Discrete surface roughness effects on a blunt hypersonic cone in a quiet tunnel

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26 November 2013
• All realistic hypersonic flight vehicles have roughness, which can cause transition to turbulence.

• Turbulent boundary layers exhibit higher skin friction and mixing, causing increased vehicle drag and heating.

• Disturbances enter the boundary layer through *receptivity*, then grow by one or more mechanisms before causing breakdown and turbulence.
• These disturbances include freestream turbulence or acoustic noise, surface roughness, curvature discontinuities, surface vibration, etc.
Transient growth: physically

- Transient growth of high and low speed streaks can form as a result of the lift-up mechanism.

- Transient growth is particularly effective for streamwise vortices, such as those produced downstream of roughness.

Subsonic experiments by Ergin and White\(^1\) (and colleagues) have measured transient growth in the wake of an array of isolated roughness elements. In doing so, they showed experimentally-realized transient growth is \textit{suboptimal}, meaning receptivity does not produce a set of initial disturbances that will achieve maximum growth downstream.

**Objective:** Measure roughness-induced transient growth in a hypersonic boundary layer.

**Model:** Stainless steel, straight, 5-degree half-angle cone with 5 interchangeable nosetips

- **Nose bluntness:** 1.59-mm radius nosetip
- **Roughness type:** 1-mm tall DRE array
- **Roughness location:** X/L = 0.25
- **Roughness wavelength:** 3.56 mm
- **Roughness spacing:** 20 degrees
- **Overall length:** 390 mm

- **Frustum base diameter:** 80 mm
- **Frustum length:** 331 mm
- **Sharp model length:** 456 mm
What is quiet flow?

Conventional hypersonic tunnels have freestream Pitot fluctuations of 2-3%.

\[ \frac{P'_{i2 \, \text{rms}}}{P_{i2}} \times 100 \% \]

2011 Pitot Fluctuations at \( Re = 10 \times 10^6 \, m^{-1} \)

2013 Pitot Fluctuations at \( Re = 10 \times 10^6 \, m^{-1} \)
• M6QT’s **40-second run time** requires constructing contours out of 15+ individual runs.

• Conditions to match include:
  • Tunnel stagnation pressure (± 2-3%)
  • Tunnel stagnation temperature (± 3%)
  • Adiabatic wall temperature ratio (± 1%)

• Each condition’s contour plot required an average of **over 130 compressor hours** to obtain.
Current experiments

- **Diagnostic:** Kulite pitot probe
- **ID:** 3 mm (wide), 1.4 mm (tall)
- **Azimuthal sampling:** 0.33-0.37 x Pitot width
Current experiments

- **Diagnostic:** Kulite pitot probe
- **ID:** 3 mm (wide), 1.4 mm (tall)
- **Pitot width:** 0.27-0.30 x streak width

Negative Angles 0 Positive angles

Flow Direction

Diagram shows a graph with axes labeled Z (mm) and φ (deg), with negative angles to the left of the zero degree mark and positive angles to the right. The pitot probe setup is indicated with a circular symbol labeled Flow Direction.
Re = $9.9 \times 10^6 / m$

Contours: mean pressure
Colormap: unsteady RMS

X/L = 0.86

X/L = 0.90

X/L = 0.94
Disturbance pressures

\[ p(t, x, y, z) = \bar{P}(x, y) + P'(x, y, z) + p'(x, y, z, t) \]

- Spanwise-invariant basic state, averaged across the azimuth
- Spanwise-varying steady disturbance
- Spanwise-varying unsteady disturbance

\[ X/L_{\text{sharp}} = 0.86; \frac{T_u}{T_{aw}} = 0.94 - 0.96; \text{Re} = 9.9 \times 10^6 / \text{m} \]
Disturbance pressures

\[ p(t, x, y, z) = \bar{P}(x, y) + P'(x, y, z) + p'(x, y, z, t) \]

Spanwise-invariant basic state, averaged across the azimuth

Spanwise-varying steady disturbance

Spanwise-varying unsteady disturbance

Steady disturbance pressures

Unsteady disturbance pressures
• Tripping to turbulence with roughness elements in quiet flow is difficult.

• The steady azimuthal disturbance pressures grow in the streamwise direction.

• The unsteady azimuthal disturbance pressures decay downstream.

• Thus far, these hypersonic observations are consistent with low-speed transient growth results.
With special thanks to...

• Dr. Bill Saric
• Dr. Rodney Bowersox
• The students and postdocs of the National Aerothermochemistry Laboratory
• Jason Monschke
• The staff at the Oran Nicks Low Speed Wind Tunnel

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