Analysis of Turbulent Boundary Layers over Moving Surfaces

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Coming Up

- Motivation
- State of the Art
- Methods
  * numerical
  * experimental
- Results
  * smooth surface
  * riblet surface
- Conclusion

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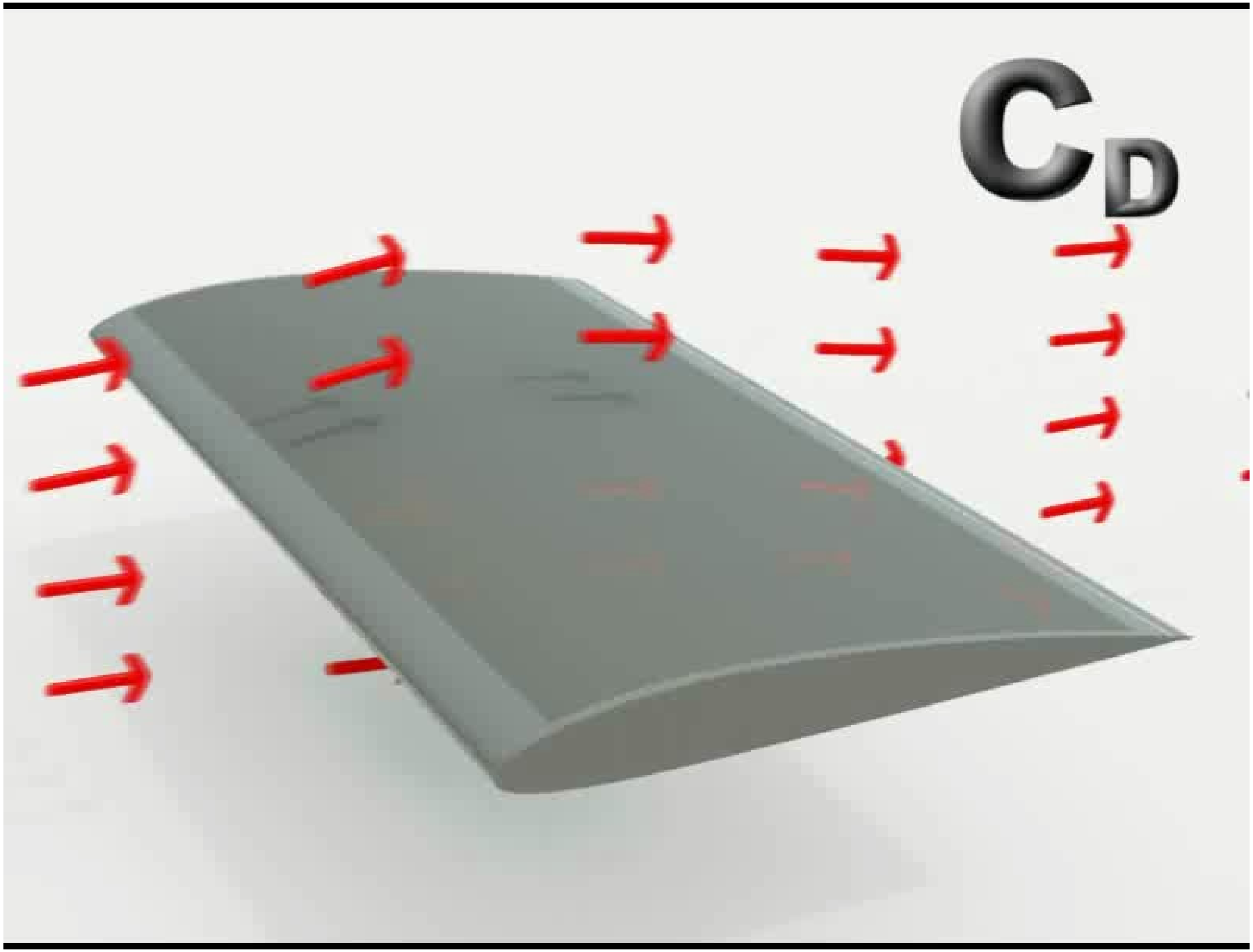
Motivation / 1

FOR 1779 RWTH Aachen



State of the Art / 1

- **passive means: riblets → DR ≤ 10%**

  (Exp: Walsh, Bechert etc.)
  (Num: Choi, Karniadakis, Goldstein, Jimenez, etc.)

- **active means: in-plane spanwise wall motion ($Re_\tau \leq 100$)**

  internal flow (channel) → 10% ≤ DR ≤ 45%
  (wall oscillation, rotating discs, Lorentz forces … ;
  Quadrio, Choi, Ricco, Leschziner, Touber etc.)

  external flow → DR ≤ 15%
  (electroactive polymers, plasma actuators … ;
  Choi, Di Cicca, Gouder, Laadhari etc.)

State of the Art / 2

- active means: spanwise transversal wall motivation ($Re_\tau \leq 750$)

  internal flow (channel) → DR ≤ 13%
  (Tomiyama, Fukagata etc.)

  external flow → DR ≤ 13%
  (Itoh, Tamano, Klumpp etc.)

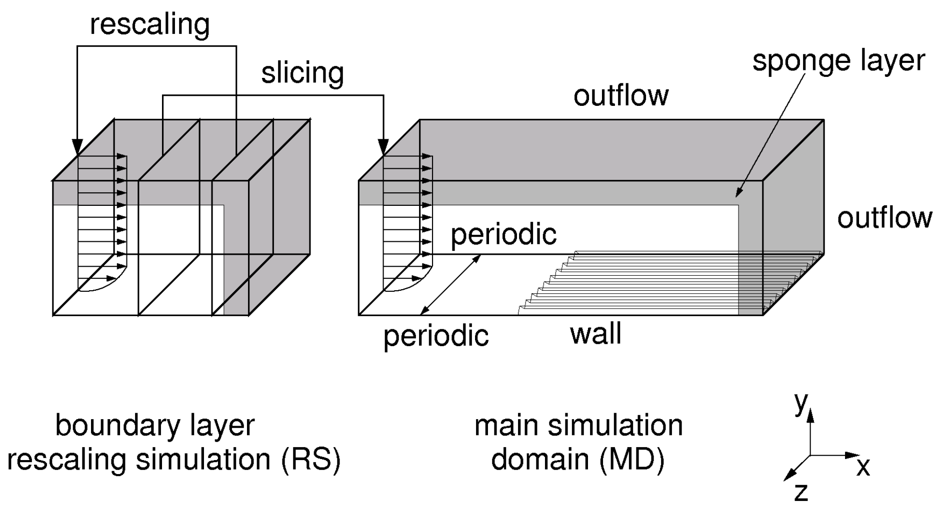
Summary:

- no combination of riblets and moving surfaces exists
- combination seems natural due to the similarity in the drag reducing mechanism
- combination possible if aluminum surface can be actuated
- actuators with high strength to displace and retract the aluminum surface are necessary

Numerical Method / 1

- **Large-eddy simulation using the MILES (monotone integrated LES) approach**
- **Discretization of the inviscid terms by a mixed centered-upwind AUSM (advective upstream splitting method) scheme at second-order accuracy**
- **Second-order centered discretization of the viscous terms**
- **Temporal integration by a second-order explicit 5-stage Runge-Kutta method**

