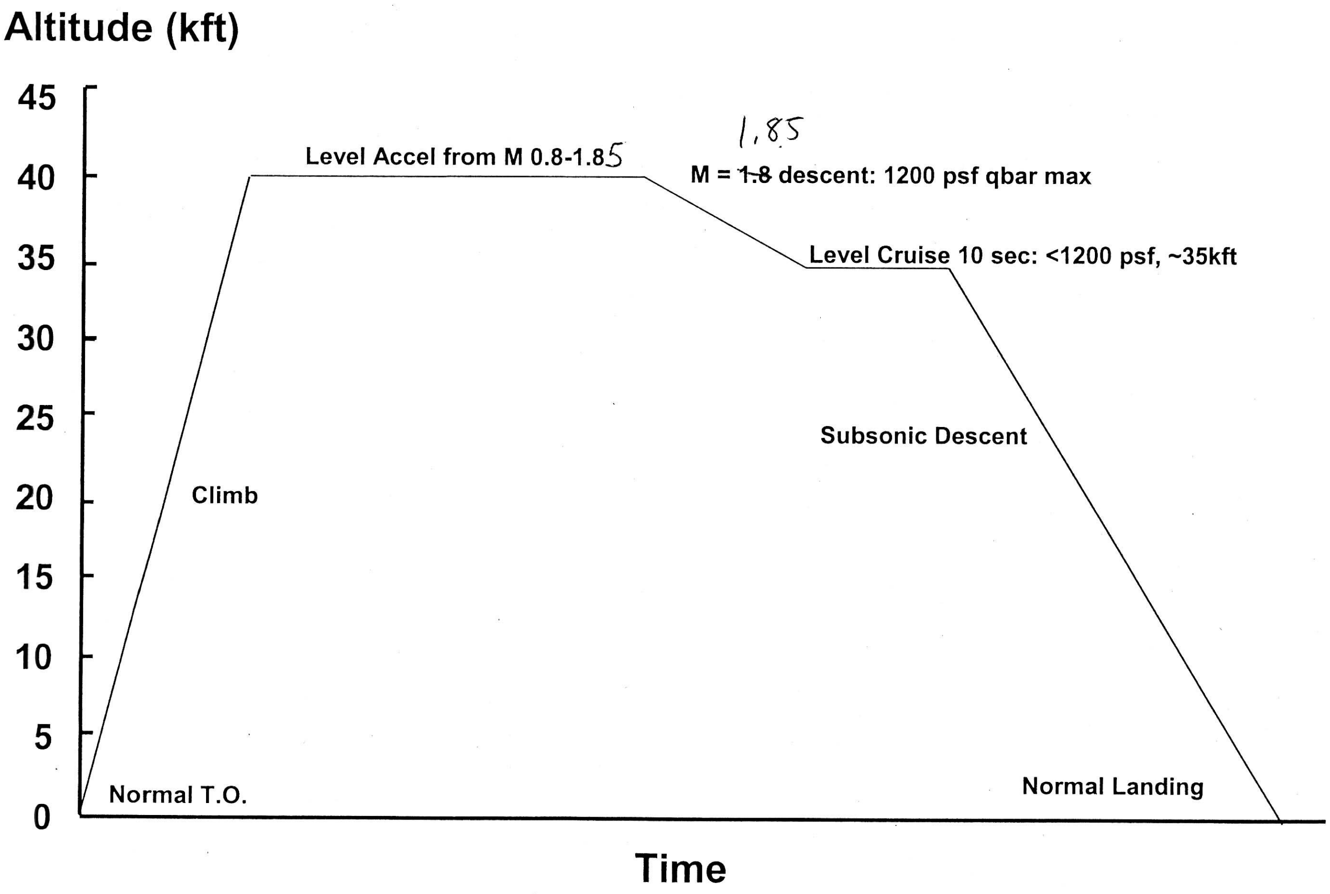
Flight Trajectory



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NASA-DFRC F-15B

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ASU side of test article, $\Lambda = 30°$

