Modifikation von (D)DES basierend auf einer Detektion von anliegenden Grenzschichten und Strömungsablösung

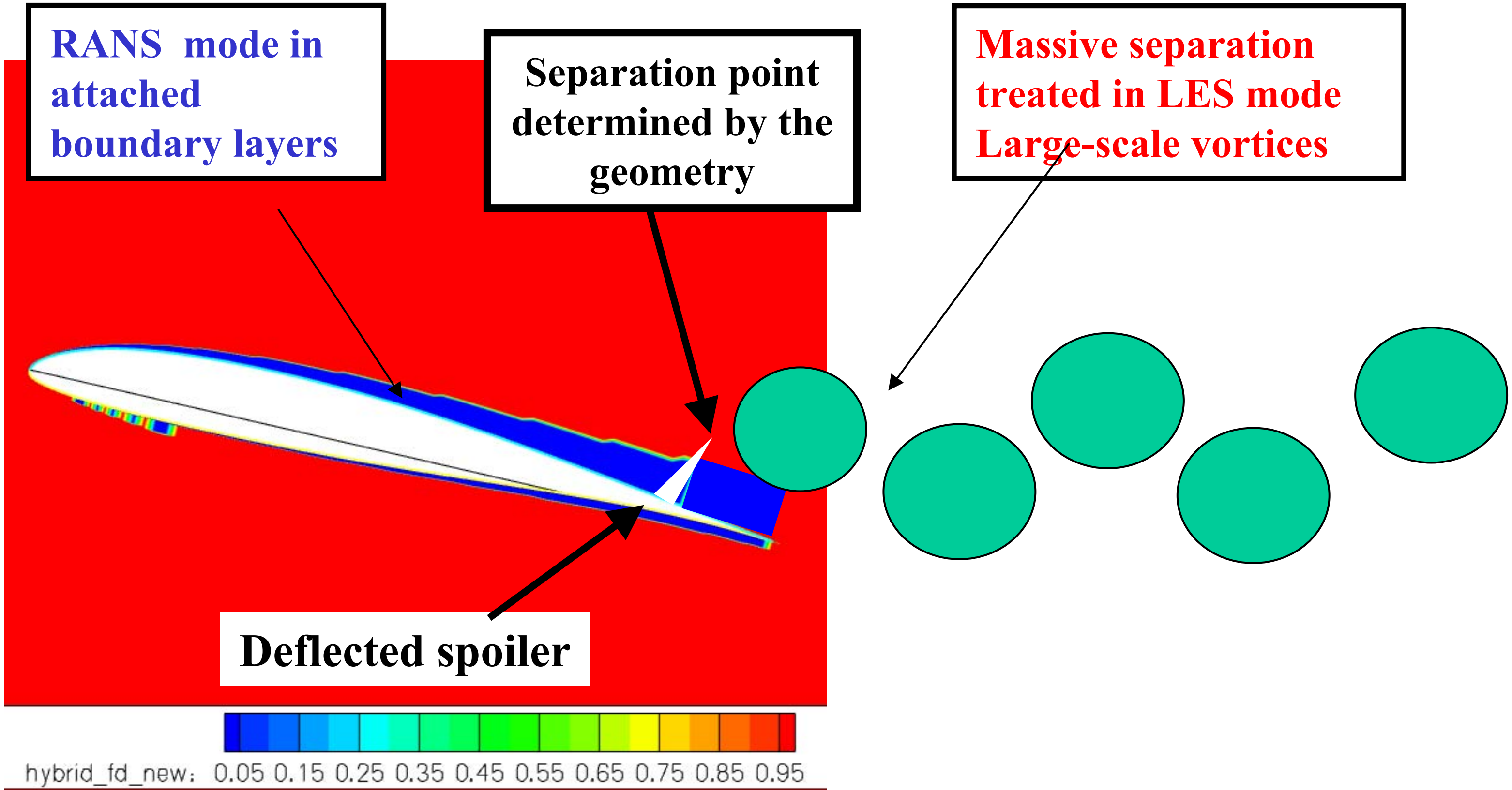
Tobias Knopp, DLR, AS-CA

Work done in cooperation with Axel Probst, Rolf Radespiel (TU-BS) Normann Krimmelbein, Christoph Wolf, Silvia Reuss, Dieter Schwamborn (DLR AS-CA)

Design application for Detached-Eddy Simulation (DES)

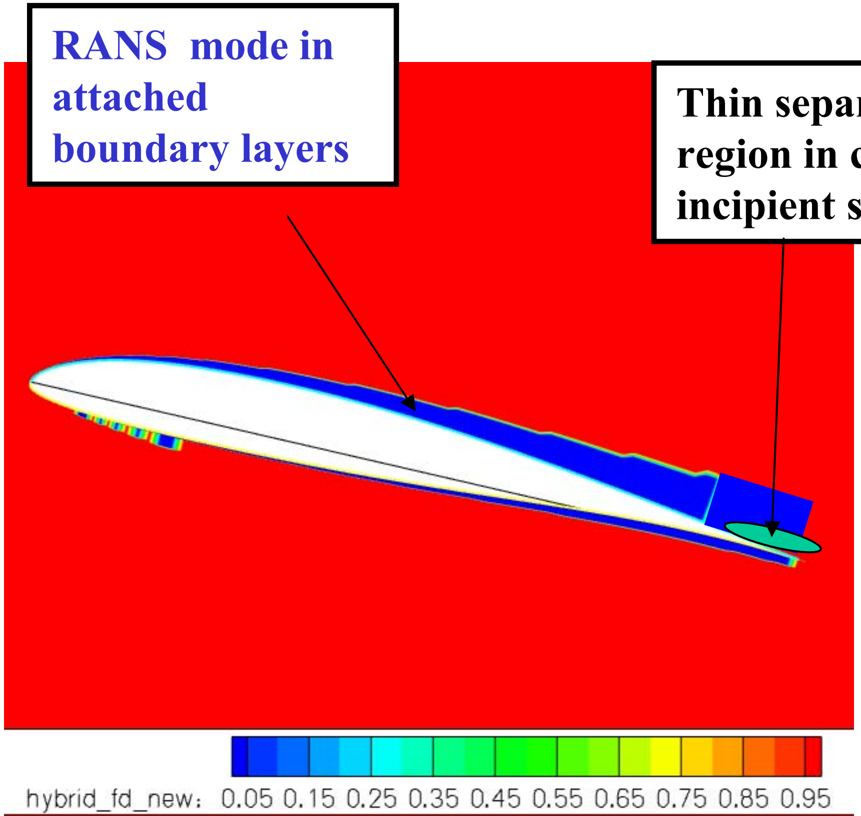
Claim of (D)DES:

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



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

- Thin separation regions inside the boundary layer at the boundary of the flight envelope
  - Incipient separation at landing/take-off
  - Shock buffet at transonic cruise
- DES97, DDES are not conceived for this flow situation



