Towards Efficient and Comprehensive Hybrid RANS/LES Methods for Border of Envelope Applications

(within the DLR project ADaMant)

DLRK Session 1.9 – Buffet and Separated Flows

Felix Möller[1], Axel Probst[2], Roland Ewert[2]

German Aerospace Center, DLR

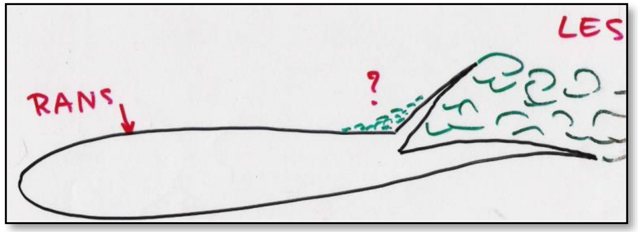
27th September 2022, Dresden

[1] Institute of Test and Simulation for Gas Turbines / Institute of Propulsion Technology, Köln / Augsburg
[2] Institute of Aerodynamics and Flow Technology, Göttingen & Braunschweig

Motivation

Why do we consider hybrid RANS/LES methods?

- **Hybrid RANS/LES methods (HRLM) combine “cheap” RANS modelling with accurate local scale-resolving simulation (LES)**



P. Spalart, 2005, DESider Keynote – The uses of DES: Natural, extended, and improper

- Potential for improved **accuracy**
- However, enormous **computational effort** due to large Reynolds numbers

Accuracy
- Capture relevant physical phenomenon, i.e. transition
- Provide powerful methods to prescribe synthetic turbulence

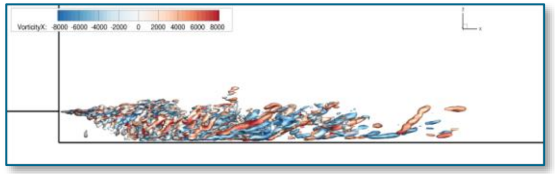
Efficiency
- Reduce computational effort by
  - Coupling with wall functions
  - Improving embedded wall-modelled LES

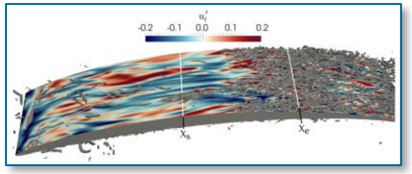
➡ Addressed within one work package in the DLR project ADaMant
- Developments in the DLR CFD-solvers *TRACE* and *TAU*
- Methods potentially adapted in new solver *CODA*

Transitional hybrid RANS/LES

Why and how?

- **Why?**
  - In the past, Delayed Detached-Eddy Simulation (DDES) model has been widely developed for fully turbulent flows
  - Transition is a relevant phenomenon in turbomachinery design process
  - To achieve a better predictive quality, DDES needs to be capable to incorporate transition process





A. Scilitoe, PhD thesis, 2017

- **How?**
  - Seamless DDES based Menter-SST turbulence model[1]
  - Couple DDES with the γ-transition model[2]
  - Eliminate undesired production term $P_k^{\lim}$

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho u_j k) = \tilde{P}_k + \cancel{P_k^{\lim}} - \tilde{D}_k + \frac{\partial}{\partial x_j}\left((\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right)$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_j}(\rho u_j \omega) = \alpha \frac{P_k}{\nu_t} - D_\omega + Cd_\omega^{[3]} + \frac{\partial}{\partial x_j}\left((\mu + \sigma_\omega \mu_t)\frac{\partial \omega}{\partial x_j}\right)$$

$$\tilde{P}_k = \gamma \, P_k$$

$$\tilde{D}_k = \max(\gamma, 0.1) \cdot D_k$$

---

[1] M. Strelets, 2012, Detached Eddy Simulation of Massively Separated Flows

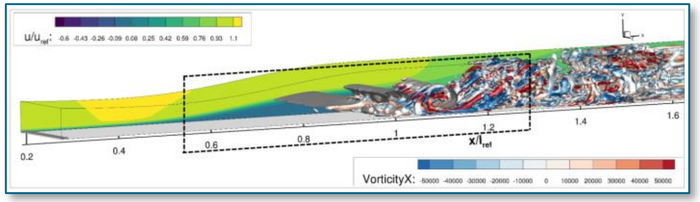
[2] Menter et al., 2015, A One-Equation Local Correlation-Based Transition Model

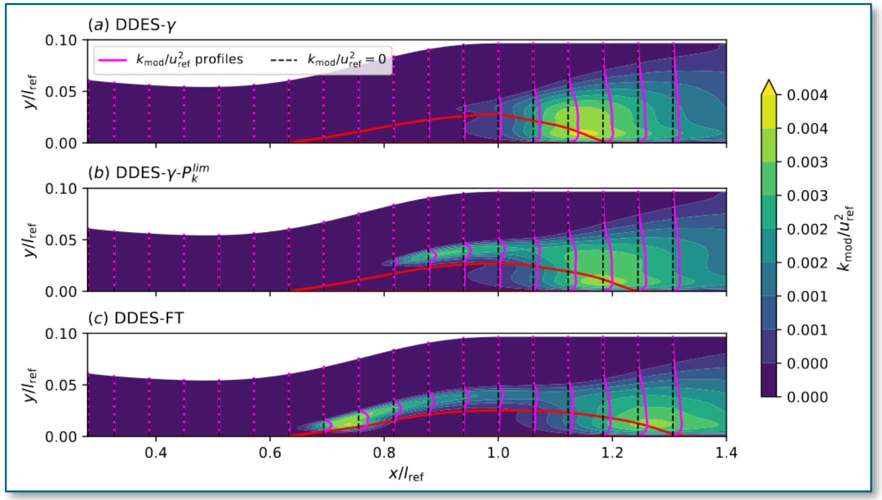
[3] Cd_ω= Cross-diffusion term of the ω-transport equation

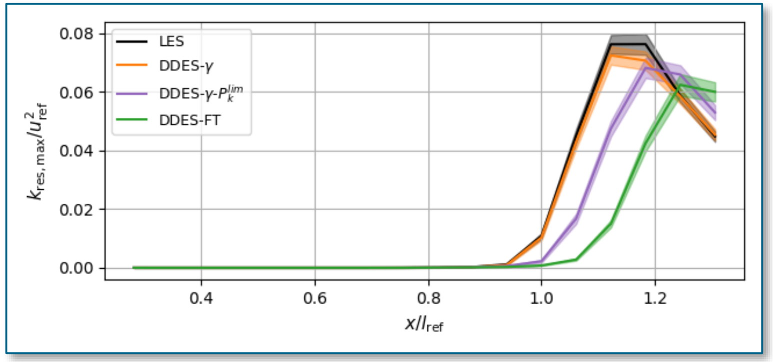
Transitional hybrid RANS/LES

Focus: separation-induced transition

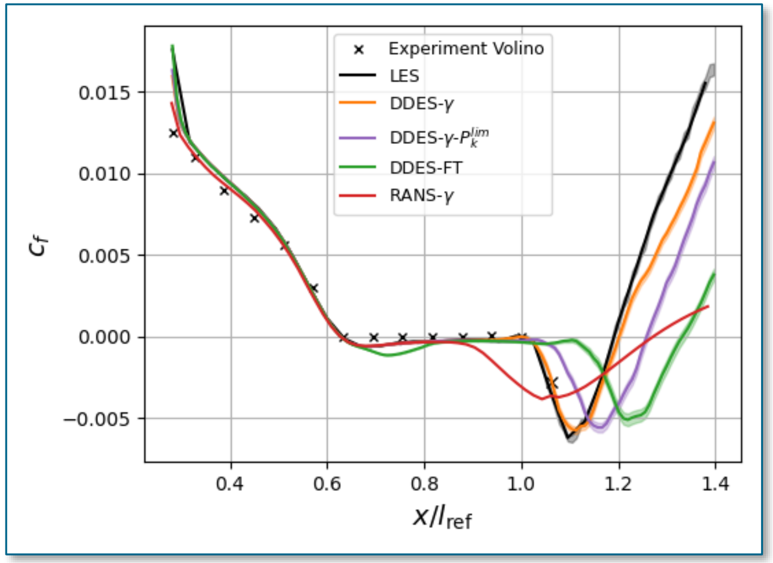
- **Canonical test case: Volino series** (flat plate with adverse pressure gradient)