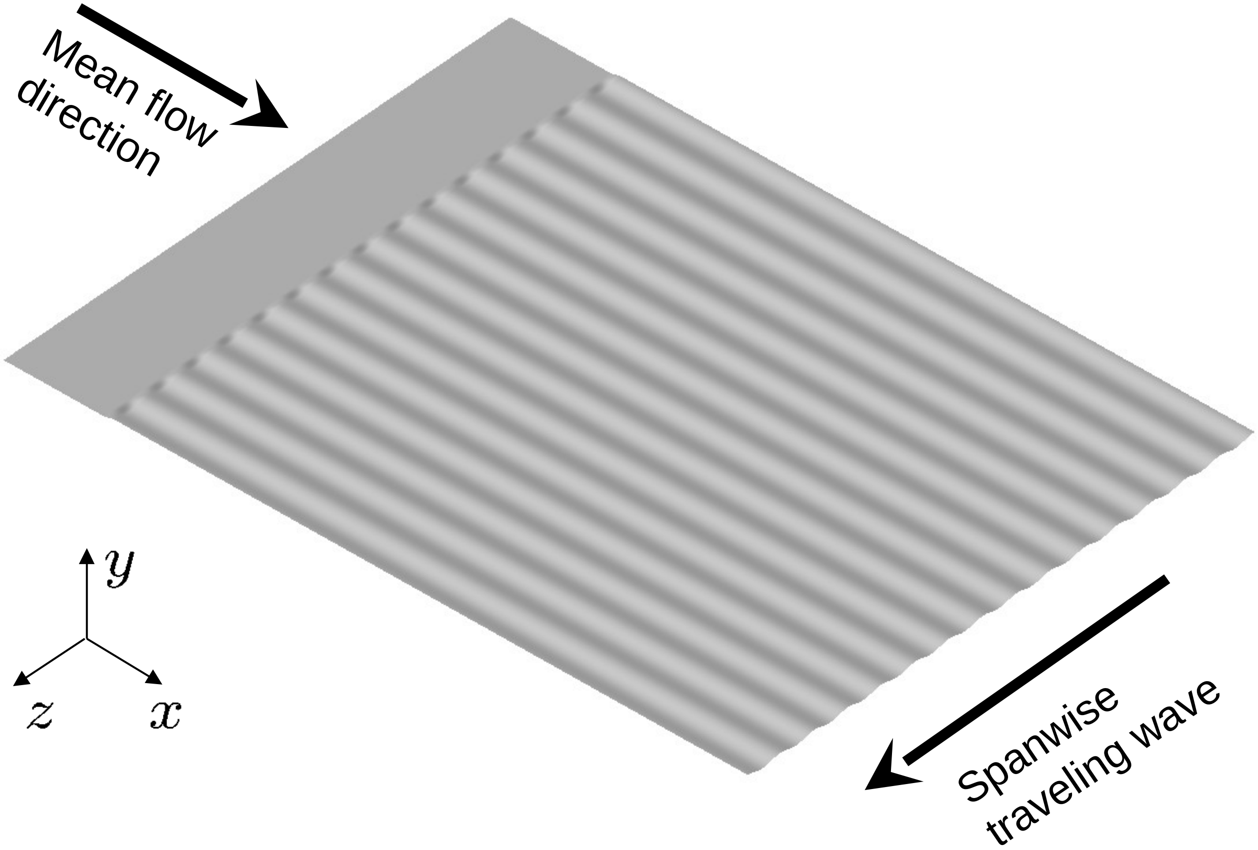
Numerical Method / 2



computational domain

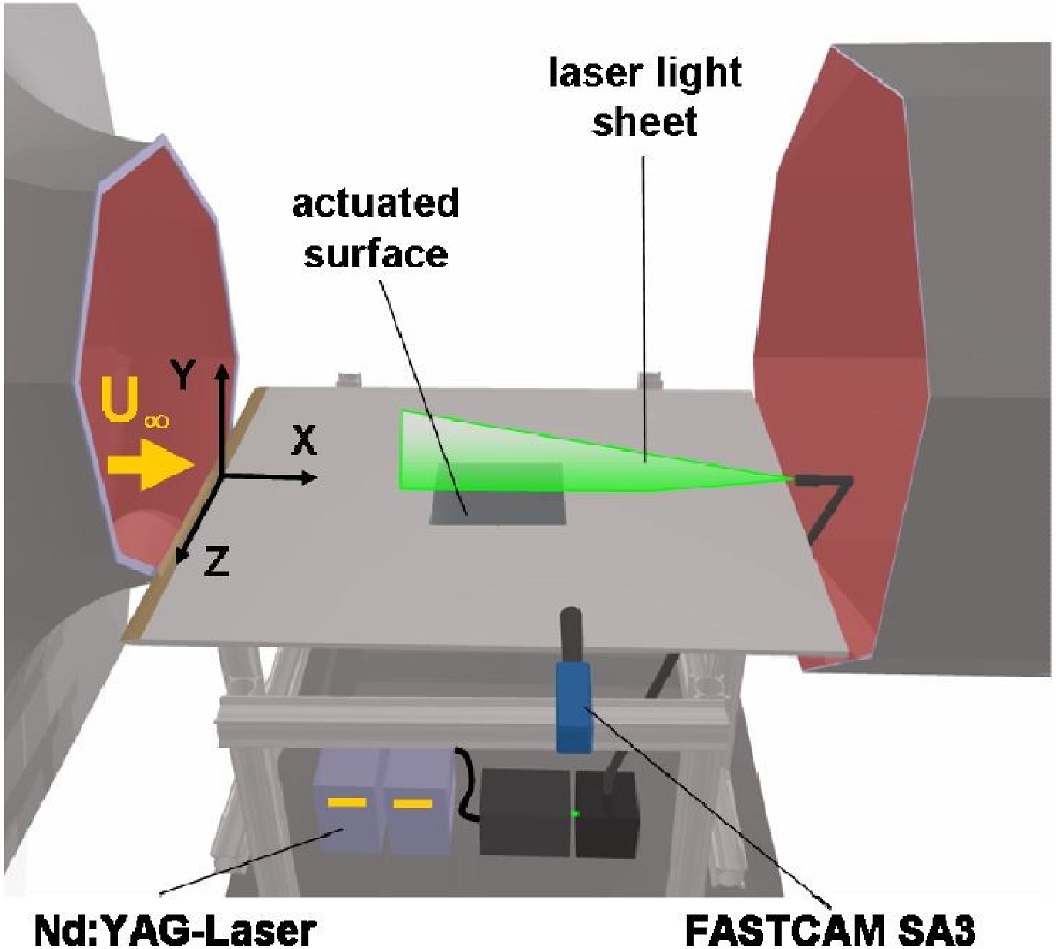
- **generation of a turbulent boundary layer via a rescaling method**
- **periodic in the spanwise direction**
- **sponge layer to damp numerical reflections**
- **no-slip condition at the wall**

Numerical Method / 3



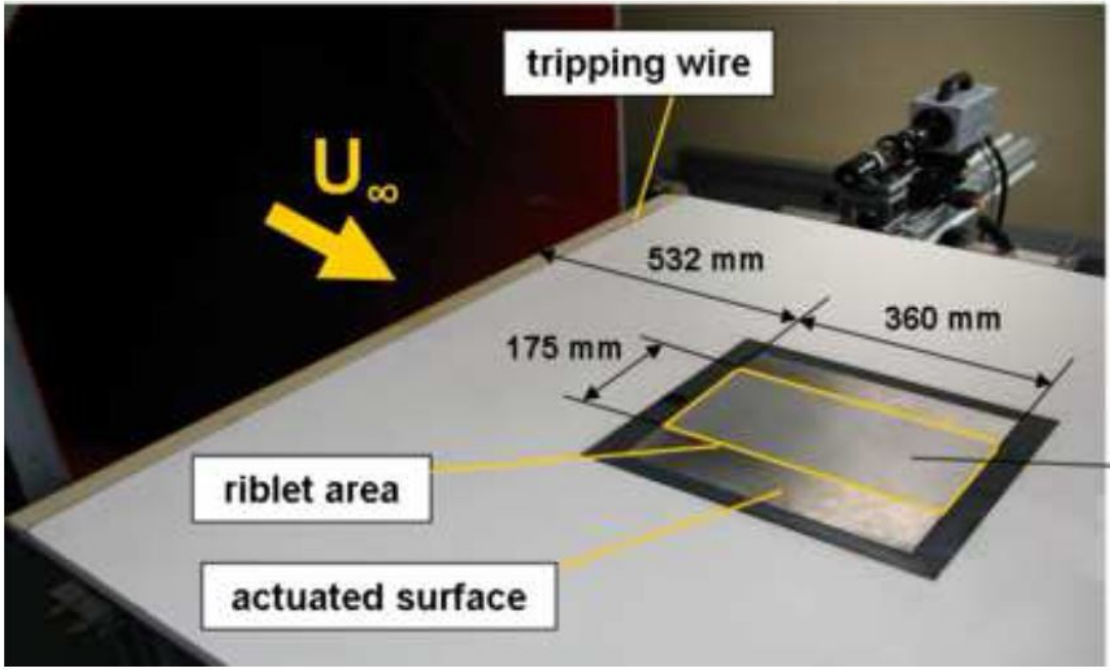
$$y(z,t) = \widehat{y}\,\sin\left(\frac{2\pi}{\lambda_z}z - \frac{2\pi}{T}t\right)$$

