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Instability of a Supersonic Boundary-Layer with Localized Roughness

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Thermal protection system (TPS) for re-entry vehicle

Introduction

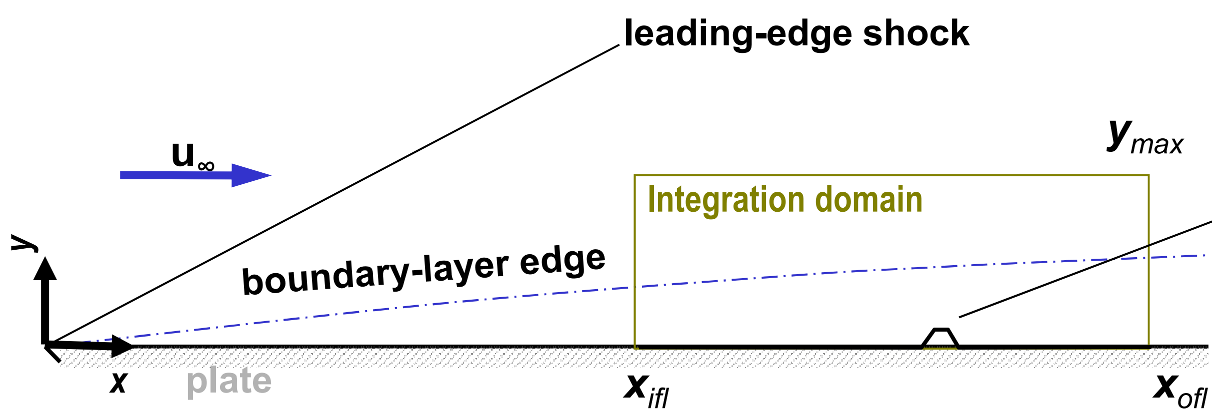
- Quantification of the **heat loads on TPS surfaces** for re-entry vehicles is required to ensure the safety of the crew
- TPS surface can exhibit **localized roughness**, which may increase heating due to early transition to turbulence

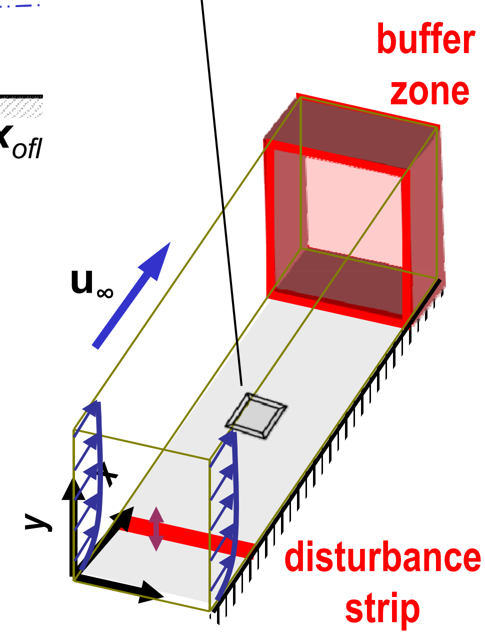
Source NASA: http://www.nasa.gov

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
- Code: *Nagarajan, Lele and Ferziger (2003)* [1]
- High order in space (O6, compact) and time (O3, explicit)
- **Immersed boundary method** to represent roughness
- Spanwise periodicity: array of roughness elements

[1] Nagarajan, S., Lele, S.K. and Ferziger, J.H. (2003), J. Comput. Phys. 191, 392-419.

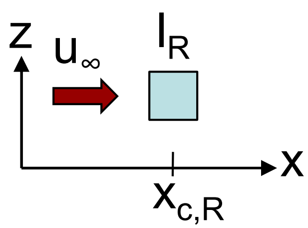
Freestream and forcing parameters

Physical model and numerical method

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

Ma_∞	Pr_∞	γ_∞	Re_∞	T_S/T_∞
4.8	0.71	1.4	10^5	1.993

- **3-D roughness** ("square") on an **adiabatic wall**



height h_R	length l_R	$x_{c.R}$	h_R/δ_{99}	Re_x
0.1	0.4	15	**0.55**	**1225**

[1] *Marxen, O., Iaccarino, G. (2008), AIAA* ***2008-4400***

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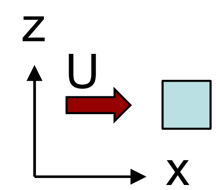
Steady-state base flow