- Reduced modeled content in separated shear layer allows the development of resolved scales

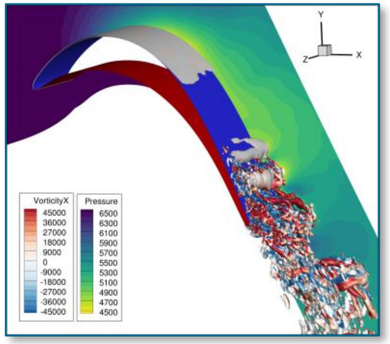


- Improved prediction of transition process

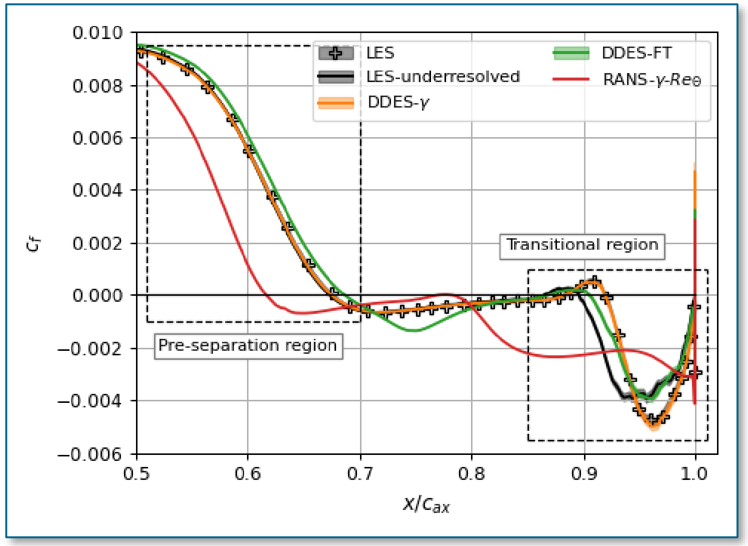
- DDES-γ: own-developed model coupling (orange)
- DDES-γ-P_k^{lim}: simple coupling of DDES and γ-transition model without relevant corrections (purple)
- DDES-FT: fully turbulent simulation without transition model (green)

Transitional hybrid RANS/LES

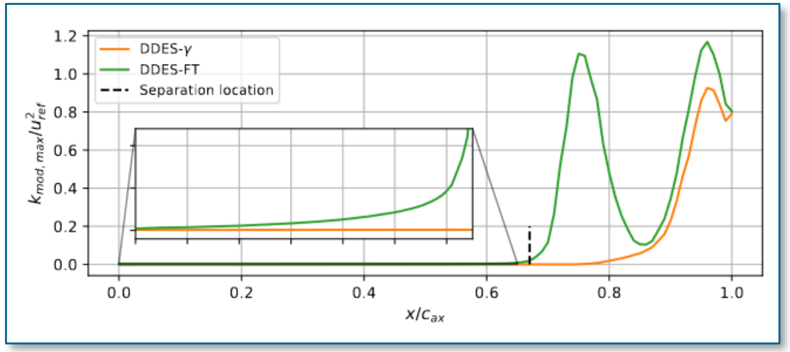
Focus: separation-induced transition

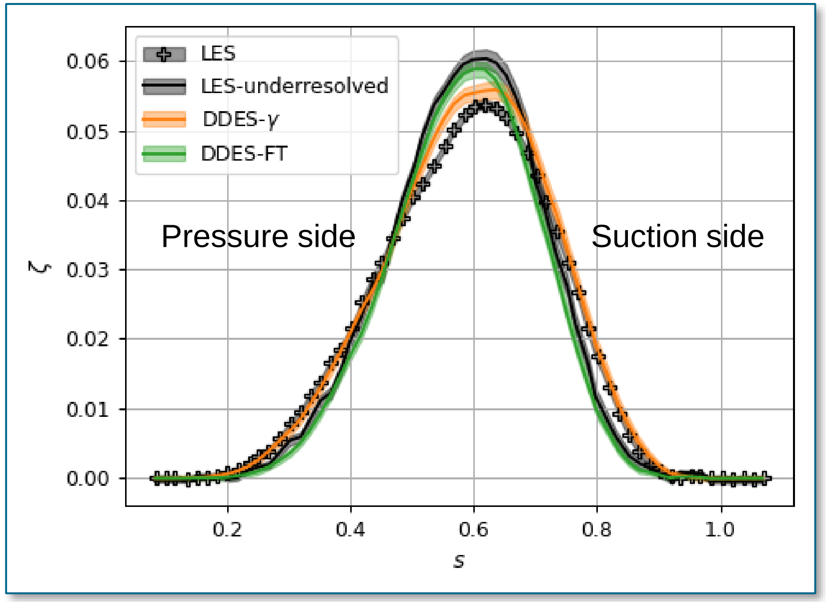


- **Turbomachinery test case: Turbine cascade T106C**



- Improved results through maintaining a laminar boundary layer prior to separation





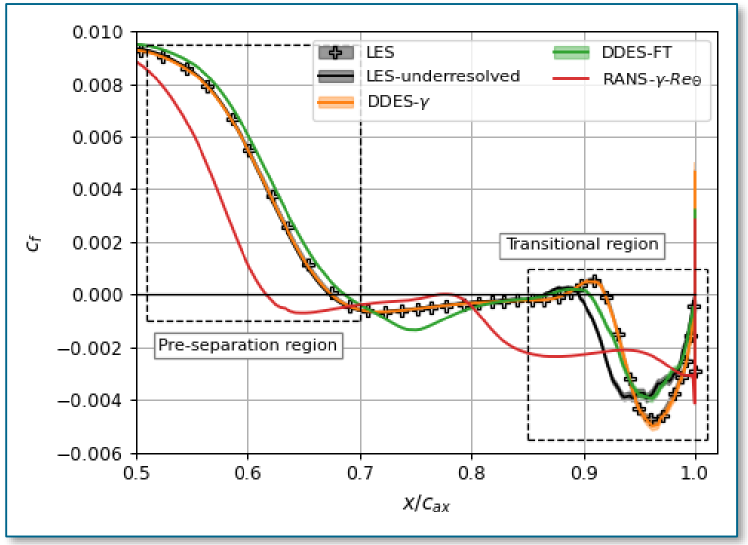
- Better prediction of wake losses on suction side

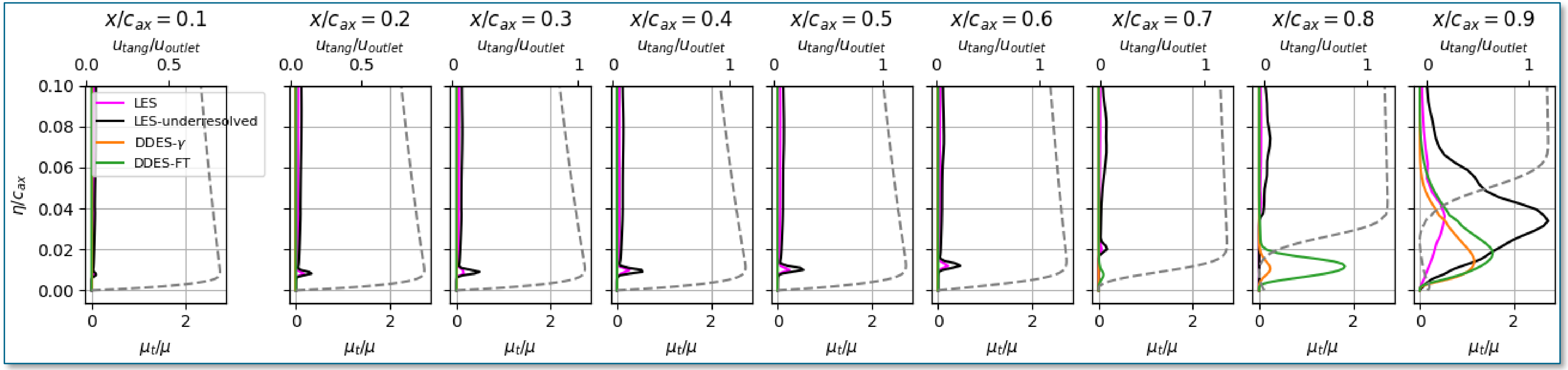
• DDES-γ: own-developed model coupling (orange)
• DDES-FT: fully turbulent simulation without transition model (green)

Transitional hybrid RANS/LES

Why is DDES superior to LES on same mesh?

