Growth of disturbances in a pre-transitional boundary layer downstream of distributed surface roughness.

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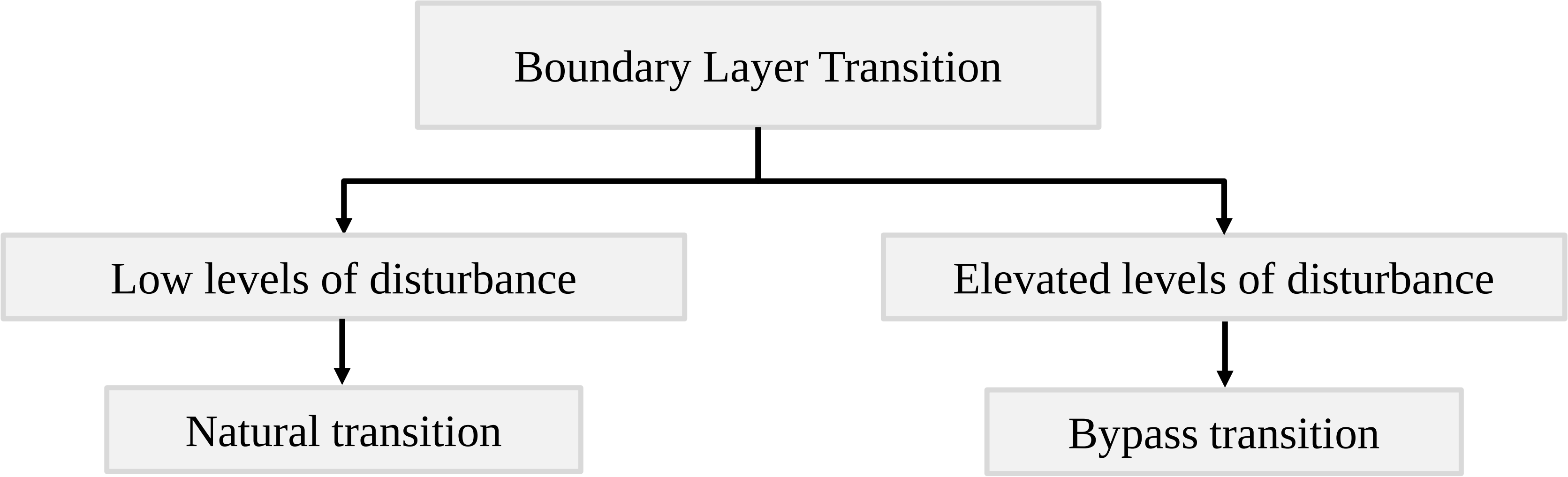
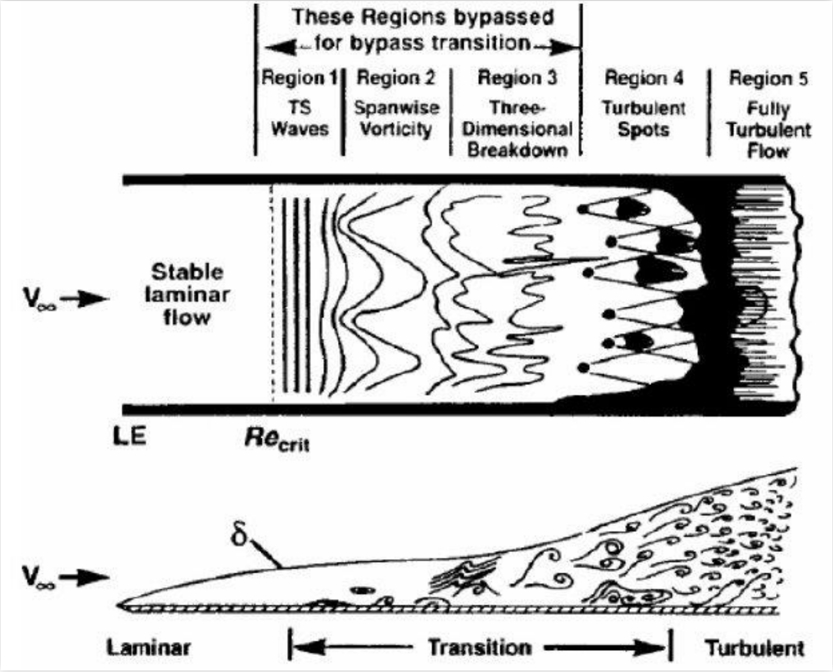
Boundary Layer Transition

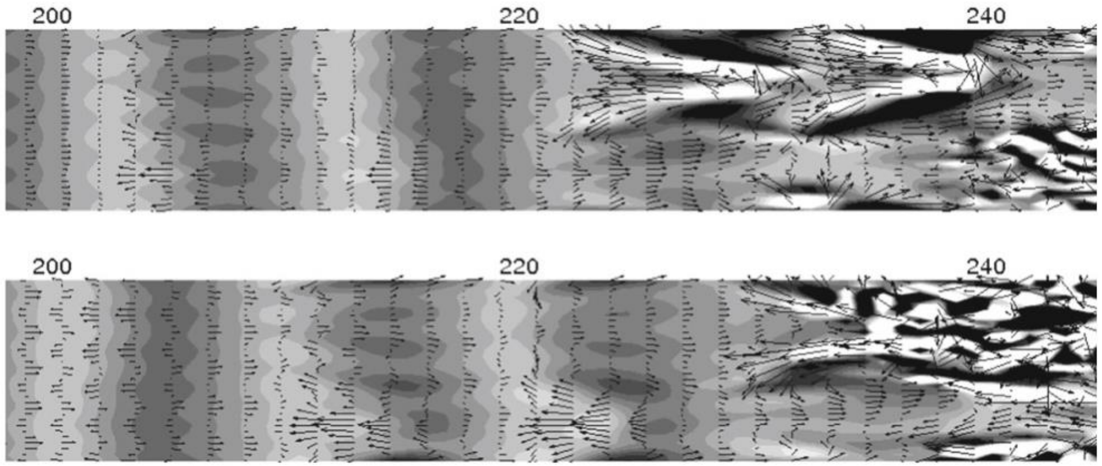


Natural Transition

- Occurs under low levels of external disturbances
- Transition via Tollmein-Schlichting waves which are Eigen solutions to the Orr-Sommerfeld equation
- The instability waves develop into Lambda vortices which breakdown to turbulence



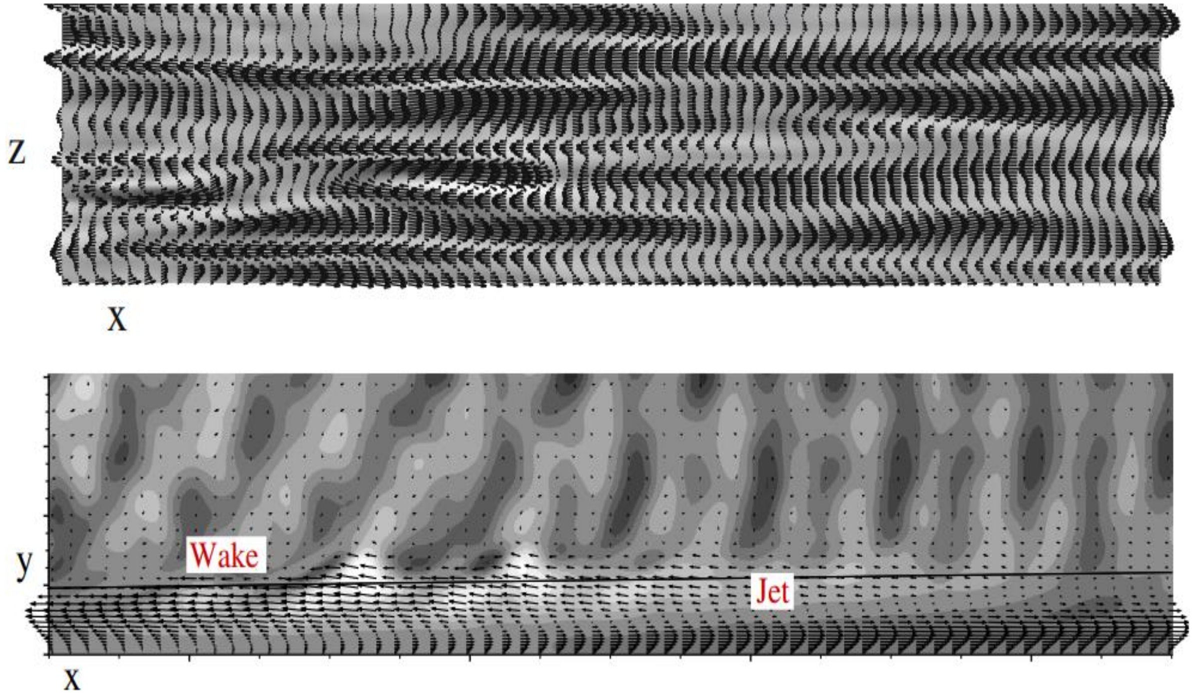
Visualization of Natural and Bypass transition. *Schlichting(1979)*