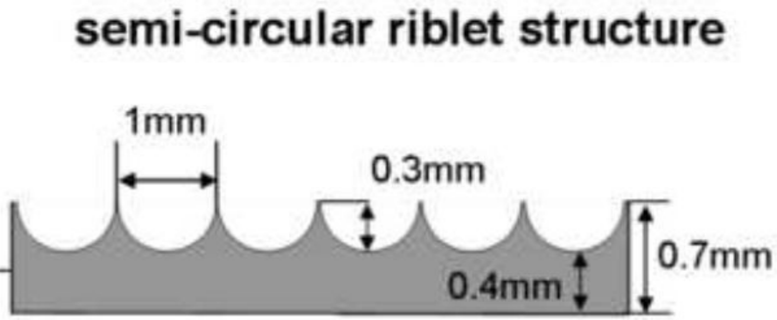
Experimental Method / 1



low-speed wind tunnel, flat plate, actuated surface, PIV and µPTV setup

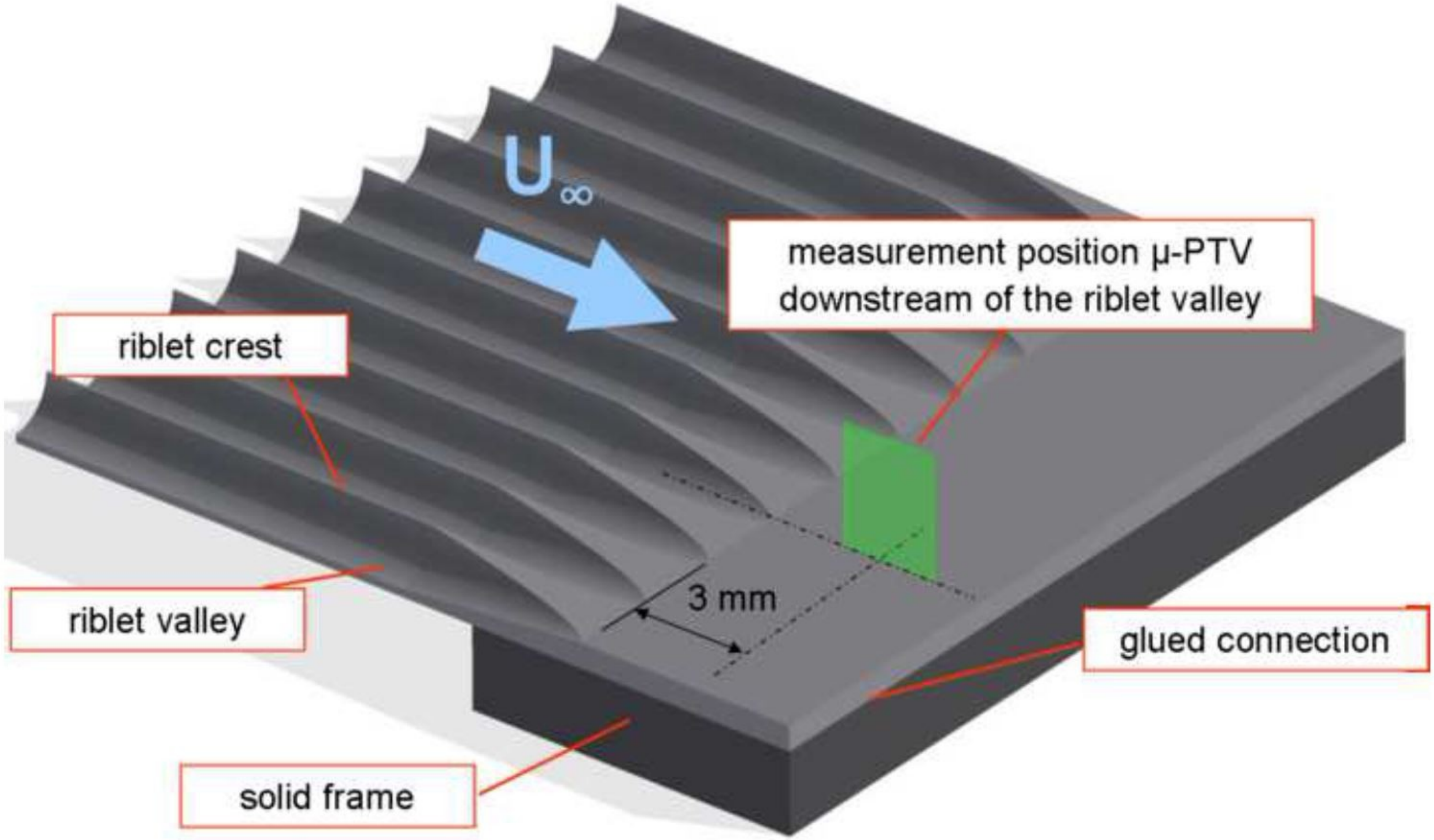
Experimental Method / 2





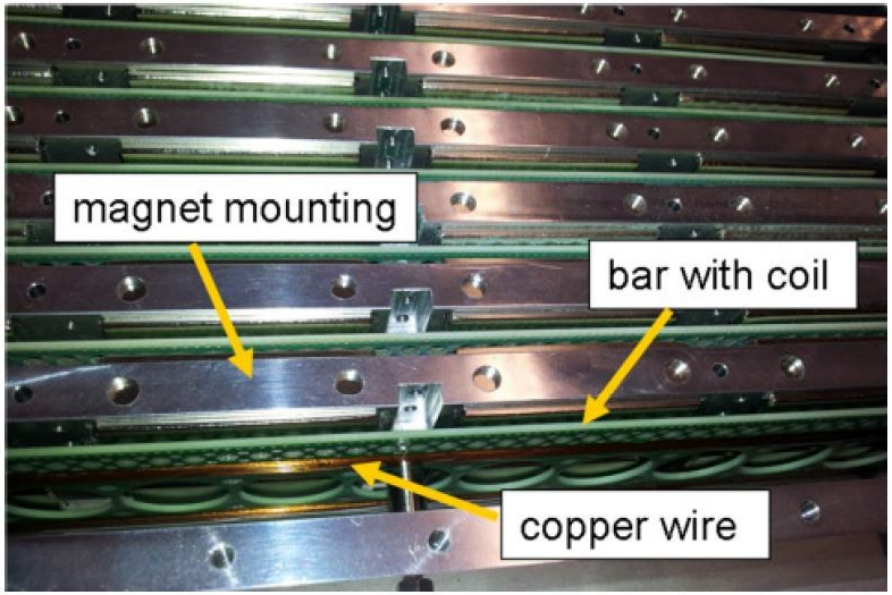
actuated surface plus riblet surface

Experimental Method / 3



transition from riblet to smooth surface and measurement location

Experimental Method / 4



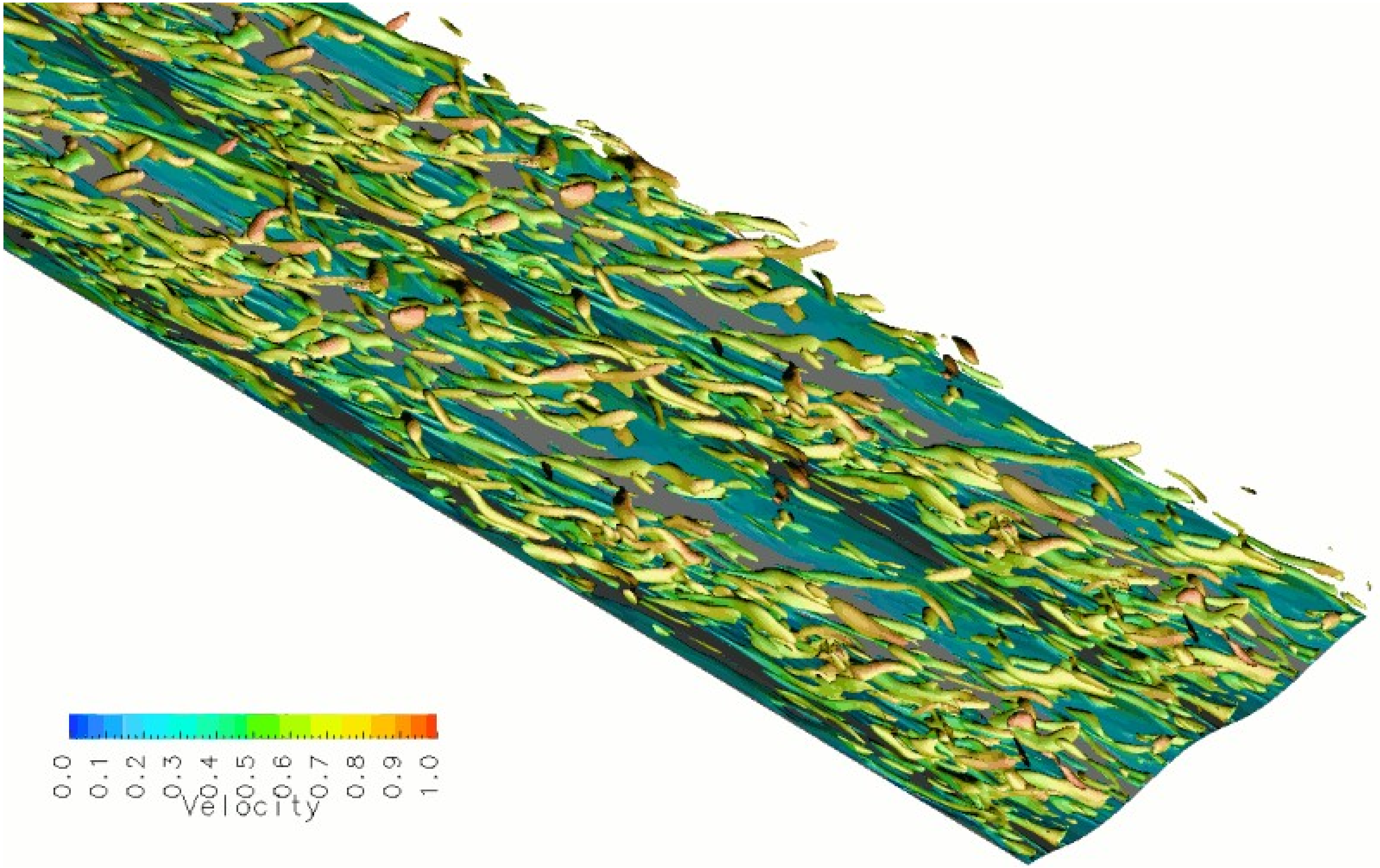
electromagnetic actuators 20mm apart; 10 actuated bars are aligned with the streamwise direction (Kaparaki et al., submitted to *Mechatronics*)