- Computation of μ_t **for LES** only based on grid information → too coarse mesh yields unphysical “overproduction” of μ_t
- Computation of μ_t **for DDES** based on k- and ω-transport equations + γ-transport equation suppresses μ_t in laminar regions → premature computation of μ_t prior to separation is prevented





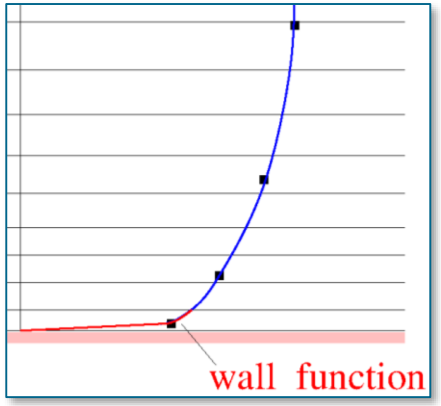
Wall functions for hybrid RANS/LES

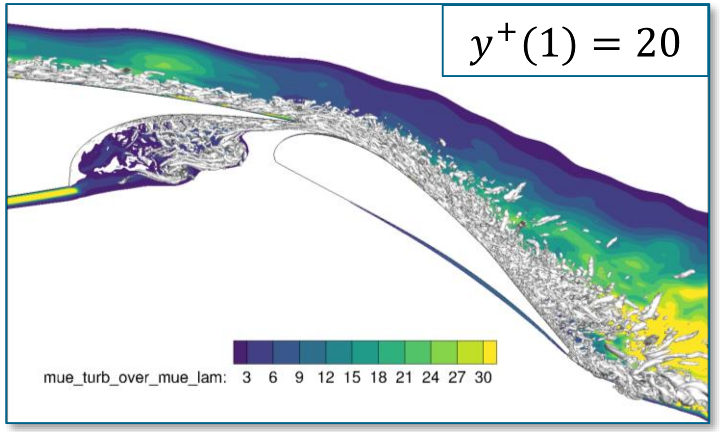
Assessment for aeronautical 2D flow

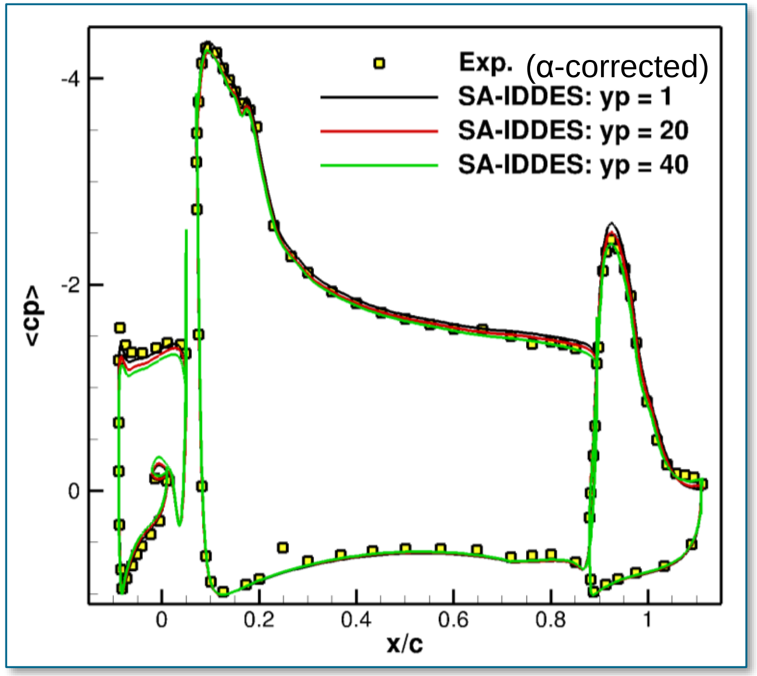
- **Approach:**
    - Combine classic analytical wall functions (*Knopp, 2006*) with DDES & IDDES
    - Assess potential for wall-normal grid coarsening, i.e. upper limit of $y^+(1)$

- **Test case:** DLR F15 3-element airfoil
    - Airfoil with deployed slat & flap at $Re = 2.1 \times 10^6$, $\alpha = 6°$
    - DLR-TAU using SA-IDDES (WMLES-mode on main-wing & flap)

- **Results:**
    - Approach feasible for relevant aerodynamic flow case
    - Widely consistent flow predictions (e.g. c_p, c_f) up to $y^+(1) = 20$
    - Increasing deviations (separation on flap, lift loss) on coarser grids



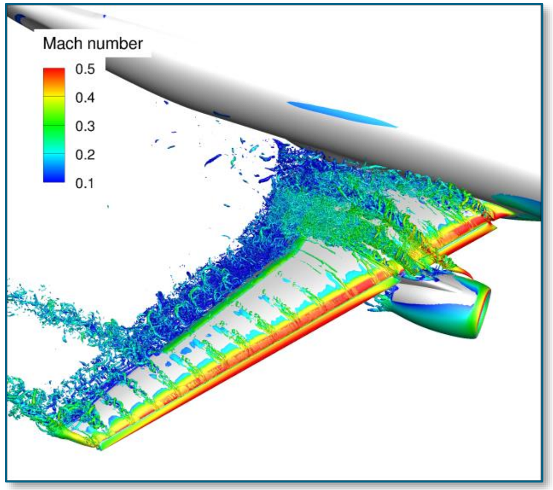




Wall functions for hybrid RANS/LES

3D demonstration

- **Test case: High-Lift Common Research Model (CRM-HL)**
    - High-Lift configuration at wind-tunnel conditions, $Re = 5.45 \times 10^6$, $\alpha = 7.05°$
    - Main test case in 4th *AIAA High-Lift Prediction Workshop* (2022)
    - DLR-TAU code using SA-DDES

