Transition in High-Speed Boundary Layers due to Discrete Roughness Elements

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Outline

- Motivation
- Periodic Array of Trip Elements on Hyper-X
  - Trip/Roughness Modified B.L.: Basic State
  - Stability Analysis
- Isolated Roughness Element on a Flat Plate: M=3.5
  - Validation of Theory via Experiment
  - Bridging the Gaps in Physical Understanding
- Isolated Roughness Element on a Flat Plate: M=6
- Summary and Remarks
Motivation

Boundary Layer Transition & Roughness Effects

- **BLT prediction important aspect of hypersonic vehicle design**
  - Impact on TPS selection, vehicle trajectory, cross-range
  - BLT prediction critical for scramjet cruise vehicles and extended glide vehicles.

- **Transition on re-entry vehicles is roughness dominated**
  - Protuberances/cavities/distributed roughness inevitable on shuttle, planetary probes, etc.
  - Trips essential to ensure efficient mixing in scramjet inlets

- **Underlying physical mechanisms remain unknown**
  - Current modeling based on purely empirical correlations
  - Recently proposed transient-growth based model successfully correlates an established database for subcritical transition due to nose-tip roughness
“Bypass” Transition in Supersonic/Hypersonic B.L.s due to Discrete Roughness Elements

- Transition occurs even though underlying boundary layer is stable
  - Transition *bypasses* usual route (and established paradigm)
Effect of Roughness Height on Transition at $M >> 1$

- $M >> 1$ => 3D trips more effective
- Effect of 3D trip height at a fixed set of flow conditions:

**Quiet facility**
(Casper et al, 2008)

**Noisy facility**
(Van Driest & McCauley, 1960)
In general:

- Accelerated growth of existing instability modes
- New class of instabilities in trip modified flow

- **convective modes** (Recall substantial impact of facility on $x_{tr}$)
  - absolute/global instabilities of separated flow
    (vortex shedding, etc.)

- Provide environment for strong transient growth
  - via seeding of appropriate disturbances
  - via enhanced algebraic growth of incoming disturbances

- **Something else? (Receptivity agent, etc.)**
Hyper-X wind tunnel experiment (Berry et al., JSR 2001)

1/3 scale model, tested at Mach 6, 7.3, and 10

- $h = 0.060'' \Rightarrow$ Transition onset over ramp 1
Laminar Mean Flow

- Computations by Jack Edwards (NCSU) under AFOSR support
  - Immersed boundary method
- Flow settles into steady state; short separated region near trip array
- Wake flow dominated by streamwise streaks that persist for long distances
- Energized B.L. more resistant to separation
  → substantially weakened 3D separation bubble near 1st compression corner
Streak Characteristics

- Streaks are amplified across the corner and substantially increase the surface heat transfer, consistent with measurements in Purdue quiet tunnel.

- Modest growth in spanwise Fourier harmonics: Combination of concave streamline curvature and transient growth?

Berry et al. (2001): Hyper-X

Borg et al. (2008)
X-51, Purdue Quiet Tunnel
- Streaks have comparable length scale in wall-normal and spanwise directions

=> PDE based eigen analysis necessary to infer instability characteristics behind trip array
Integrated Amplification of Streak Instabilities (N factors)

**Fundamental Modes**
- Mode 1 = odd/sinuous
- Mode 2 = even/varicose

**Subharmonic Modes**

- Relatively stable region near the corner between ramps 1 and 2 =>
  - N < 7 → transition onset within $\Delta x/L = 0.05$ from the trip*
  - N > 7 → transition may jump past the middle of ramp 2

* Not considering the role of immediate vicinity of the trip here!
Other Trip Configurations

- Effect of array spacing $\delta$
- Effect of trip shape: diamond trips

Similar findings, Stronger streaks
Diamond Trip Located at $X \approx 1.6''$
(plate length = 16'')

- $M = 3.5$
- $P_0 = 25$ psi
- $Re \approx 3M/ft$
- $\delta_{0.995} \approx 0.027''$