Visualization of Lambda structures in Bypass transition, *Durbin(2017)*

Bypass Transition

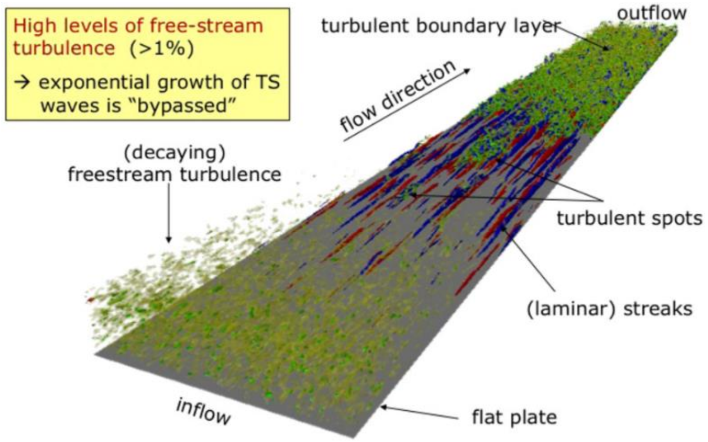
- Occurs under elevated levels of external disturbances
- The TS-wave transition route is **bypassed**
- Disturbances can be introduced outside the boundary layer(FST) or inside the boundary layer(Surface roughness)
- A commonly reported feature reported in bypass transition is the appearance of streaks which are elongated contours of streamwise velocity perturbation



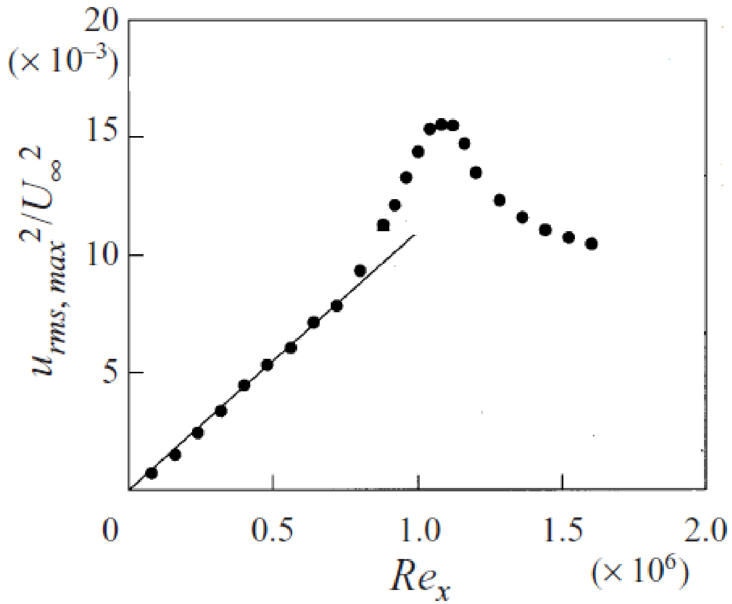
Visualization of streaks, wakes and jets in Bypass transition, *Durbin(2017)*

FST induced Transition

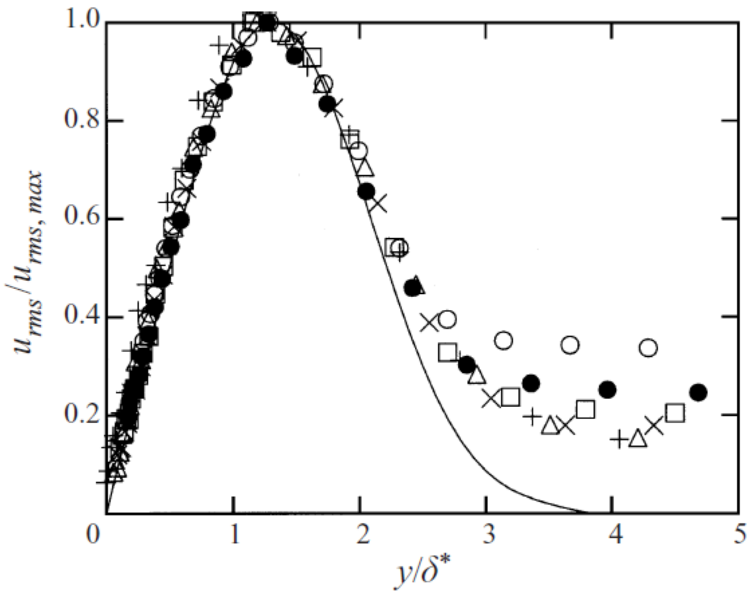
- Low frequency components of FST penetrate into the boundary layer resulting in the formation of streaks by **shear sheltering**
- The u_{rms} profiles are self-similar having a peak around y/$\boldsymbol{\delta}^*$=1.3 and growth of $(u_{(rms,max)})^2$ is linear with Re_x
- *Luchini(2000):* Optimal perturbation for Blasius boundary layer are steady streamwise vortices
- *Luchini(2000):* The wall normal location of peak in the fluctuating velocity profiles is largely invariant of the sub-optimality of the disturbance



Transition due to free stream turbulence. *Brandt et.al (2014)*



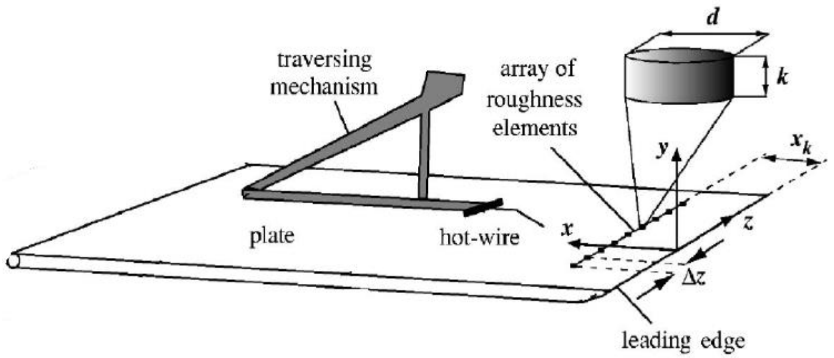
Linear Growth of $u^2_{rms,max}$ in FST induced transition, *Matsubara & Alfredsson(2000).*