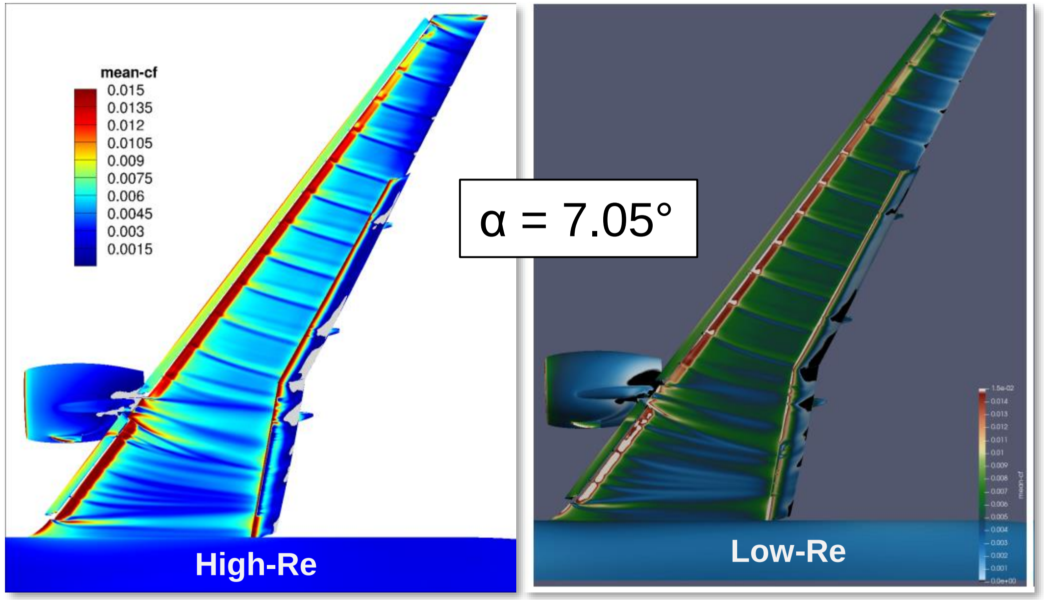


A. Probst and S. Melber-Wilkending, *AIAA 2022-3590*

- **Results:**

CRM-HL	Low-Re	High-Re
Mesh points	218×10^6	115×10^6
$y^+(1)$	~ 1	~ 35
C_L / C_D / C_{my}	$1.747 / 0.1793 / -0.339$	$1.752 / 0.1795 / -0.337$
Runtime saving	-	-25 % *

- Consistent results in linear lift range (higher AoA t.b.d.)
- Reduced computation time, with further potential
  (* wall-functions not yet optimized for unsteady runs)

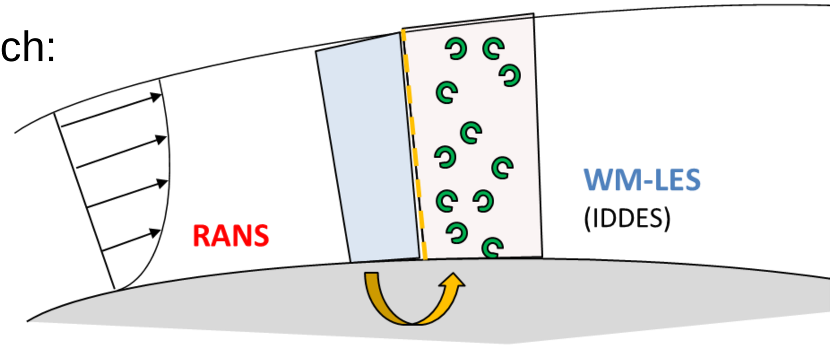


Embedded WMLES in DLR-TAU code

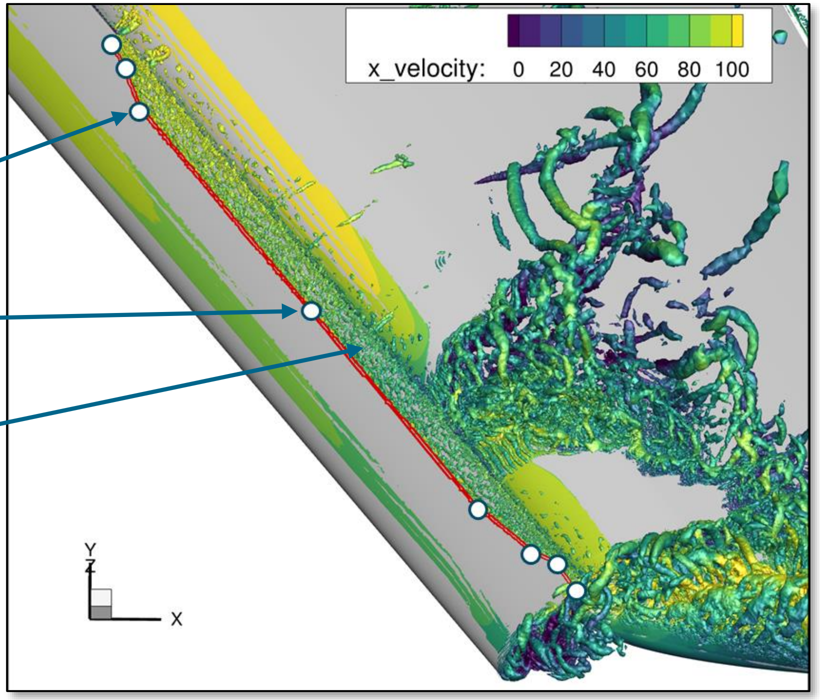
Outline of approach

- **Embedded WMLES:** Local wall-modelled LES (IDDES) zone within RANS simulation
  - Additional grid-point savings possible compared to non-zonal (global) IDDES
  - Essential part: Synthetic turbulence (STG) at RANS/WMLES interface

2D sketch:



Local ST injection on swept high-lift wing (initial phase of simulation):

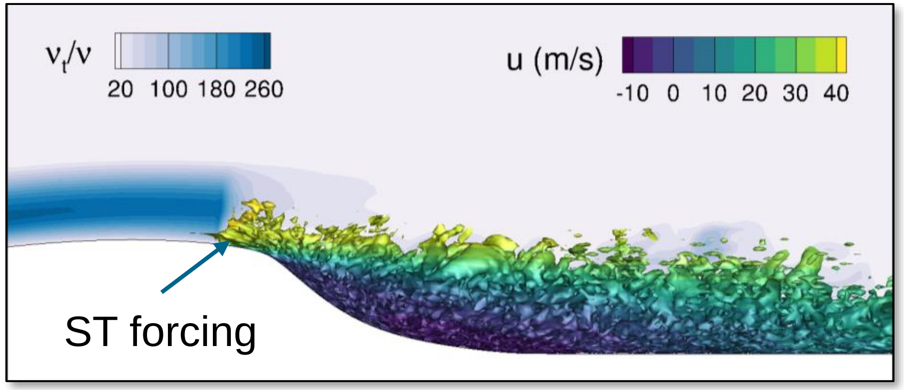


- **Application in 3D:**
  - User-defined ST fronts via polyline control points
  - Automatic extraction of RANS-input (upstream)
  - Automatic switch to WMLES-mode in ST forcing region
  - ST injection via smoothly varying source terms

Embedded WMLES with wall functions

Assessment for canonical 2D flow

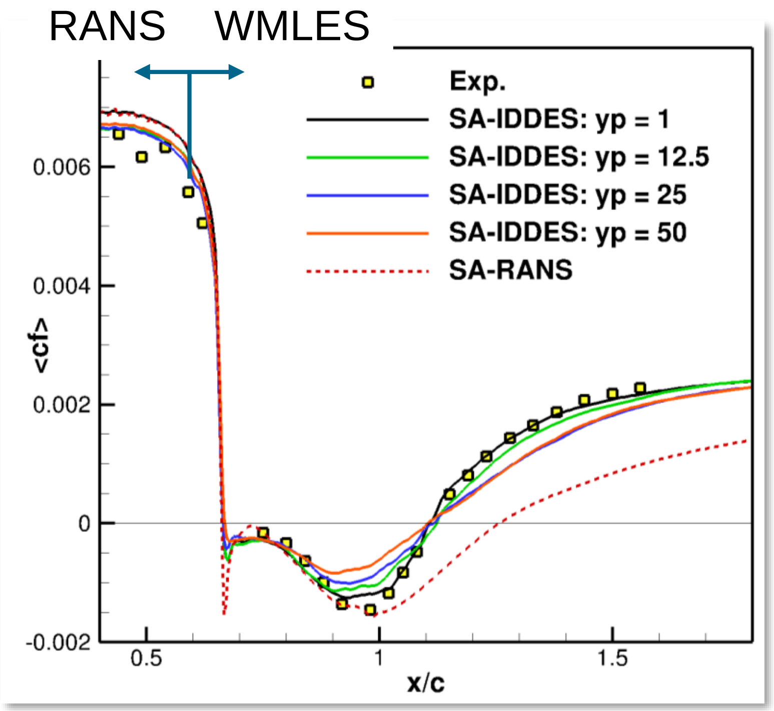
- **Test case: NASA wall-mounted hump**
    - Local separation with reattachment, $Re_c = 0.94 \times 10^6$
    - WMLES embedded in the separated region
    - Variation of wall-normal resolution using wall functions



