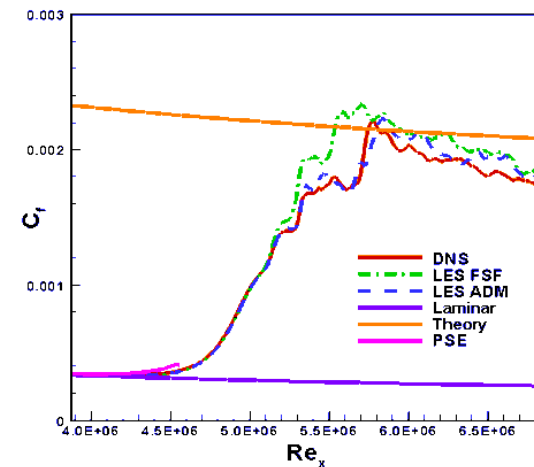
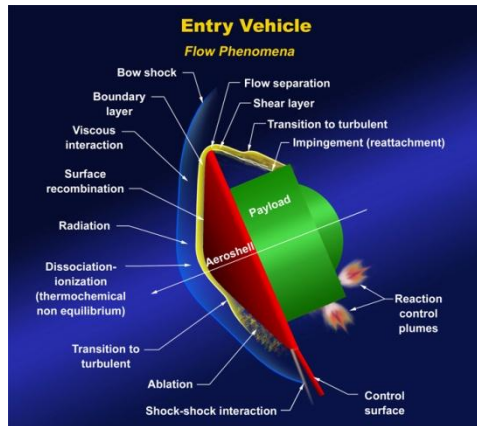


Laminar-Turbulent Transition in Three-Dimensional Boundary Layers

Mujeeb.R. Malik
NASA Langley Research Center
Hampton, VA

University of Western Ontario
London, ON
March 25, 2010



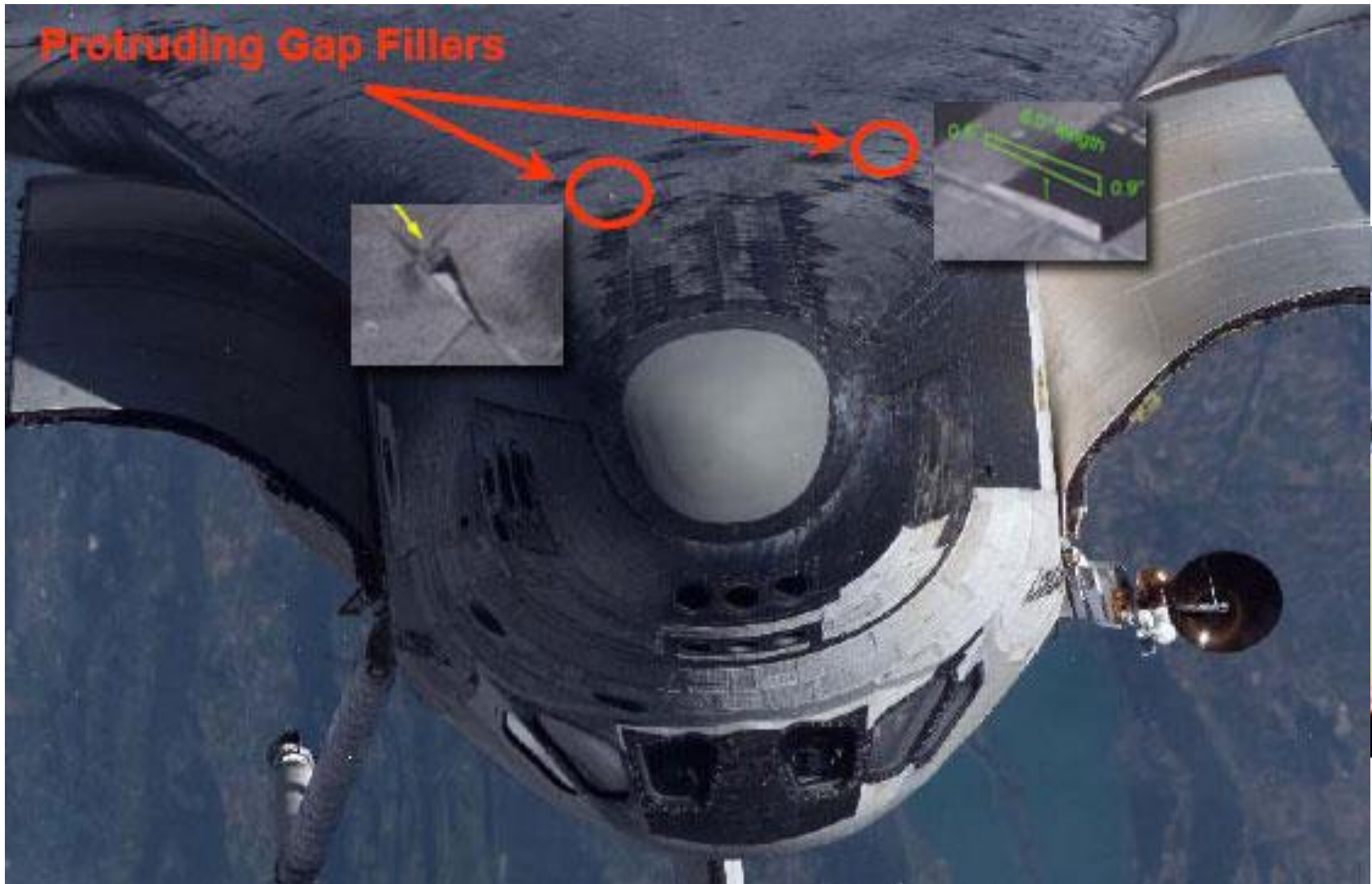
Outline

- **Significance of Boundary-Layer Transition (BLT)**
- **Mechanisms for BLT**
- **A Supersonic BLT Flight Experiment**
- **Roughness-induced transition**
- **Challenges in BLT**
- **Concluding Remarks**



Significance of Boundary Layer Transition - 1

- BLT prediction important aspect of hypersonic vehicle design

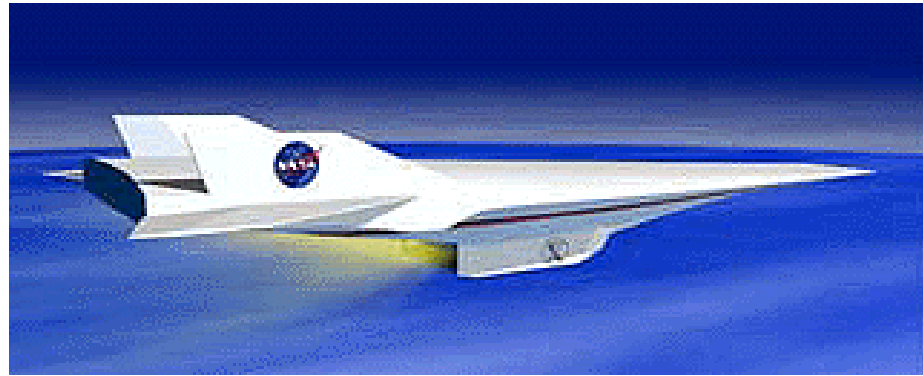


Significance of Boundary Layer Transition - 2



- **BLT prediction critical for scramjet cruise vehicles**

- BL tripped to assure turbulent flow entering engine inlet, to prevent engine “unstart”

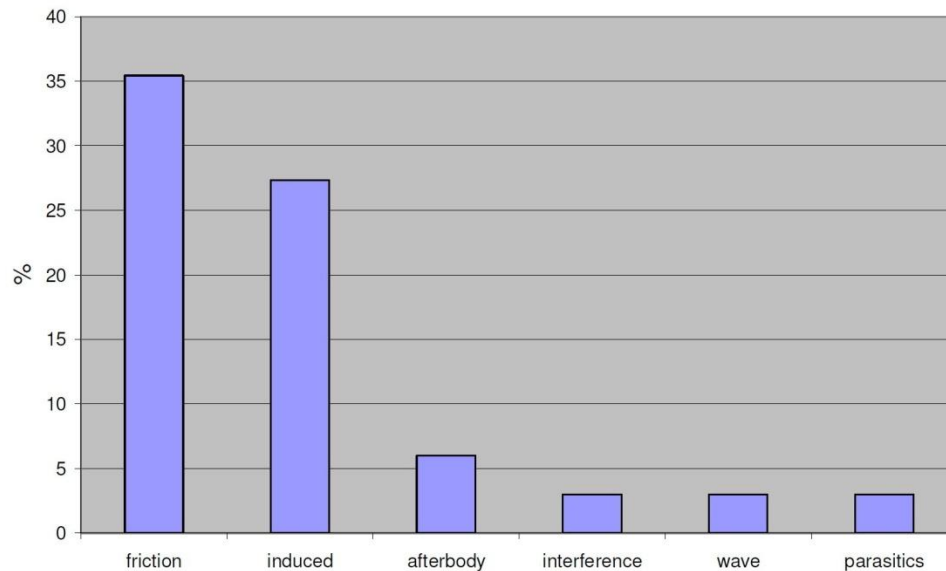


X-43

Significance of Boundary Layer Transition - 3



Delaying BLT - an Environmental ('Green') Issue



Drag Breakdown Typical of a Modern (Turbulent) Swept-winged Aircraft (Marec, 2000)



Laminarizing (LFC) Boundary-Layer Provides Substantial Reduction in Aircraft Drag

Significance of Boundary Layer Transition - 4



Delaying BLT - an Enabling Technology

Boeing systems study (NASA CR-181917; July 1990)