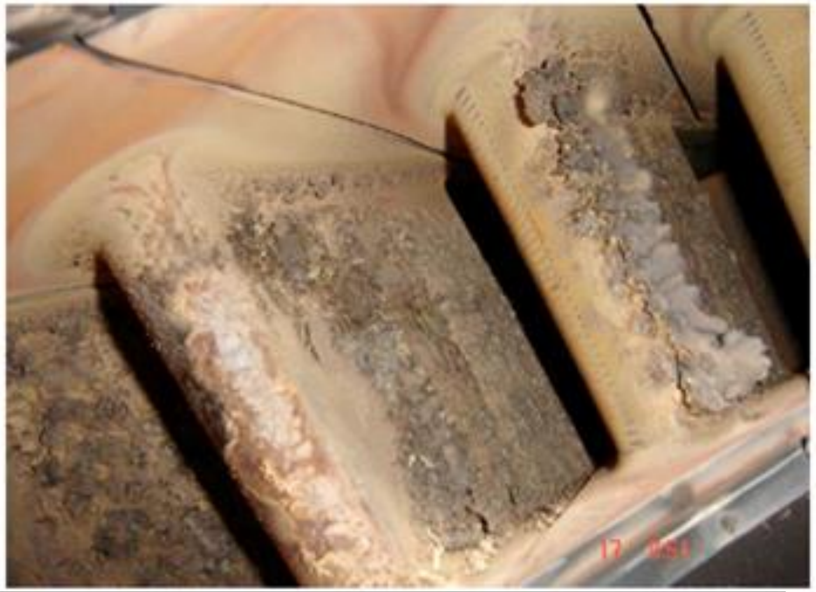
u_{rms} profiles, *Matsubara & Alfredsson(2000).* Solid line*: Luchini(2000)*

Roughness induced Transition

- Introduces disturbances **inside** the boundary layer(avoids shear sheltering)
- Several parameters like height of the roughness(k), gap between the roughness elements(Δz), distance from leading edge(x_k) etc. become important
- Random distributed roughness is representative of practical engineering surfaces, but it lacks a clear length scale
- *Durbin (2017):* Bypass transition caused by distributed surface roughness is not understood
- In gas turbines, roughness is characterized by converting it to an equivalent sandgrain roughness. Hence, for the present experiments, Sandpaper roughness will be used*(Bons (2010))*



Bypass transition by array of roughness. *Fransson et al. (2005)*

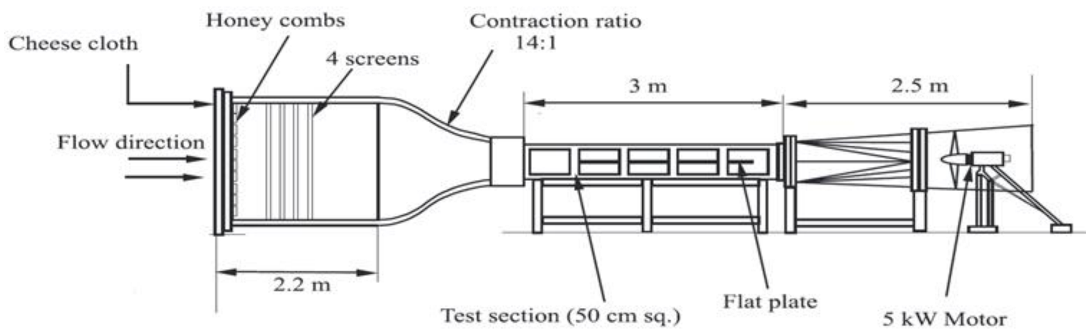


Deposition on first stage vane of gas turbine. *Bons(2010)*

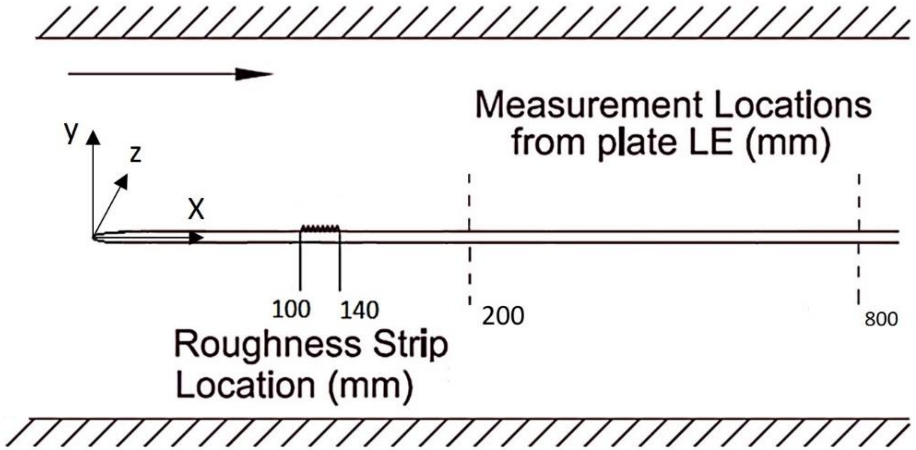
Objectives of the present work

- Investigate the growth of disturbances in the pre-transitional region of a boundary layer downstream of distributed roughness
- Compare the results with FST induced transition and existing theoretical results

Low speed wind tunnel

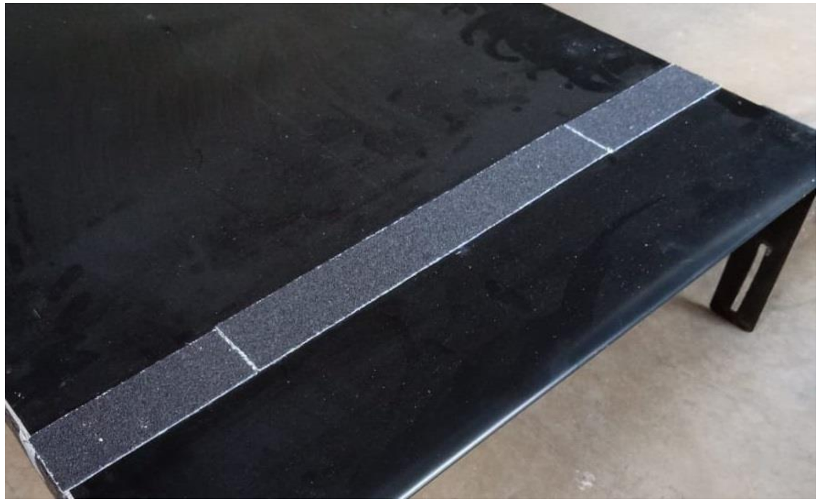


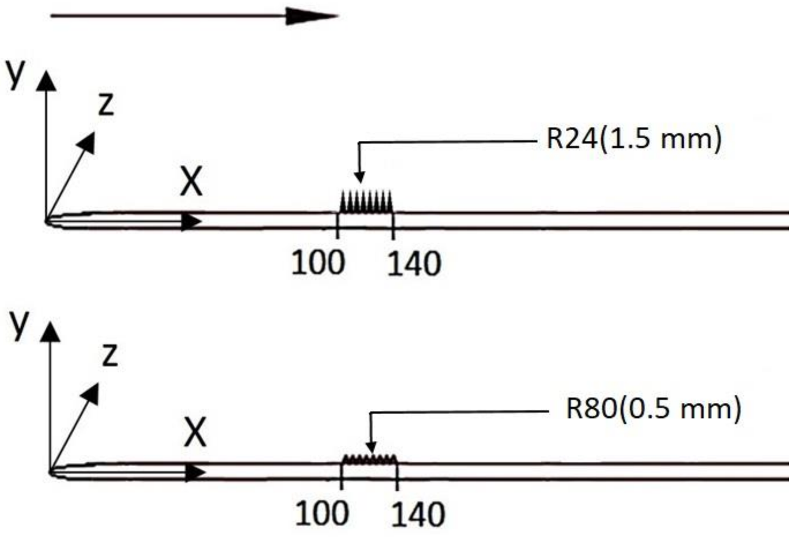
- Low speed open circuit wind tunnel(test section 50cm X 50cm) at Dept. of Aerospace Engineering, IISc-Bangalore
- Turbulence intensity is around 0.09% at U_∞=10 m/s
- Roughness strip is pasted that spans the full plate
- Strips of sand paper are used as distributed roughness
- Velocity signals are acquired using Constant Temperature single axis hot-wire anemometer from Dantec Dynamics



Roughness Specification

- Both roughness are 40 mm in the streamwise direction and cover the entire span
- Extra coarse emery cloth (Grade 24,~1.5 mm thickness) : hereon referred to as R24 roughness
- Silicon carbide waterproof (Grade 80,~0.5 mm thickness) : hereon referred to as R80 roughness
- The start of transition zone is fixed at X=500 mm from the leading edge and the free stream velocity is such that spots just start to appear at this location
- For R24, U_∞ = 6.7 m/s and for R80, U_∞ = 11.5 m/s.