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)



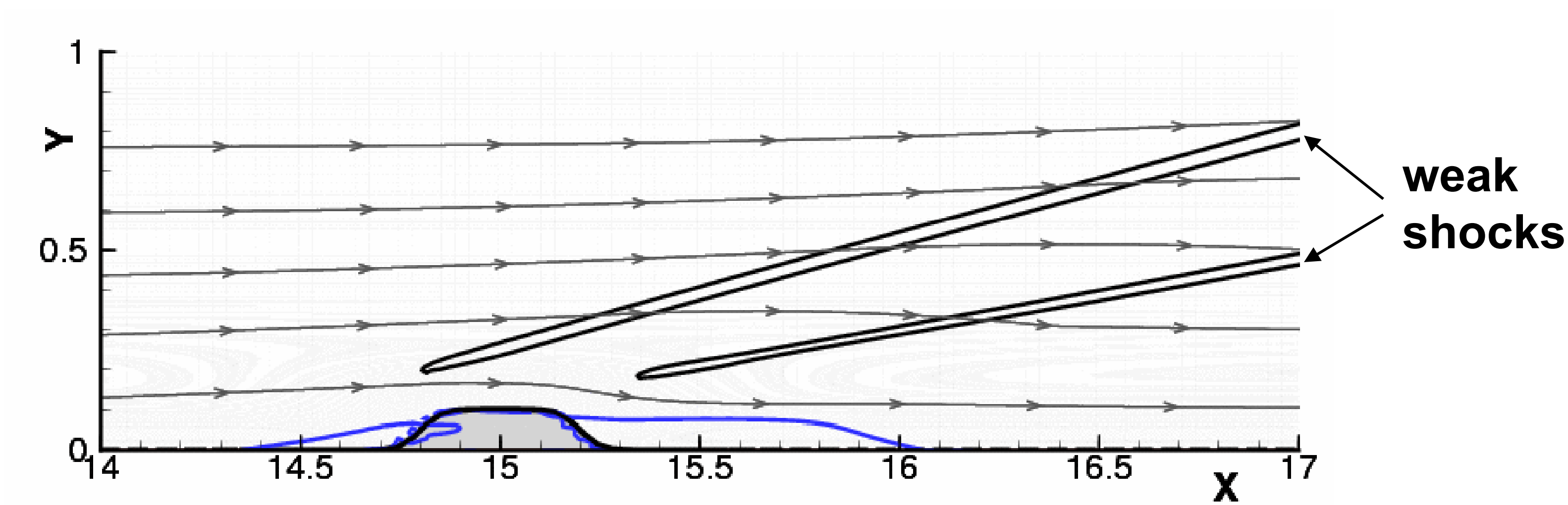


Figure: Contours of ∂ρ/∂x = 0.4 (black) together with contours of u=0 (blue) and selected streamlines (grey lines with arrows) in the center plane z = 0.

Mean flow II: streamwise vortices

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

Streamwise vortices (grey) ➔ streamwise streak(s) ➔ mean-flow gradients (color)