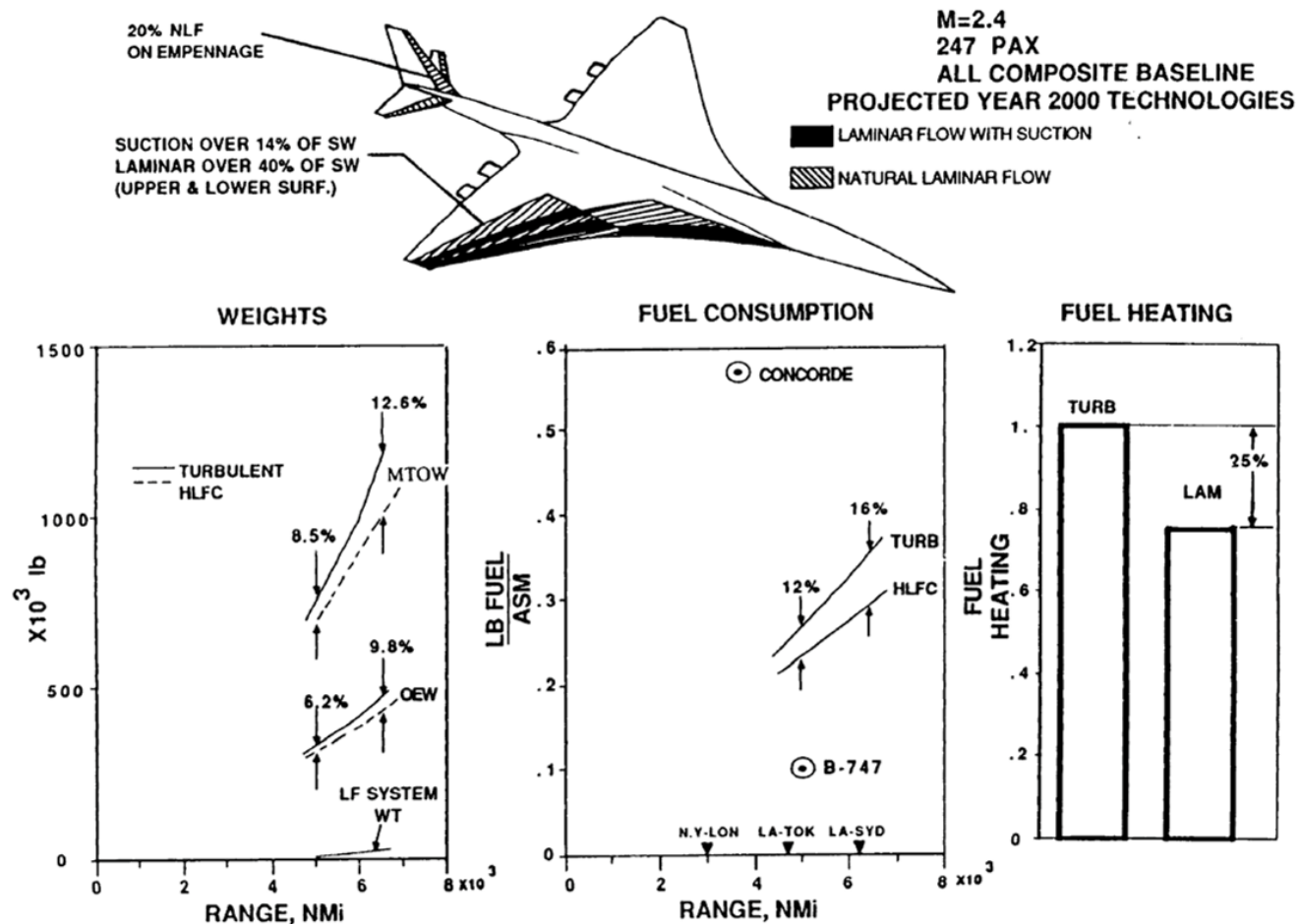


Figure 2 Net Performance Benefits of HLFC (Scheme 2) Implementation

Mechanisms for Boundary Layer Transition

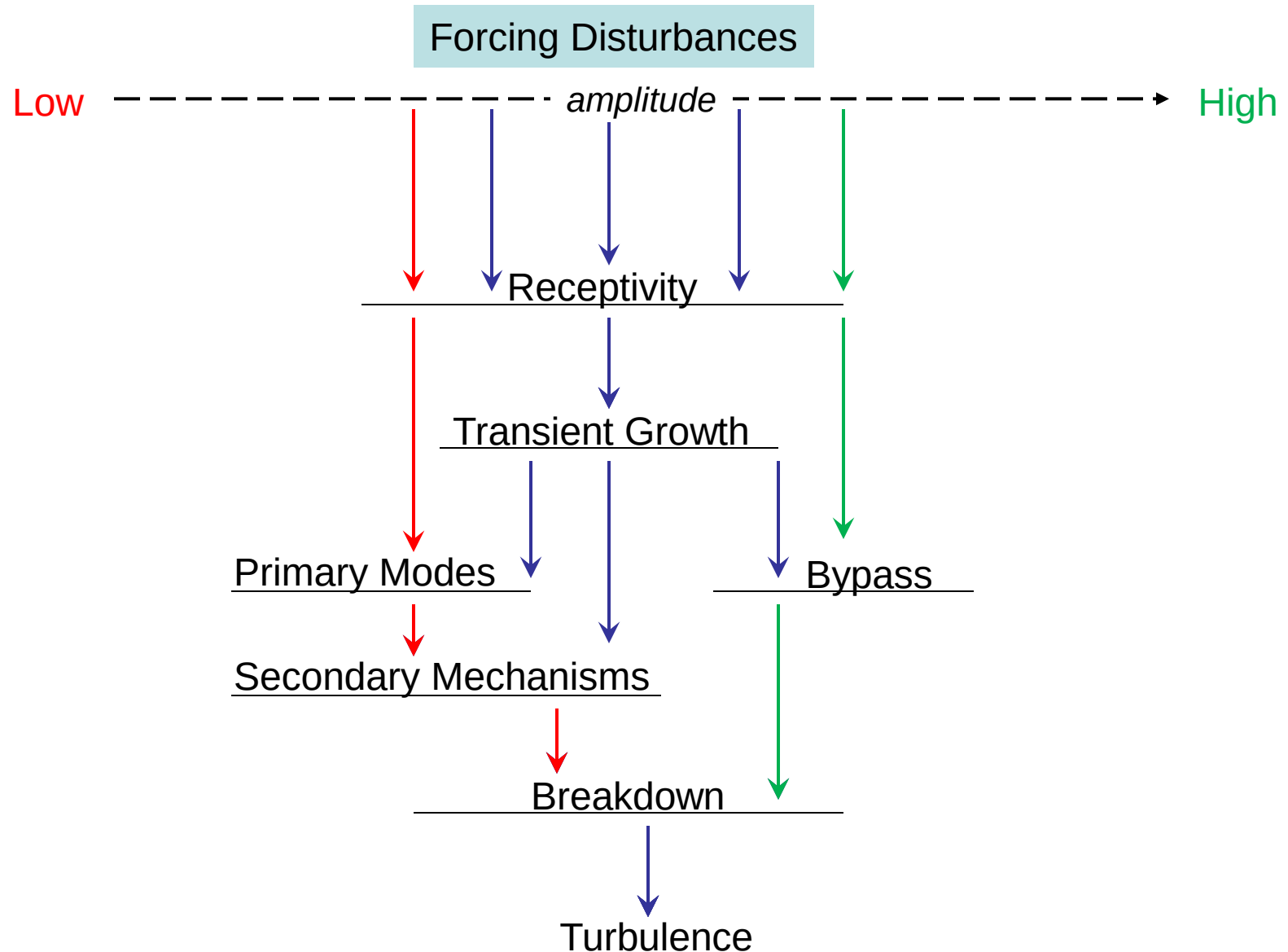


- **Transition an initial boundary-value problem**
 - Spatio-temporal details of the forcing are generally unknown

Paths to Turbulence

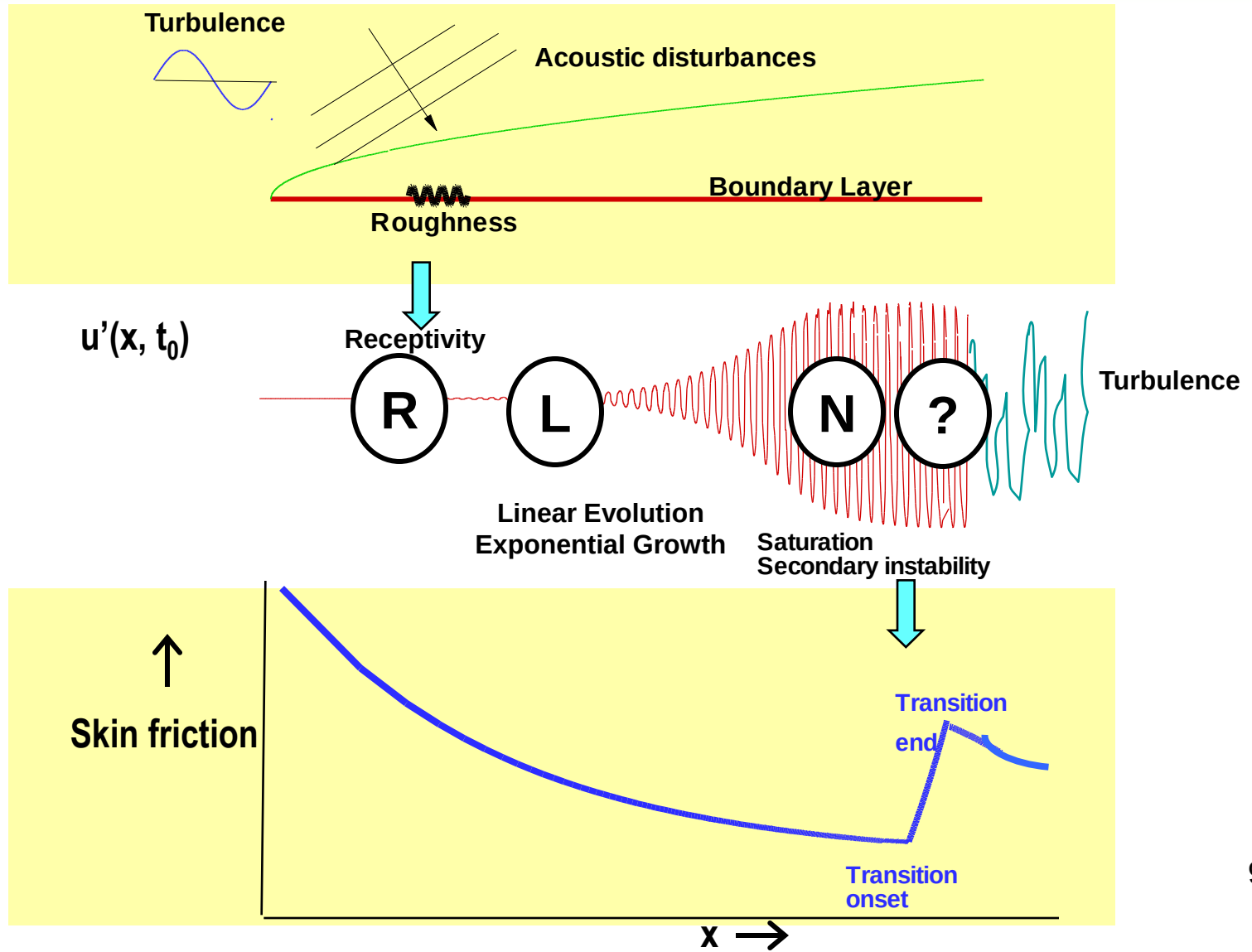


(After Reshotko et al., 2001)



Transition in Low Disturbance Environment

- Transition = forced response of deterministic, large dimensional system to stochastic input