$\Rightarrow Re_{kk} \approx 550$

- $x_{tr}(N=9) \approx 48''$; $x_{tr}(N=5) \approx 18''$, i.e., no transition over smooth plate
- Most amplified first mode instabilities over plate length
  - $f = 20-25$ kHz, spanwise wavelength $>> b$
Laminar Mean Flow Behind Roughness

- Navier-Stokes computations using immersed boundary method by Choi et al. (‘08)
- Long range wake signature includes a prominent centerline streak with increased boundary layer thickness, surrounded by higher-speed streaks associated with horse-shoe vortex system wrapping around the trip

Near-wall flow

![Diagram showing near-wall flow patterns with streaks at different X values](image_url)
- Streak has comparable length scale in wall-normal and spanwise directions

=> PDE based eigen analysis necessary to infer instability characteristics behind trip array.

(yellow) dashed line: cross-section of trip
Integrated Amplification of Streak Instabilities (N factors)

Mode 1: odd / sinuous
f = 120 kHz, X = 0.0766 m

Mode 2: even / varicose
f = 175 kHz, X = 0.0766 m
**Isolated Diamond Trip Over Flat Plate**

**Evolution of Streamwise Velocity Contours**

- **k = 0.015” (baseline trip height)**
- **k = 0.0075”**

- $k = 0.0075” \Rightarrow$ weak wake signature ($\Rightarrow$ weaker wake instabilities)
  - Nonlinear dependence of streak amplitude on roughness height
Isolated Diamond Trip Over Flat Plate
Effect of Trip Height on Growth of Streak Instabilities

- Heights large enough to ensure $N > 5$: $k = 0.010"$, 0.012", and 0.015"

- Post “critical” heights: odd mode significantly stronger
- $k \geq 0.015"$: even mode reaches $N=5$ and $N=9$ first
Evolution of Streamwise Velocity Contours at Larger Height

- **Vorticity structure pinching off at large heights (k ≥ 0.02")**
Can wake modes with large enough N-factor cause transition? Nonlinear PSE Computations for Odd Mode Evolution

Initial disturbance amplitudes (i.e., disturbance environment) can impact streak induced transition

“Amplitude” criterion for transition onset, provided initial amplitudes (i.e., excitation mechanisms) are known

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- “Amplitude” criterion for transition onset, provided initial amplitudes (i.e., excitation mechanisms) are known

\[
\begin{align*}
A_T & = 0.01 \\
(a) & X = 0.121 \text{ m} \\
(b) & X = 0.141 \text{ m} \\
(c) & X = 0.161 \text{ m}
\end{align*}
\]
Excitation of wake instability via interaction between upstream disturbances and roughness nearfield

- Roughness nearfield scatters upstream 2D disturbances into wake instability modes
  i.e., no special ingredients necessary to induce receptivity!
- Signs of transition onset seen within downstream portion of simulation
Wake interaction with instability modes in approaching boundary layer
Effect of trip height

$X_{tr, \text{ natural}}$

$X_t$

$X_k$

Leading Edge

Critical

Effective

Re$_k$ (Roughness height)

Weak Streaks
Effect of “Smaller” Height Roughness on 1st Mode Growth

- Higher 1st mode growth within near wake
Effect of “Smaller” Height Roughness on 1st Mode Growth

- Moderately higher growth in near to intermediate wake
- Effect analogous to backward facing step
Effect of trip height

Chang et al. (2009-0173)
- Instability originates in front separation region
- Feeds into wake amplifier

“Large” roughness in hypersonic b.l.
Variation in transition location similar to existing measurements in conventional and quiet facilities
Validation of Streak Instability Theory
**Computation vs. Experiment: Steady Flow**

Measurements by Kegerise et al. (2012)

- **Mean mass-flux distribution**
  \[ X \approx 4.4" \]

- **Mean mass-flux profiles along wake centerline**

- **Excellent quantitative agreement between computation + measurement**
Unsteady Fluctuations

