Receptivity of Boundary Layers

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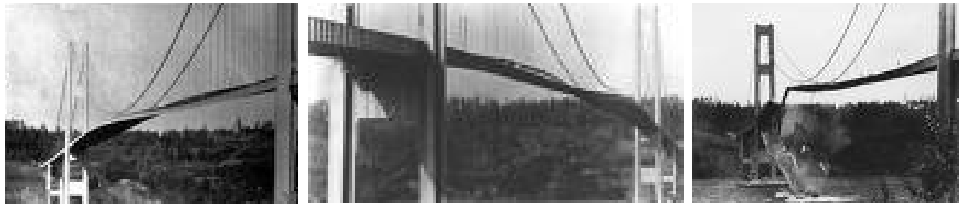
12th Ercoftac NPC meeting, Näsby slott, Stockholm
May 29-30, 2008

Outline

- What is ***receptivity***?
- Disturbances
- Swept flat-plate boundary layer
- Boundary layer on a 2D leading edge
- Conclusions
- Outlook

Receptivity - I

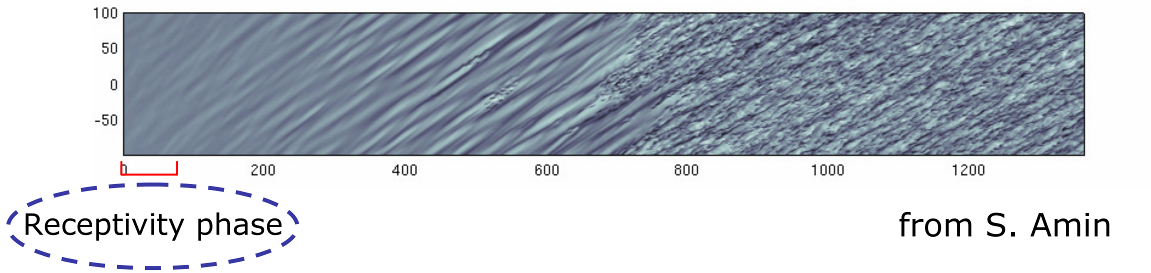
- Tacoma Narrows Bridge, WA, USA (1940)



- Bridge = dyn. system subject to B.C.
  - Eigenmodes with char. frequency and wavelength
- Forcing through external perturbation by wind
  - Vortex shedding at pillars near resonance frequency
  - Energy transfer from vortices to eigenmode of bridge
  - Bridge is ***receptive*** to shed vortices
- Disturbance growth and “breakdown”

Receptivity - II

- <u>Swept-plate boundary layer, SE, EU (2008)</u>



from S. Amin

- BL = dyn. system subject to B.C.
  - Eigenmodes with char. frequency and wavelength
- Forcing through free-stream turbulence
  - Energy transfer from FS vortices to BL eigenmodes
  - BL is ***receptive*** to FS vorticity
- Disturbance growth and “breakdown” to turbulence

Receptivity - III

- Efficiency of energy transfer measured in terms of ***receptivity coefficient***

$$C = \frac{\text{Amplitude of BL eigenmode}}{\text{Amplitude of forcing disturbance}}\Bigg|_{\text{Receptivity site}} = \frac{A_{BL}}{\varepsilon_f}\Bigg|_{\text{Rec. site}}$$

- Effective (=branch I) receptivity coefficient…

$$C_{eff} = \frac{A_{BL,I}}{\varepsilon_{f,Rec.\ site}} = \frac{C}{e^{N_{Rec.\ site}}}$$

- …and its usefulness

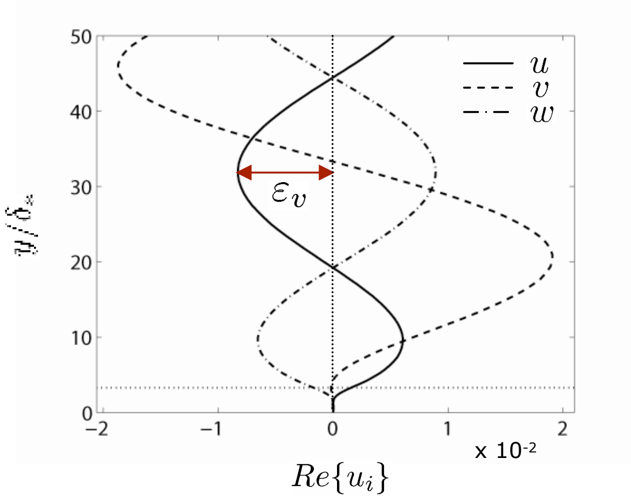
$$A_{BL}(x) = \varepsilon_{f,Rec.\ site} C_{eff} e^{N(x)}$$