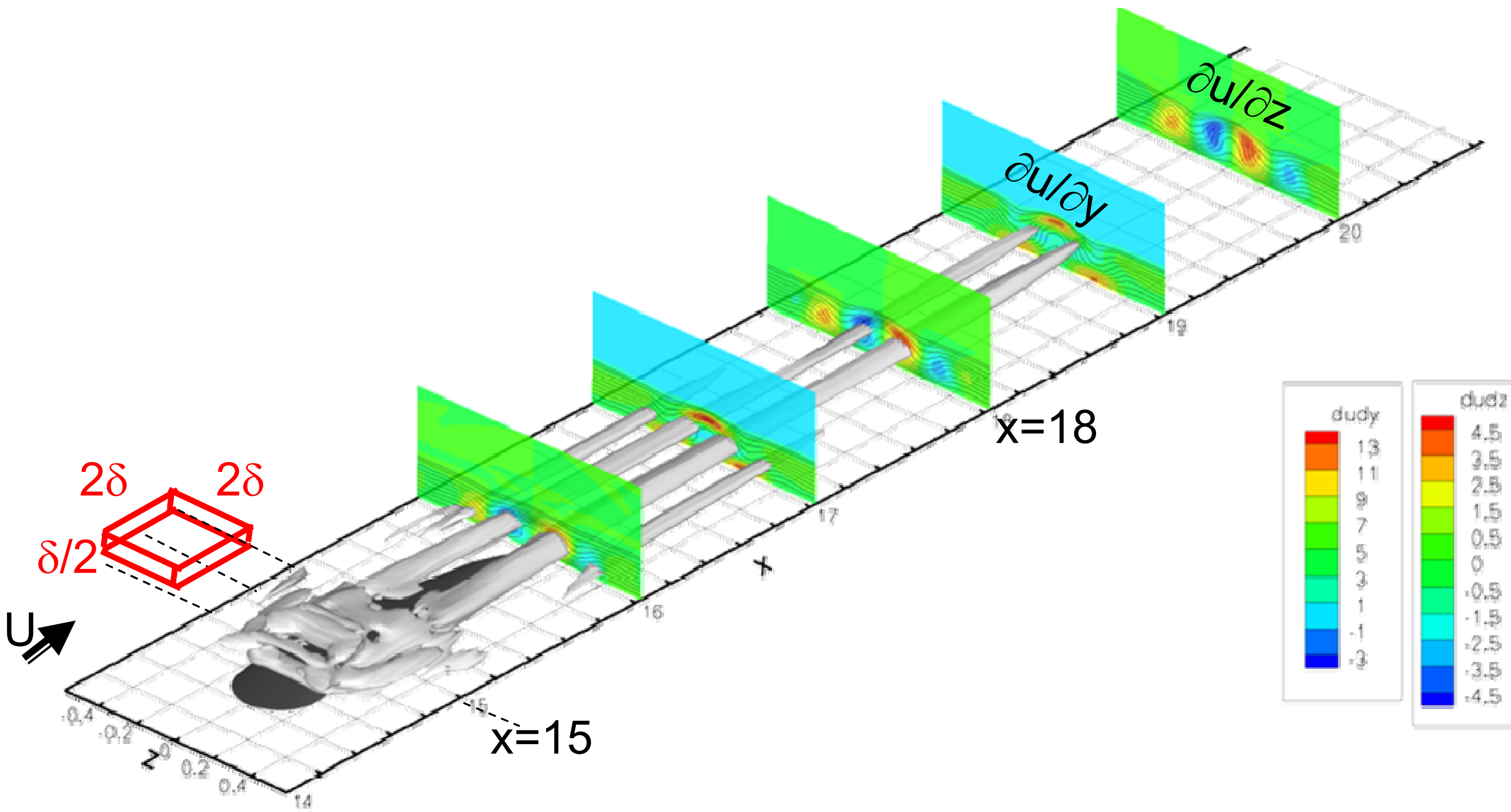
