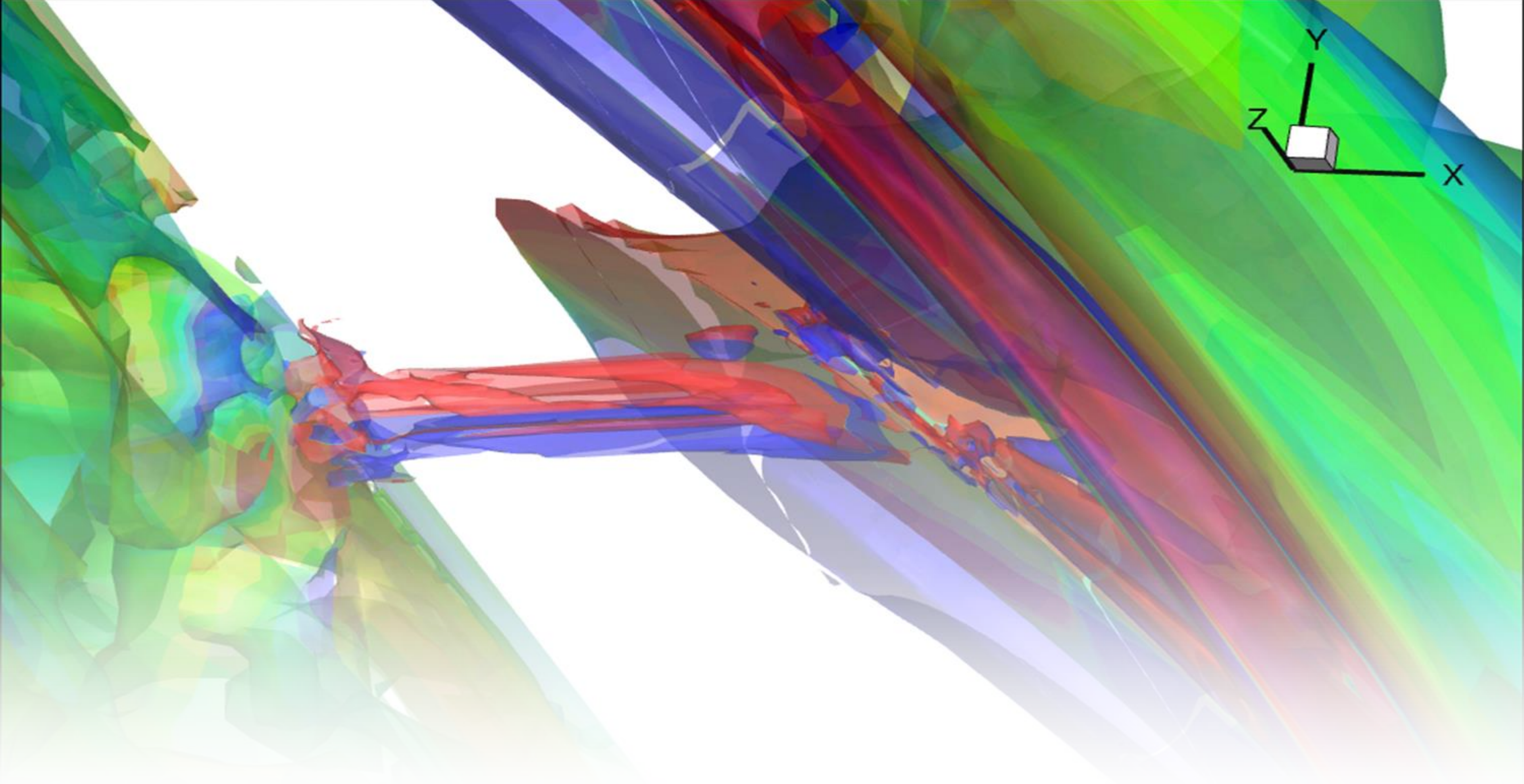

Investigation of Local Flow Phenomena of Misaligned Riblets in a Turbulent Boundary Layer

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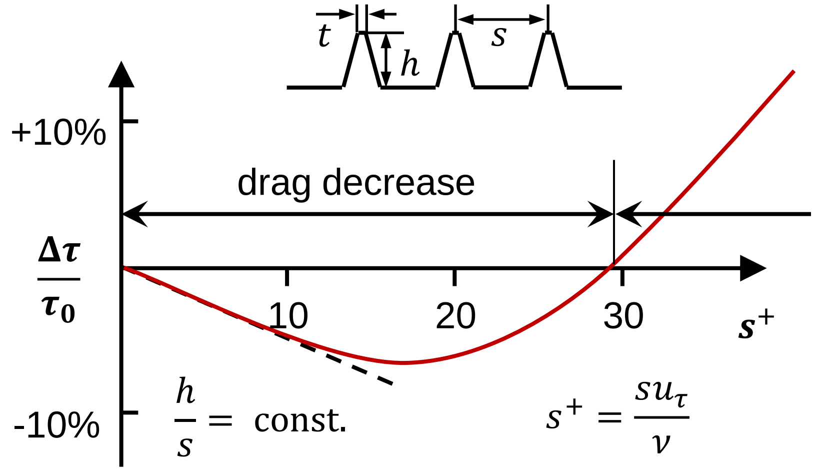
European Drag Reduction and Flow Control Meeting
6 April, 2017, Rome, Italy

Outline

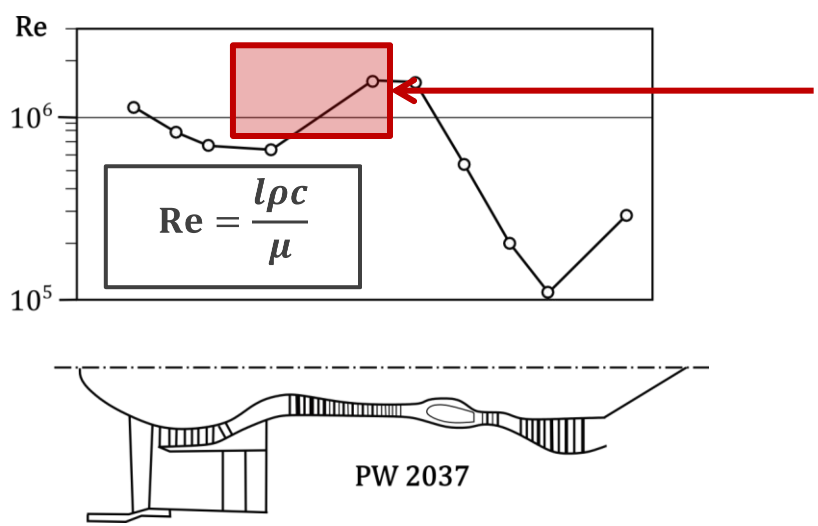
1. Motivation
2. Method and Validation
3. Results
4. Conclusions

Riblets in Industrial Applications (e.g. Gas Turbine Engines)



Prospects

- In turbulent boundary layers
- Up to **10% drag reduction** for ideal riblets
- Changing potential for varying geometry/ operating point
- **Severe Drag increase possible**