6μm roughness spaced at 4 mm, 2%C

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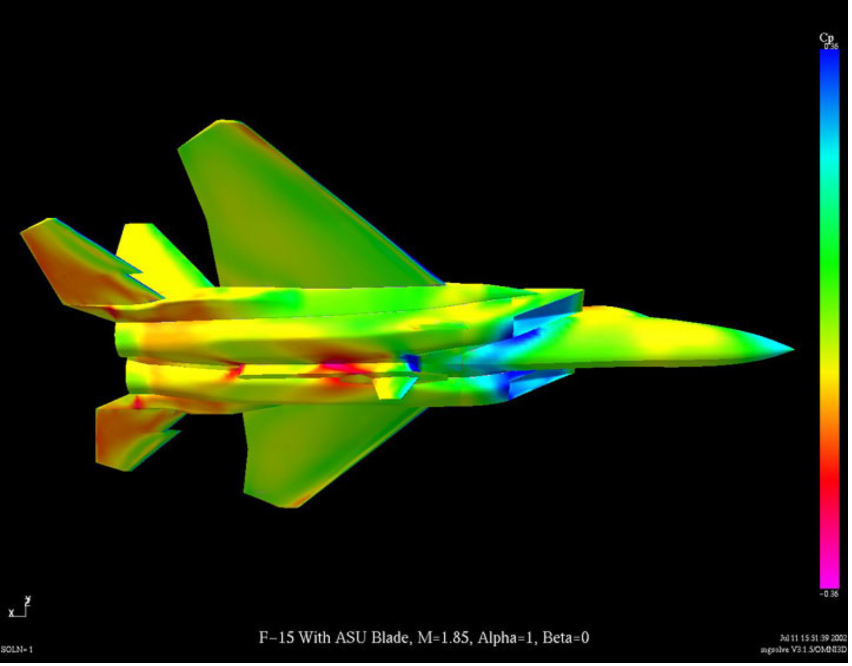
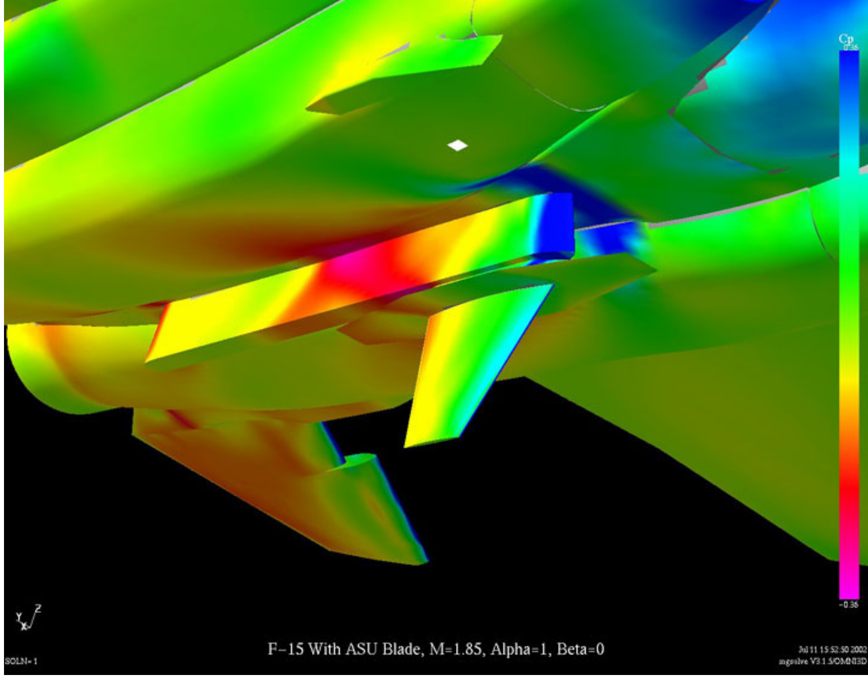
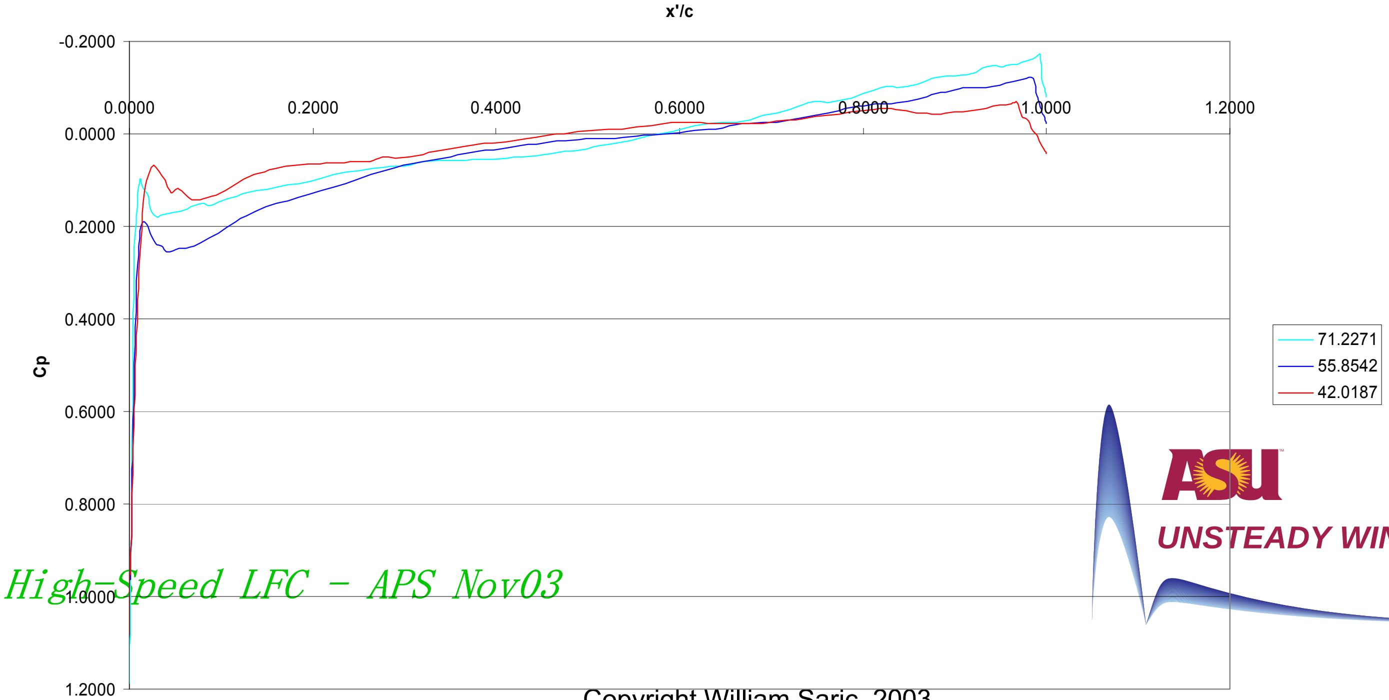