Results: Smooth Surface / 1

Re_θ	A^+	λ^+	C^+	T^+	$Re_{\tau,0}$	A_0^+	λ_0^+	C_0^+
1000	50	500	6.25	80	540	43.5	506	6.03
2000	50	500	6.25	80	906	53.5	536	5.84
5000	50	500	6.25	80	1908	55.8	550	5.84
7000	50	500	6.25	80	2250	69.4	598	5.79

flow parameters, Re_θ = momentum based Reynolds number, Re_τ: friction velocity based Reynolds number, A^+: amplitude, λ^+: wave length, c^+: phase speed, T^+: period

Results: Smooth Surface / 2

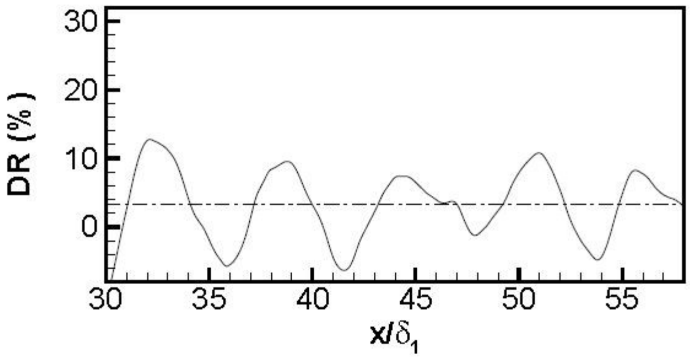


turbulent structures over the actuated surface visualized by λ_2-contours

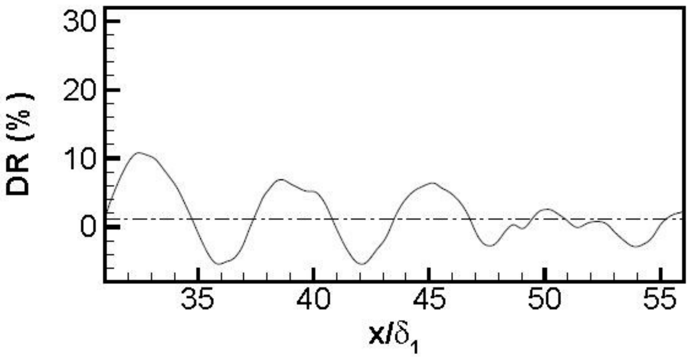
Results: Smooth Surface / 3

DR : ratio of the difference of the non-ac. wss and the ac. wss to the non-ac. wss

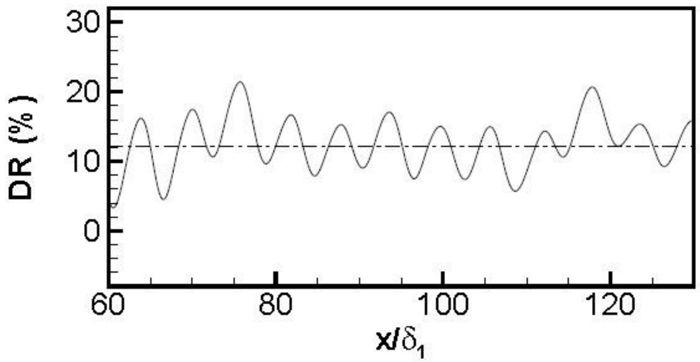
Re_θ = 1000, DR = 12,5%



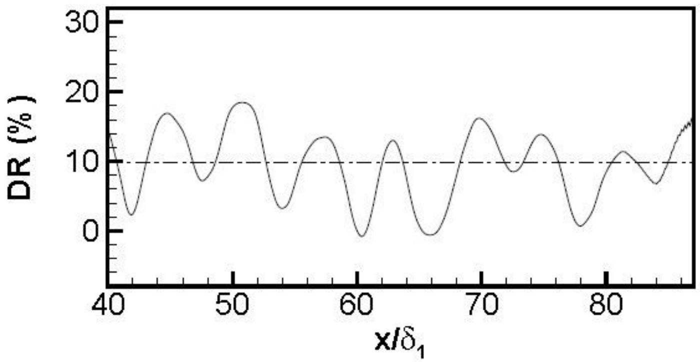
Re_θ = 2000, DR = 9,9%



Re_θ = 5000, DR = 3.3%

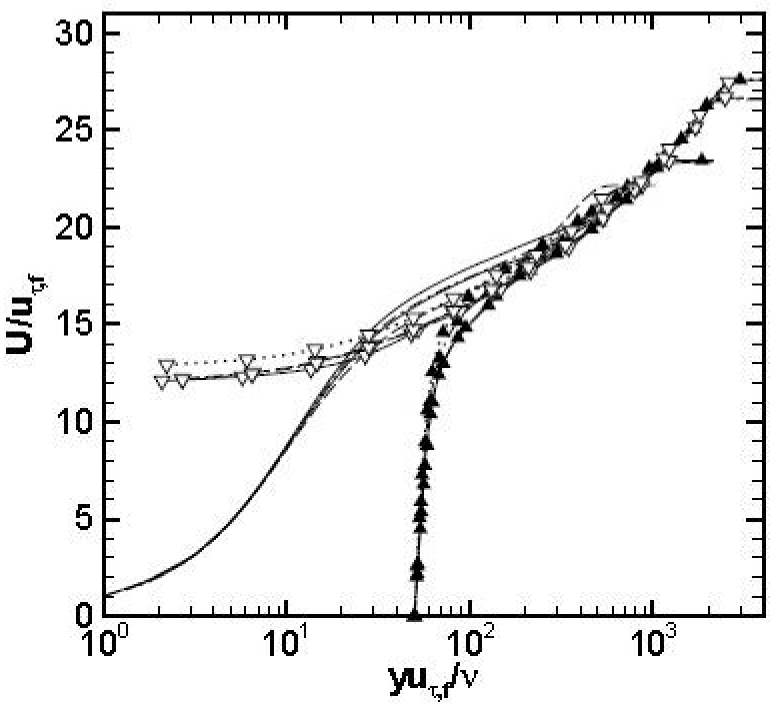


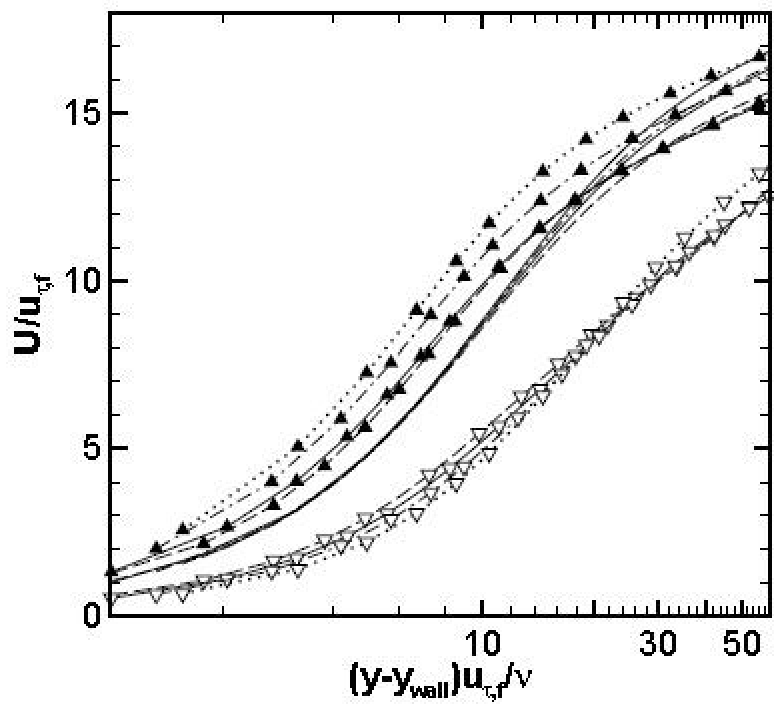
Re_θ = 7000, DR = 1.2%



streamwise distribution of the drag reduction (local and mean value)