→ ***Rec. coeff.+standard e^N-method give disturbance ampl. at any downstream location in region of linear growth***

Disturbances - I

- Vortical free-stream disturbance
  - Fourier mode or continuous-spectrum Orr-Sommerfeld mode

$$C_v = \left.\frac{A_{BL}}{\varepsilon_v}\right|_{\text{Rec. site}}$$



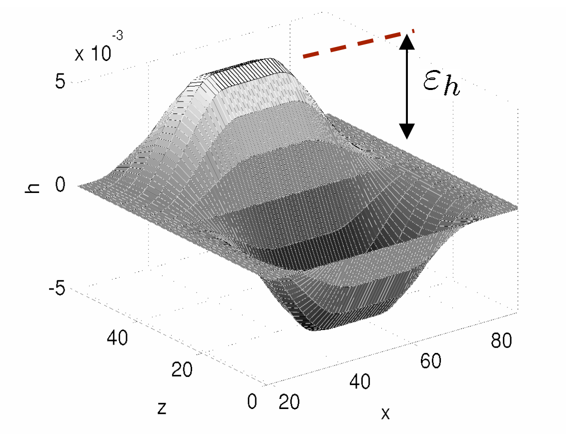
- Acoustic free-stream disturbance
  - Planar wave with zero streamwise wavenumber (incompr. flow)