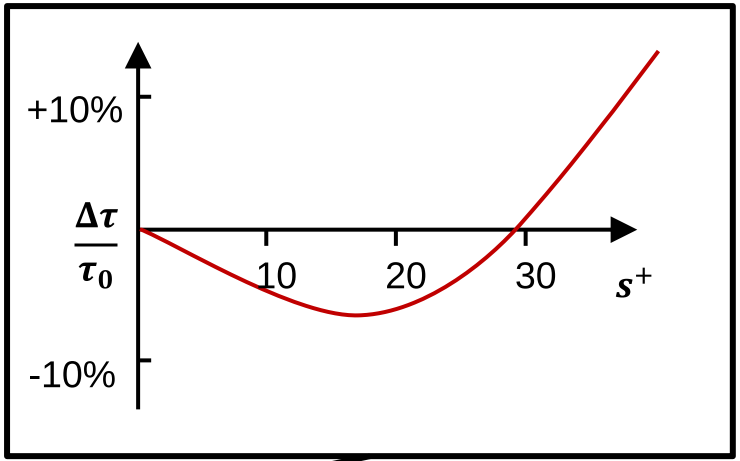


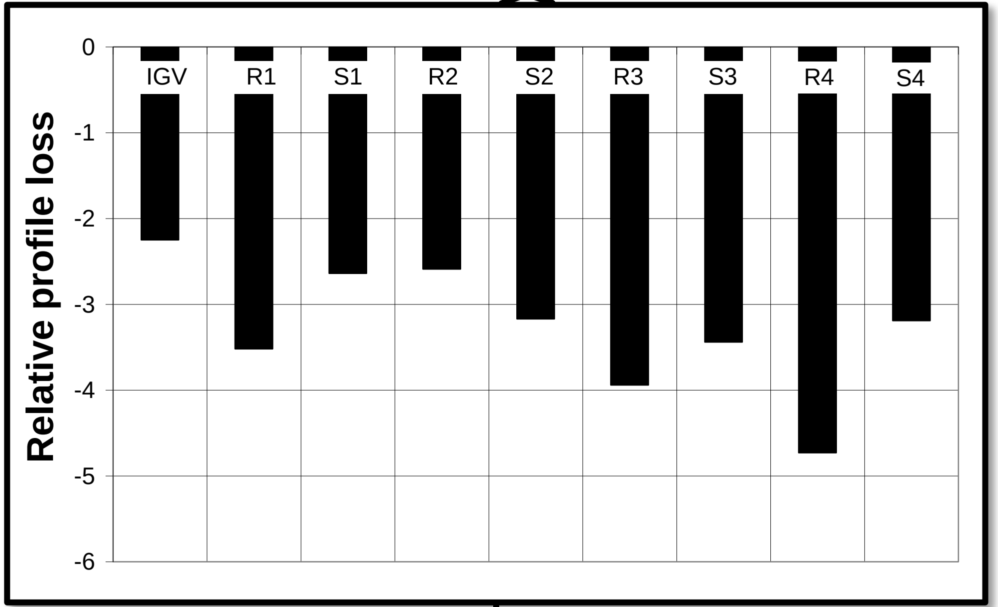
Reynolds number at cruise of typical mid-thrust mid-range engine

High- and intermediate pressure compressor

- High Re
- Subsonic flow
- Erosion less severe
- Stationary gas turbines even more appropriate

Estimation of Riblet Potential for a 4.5 Stage Compressor



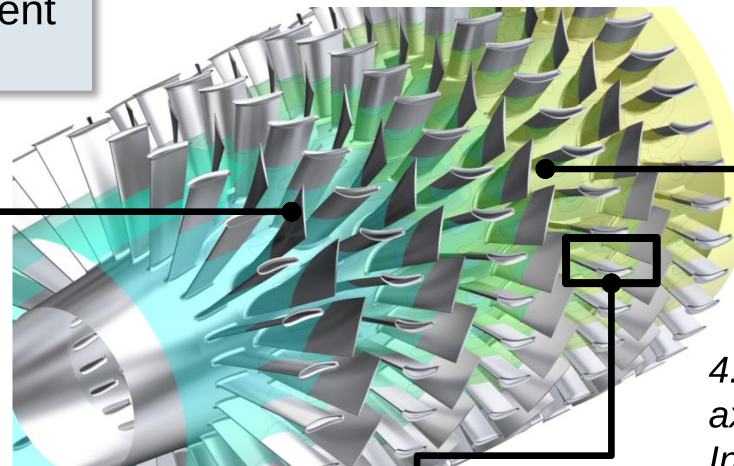


Relative increase of adiabatic efficiency at design point: approx. 0.2%

Aerodynamic Challenges for the Application in Turbomachinery

Pressure gradient effects

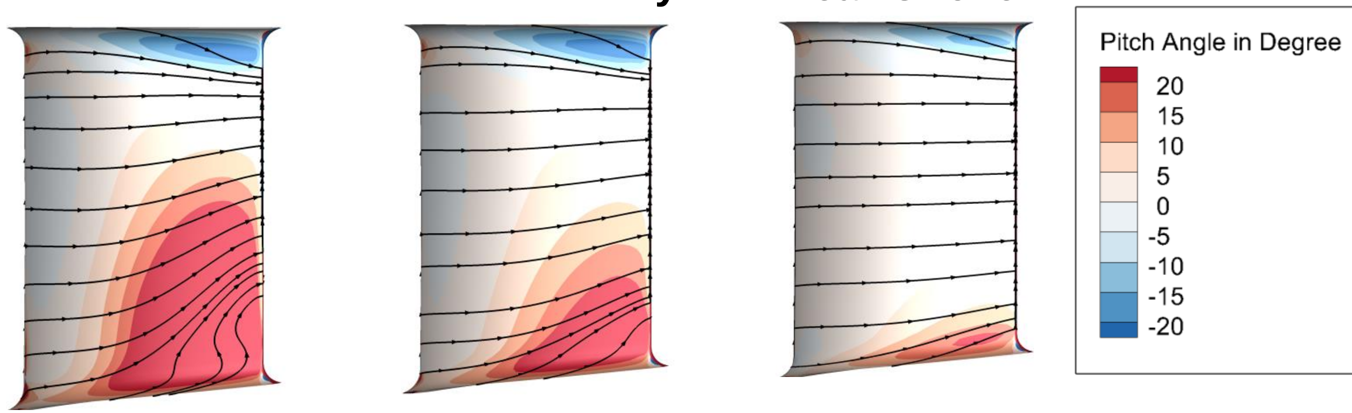
Change in blade loading



4.5 stage high-speed axial compressor Institute of Turbomachinery and Fluid Dynamics

Variation of flow directions with **operating point**

Near Stall | **Best Efficiency** | **Near Choke**



Suction side streamlines stator 3

Proposed RANS-Model[1]

Ideal and manufactured Riblets

$\frac{\Delta\tau}{\tau}$ → $\frac{\Delta\tau}{\tau}$ ➡ ΔU^{+} Okabayashi et al. (2014) → k-ω modification Aupoix et al. (2012)

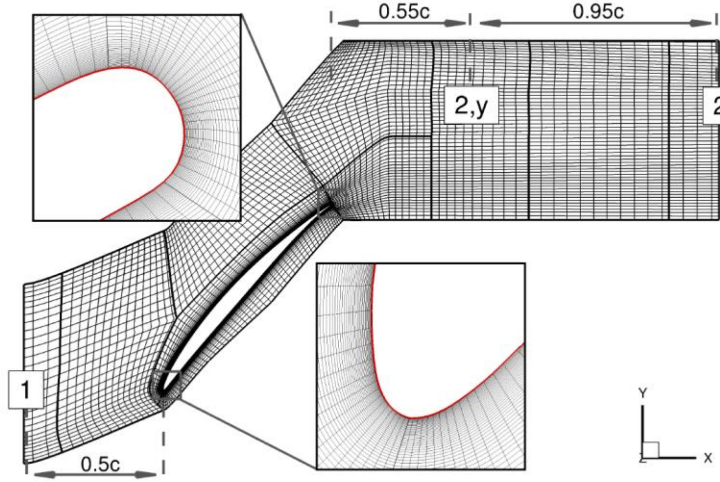
$$\frac{D\omega}{Dt} = 2\gamma s_{ij}s_{ij} - f_{damp}\cdot\beta\omega^{2} + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma_{\omega}\nu_t\right)\frac{\partial\omega}{\partial x_j}\right]$$