ASU Side



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F-15B Flight Tests Cont.

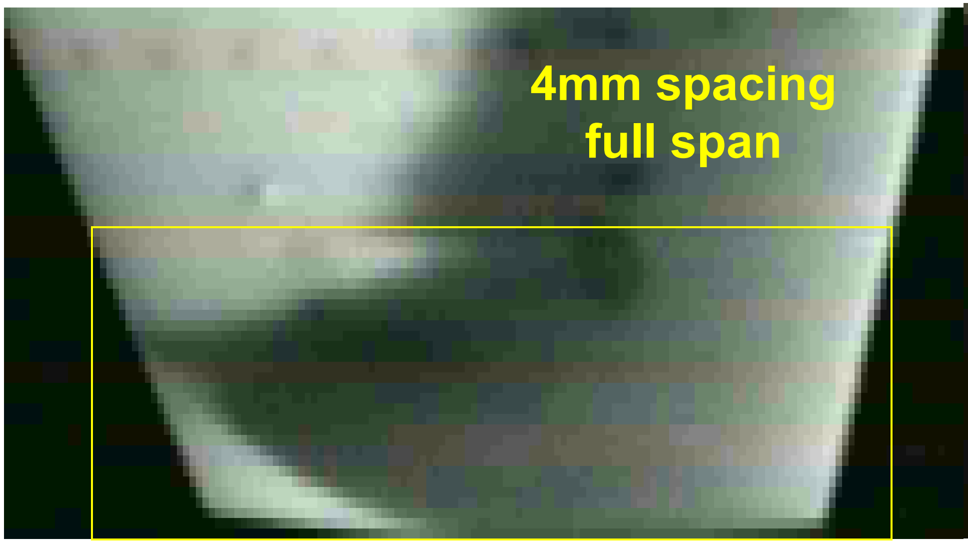
- *F-15B limited to Mach 1.5 by Eglin AFB on 14 May 02*
- *Delays pushed testing back*
  - *e.g. 3 aborts during March 03*
  - *Low priority and equipment problems*
- *Flight tests resumed July 03*
  - *1. Improved landing technique minimized oil splashes*
  - *2. Pressure tests conducted first (4 channels at a time)*
  - *3. Distributed roughness with periodic roughness elements*
  - *4. Obtain data at M = 1.85 and M = 0.9*