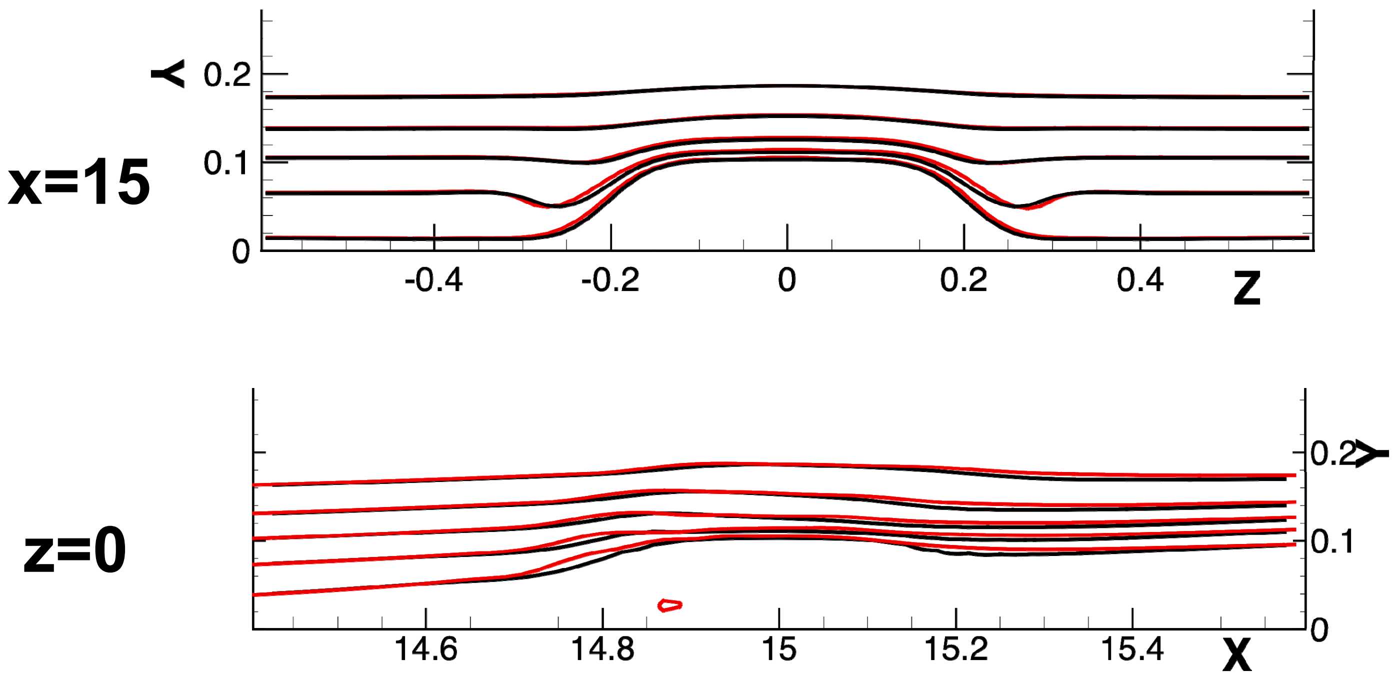