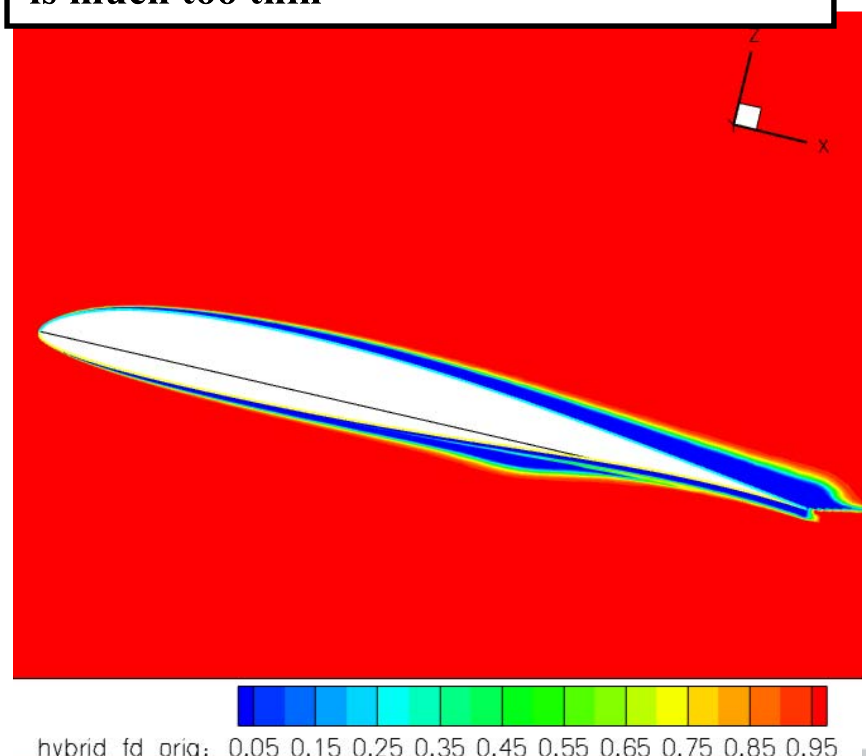
<u>Subject of this talk:</u>

- **DES for flows with small separation**
- **Description of shortcomings of standard DDES for flows with incipient separation**
- **Modification of standard DDES to overcome these problems**

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

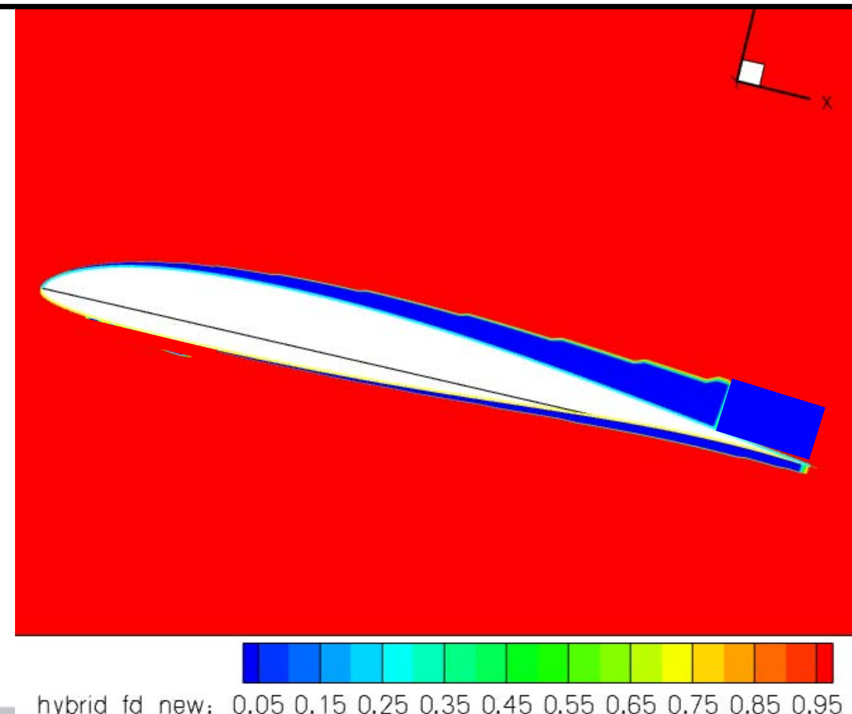
Shortcoming 1: DDES underpredicts the boundary layer thickness in case of a strong adverse pressure gradient

Boundary layer thickness detected using the fd-function of DDES is much too thin



Step 1:

- **Detect the thickness of attached boundary layers properly**
- **E.g.: δ_{99}, where U_{edge} is computed using the compressible version of Bernouilli's eq.**

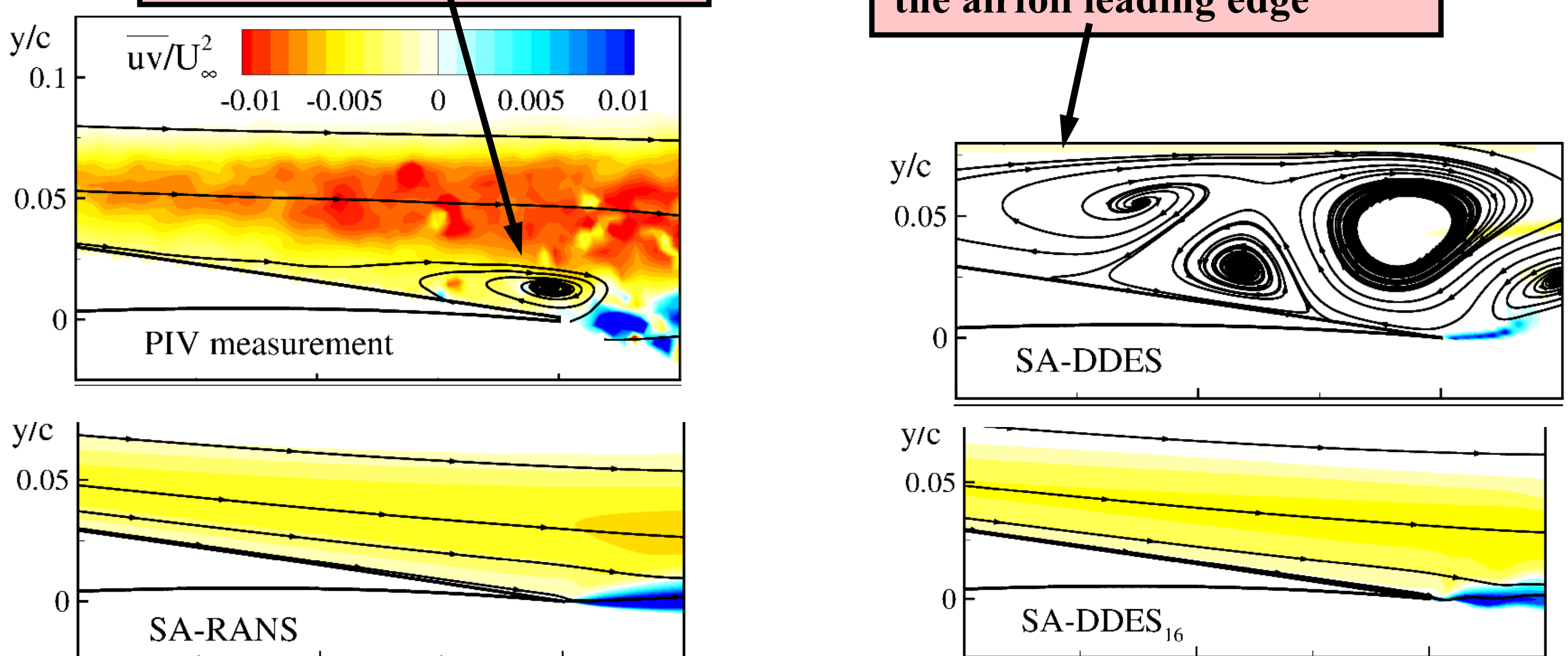


Shortcoming 1: Too early flow separation for HGR01 airfoil because f_d underpredicts the boundary layer thickness