Mass Flux Distribution over Streak Cross-Section

Theory

Even Mode, \( f = 120 \text{ kHz} \)

Measurement

\( X \approx 4.4'' \) (\( f = 100 \text{ kHz} \))

Kegerise et al. (2012)

- Same fluctuation mode shapes in computation and measurement
Mass-Flux Spectra in Roughness Wake

**Measured** mass-flux spectra
(selected stations along wake centerline)
Kegerise et al., 2012

\[ f_p \approx 100 \text{ kHz} \]

\[ Re_{kk} = 462 \quad k/\delta = 0.48 \]

**Predicted** spectra
(even mode)

Stability analysis for:
Frequency (kHz)
Amplitude Growth of Dominant Fluctuations

- Linear Growth
- Nonlinear (Harbingers transition)

In depth comparison with quiet tunnel measurements

⇒ Whodunit verdict:
- Ms. Streak in far wake using (new class of) instabilities
Stronger low-speed streak behind downstream end of inclined fence

Instability characteristics of asymmetric streak remain to be investigated
Trip Element on a Blunt Capsule

- Protuberance
- Cavity

Often designed for fully turbulent heat loads

Chang et al. (2011)
Isolated Roughness Element in Mach 6 Boundary Layer
Roughness Element in $M \approx 6$ B.L.

- **$M = 3.5$ vs. $M \approx 6$**
  
  $\Rightarrow$ Change in instability mechanism in unperturbed/approaching flow  
  
  (1st mode $\rightarrow$ 2nd mode $\Rightarrow$ reduced gap between roughness and instability length scales)
  
  $\Rightarrow$ Change in B.L. profile
  
  $\Rightarrow$ Streak instability characteristics may change as well

- **Maintain partial dynamic similarity**
  
  $- k/\delta \approx 0.55$, $b/k \approx 3.33$, $Re_{kk} \approx 550$
  
  $- Just one way of posing the comparison, useful precursor to study of Purdue exp.

### Summary of Flow Configurations

<table>
<thead>
<tr>
<th>Case</th>
<th>$M_\infty$</th>
<th>$Re_u (m^{-1})$</th>
<th>$T_\infty (K)$</th>
<th>$x_r (m)$</th>
<th>$T_{wall}/T_{ad}$</th>
<th>$Re_\delta$</th>
<th>$Re_\theta /M_e k/\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3.5T</td>
<td>3.5</td>
<td>$9.89 \times 10^6$</td>
<td>87.0</td>
<td>0.0411</td>
<td>1.00</td>
<td>$6.7 \times 10^3$</td>
<td>66</td>
</tr>
<tr>
<td>M6T</td>
<td>5.91</td>
<td>$9.84 \times 10^6$</td>
<td>54.2</td>
<td>0.3853</td>
<td>0.90</td>
<td>$36.9 \times 10^3$</td>
<td>119</td>
</tr>
<tr>
<td>M6F</td>
<td>5.91</td>
<td>$2.07 \times 10^6$</td>
<td>226.9</td>
<td>0.1985</td>
<td>0.25</td>
<td>$6.3 \times 10^3$</td>
<td>35</td>
</tr>
</tbody>
</table>
- \( \text{Re}_{kk}, \frac{T_k}{T_\infty} \) vs. \( \frac{k}{\delta} \)

- \( \text{Re}_{kk} \) and \( \frac{T_k}{T_\infty} \) variation in M6F case rather similar to M3.5T, despite differences in Mach number
- Steep variation in \( \text{Re}_{kk} \) for \( \frac{k}{\delta} > 0.7 \): Is it accompanied by abrupt change in flow physics?