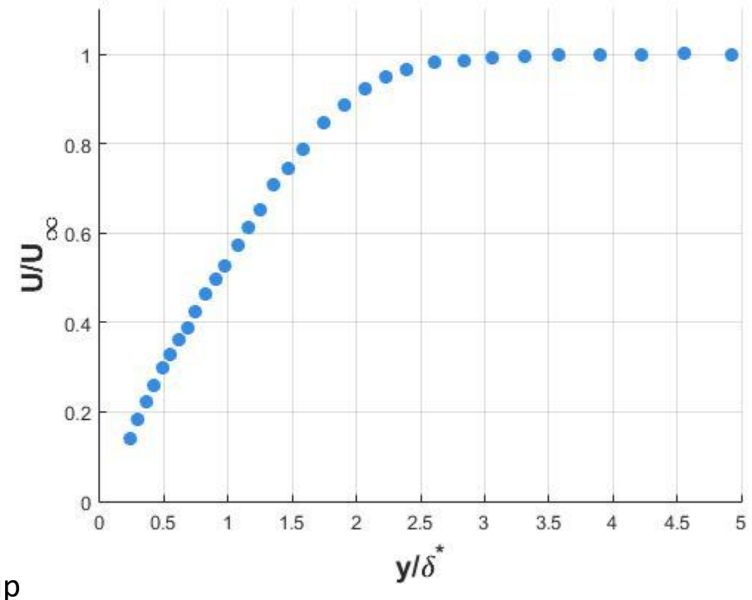




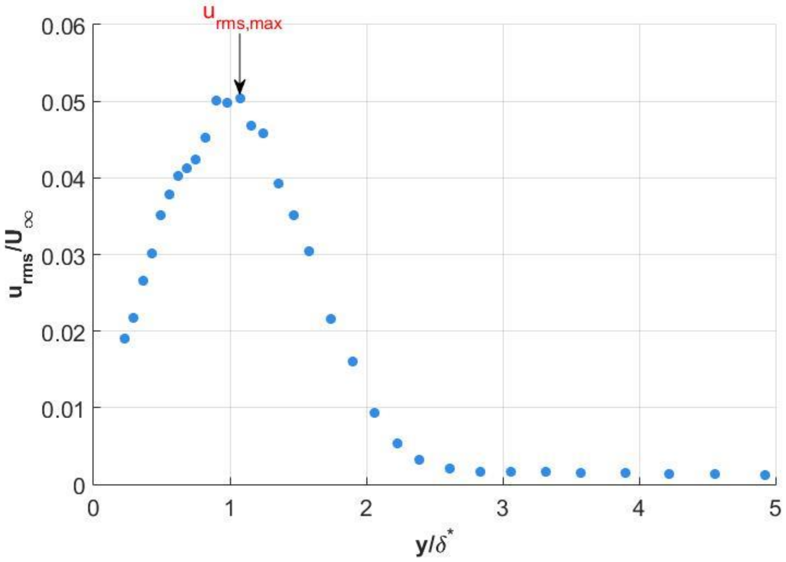
Photograph and Schematic of roughness configurations

Terminology

- X=Streamwise distance, y=wall normal distance.
- U=mean velocity ,U_∞ = Free stream velocity, u_{rms}= Root mean square of fluctuating velocity
- δ^* = Displacement thickness , k/ δ_{99} represents the ratio of height of the roughness to local boundary layer thickness.
- U and u_{rms} are non-dimensionalized by U_{∞}, y is non-dimensionalized by displacement thickness

