A modification of hybrid RANS-LES methods of DES type for flows around airplane wings

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Outline

- Introduction: Aerospace applications are „special“
- Cost estimate for wall-modelled LES of wing-body configuration at realistic Reynolds number
- From wall-modelled LES to hybrid RANS-LES (DES-type coupling)
- Shortcomings of (D)DES for aerodynamic flows at the onset of separation (incipient separation)
- Concept for a modified (D)DES method based on properties of the velocity profiles in the boundary layer
- Conclusions

Introduction.
Aerospace applications are „special“

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Aerospace science applications are „special“

- **Extremely high accuracy demands** (each % in lift and drag is crucial)
  - 10% error in viscous drag e.g., due to log-law mismatch is not acceptable
- **Very high Reynolds numbers**
  - **Compressor blades** (transonic)
    - u_∞= 400m/s, ρ=1kg/m^3, **L = 0.05m**, $\mu = 1.5\text{x}10^{-5}$ kg/(ms) $\Rightarrow$ **Re = 1.3 x 10^6**
  - **A380 at take-off**
    - u_∞= 70 m/s, ρ=1kg/m^3, **L = 10m**, $\mu = 1.5\text{x}10^{-5}$ kg/(ms) $\Rightarrow$ **Re = 4.6 x 10^7**
- **Very large number of simulations** necessary for **design** and **certification**
  - **Certification** demands **20,000-200,000** simulations for a variety of flight states
    - Mach number for different flight speeds (Landing/take-off, cruise, dive, …)
    - Reynolds number variation (Density is a function of altitude)
    - Angle of attack, control deflection devices, …
  - Additionally: Geometry optimization during **design phase**

Review of LES work.

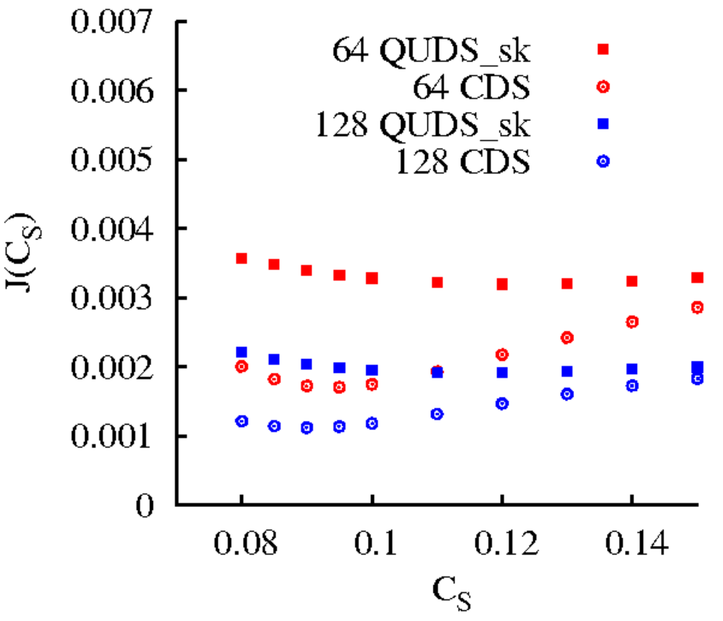
LES convergence study for grid and time step size.

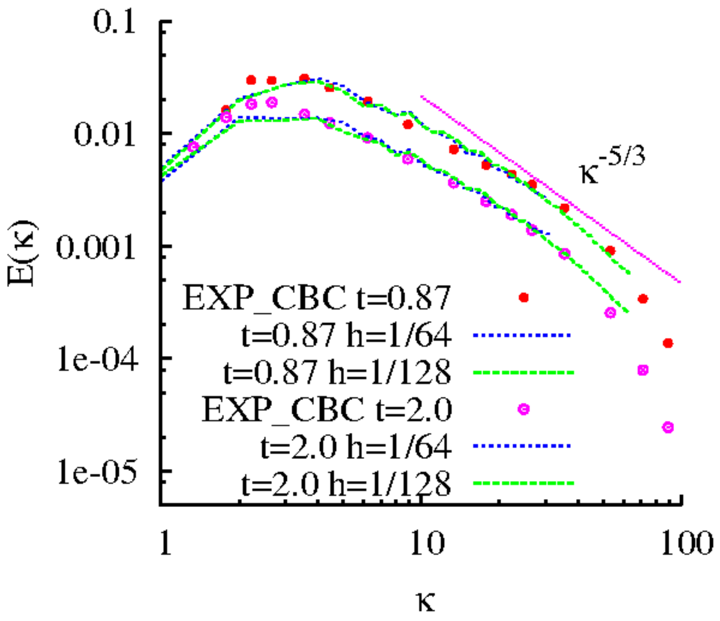
Implications for aerospace applications

Numerical method and LES modelling

- DLR TAU code with incompressible flow solver THETA
  - Unstructured finite-volume solver for flows with small compressibility effects
  - Projection scheme using the interpolation scheme by Rhie and Chow
  - Discretization of convective fluxes using central differencing scheme (CDS)
    - Quadratic upwind scheme was found to be much too dissipative for LES
  - Time discretization using 2nd order backward differencing formula (BDF-2)
  - 5 times faster than CFX, FLUENT, …
  - Subgrid-scale models: Smagorinsky model (with van Driest damping)

Calibration of C_S for DIT,
No tuning for more complex flows (see Knopp, Zhang, Kessler, Lube, CMAME 2010)



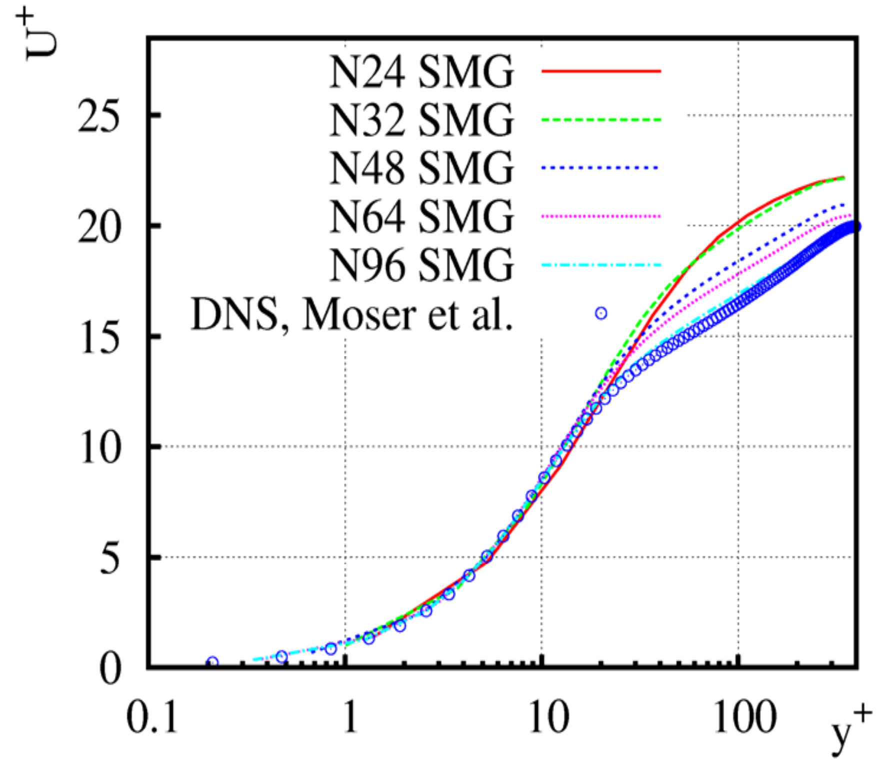


„Grid“ converged LES solutions

- Converged solutions w.r.t. time step size and spatial resolution in the sense that **mean-flow and fluctuating quantities do not change largely** when refining the mesh
- Authors opinion:
  - Static calibration of model coefficients only meaningful after sufficient convergence has been achived
  - For standard Smagorinsky:
    - Calibration of C_S for DIT
    - „successfully“ applied to turbulent channel flow and backward-facing step without later „tuning“
  - Dynamic calibration $C(U,\Delta)$ which allows *coarse-grid LES* (… beyond the limits of my intellectual capabilities…)

Resolution requirements for wall-resolved LES at low Re
Turbulent channel flow $Re_\tau = 395$

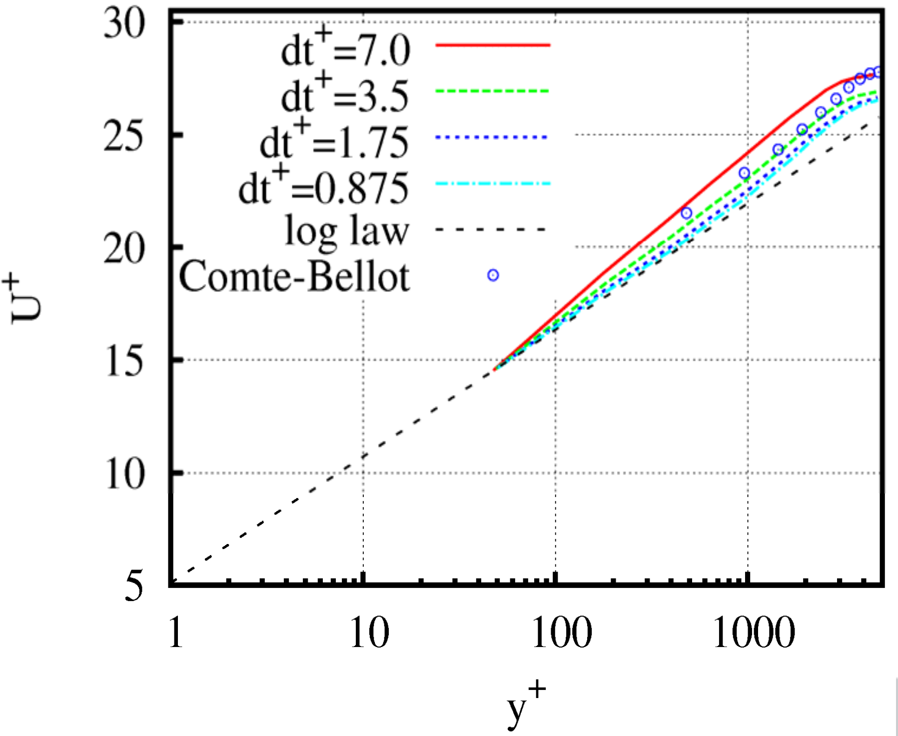
- Motivation: Wall-resolved LES avoids possible additional problems (e.g., „log-layer mismatch“) due to near-wall modelling
- Required time step size : $\delta t^+ = \delta t\, u_\tau^2/\nu = 0.4$ (precursor study, Choi & Moin JCP 1994)
- Insufficient resolution even on 64x64
- Only on 96x96x96 mesh, results are close to DNS data
- No simulation on 128^3 mesh yet

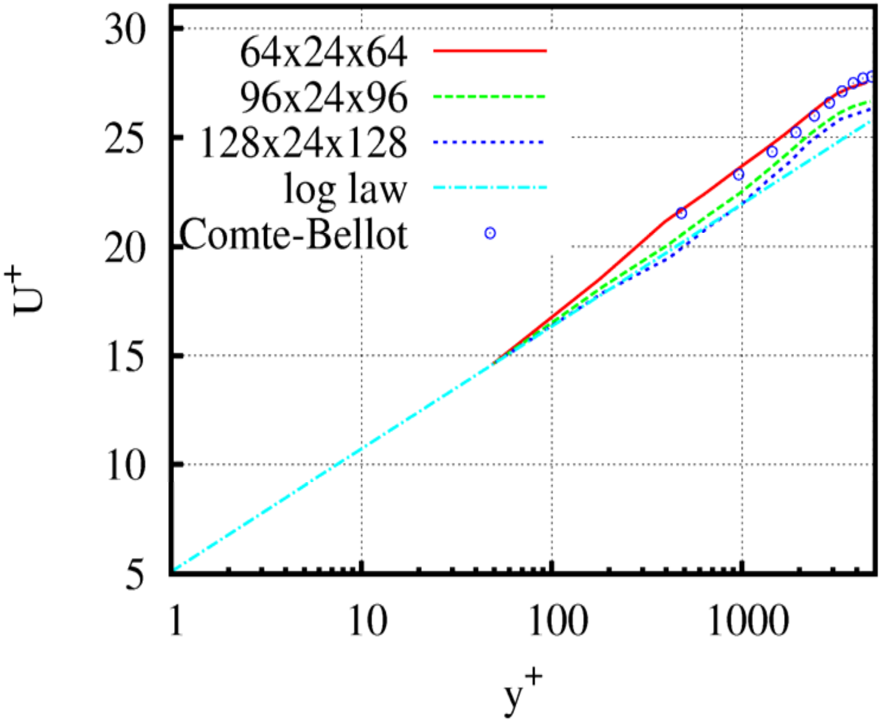


Standard Smagorinsky model with van Driest damping

Resolution requirements for wall-modelled LES at high Re Turbulent channel flow $Re_\tau = 4800$

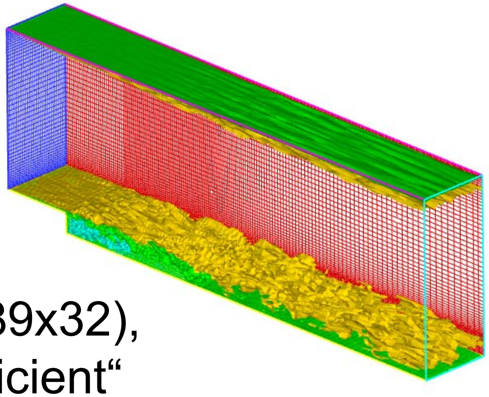
- Standard Smagorinsky model and hybrid wall functions as near-wall model, matching node at $y^+=50$
- Unsufficient resolution (in space or time) causes log-layer mismatch
  - Danger of 10% error in viscous drag



