Instability of a Supersonic Boundary-Layer with Localized Roughness

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Thermal protection system (TPS) for re-entry vehicle

Introduction

- Quantification of the heat loads on TPS surfaces for re-entry vehicles is required to ensure the safety of the crew.
- TPS surface can exhibit localized roughness, which may increase heating due to early transition to turbulence.

Source NASA: http://www.nasa.gov

Figure: heat shield of the Space Shuttle in orbit during flight STS-114 with gap filler sticking out.
General configuration

Physical model and numerical method

- Compressible Navier-Stokes equations
- High order in space (O6, compact) and time (O3, explicit)
- Immersed boundary method to represent roughness
- Spanwise periodicity: array of roughness elements

Freestream and forcing parameters

Physical model and numerical method

- Similar setup as in Marxen & Iaccarino (2008) [1]
- Calorically perfect gas, Sutherland’s law with $T_S$

<table>
<thead>
<tr>
<th>$Ma_\infty$</th>
<th>$Pr_\infty$</th>
<th>$\gamma_\infty$</th>
<th>$Re_\infty$</th>
<th>$T_S/T_\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8</td>
<td>0.71</td>
<td>1.4</td>
<td>$10^5$</td>
<td>1.993</td>
</tr>
</tbody>
</table>

- 3-D roughness (“square”) on an adiabatic wall

<table>
<thead>
<tr>
<th>height $h_R$</th>
<th>length $l_R$</th>
<th>$x_{c,R}$</th>
<th>$h_R/\delta_{99}$</th>
<th>$Re_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.4</td>
<td>15</td>
<td>0.55</td>
<td>1225</td>
</tr>
</tbody>
</table>

Steady-state base flow
Mean flow I: streamlines & shocks

Flow over surface with localized 3-D roughness at $Ma=4.8$

- Separation in front < separation in the back
- No shock present in x-y planes away from the roughness element(s)

Figure: Contours of $\partial \rho / \partial x = 0.4$ (black) together with contours of $u=0$ (blue) and selected streamlines (grey lines with arrows) in the center plane $z = 0$. 
Mean flow II: streamwise vortices

Flow over surface with localized 3-D roughness at Ma=4.8

Streamwise vortices (grey) $\rightarrow$ streamwise streak(s) $\rightarrow$ mean-flow gradients (color)

Figure: isosurface of $\lambda_2$ (light grey) and recirculation regions (dark grey)
Mean flow III: verification

Flow over surface with localized 3-D roughness at Ma=4.8

Overall good agreement between body-fitted (FLUENT) and immersed boundary results

Figure: Contours of $U$ from body fitted (black contours) and immersed boundary method (red contours), planes cutting through the roughness.
Mean flow IV: verification (cont’d)

Flow over surface with localized 3-D roughness at Ma=4.8

Some difference in the spanwise position of the streamwise vortices / streaks behind the roughness

Figure: Contours of $\mathbf{U}$ & $\mathbf{T}$ from body fitted (black contours) and immersed boundary method (red contours) behind the roughness, $x = 18$. 

O. Marxen
Mean flow V: transient growth?

Flow over surface with localized 3-D roughness at Ma=4.8

- Streamwise vortices cause a streamwise (u’) streak
- Transient growth in individual modes, but no significant growth visible in the sum (a non-linear effect?)

**Figure**: streamwise velocity $u'_\text{max}$ for $F=0$ (steady component) for several spanwise wave numbers $k$ and their sum. Location of the roughness in grey.
DNS of the perturbed flow and comparison with stability analysis by *Groskopf & Kloker, 2008* [1]

Disturbance evolution I: DNS with 2-D forcing

Localized 3-d roughness: disturbance flow

- 2-D forcing with frequency \( F = 2\pi f \left( \mu / (\rho u^2) \right) = 0.41 \times 10^{-4} \) upstream of the roughness ("first mode")

- Fourier analysis in time, disturb. maximum over y&z

*Figure: streamwise velocity \( u'_{\text{max}} \) for \( F = 0.41 \times 10^{-4} \)*
Disturbance evolution II: DNS vs. bi-global theory

Localized 3-d roughness: disturbance flow

Figure: $u_{\text{max}}^\prime$ (max. over $z$&$y$) for $F=0.41 \times 10^{-4}$ (red: DNS, black: theory)

Presence of a y-mode in DNS due to 2-D forcing

Figure: Amplitude functions of the streamwise velocity $u'$ for $F=0.41 \times 10^{-4}$, $x=18$
Conclusions

Conclusions and outlook

- A localized 3-D roughness causes boundary-layer separation and (weak) shocks
- Most importantly, streamwise vortices occur which induce streamwise (low U, high T) streaks
- Immersed boundary method (volume force) suitable to represent roughness element in DNS
- Favorable comparison between bi-global stability theory and DNS for a “y-mode”

Outlook:
- Understand the flow physics (investigate “z-modes” in DNS through sinuous spanwise forcing, study origin of the beat in DNS)