- **Results:**
    - Accurate predictions of separation length
    - Growing deviations in skin friction for $y^+(1) \geq 25$

NASA hump	EWMLES			
$y^+(1)$	1	12.5	25	50
Sep. length vs. Exp.	-1,8 %	1,4%	0,1 %	-3,4 %
Runtime saving	-	-27.2 %	-35,4 %	-43 %

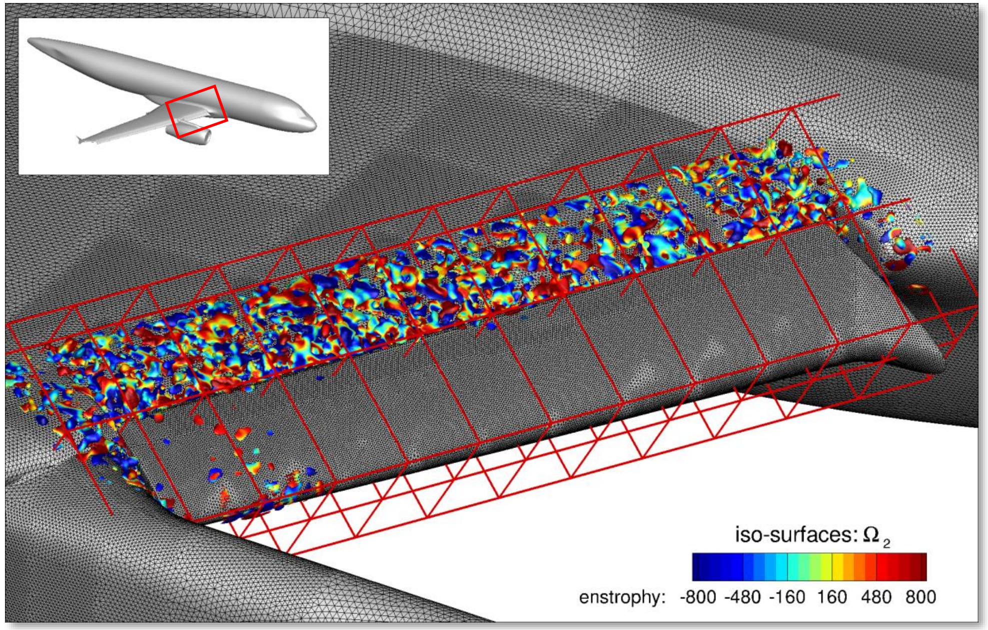
➢ Combined approach offers potential for significant efficiency gain



Synthetic Turbulence Generator for WM-LES

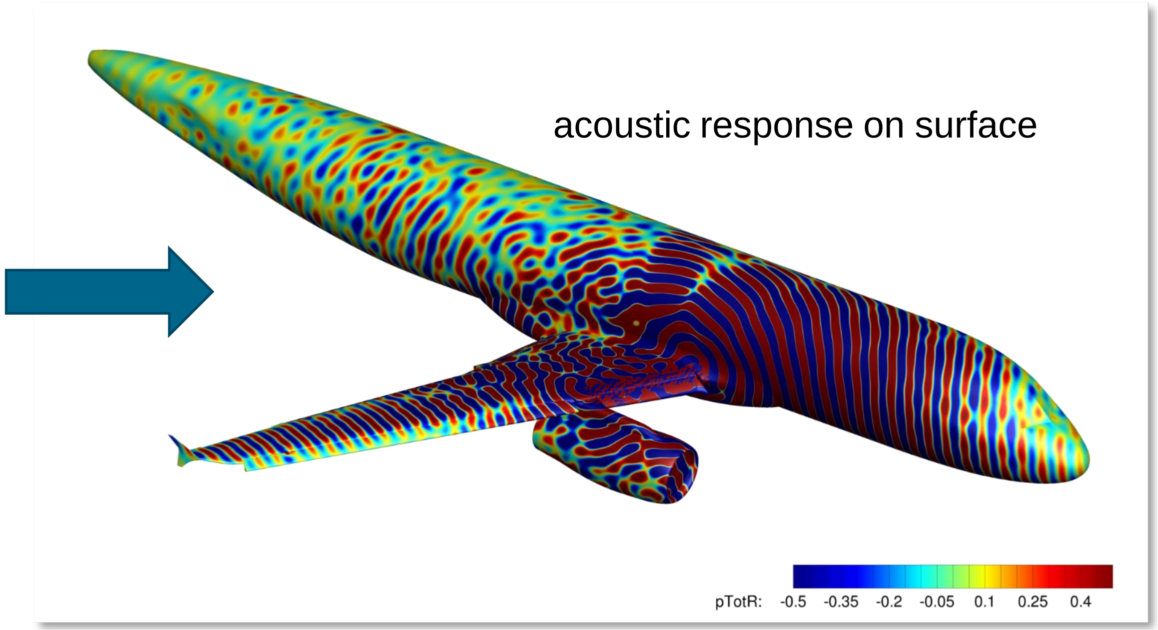
Fast Random Particle-Mesh Method (FRPM) for WMLES inflow forcing

- **Synergy from Aeroacoustics**: Application and adaptation of highly parallelized synthetic turbulence generator from aeroacoustics sound sources to LES inflow forcing in potentially large forcing sub-volumes



FRPM: Unsteady (3+1-D) sound sources at inboard slat

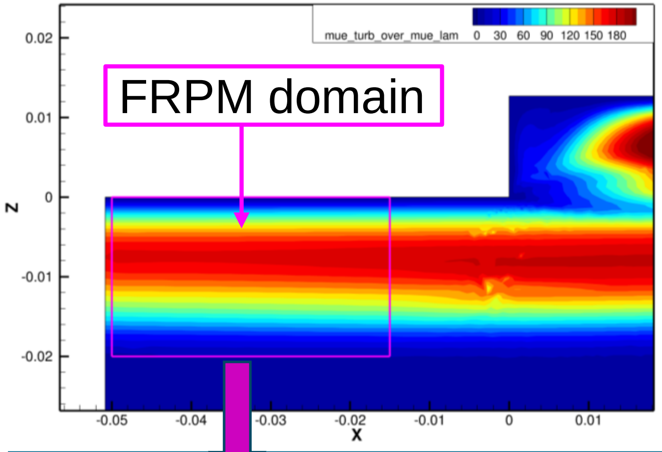
- 200x800x111 vol. points, 35 mio. particles
- ~0.8h on 48 CPUs (for 1 acous. spectrum)



Resulting sound field on fuselage of full-scale aircraft from inboard slat, Fast Multipole BEM propagation of sources, $f \approx 1kHz$