Numerical Methods for Boundary Layer Transition



▪ Eigen-Value Method

- BL stability based on linear theory: determines linear growth of disturbances

▪ Parabolized Stability Equations

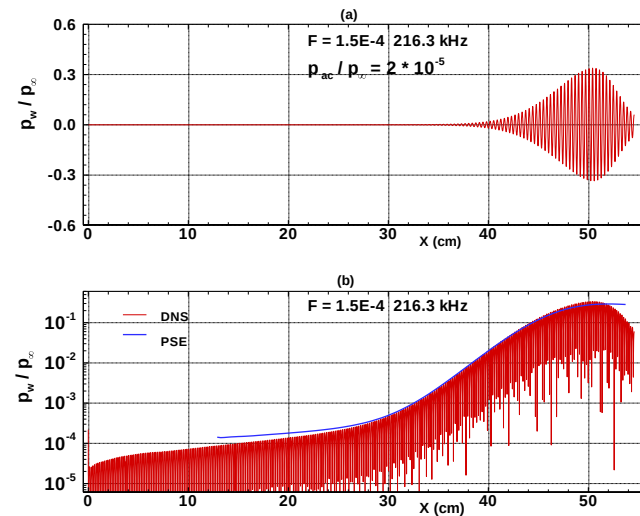
- Efficient technique for linear and nonlinear disturbance growth computations

▪ Direct Numerical Simulation (DNS)

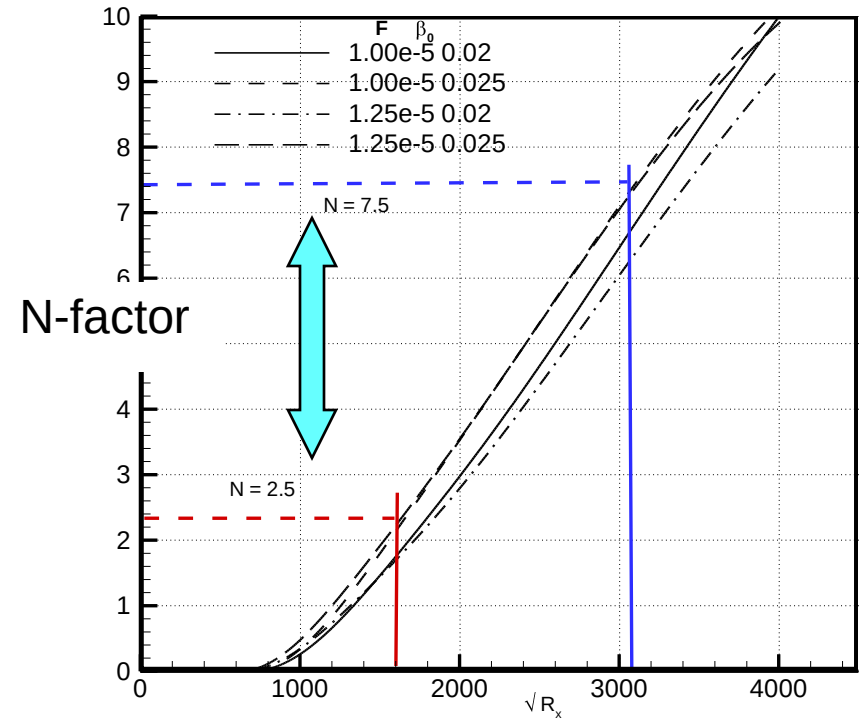
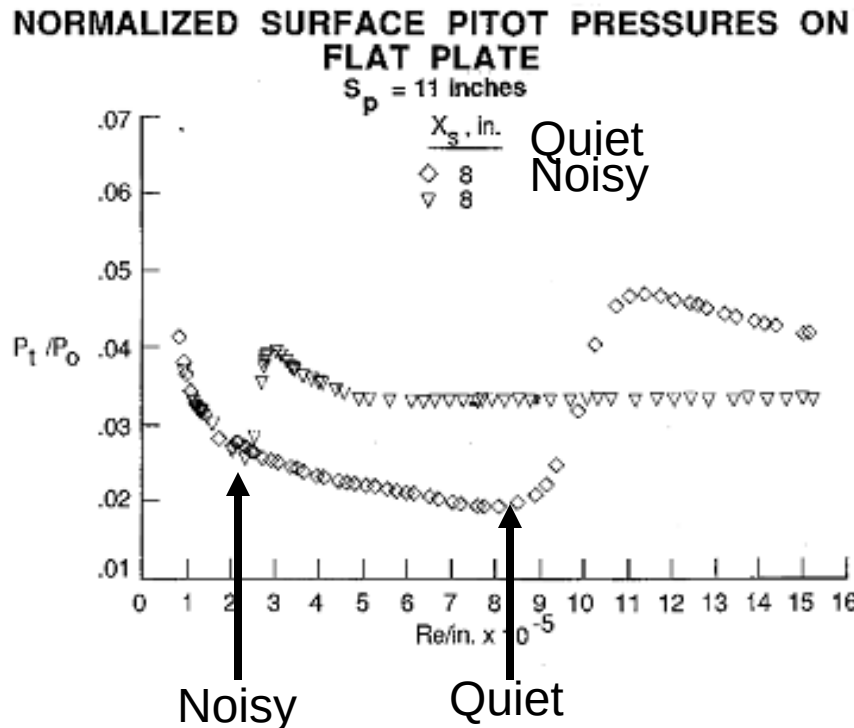
- Solve full Navier-Stokes Equations
- Compute receptivity, linear and nonlinear growth and eventual breakdown

▪ N Factor Method

- Integral Growth Factor based on
linear growth only: $A(x)/A(0) = \text{Exp}[N]$



Transition on a Flat Plate at $M=3.5$ at Quiet and Noisy Conditions



- Large disparity in transition onset depending on disturbance environment $\Rightarrow$ large variations in correlating N-factor, i.e., corresponding uncertainty in transition prediction
- This can be narrowed by including receptivity to free-stream disturbances

Boundary-Layer Instability Modes - 1

Boundary-Layer Amplifies these Modes, resulting in Transition on Smooth Surfaces

- **Tollmien-Schlichting (TS) Mode**
 - viscous mode
 - responsible for transition in 2D BL
 - stabilized by $-dp/dx$, suction and cooling
- **First Mode**
 - most amplified when oblique
 - responsible for transition in 2D supersonic flows
 - stabilized by wall cooling
 - controlled by suction, $-dp/dx$, curvature

Boundary-Layer Instability Modes - 2

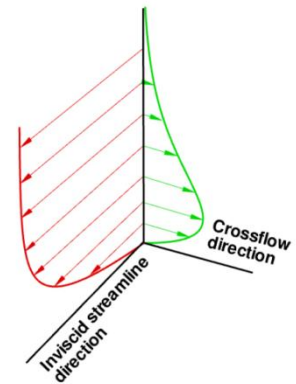


- **Second Mode**

- most amplified when 2D
- responsible for transition in 2D BL at high M
- destabilized by wall cooling
- controlled by suction, $-dp/dx$, curvature; acoustic absorption

- **Crossflow**

- due to inflection point in the crossflow velocity profile
- responsible for transition in 3D BL at all M
- Stationary (roughness-induced) disturbances
- stabilized by wall suction/shaping/sweep

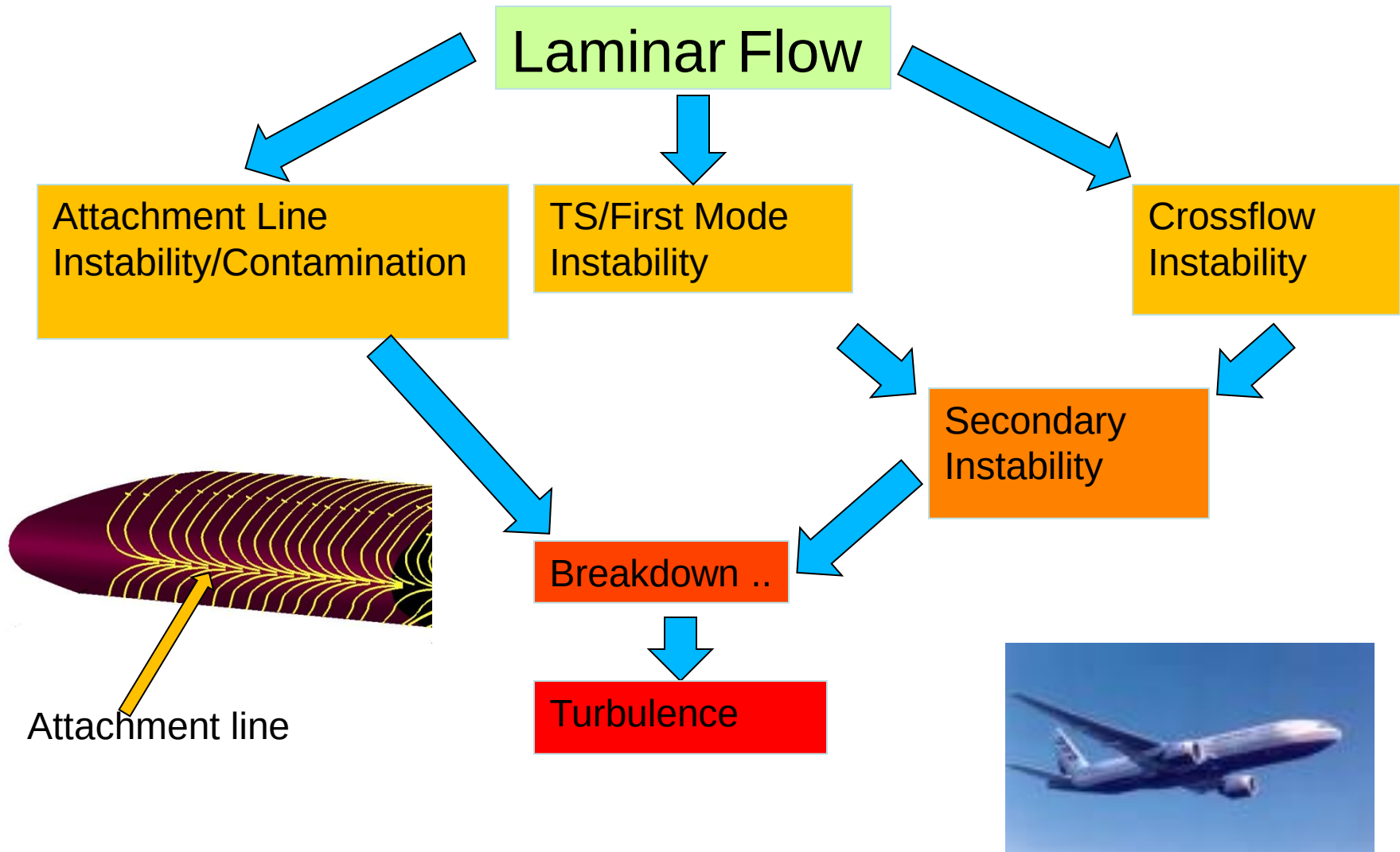


- **Gortler**

- due to concave wall/streamline curvature
- relevant at all M (e.g., nozzle walls, compression ramp)
- stationary vortices
- Control via surface curvature

