Surface Roughness Effects on a Blunt Hypersonic Cone

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• Real hypersonic surfaces are rough.

• Isolated roughness includes:
  • Fasteners
  • Joints
  • Tripping elements
  • Gap filler

• Distributed roughness
  • Machining marks
  • Ablative heat shields
  • Thermal protection tiles

Images credits: NASA and Shannon D. Moore (OutdoorPhoto.com)
• Surface roughness introduces disturbances into the boundary layer, which may be enhanced through transient growth.

• Transient growth, being nonmodal in nature, can exist in regions subcritical to other transition mechanisms.

• The “blunt-body paradox,” in which transition occurs earlier than predicted even on highly polished surfaces, may be explicable through roughness-induced transient growth.

Transition map adapted from Morkovin et al (1994)
• Computations of surface roughness are expensive, except in cases of isolated roughness.

• Existing literature on experimental roughness-induced transition is vast, but:
  • Focuses on empirical correlations for transition prediction
  • Often utilizes noisy, conventional wind tunnels
  • Physics-based transition correlation is desirable.

Nosetip transition data from ballistics-range experiments; three-dimensional distributed roughness, compressible flows (Reda 2002).
• Computations of optimal disturbances for compressible boundary layers exist:

• Transient growth is destabilized by wall cooling and increasing spherical radius but stabilized by flow divergence.


Optimal growth factors for zero pressure gradient; $Re_L = 9 \times 10^4$ (Reshotko and Tumin 2004).

Optimal spanwise wavenumber for zero pressure gradient; $Re_L = 9 \times 10^4$ (Reshotko and Tumin 2004).
Mach 6 Quiet Tunnel (M6QT)

- Low-disturbance test environment up to a Re = $10 \times 10^6 \, \text{m}^{-1}$
- 40 second nominal run-time
- Hotwire anemometry used as primary diagnostic (presently uncalibrated)

Straight-wall section and slow expansion contour minimizes growth of the Görtler instability

Quiet test core defined upstream by Mach 5.91 uniform flow and downstream by acoustic disturbances generated by nozzle-wall turbulent boundary-layer eddies and radiated along Mach waves

Settling chamber boundary layer removed via vacuum ejectors, initiating new laminar boundary layer on nozzle

Toggling bleed valves allows quiet (0.05% Pt' / Pt) or noisy operating conditions

Vacuum-pressure blow-down configuration using a two-stage air ejector system

Enclosed free-jet test section with two-axis traverse
Smooth, 5-degree cone with interchangeable nosetips

1.59 mm radius, smooth

1.59 mm radius, discrete roughness elements

6.35 mm radius, smooth

6.35 mm radius, discrete roughness elements

6.35 mm radius, quasi-random distributed roughness
Quasi-random distributed roughness

- Roughness generated via Fourier series

\[
h(x, \theta) = \sum_{n=1}^{N} \sum_{m=1}^{M} A_{n,m} \cos \left( \frac{2\pi nx}{\lambda_k} \cos \gamma_c \right) + mK\theta + \phi_{n,m}
\]

- Roughness repeats over two 150° arcs separated by two 30° sections of nominally smooth surface

- \( A_{n,m} \) coefficients selected from a half-normal distribution and scaled

- Quasi-random distributed roughness nosetip constructed via direct metal laser sintering

6.35 mm radius nosetips, quasi-randomly distributed roughness (left) and nominally smooth (right)

Initial experiments

- Tested 6.35 mm radius smooth and distributed rough nosetips

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal $M$</td>
<td>5.9</td>
<td>5.9</td>
<td>5.9</td>
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<tr>
<td>$P_0$</td>
<td>551 kPa</td>
<td>689 kPa</td>
<td>896 kPa</td>
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<tr>
<td>$T_0$</td>
<td>430 K</td>
<td>430 K</td>
<td>430 K</td>
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<tr>
<td>$Re$</td>
<td>$6.1 \times 10^6$ m$^{-1}$</td>
<td>$7.7 \times 10^6$ m$^{-1}$</td>
<td>$10 \times 10^6$ m$^{-1}$</td>
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<tr>
<td>$Re_n$</td>
<td>$3.9 \times 10^4$</td>
<td>$4.9 \times 10^4$</td>
<td>$6.3 \times 10^4$</td>
</tr>
</tbody>
</table>

\[
Re_\theta \left( \frac{k}{\theta} \right) = \frac{U_e k}{\nu_e}
\]


- For $k = 0.11$ mm:

\[
\frac{U_e k}{\nu_e} = 780 \text{ to } 1340
\]

• Wall-temperature during run is 5-8% higher than adiabatic due to subsonic preheating.

6.35 mm radius nosetips, quasi-randomly distributed roughness (left) and nominally smooth (right)
Mean boundary layer profiles

Increasing Reynolds number

- Re = 6.1 x 10^6 m\(^{-1}\); x/L\(_{\text{sharp}}\) = 0.78
- Re = 7.7 x 10^6 m\(^{-1}\); x/L\(_{\text{sharp}}\) = 0.78
- Re = 10 x 10^6 m\(^{-1}\); x/L\(_{\text{sharp}}\) = 0.78

Increasing streamwise distance

- Re = 6.1 x 10^6 m\(^{-1}\); x/L\(_{\text{sharp}}\) = 0.94
- Re = 7.7 x 10^6 m\(^{-1}\); x/L\(_{\text{sharp}}\) = 0.94
- Re = 10 x 10^6 m\(^{-1}\); x/L\(_{\text{sharp}}\) = 0.94
RMS fluctuation profiles

Increasing Reynolds number

Increasing streamwise distance
Conclusions

- Growth of fluctuation amplitudes is observed but distributed roughness only marginally increases growth compared to a smooth wall.

- The distributed roughness nosetip is insufficient to trip the boundary layer, possibly due to the bluntness of the nose.

- Future experiments will include:
  - azimuthal measurements for detection of streaky structures to confirm transient growth
  - sharper nosetips and discrete roughness elements spaced according to optimal disturbance theory
Acknowledgements