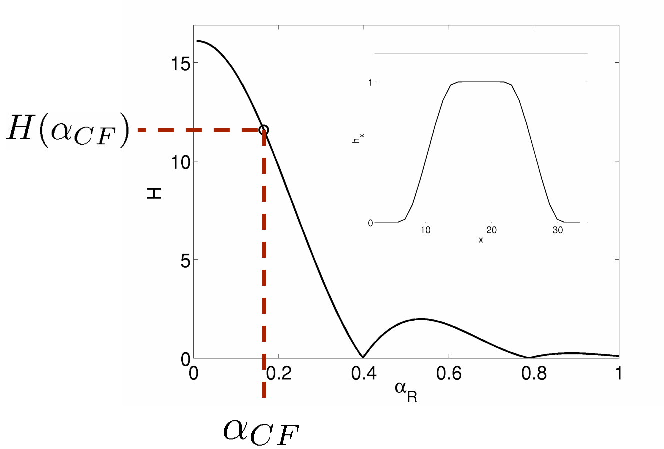
$$u' = \varepsilon_{ac} e^{i\omega t}$$

$$C_{ac} = \left.\frac{A_{BL}}{\varepsilon_{ac}}\right|_{\text{Rec. site}}$$

Disturbances - II

- Localised surface roughness

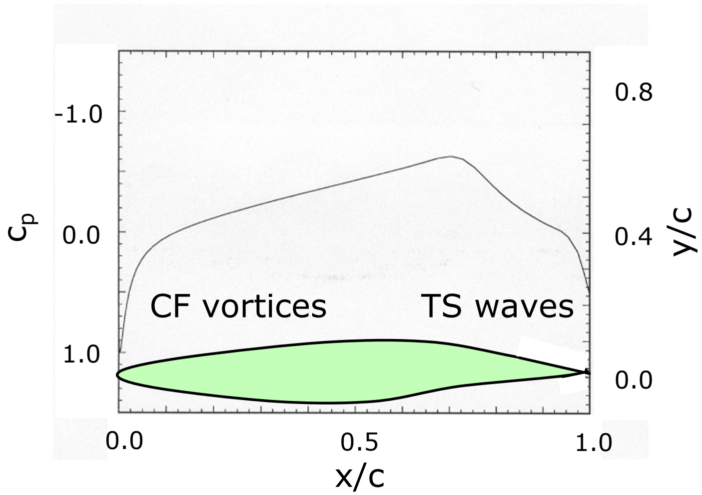




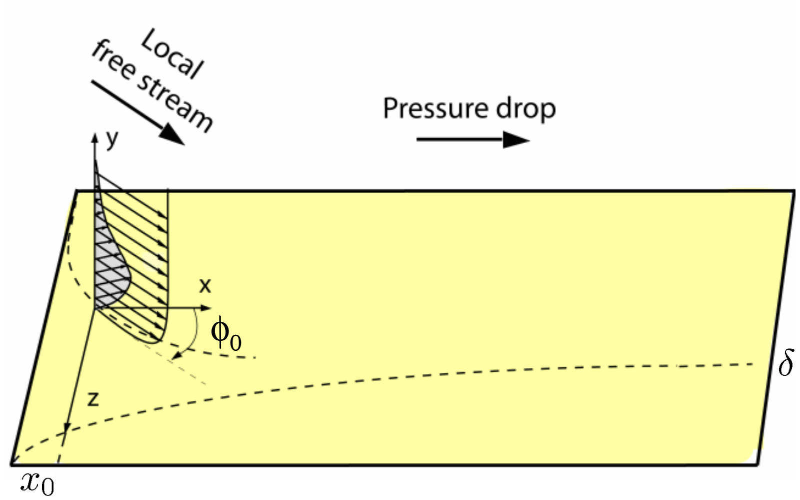
$$C_R = \left. \frac{A_{BL}}{\varepsilon_h H(\alpha_{CF})} \right|_{\text{Rec. site}}$$

Swept flat-plate BL - I

- Model problem for favorable p-gradient region on swept wings
  - Excitation of cross-flow instability



Based on Saric et al. (1998)

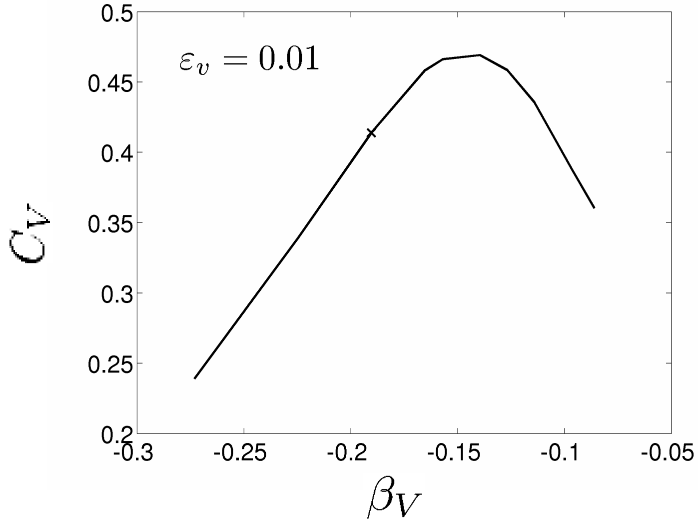


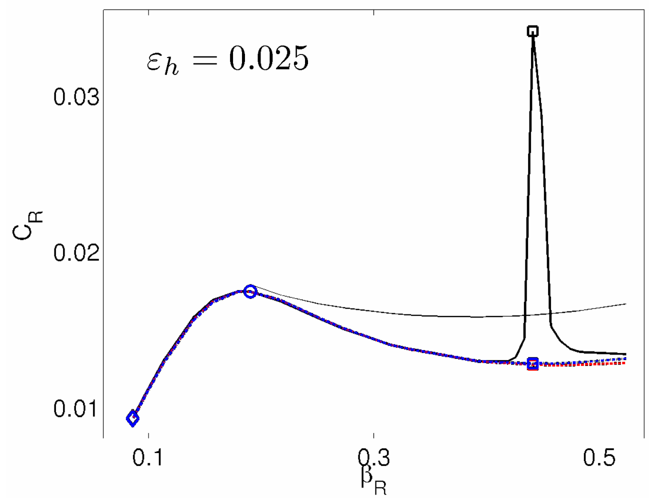
Swept flat-plate BL -II

- Receptivity to FS vortex and roughness element
  - Optimal spanwise wavenumber

$$C_v = \left.\frac{A_{BL}}{\varepsilon_v}\right|_{\text{Rec. site}}$$

$$C_R = \left.\frac{A_{BL}}{\varepsilon_h H(\alpha_{CF})}\right|_{\text{Rec. site}}$$