- HGR01 airfoil at Re=0.65Mio, Ma=0,07, incidence α=12°

Small trailing edge separation found using PIV at x/c>0.85

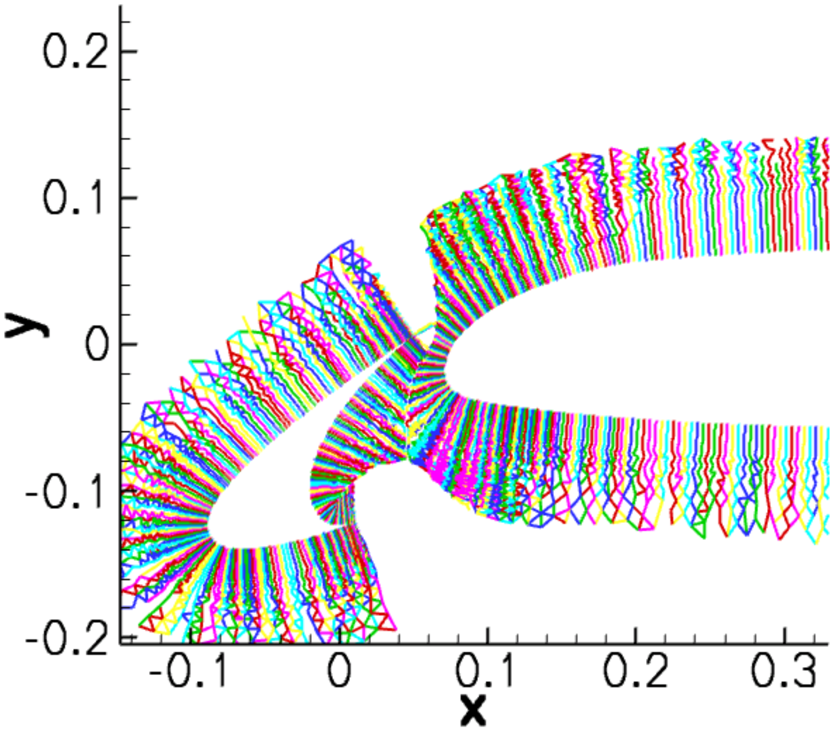
With default DDES: Massive separation at x/c>0.45 running towards the airfoil leading edge



Results by Axel Probst, TU-BS

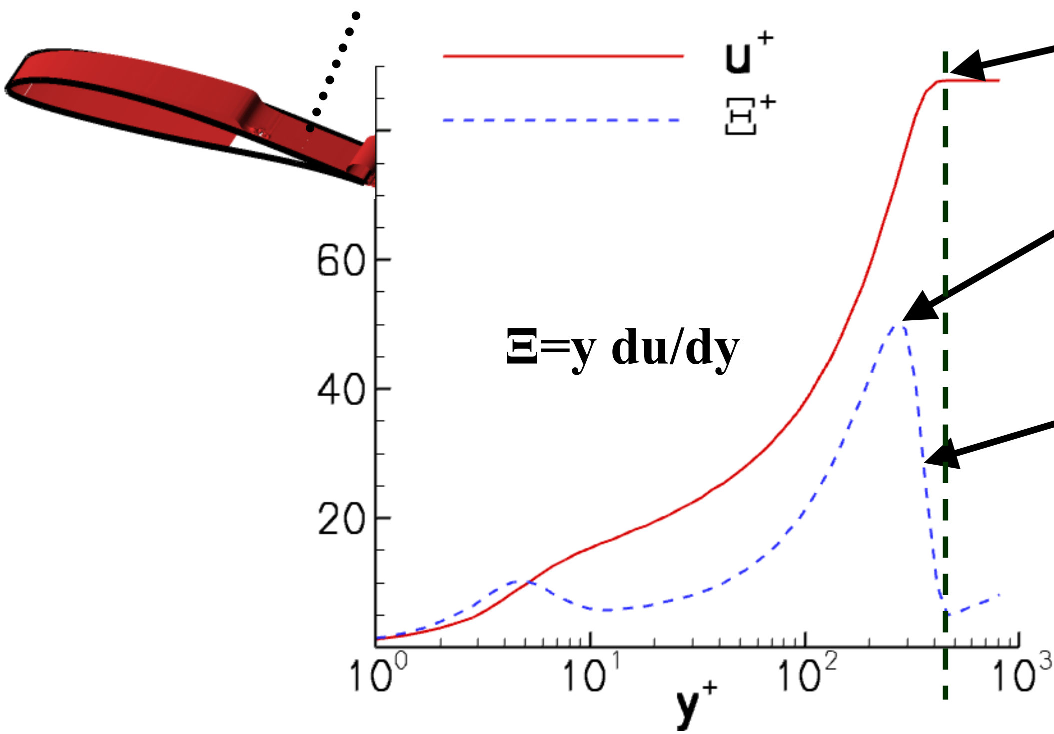
Extension of the unstructured flow solver TAU

- 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}

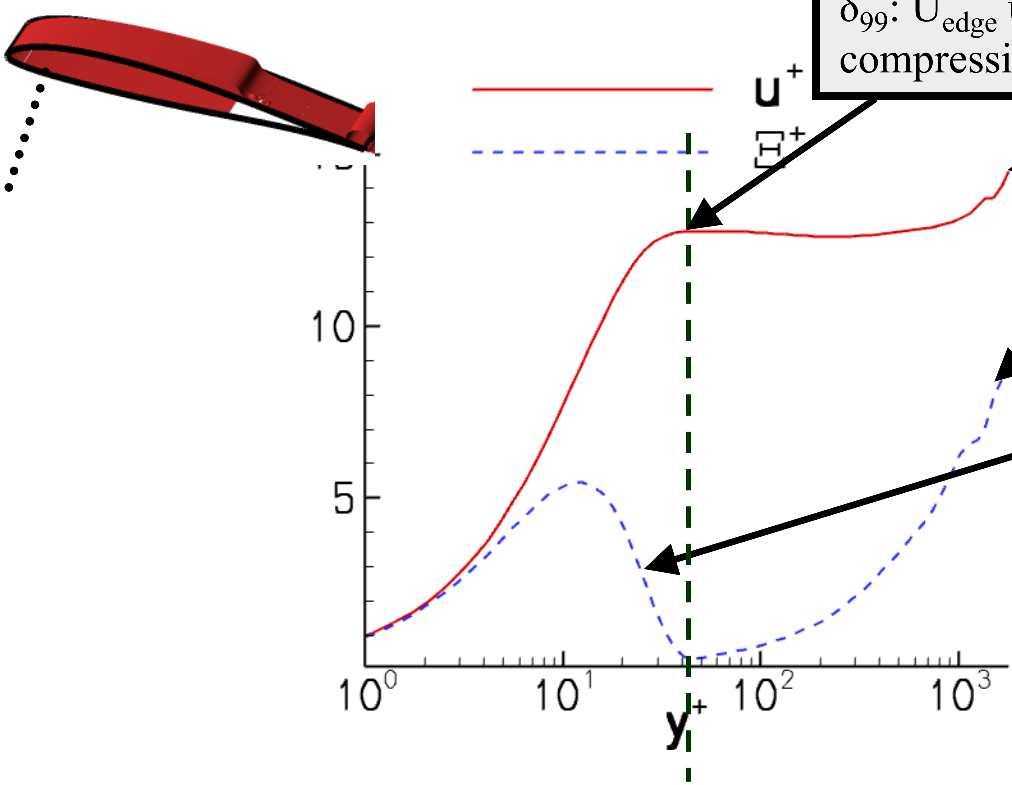
Proposal by Stock & Haase (1987):
$y_{\Xi,max}$ (without calibration const)
Constant from Coles law-of-the-wall

$y_{\Xi',min}$ (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

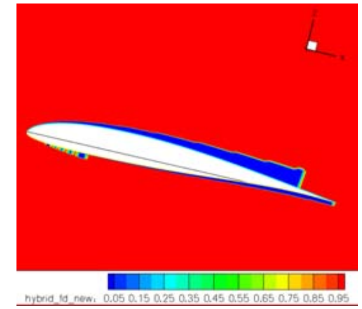
$y_{\Xi,max}$ (without calibration const)