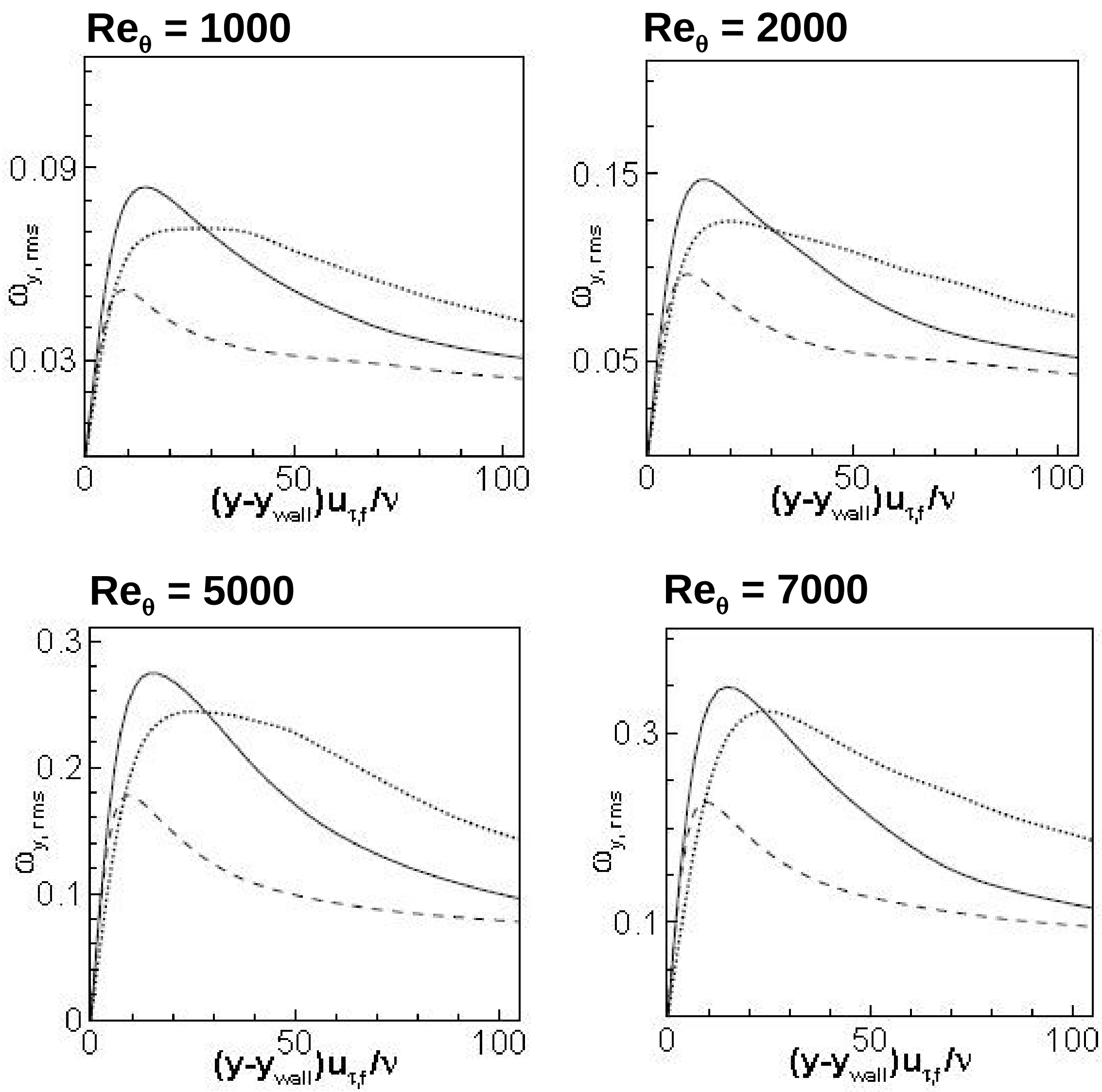
Results: Smooth Surface / 4





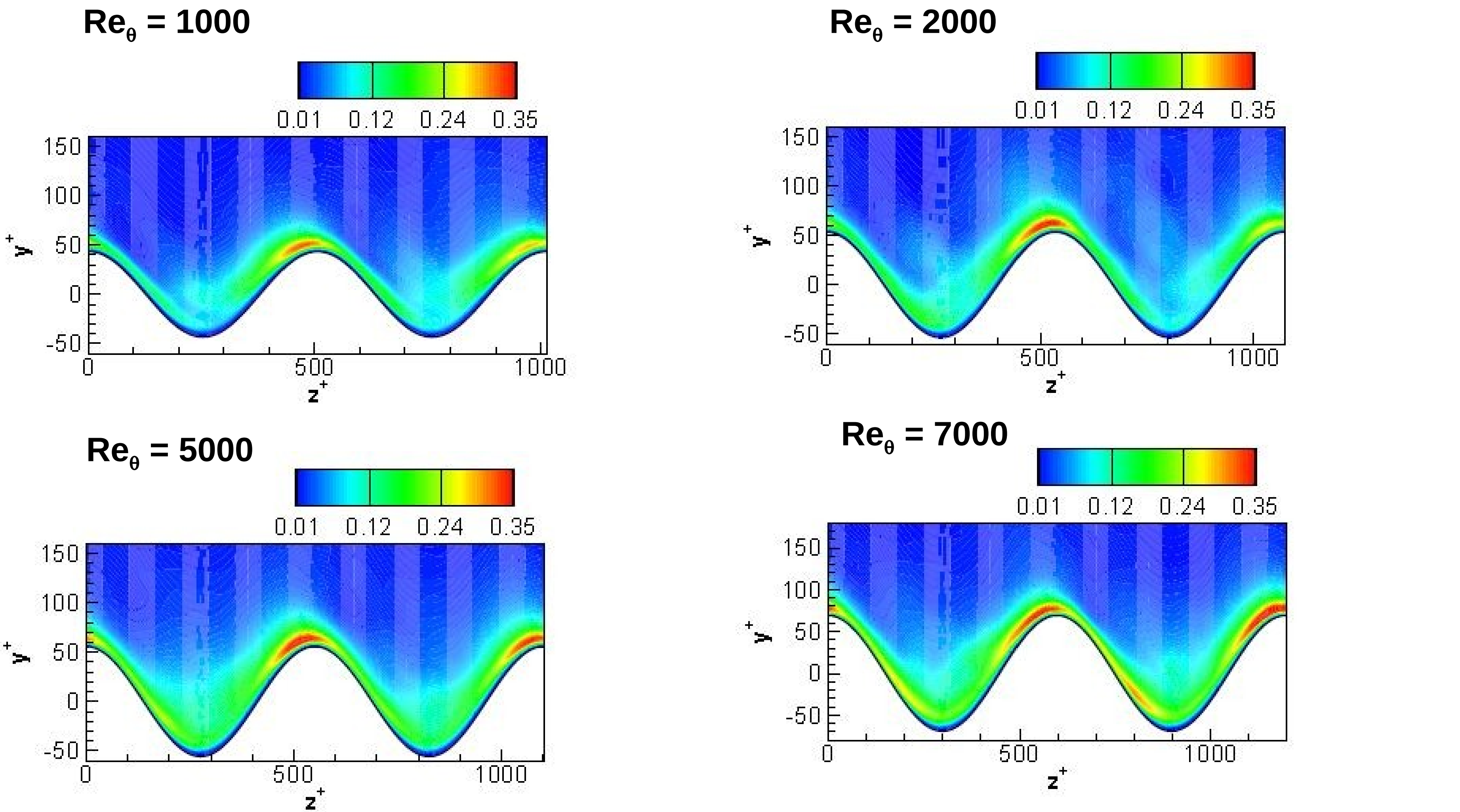
Phase-averaged profiles of the streamwise velocity u, the symbols indicate the crest (▲) and the trough (∇), the non-actuated configurations are denoted by lines at – – – (Re_θ = 1000), ——— (Re_θ = 2000), · – · – (Re_θ = 5000), ·········· (Re_θ = 7000), (left) absolute coordinate, (right) relative wall distance.