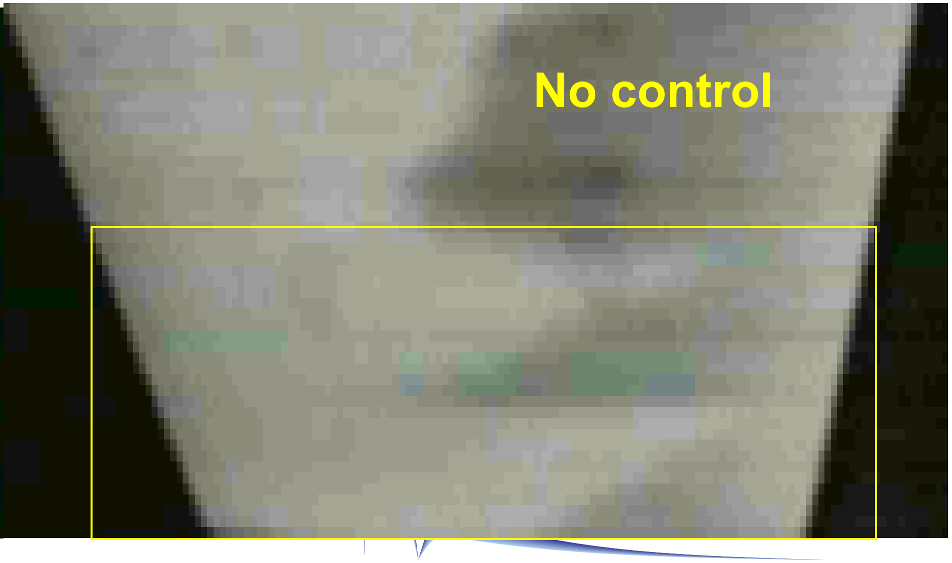
M =1.85 @ 40k ft altitude

Overshoot on *Cp* nullifies control inboard

Rec approx 9 million

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

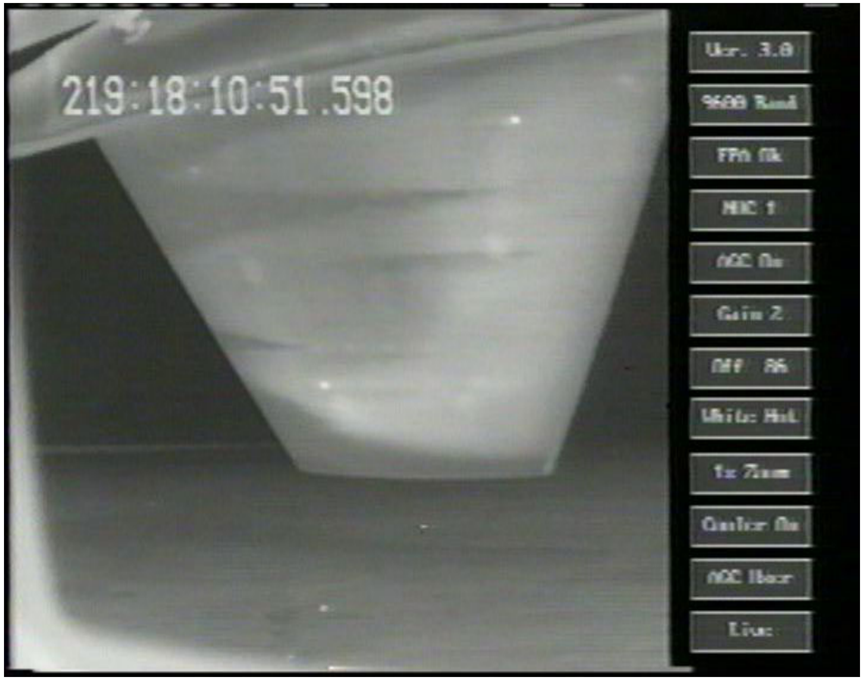




F-15 Subsonic IRT Results

- $M = 0.9$
- $\Lambda = 30°$
- $H = 36,000$ ft
- $Re' = 2.5 \times 10^6$/ft
- mid-span chord = 2.5 ft
- $Re_c = 6.25 \times 10^6$

- Baseline, 80% chord, pressure minimum
- With 4 mm control, full chord laminar flow



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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***

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NASA Langley UPWT

