Leading-Edge Effects on the Response of 2D Boundary-Layer Flow to Vortical Disturbances

L.-U. Schrader, L. Brandt, D. Henningson

Linné FLOW Centre, KTH Mechanics, Stockholm, SE

7TH ERCOFTAC SIG33-FLUBIO WORKSHOP

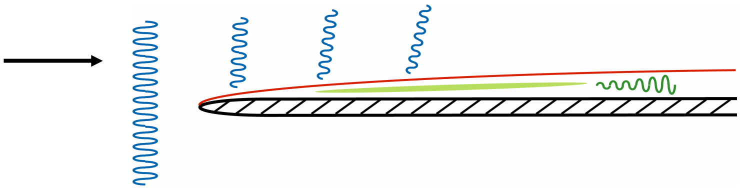
Genova, IT, 16-18/10 2008

Overview

- Problem & Motivation
- Method & Set-up
- Results
  - Mean flow
  - 2D simulations
  - 3D simulations
- Conclusions
- Outlook

Problem & Motivation

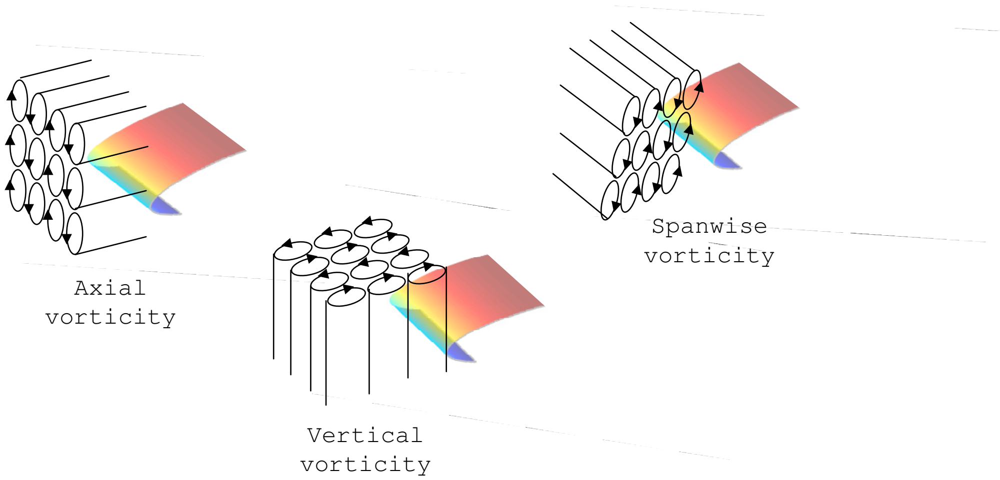
- <u>Problem:</u>
  - Flow past a flat plate with elliptic leading edge exposed to vortical free-stream disturbances



- <u>Motivation:</u>
  - Typical set-up in wind-tunnel experiments
  - Relevance in aeronautics and turbo-machinery

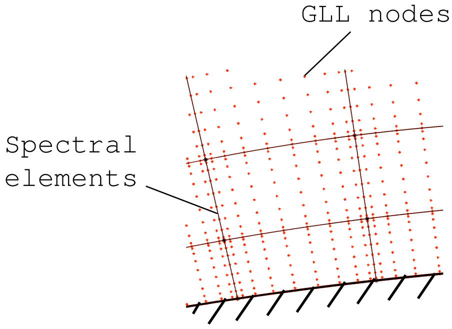
Problem & Motivation

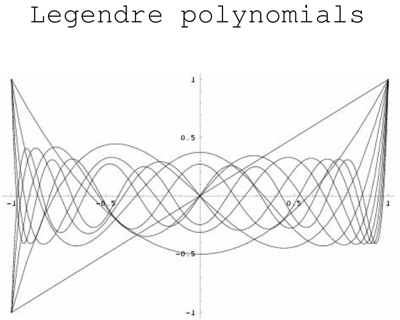
- Effect of leading-edge bluntness
- Receptivity to free-stream turbulence complex
  - Each vorticity component separately considered
  - Influence of frequency



