Drag Reduction via Transversal Wave Motions

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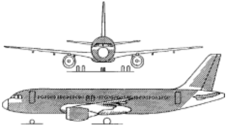
What is the objective:

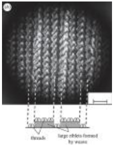
Local skin friction reduction or integral drag reduction?

Drag reduction

Riblets have proven their drag reducing potential in real life applications [1,2]



Airbus A320 with Riblet surface (taken from [1]).



Riblet geometry on Speedo Fastskin swimsuit (taken from [2]).

Can **active drag reduction methods** reach the same stage or even be combined with **riblets**?

➡ Key necessities for robust active drag reduction:

- Integration into current aircraft design
- Low power input
- Small geometry changes
- Reduction of the **integrated drag**

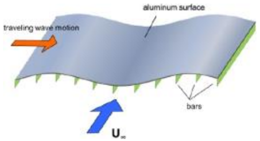
[1] Szodruch (1991, AIAA Paper)

[2] Dean and Barat (2010, Philos. Trans. R. Soc. London, Ser. A)

Spanwise traveling surface waves

The concept of spanwise traveling transversal surface waves offers some advantages for real applications:

- Tested in wind-tunnel experiments using actuated aluminum sheets [3].
- Mechanism allows drag reduction over large surface areas without adding major disturbances to the flow.



- Validated by experimental and numerical investigations[4] for drag reduction in **turbulent boundary layers.**
- No limitation on the surface type, can be combined with a ribbed surface $\Rightarrow$ **hybrid method.**

[3] Meysonnat *et al.* (2016, Eur. J. Mech. B. Fluids)

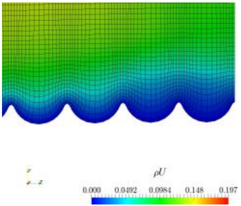
[4] Koh *et al.* (2015, Comput. Fluids)

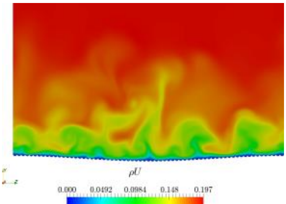
Numerical Method

A node-centered finite volume method to solve the unsteady compressible viscous Navier-Stokes equations

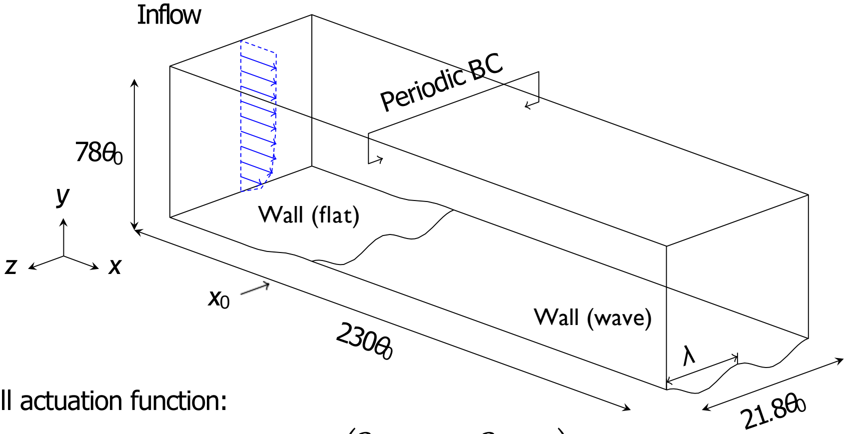
- Structured curvilinear meshes.
- Convective flux discretization by the Advection Upstream Splitting Method (AUSM)
- Implicit LES (MILES).
- Temporal integration by a linear 5-stage Runge-Kutta scheme.
- Moving grid method using ALE formulation and Geometry Conservation Law (GCL).
- Synthetic turbulence generation method which efficiently reduces the LES transition lengths.