Symmetric, 3.5% thick

LE sweep 68°, TE sweep 66.5°

Unit Re = 7 million/foot, q = 1600 psf, M = 2.16

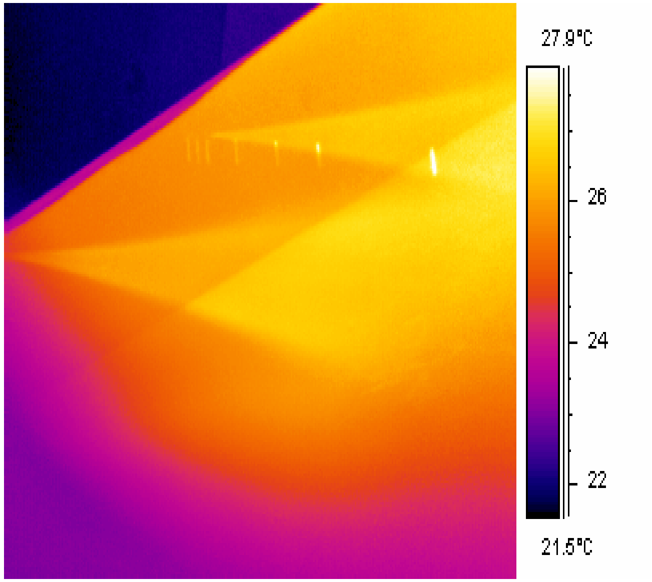
Streamwise chord = 7 feet, Span = 4 feet

Normal-to-LE radius = 1/16 inches

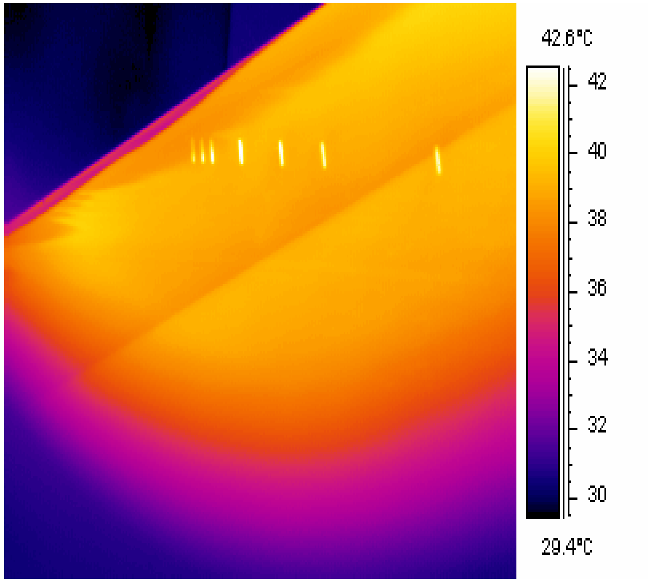
Attachment line $Re_\theta \approx 100$

LaRC Experiments

- Leading-edge radius was twice as large as originally designed.
- Attachment line contamination at $Re' = 2.7\text{x}10^{6}/\text{ft}$
- Corresponds to $Re_{\theta AL} = 100$
- Model Machined with new leading edge and improved dp/dx



1M/ft



2.7 M/ft

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

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