Synthetic Turbulence Generator for WMLES

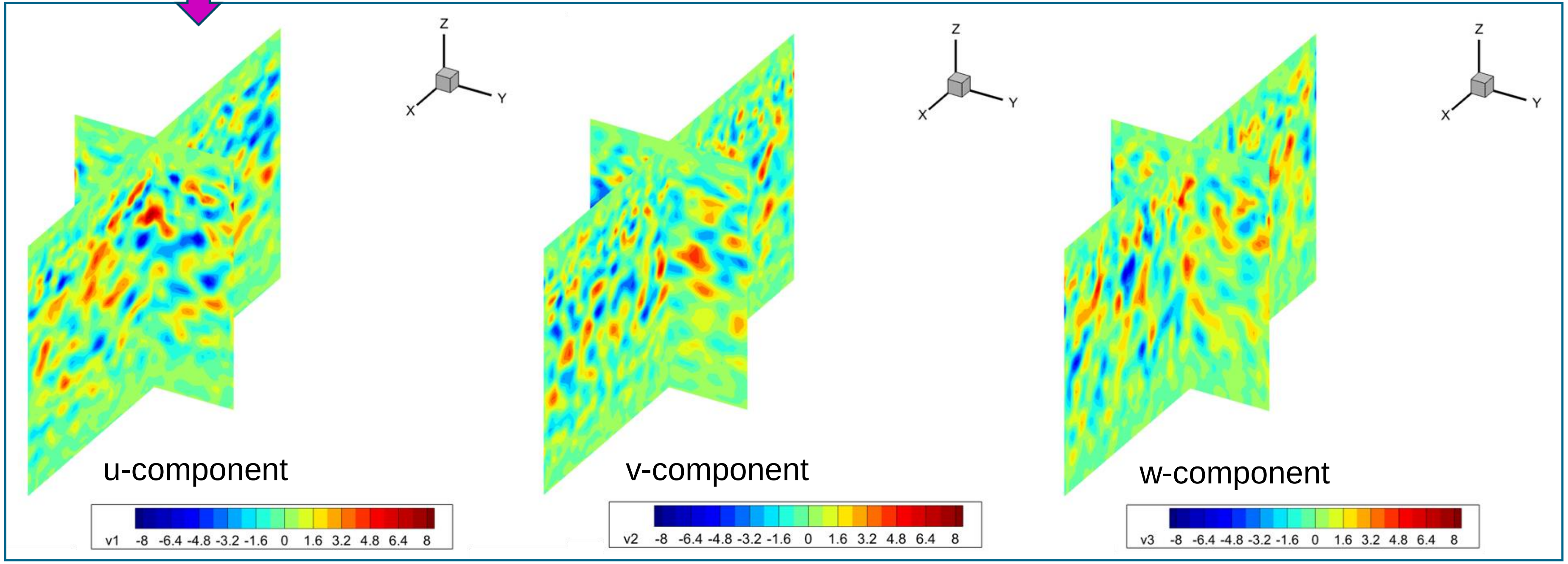
TAU/FRPM volume forcing test case: Backward Facing Step (BFS)



FRPM domain

- **Mesh sizes:**
    - #1: coarse: $\Delta x = 0.0004$ (0.143 mio. points)
    - #2: medium: $\Delta x = 0.0002$ (1.138 mio. points)
    - #3: fine: $\Delta x = 0.0001$ (9.031 mio. points)
- *Gauss* spectrum with realized local integral length scale
- No length scale limits
- Performance: $3\mu s/(pnt * tstep)$ using 6 CPUs

Snapshot of synthetic turbulence fields, coarse mesh $\#1$: $\Delta x = 0.0004$; 143k points



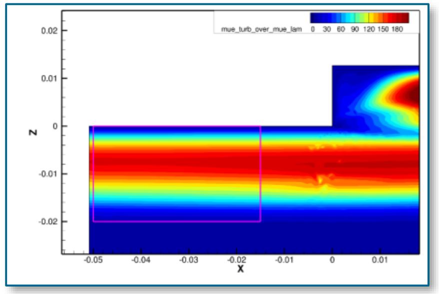
u-component

v-component

w-component

Synthetic Turbulence Generator for WMLES

TAU/FRPM volume forcing test case: Backward Facing Step (BFS)

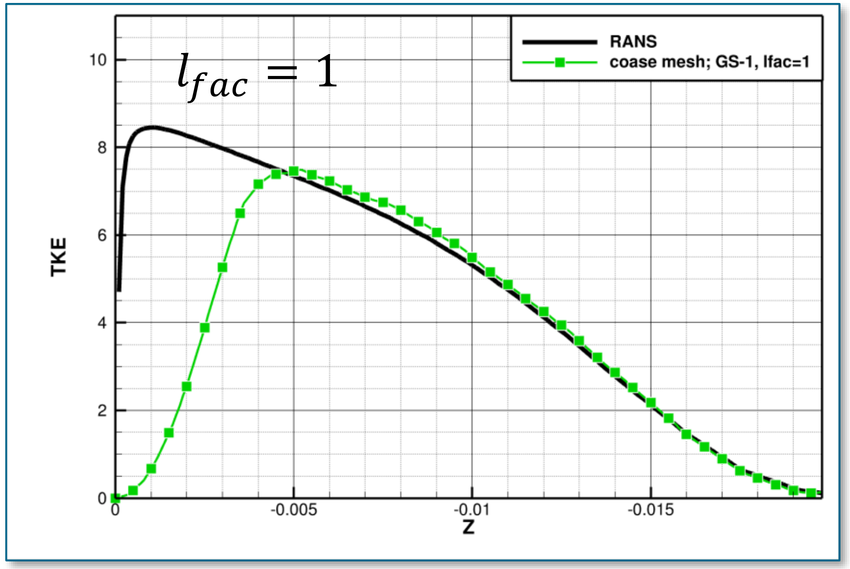


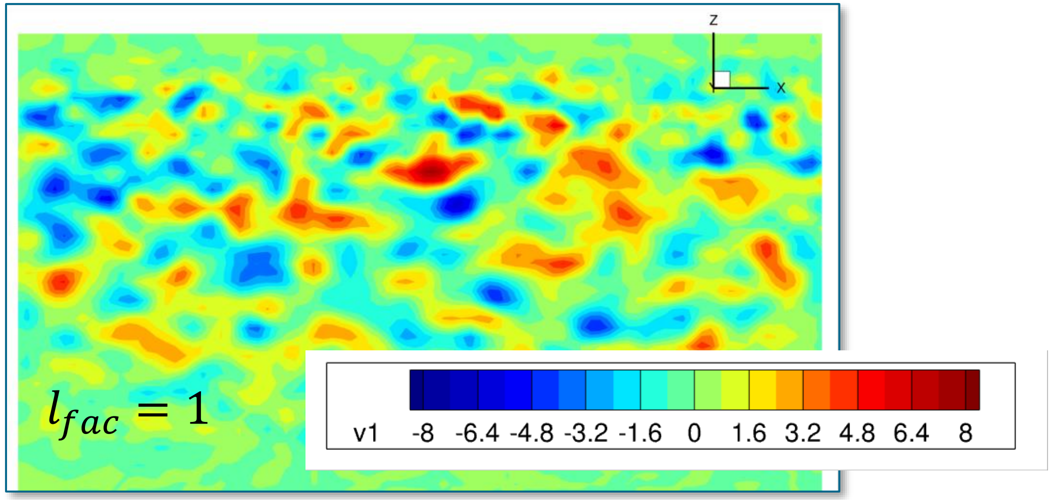
TAU/ FRPM test case
Backward Facing Step

- *Gauss* spectrum with realized local integral length scale
- Realized synthetic turbulence length scale

$$L_{synth.turb} = l_{fac} \frac{\sqrt{k_t}}{\omega}$$

- Accurate reconstruction for $l_{fac} = 1$

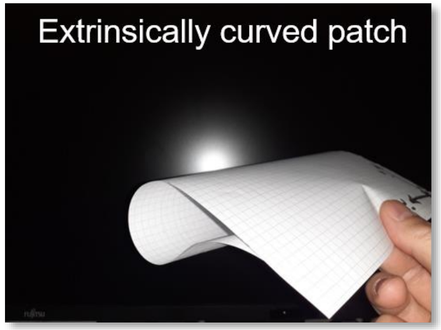


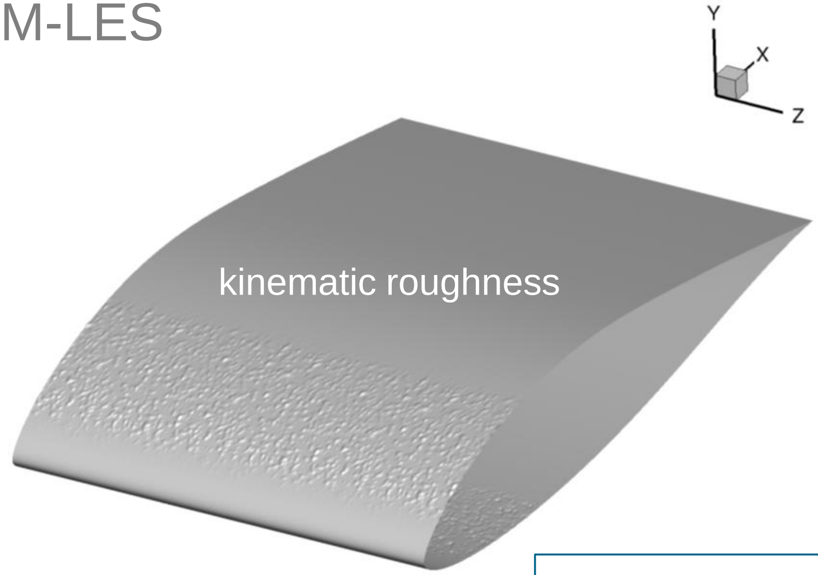


Left: reconstruction of turbulence kinetic energy (green) relative to RANS (black), near wall missing amplitudes due to WMLES adapted resolution of synthetic turbulence reconstruction; **Right:** snapshot of u-component of velocity