⇒ **Unique approach to accurately resolve the riblet structure on moving meshes in turbulent boundary layer flow.**





General Testcase Setup



Wall actuation function:

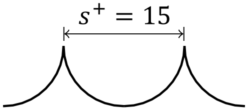
$$y^+\Big|_{wall}(z^+, t^+) = A^+\cos\left(\frac{2\pi}{\lambda^+}z^+ + \frac{2\pi}{T^+}t^+\right)$$

General Testcase Setup

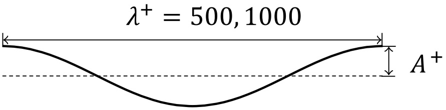
The investigated cases are combinations of:

- smooth/ribbed surface
- non-actuated/actuated wall
- actuation amplitudes $A^+ = 10 - 70$

Parameter	Value
Ma_∞	0.2
Re_θ	1,000
Δx^+	12
Δy^+	0.85
Δz^+	0.9, 3.75
n_{nodes}	$148 \cdot 10^6$
$s^+_{riblets}$	15
$A^+ = \lambda u_\tau/\nu$	$0 - 70$
$\lambda^+ = \lambda u_\tau/\nu$	500, 1000
$c^+ = \lambda^+/T^+$	12.5, 25



Riblet spacing

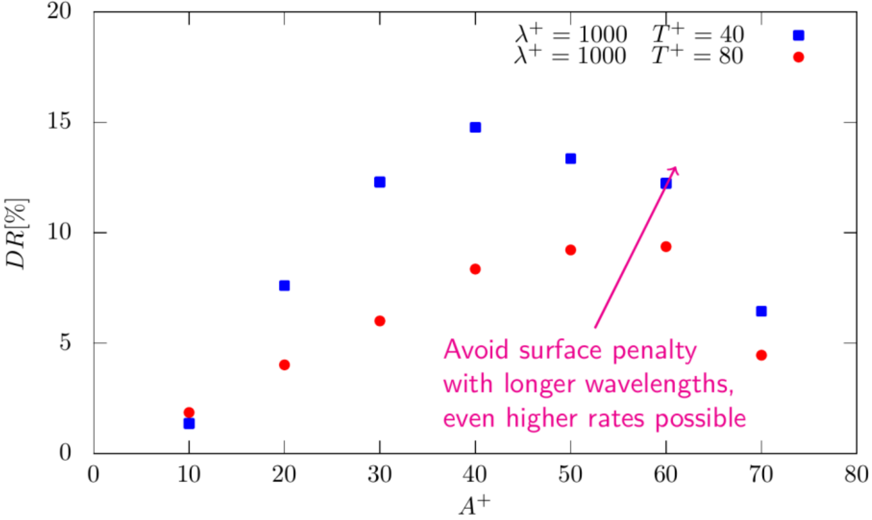


Wave parameters

Actuated smooth flat plate

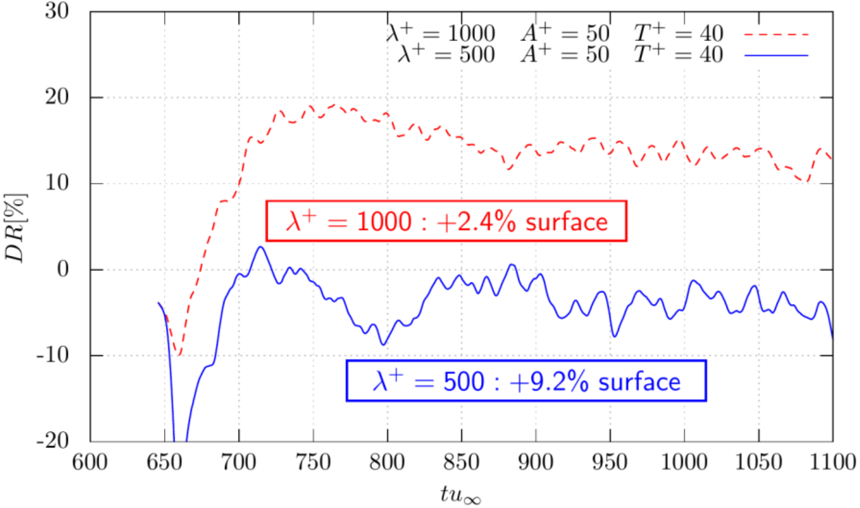
Drag reduction depending on the amplitude

Highest achievable integral drag reduction rate is a tradeoff between actuation strength and increase of the wetted surface ($f\ (\lambda,\ A)$).