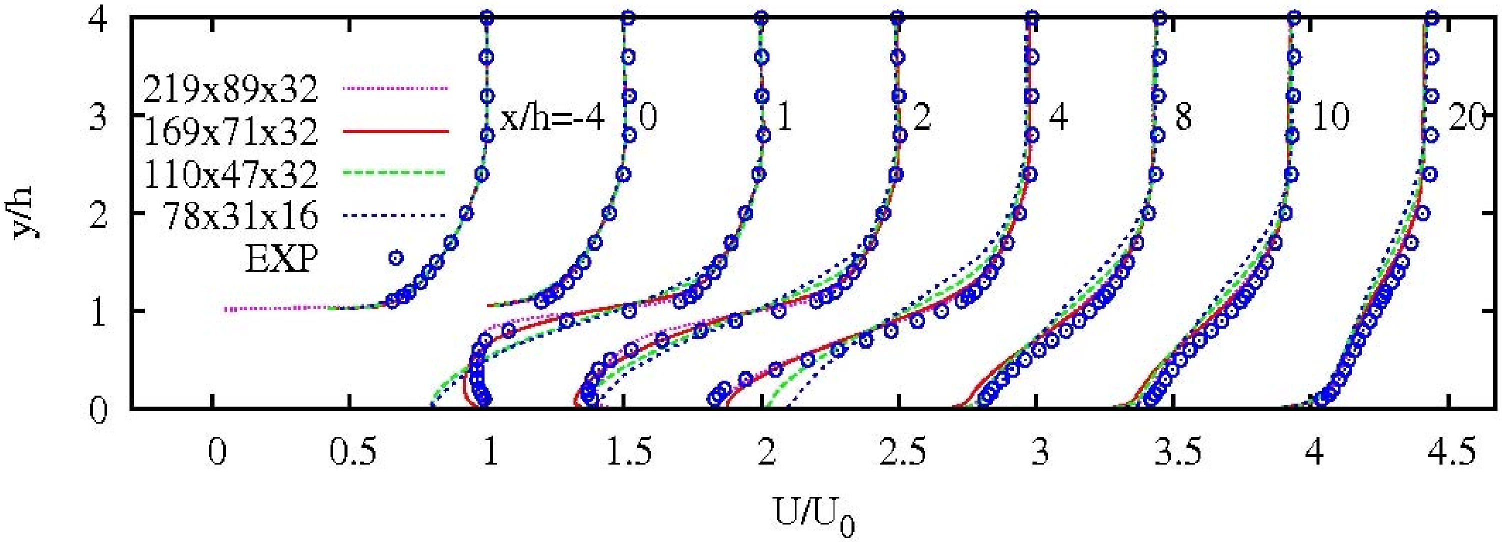


Resolution requirements for flow over a backward-facing step at Re_h=37500 (experiment by Driver and Seegmiller)

- First step: Investigation of required time steps size
- Second step: Convergence study on globally refined grids
- Synthetic turbulence at inlet by Klein, Sadiki, Janicka (2003)

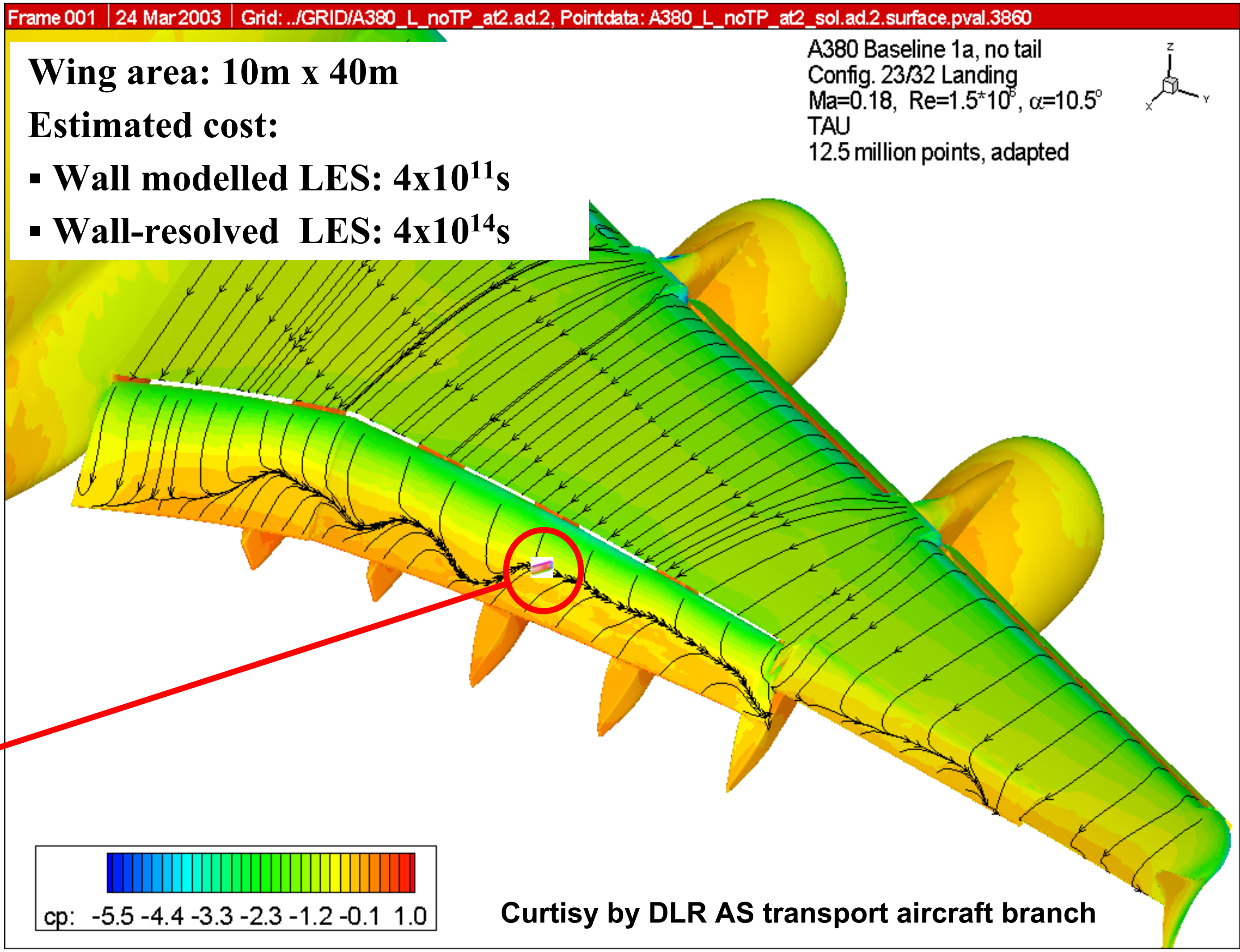


On finest mesh (219x89x32), resolution „almost sufficient“



Estimation of costs for A380 take-off/landing

Attached boundary layer flow with separation on flap of a wing at high-lift „approximated“ by flow over a backward facing step.



Wing area: 10m x 40m

Estimated cost:

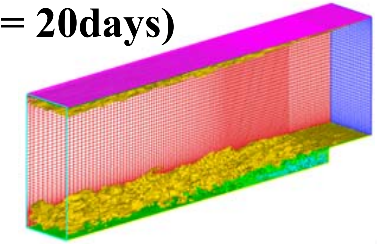
- Wall modelled LES: 4×10^{11}s
- Wall-resolved LES: 4×10^{14}s

Curtisy by DLR AS transport aircraft branch

LES with wall-functions

Surface: 0.38m x 0.05m

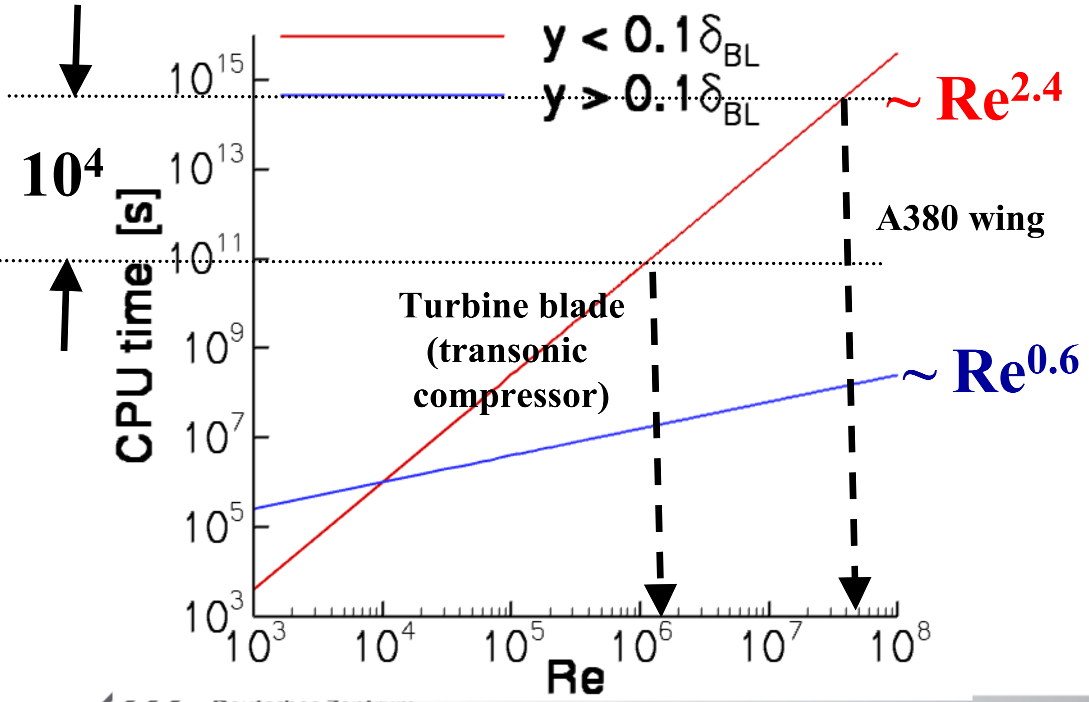
Cost: 10^6s on single CPU (= 20days)



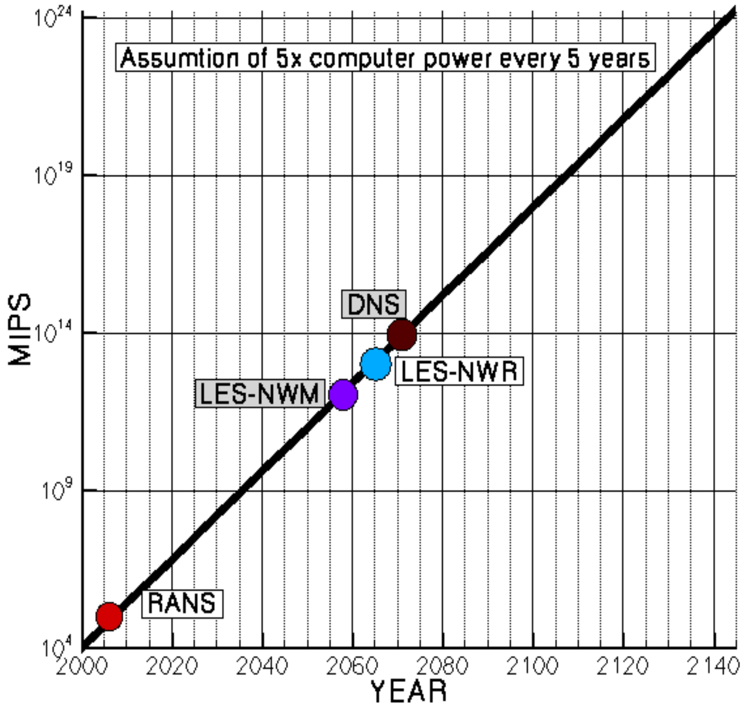
Infeasibly large computational of wall-resolved LES at high Re

- Estimate by Piomelli (Progress in Aerospace Science, 2008) and Spalart (1997)
- Costs for resolution of near-wall turbulence dominant in high Re flows
- Supposed reason: Resolution of streaks ($\Delta x^+\sim 450$, $\Delta z^+\sim 100$)

Conclusion: Treat (attached) boundary layers using RANS

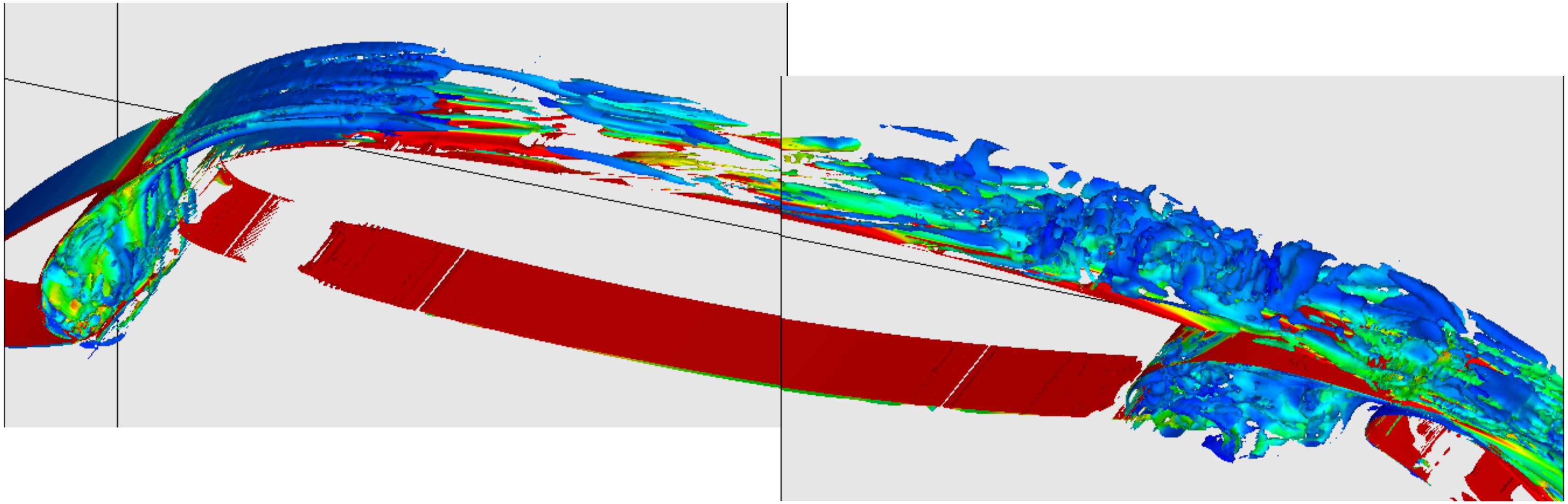


Courtisy by Spalart



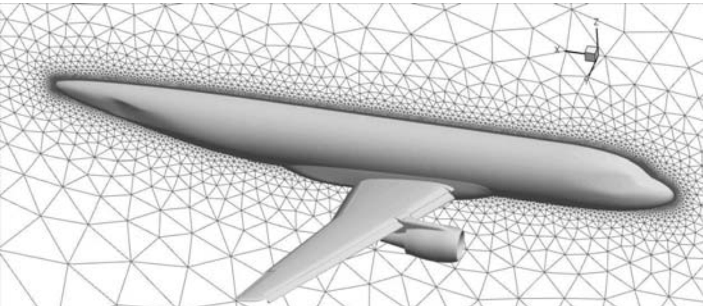
F15 3-element airfoil at high lift. Cost for wall-modelled LES