Method & Set-up

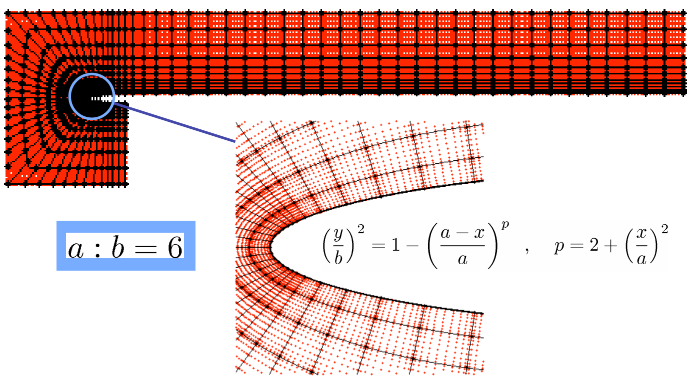
- Spectral-Element Method
  - A. Patera, [J. Comp. Phys. **54**, 468-488 (1984)]
  - *nek5000*, H. Tufo, P. Fischer [Procs. ACM/IEEE Conf., Portland, USA (1999)]
  - Local approach with spectral accuracy, *h* and *p* refinement
    → Accurate method for complex geometries
  - Efficient parallelization (here: 256 procs.)





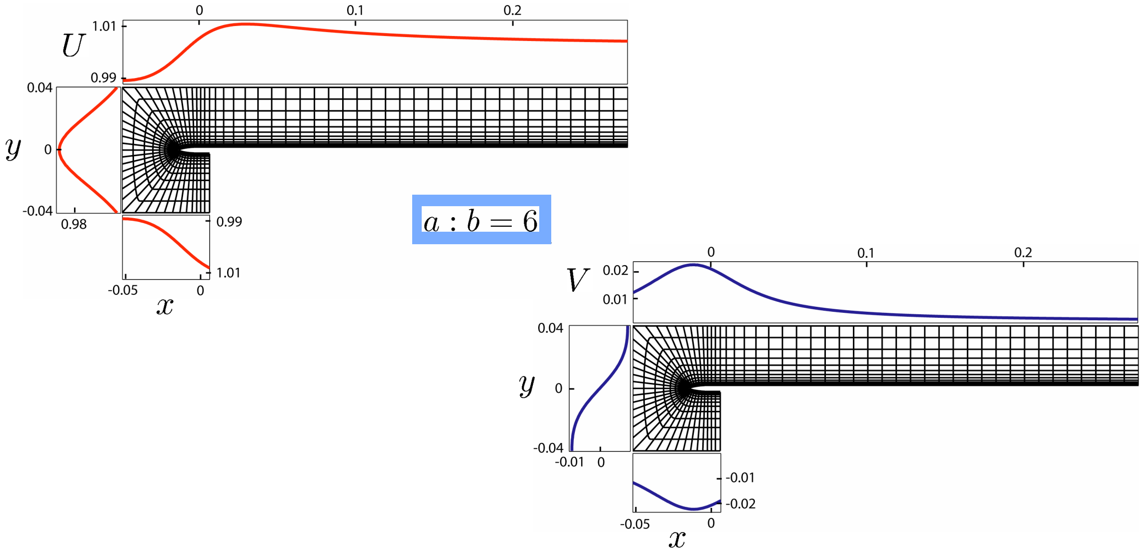
Method & Set-up

- Computational grid
  - Polyn. order N=9, ~6200 elements → ~4.6 million GLL nodes
  - Two leading edges (MSE): $a:b=6$ and $a:b=20$
  - $Re_b = \frac{U_\infty b}{\nu} = 2400\ ,\ Re_L = \frac{U_\infty L}{\nu} = 2.88 \cdot 10^5$



Method & Set-up

- Far-field B.C.
  - Potential-flow solution combined with boundary-layer solver



Method & Set-up

- Vortical free-stream disturbances
  - Div.-free inflow perturbation fields with 1 vortical component

Axial vorticity ξ

$$\hat{v} = \frac{i\beta}{\beta^2+\gamma^2}\hat{\xi} \ , \ \hat{w} = -\frac{i\gamma}{\beta^2+\gamma^2}\hat{\xi}$$