Figure: isosurface of λ_2 (light grey) and recirculation regions (dark grey)

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



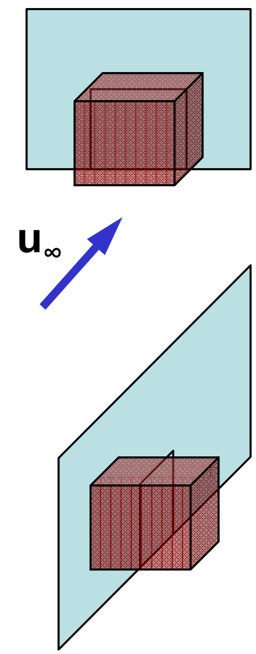


*Figure: Contours of **U** from body fitted (black contours) and immersed boundary method (red contours), planes cutting through the roughness.*

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

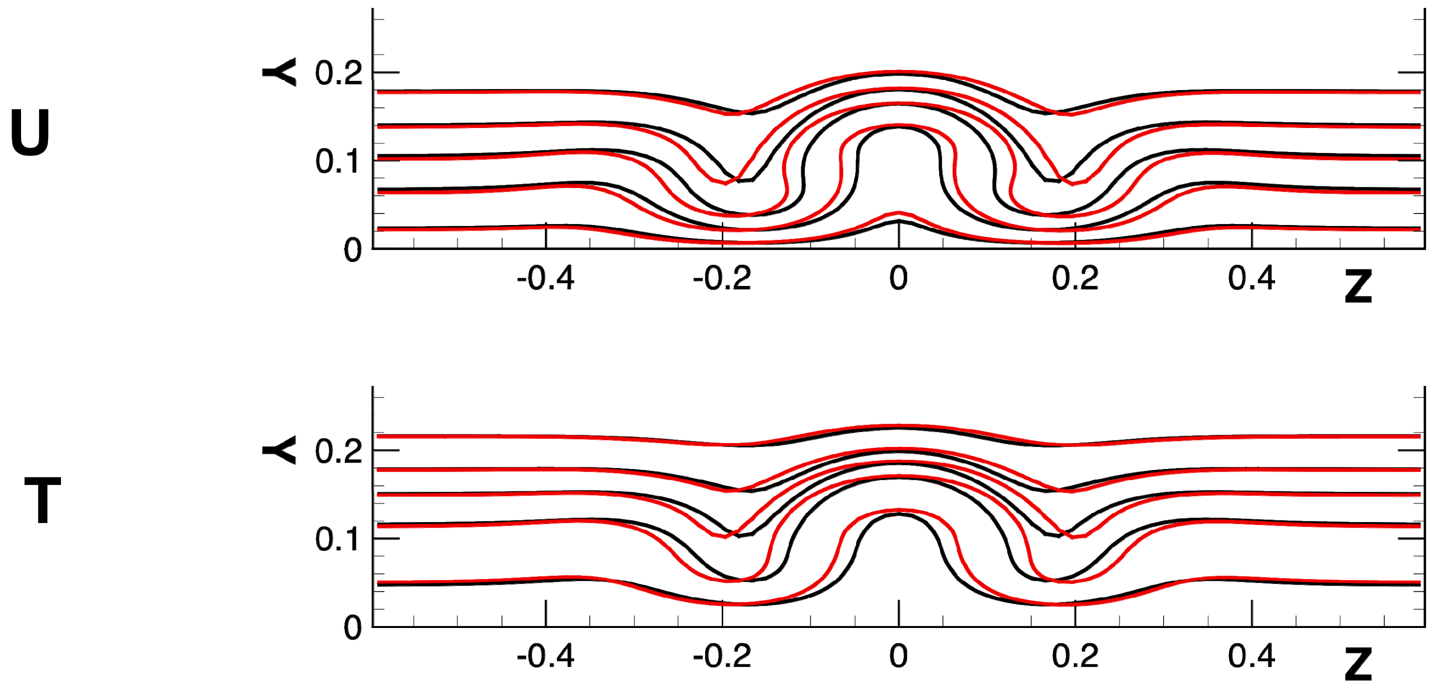


*Figure: Contours of **U & T** from body fitted (black contours) and immersed boundary method (red contours) behind the roughness, **x = 18**.*

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?)