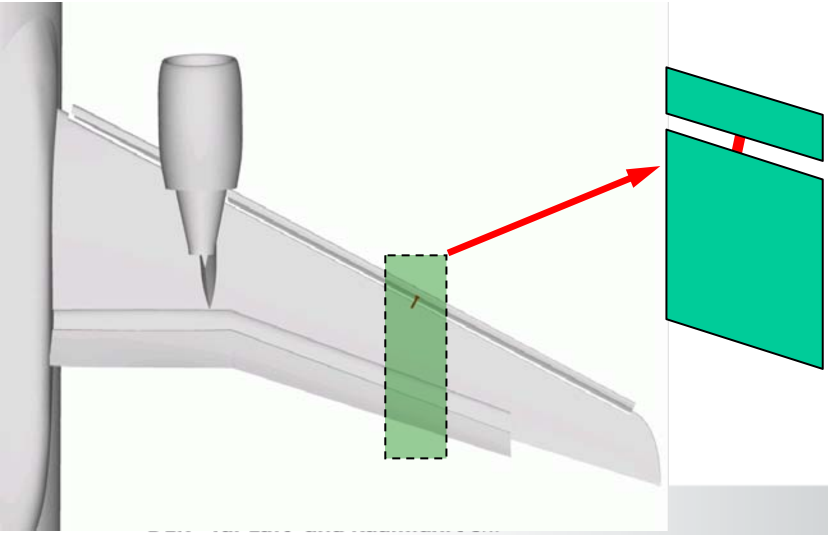
- F15 3-Element airfoil at Re=2Mio, Ma=0.15, incidence angle 7°
- Retracted chord=1m, L=1.2m, span=0.1c
- Wing area = 0.196m^2 (both upper and lower side)
  - ⇒ $A_{\text{Wing, F15}} / A_{\text{Backward facing step}} = 10$
  - ⇒ Additional factor of 5 for the surface grid due to surface curvature
  - ⇒ Wall-modelled LES expensible but feasible



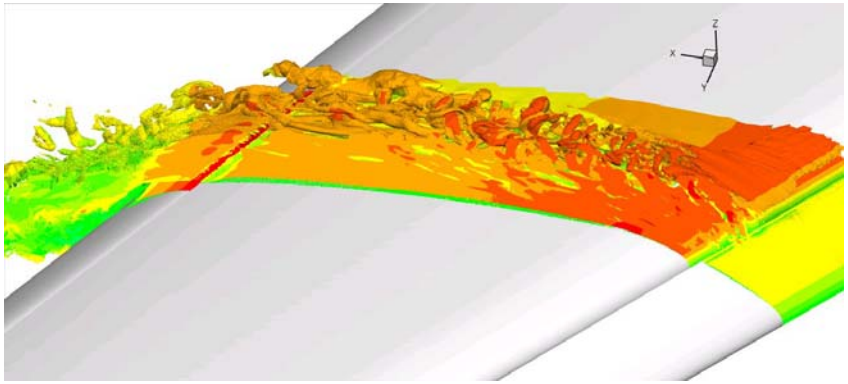
Zonal DES-RANS for predicting slat track noise

- Zonal DES for A320 wing-body-nacelle-pylon
- 30Mio nodes for RANS mesh, 50Mio nodes for embedded DES mesh
    - Spanwise extent of DES mesh: 6% half-span
- L=0.308m, $Re=1.34 \times 10^6$ is really low, Mach number Ma=0.2, incidence $\alpha=3.93°$
- **Computing costs ~ 6month on 2048 cores**





Work by Silvia Reuss

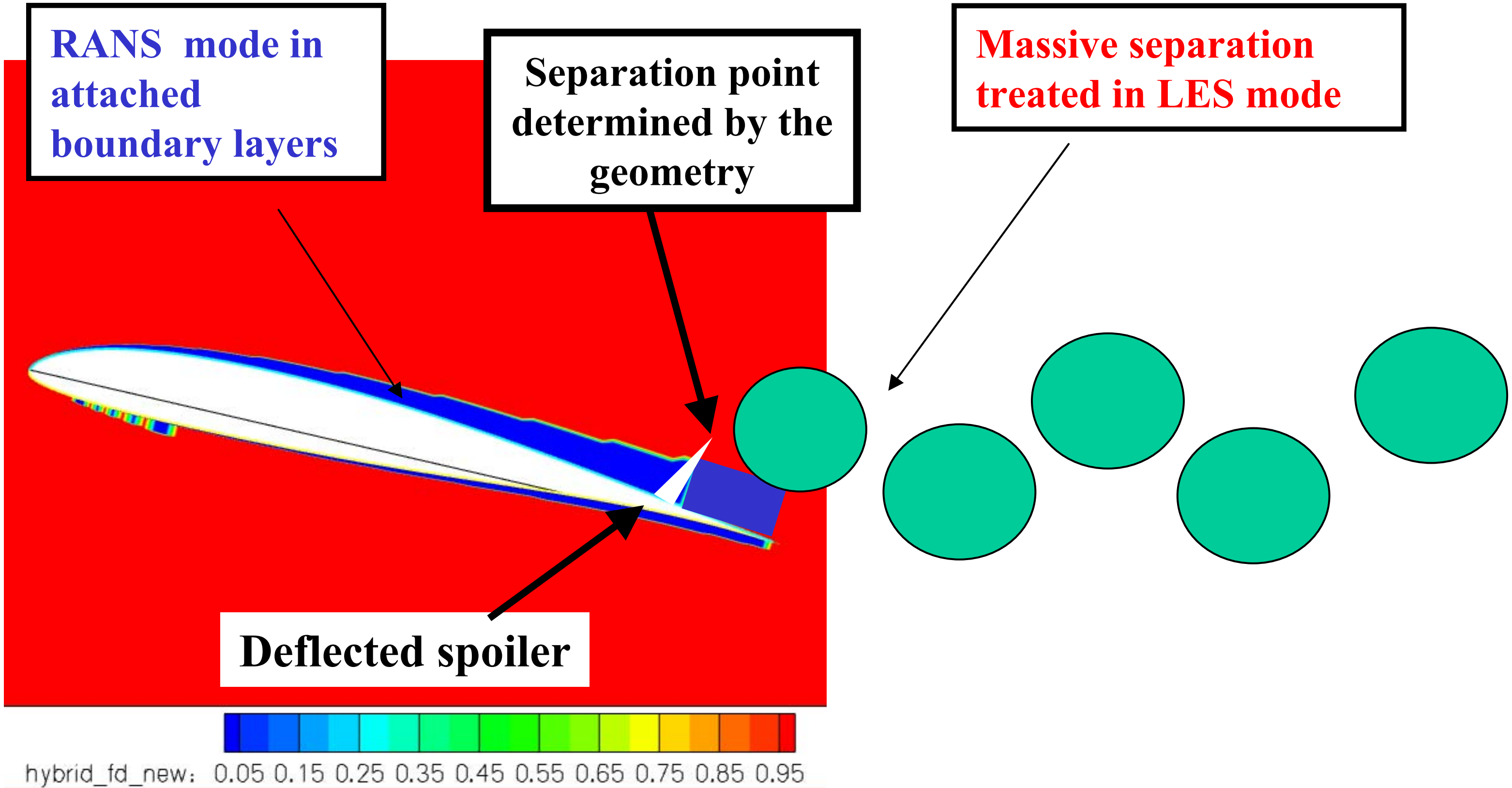


Definition of (D)DES.
Definition of RANS and LES region

Design application for Detached-Eddy Simulation (DES)

Claim of (D)DES:

- Attached boundary layers treated in RANS modus,
- LES in outer flow regions of large-scale separation



RANS mode in attached boundary layers

Separation point determined by the geometry

Massive separation treated in LES mode

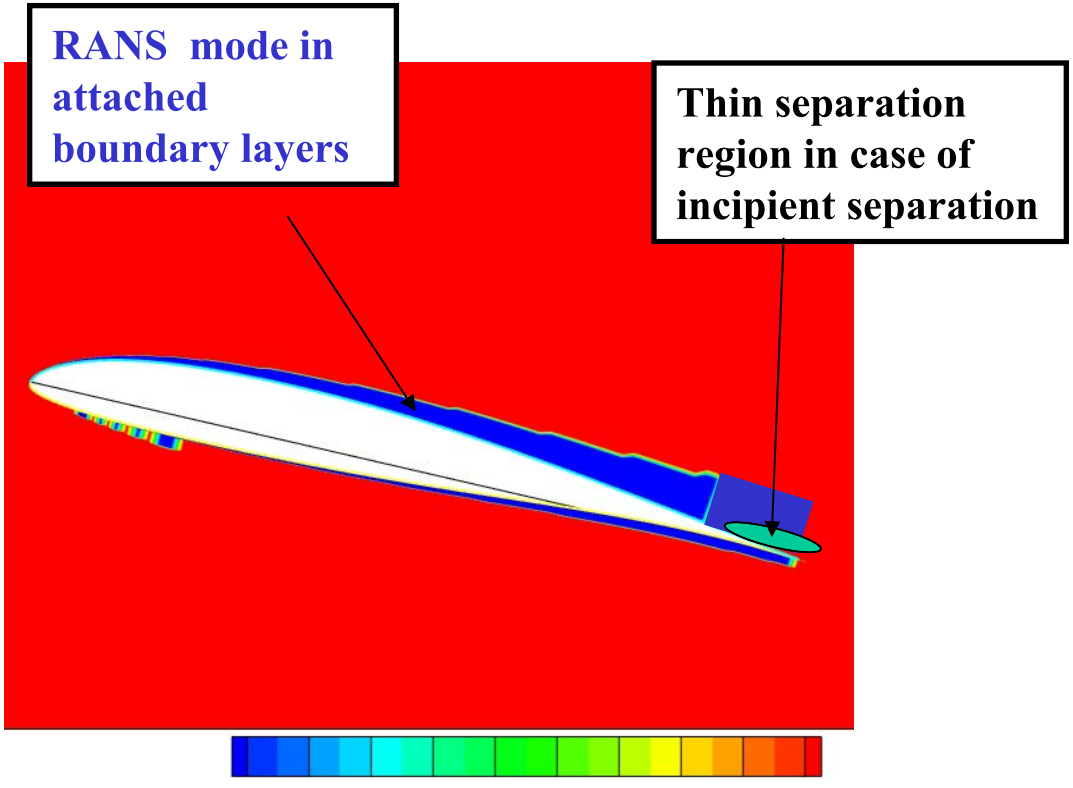
Deflected spoiler

What is the potential of DES for flows with small separation?

Claim of (D)DES:

- Attached boundary layers treated in RANS modus,
- LES in outer flow regions of large-scale separation

But (D)DES does not really do this …



RANS mode in attached boundary layers

Thin separation region in case of incipient separation

Non-zonal hybrid RANS-LES coupling of DES-type

- (D)DES: Different length scale substitution in Spalart-Allmaras RANS model

$$\vec{u}\cdot\vec{\nabla}\tilde{\nu} - \vec{\nabla}\cdot\left(\frac{\nu+\rho\tilde{\nu}}{\sigma}\vec{\nabla}\tilde{\nu}\right) - \frac{c_{b2}}{\sigma}(\vec{\nabla}\tilde{\nu})\cdot(\vec{\nabla}\tilde{\nu}) = c_{b1}\tilde{S}\tilde{\nu} - c_{w1}f_w\left(\frac{\tilde{\nu}}{d}\right)^2$$

- DES length scale in SA-DDES: $\tilde{d} = d_W - f_d \max\left(0, d_W - C_{DES}\cdot\Delta\right)$

- This is a hybrid formula which can reduce to the following special cases:

  - **Formal RANS region**: $\tilde{d} = d_W$ Spalart-Allmaras RANS model

  - **Formal LES region:** $\tilde{d} = C_{DES}\cdot\Delta$ „Smagorinsky model“ if left hand side is zero

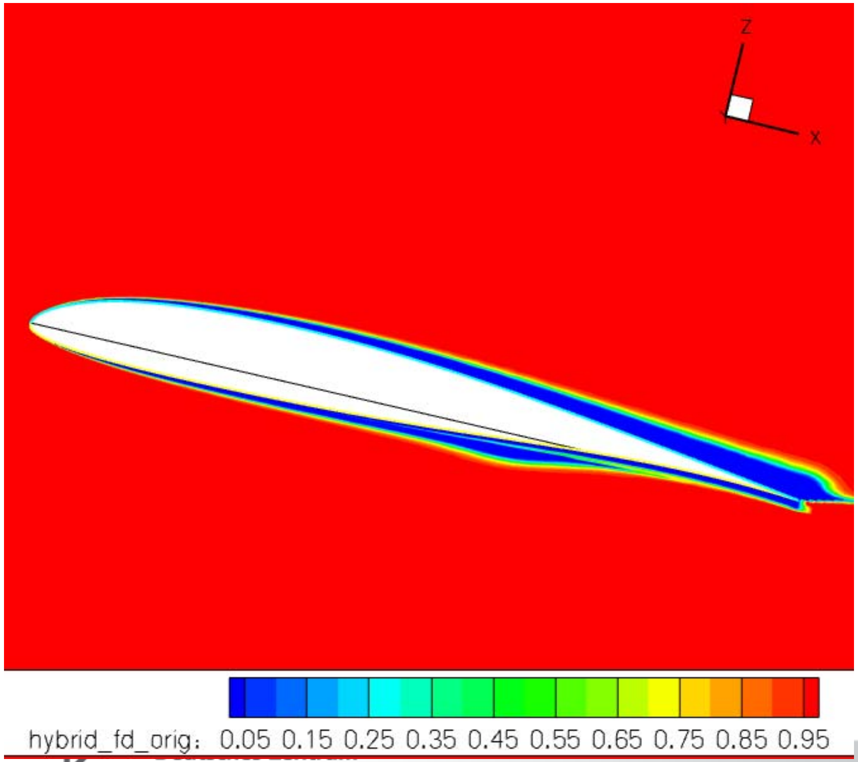
- Function for RANS-LES switch $f_d=f_d(\tilde{\nu},d)$ based on log-layer solution for $\tilde{\nu}$ in TBL at ZPG
- RANS and LES region are determined by f_d (and by the mesh)