N factor method for transition prediction is based on integral growth of one of these modes

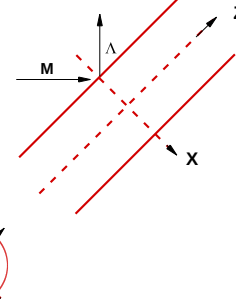
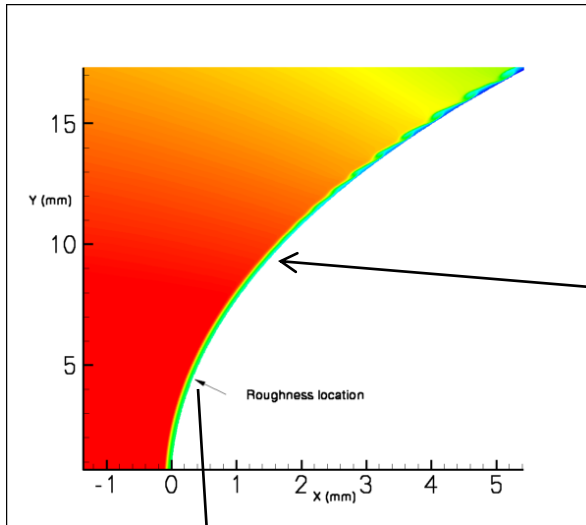
LAMINAR-TURBULENT TRANSITION ON A SWEEPED-WING



3D Boundary Layer Transition

■ DNS of crossflow vortices in a swept-cylinder boundary-layer

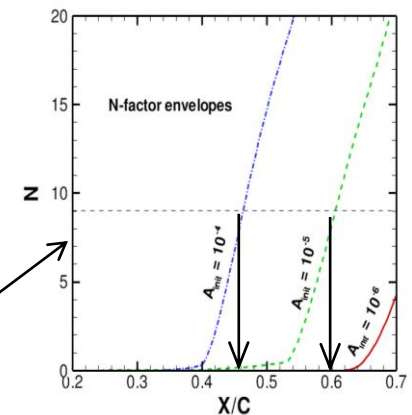
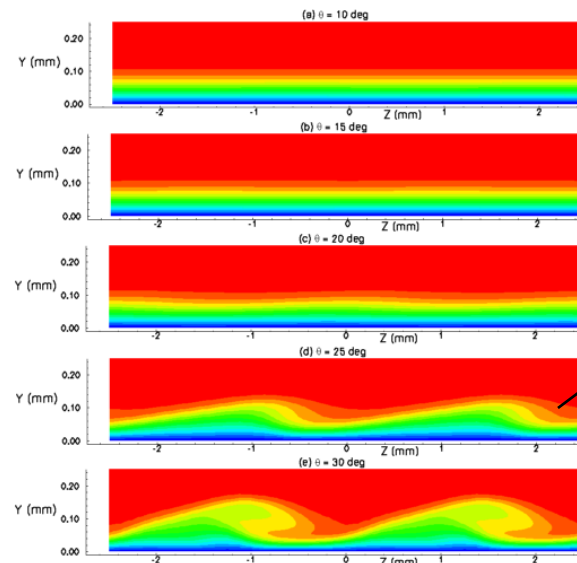
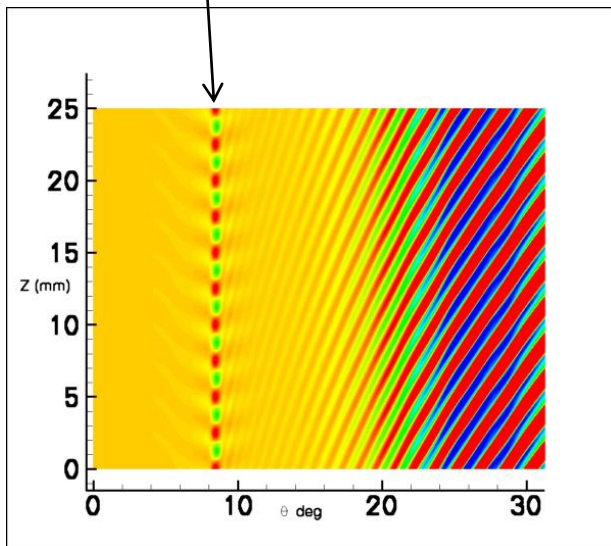
Balakumar (2009)



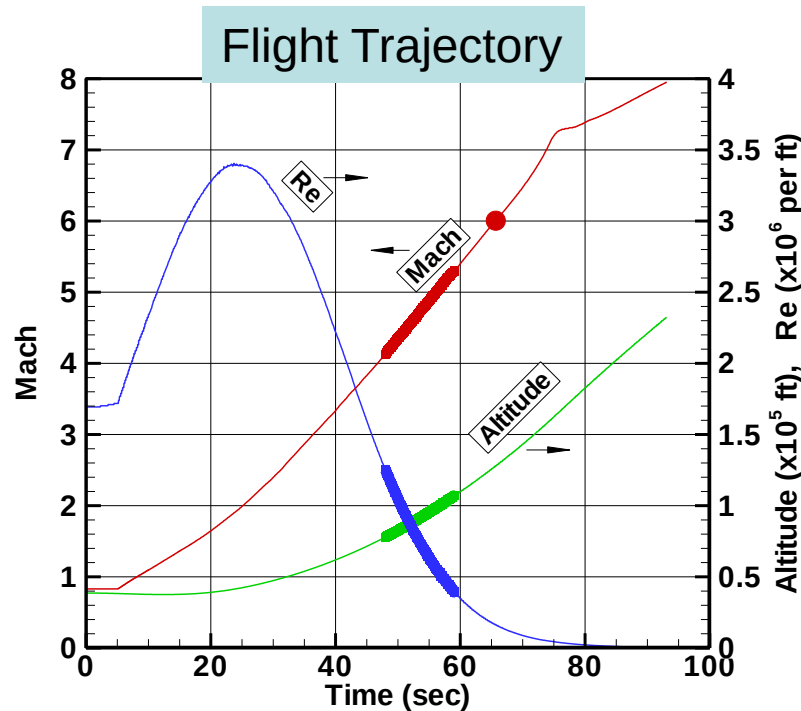
Crossflow Vortices

Partial-differential
Eigen-value problem

Secondary Growth

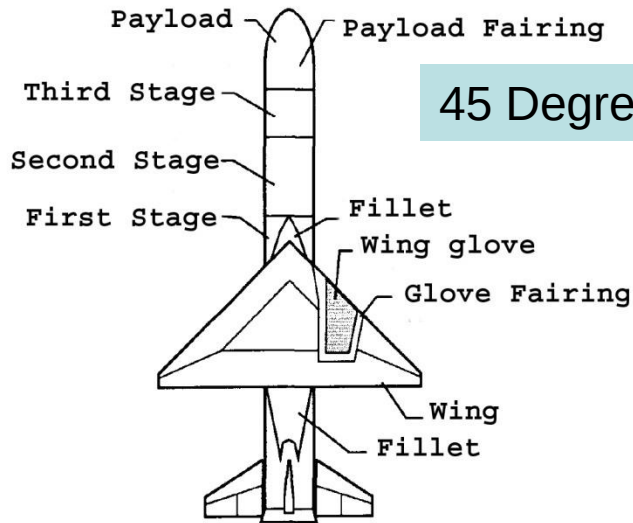


Pegasus Flight Transition Experiment



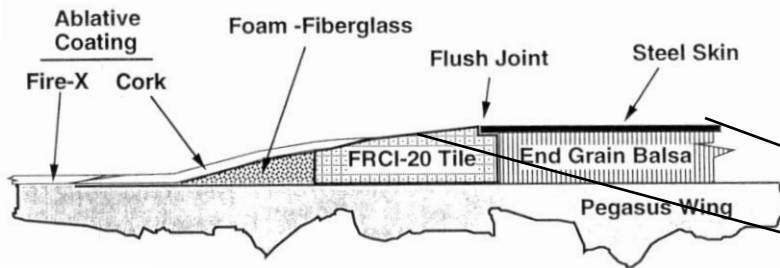
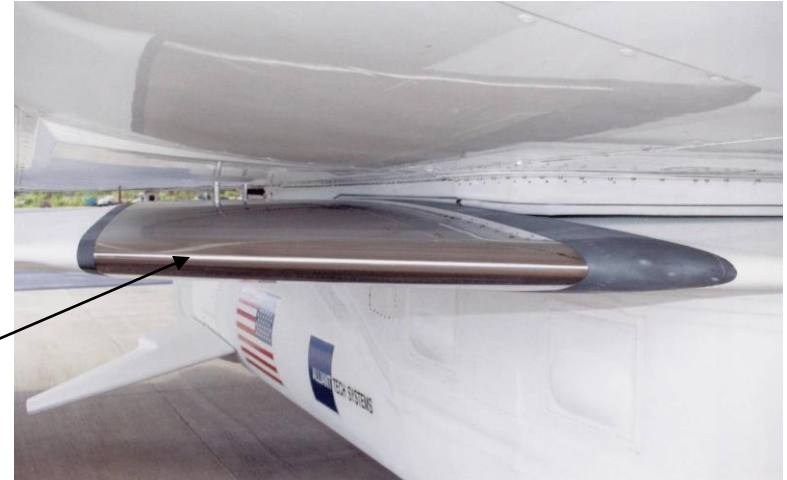
- **Unique crossflow transition flight data for BLT prediction tool validation**
 - *Mach number range of 4 to 5.3*
 - *Effect of wall temperature also studied*