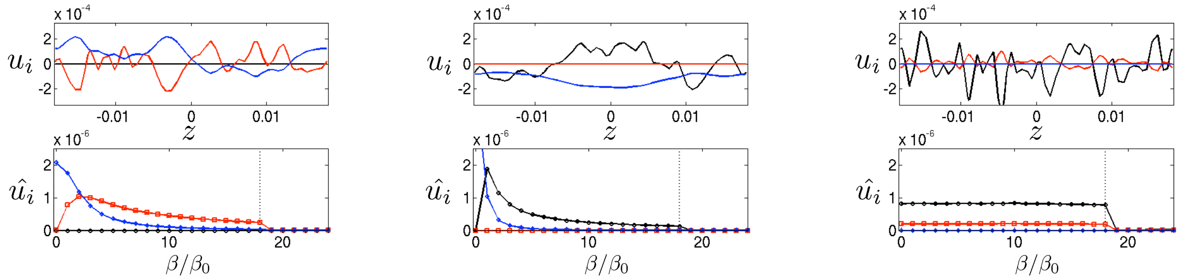
Vertical vorticity η

$$\hat{u} = -\frac{i\beta}{\alpha^2+\beta^2}\hat{\eta} \ , \ \hat{w} = \frac{i\alpha}{\alpha^2+\beta^2}\hat{\eta}$$

Spanwise vorticity ζ

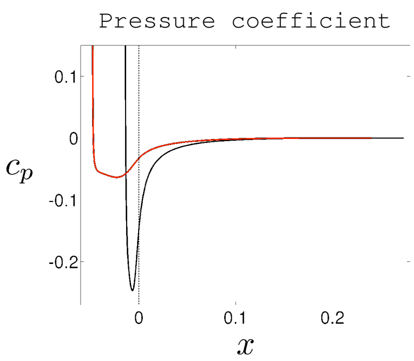
$$\hat{u} = \frac{i\gamma}{\alpha^2+\gamma^2}\hat{\zeta} \ , \ \hat{v} = -\frac{i\alpha}{\alpha^2+\gamma^2}\hat{\zeta}$$

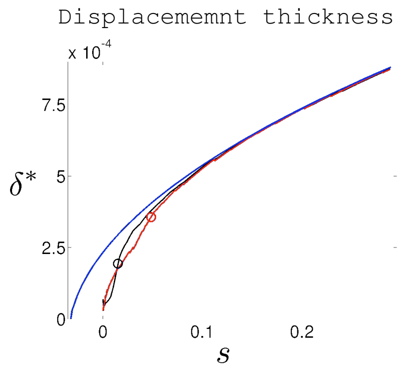
- Taylor's hypothesis: $\alpha \to \omega$ resp. $F = (\nu \cdot 10^6 / U_\infty^2)\omega = 96$ here