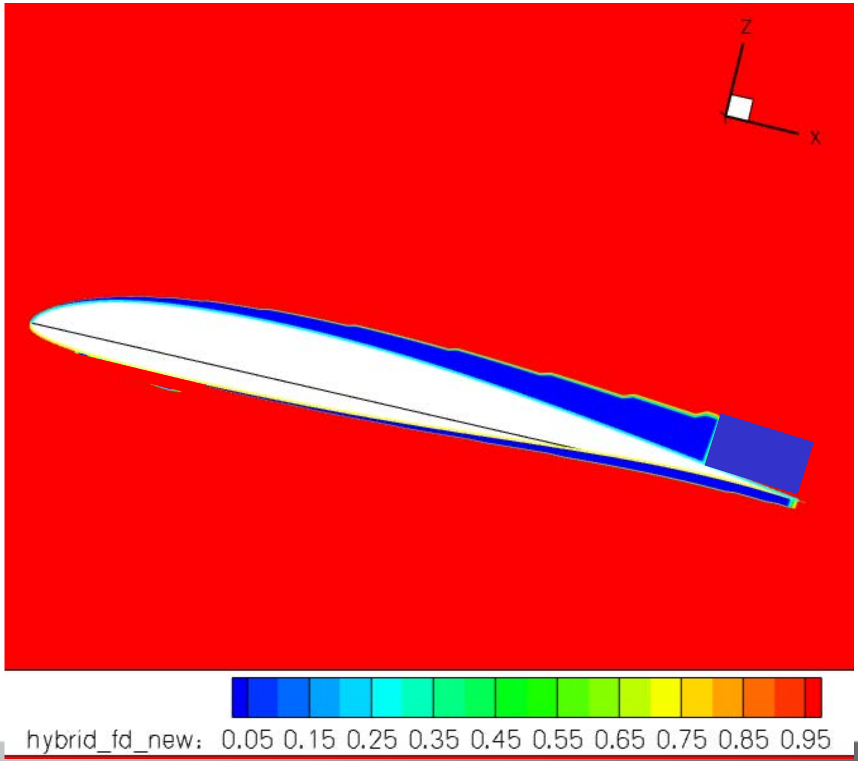
Short-comings of SA-(D)DES for flows over airfoils close to stall at incipient separation (high-lift)

Shortcoming 1: DDES significantly underpredicts the boundary layer thickness in case of a strong adverse pressure gradient

Boundary layer thickness detected using the fd-function of DDES

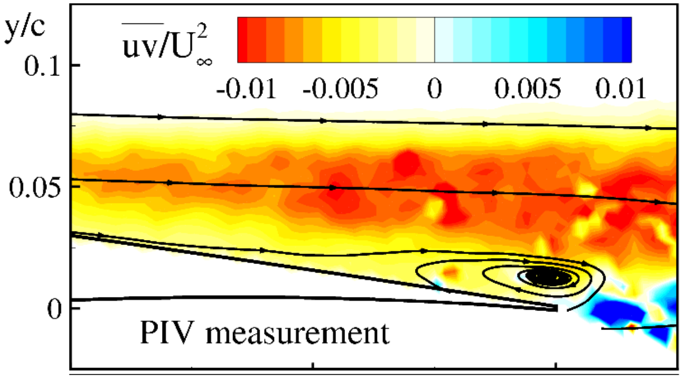
Boundary layer thickness detected using δ_{99}, where U_{edge} is computed using the compressible version of Bernouillis eq.

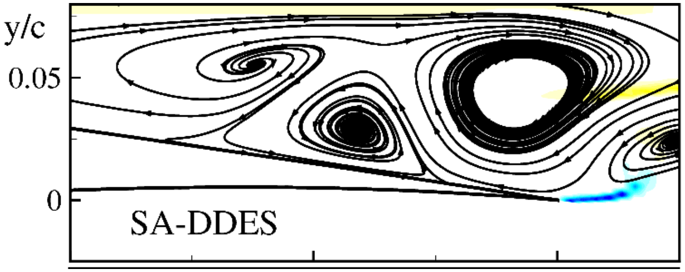


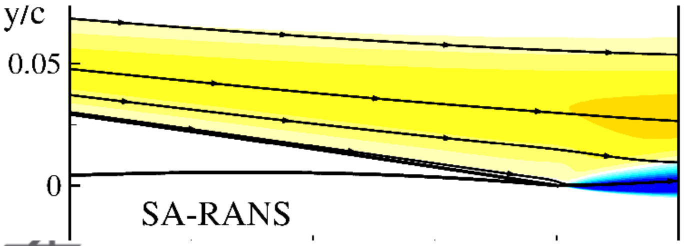


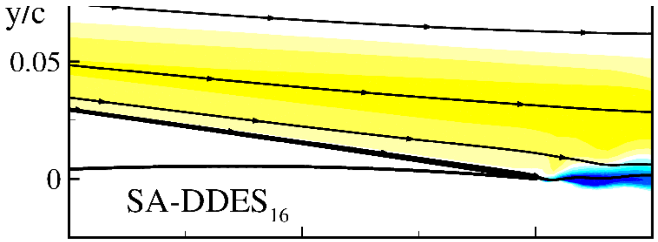
Shortcoming 1: Too early flow separation for HGR01 airfoil because f_d underpredicts the boundary layer thickness

- HGR01 airfoil at Re=0.65Mio, Ma=0,07, incidence α=12°
- Incipient flow separation near trailing edge
  - SA-RANS predicts separation much too late
  - SA-DDES (standard version) predicts large separation at x/c=0.5
  - SA-DDES (fd with constant 16 instead of 8) gives SA-RANS result



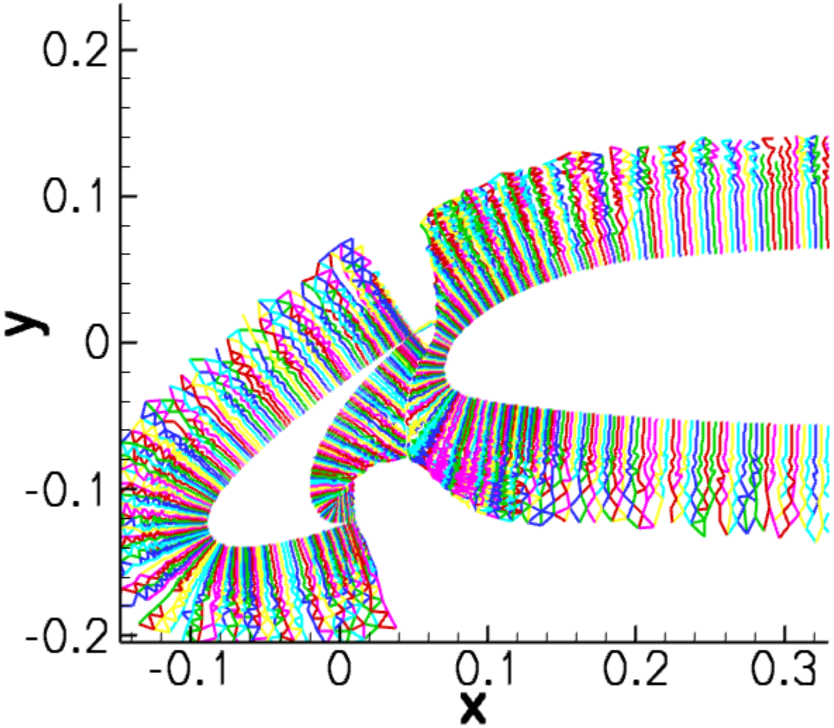






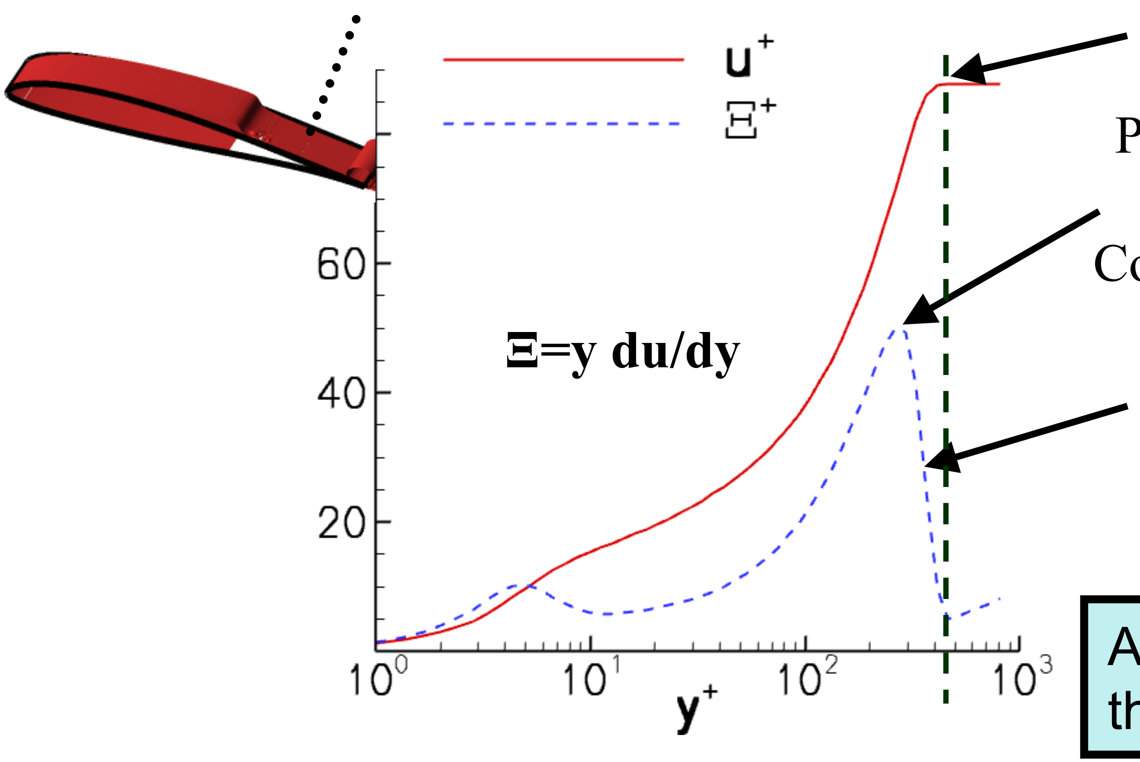
Extension of the unstructured flow solver TAU

- New data structure: Approximative wall-normal rays for each wall-node
  - Computation of integral boundary layer quantities in wall normal direction
  - Study the form of velocity profiles in wall-normal directions



Velocity profiles and implications for algebraic estimates of the boundary layer thickness

- HGR01 airfoil at α=13°, Re=0.65Mio, Ma=0.07
- **Suction side at x/c=0.79**: Decelerated flow (adverse pressure gradient, APG)



δ_{99}

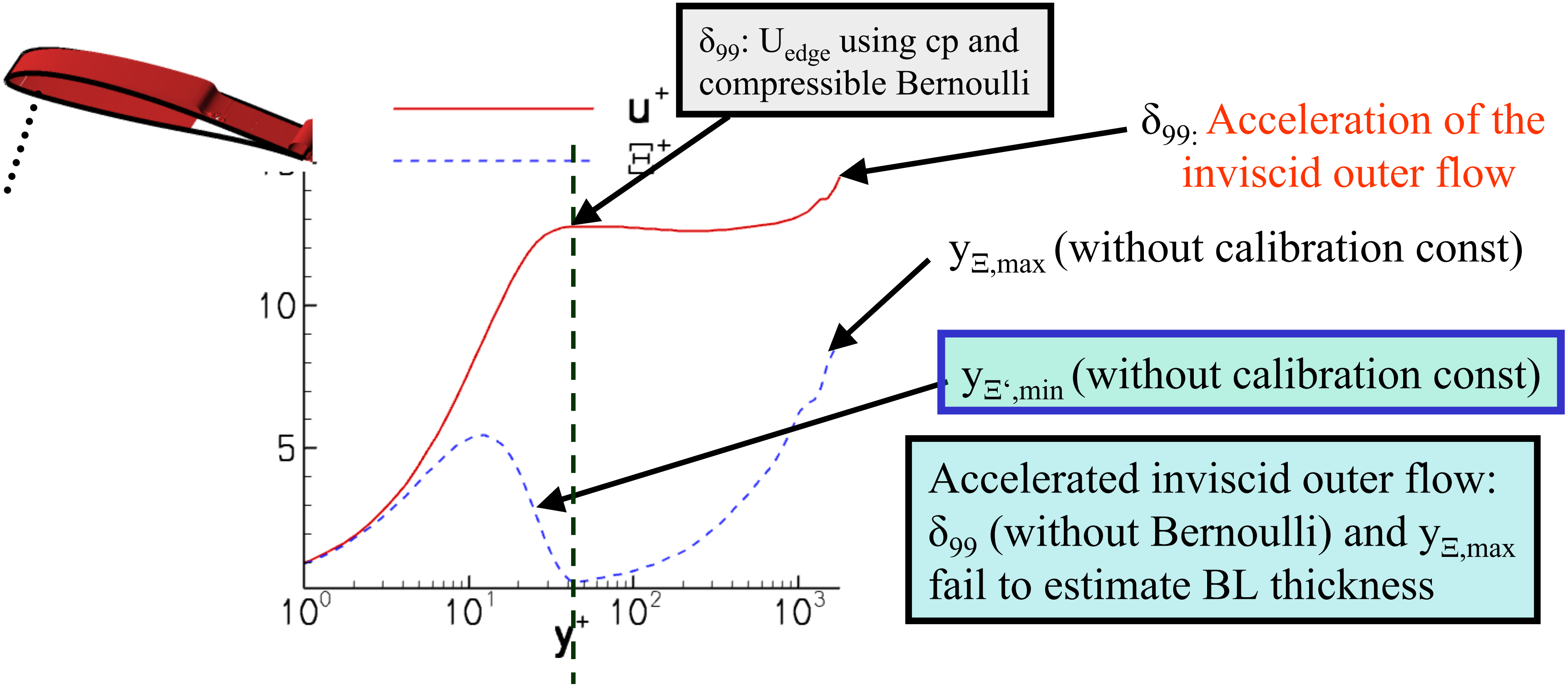
Proposal by Stock & Haase (1987)
$y_{\Xi,max}$ (without calibration const)
Constant from Coles law-of-the-wall

$y_{\Xi',min}$ (without calibration const)

APG flow: All estimates for BL thickness can be used

Velocity profiles and implications for algebraic estimates of the boundary layer thickness

- HGR01 airfoil at α=13°, Re=0.65Mio, Ma=0.07
- **Pressure side at x/c=0.11**: Accelerated flow (favourable pressure gradient, FPG)



δ_{99}: U_{edge} using cp and compressible Bernoulli

δ_{99}: Acceleration of the inviscid outer flow

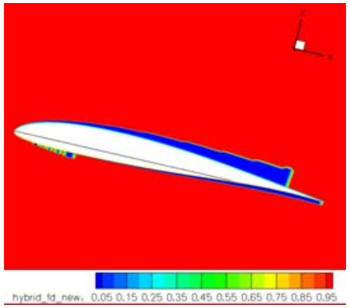
$y_{\Xi,max}$ (without calibration const)