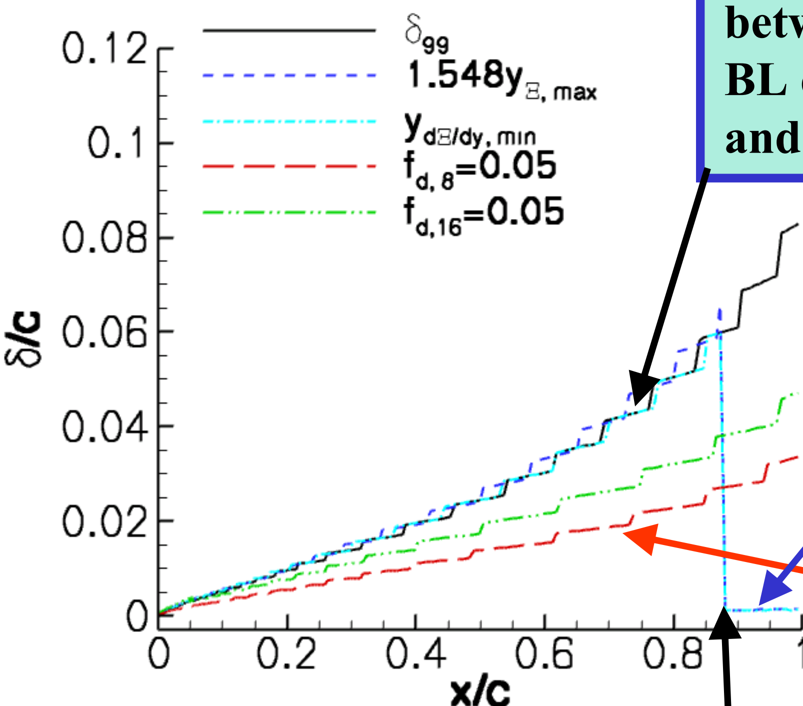
$y_{\Xi',min}$ (without calibration const)

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)





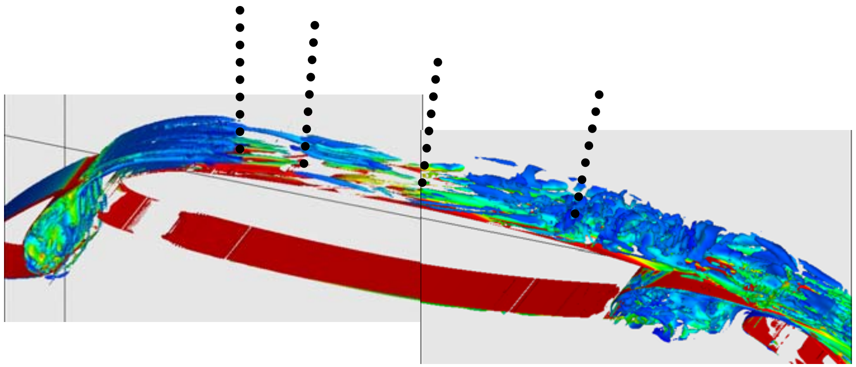
Good agreement between algebraic BL estimates $y_{\Xi',min}$ and $y_{\Xi,max}$ and δ_{99}

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

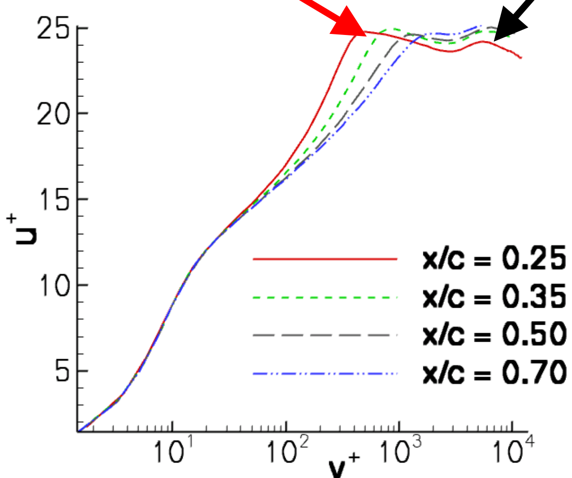
F15 with prescribed transition. Wing upper side

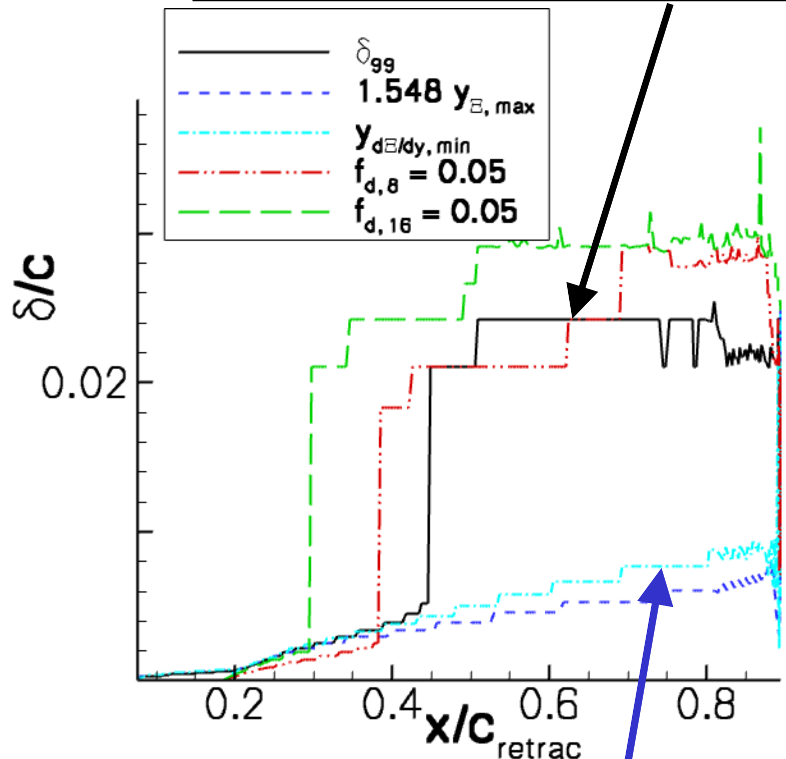


δ₉₉ detects the thickness of the free-shear layer (slat wake and convected slat BL)

Attached wing BL

Free-shear layer

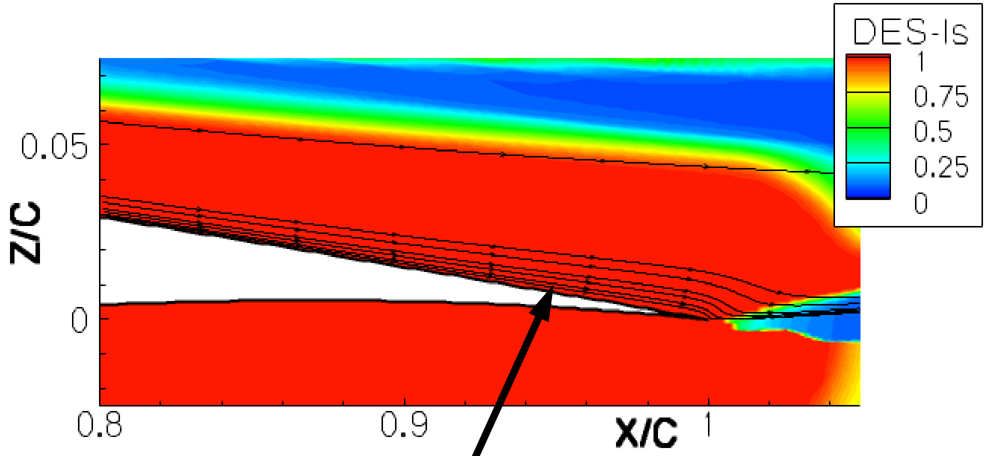




$y_{\Xi',min}$ and $y_{\Xi,max}$ still detect the thickness of the attached wing BL

