RANS TURBULENCE MODELING VALIDATION AND PROSPECTS FOR IMPROVEMENT

APA-19/GT-03: INTEGRATION OF COMPUTATIONAL AND EMPIRICAL EXPERIMENTATION TECHNIQUES

Tobias Knopp, DLR AS CAS

Experiences and collaborations with

DLR AS CAS: B. Eisfeld†, S. Probst, D. G. Francois, A. Probst, P. Ströer, M. Burnazzi, P. Korsmeier, M. Schäfer, C. Dormoy, A. Krumbein, C. Grabe, D. Schwamborn, C. Rossow

DLR AS EXV: Andreas Schröder, Daniel Schanz, Matteo Novara, M. Costantini

DLR AS HGK: E. Schülein, W. Lühder

UniBw München: Christian J. Kähler, N. Reuther, M. Bross, F. Eich, R. Hain, S. Scharnowski

ISM, TU Braunschweig: R. Radespiel, S. Scholz, T. Landa, N. Rathje, W. Breitenstein

Saint Petersburg Polytechn. Univ. (SPbPU): M.Kh. Strelets, M. Shur, E.K. Guseva, A.K. Travin (until Feb. 2022)

Relevance of RANS models for civil aircraft design

- Use of CFD for aerodynamic design is characterized by:
  - High accuracy demands (drag → fuel)
  - Huge number of flight conditions
  - High Reynolds number at full-scale, $Re_L=3\text{-}6 \times 10^7$
  - Variety of flow features and scales (attached boundary layer (small scale), unsteady separation (large scale))
- Hierarchy of different methods needed (low-fidelity – RANS – hybrid RANS/LES – local LES)
  - RANS needed for design (steady solution for adjoint based optimization)
- Within the scope of RANS
  - Flows governed by thin boundary layers, statistically steady flow
  - → A/C performance prediction for clean wing cruise
- Beyond present RANS
  - Flows with massive flow unsteadiness → perhaps only possible using hybrid RANS/LES methods
  - Flows with mild (low-frequency) unsteadiness → novel URANS (?)

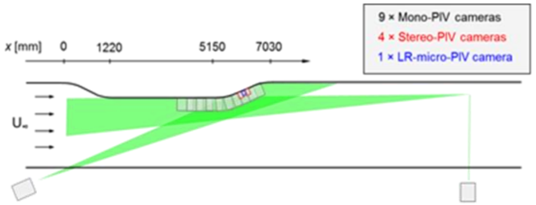
Potential for RANS model improvement. Work at DLR since 2010

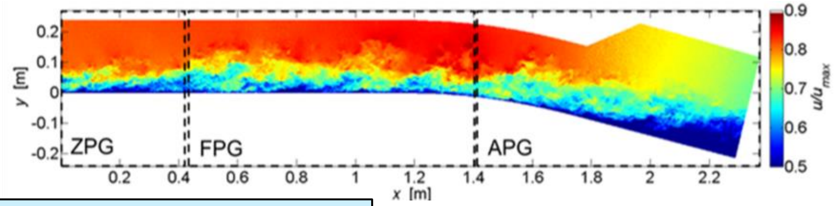
- **Overall goal: Improvement of SSG/LRR model.**

Classical idea: Isolation of building block flow problems
Potential seen for statistically steady flows features

DLR

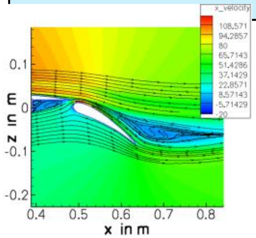
Turbulent boundary layers in strong pressure gradient (with and w/o separation)

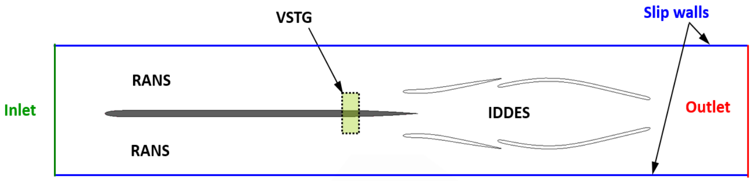


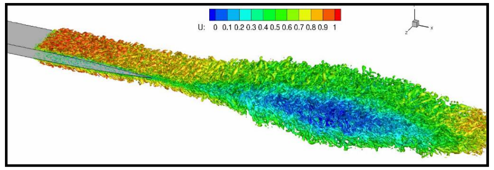


DLR, UniBw Munich
(3 experiments)
2011-2022

Turbulent wake flow in adverse pressure gradient (APG)





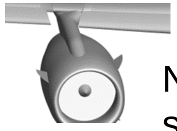


APG generated by liner foils (exactly defined geo)

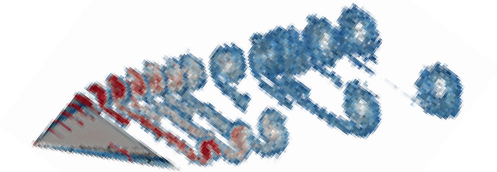
WT experiment and LES

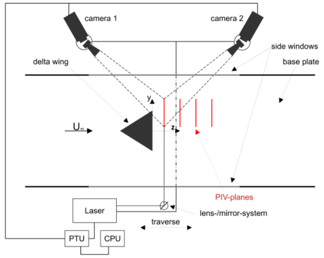
DLR, TU BS, SPbPU
2018-2022

Longitudinal vortices (e.g., delta wing)