Pegasus Wing Glove

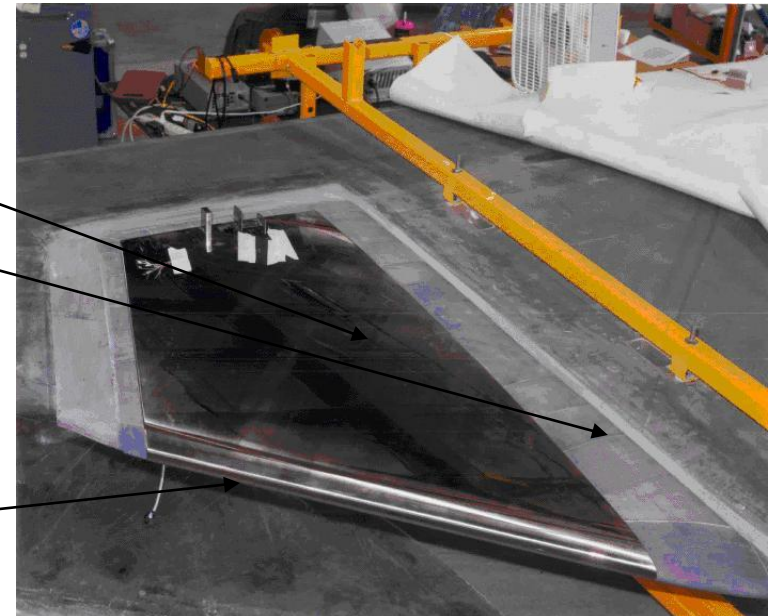
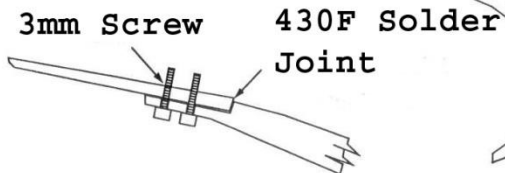


45 Degree Swept Wing

1 in. radius



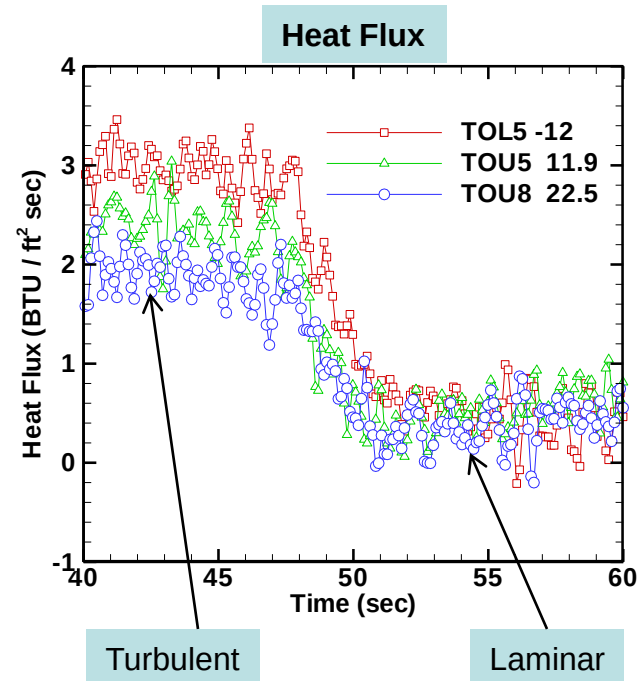
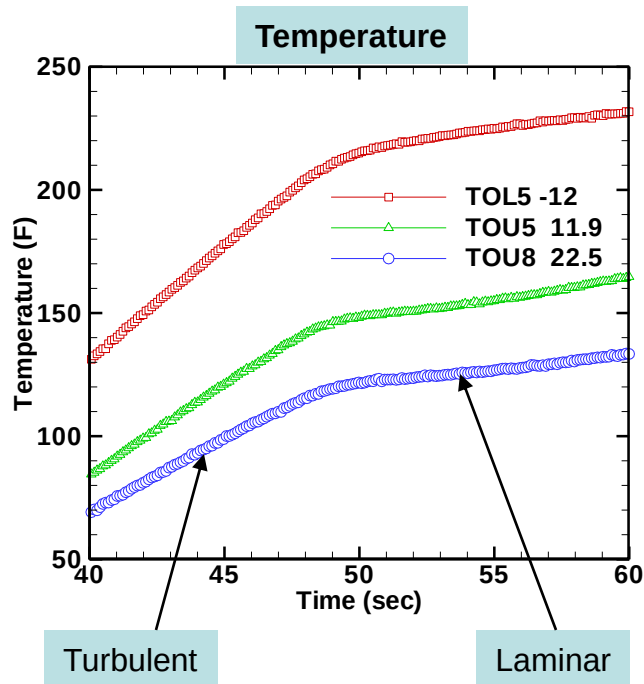
2.3 mm



Pegasus Flight Experiment



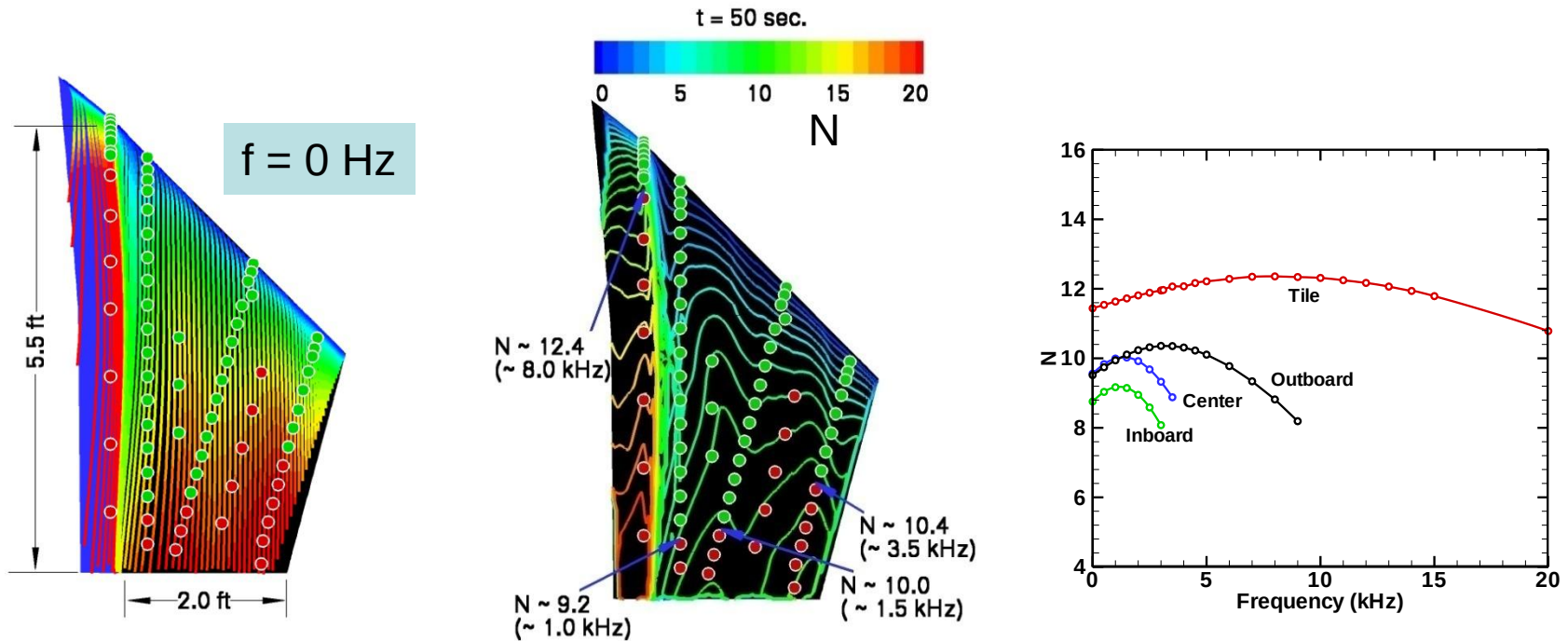
Determination of Transition Onset using Thermocouple Data



Transition from Turbulent to Laminar Flow for Ascending Vehicles

N Factor Analysis for $t = 50$ Seconds Case

$M = 4.35$; $Re/ft = 1.05$ million

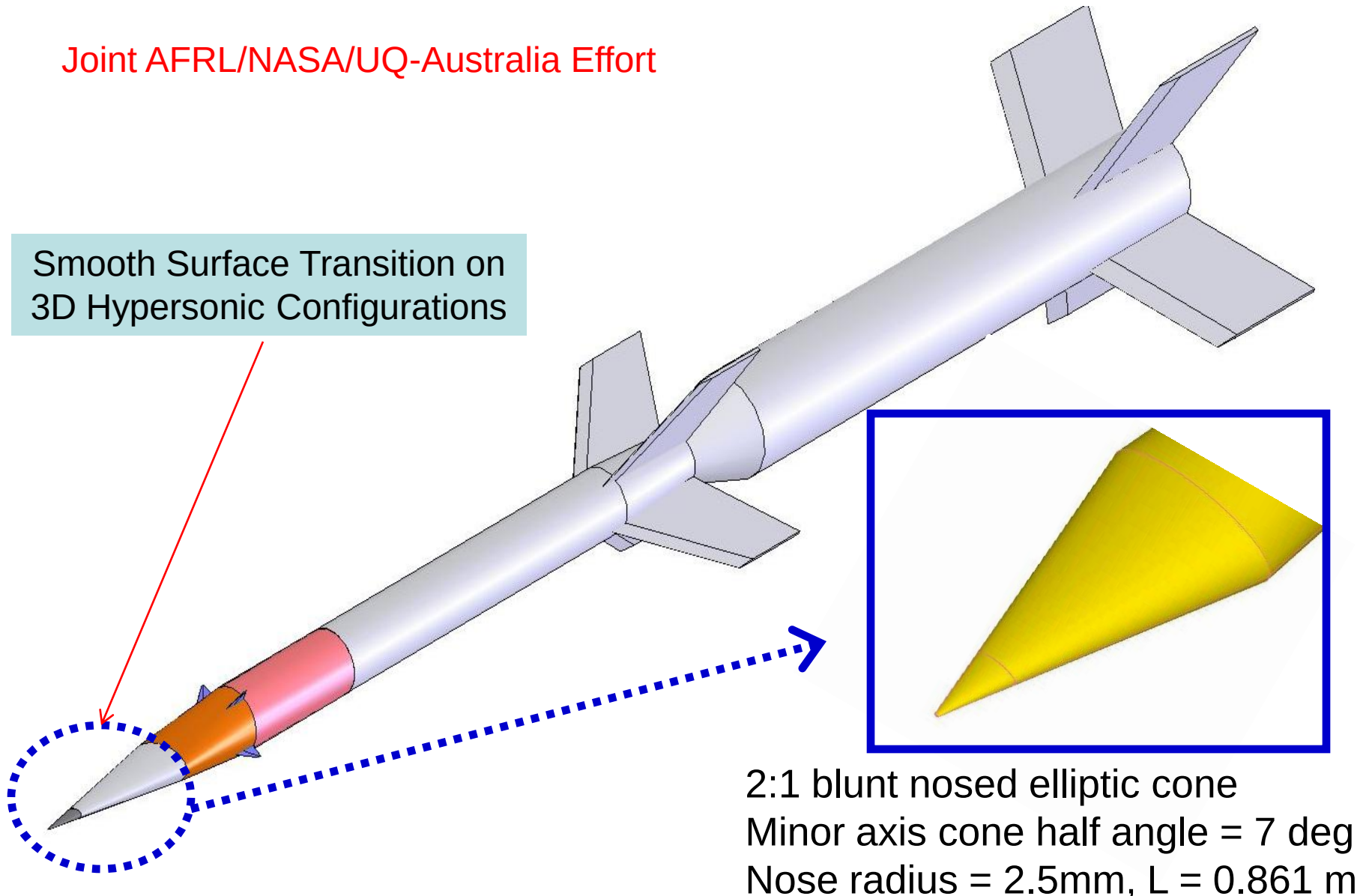


- Glove BL much less unstable than tile BL – effect of lower wall temperature
- Stationary crossflow N factor values between 9 and 11.5
- “Reasonable” N factor correlation