Shortcoming 2: Thin separation regions treated in RANS

α=14deg
Red: formal RANS-region of the DES
Blue: formal LES-region of the DES



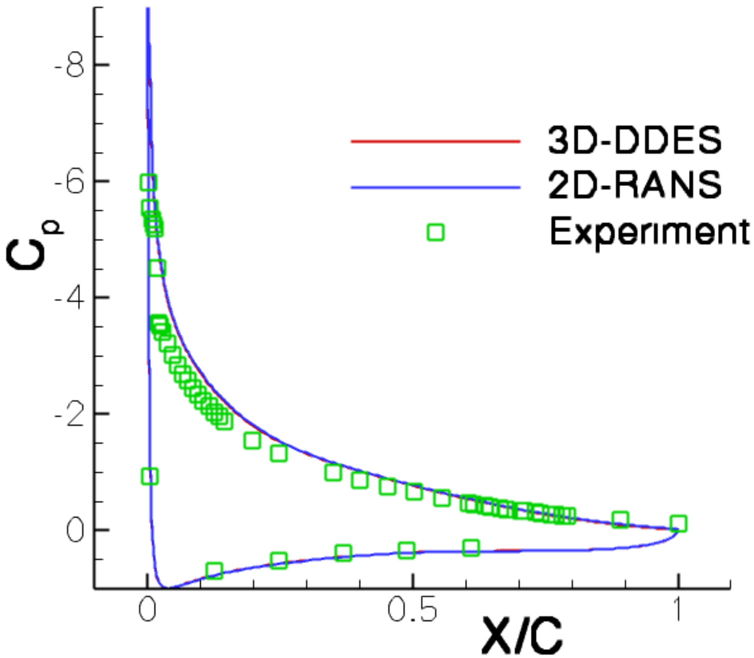
Very thin separation region near the trailing edge
lying completely in the RANS region

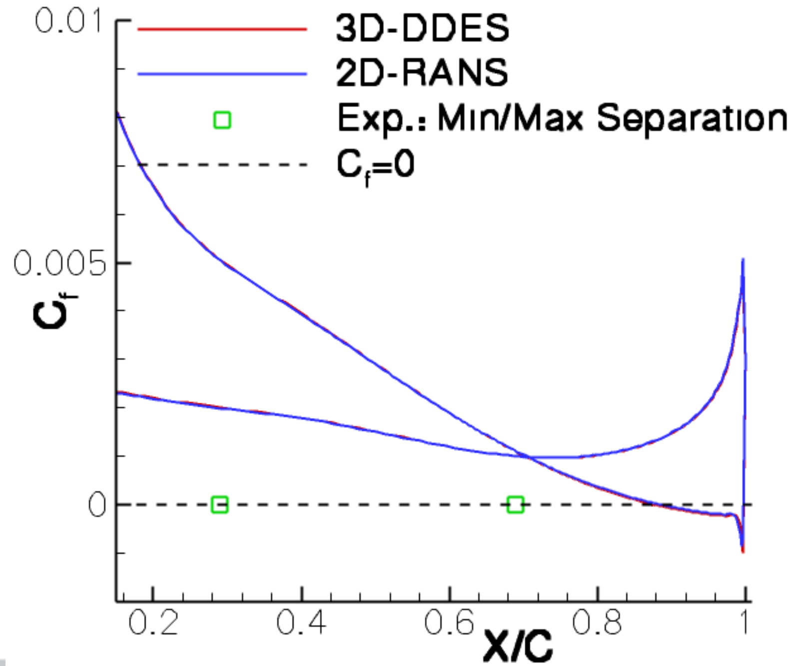
Shortcoming 2: Thin separation regions treated in RANS

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

Results by Christoph Wolf (DLR AS-CA)

α=14°

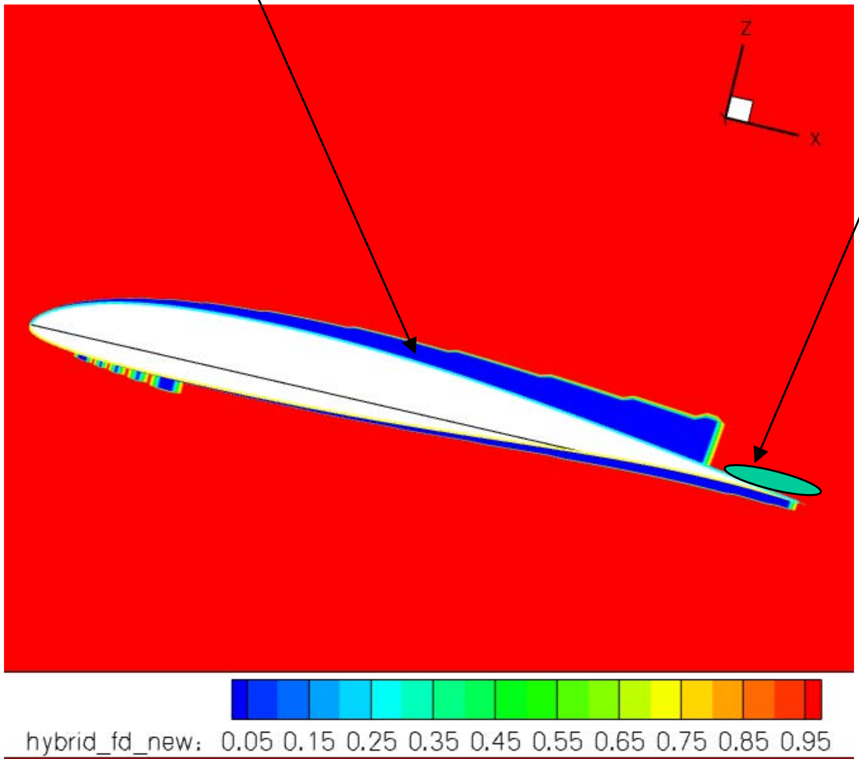




Aim: Detect separation and switch to LES mode

Step 1: Detect the entire attached boundary layer

Step 2:
- **Detect regions of separated flow**
- **Switch to LES mode**



Challenge: How to detect
- **the separation point?**
- **regions of separated flow?**

How to detect flow separation?

Focus here: pressure-induced flow separation on smooth surfaces
- **low-speed flows (not shock-induced separation)**
- **separation point not determined by the geometry**

- Characteristic parameters for boundary layers at adverse pressure gradient
  - Pressure gradient parameters β (outer coord.), Δp_x^+ (inner coord.)
  - Shape factor **H**, G (by Clauser)

- 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): $$\boxed{H_{12} \equiv H = \frac{\delta^*}{\theta}}$$

Critical value for the shape factor H at separation?

Experimental + semi-theoretical evidence:

- Paper by 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

What about RANS simulations?

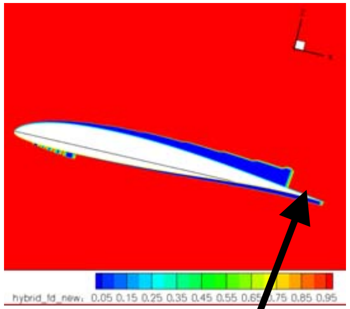
- **Is there a critical value for H at separation?**
- **H_{crit} needs to be independent of Re, Ma, test-case (airfoil geometry)**

Additional Question:

Is H_{crit} specific for each RANS turbulence model (or independent)?