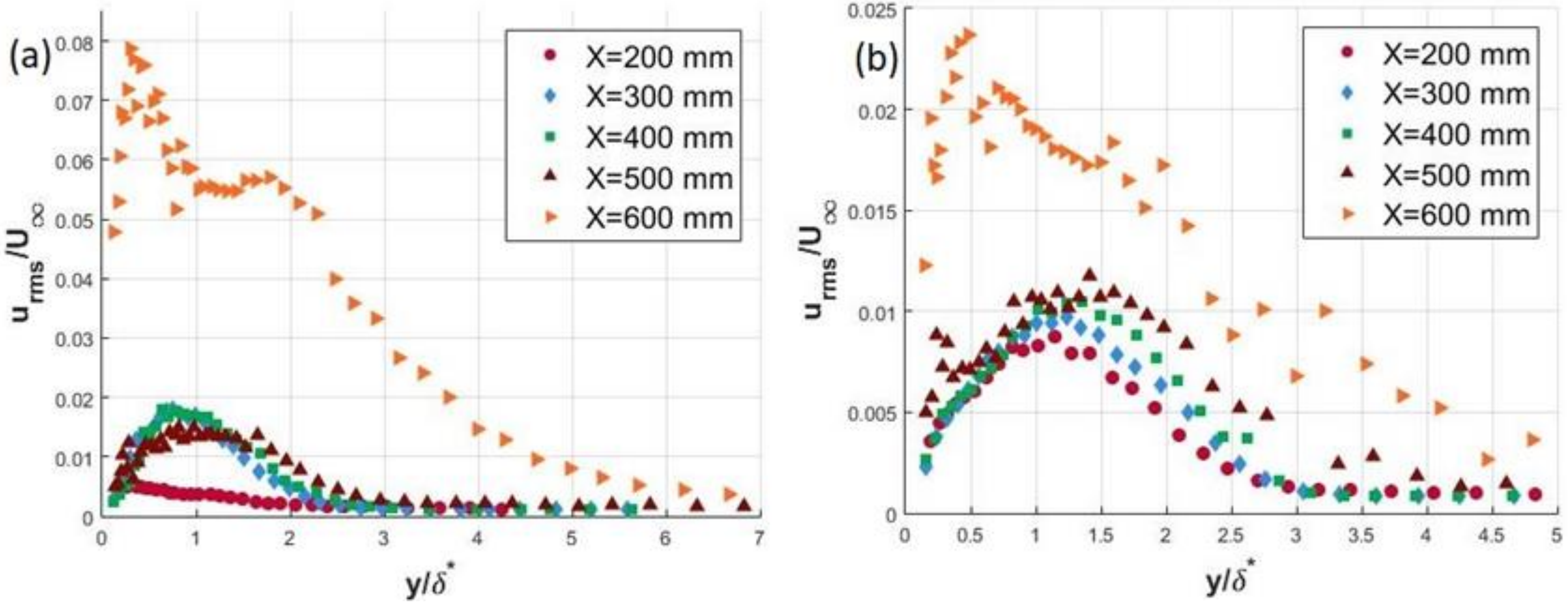


Mean velocity profile



Fluctuating velocity profile

Fluctuating velocity profiles

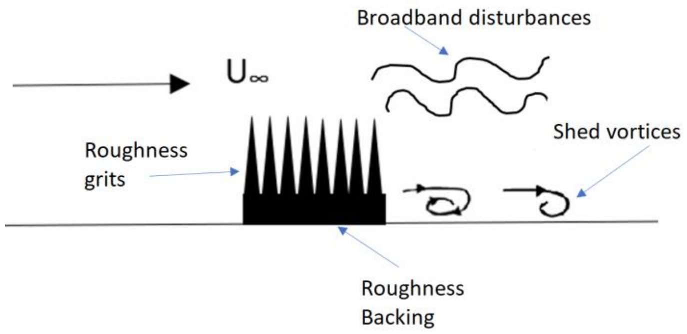


R24: U_∞ = 6.7 m/s

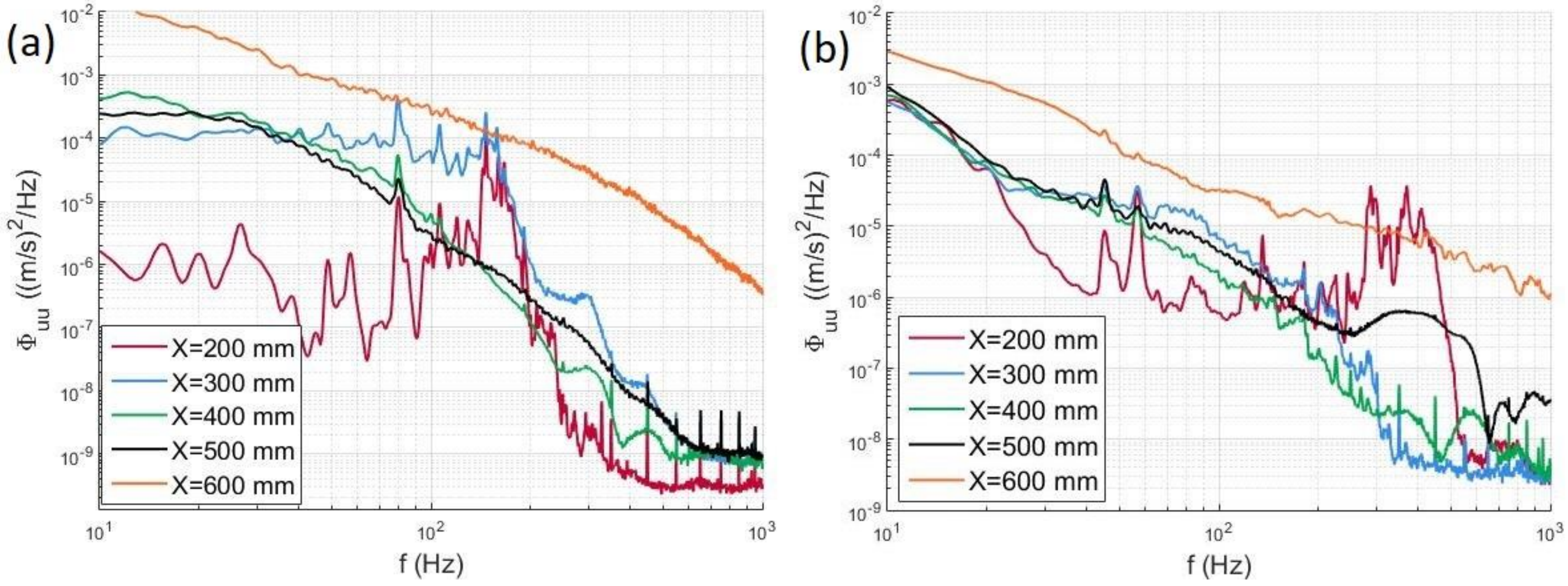
R80: U_∞ = 11.5 m/s

- The flow is transitional at X=600 mm. This justifies our decision of using appearance of spots as the location of start of transition
- A secondary peak is observed at X=500 mm(where turbulent spots just start to appear). This peak appears to later become the primary peak
- The scatter in data at X=500 and 600 mm is typical of early stages of transition and does not imply measurement inaccuracies. The acquisition duration of 60 seconds is more than 10^5 times the eddy turnover time($\boldsymbol{\delta}^*/U_\infty$)

Power Spectral Density



Types of disturbance

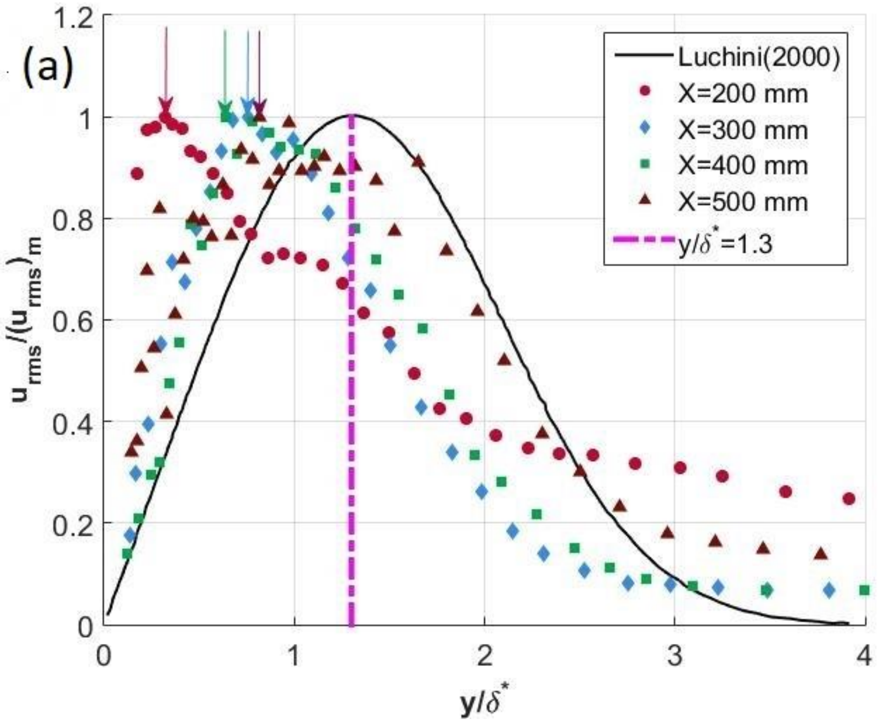


R24: U_∞ = 6.7 m/s

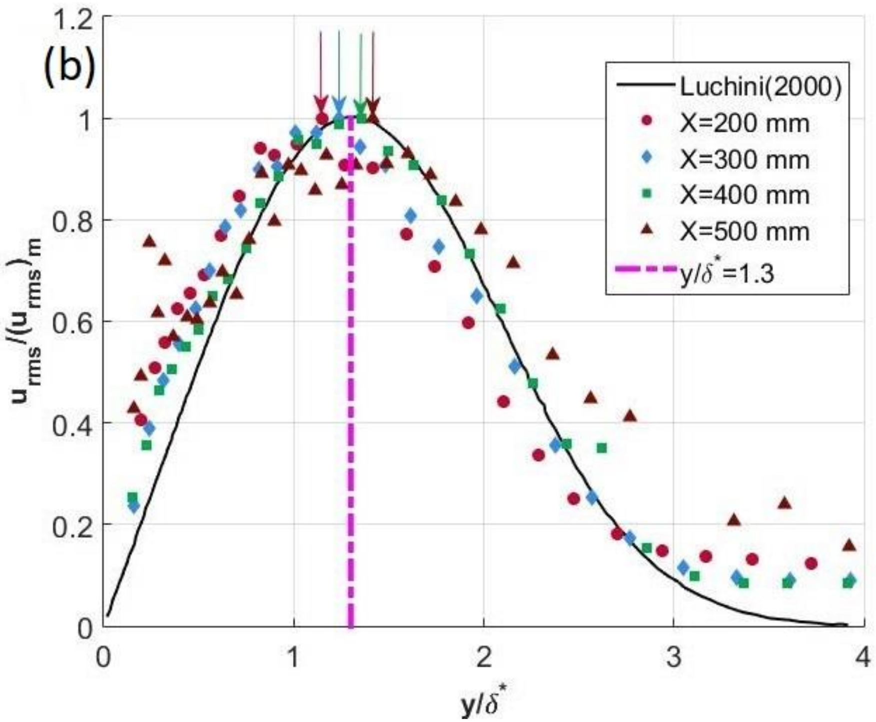
R80: U_∞ = 11.5 m/s

- At each streamwise location, the signal at the wall-normal location of maximum $u_{rms,max}$ is used to calculate the spectra
- The peaks are possibly due to vortices shed by the distributed roughness backing
- When the flow becomes transitional, the peaks have died out, hence we assert that transition is caused by broadband disturbance due to the roughness and not due to the vortices