Planned HIFiRE-5 Flight Experiment

Joint AFRL/NASA/UQ-Australia Effort

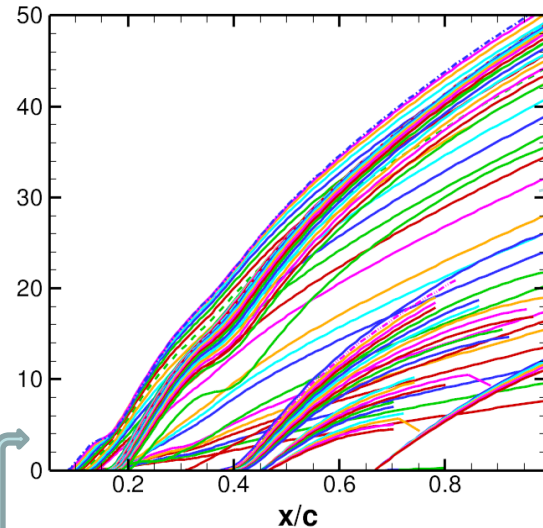
Smooth Surface Transition on
3D Hypersonic Configurations



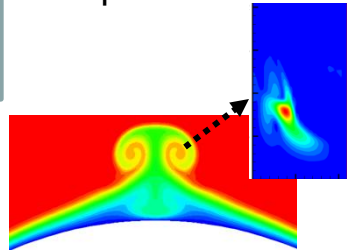
HIFiRE-5: Pre-Flight Computations

Choudhari et al. (2009)

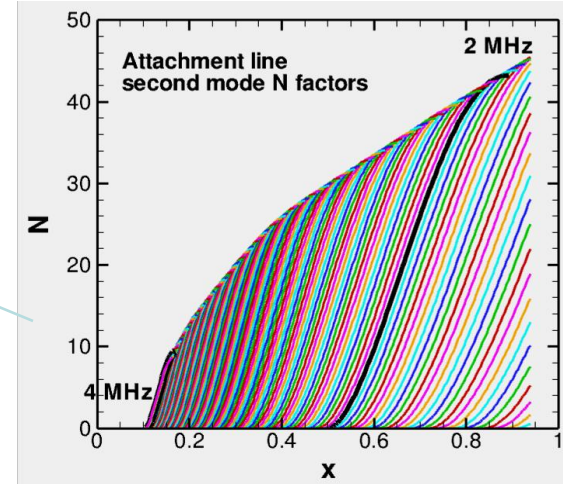
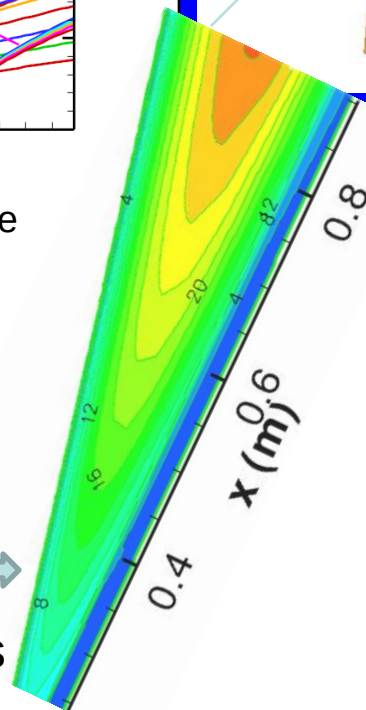
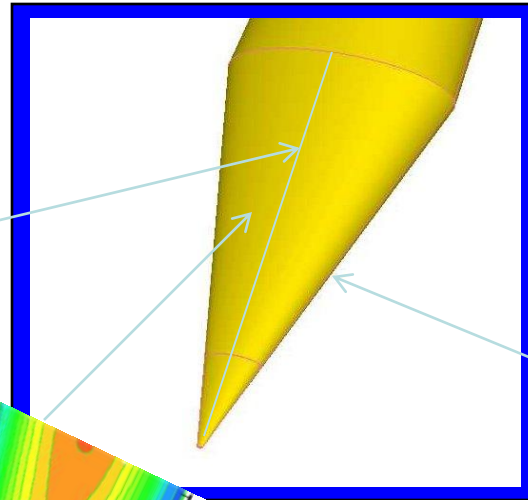
2nd mode/shear layer Instability



200 – 400 kHz disturbance frequencies



Crossflow N factors
(0 Hz)



Elliptic cone BL rich in instability modes

- wide range of disturbance frequencies
- **an instrumentation challenge!**
- **a DNS challenge!**

Effect of Roughness on BLT



From correlations to understanding of the physical mechanisms.

Background

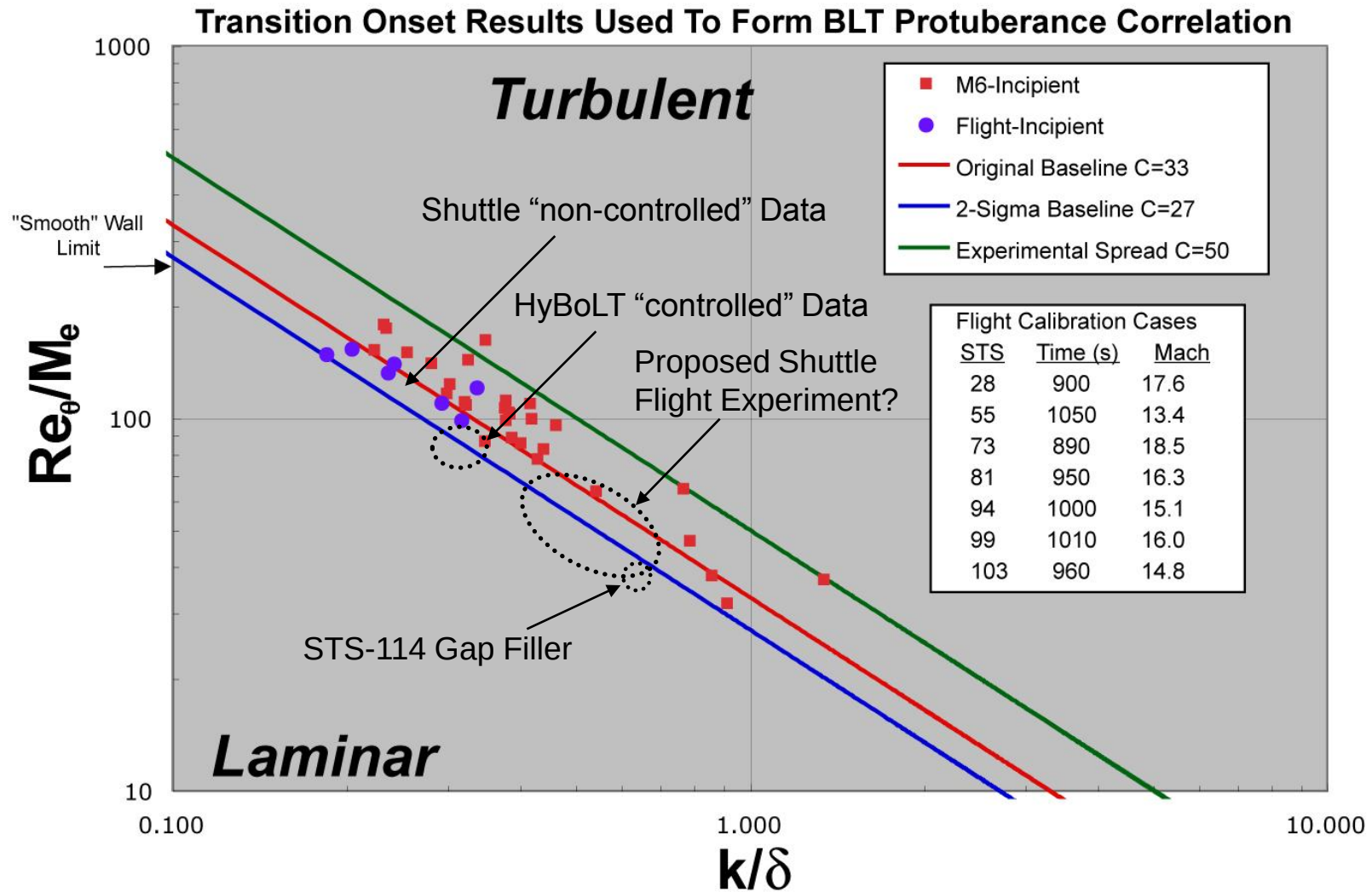
Roughness Effects



- **Transition on re-entry vehicles roughness dominated**
 - protuberances/cavities/distributed roughness inevitable on shuttle, planetary probes, CEV, etc.
 - trips essential to ensure efficient mixing in scramjet inlets
- **Underlying physical mechanisms remain unknown**
 - Current modeling based on purely empirical correlations, largely derived from ground test data from noisy facilities and flow geometry with weak/no crossflow and calibrated against sparse flight data (with questionable knowledge of roughness geometry)
 - Recently proposed transient-growth based model successfully correlates an established database for subcritical transition due to nose-tip roughness

Effect of Discrete Protuberances

Berry et al (2008)



Requirement for Prediction of Roughness Effect using Correlations



“ Because there are infinite number of combinations of geometries, approach flows, ... boundary conditions,....., potential roughness patterns, no universal value for the critical roughness Reynolds number exists. **The critical value for any flow-field/geometry must be determined empirically in a quiet ground-based test facility or in-flight. ”** (Reda 2002)