Nacelle
strake

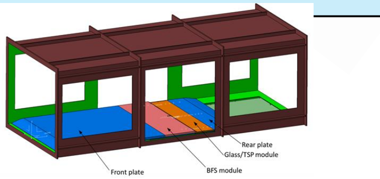


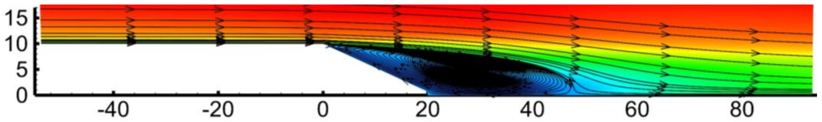


WT experiment and LES

DLR, TU
Braunschweig (BS)
2018-2023

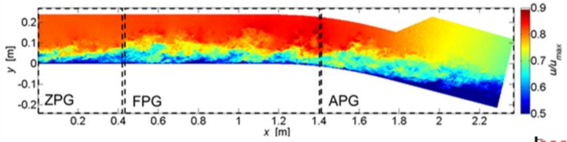
Thin separation bubbles and reattachment (work initiated by Bernhard Eisfeld†)

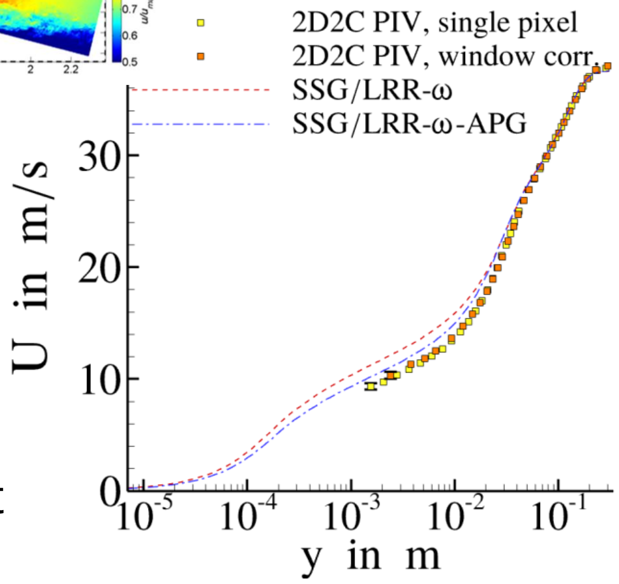




DLR, (TU BS)
2021-present

What did we learn from modeling experiments?





- 2D flow experiments still attractive
  - Fast RANS simulations (RANS model calibration, machine-learning …)
  - Careful design needed to achieve a quasi 2D flow
- What to measure in 2D flow?
  - Symptoms of RANS model deficiency can often be seen in the mean flow
  - Full streamwise flow evolution and global 3D flow picture needed
- 2D computational set-up is hard to achieve, if flow separation occurs in the test section
  - Possible strategies:
    - Exp: ensure attached flow as much as possible (fairings)
    - **DNS/LES** can give ideal 2D flow (spanwise periodic b.c.)

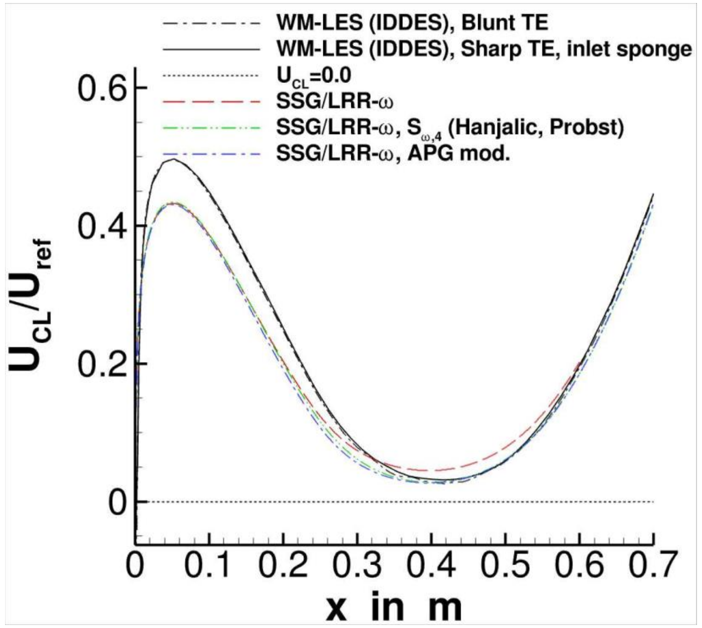
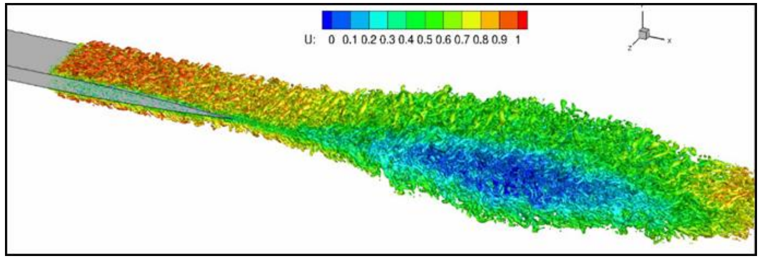
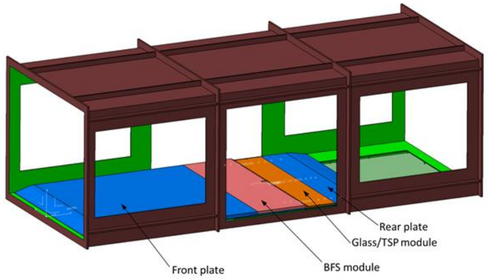