(vs. linear variation in \( \text{Re}_{\theta}/M_e \frac{k}{\delta_{0.995}} \))
- No roughness case: $N=10$ at $x=2.2m$
- Nearly comparable $N$ factors for 2nd mode and oblique first mode waves
- Faster growth of streak instabilities than 1st and 2nd mode waves
- M6F: cold wall case $\Rightarrow$ 2nd mode waves dominate in no-roughness case
- $N<10$ for $X<5m$
- Streak instabilities achieve higher amplification than 2nd mode waves
• Same values of \((X - X_f)/k\) in all cases

\begin{align*}
(X - X_f)/k &= 7 & 15 & 68 & 262 & 482 & 742 & 973
\end{align*}

• u-contours in Mach 6 cases similar to M3.5T case
M6T: $u'$ Mode Shapes

Wake Modes  B.L. Mode(s)  Hybrid Mode(s)
M6T: $u'$ Mode Shapes for Wake Modes

\[
\frac{(x-x_r)}{k} \approx 92
\]

**Even Modes**

(a) Mode S

(b) Mode CS

(c) Mode SI

**Odd Modes**

(a) Mode SI

(b) Mode S

(c) Mode C
(x-x_r)/k ≈ 47

Even (i.e., symmetric) modes.

Odd (i.e., antisymmetric) modes.
M6F: Local Growth Rate vs. Frequency

\[(x-x_r)/k \approx 47\]

Even (symmetric) modes.

Odd (antisymmetric) modes.
Summary

- 3D discrete roughness element with “intermediate” height
  - Earlier transition due to streak instabilities
  - Increased richness to modal structure at hypersonic speeds
- Understanding of other physical regimes via numerical simulations
- With sustained effort, it is possible to translate the outcomes into improved predictive capability for future hypersonic vehicles
  - Broader parameter study + comparison with additional measurements
  - Modeling enhancements
  → Reduced risk/conservatism in TPS design for new vehicles
NASA Quiet Tunnel Experiment: Isolated Roughness on Flat Plate

Diamond Trip

M = 3.5
Diamond vs. Ramp Trips: Streak Amplitudes

$h=0.060”$, $\delta = 0.081”$

- Diamond trips: Analogous streaks as ramp trips, but stronger
  Streaks decay slowly, amplify rapidly
  $\Rightarrow$ Much stronger flow distortion, similar to expt.

Ramp, $h=0.060”$

Diamond, $h=0.060”$
Effect of Roughness Shape: Diamond Trips

- Strong mushroom shaped structures in crossflow plane

$$h=0.060''$$, $$\delta = 0.081''$$
Effect of Array Spacing $\delta$: Ramp Trips

- $\delta = 0.12" \Rightarrow z$-modes still dominant
  - $N>10$ over ramp 1 $\rightarrow$ very likely transition onset over ramp 1, perhaps regardless of noisy or quiet disturbance environment
  - Sustained growth across the compression corner
Modal Energy Evolution

- Modest logarithmic energy growth, details dependent on trip geometry
  (Similar to low-speed observations: White & Ergin 2003, Choudhari & Fischer 2005)
- Higher harmonics slaves to self-interaction of fundamental?
- Transient growth and/or curvature effects?

Ramp Trip, h=0.060”

Diamond Trip, h=0.060”
Oil Flow Visualization for Diamond Trip

Streamlines along $j=2$ surface superposed on $u$-velocity contours
Effect of Array Spacing $\delta$: Ramp Trips

$\delta = 0.12'' \Rightarrow$ larger streak amplitudes

$\delta = 0.081''$ and heat transfer (mean/peak/rms)
Preliminary simulation indicates spontaneous vortex shedding for a model configuration.
Isolated Diamond Trip Over Flat Plate

- Mach 3.5 Flat Plate Experiment in SLDT, NASA LaRC (M. Kegerise)

- Peak variation decays nearly monotonically
- Streak amplitude is nonlinear function of trip height
Effect of Roughness Height on Transition Location

(The Evidence)

- Investigative process
  - Empirical evidence + previous record → help identify suspects
  - Modeling + simulation → verify alibis, establish modus operandi
  - Experiment → Set up sting operation to confirm “theory”
Variation in transition location similar to existing measurements in conventional and quiet facilities – detailed comparisons after the completion of planned experiment at NASA LaRC