Roughness Induced Transition

In Search of 'Potential' Physical Mechanisms



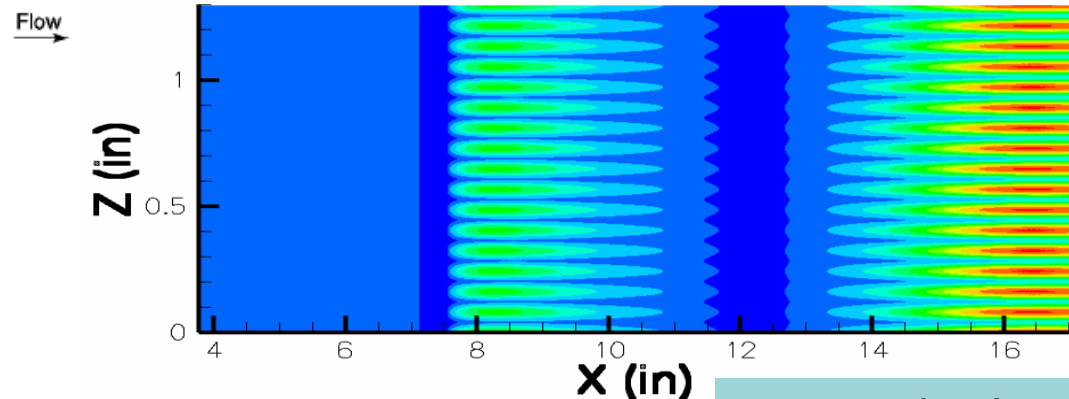
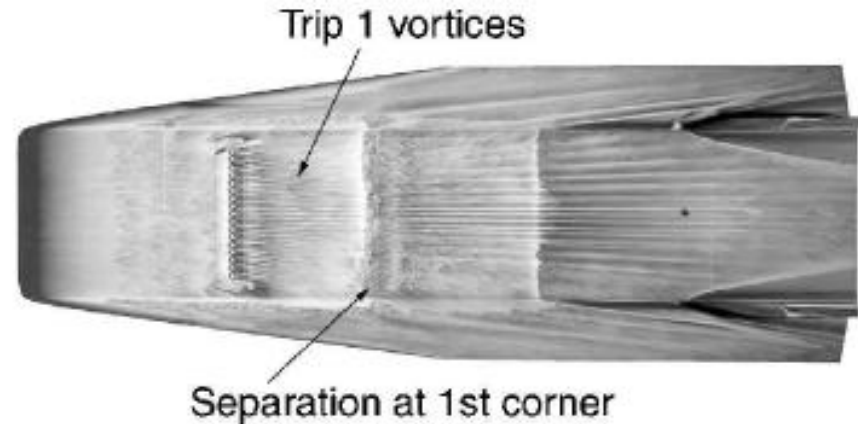
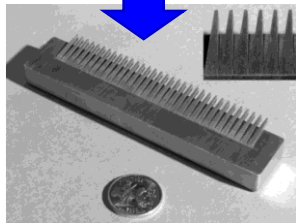
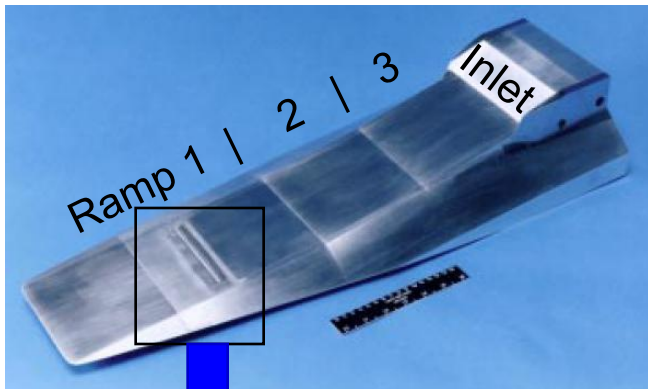
- **Accelerated growth of existing instability modes**
- **Provide environment for strong transient growth**
 - via seeding of appropriate disturbances
 - via enhanced algebraic growth of incoming disturbances
- **New class of instabilities in trip modified flow**
 - **convective modes**
 - **absolute/global instabilities of separated flow**
(vortex shedding, etc.)
- **Something else? (Receptivity agent, etc.)**

Transition due to Streak Instabilities



X-43 Case Study (Choudhari et al. 2009)

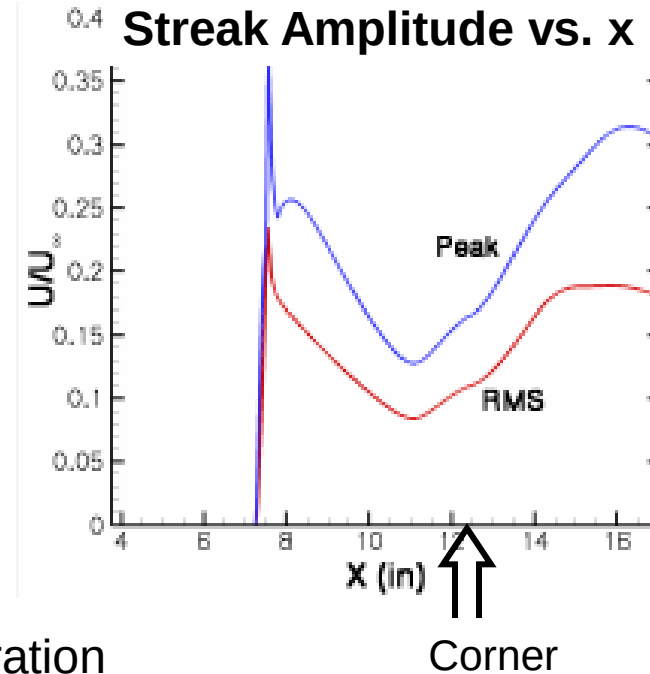
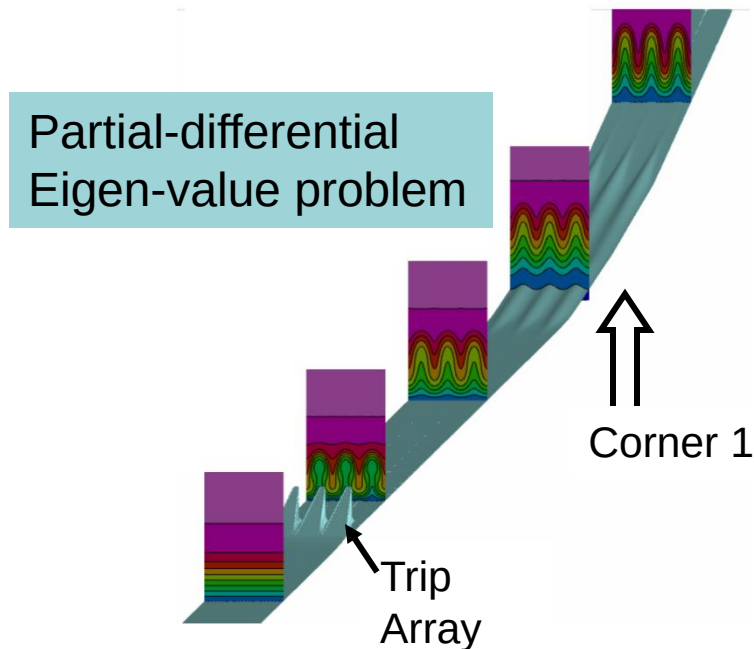
- Wind tunnel experiment (Berry et al. 2001)



- $k = 0.060'' \Rightarrow k/\delta \approx 0.75 \rightarrow$ Transition onset over ramp 1
- Heat transfer augmentation due to vortices/streaks

Streak Mean Flow

- **Trip wake flow dominated by streamwise streaks** that persist for long distances
- Streak growth due to concave streamline curvature and transient growth?

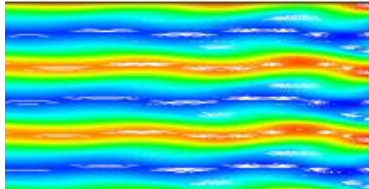


- Energized B.L. more resistant to separation
→ substantially weakened 3D separation bubble near 1st compression corner

Streak Instability Modes

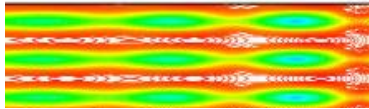
(Similar to Gortler vortex or Crossflow vortex secondary instabilities)

Sinuuous

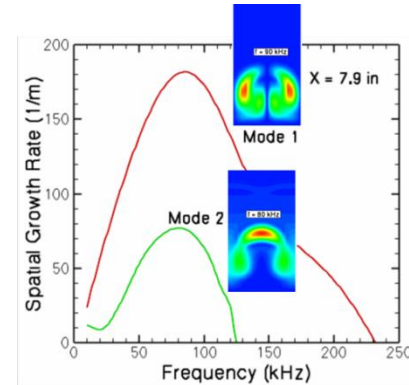


Mode 1, Z

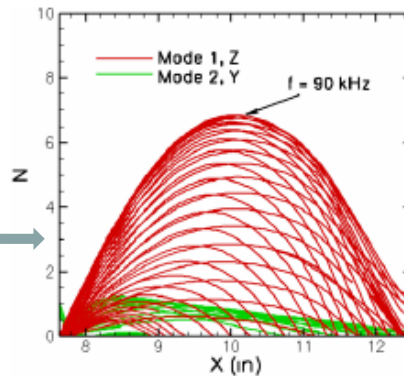
Varicose



Mode 2, Y

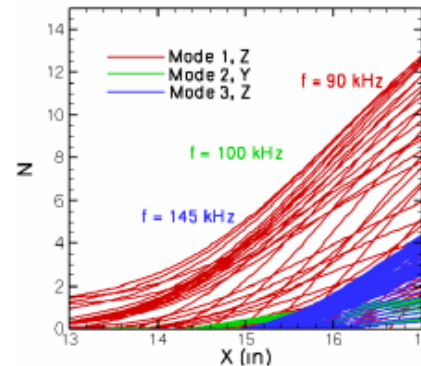


Secondary
N factors



Ramp 1

Corner



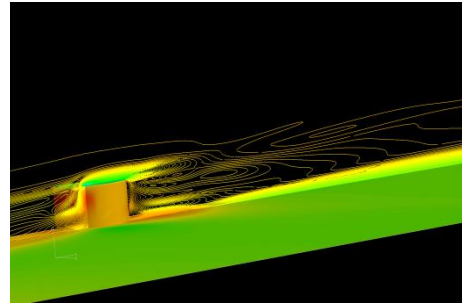
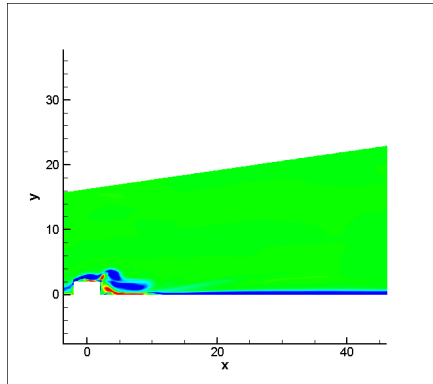
Ramp 2