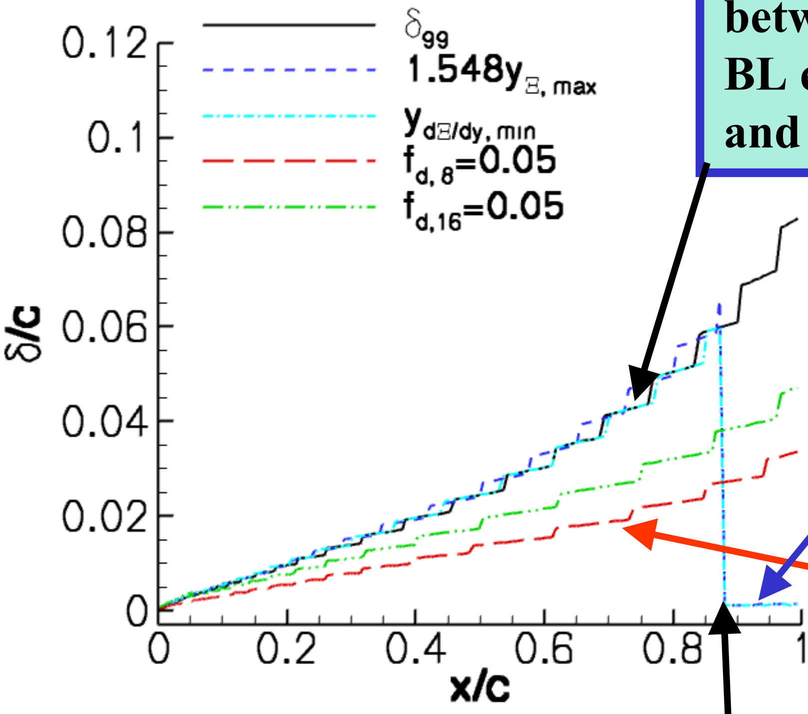
$y_{\Xi',min}$ (without calibration const)

Accelerated inviscid outer flow: δ_{99} (without Bernoulli) and $y_{\Xi,max}$ fail to estimate BL thickness

HGR01-airfoil: Estimation of boundary layer thickness

- HGR01 airfoil at α=13°, Re=0.65Mio, Ma=0.07
- Suction side: Decelerated flow (adverse pressure gradient, APG)





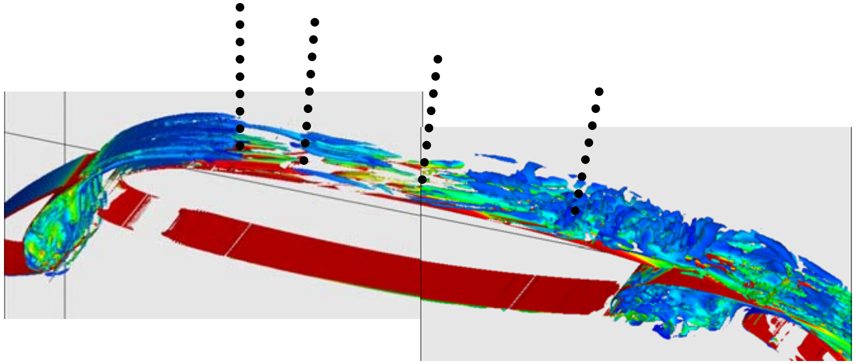
Good agreement between algebraic BL estimates $y_{\Xi',min}$ and $y_{\Xi,max}$ and δ_{99}

Both algebraic BL estimates drop down in the separation region

f_d significantly underestimates the growth of the BL thickness in streamwise direction, Independent of factor 8 or 16

Flow separation

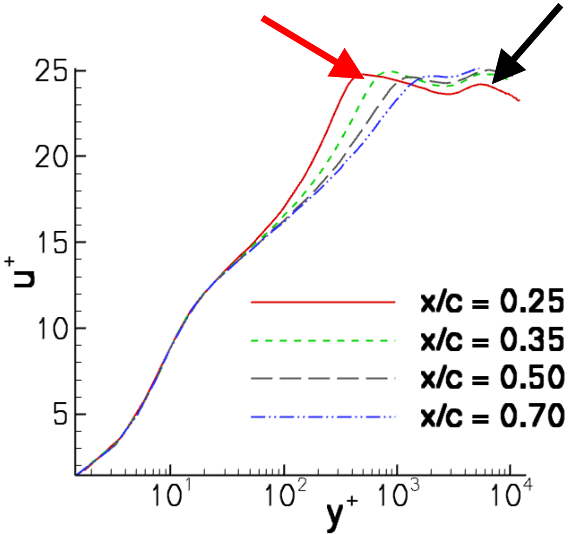
F15 with prescribed transition. Wing upper side

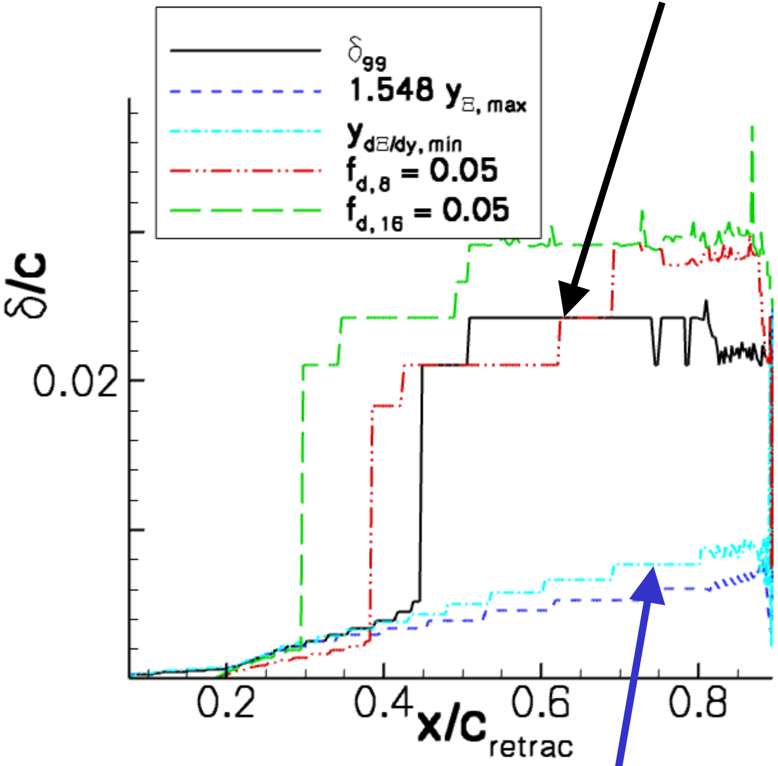


δ_{99} detects the thickness of the free-shear layer (slat wake and convected slat BL)

Attached wing BL

Free-shear layer





$y_{\Xi',min}$ and $y_{\Xi,max}$ still detect the thickness of the attached wing BL

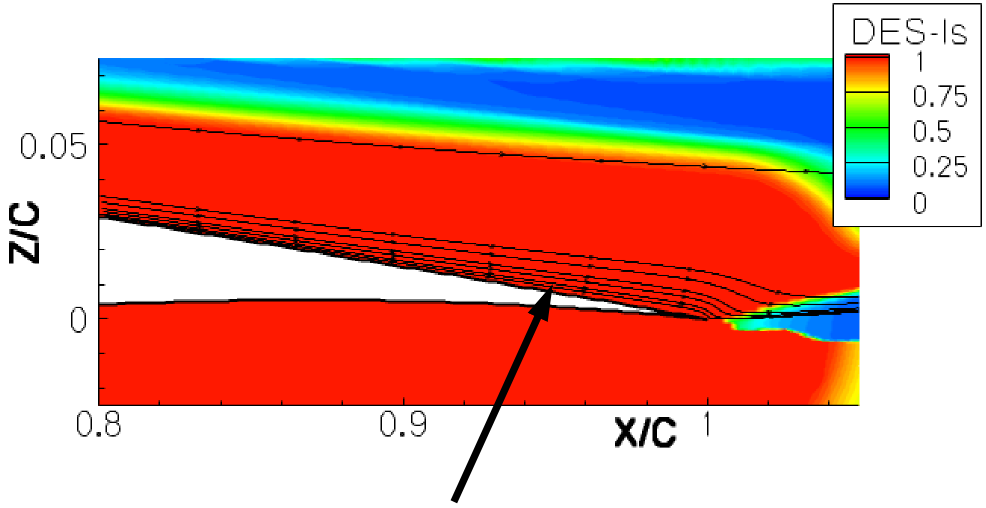
Shortcoming 2: Thin separation regions treated in RANS

- Thin separation regions inside the boundary layer appear characterize the boundary of the flight envelope
  - Incipient separation at landing/take-off
  - Shock buffet at transonic cruise (oscillating shock and separation bubble)
- DES97, DDES do not conceived for this flow situation

α=14deg

Red: formal RANS-region of the DES

Blue: formal LES-region of the DES

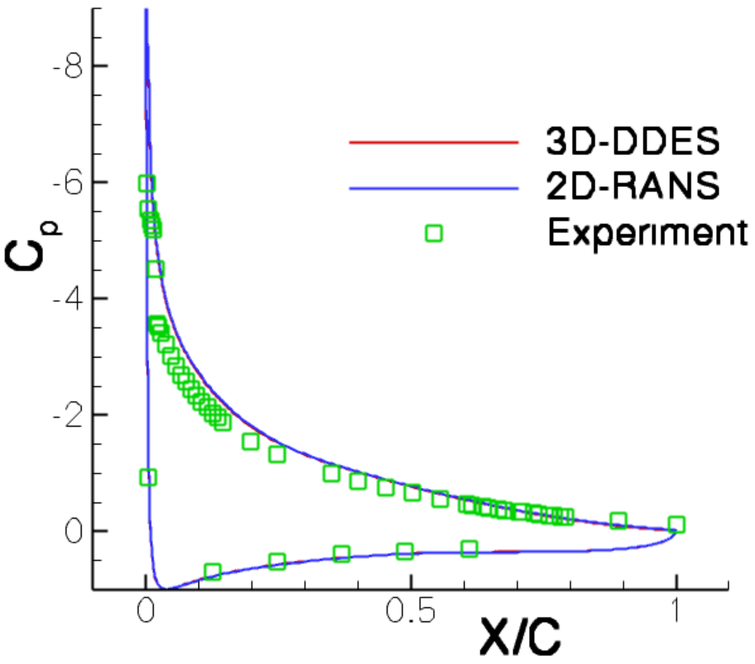


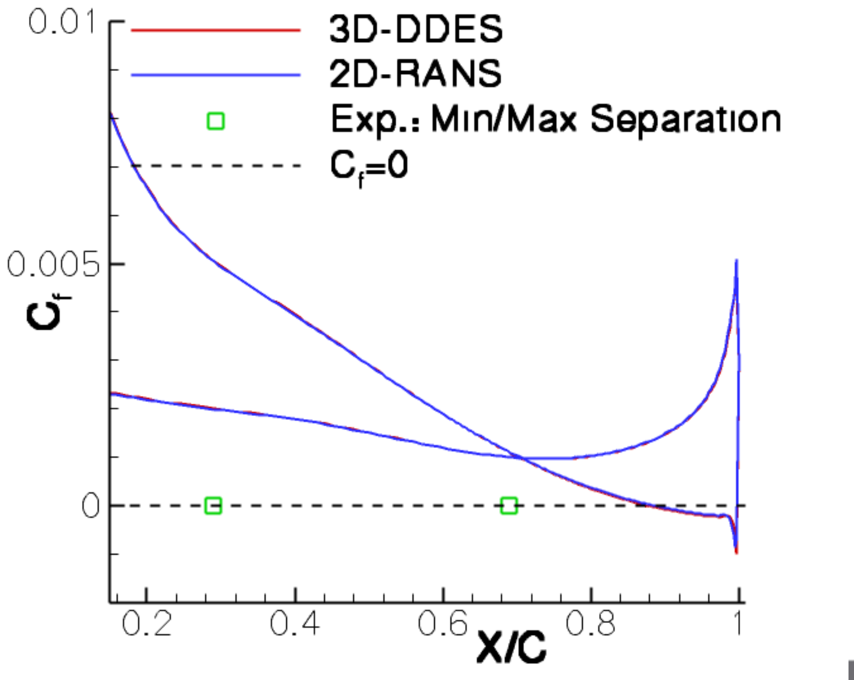
Very thin separation region near the trailing edge

Shortcoming 2: Thin separation regions treated in RANS

- DDES-16 gives practically the same result as SA-RANS

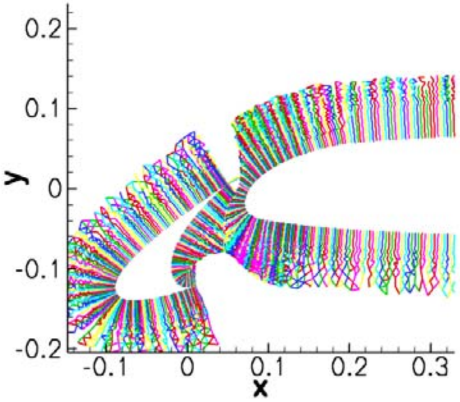
α=14°

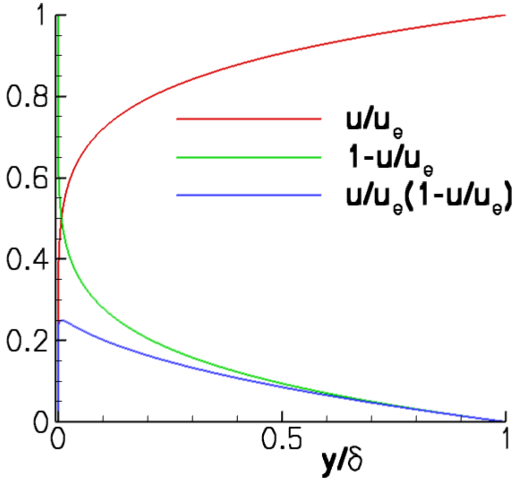




How to detect flow separation?
Integral boundary layer quantities

- Appear naturally in the integral boundary layer equation by von Karman
- Displacement thickness: $$\delta^* = \delta^*(x,z) = \int_0^\infty \left(1 - \frac{U}{U_{\text{edge}}}\right) \mathrm{d}y$$
- Momentum thickness: $$\theta = \theta(x,z) = \int_0^\infty \frac{U}{U_{\text{edge}}} \left(1 - \frac{U}{U_{\text{edge}}}\right) \mathrm{d}y$$
- Shape factor (flatness): $$H_{12} \equiv H = \frac{\delta^*}{\theta}$$





Critical value for the shape factor H at separation?