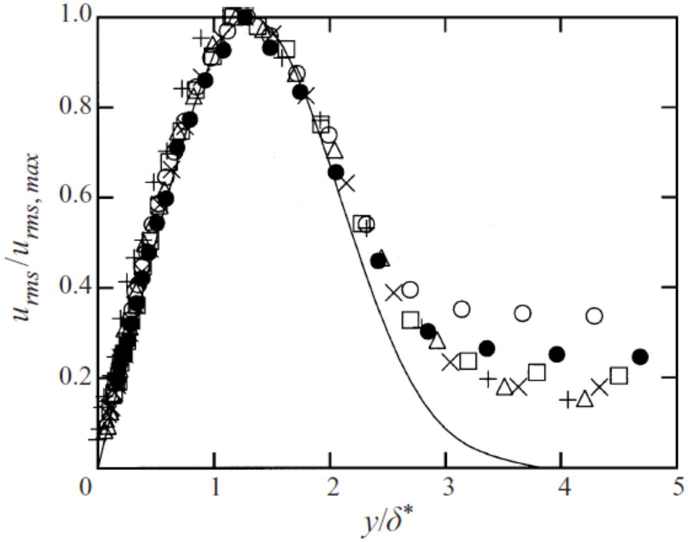
Fluctuating velocity profiles: Comparison with FST induced transition



R24: U_∞ = 6.7 m/s



R80: U_∞ = 11.5 m/s

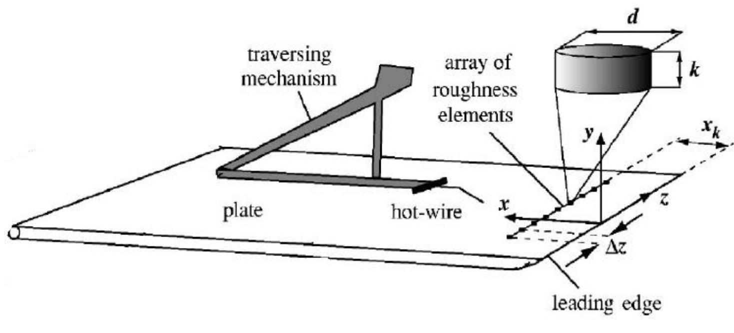


Self similar fluctuation velocity profiles, *Matsubara & Alfredsson(2000)*

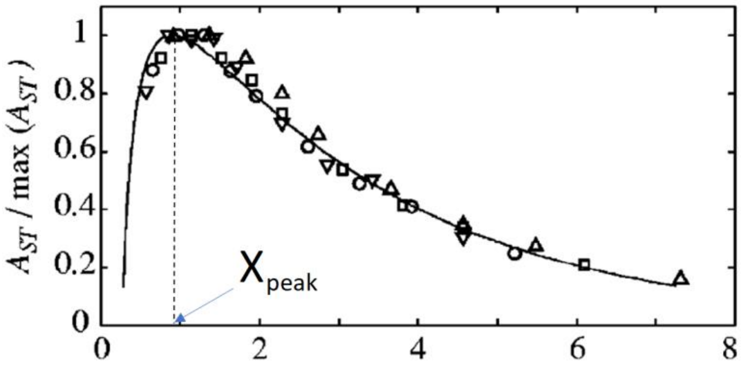
- The profiles are normalized with $u_{rms,max}$
- Clear deviation from *Luchini(2000*) and FST induced transition is observed

Fluctuating velocity profiles: Comparison with roughness induced transition

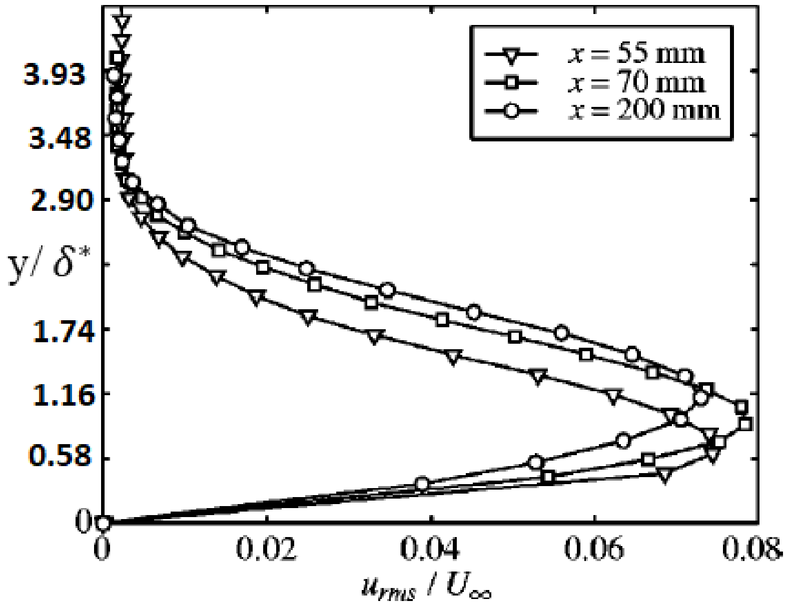
- *Fransson et al.(2004)* conducted **experimental and theoretical** measurements into the growth of disturbances introduced inside the boundary layer using an array of roughness elements
- With respect to the wall normal location of $u_{rms,max}$, these results **differ from *Luchini(2000)* and do not show self similar profiles**
- However, these are steady disturbances, unlike the results from FST induced transition



Bypass transition by array of roughness. *Fransson et al.(2004)*



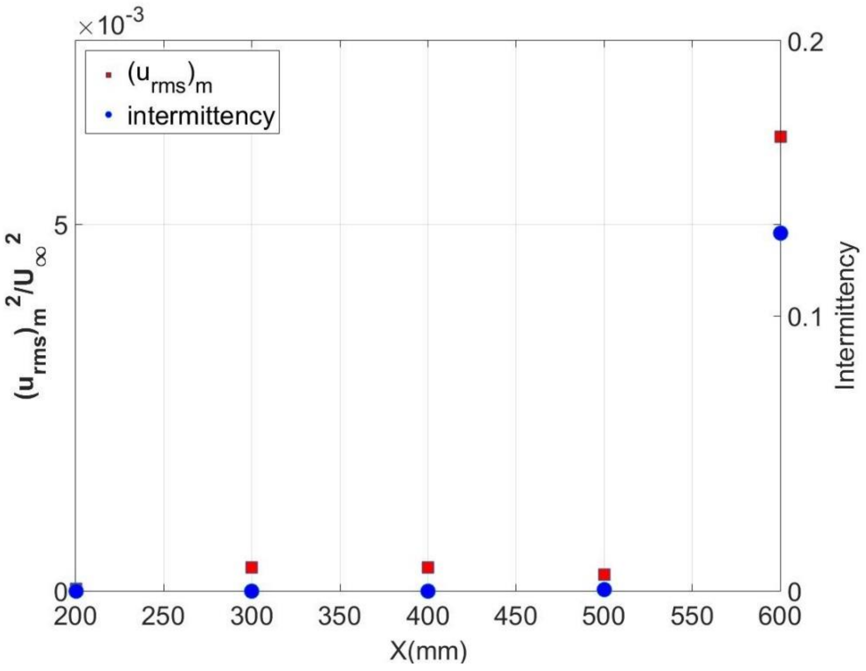
X_{peak} is the location of maximum streak amplitude



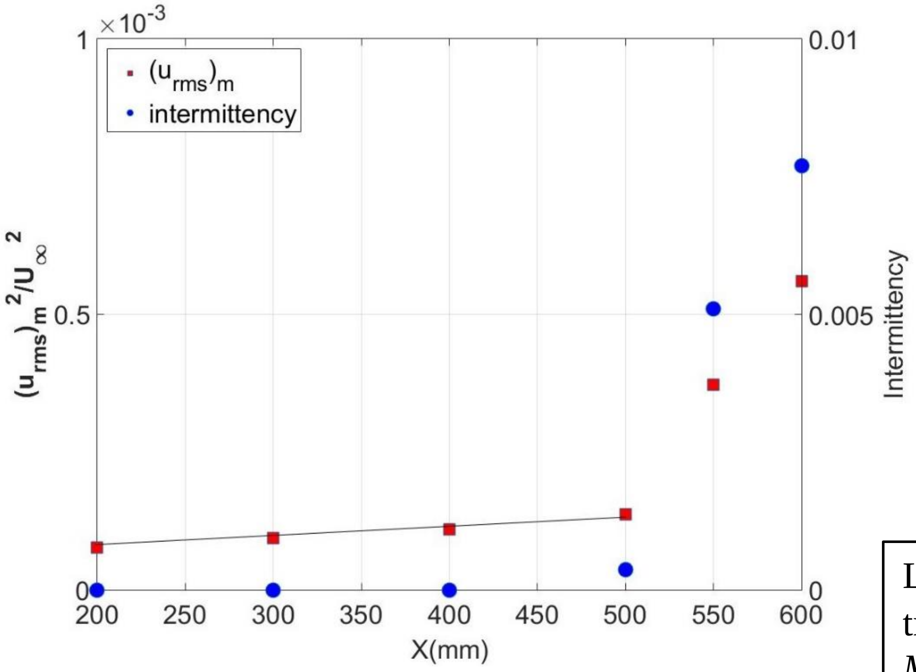
Disturbance profiles in the wall-normal direction for different down-stream locations. U_∞=7 m/s.