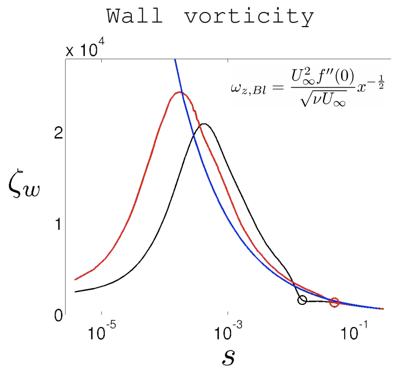


Results

- Mean flow

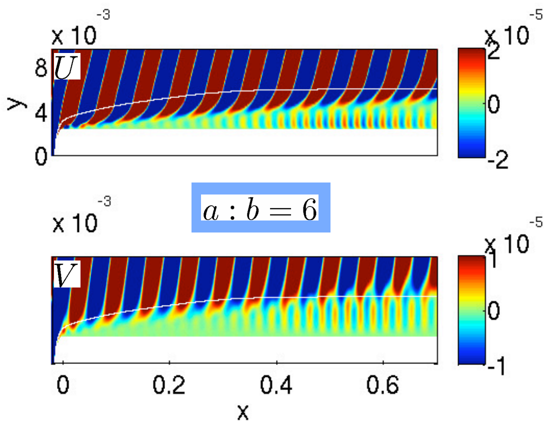


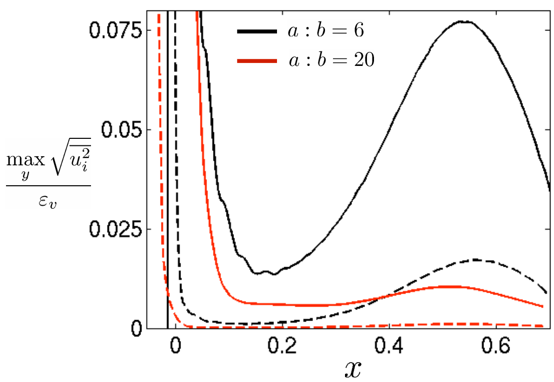




Results – 2D

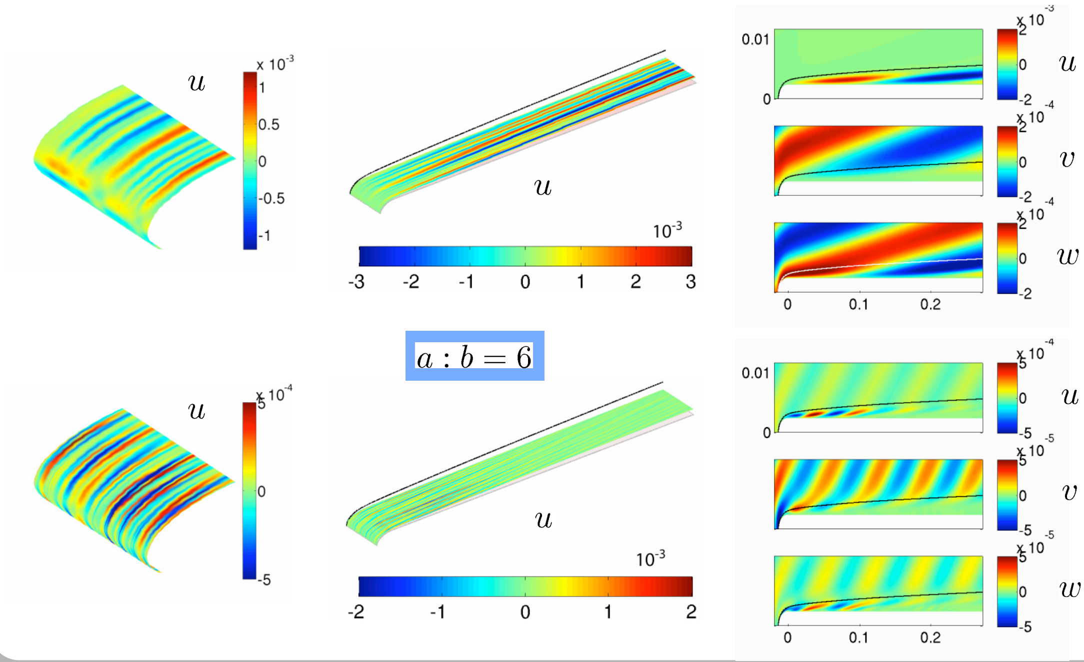
- Spanwise vorticity
  - Frequency $F = 96$ and amplitude $\varepsilon_v = \sqrt{0.5(\overline{u^2} + \overline{v^2})} = 10^{-4}$