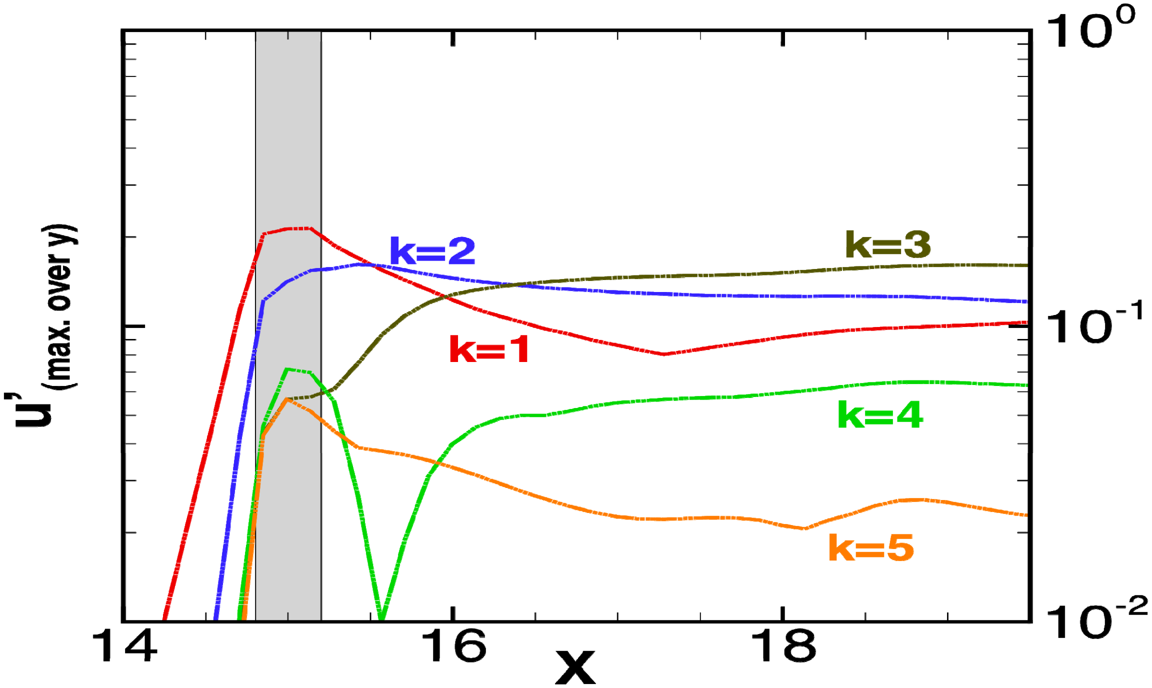


Figure: streamwise velocity u'_{max} for F=0 (steady component) for several spanwise wave numbers k and their sum. Location of the roughness in grey.

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DNS of the perturbed flow and comparison with stability analysis by *Groskopf & Kloker, 2008* [1]

[1] Groskopf, G., Kloker, M., Marxen, O. (2008), Proc. of the Summer Program, CTR, Stanford

Disturbance evolution I: DNS with 2-D forcing

Localized 3-d roughness: disturbance flow

- 2-D forcing with frequency $F=2\pi f^*(\mu^*/(\rho^* u^{*2}))=0.41\times10^{-4}$ upstream of the roughness ("first mode")
- Fourier analysis in time, disturb. maximum over y&z

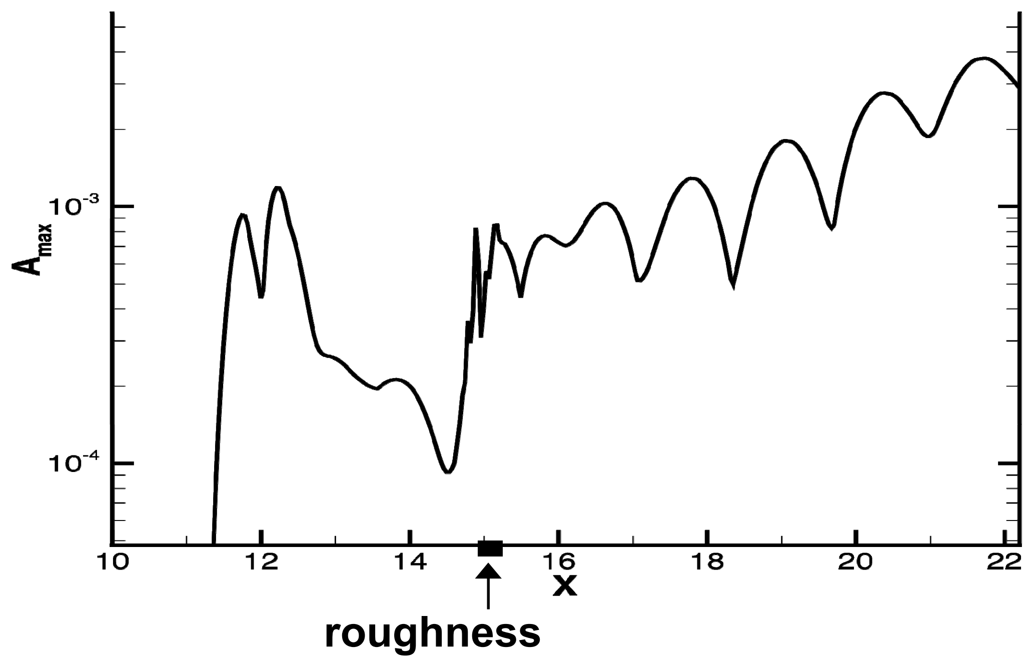

Figure: streamwise velocity u'_{max} for $F=0.41x10^{-4}$

Disturbance evolution II: DNS vs. bi-global theory

Localized 3-d roughness: disturbance flow

- DNS vs. bi-global Theory (*Groskopf et al., 2008* [1])