Drag reduction depending on the wavelength

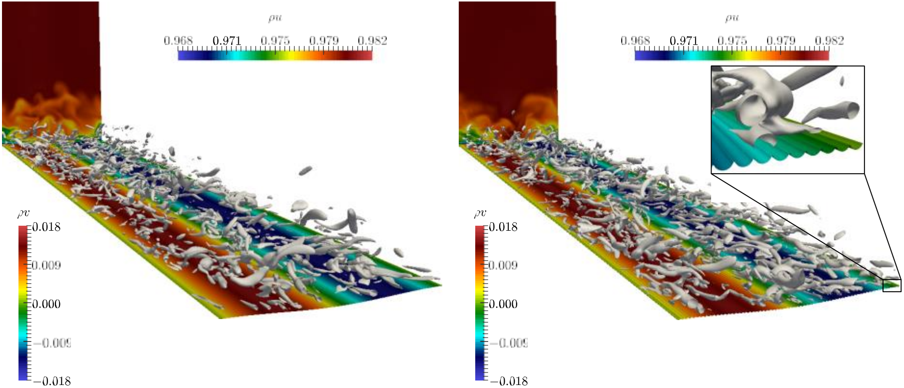
Long wavelengths are not only favorable in a drag reduction sense, but also for a technical application to avoid strong bending.



Actuated ribbed surface

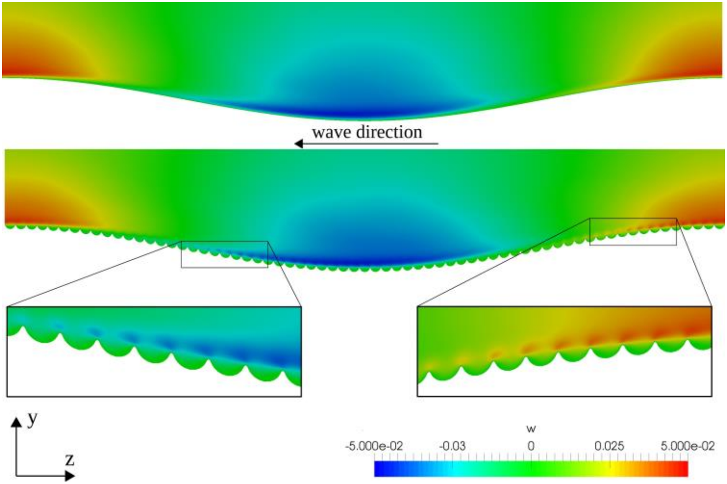
Turbulent Flow Field above the Traveling Wave

Vortical structures visualized by the Q-criterion ($Q = 0.02$).



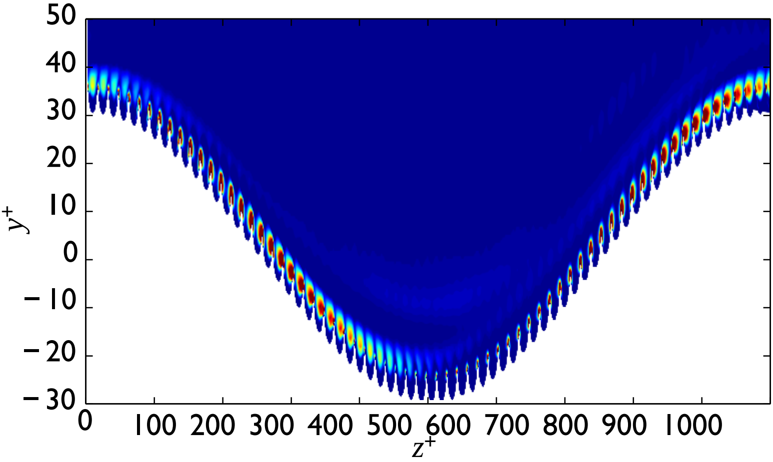
(a) Smooth surface actuated $A^+ = 10$ (b) Riblet surface actuated $A^+ = 10$

Secondary Flow Field



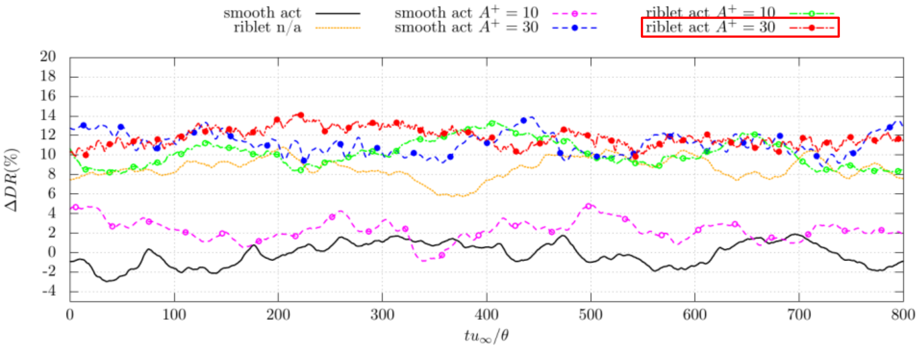
Secondary flow field of the spanwise velocity component in the $y - z$ plane for the actuated smooth setup (top) and the actuated riblet setup (bottom).