Fluctuating velocity profiles are not self similar, *Fransson et al.(2004)*

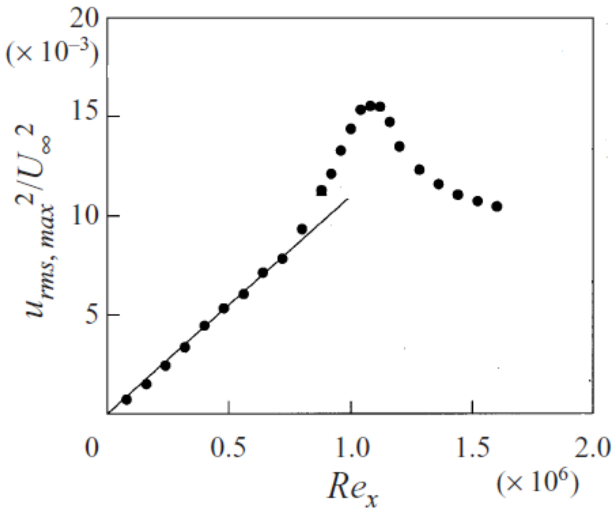
Growth of $u^2_{rms,max}$ and intermittency



R24: U_∞ = 6.7 m/s



R80: U_∞ = 11.5 m/s

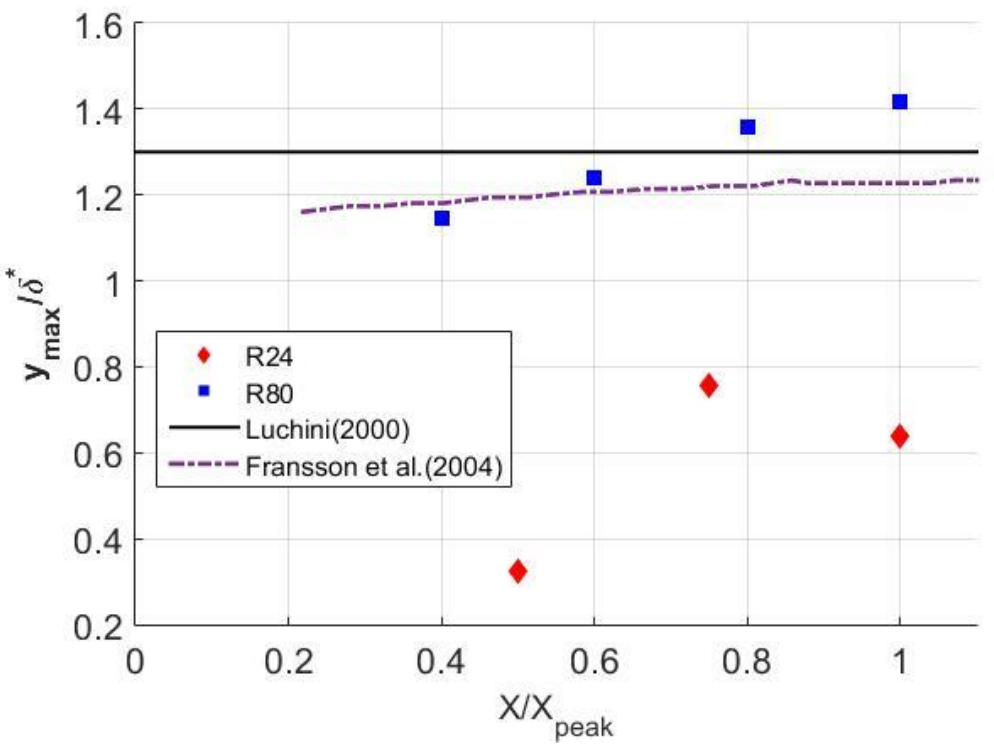


Linear Growth of $u^2_{rms,max}$ in pre-transitional stage of FST induced transition, *Matsubara & Alfredsson(2000).*

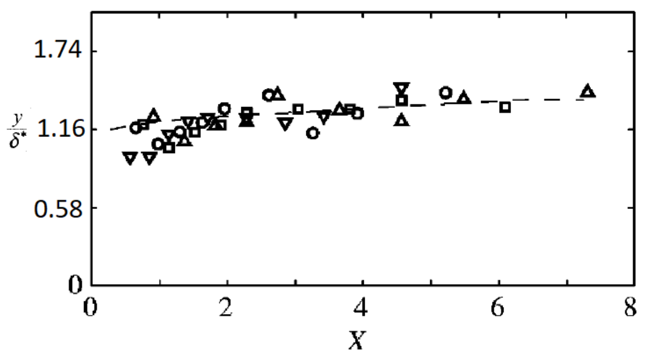
- Growth of $u^2_{rms,max}$ is linear for the R80 roughness, but not so for R24 roughness
- The apparent linear growth of R80 roughness is consistent with results from FST induced transition

Rough ness	Height (mm)	U_∞ (m/s)	δ_{99}(mm)	k/ δ_{99}
R24	1.5	6.7	2.40	0.64
R80	0.6	11.5	1.81	0.33

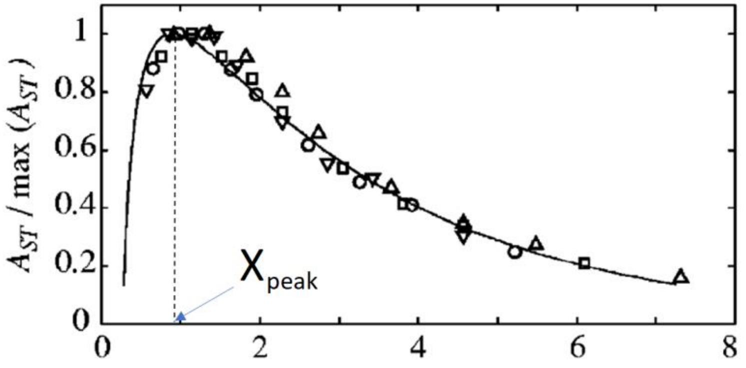
Fluctuating velocity profiles: Comparison with theoretical results



Comparison of y_{max} with existing theoretical results



Dashed line - best fitting to U_∞ =7 m/ s obtained theoretically.



X_{peak} is the location of maximum streak amplitude

- y_{max} is the wall normal location of $u_{rms,max}$. Unlike *Luchini(2000)*, it is clearly not at y/δ*=1.3
- The R80 roughness shows qualitative similarity to *Fransson et al.(2004)*
- *Fransson et al.(2004)* considered **steady disturbances** from an array of roughness elements and adjusted their sub-optimality parameters to match the experimental results.