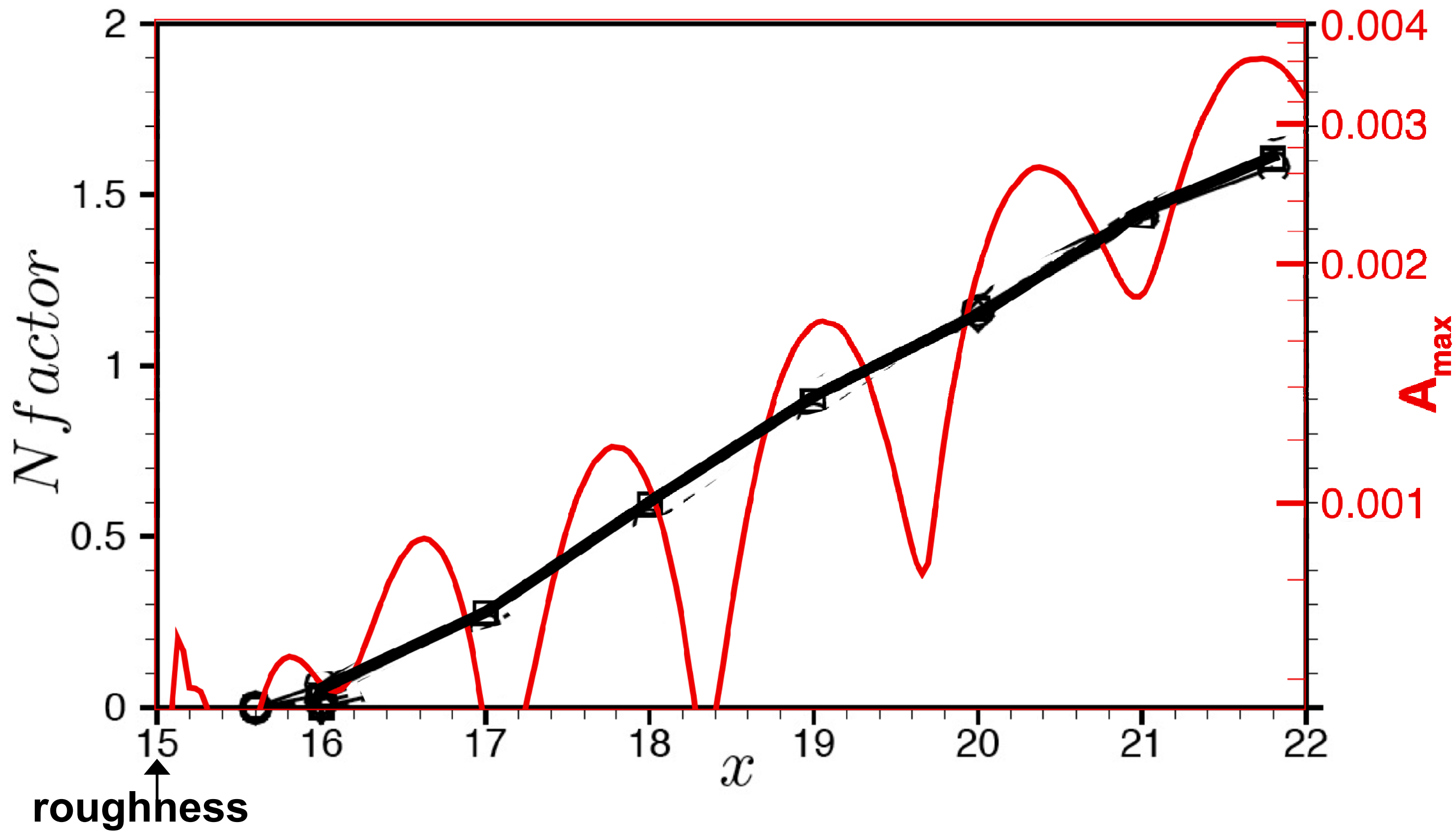

Figure: u'_{max} (max. over z&y) for $F=0.41x10^{-4}$ (red: DNS, black: theory)