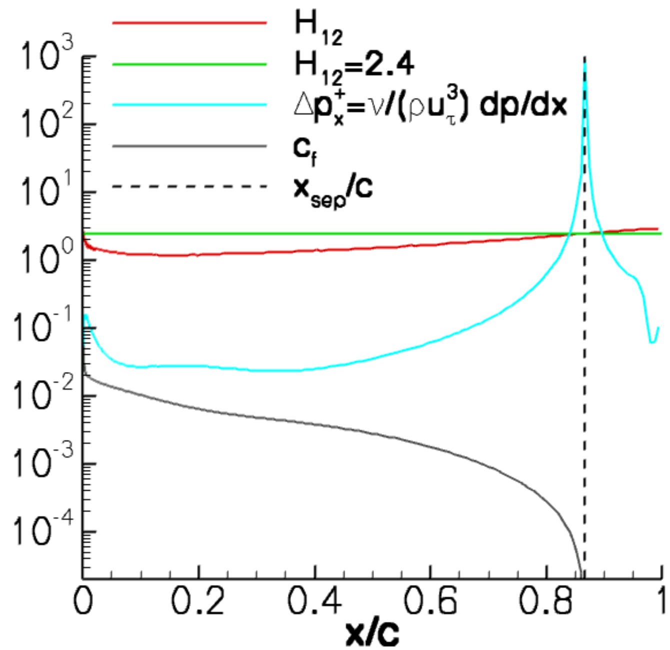
Critical value for H at the separation point?

- For SA model: Yes, $H_{crit}=2.4$
  - For HGR01 at Re=0.65Mio - 5.2Mio, α=12°-16°
  - Also for AS-A airfoil and diffusor-flow
- **H < 2.4: attached boundary layer flow**
- **H > 2.45: separation region**
- Addition goal: How to detect the vicinity of the separation point?
  - $\Delta p_x^+ > 1$ in the neighbourhood of the separation point



Detect the region of flow separation => Switch to LES

HGR01 airfoil at α=14°

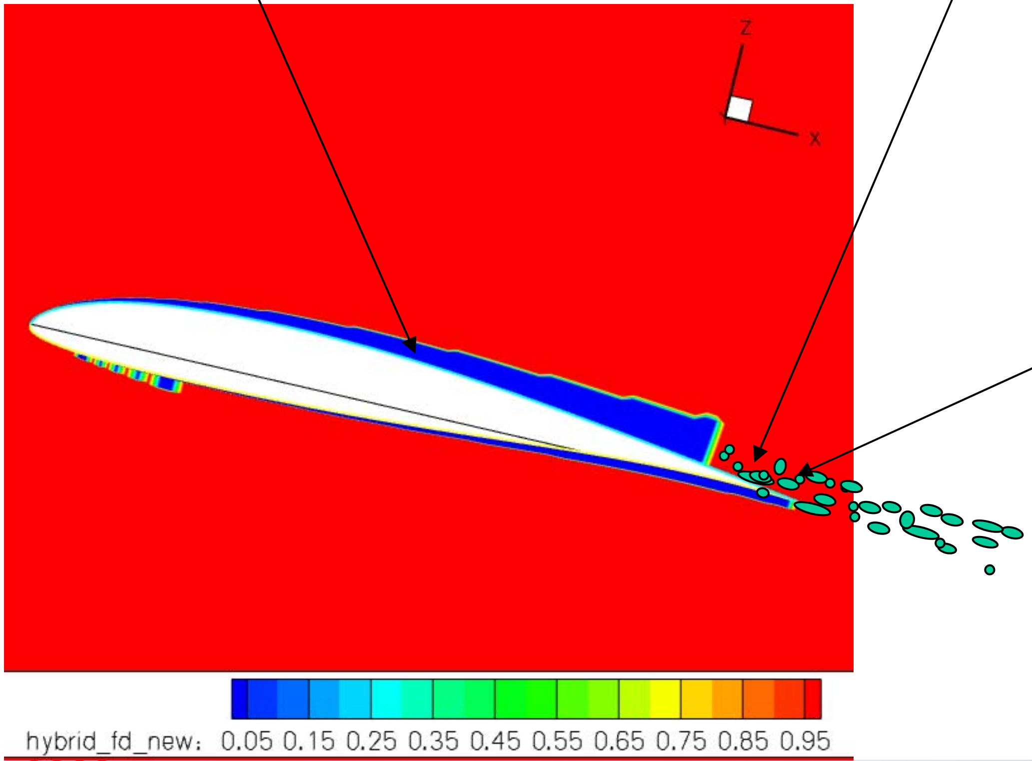


Aim: Force the generation of turbulent content in the LES region

Step 1: Detect the entire attached boundary layer

Step 2:
- **Detect regions of separated flow**
- **Switch to LES mode**

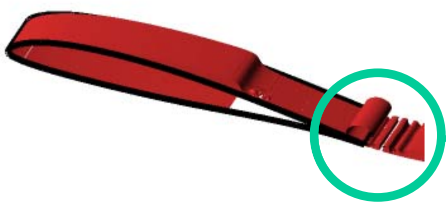
Step 3: Force the generation of turbulent content in the LES region



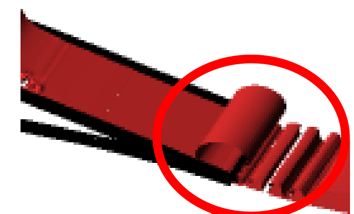
Shortcoming 3: Too slow development of turbulent content after separation on a single-element airfoil

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

HGR01 airfoil at α=14deg



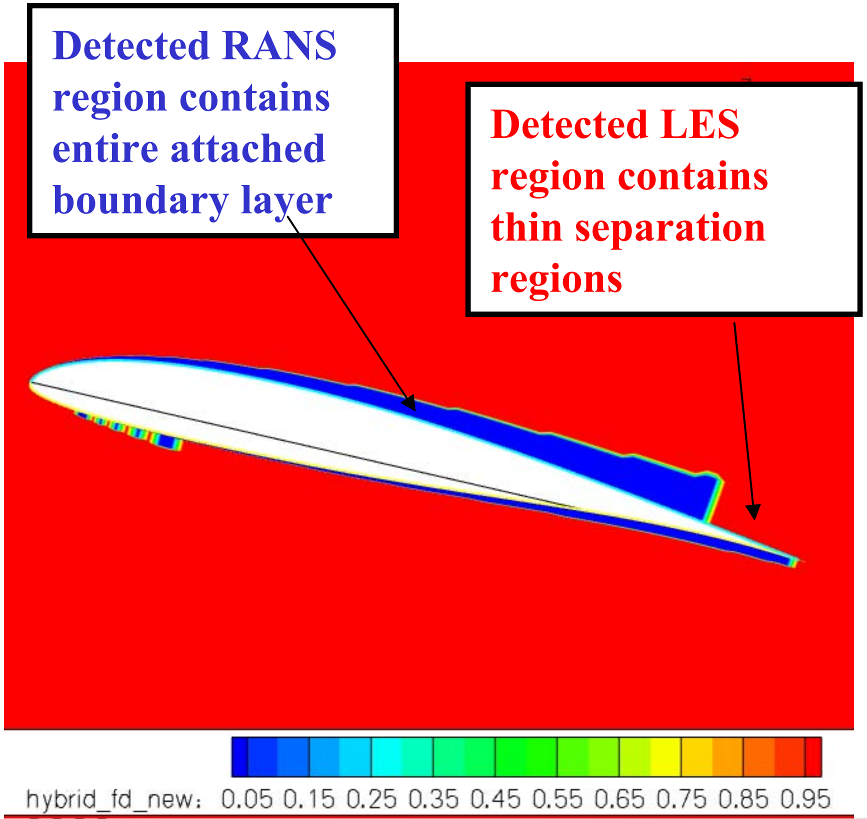
2D roller characteristic for 2D URANS (cf. Spalart 2009)