Summary of Results

- There seems to be linear of growth of disturbance energy in the pre-transitional region similar to FST induced transition for R80 roughness
- But, unlike FST induced transition and Luchini(2000), the fluctuating velocity profiles are not self-similar
- The gradual movement of the wall-normal location of the fluctuation velocity peak away from the wall as we move downstream is qualitatively similar to Fransson et al. (2004), who considered **steady** disturbances introduced **inside** the boundary layer
- The R24 roughness does not show similarity to existing results from FST induced transition or Roughness induced transition
- The growth of disturbance energy is not linear and the fluctuation velocity profiles all have their peaks at $y/\delta^* < 1$.
- The higher k/δ_{99} of R24 roughness(0.64)compared to R80(0.33), which might distort the boundary layer substantially

Conclusions

- Distributed roughness introduces disturbances **inside** the boundary layer, unlike FST which introduces disturbances **outside** the boundary layer
- Based on the present results and experiments conducted by *Fransson et al.(2004)*, it appears that *Fransson et al.(2004)* 's theoretical analysis might be more appropriate for roughness induced transition instead of *Luchini'(2000)*
- Future work involves analysing similar experiments using other types of distributed roughness and PIV measurements

Thank you

Fransson et al.(2004) growth and decay of disturbances

Roughness	**Height (mm)**	**U_∞ (m/s)**	**δ_{99}(mm)**	**k/ δ_{99}**
R24	1.5	6.7	2.40	0.64
R80	0.6	11.5	1.81	0.33
Fransson et al. (2004)	0.78	8	1.42	0.55

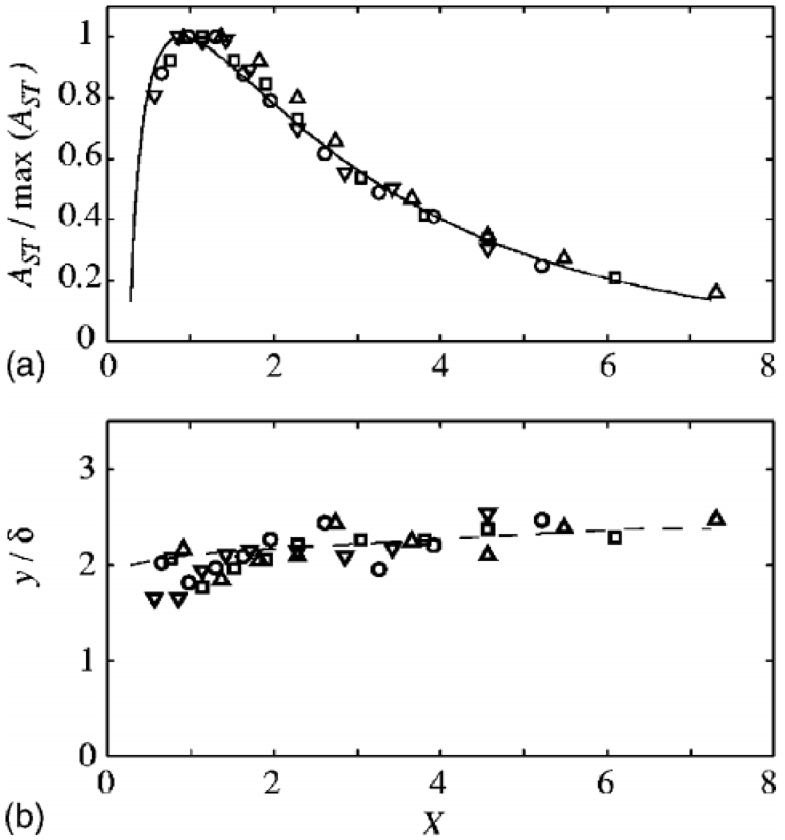
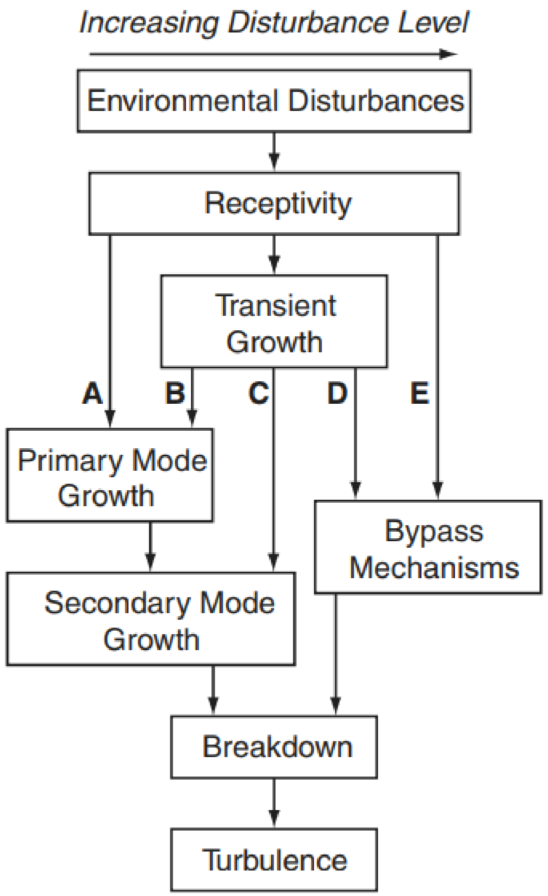


FIG. 11. Comparison between the experimental results for all U_∞ in Table I and the best fitting to U_∞=7 m/s obtained using initial vortices confined closer to the wall (c=0.78). (a) Wall-normal maximum of the streak amplitude. (b) Wall-normal position of the maximum perturbation.

Routes to transition



Transition Roadmap, *Morkovin et al. (1994).*

At times, the freestream disturbances are so strong that the growth of linear disturbances is bypassed (Morkovin 1969, 1993) and turbulent spots or subcritical instabilities occur and the flow quickly becomes turbulent. This corresponds to path *E* in Figure 1, and although the phenomenon is not well understood, it has been documented in cases of roughness and high freestream turbulence (Reshotko 1984, 1994, 2001). In this case, transition prediction schemes based on linear theory fail completely

BOUNDARY-LAYER RECEPTIVITY TO FREESTREAM DISTURBANCES
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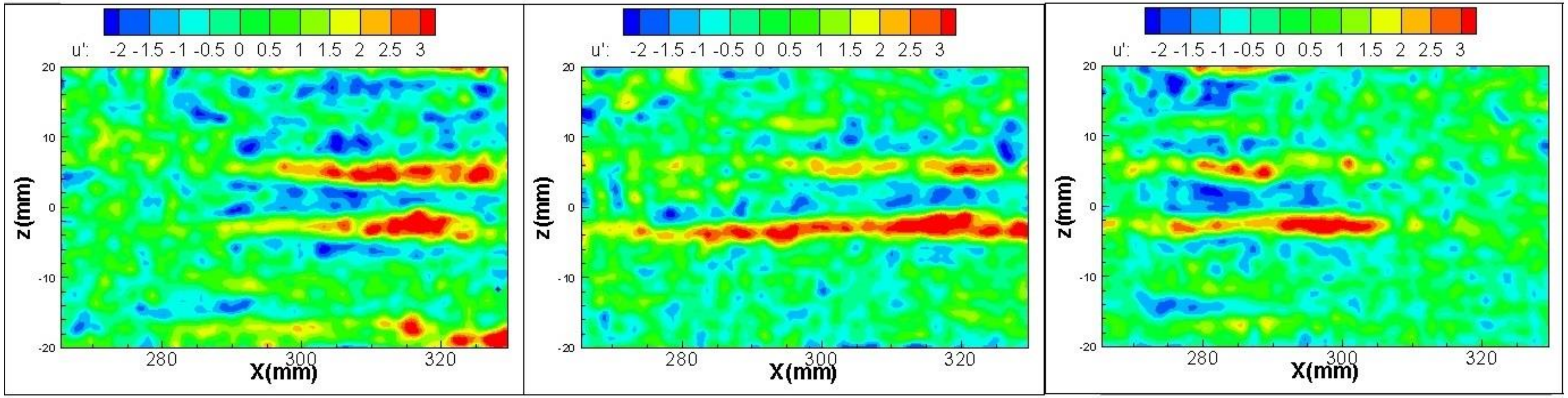
Appendix

R80 roughness



R80: U_∞ =13.3 m/s, y=0.5 mm , fluctuating velocity contours

- Features similar to streaks can be observed in the fluctuating contours.
- The streaks do not appear in the mean velocity contour.

R80: U_∞ =13.3 m/s , y=0.5 mm , mean velocity contour