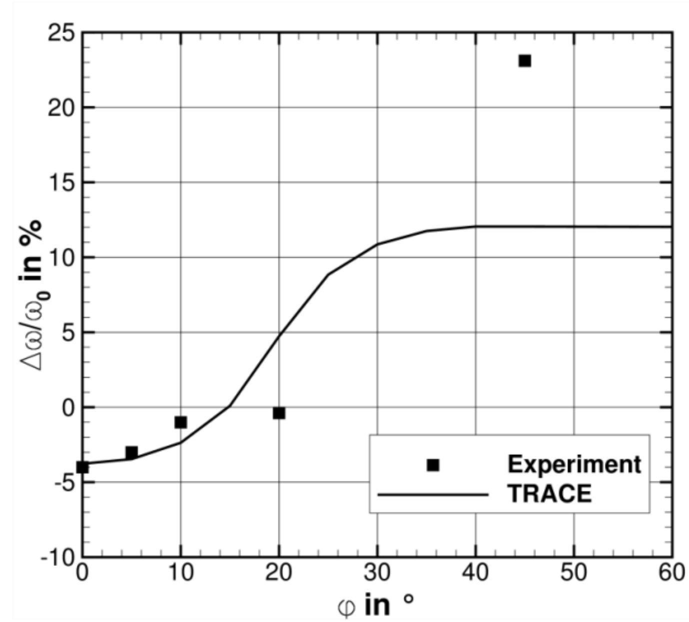
$$f_{damp} = 1 - A\exp\left(-\frac{\omega y^{2}}{500\nu}\right)$$

- Effect of Misalignment
- Adapted Pressure Gradient Effect calculation
- Improved drag increase regime prediction

[1]*Koepplin V., Herbst F.; Seume JR. (2017): Correlation-Based Riblet Model for Turbomachinery Applications. ASME Journal of Turbomachinery;139(7)*

RANS-Predictions[1] of Integral Effect: Compressor Cascade





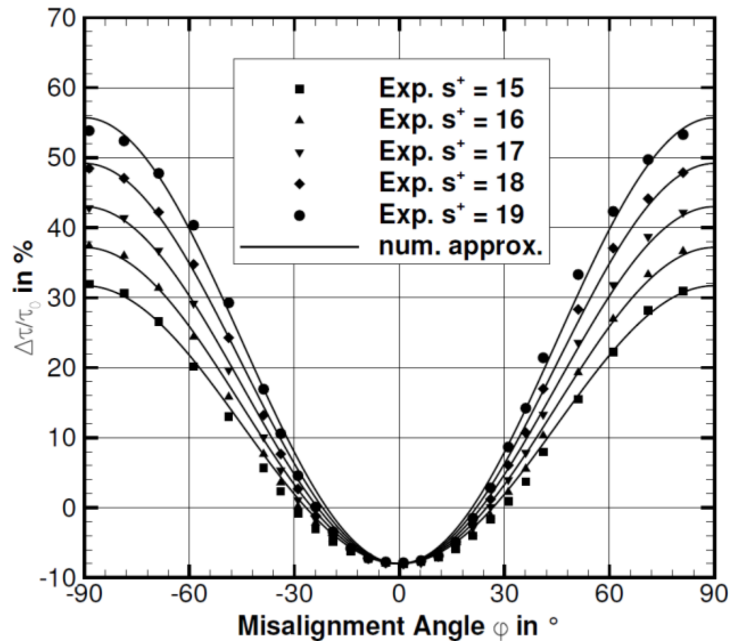
Relative change of total pressure (profile) loss

$$\omega_{\text{loss}} = \frac{p_{\text{tot,in}} - p_{\text{tot,out}}}{p_{\text{tot,in}} - p_{\text{in}}}$$

- predicted excellent for aligned Riblets
- deviates for misaligned Riblets
- alternating under- and over-predicition with increasing misalignment

[1]*Koepplin V., Herbst F.; Seume JR. (2017): Correlation-Based Riblet Model for Turbomachinery Applications. ASME Journal of Turbomachinery;139(7)*

Objectives of this Misalignment Study



- Increase quantitative data base for correlation-based RANS-model
- Understand locally relevant flow features to criticize chosen RANS-modeling strategy
- Setup reliable DNS for prediction of Riblet misalignment in turbulent boundary layers

Exp. data acc. to: Hage, W. (2004): Zur Widerstandsverminderung von dreidimensionalen Riblet-Strukturen und anderen Oberflächen. PhD Thesis, TU Berlin

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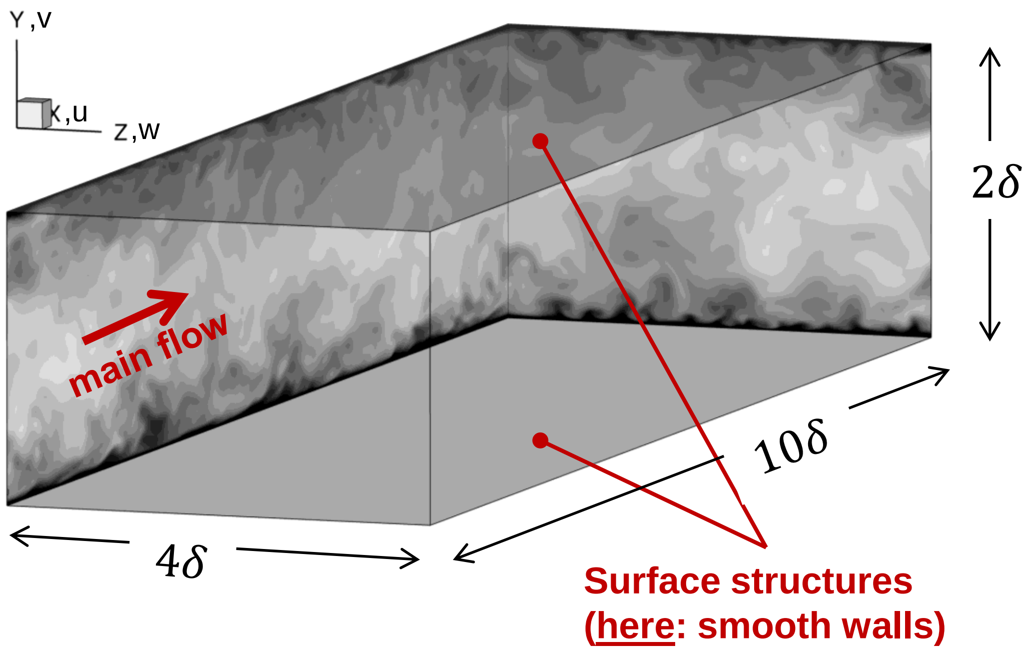
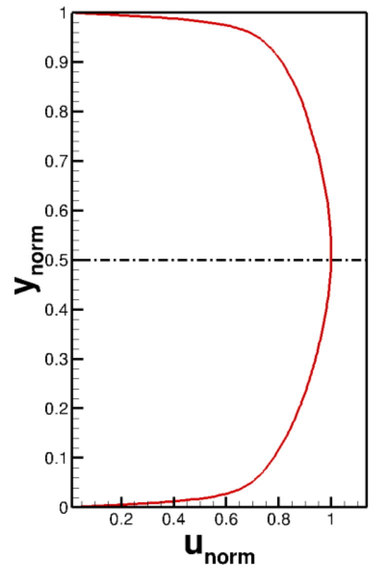
Numerical Method and Principal Setup





Setup und Boundary Conditions

- Plane channel flow
- Periodic in stream- and spanwise direction
- No-slip walls at bottom and top
- $\mathrm{Re}_\tau = 395$ with $\mathrm{Re}_\mathrm{B} = 14000$
- Spatial resolution:
  - $\Delta y^+ = 0.4 \ldots 10$
  - $\Delta x^+ = 10$
  - $\Delta z^+ = 5$