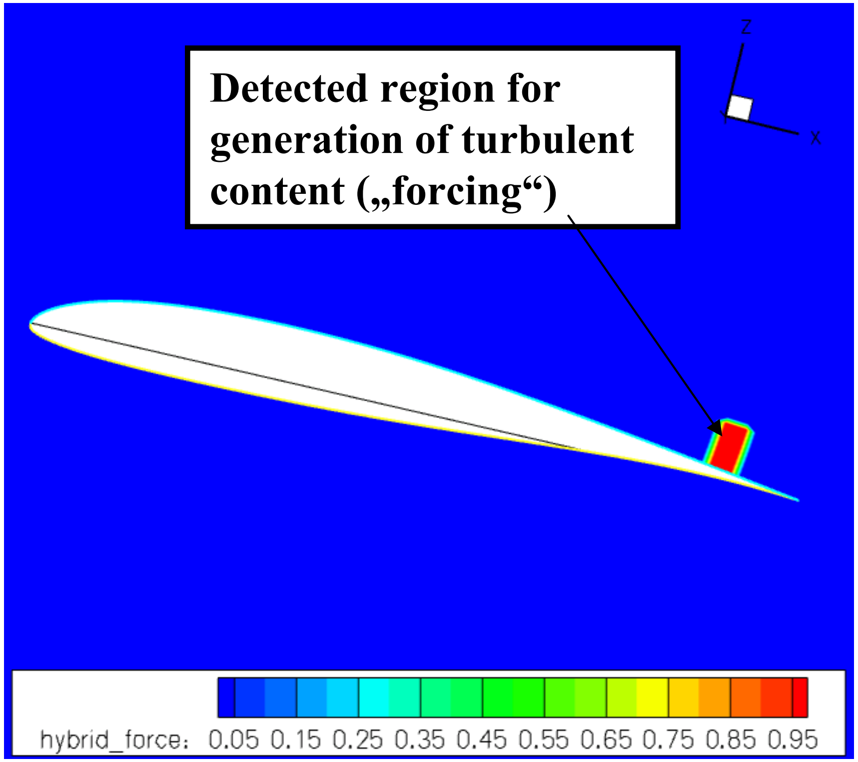


Aim: Force the generation of turbulent content

Conclusion

- Standard (D)DES not suited for aerodynamic flows with small (incipient) separation
- Presentation of a new hybrid RANS-LES method of DES-type





End of the presentation

Review of LES work.

LES convergence study for grid and time step size.

Implications for aerospace applications

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: $\tilde{d} = d_W - f_d \max(0, d_W - C_{DES}\cdot\Delta)$

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

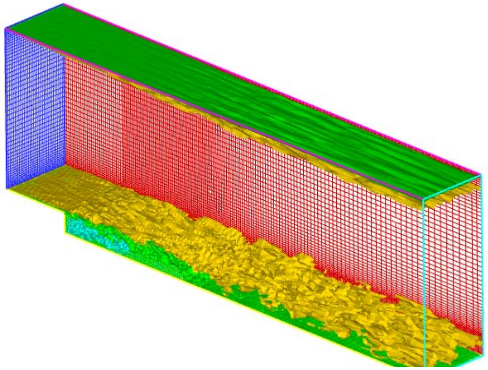
  - **Formal RANS region**: $\tilde{d} = d_W$ Spalart-Allmaras RANS model

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

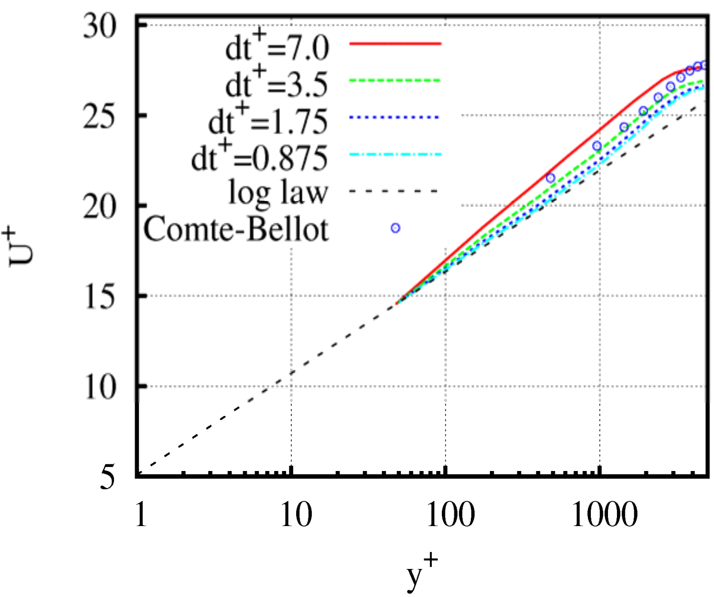
- Function for RANS-LES switch $f_d = f_d(\tilde{\nu}, d)$ based on log-layer solution for $\tilde{\nu}$ in TBL at ZPG
- RANS and LES region are determined by f_d (and by the mesh)

Costs for LES with near-wall modelling

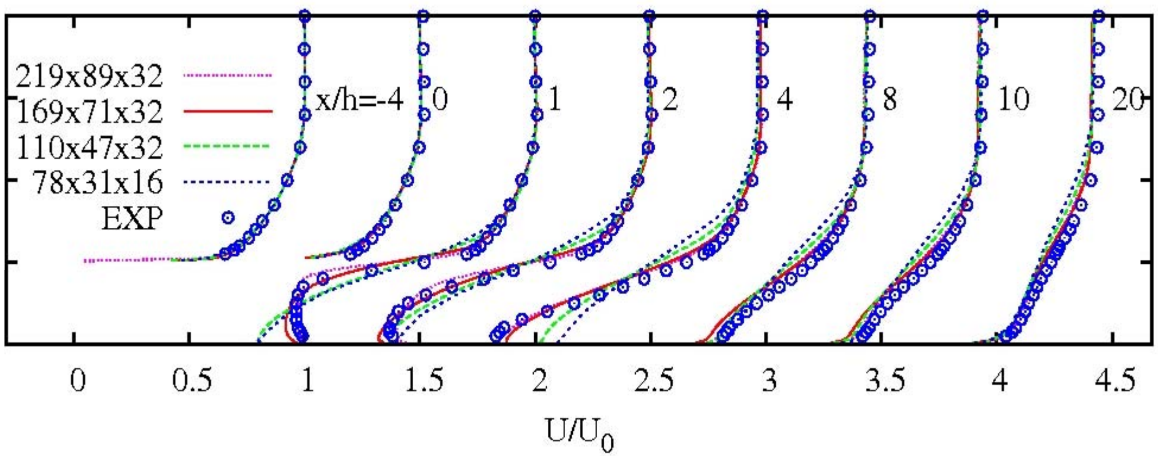
- Turbulent channel flow at Re_τ=4800 ($Re_b=U_b(2b)/\nu$)=120000, b=0.36m, U_b=5m/s
- Turbulent flow over backward facing step Re_h=37500, h=0.0127m, U_∞=44m/s
- **High accuracy demands typical for aerospace research requires an extremely fine spatial and temporal resolution**



Δt with wall-functions ~ 4 Δt for wall-resolved LES



Backward-facing step:
On finest mesh (219x89x32),
resolution „almost sufficient“



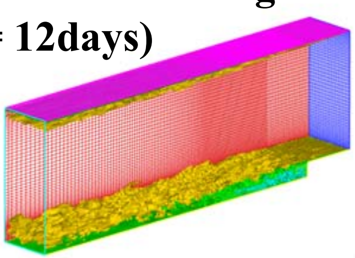
Estimation of costs for A380 take-off/landing