- Castillo et al. (J. Fluids Eng. 2004)
- „… one common design criterion for industrial turbine designers to **avoid separation** on compressor blades is to **not allow the shape factor to exceed 2.5**…“
- „… keep the shape factor below 2.6 …“ to avoid separation

Experiment	Λ_θ	H at/close prior to separation	H by Castillo et al. [2]
Dengel & Fernholz [5]	—	2.85	—
Alving & Fernholz [1]	0.21	2.78	2.76
Schubauer & Klebanoff [8]	0.21	2.84	2.76
Newman [7]	0.22	2.46	2.55
Simpson et al. [9]	0.21	2.62	2.76
Simpson et al. [3]	0.21	2.97	2.76

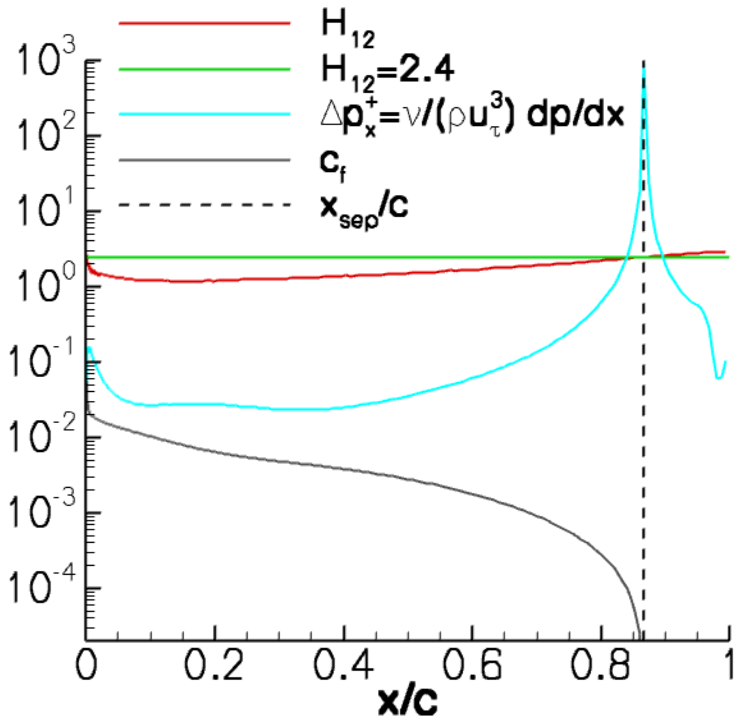
$$\Lambda_\theta = \frac{\theta}{\rho U_\infty^2 \mathrm{d}\theta/\mathrm{d}x} \frac{\mathrm{d}P_\infty}{\mathrm{d}x}$$

HGR01 at Re=0.65Mio. Criteria for flow separation

- Criteria based on shape factor H (for SA model)
  - $H < 2.4$: attached boundary layer flow
  - $H > 2.45$: separation region
- Criteria based on pressure gradient parameter
  - $\Delta p_x^+ > 1$ in the neighbourhood of the separation point

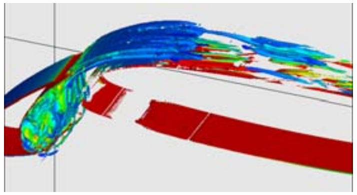
Detect the region of flow separation
=> Switch to LES

HGR01 airfoil at $\alpha=14°$

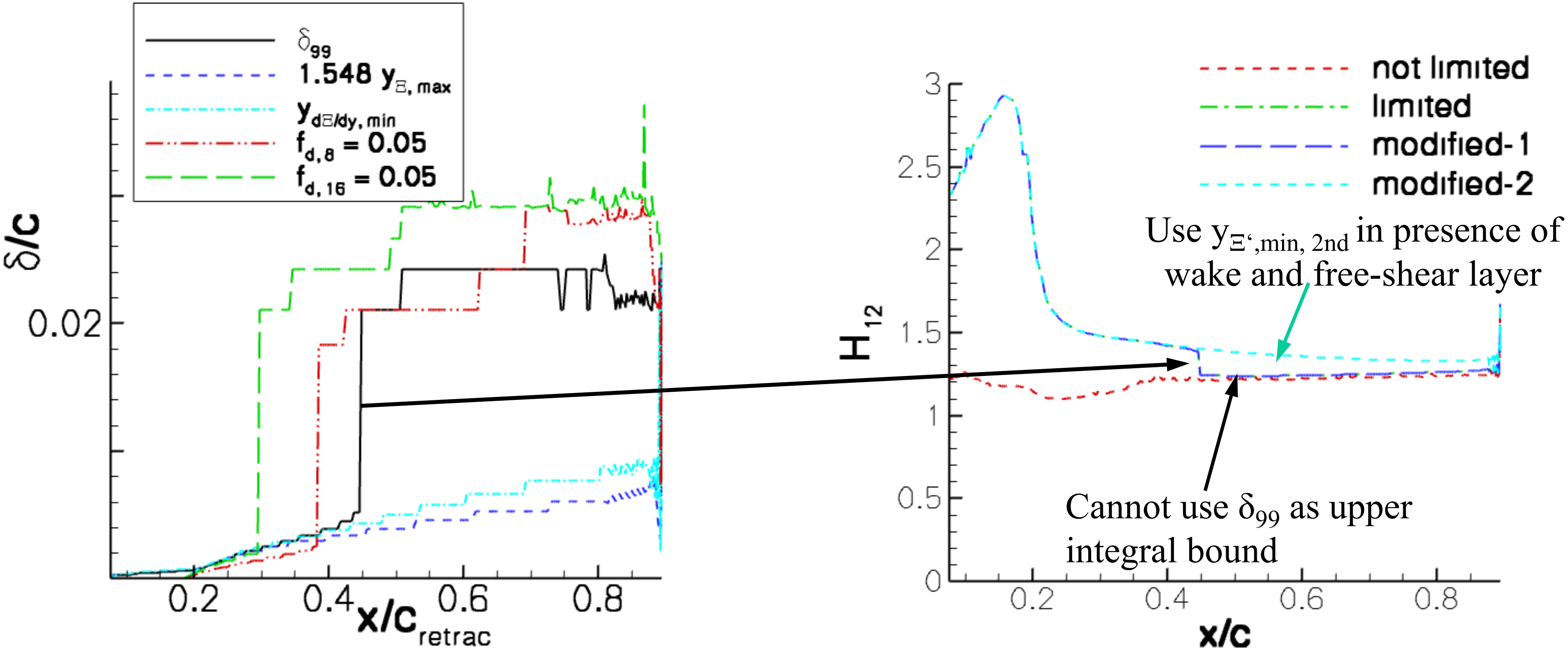


F15 3-element airfoil with prescribed transition. Prediction of shape factor H for wing upper side

$$\delta^* = \delta^*(x,z) = \int_0^{\infty}\left(1-\frac{U}{U_{\mathrm{edge}}}\right)\mathrm{d}y$$



- For comparison:
  - H~1.3 (ZPG turb. BL), H~2.5 (turb. BL separation)
  - H~2.6 (Blasius profile, ZPG lam. BL), H~3.5 (lam. BL separation)

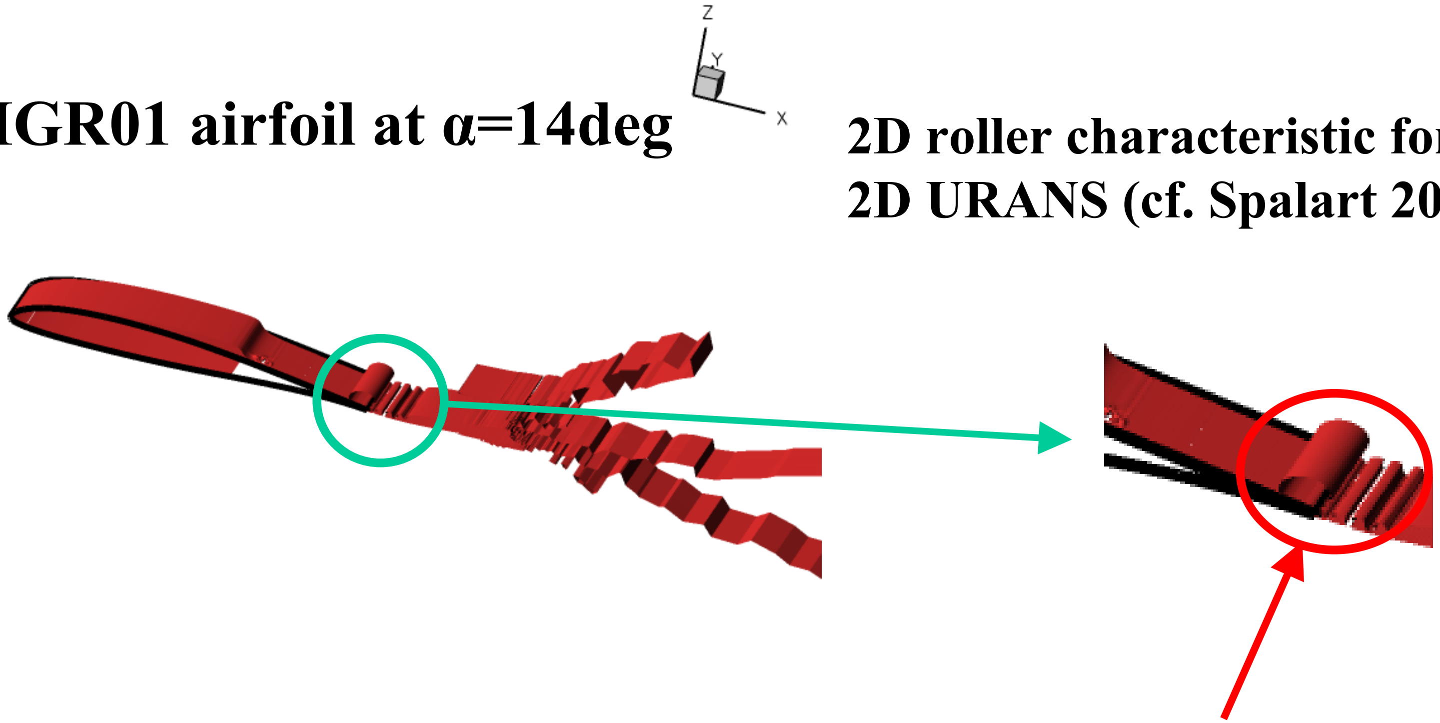


Use $y_{\Xi',\min,\ 2nd}$ in presence of wake and free-shear layer

Cannot use δ_{99} as upper integral bound

Shortcoming 3: Too slow development of turbulent content after separation on a single-element airfoil

- $2Qinv = ||\Omega|| - ||S||$ with $2\Omega = \text{Grad } U - (\text{Grad } U)^T$, $2S = \text{Grad } U + (\text{Grad } U)^T$



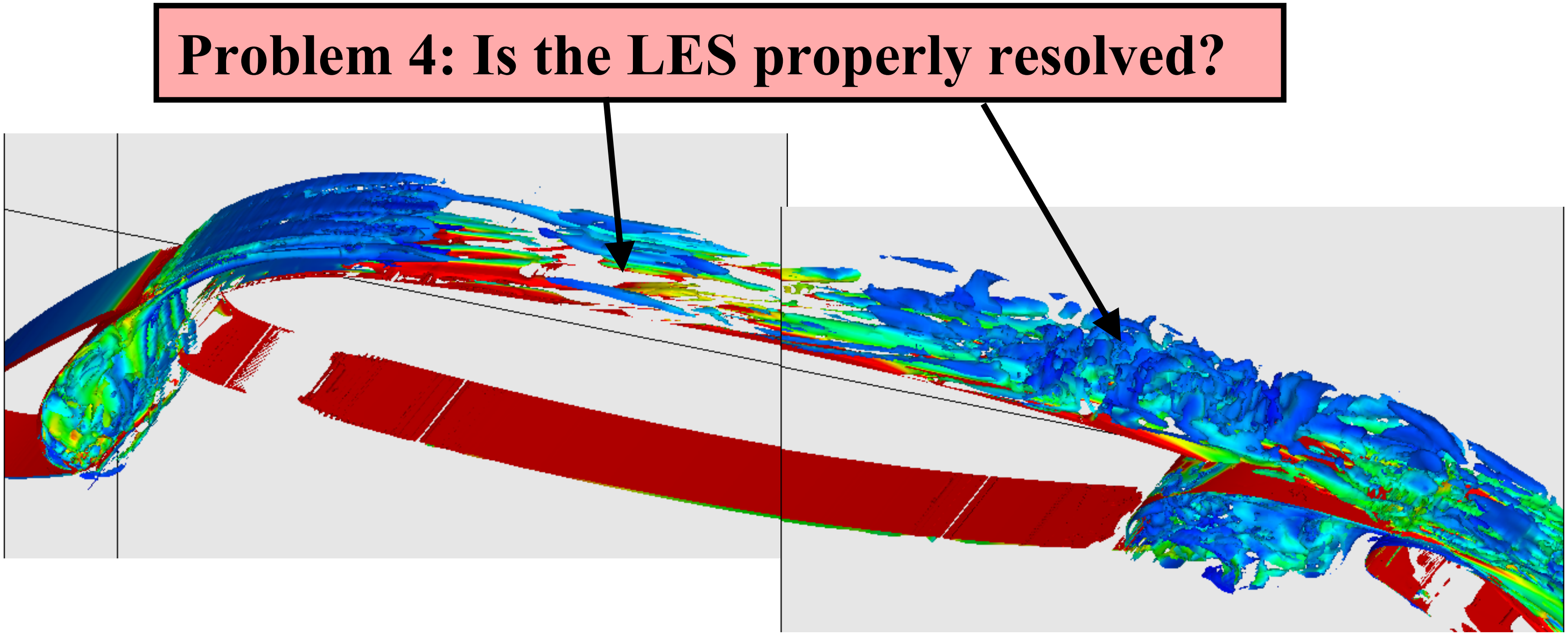
HGR01 airfoil at α=14deg

2D roller characteristic for 2D URANS (cf. Spalart 2009)

Aim: Force the generation of turbulent content

Short-coming 4. Is the LES properly resolved?

- F15 3-Element airfoil at Re=2Mio, Ma=0.15, incidence angle 7°
- Plot of instationary Qinv

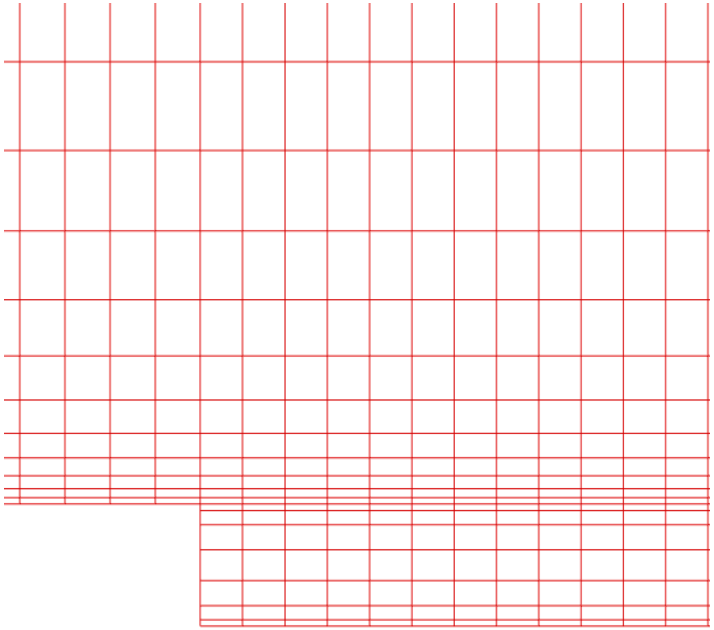


Problem 4: Is the LES properly resolved?