Figure by SPbPU, published in:
Guseva, Strelets et al., J. Phys. Conf. Ser., (2018), Knopp, Korsmeier, Strelets, Guseva, STAB Symposium, 2020)

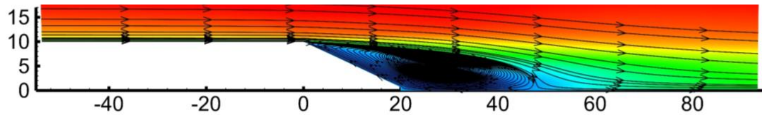


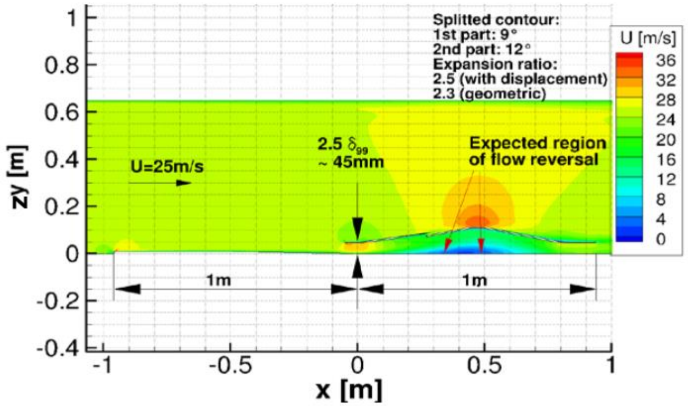
What did we learn from modeling experiments?

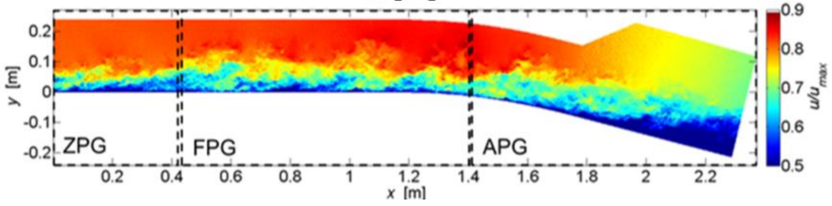
- Make best use of an available/existing wind tunnel (for 2D flow experiments)
  - Large spanwise aspect ratio → reduce effects of spanwise side walls
  - Importance of well-defined, homogenous flow in the test section
    - Quantification of non-homogeneity over entire cross section useful
    - Choose „cleanest“ part of test section for experiment (splitter plate?)

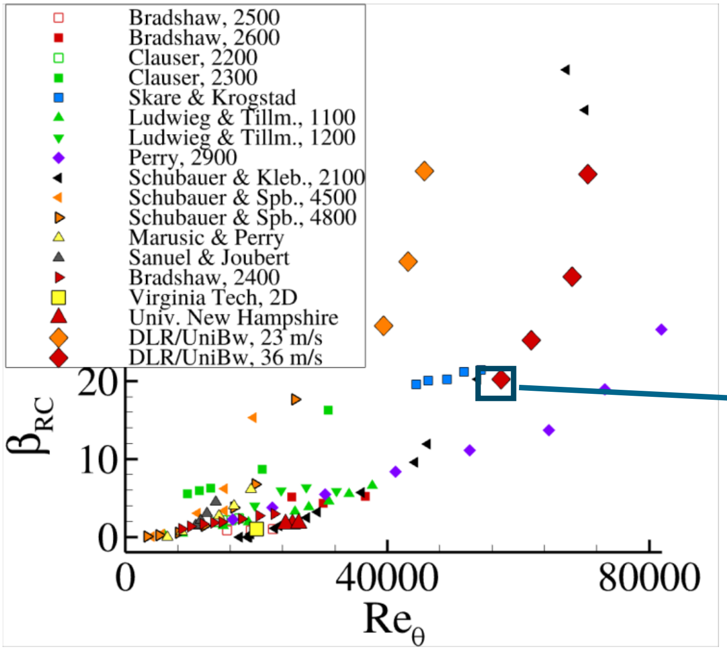


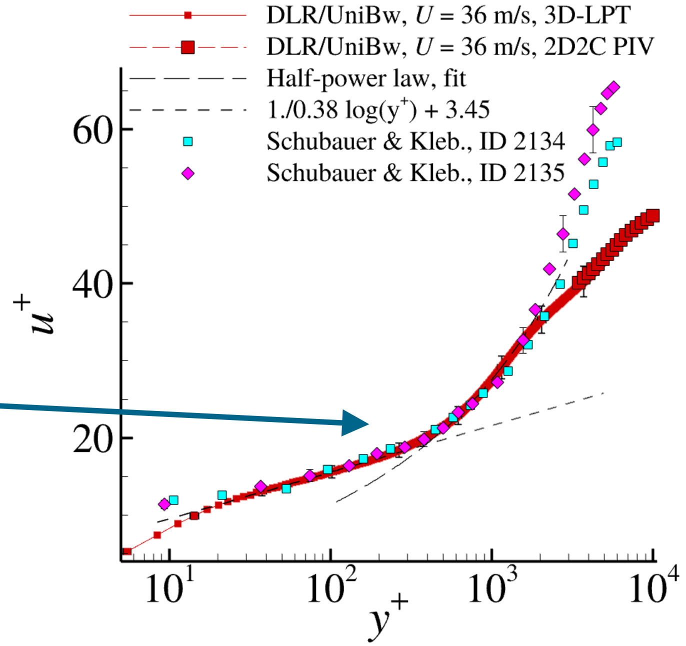
- RANS-based design of a wind-tunnel experiment
  - Check if characteristic flow parameters (β_{RC}, Re_θ, curvature effects) are in the desired range