Results: Smooth Surface / 5



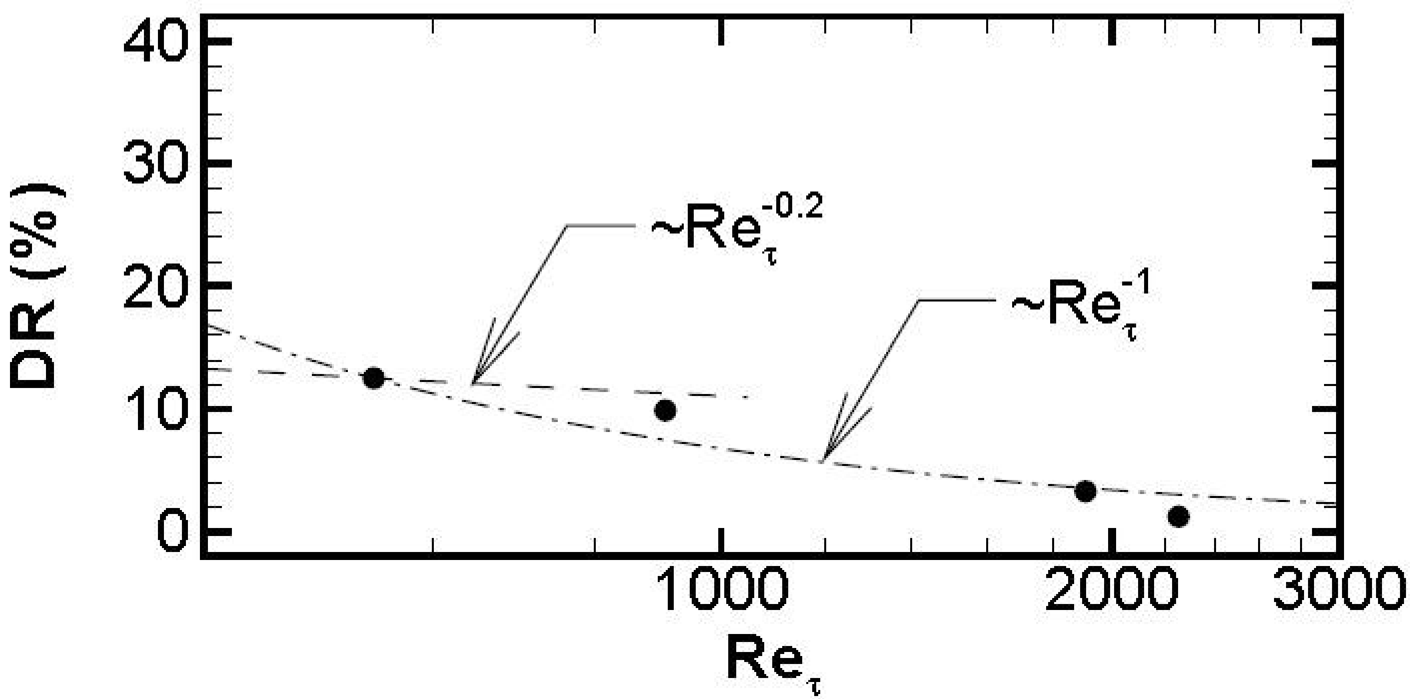
Phase-averaged profiles of the root-mean square values of the wall-normal vorticity fluctuations
(non-actuated wall),
(actuated wall crest),
(actuated wall trough)

Results: Smooth Surface / 6



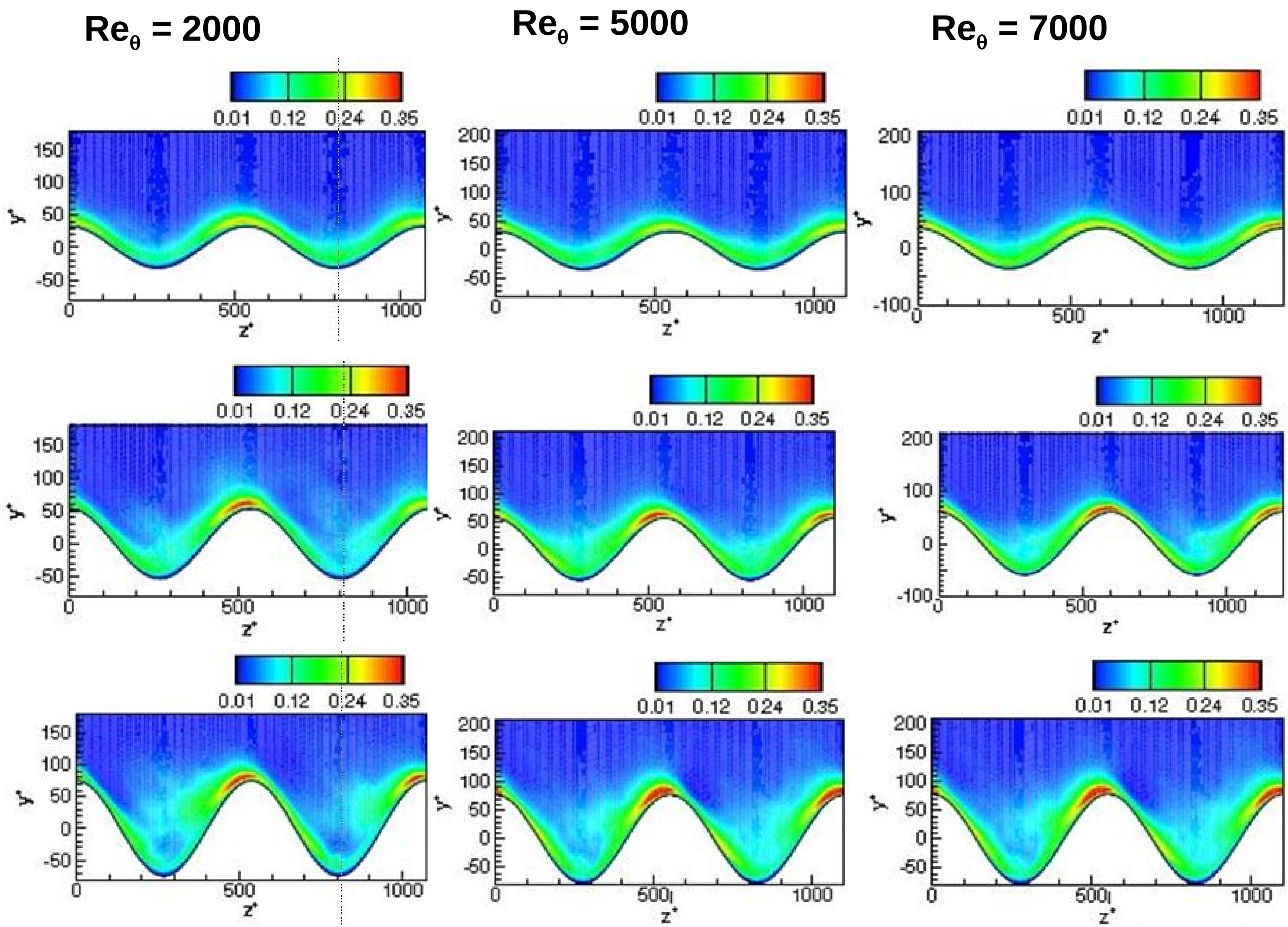
Contours of the phase-averaged production term $P_{ij} = -\overline{u_i' u_j'}\; \partial \overline{u_i} / \partial x_j$

Results: Smooth Surface / 7



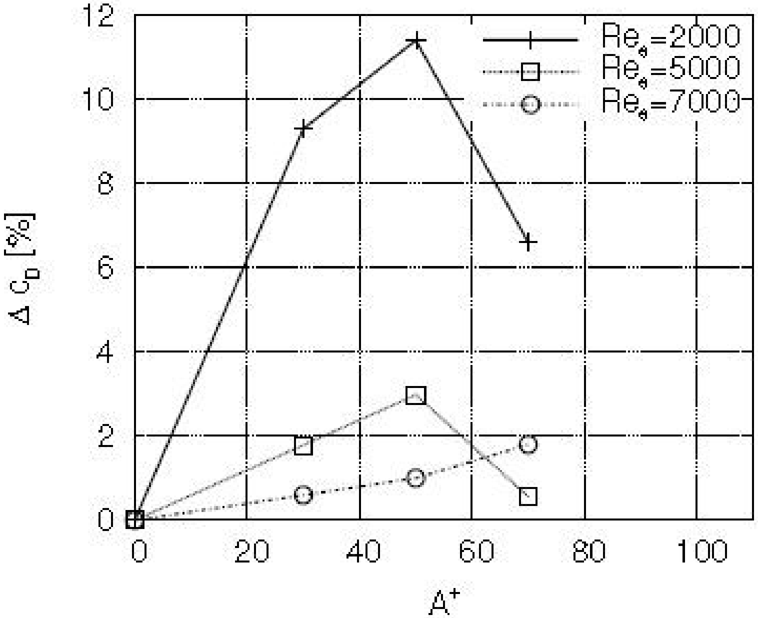
Drag reduction as a function of the Reynolds number based on the friction velocity Re_τ, - - - - turbulent channel flow from [28] for $10^2 \leq Re_\tau \leq 10^3$, - · - · · current flat plate turbulent boundary layer flow $540 \leq Re_\tau \leq 2250$.