Flow Solver

- OpenFoam
- Finite Volume
- Spatial discretization: bounded 2nd order TVD scheme
- Time integration: 2^{nd} order Euler backward (implicit)

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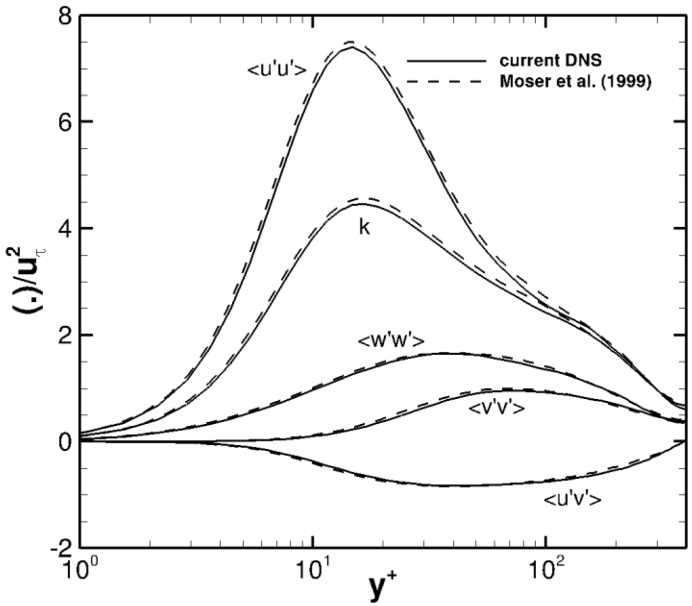
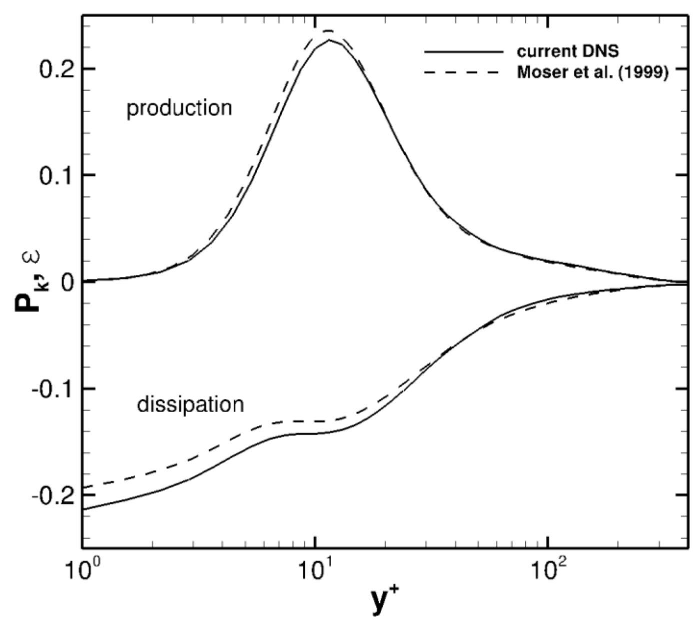
Validation for Smooth Wall at $Re_\tau = 395$

Reynolds Stresses



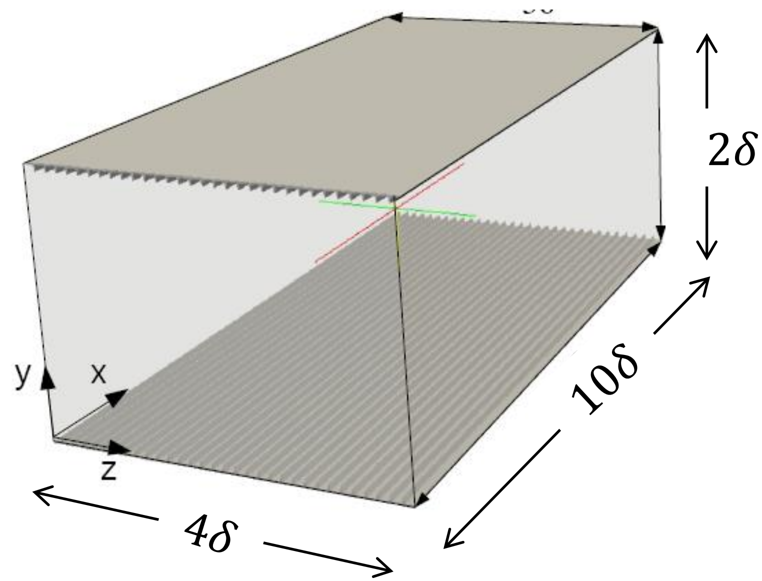
Turbulent Kinetic Energy Balance

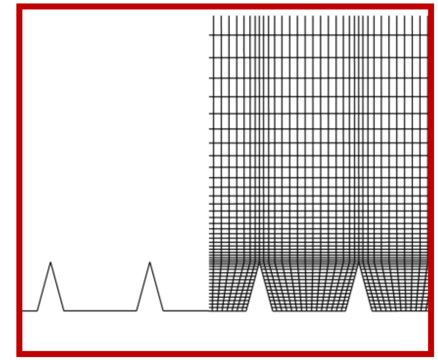


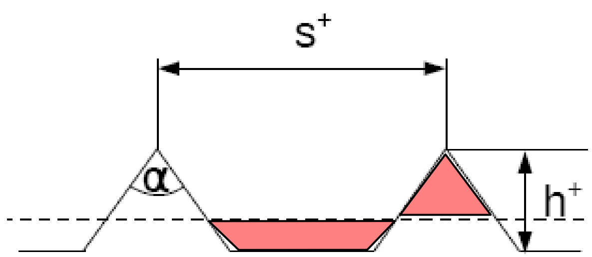
All quantities averaged over $t^+ \approx 120$

Reynolds stresses and turbulence kinetic energy balance in (very) good accordance with Moser et al. (1999)

Aligned Riblets: Numerical Setup







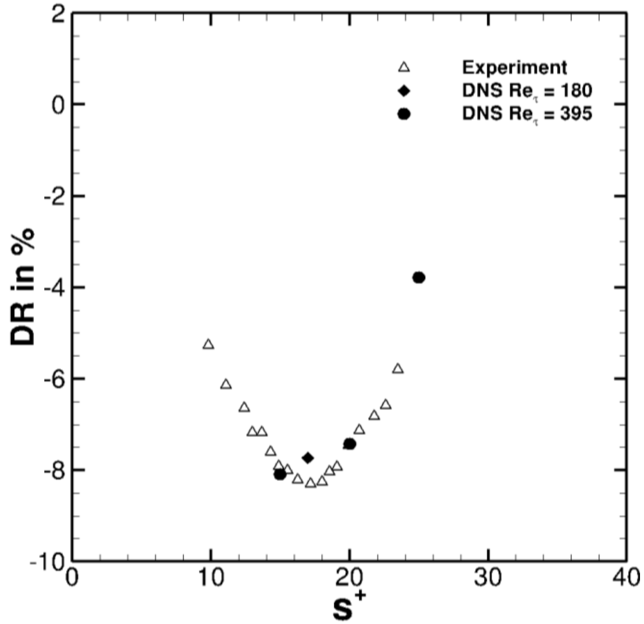
Setup und Boundary Conditions

- Ideal trapezoidal Riblets
- Variation of Riblet spacing s^+
- Riblet height $h^+ = 0.5s^+$
- Riblet tip-angle: $\alpha = 30°$
- Body-fitted hexa mesh
- $\mathrm{Re}_\tau = 395$ with $\mathrm{Re}_\mathrm{B} = 14000$
- $\mathrm{Re}_\tau = 180$ with $\mathrm{Re}_\mathrm{B} = 5700$