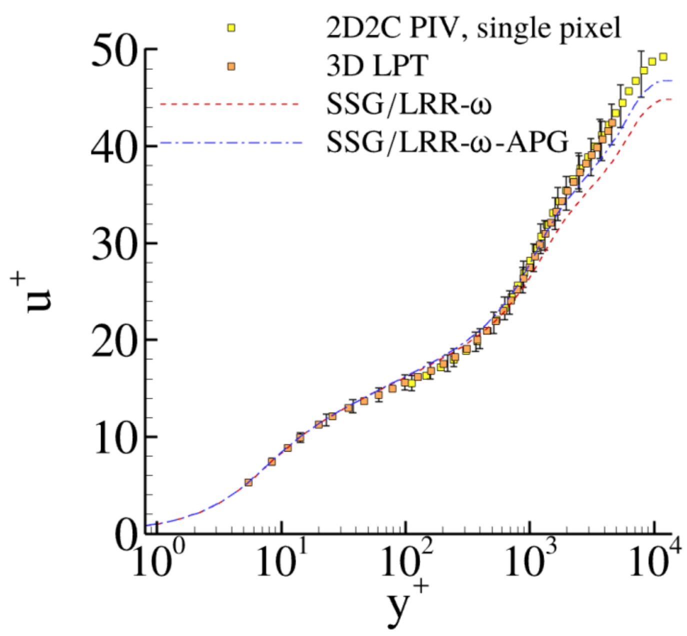


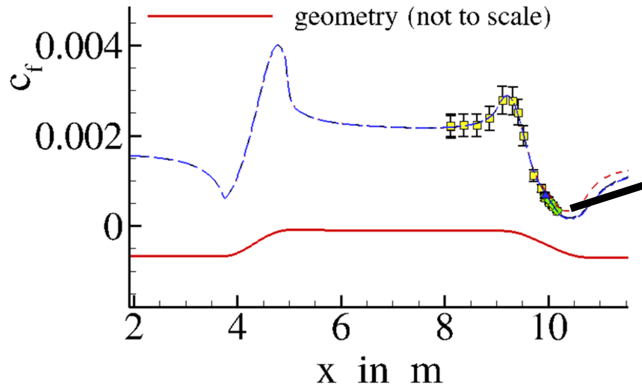
Further thoughts on validation experiments

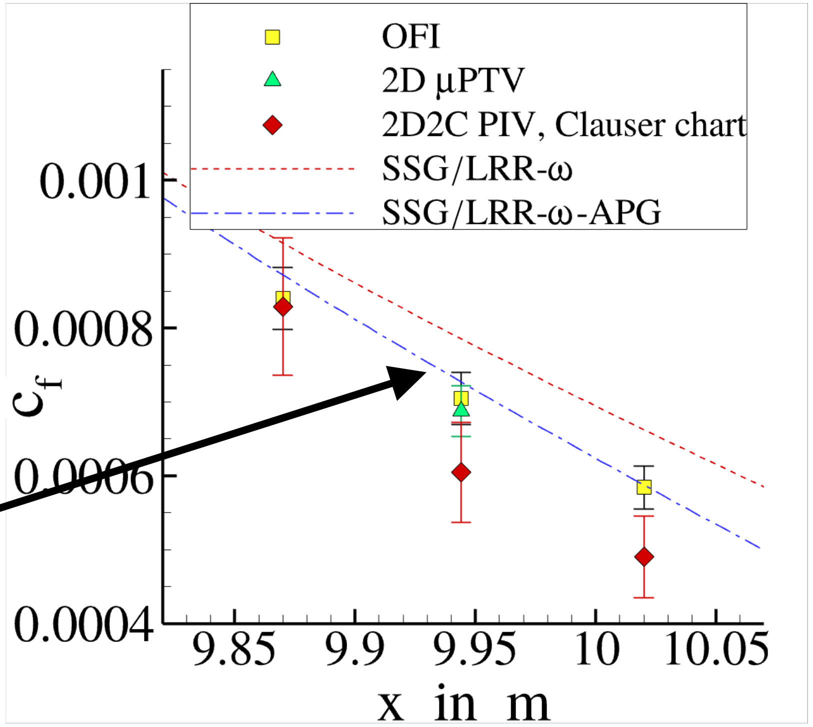
- Validation experiments will be needed not only for RANS
- Needed also for hybrid RANS/LES and other wall-modeled LES
- Measurement accuracy assessed by reference to DNS/LES data

<u>Measurement technique:</u>

- Improvement in measurement technique for high Re turbulent boundary layers still needed
  - Example: 3D Lagrangian Particle Tracking (3D LPT) with Shake-the-Box method developed as DLR AS
- Need for accurate method for skin-friction coefficient c_f:
  - Very good experience with Oil Film Interferometry (OFI)
- Error bars for experimental data