Results: Smooth Surface / 8



Contours of the phase-averaged production term $P_k = -\overline{u_i' u_j'}\ \partial \overline{u_i} / \partial x_j$

Results: Smooth Surface / 9

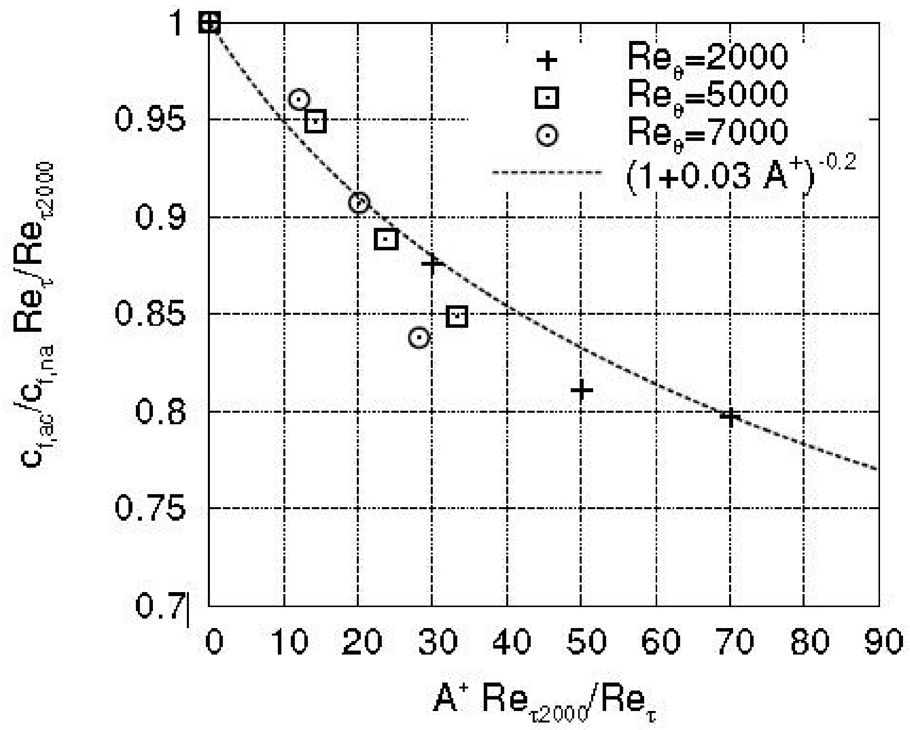


Reynolds number	A^+	S_{ac}/S_{nc}	$c_{f,ac}/c_{f,na}$	Δc_D [%]
Re_θ=2000	30	1.03451	0.88	9.3
Re_θ=2000	50	1.09204	0.81	11.4
Re_θ=2000	70	1.17120	0.80	6.6
Re_θ=5000	30	1.03467	0.95	1.8
Re_θ=5000	50	1.09246	0.89	3.0
Re_θ=5000	70	1.17197	0.85	0.6
Re_θ=7000	30	1.03464	0.96	0.6
Re_θ=7000	50	1.09240	0.91	1.0
Re_θ=7000	70	1.17185	0.84	1.8

drag reduction DR = Δc_D versus A$^+$

- **+ : Re$_\theta$ = 2000**
- **□ : Re$_\theta$ = 5000**
- **○ : Re$_\theta$ = 7000**

Results: Smooth Surface / 10



Friction coefficient ratio $c_{f,ac}/c_{f,na}$ scaled by $Re_\tau/Re_{\tau,2000}$ versus A⁺ scaled by $Re_{\tau,2000}/Re_\tau$

+ : Re_θ = 2000 □ : Re_θ = 5000 ○ : Re_θ = 7000

Result: Riblet Surface / 1

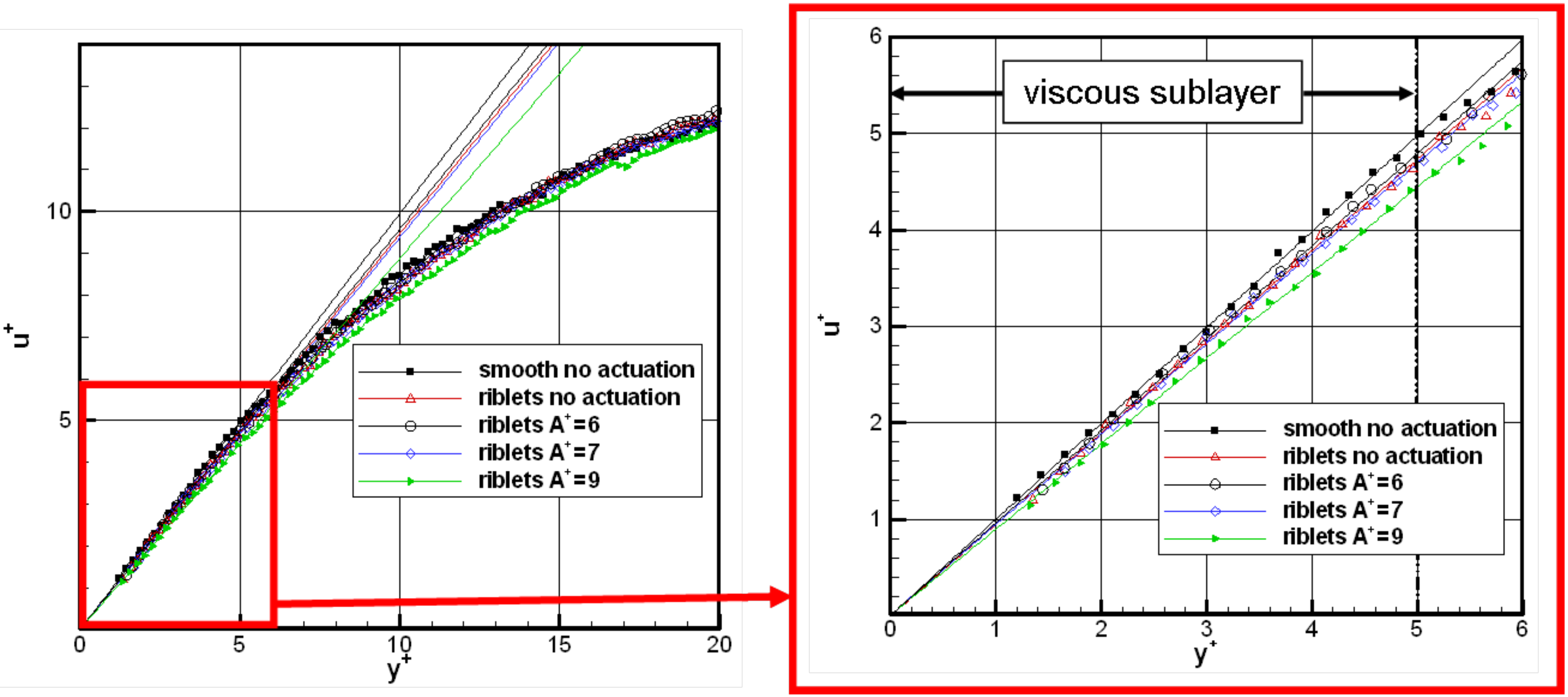
test parameter	parameter range	normalized parameter range
velocity	$U_\infty = 8$ m/s, 16 m/s	$Re_\theta = 1200, 2080$
excitation frequency	$f = 81$ Hz	$T^+ = 110, 380$
wavelength	$\lambda = 160$ mm	$\lambda^+ = 3862, 7170$
amplitude	$A = 0.25$ mm, 0.3 mm, 0.375 mm	$6 \leq A^+ \leq 17$
riblet spacing	$s = 1$ mm	$24 \leq s^+ \leq 45$
riblet height	$h = 0.3$ mm	$7 \leq h^+ \leq 13$