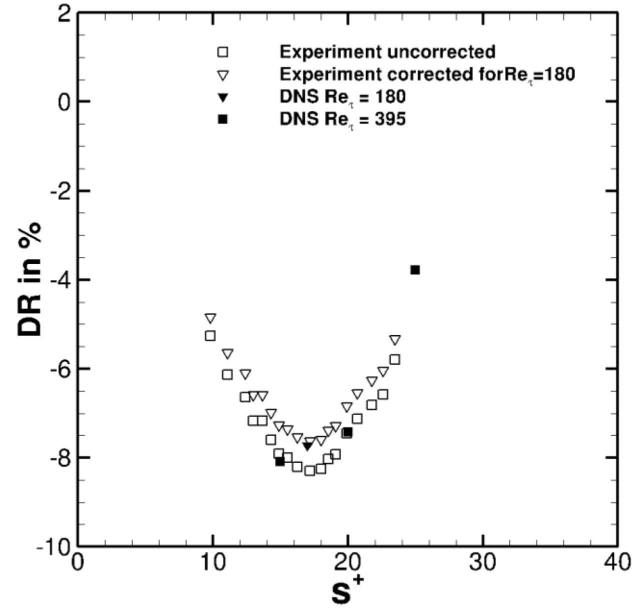
Predicted Drag Reduction of Aligned Riblets

Investigation of Local Flow Phenomena of Misaligned Riblets in a Turbulent Boundary Layer

Experimental Data[1]



Adjusted Exp. Data



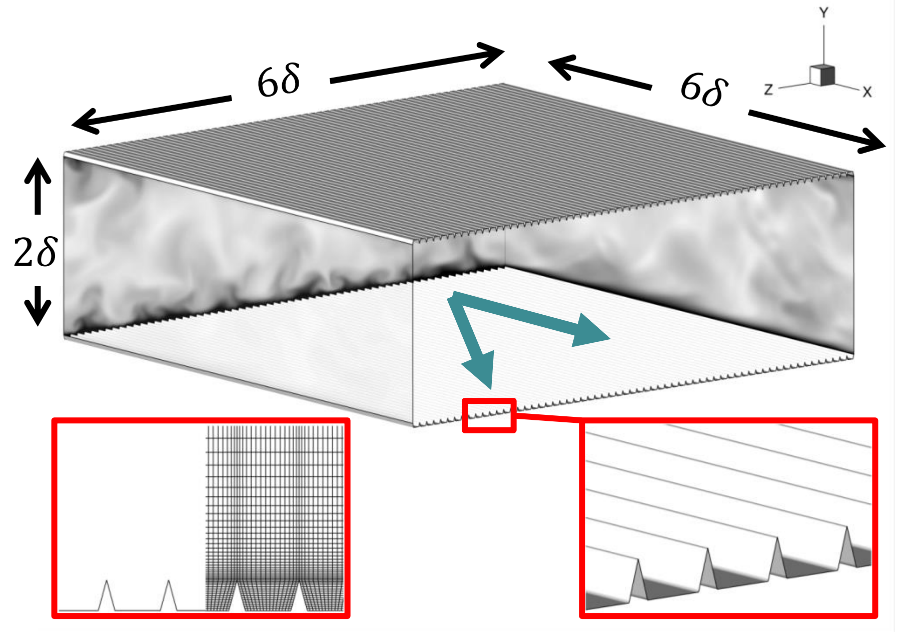
- Excellent prediction of experimental drag reduction (DR) for $\mathrm{Re}_\tau = 395$ and
- for adjusted experimental data of $\mathrm{Re}_\tau = 180$
- Experiments adjusted for Reynolds number according to[2]

$$\Delta U^+ = -\left[(2C_{\mathrm{f0}})^{-\frac{1}{2}} + (2\kappa)^{-1}\right]\frac{\Delta C_\mathrm{f}}{C_{\mathrm{f0}}}$$

[1]Exp. data acc. to: Hage, W. (2004): Zur Widerstandsverminderung von dreidimensionalen Riblet-Strukturen und anderen Oberflächen. PhD Thesis, TU Berlin

[2]Garcıa-Mayoral, R.; Jimenez, J. (2011): Drag Reduction by Riblets. Philos. Trans. R. Soc. A, 369(1940), pp. 1412–1427.

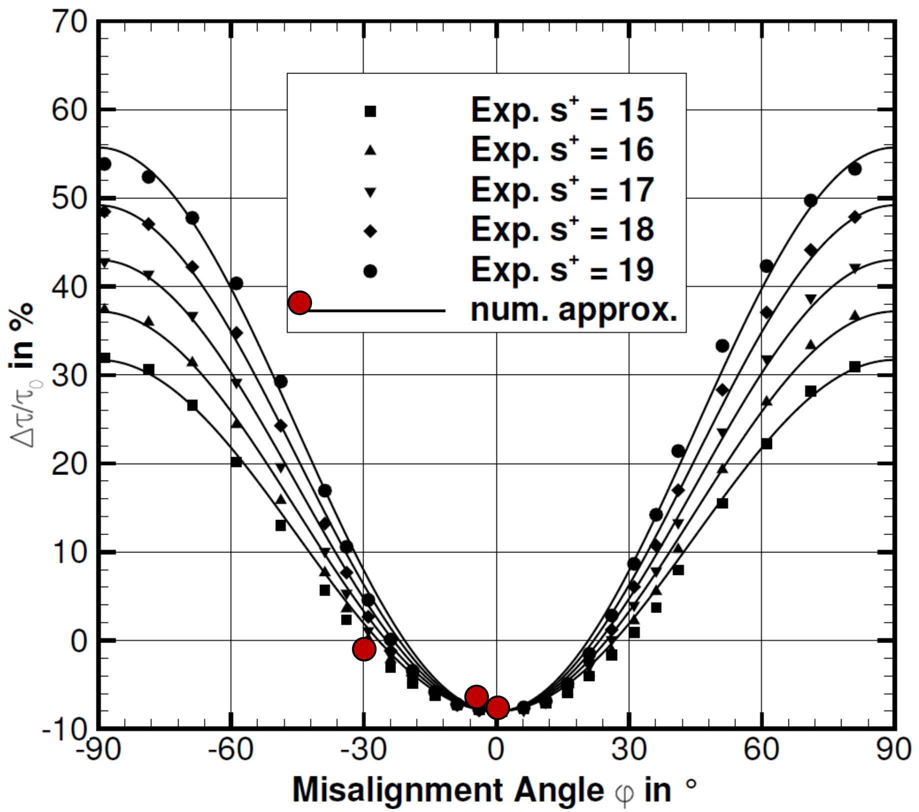
Misaligned Riblets: Numerical Setup



Setup und Boundary Conditions

- Ideal trapezoidal riblets with $s^+ = 17$
- Riblet height $h^+ = 0.5s^+$
- Riblet tip-angle: $\alpha = 30°$
- Body-fitted hexa mesh
- Variation of mean flow angle $\alpha = 0°; 5°; 30°; 45°$
- $\mathrm{Re}_\tau = 180$ with $\mathrm{Re}_\mathrm{B} = 5700$
- Spatial resolution (33 million nodes):
  - $\Delta y^+ = 0.4 \dots 10$
  - $\Delta x^+ = \Delta z^+ = 1$
- Averaging for $t^+ = 25$