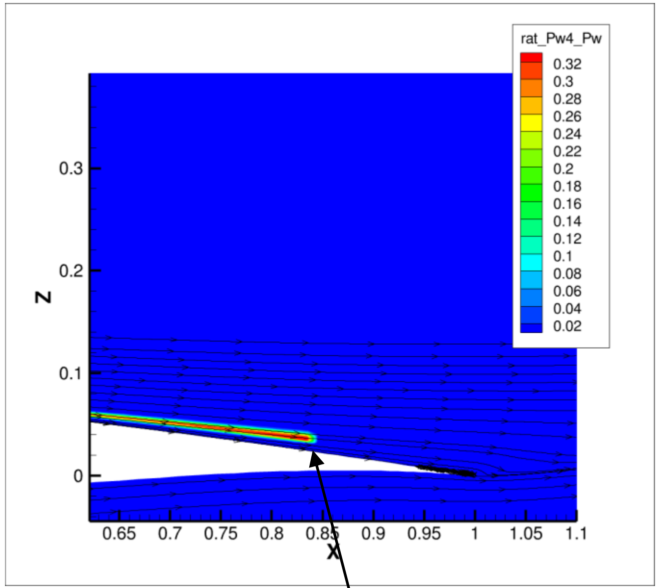


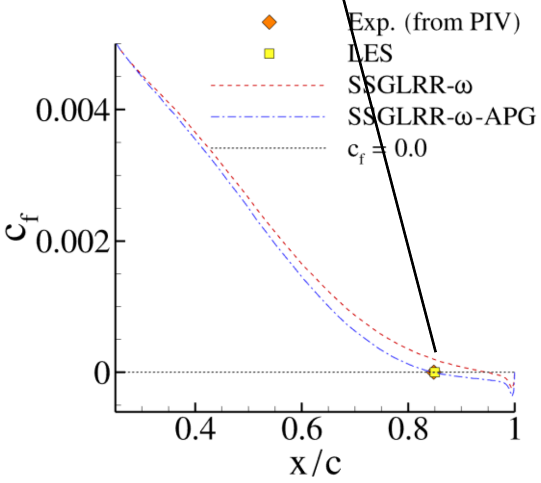




Possible future paths for RANS modeling

- RANS models involve different coefficients and functional terms.
  - ***Dilemma:*** coefficients found to be different in different flow situations (for attached versus separated boundary layers (see Durbin (2001), Eisfeld (2022))
- Possible strategy:
  - Step 1: Design modifications for specific flow phenomena (TBL in APG, curvature, reattachment)
    - ➔ Calibration using data for (2D) building-block flow exp.
  - Step 2: Local activation via blending functions
- Examples:
  - SA-RC, SST-RC : modification for curvature effects
  - SSG/LRR-APG : modification for adverse-pressure-gradient boundary layers
  - General model: GEKO model (Menter et al.)
- Viable route also for „data-driven methods/machine learning“ (FI/ML, GEP)

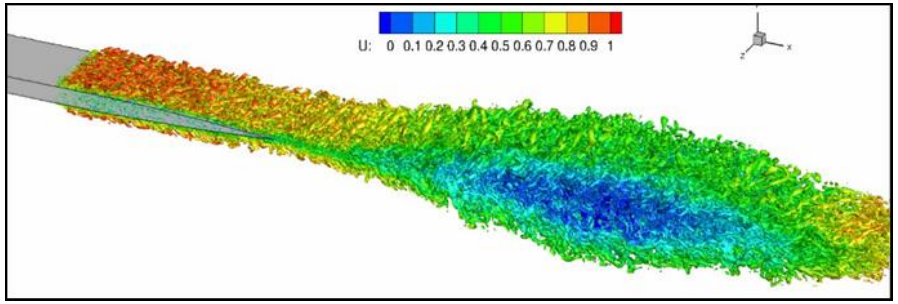




Thoughts on future experiments

- **Complementary use of wind-tunnel experiment and DNS/LES is strongly recommended**
  - Mutual assessment (experiment versus DNS/LES) for small Re
  - Complete data (Reynolds-stress budget) from DNS/LES for small Re
  - DNS/LES to investigate problematic flow behavior suspected in wind-tunnel experiment
    - Example: LES to study unsteady vortex shedding of turbulent wake flow in an APG
  - Can go to high Re using wind tunnel experiment
  - Examples: Boeing speed bump, DLR/TUBS/SPbPU Wake flow in APG, …
- What are the **needs for data for future turbulence modelling** (RANS, hybrids)?
  - Very accurate experiments (possible only for a few test cases → NASA JFE, VT BeVERLI Hill)
  - Parametric-variation experiments
    - Rapidly built/modified geometry, rapid overview measurement techniques

    ➔ Large parametric database for ML



Thoughts on complex validation cases

- Given all the uncertainties and errors in experiments for (seemingly) **simple 2D** building block flows

  → warning of what might happen for complex 3D configurations

- For **complex 3D test cases**: Additional errors/uncertainties in the computational set-up
  - Model geometry as-built versus as-designed
  - Model deformation due to aero loads (depending on flow conditions (Ma, AoA))
  - Effects of slotted/perforated test-section at transonic flow speed
  - Influence and stiffness of model support
- Are empirical wind-tunnel corrections for free-flight conditions (calibrated using simple methods of the 1960s) suitable for subtle calibration of RANS models in 2020s?