- Transition on Ramp 1 as N factor exceeds 7 for this conventional $M = 6$ tunnel
- **All streaks** breakdown via secondary instability mechanism studied by Malik et al. (JFM 1994, 1999)

Vortex Shedding vs. Streak Instability

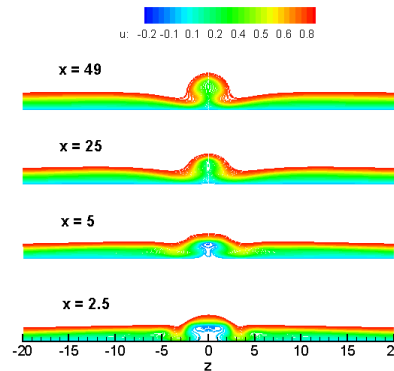
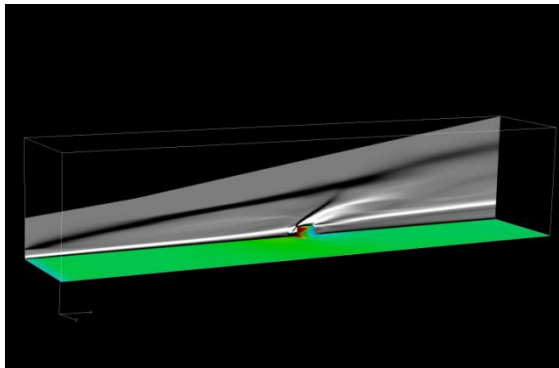


Effect of Mach Number



- Vortex shedding at low M

Chang et al. (2009)

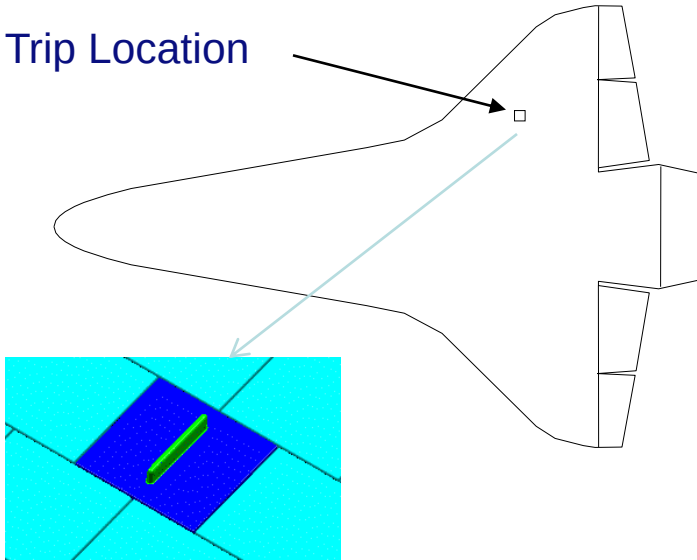


- Streak behind discrete roughness at high M

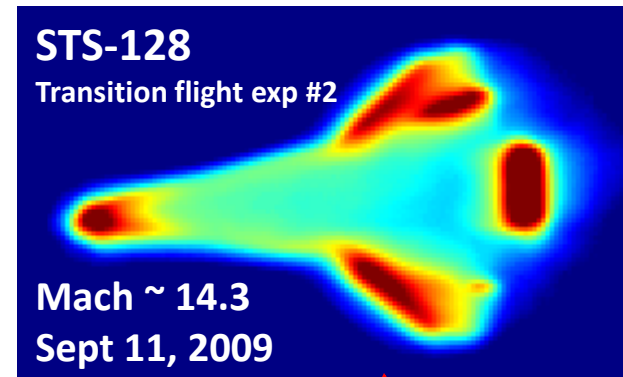
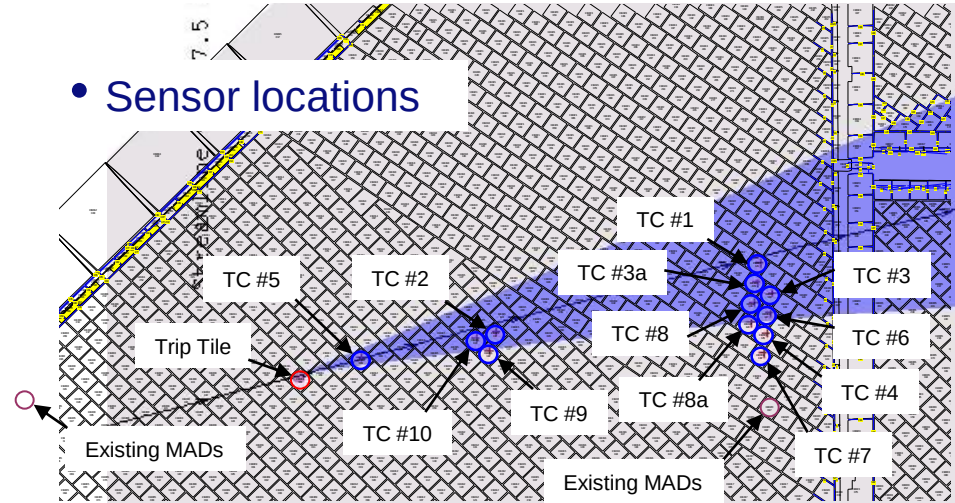
Vortex shedding ceases above a critical Mach number, in which case streak instability becomes the dominant cause of transition due to roughness

Orbiter BLT Flight Experiment

- Trip Location

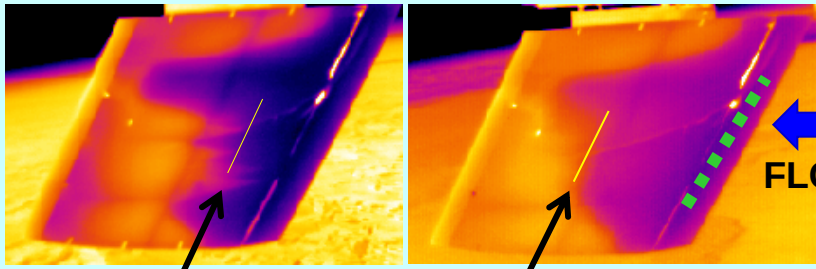


- Sensor locations



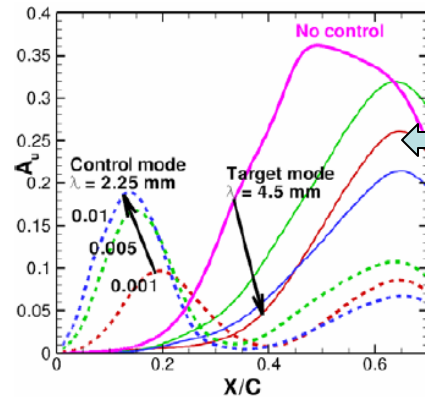
- BLT experiment with fixed protuberances
 - Use 3 separate flights with incremental fixed heights
- Global in-flight imaging of transition front (Horvath et al. 2009)
- Streak instability a possible scenario?

Roughness (micron-sized) for Transition Delay

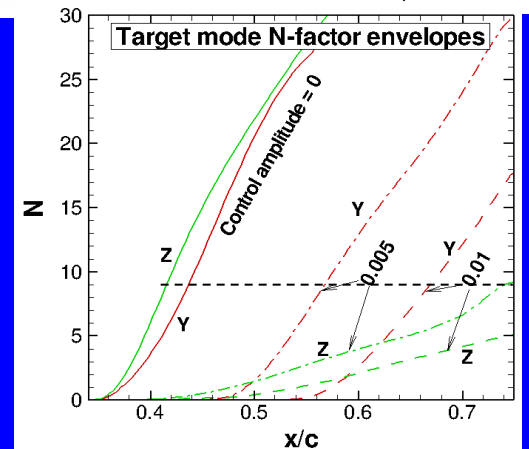


without

Transition with DRE



Control input =>
Delayed/reduced growth
of crossflow modes and,
hence,
delayed onset of
transition via high-freq.
secondary instabilities



- To date, DRE technology (Saric) demonstrated at low Re only ($\sim 8M$)
- Work underway at Texas A&M to push technology to higher Re
- DRE could help relax surface quality (ultra-smooth finish) requirement

BLT Challenges

- **Effect of roughness**
 - *Rich in transition mechanisms*
 - *Fully replacing correlation based transition prediction with physics-based methods, a challenge*
- **Experiments**
 - *Need instruments with dynamic response up to several MHz*
 - *Measure free-stream environment (amplitude and spectra) to effectively use receptivity in transition prediction*
- **Materials Research**
 - *Need ‘bug repellant’ coatings for LFC*
- **Myriads of factors/parameters influence transition**
 - *Maintaining a laminar flow A/C a Challenge!*
 - *But, “Jetstar” experience very positive*

Parameters Influencing Transition

•ROUGHNESS

- ☐ Discrete
- ☐ Distributed
- ☐ Two-Dimensional
- ☐ Three-Dimensional
- ☐ Steps
- ☐ Gaps
- ☐ Particle Impact/Erosion
- ☐ Corrosion
- ☐ Leakage

•ACOUSTIC ENVIRONMENT

- ☐ Attached Flow
- ☐ Separated Flow
- ☐ Propulsion System
- ☐ Vortex Shedding

•PARTICLES

- ☐ Ice Clouds
- ☐ Rain
- ☐ Algae
- ☐ Suspensions
- ☐ Fauna (Insects, Fish, etc.)

•WALL WAVINESS

- ☐ Two-Dimensional
- ☐ Three-Dimensional
- ☐ Single Wave
- ☐ Multiple Wave
- ☐ Distortion Under Load

•SURFACE AND DUCT VIBRATION

•STREAM FLUCTUATIONS AND VORTICITY

- ☐ Propeller Wakes
- ☐ Ocean Surface
- ☐ Body Wakes (Aircraft/Fish)
- ☐ High Shear Areas (weather fronts/jet stream edges/ocean currents)

•LFC SYSTEM-GENERATED DISTURBANCES

- ☐ Vortex Shedding (blocked slots, holes, pores)
- ☐ Acoustic
- ☐ Non-Uniformities

Concluding Remarks

- **Boundary Layer Transition**
 - A complex problem
 - Important for Vehicle design
 - Laminar flow control promises significant reduction in fuel burn
- **Smooth Body Transition**
 - Prediction methods well in hand
 - Further 3D validation needed/experiments planned
- **Distributed Roughness**
 - Prediction mostly based on engineering correlations
 - Transient growth theory the only successful explanation to-date
- **Discrete Roughness Elements**
 - Richness of possible scenarios (vortex shedding, absolute/global instability, streak instability, etc.)
 - Streak instability appears to be one of the leading causes of roughness-induced transition at high M
- **Prescription of Disturbance Environment will remain a Challenge**
 - “True” prediction an illusive goal