Ad problem 4: Ensure sufficient grid resolution in LES regions

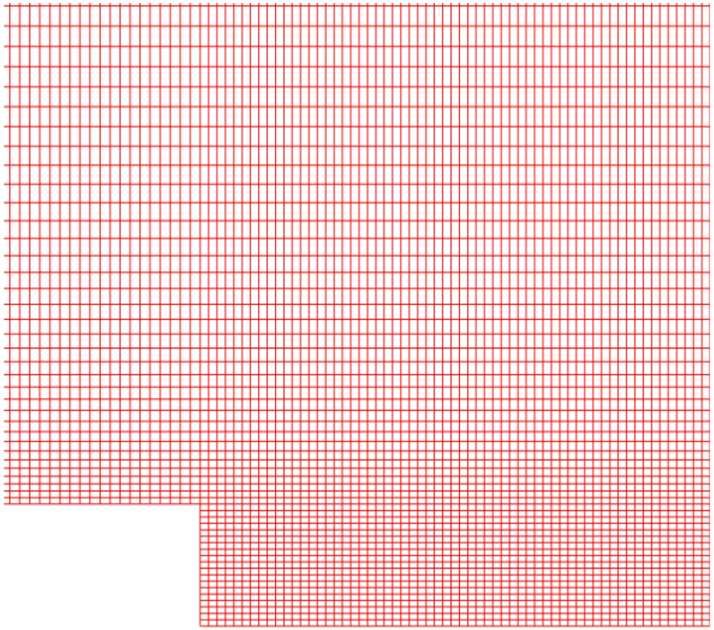
Coarse mesh 78x31x16 nodes

x/h	-0.5	10
Δx+	660	420
Δz+	300	260

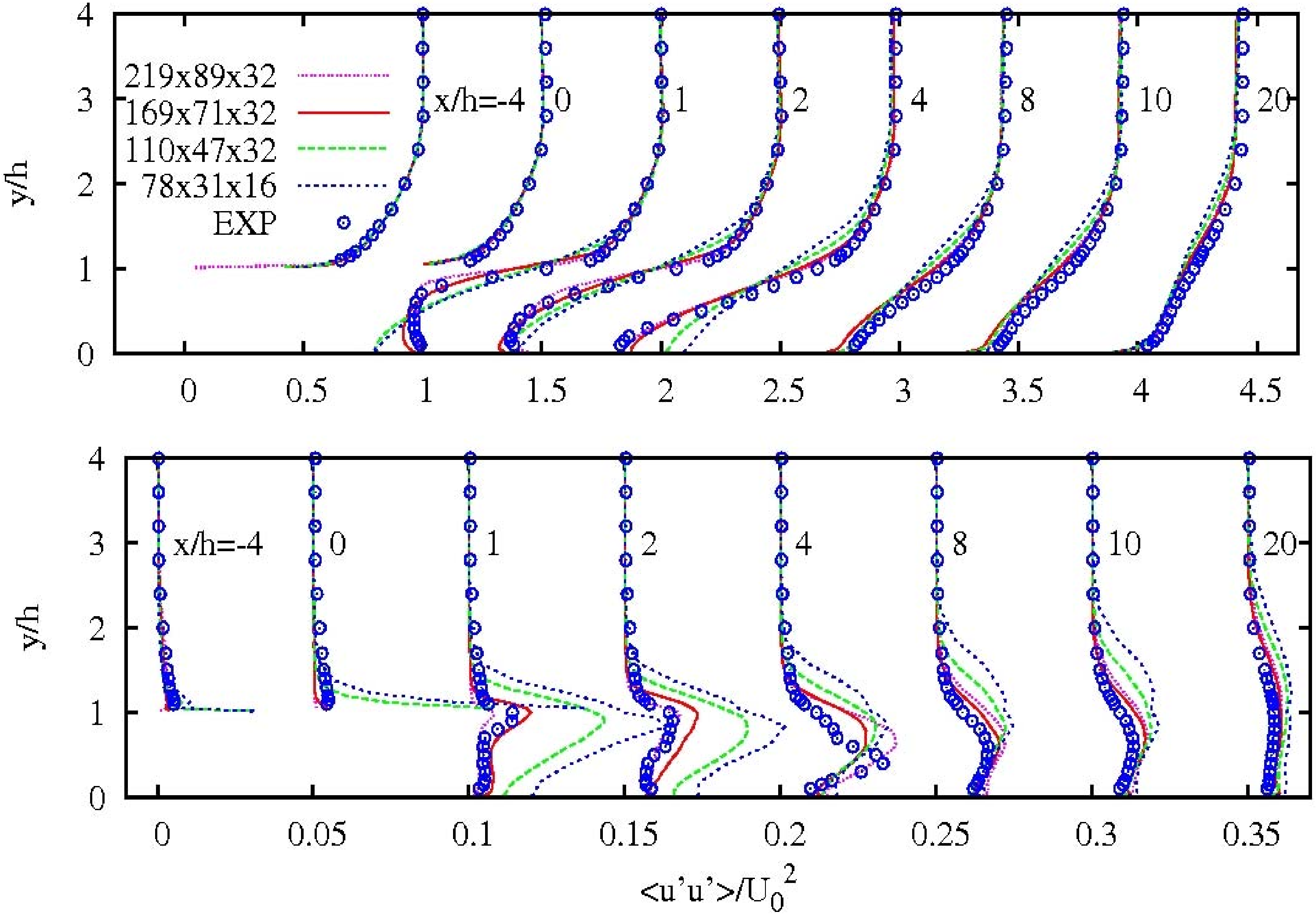


Very fine mesh 219x89x32 nodes

x/h	-0.5	10
Δx+	110	160
Δz+	150	130



Resolution requirements for Smag-LES with wall-functions for the flow over a backward-facing step

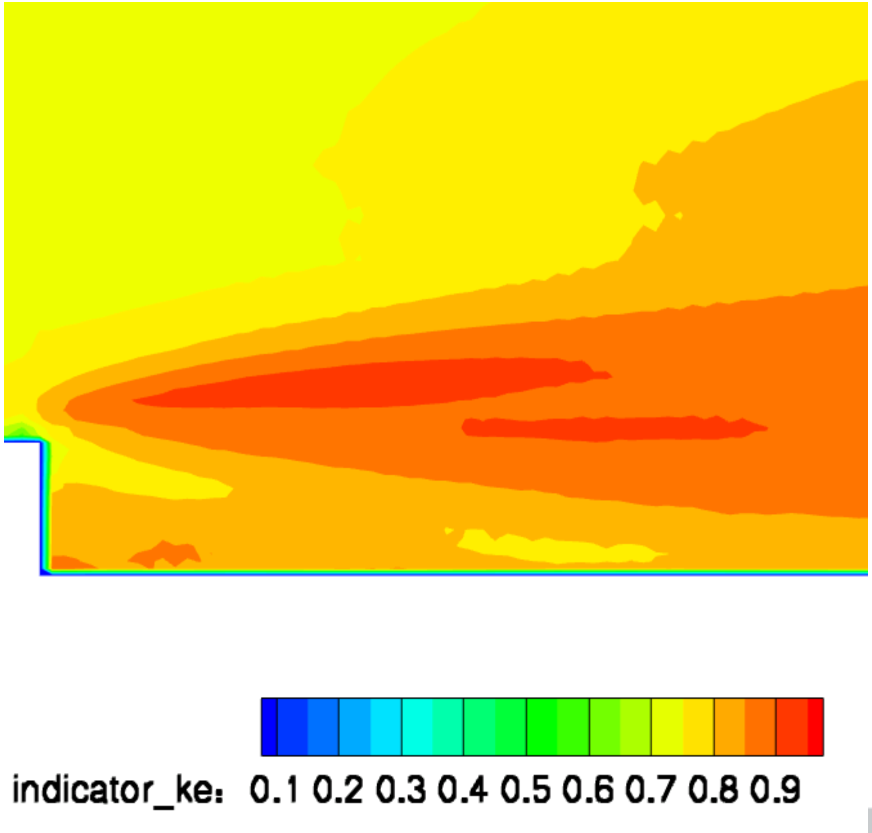


Single-grid estimator for resolved turbulent kinetic energy

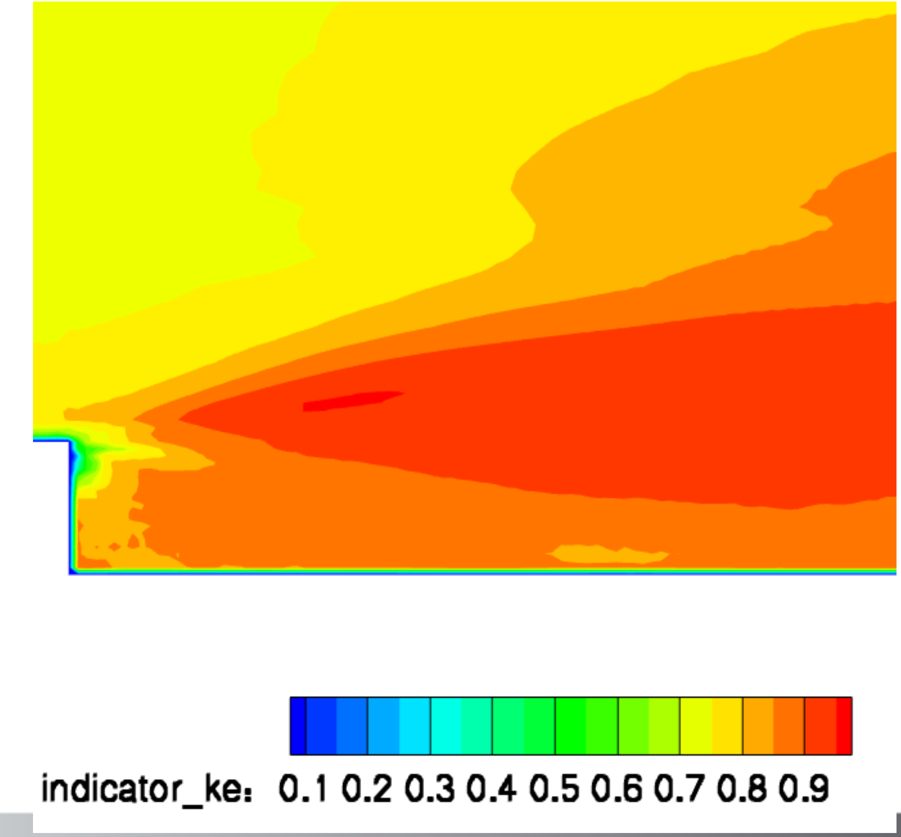
Top-hat filter

$$S_k(\boldsymbol{x}) = \frac{k}{k + k_{\mathrm{sgs}}}\,, \quad k = \frac{1}{2}\langle(\boldsymbol{u} - \langle\boldsymbol{u}\rangle)^2\rangle\,, \quad k_{\mathrm{sgs}} = \frac{1}{2}\langle(\boldsymbol{u} - \overline{\boldsymbol{u}})^2\rangle$$

Coarse mesh: S(x) < 0.8

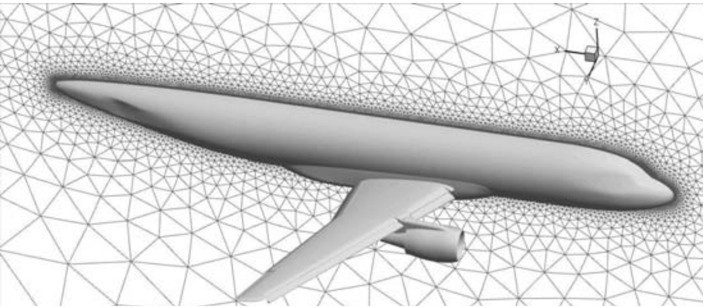


Very fine mesh: S(x)>0.9

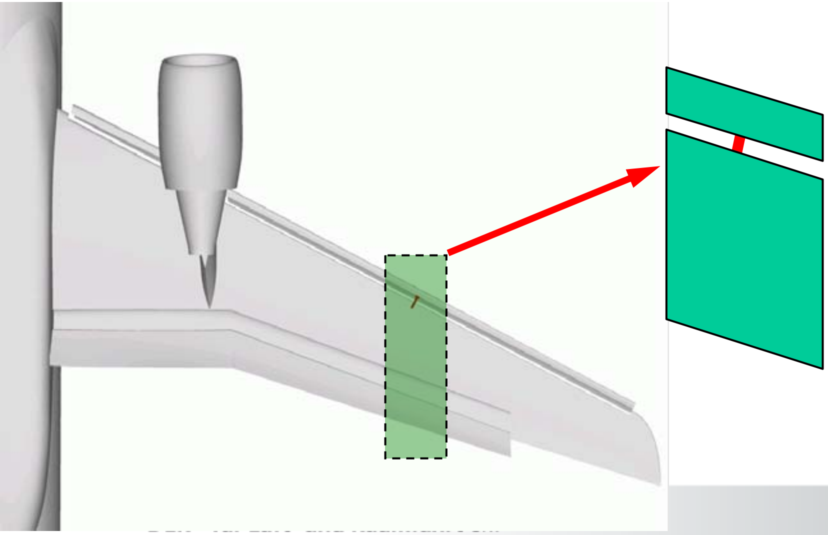


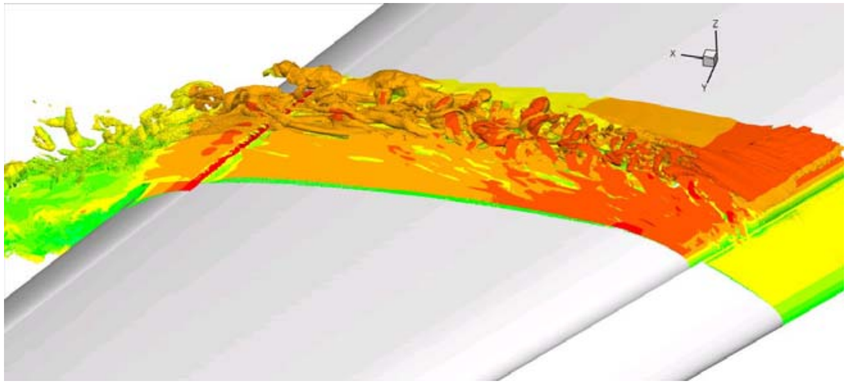
Zonal DES-RANS for predicting slat track noise