Acknowledgement

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- Vortical flow over a delta wing. German Research Foundation (DFG), grant numbers KN 888/2-2 and RA 595/25-2Computer resources provided by the Gauss Center for Supercomputing/Leibniz Supercomputing Center under grant *pn69mu*
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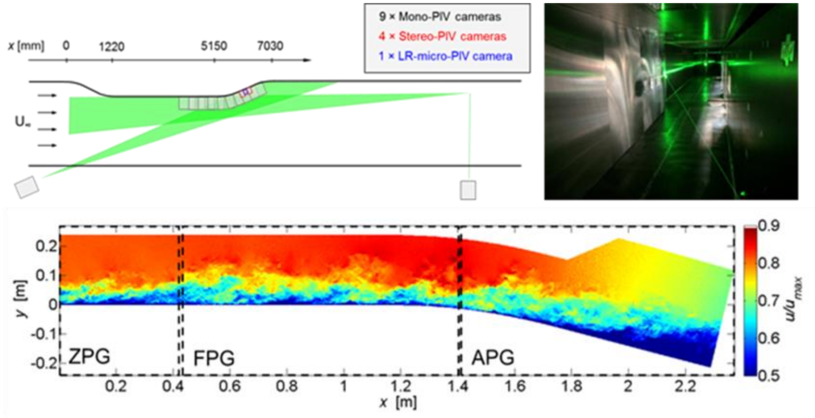
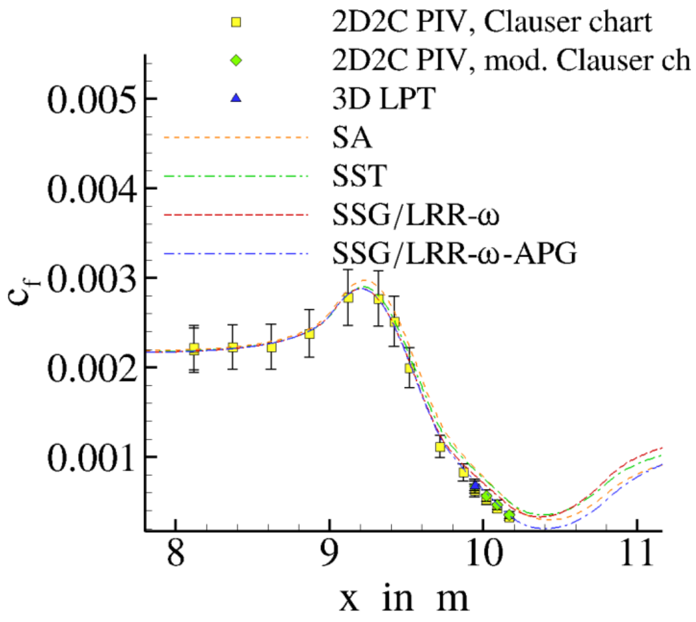
Additional slides, potentially for discussion

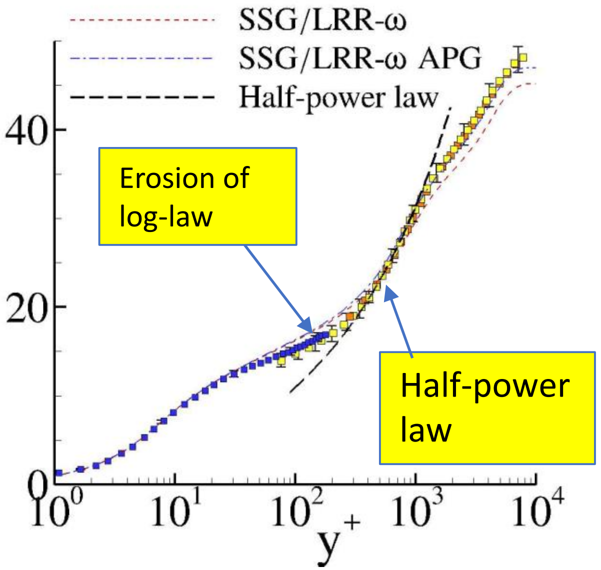
Turbulent boundary layer in strong APG

- Experiment of a turbulent boundary layer in a strong adverse pressure gradient (APG) on convex wall with & w/o separation
- Developing of a wall-law for the mean velocity in adverse pressure gradient (APG)
  - Erosion of the log law in strong APG
  - Emerging of a half power law above the log-law
- Modification of the RANS RSM SSG/LRR-ω for APGs
  - RSM-APG becomes more susceptible to separation



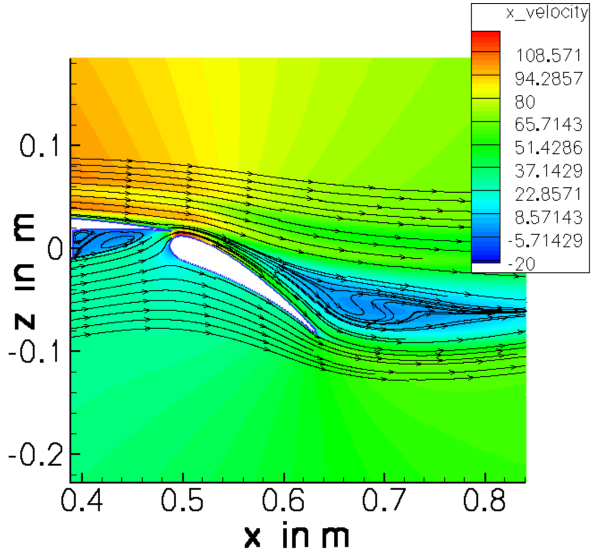
Figures: APG modification for RANS RSM SSG/LRR