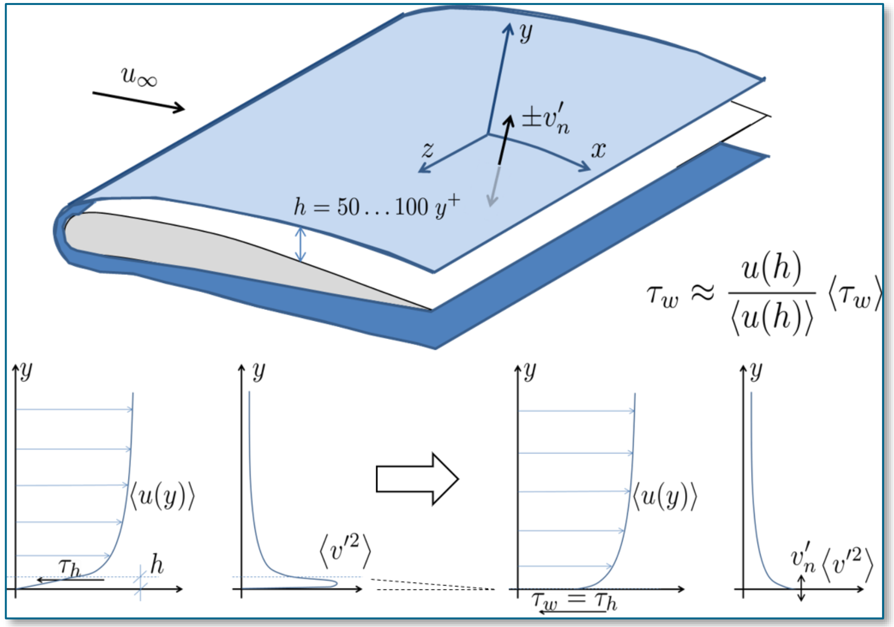
Synthetic Turbulence Generator for WMLES

Active 2+1-D wall forcing for overset WM-LES



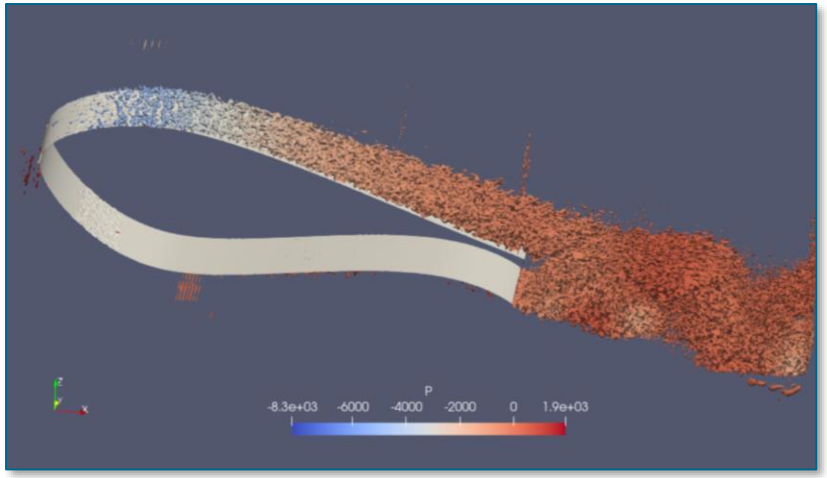


- **Approach:**
    - Adaption of 3+1-D synthetic turbulence generator (FRPM) to setup wall normal turbulence (based on *AIAA 2009-3269*)
    - Extraction of RANS turbulence statistics from precursor RANS at virtual slip-wall distance
    - First test via weak coupling: transformation of wall normal turbulent velocity fluctuations into equivalent kinematic wall roughness (Lagrangian frame) and generation of modified surface description (STL)
    - Simulation with modified surface roughness („kinematic roughness“)

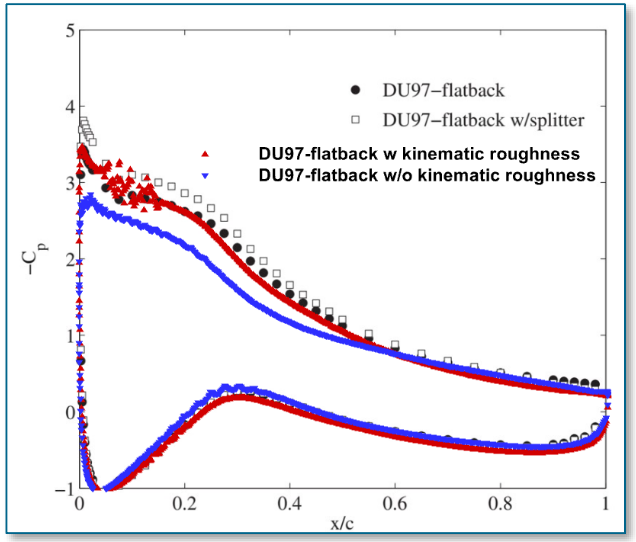


Active Wall Model

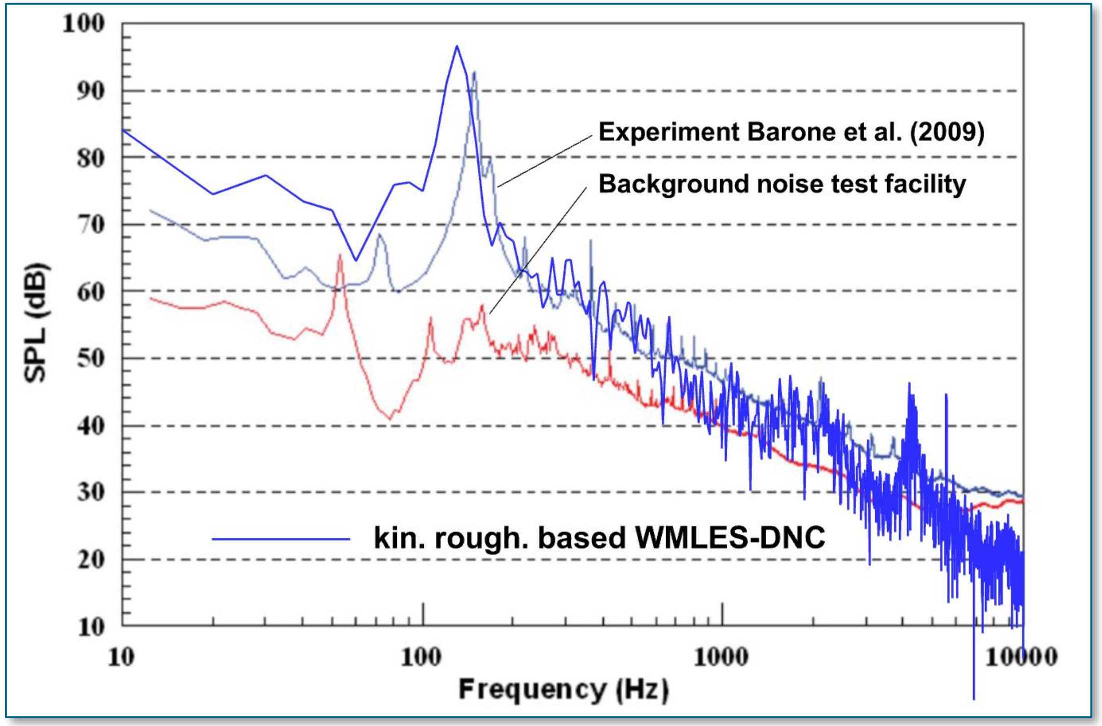
Application example – DU97 profile



DU97W300-FB kinematic roughness based WMLES-DNC
(4kCPUh total for 0.4sec real-time sample)