Integral Effect on Wall Friction



$$\left.\frac{\Delta\tau}{\tau_{smooth}}\right|_{0°} = -7.73\%$$

$$\left.\frac{\Delta\tau}{\tau_{smooth}}\right|_{5°} = -6.28\%$$

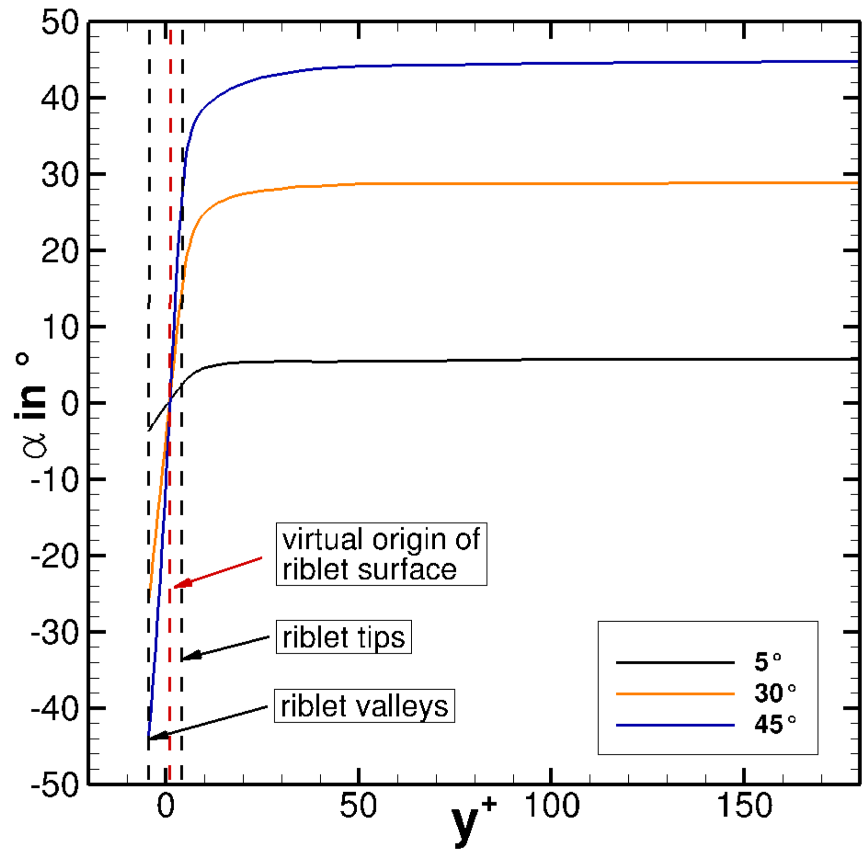
$$\left.\frac{\Delta\tau}{\tau_{smooth}}\right|_{30°} = -1.21\%$$

$$\left.\frac{\Delta\tau}{\tau_{smooth}}\right|_{45°} = +37.47\%$$

- Principal trend captured
- Slightly under-predicted for 30°
- Significantly over-predicted for 45°
- Notable coincidence with RANS predictions of compressor cascade

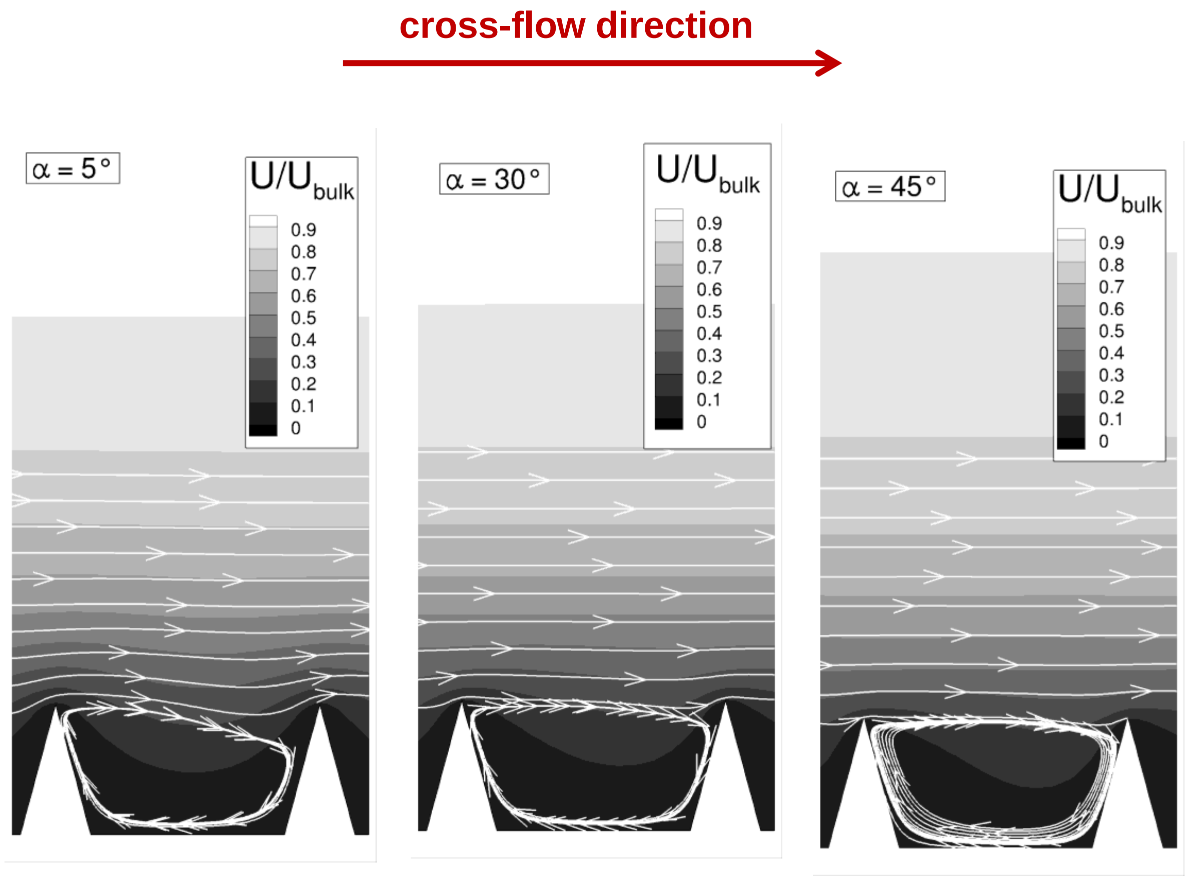
Exp. data acc. to: Hage, W. (2004): Zur Widerstandsverminderung von dreidimensionalen Riblet-Strukturen und anderen Oberflächen. PhD Thesis, TU Berlin