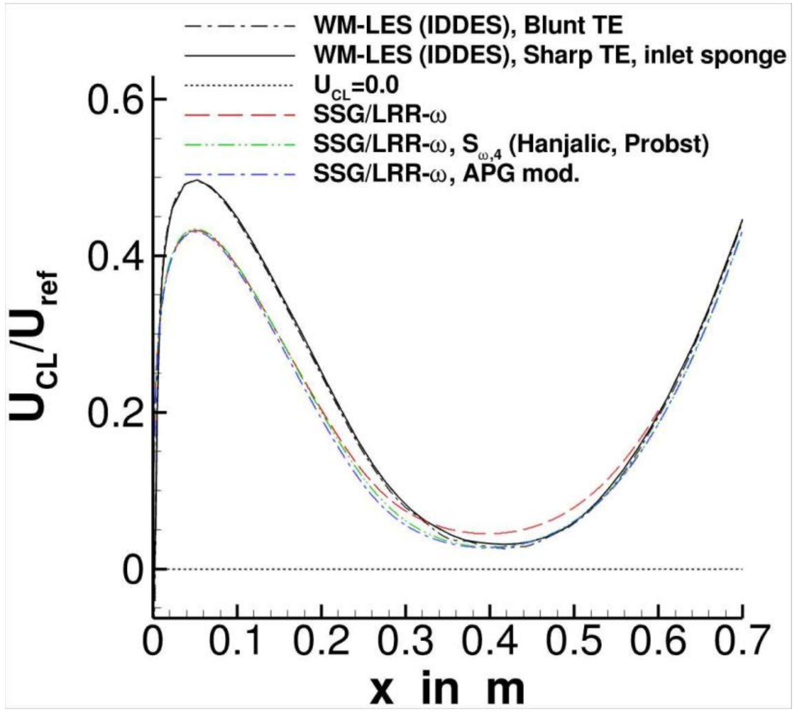


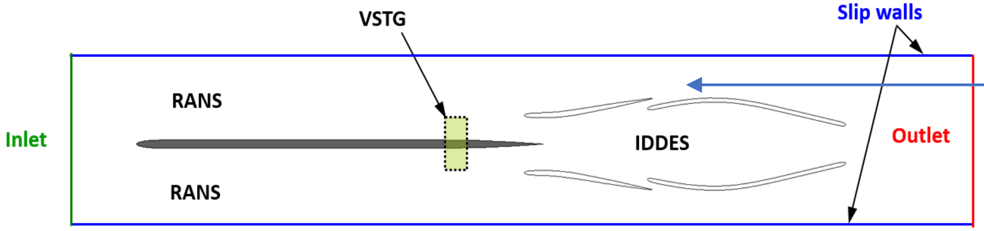
Wake flow in adverse pressure gradient

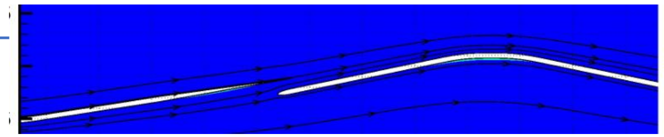
- Phase 1: Wake flow in an adverse pressure gradient (APG)
- Reference data for improvement of RANS models
- CFD friendy experiment: exactly defined boundary condition to generate the wake at APG: liner foils instead of suction/blowing
- Aim: Reverse flow in the wake, but attached flow at liner foils
  - Wind tunnel experiment (ISM, P. Scholz, W. Breitenstein)
    - Problem: large-scale unsteadiness of wake (→ later confirmed by LES)
  - Wall-modelled Large-Eddy Simulation using IDDES (St. Petersburg Polytechnic University, M. Strelets, M. Shur, E. Guseva)
- Phase 2: Curved wake flow (stopped February 2022)



3-Element Airfoil MD 30P-30N, simulation using SSG/LRR-omega







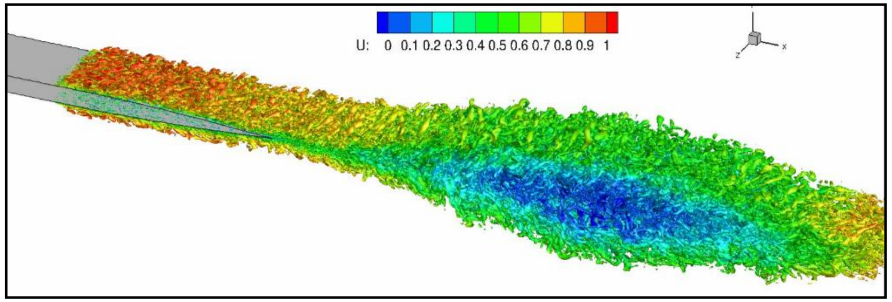
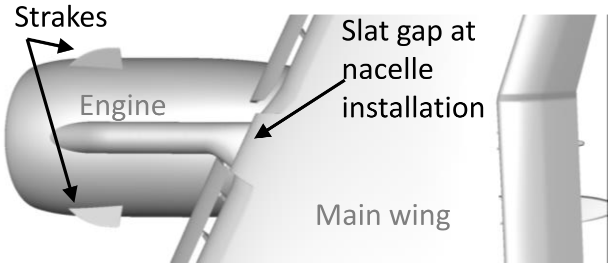


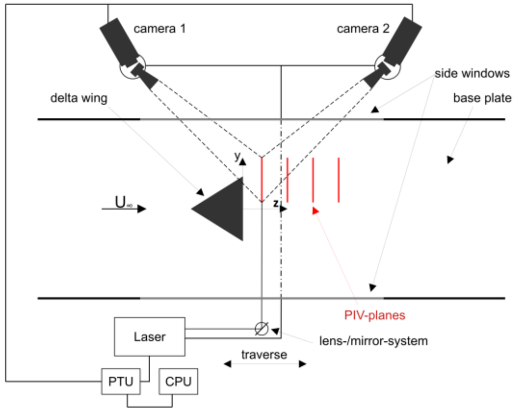
Figure by SPbPU (Knopp, Korsmeier, Strelets, Guseva, STAB Symposium, 2020)