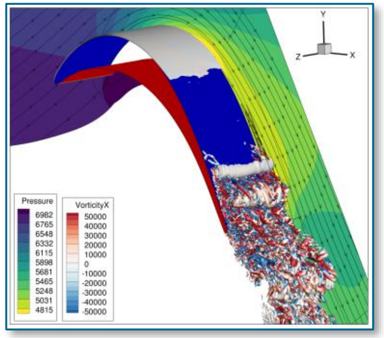
Pressure coefficient along blade surface

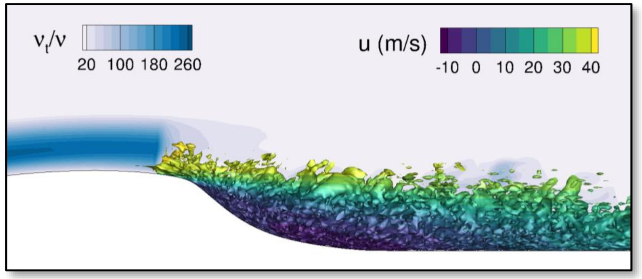


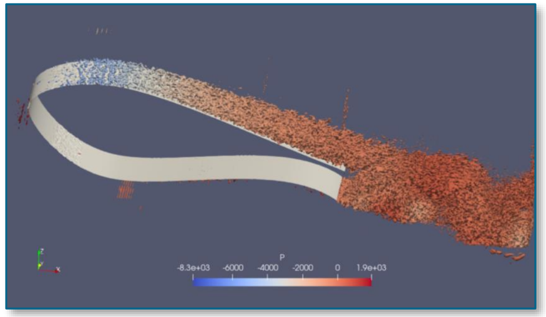
Direct Noise Computation (DNC) with kinematic roughness model

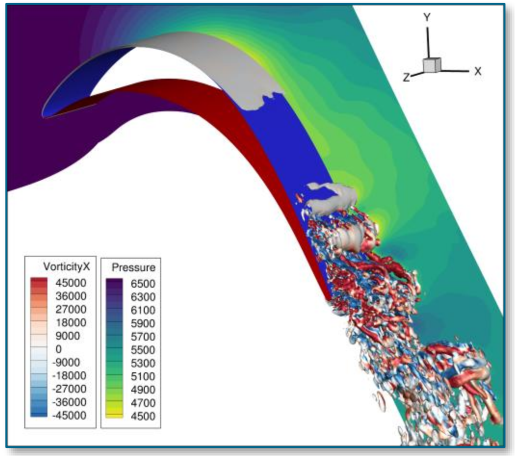
To put in a nutshell…

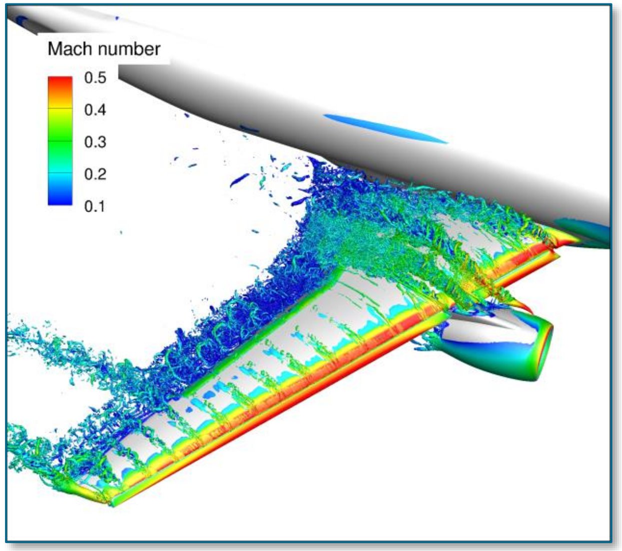
- *Lessons learned #1*
    - **The coupling of DDES and γ-transition model yield promising results for the prediction of separation-induced transition**
- *Lessons learned #2*
    - **The combination of I/DDES with wall functions showed significant improvements in terms of computational cost**
- *Lessons learned #3*
    - **The prescription of synthetic turbulence with the FRPM method showed good agreement with experimental reference data**

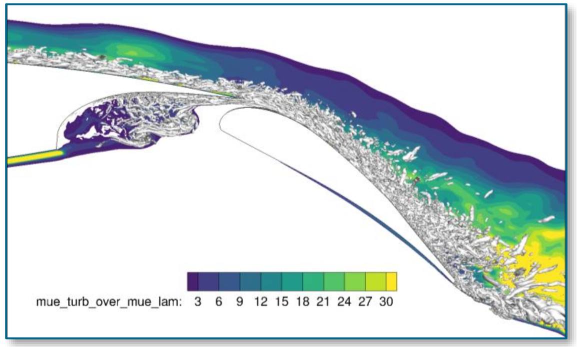


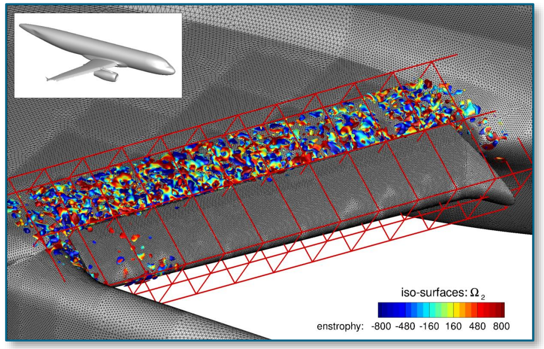


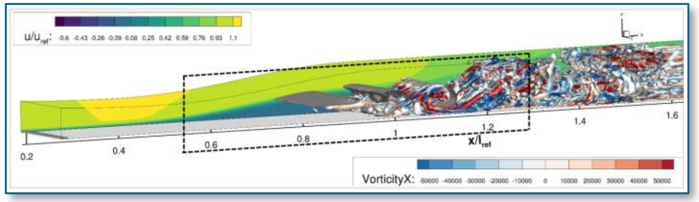


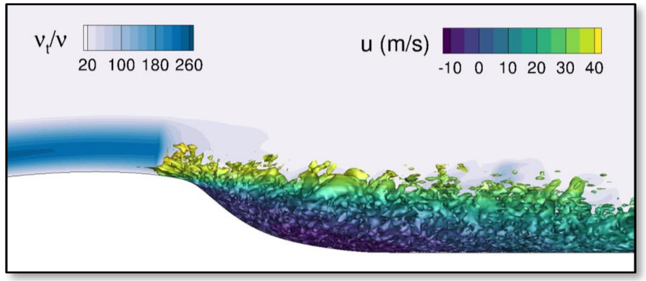


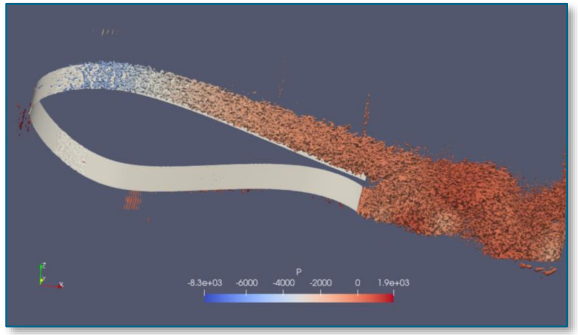












Thanks for your attention! Any questions?