- Zonal DES for A320 wing-body-nacelle-pylon
- 30Mio nodes for RANS mesh, 50Mio nodes for embedded DES mesh
    - Spanwise extent of DES mesh: 6% half-span
- L=0.308m, Re=1.34×10^6 is really low, Mach number Ma=0.2, incidence α=3.93°
- Computing costs ~ 6month on 2048 cores



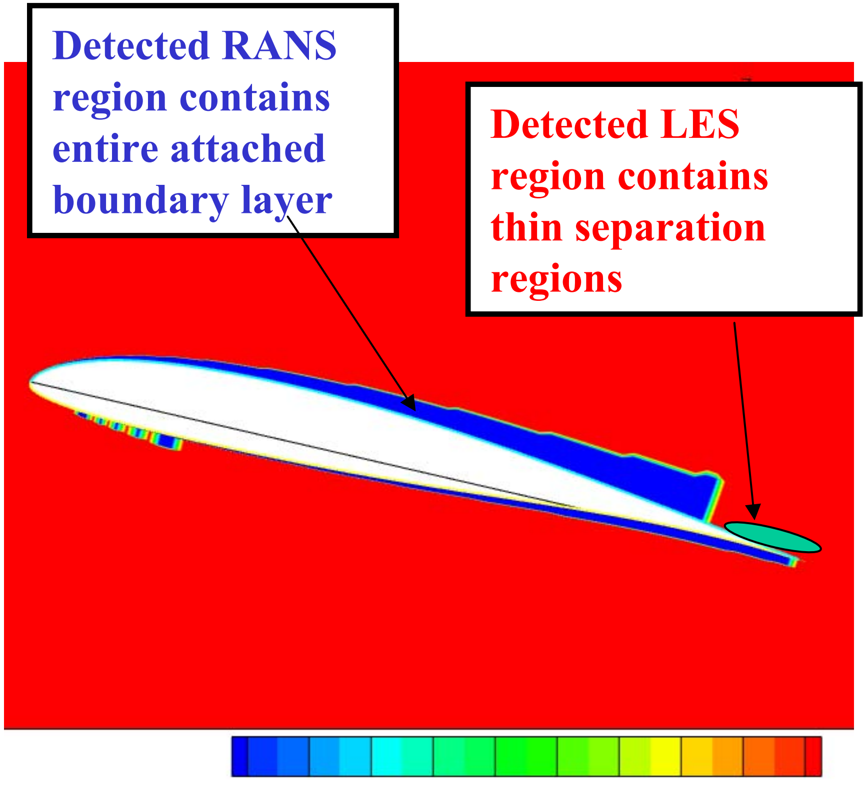
Work by Silvia Reuss





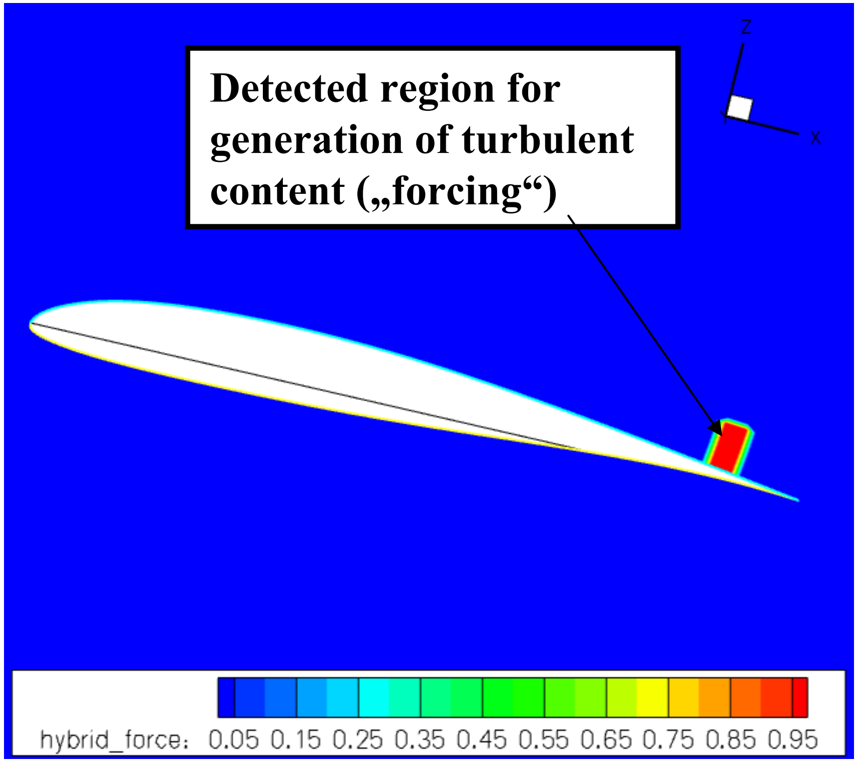
Conclusion

- Zonal RANS-DES feasible (although very expensive) for full-aircraft configurations
- Standard (D)DES not suited for aerodynamic flows with small (incipient) separation
- Presentation of a new hybrid RANS-LES method of DES-type



Detected RANS region contains entire attached boundary layer

Detected LES region contains thin separation regions



Detected region for generation of turbulent content („forcing“)

End of the presentation

Actual RANS and LES regions (presence of turbulent content)

- Consider relative constribution of modelled to resolved shear stress

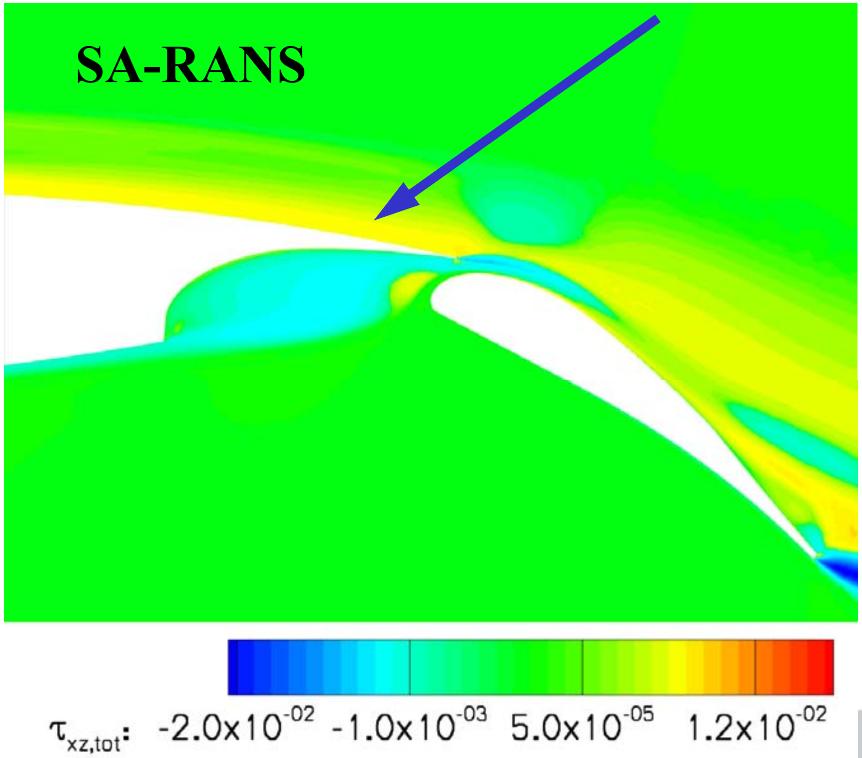
$$(\tau_{xz})_{tot} = \underbrace{\mu_l\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)}_{\text{laminar shear stress}} + \underbrace{\mu_t\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)}_{\text{modelled turbulent shear stress}} - \underbrace{\rho\langle u'w'\rangle}_{\text{resolved turbulent shear stress}}$$

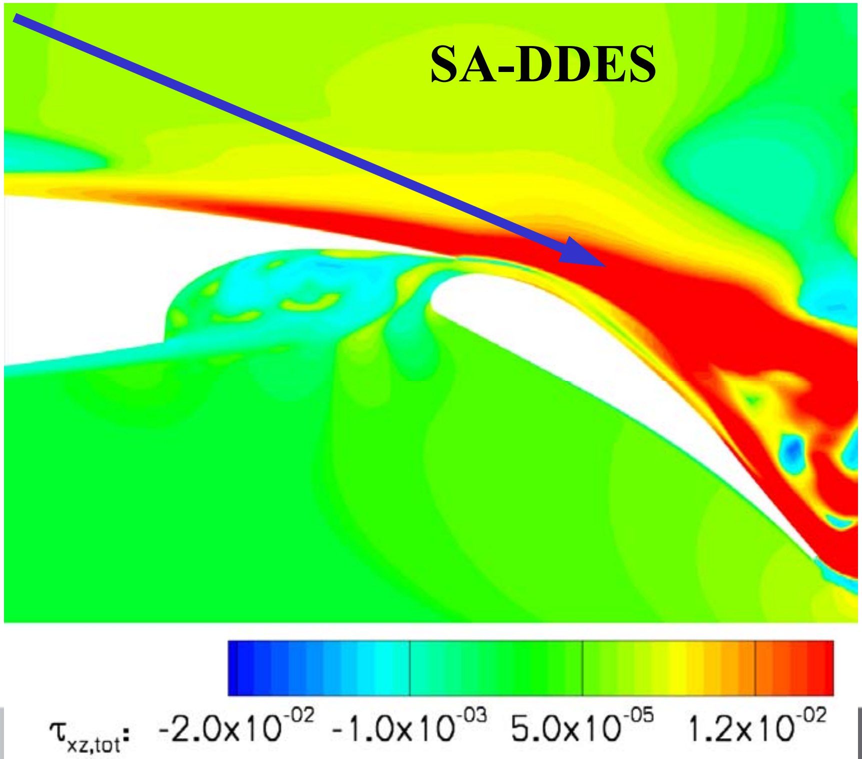
$$= (\tau_{xz})^{lam} + (\tau_{xz})^{turb}_{mod} + (\tau_{xz})^{turb}_{res}$$

Actual DES modus	τ_{xz}-modelled	τ_{xz}-resolved
RANS simulation	100%	0%
(D)DES simulation	100% in RANS mode	0% in RANS mode
	~50% „grey area“ ~50%	
	<10% in LES mode	> 90% in LES mode

Ad problem 4: Total shear stress overprediction

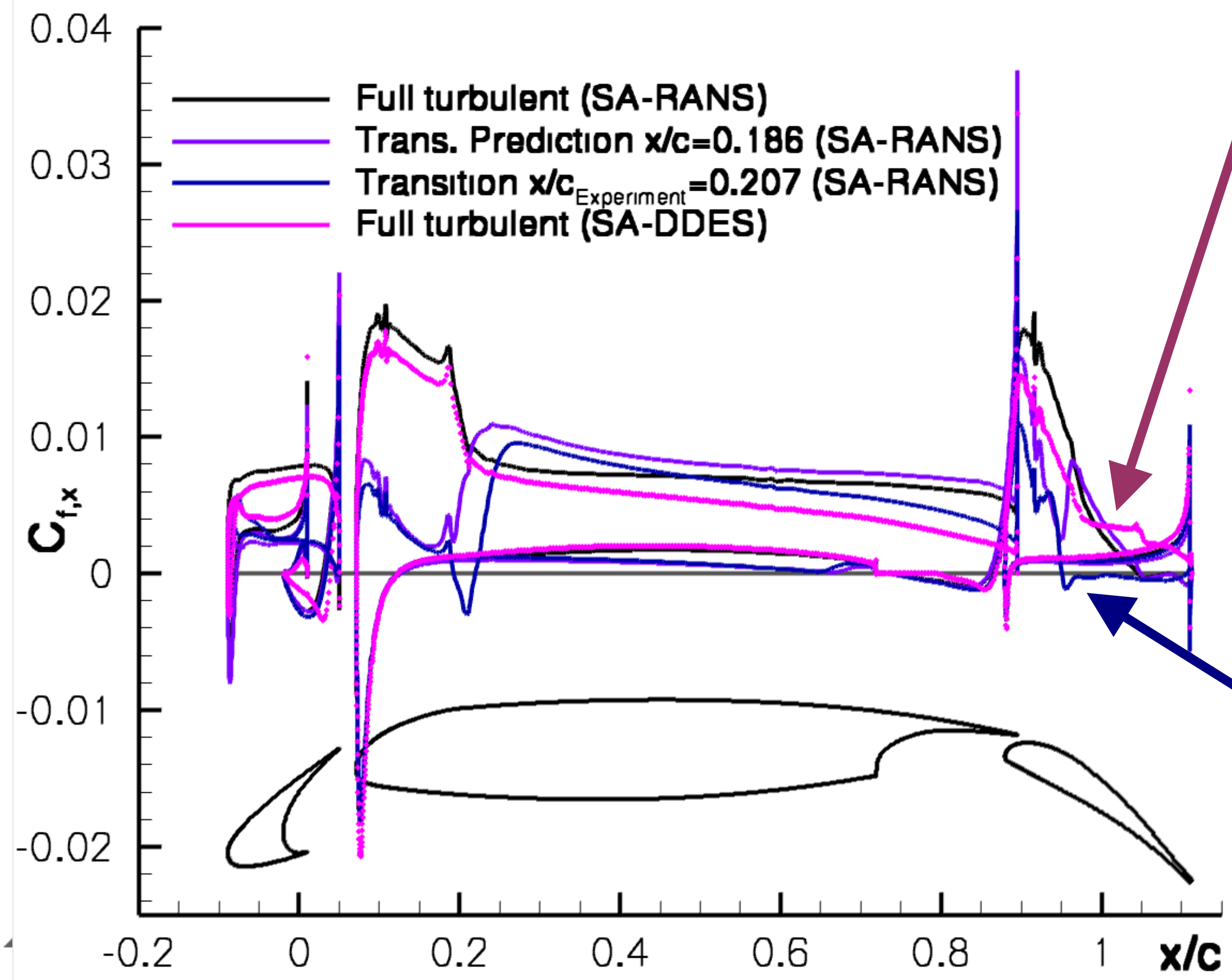
- Consider the total turbulent shear stress (modelled + resolved)
- Unsteady large-scale vortical events (too large for being resolved turbulence) of slat wake penetrate down into the atached boundary layer
- Total turbulent stress much larger for SA-DDES than for SA-RANS
- Increased transport of momentum towards the wall prevents flow separation on the flap





Comparison SA-DDES and SA-RANS. Cf-distribution

- Differences between SA-DDES and SA-RANS (both fully-turbulent)



No flow separation on flap predicted by SA-DDES

Significant increase of size of separation region on flap for SA-RANS with lam.-turb. transition compared to full-turbulent simulation