Vortical flow above and downstream of a delta wing

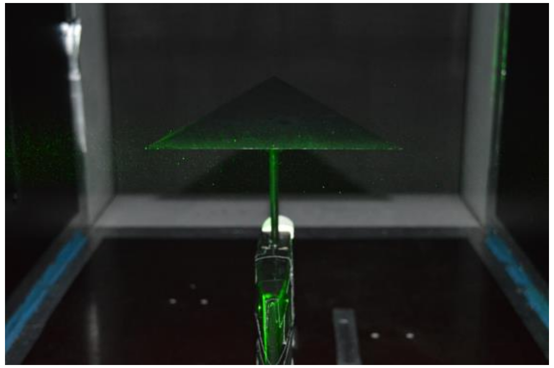
- Reference data for 65deg swept delta wing at $Re_c=1\times10^6$, AoA = 8deg
- Wall-resolved LES (DLR)
- Wind-tunnel experiment (ISM, TU Braunschweig): time-resolved sPIV
- Aim: Improvement of hybrid RANS/LES and RANS

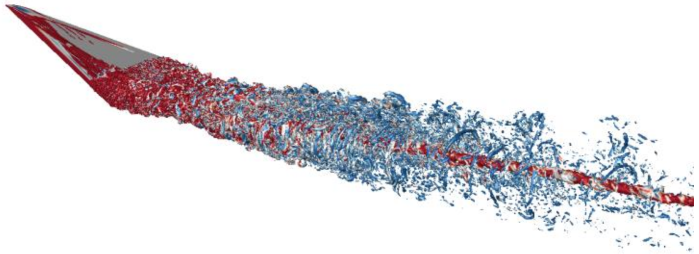
Full complexity:
Wing with engine nacelle



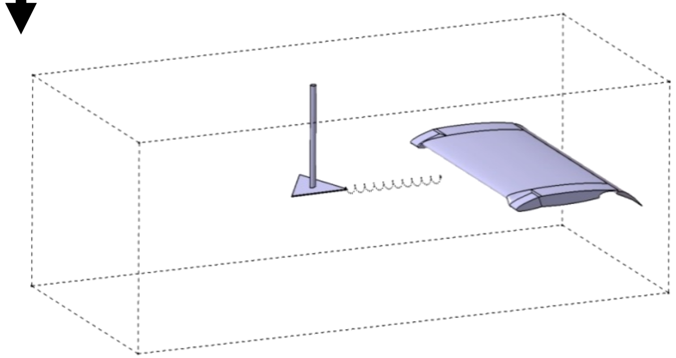


Experiment in MUB wind-tunnel at ISM





Reduction of Complexity



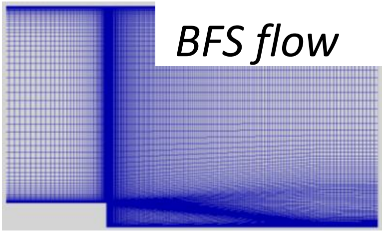
Wall-resolved LES
- Total mesh size 787 x 10^6 cells
- Physical time-step size for wall-resolved LES
- Initial phase and transient: 10 CTUs (1 CTU = c/U) and then 10 CTUs for sampling statistics
- Simulations performed on at least 350 computing nodes on SuperMUC-NG of TU München (on 350 computing nodes), 1.5 TB data

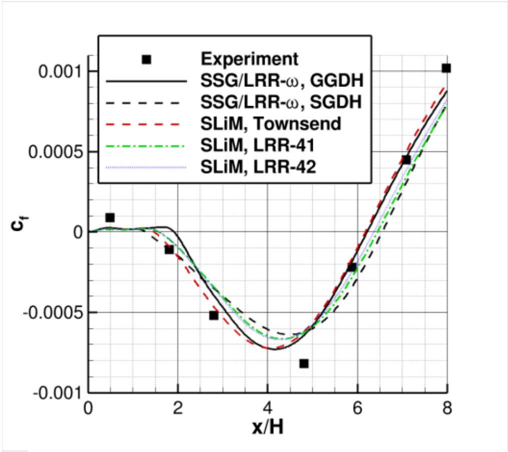
Target configuration:
Delta wing + DLR-F15 two-element

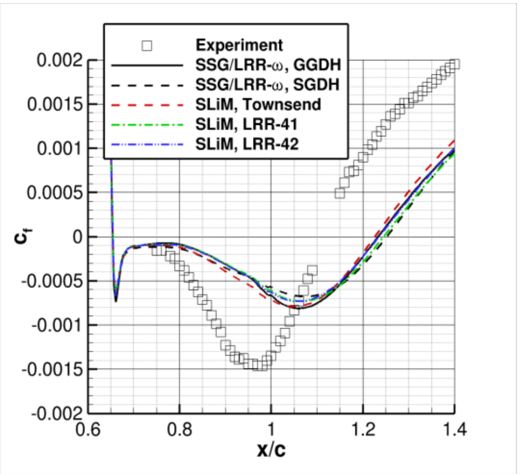
Reduced configuration:
Isolated Delta wing

Thin separation bubbles and reattachment

- *NASA CFD Prediction Error Assessment Workshop 2018* showed discrepancies in the capabilities of RANS turbulence models to predict the shape and size of turbulent separation bubbles
- Apparently contradictive experimental situation: *Backward-Facing Step (BFS) Flow* versus *Hump Flow*
- Design of a new experiment (step at 90, 45, 25 deg) performed in two facilites within the DLR project *ADaMant*
  - Ratio of boundary layer thickness to wind-tunnel span : around 1 / 40.
  - Step height to BL thickness : H/δ = 0.4
  - Lagrangian particle tracking (LPT) and temperature sensitive paint (TSP)







https://turbmodels.larc.nasa.gov/nasa40percent.html

Exp. by Driver & Seegmiller (left) and Seifert, Greenblatt et al. (right)
RANS by B. Eisfeld (2022) *Physics of Fluids* (34):1-12