Mean Flow Angle α of the Wall-Parallel Components



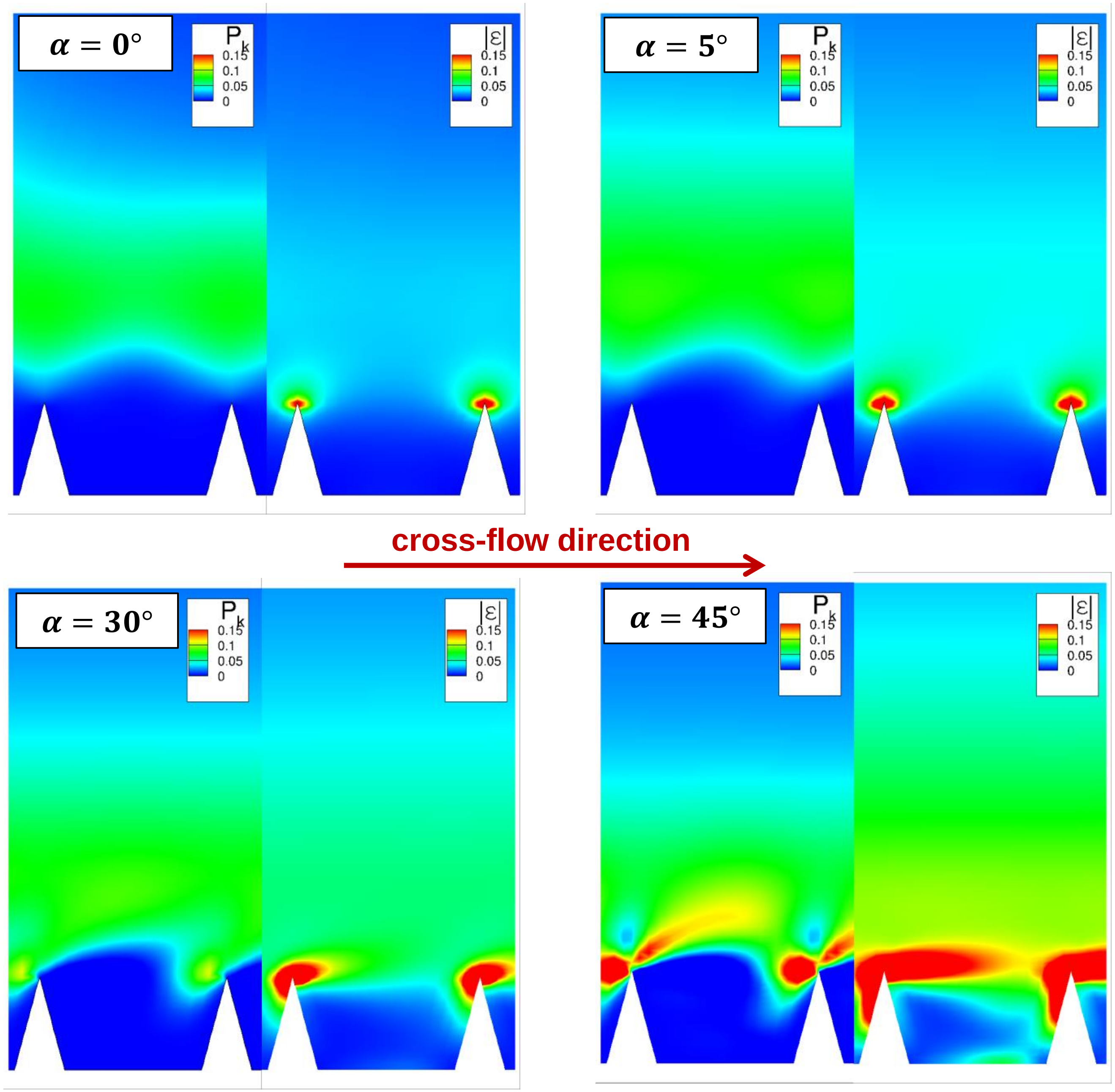
- Prescribed misalignment angle a attained in main flow
- Near-wall reduction of a
  ➔ Increased shear
- Opposite flow direction in Riblet valley
- All curves intersect at one wall-normal point: $y^+ = 1.02$
  ➔ Virtual origin of riblet surface (red dashed line)

Cross-Flow Streamlines of Mean Flow



Turning of mean flow may result from vortical cross-flow in Riblet valley

Turbulent Kinetic Energy Balance



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Wall-Normal Profiles at Mid-Valley

Investigation of Local Flow Phenomena of Misaligned Riblets in a Turbulent Boundary Layer

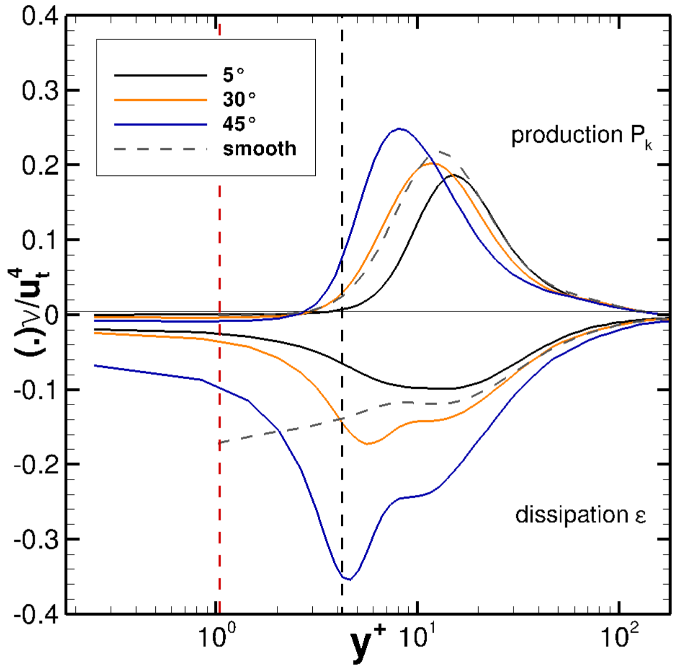
Motivation

Method/Validation

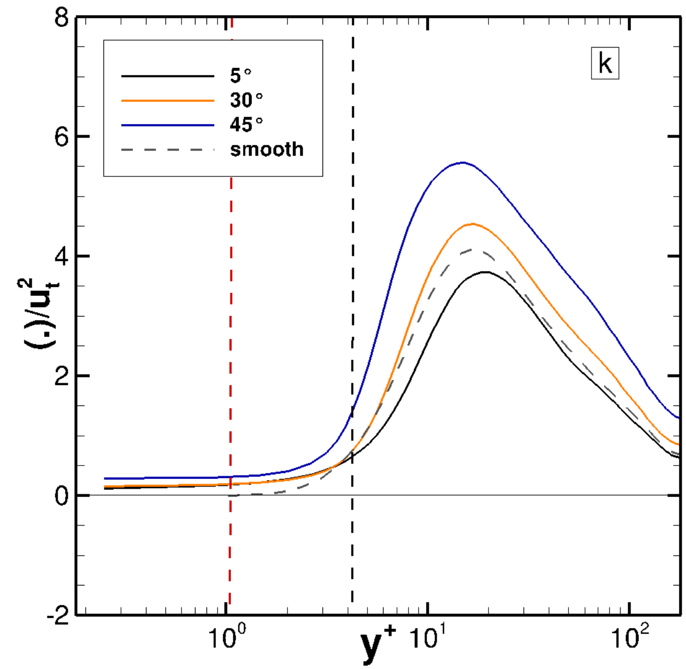
Results

Conclusions

Turbulent Kinetic Energy Balance



Turbulent Kinetic Energy



- Maxima of production and dissipation move closer to surface for increasing misalignment a
- Production P_k increases with a
  ➔ **Effect of shear?**
- Dissipation doubles from 30° to 45°
- For drag-neutral case (30°) P_k and k nearly coincide with smooth-case…
- …dissipation not
  ➔ **Dissipation most sensitive quantity**