[1] Groskopf, G., Kloker, M., Marxen, O. (2008), Proc. of the Summer Program, CTR, Stanford

Disturbance evolution III: amplitude functions

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

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

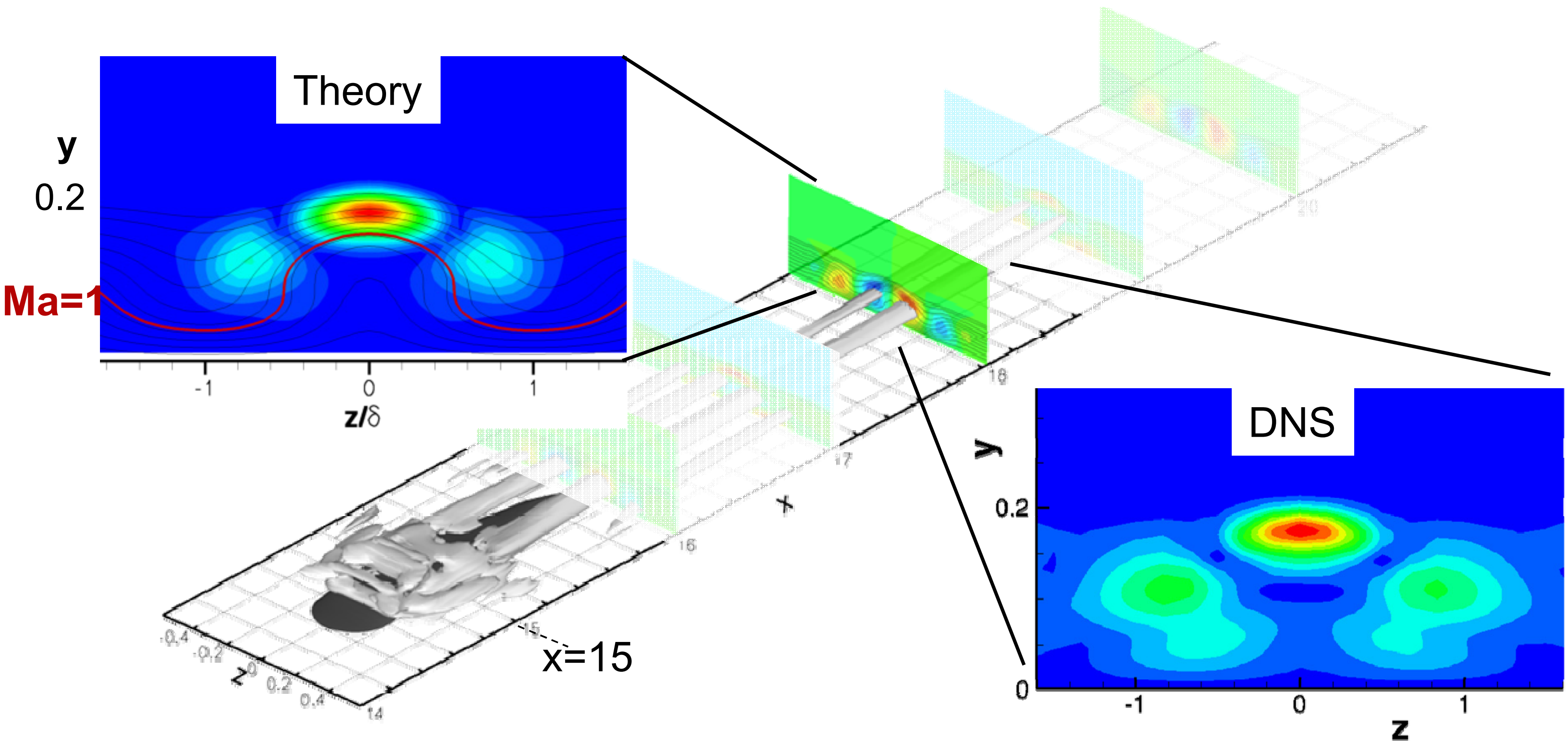

Figure: Amplitude functions of the streamwise velocity u' for F=0.41x10^{-4}, ***x=18***

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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)