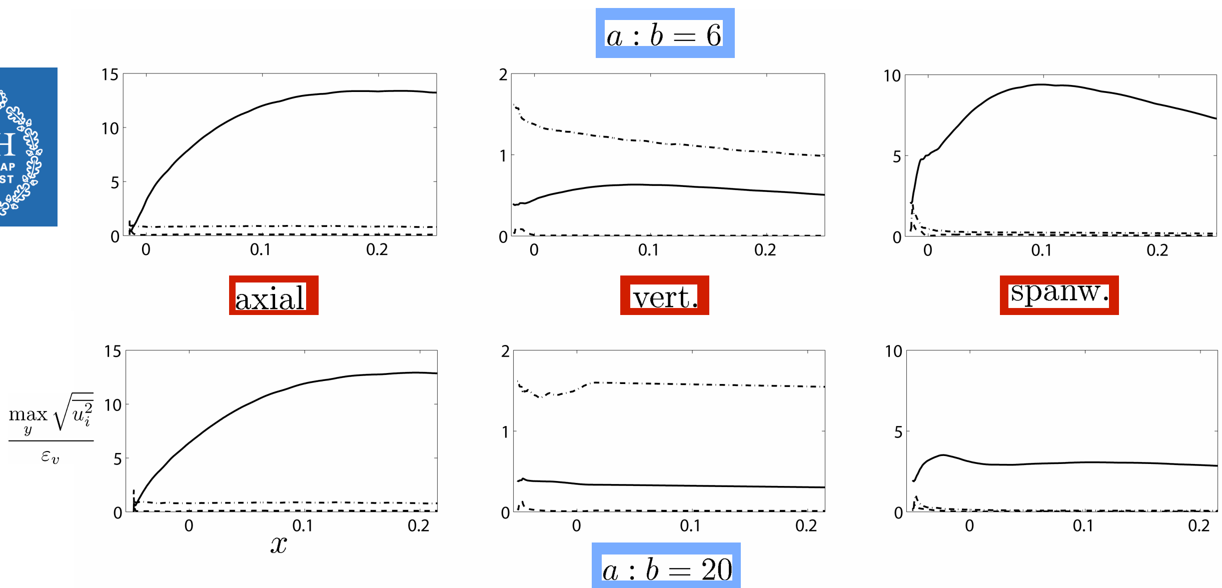
Results – 3D

- Axial/spanwise vorticity with $F = 16$ / $F = 96$



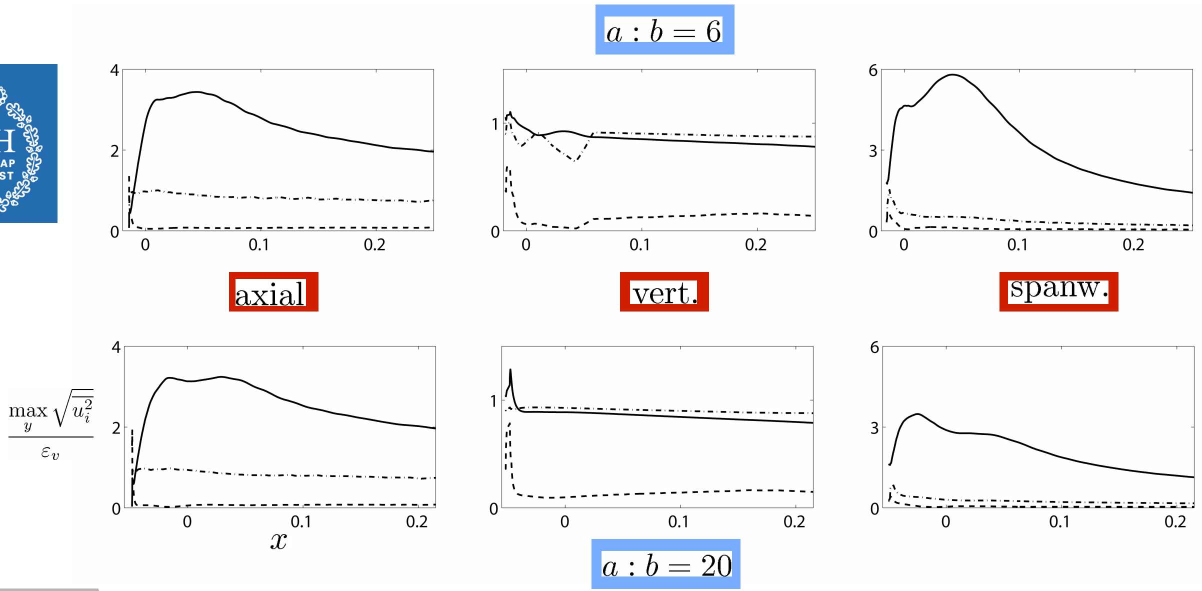
Results

- Relative disturbance amplitudes
  - FS vorticity with $F = 16$ and $\varepsilon_v = \sqrt{0.5(\overline{v_1^2} + \overline{v_2^2})} = 10^{-4}$