Streamwise Vorticity Fluctuations



Contours of the root-mean-square streamwise vorticity intensity.

Drag Reduction over Time

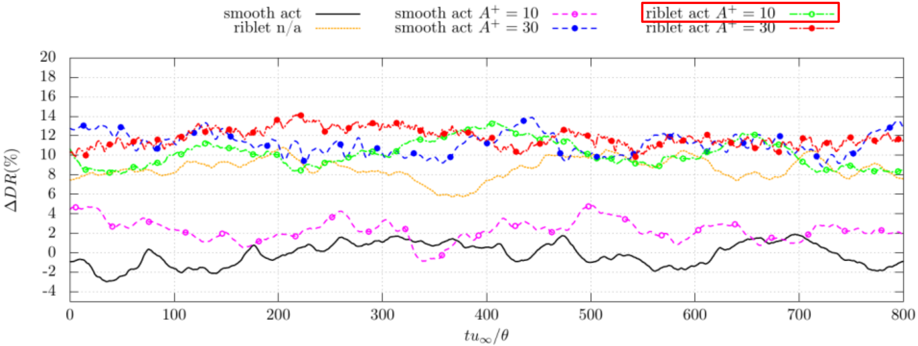


$$\Delta DR = \frac{\int_{A,na} \tau_{w,na} dA - \int_{A,ac} \tau_{w,ac} dA}{\int_{A,na} \tau_{w,na} dA}$$

Case	$\Delta\ DR[\%]$
riblet n/a	8.9
smooth act $A^+ = 10$	2.3
smooth act $A^+ = 30$	11.0
riblet act $A^+ = 10$	10.0
riblet act $A^+ = 30$	11.6

+ 0.6

Drag Reduction over Time



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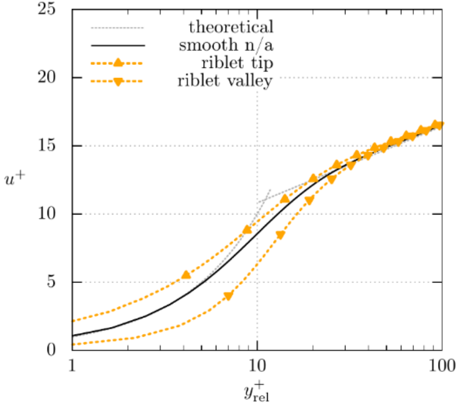
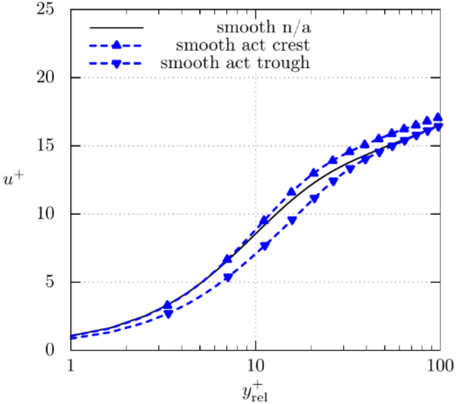
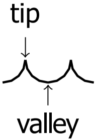
riblet act $A^+ = 30$	11.6