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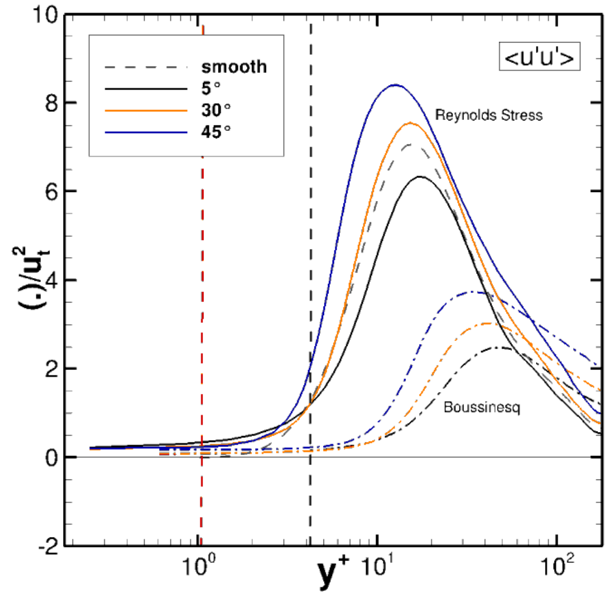
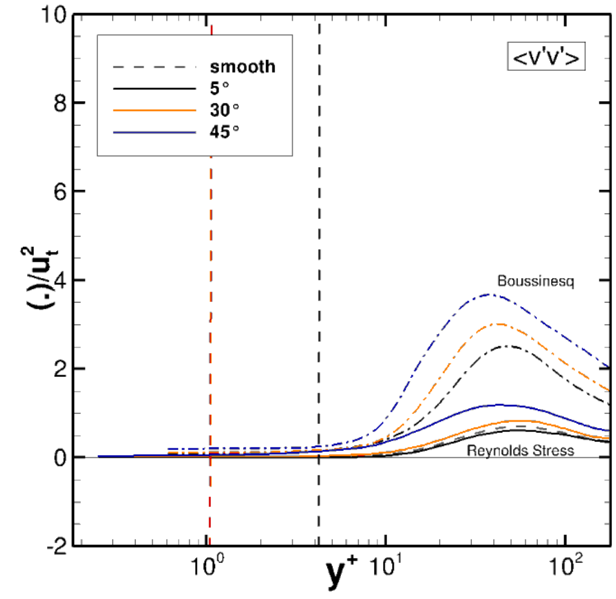
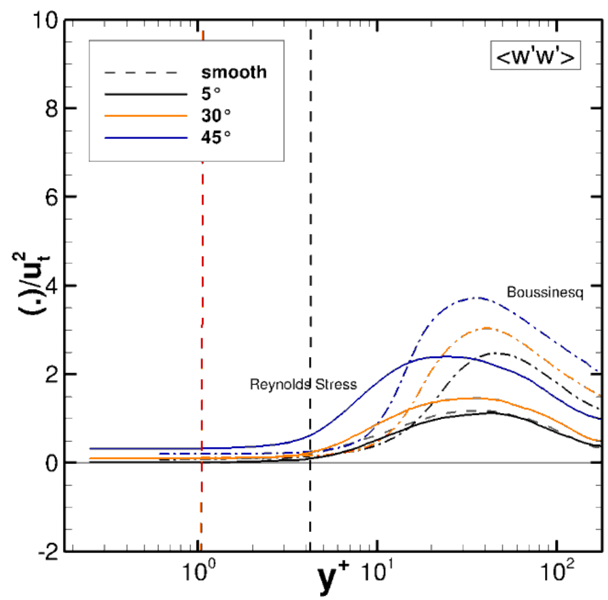
Investigation of Local Flow Phenomena of Misaligned Riblets in a Turbulent Boundary Layer

Reynolds Normal Stresses: Resolved vs. Ideal Boussinesq







Note: wall-parallel stresses transformed acc. to α

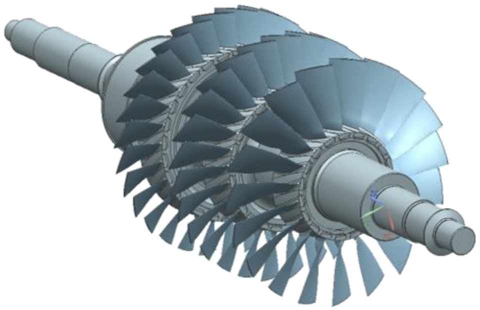
- Resolved $\overline{w'w'}$ doubles from 30° to 45°
- Other stresses increase but relatively less
- Boussinesq captures neither basic anisotropy and its change
- nor the peak positions

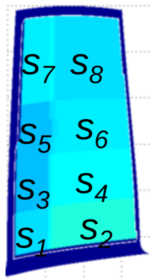
Conclusions

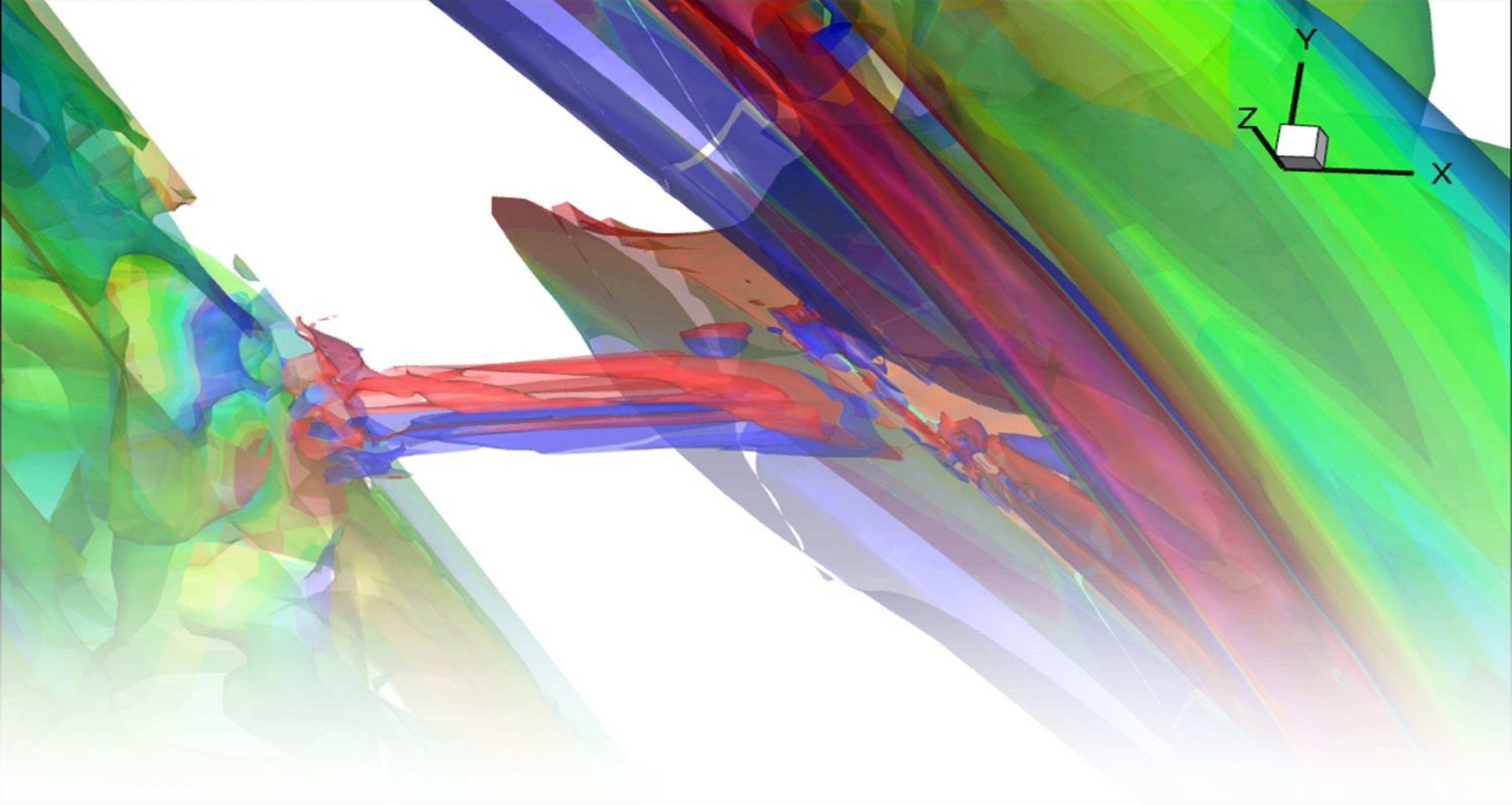
- DNS results successfully validated
- Misalignment effect slightly deviates from oil channel experiment but correlates with cascade experiments
- Misaligned Riblets turn the mean flow in the wall-near region due to induced cross-flow vortices in Riblet valleys
- Increasing misalignment increases maxima of turbulent quantities and shifts them closer to wall
- Turbulent kinetic energy and its production correlate with drag change
- Dissipation does not
- Ideal Boussinesq Reynolds stresses do not capture anisotropy

Outlook

- Re-assess RANS model regarding
  - turning of mean flow in wall-near region
  - relevance of anisotropy
  - empiric correlations for dissipation
- Evaluation of local loss contributions (viscous vs. turbulent stresses)
- Compressor rig validation (in preparation)







Thank you for your Attention!

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