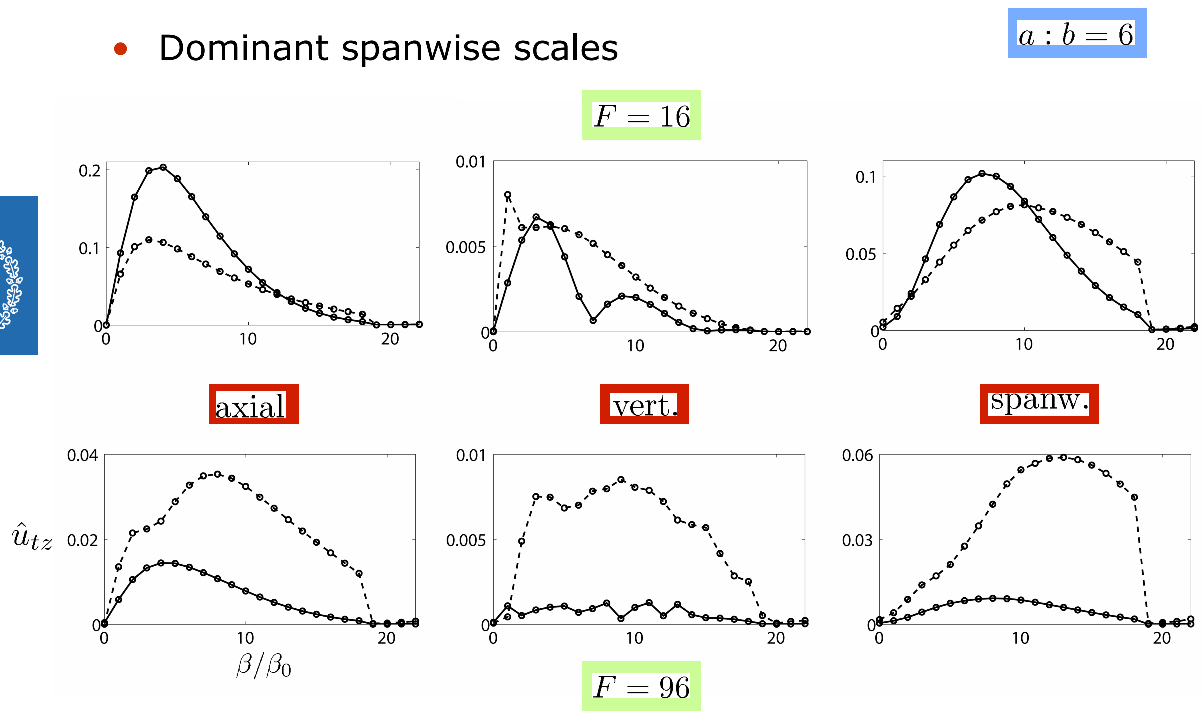
Results

- Relative disturbance amplitudes
  - FS vorticity with $F = 96$ and $\varepsilon_v = \sqrt{0.5(\overline{v_1^2} + \overline{v_2^2})} = 10^{-4}$



Results

- Dominant spanwise scales

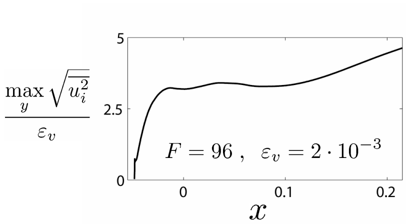


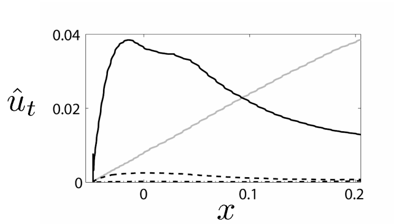
Conclusion

- Boundary-layer response dominated by non-modal instability (streaks)
- Axial low-frequency FS vorticity most efficient in triggering streaks; weak dependence on LE bluntness
- Spanwise low-frequency FS vortices cause strong upstream transient growth, in particular for blunt LE
- Receptivity to vertical FS vortices negligible
- Amplitudes of TS waves 2 orders of magnitude lower; LE bluntness enhances TS instability

Outlook

- Definition/computation of receptivity coefficients
- Nonlinear effects at high frequencies





- Swept flat plate with elliptic leading edge
  - Receptivity coefficients for cross-flow instability
  - Comparison with experimental data from KTH Mechanics

- Low-frequency axial FS vorticity