Re_θ	s^+	h^+	T^+	λ^+	A^+	DR [%]
1200	24	7	110	3862	0	4.7
1200	24	7	110	3862	6	4.1
1200	24	7	110	3862	7	5.8
1200	24	7	110	3862	9	9.4
2080	45	13	380	7170	0	0.7
2080	45	13	380	7170	11	0.9
2080	45	13	380	7170	14	2.2
2080	45	13	380	7170	17	2.7

flow parameters, riblet parameters, wave parameters

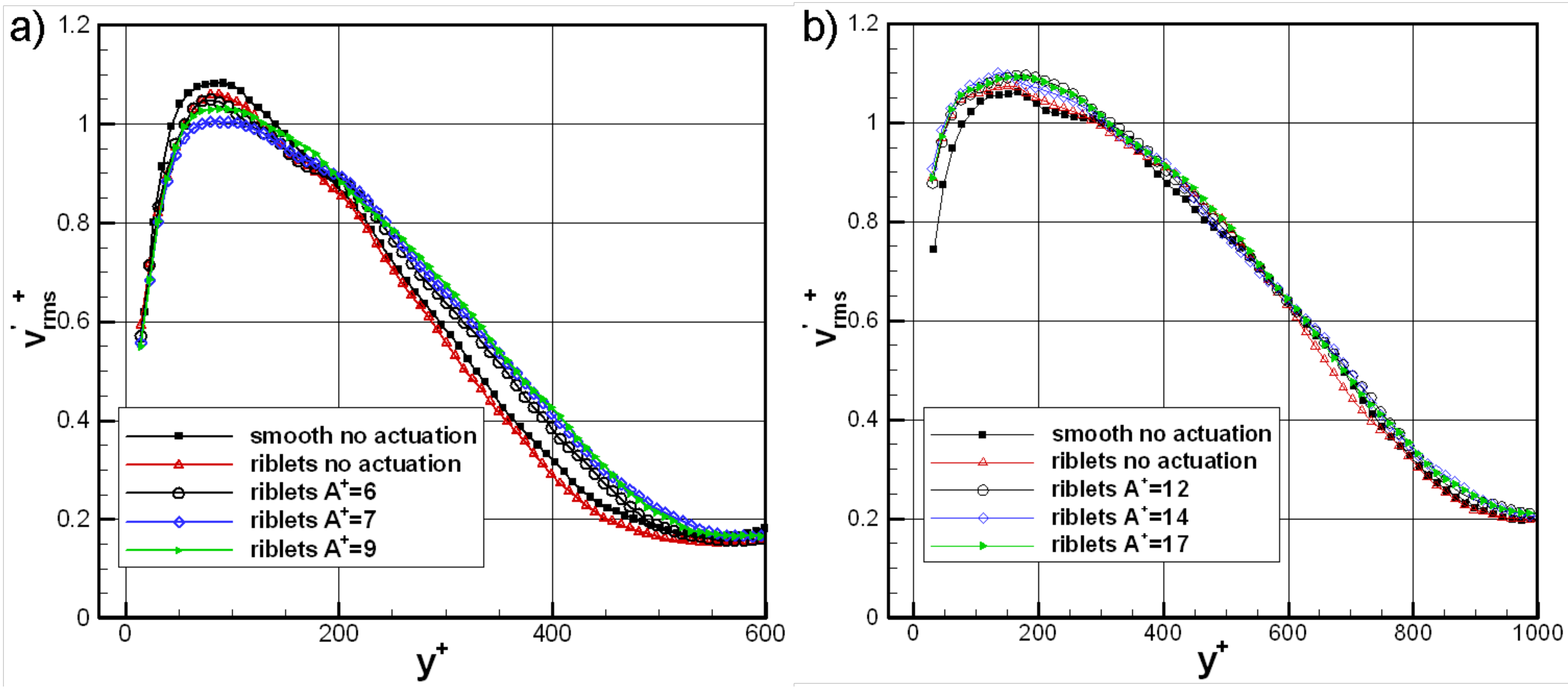
$$A^+ = A u_\tau / \nu \, , \lambda^+ = y \, u_\tau / \nu \, , T^+ = u_\tau^2 / (f \cdot \nu)$$

Result: Riblet Surface / 2



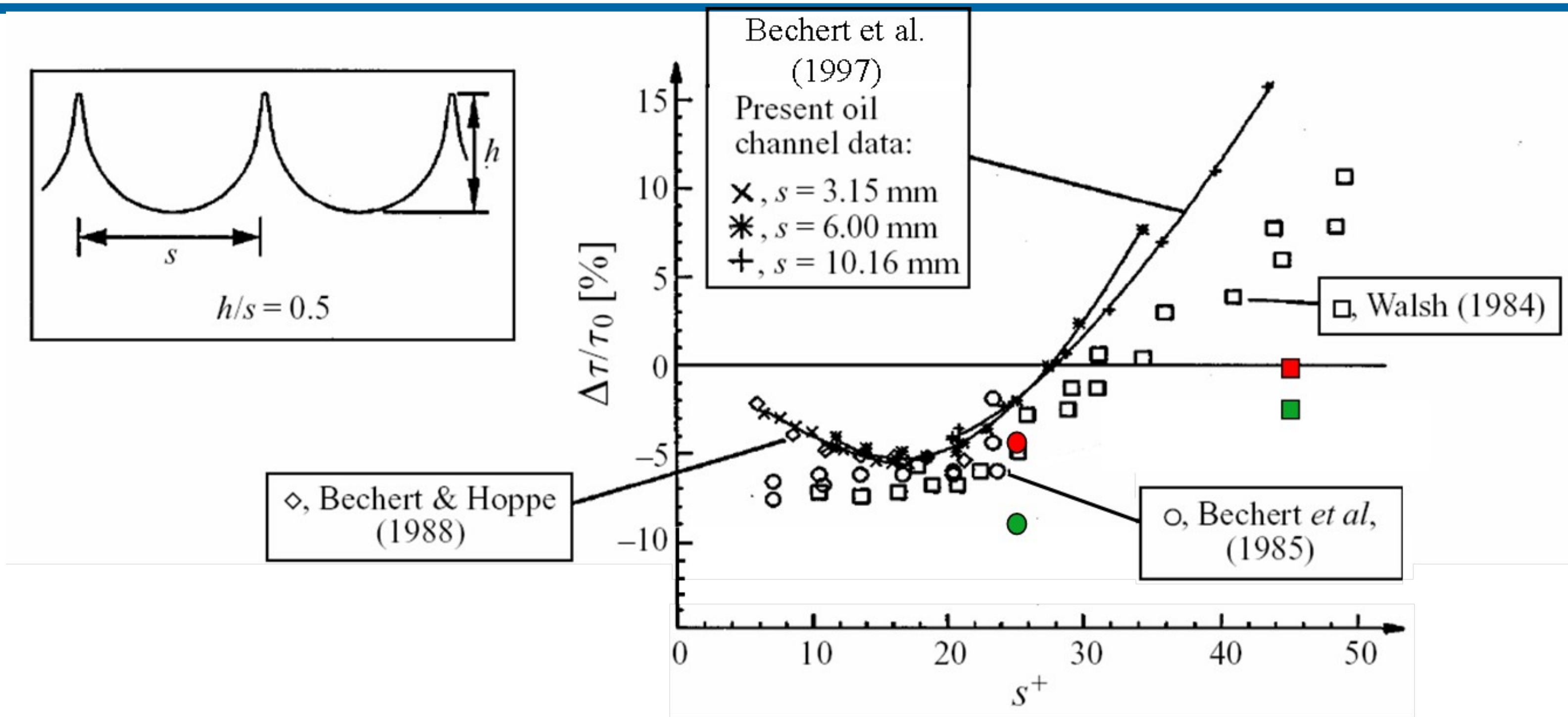
comparison of mean streamwise velocity distribution in the viscous sublayer

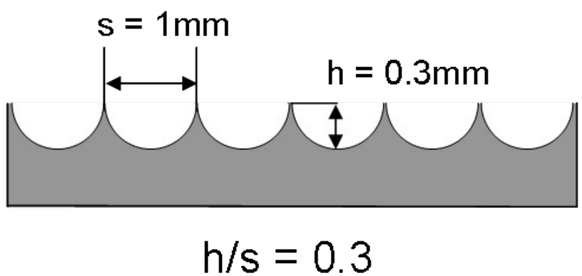
Result: Riblet Surface / 3



rms-value of the wall-normal velocity fluctuations Re_θ = 1200 (left) and Re_θ = 2080 (right)

Results: Riblet Surface / 4





- Re_θ = 1200 no actuation
- Re_θ = 2080 no actuation
- Re_θ = 1200 $A^+ = 9$
- Re_θ = 2080 $A^+ = 17$

drag reduction $DR = \Delta\tau/\tau_0$ of a riblet structure with and without actuation

Conclusion / 1

- impact of spanwise transversal surface waves on drag reduction was experimentally and numerically analyzed for turbulent flat plate boundary layers
- the investigation considered smooth and riblet surfaces
- new actuators were developed to excite the aluminum surface (Kaparaki et al., submitted to *Mechatronics*)
- parameter range: $1000 \leq Re_\theta \leq 7000$, $0 \leq A^+ \leq 70$, $\lambda^+ =$ const., $T^+ =$ const, $0 \leq s^+ \leq 45$

Conclusion / 2

- at varying Re_θ and λ^+ = const., T^+ = const, A^+ = const. DR reduces at higher Re_τ $(\sim Re_\tau^{-1})$
- at varying A^+ and λ^+ = const, T^+ = const, Re_θ = const, DR possesses a maximum due to the increased surface area
- the riblet surface enhances the drag reducing effect
- the transversal wall motion reduces the dimensional sensitivity of the riblets to the flow parameters