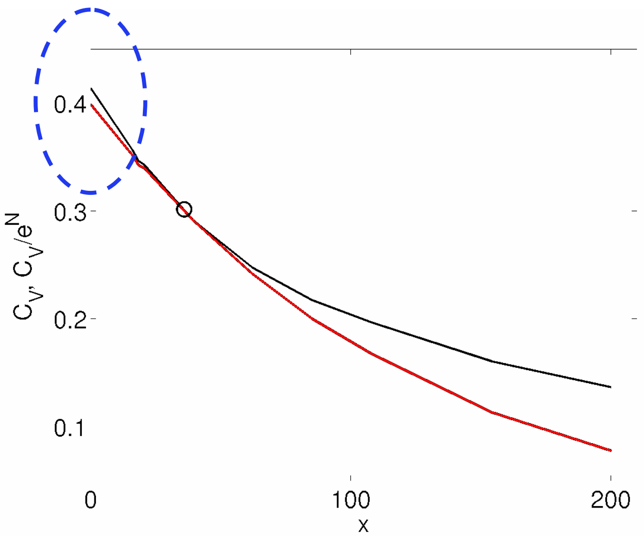




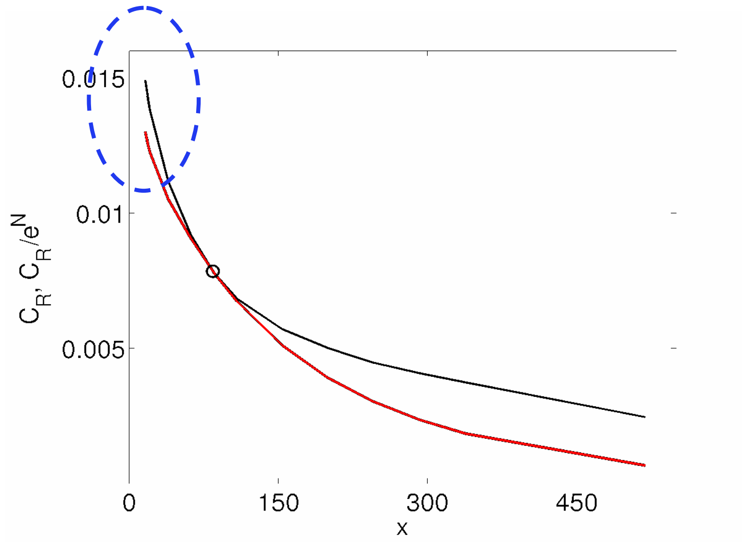
Swept flat-plate BL -III

- Receptivity to FS vortex and roughness element
  - Optimal chordwise location

$$C_v = \left. \frac{A_{BL}}{\varepsilon_v} \right|_{\text{Rec. site}}$$



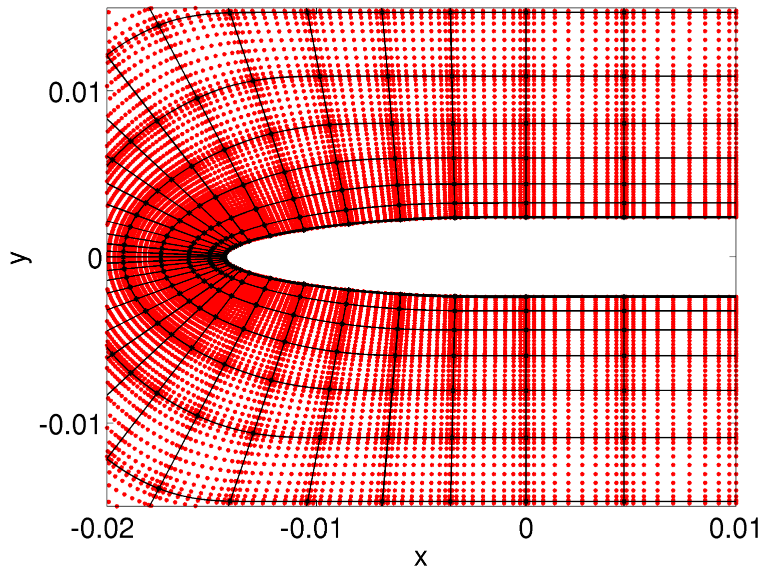
$$C_R = \left. \frac{A_{BL}}{\varepsilon_h H(\alpha_{CF})} \right|_{\text{Rec. site}}$$