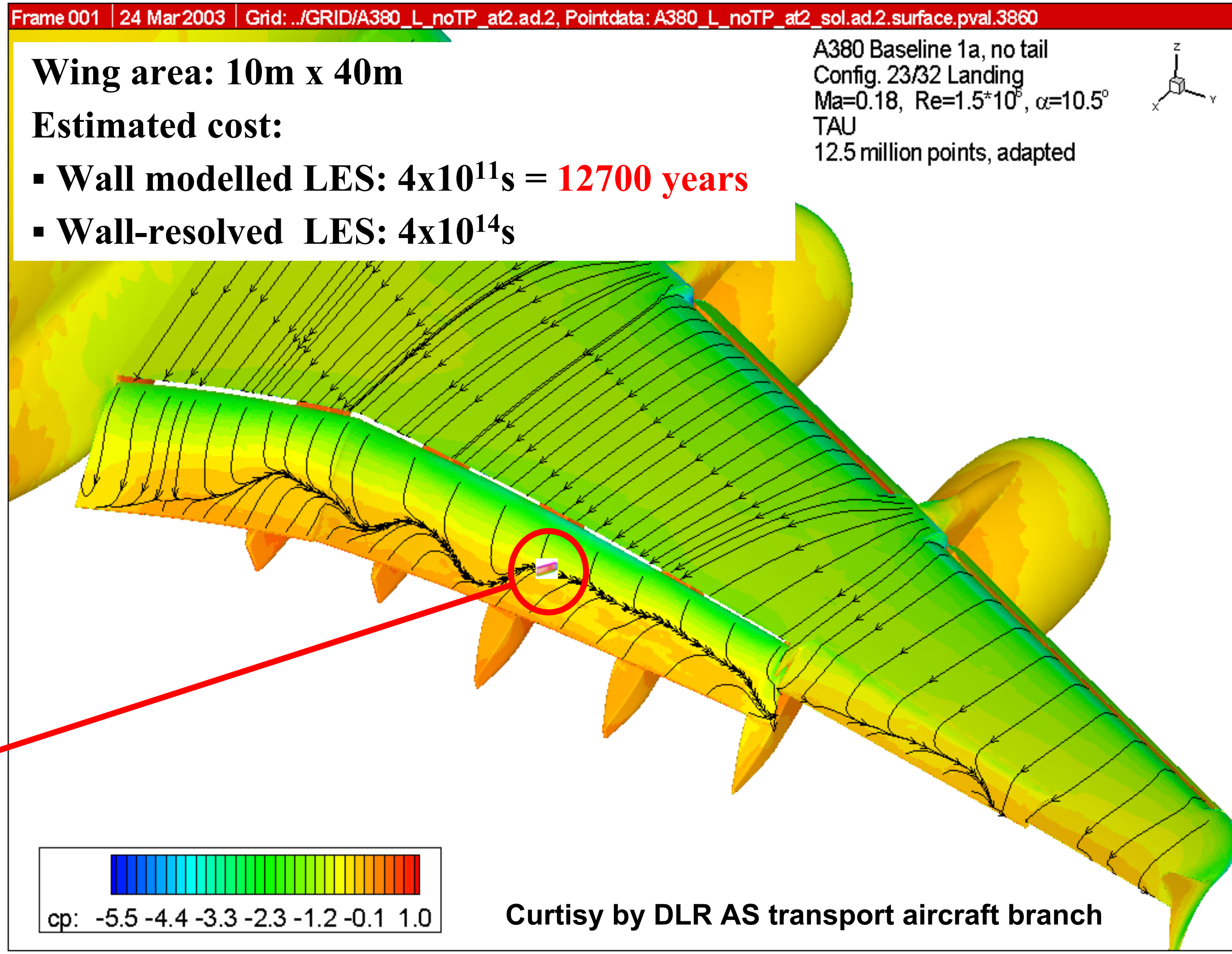
Attached boundary layer flow with separation on flap of a wing at high-lift „approximated“ by flow over a backward facing step.

LES with wall-functions

Surface: 0.38m x 0.05m

Cost: 10^6s on single CPU (= 12days)

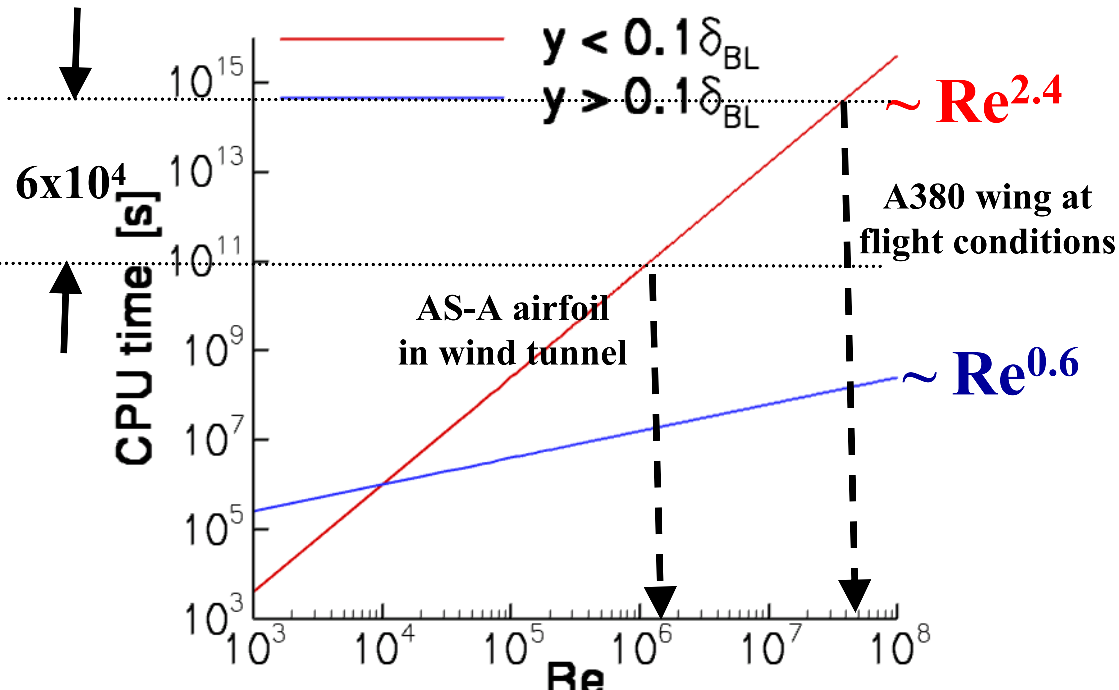




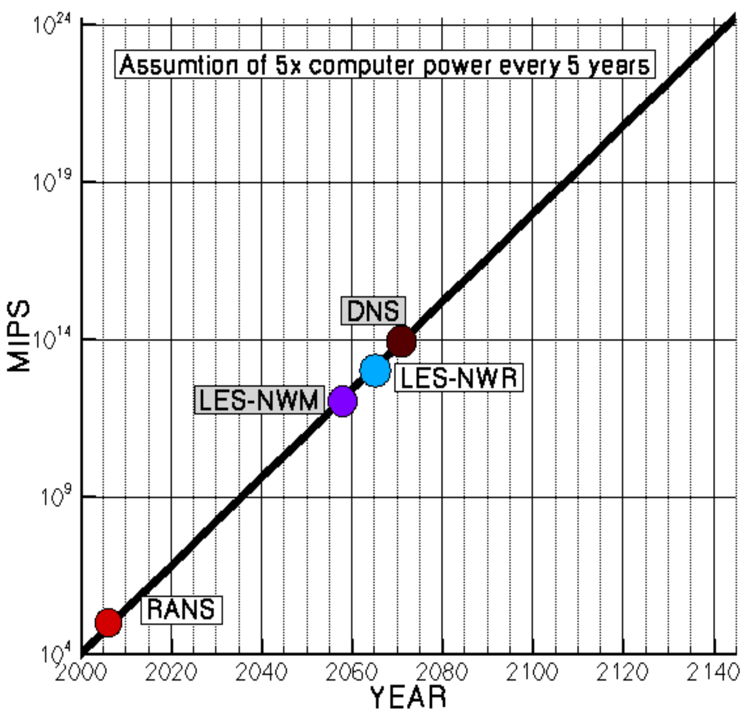
Infeasibly large computational of wall-resolved LES at high Re

- 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

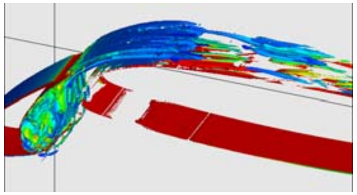


Courtisy by Spalart



F15 3-element airfoil 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)