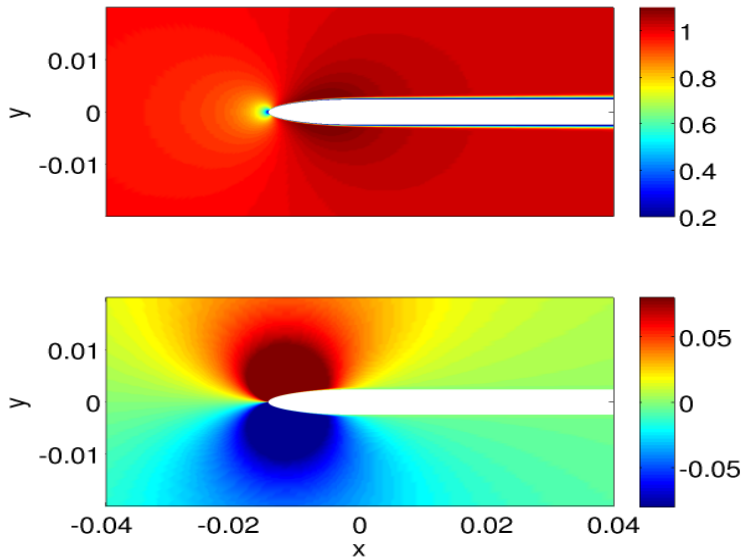


→ ***Need to include leading-edge region***

BL on a 2D leading edge - I

- Elliptic leading edge attached to flat plate

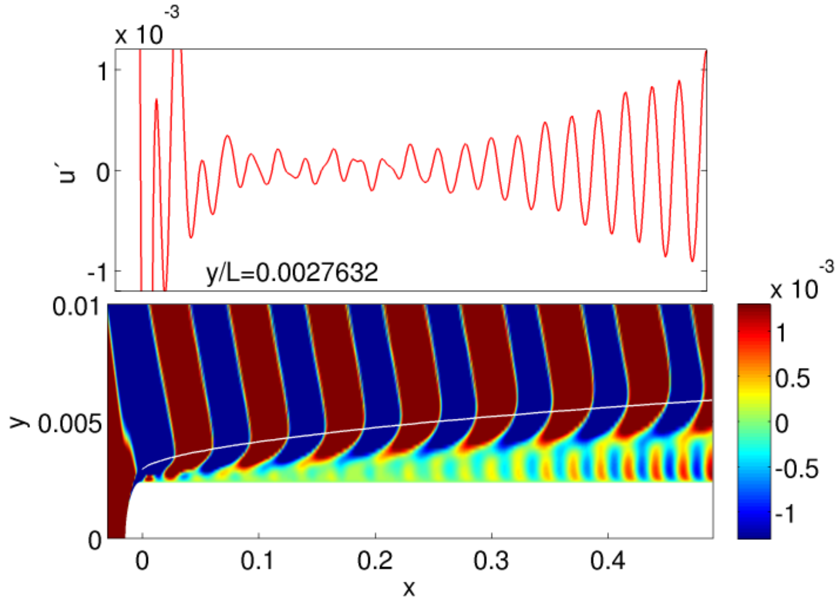




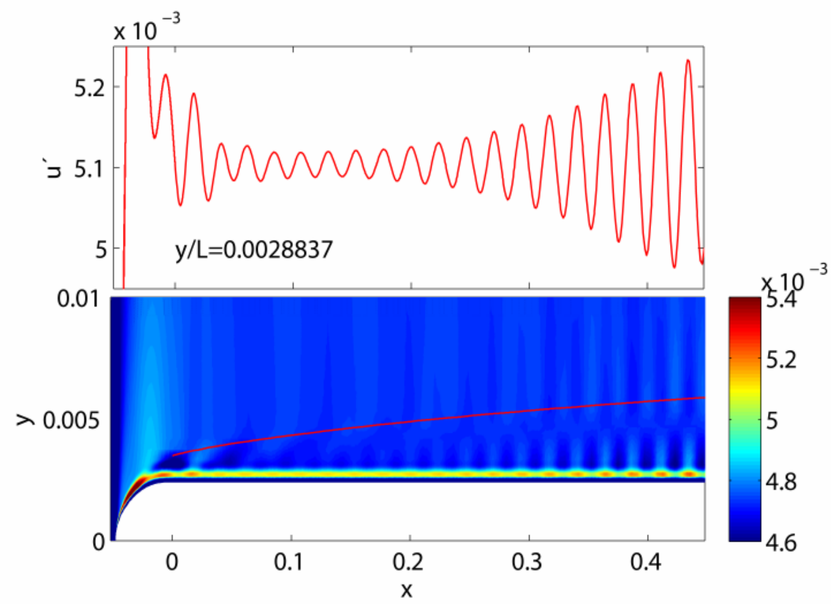
BL on a 2D leading edge - II

- Vortical and acoustic FS disturbance
  - Excitation of Tollmien-Schlichting instability

$\varepsilon_v = 0.015$



$\varepsilon_{ac} = 0.01$



Conclusions

- ***Receptivity*** phase crucial for the whole transition process (transition location, …)

- Receptivity analysis provides ***efficiency coefficient***, which is “input” for stability analysis (e^N-method, …)

- Swept flat-plate BL receptive to free-stream vorticity and localised roughness, both triggering ***cross-flow instability***

- 2D boundary layer around leading edge receptive to free-stream vortices and sound, both exciting ***Tollmien-Schlichting instability***

Outlook

- Computation of ***receptivity coefficients*** for 2D and 3D flow around a leading edge

- Study of ***different types of forcing***: Free-stream vortical modes, free-stream sound, localised and distributed surface roughness and a combination of them

- Analysis of the effect of ***leading-edge geometry*** (bluntness,…)