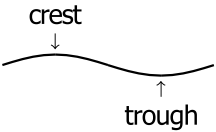
+ 1.1

Velocity Distribution Non-Combined Methods

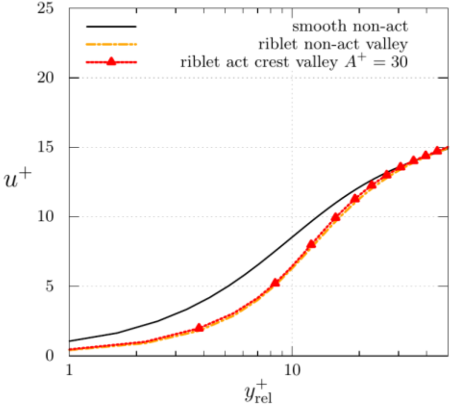


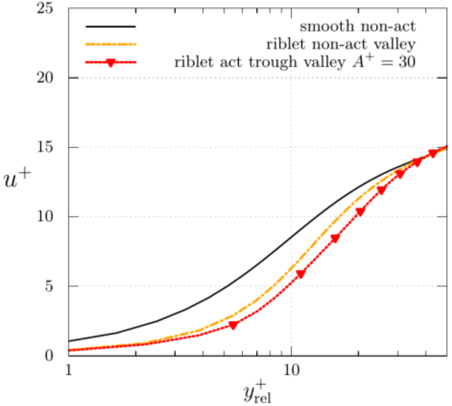


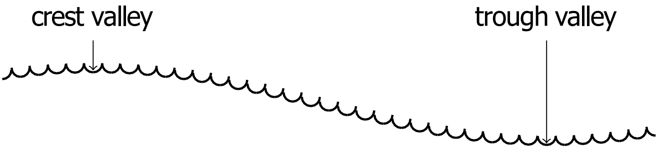




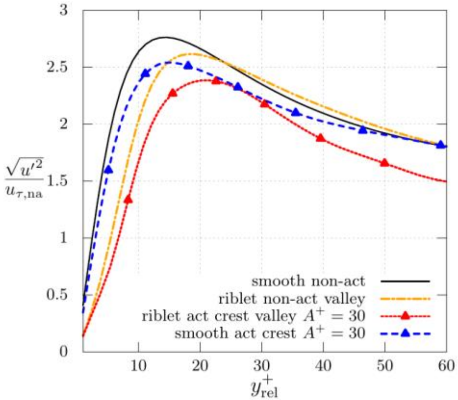
Velocity Distribution Combined Method

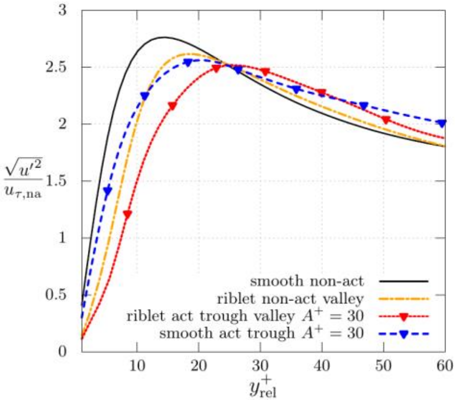


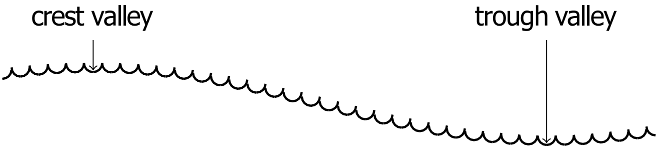




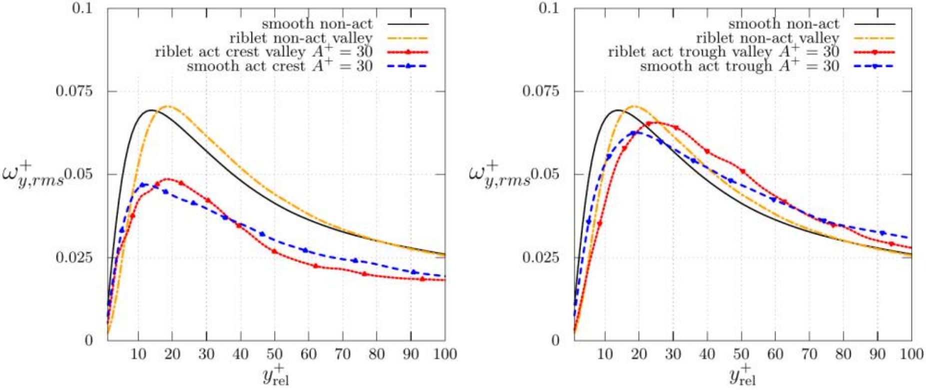
Streamwise Reynolds Stresses

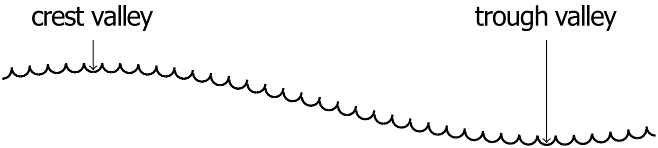






Wall-normal Vorticity Fluctuations





Conclusion

- Focus on integral drag reduction with technically feasible methods.
- Long wavelengths are favorable for high drag reduction and also in the technical application sense.
- Drag reduction can be increased by a combination of passive and active methods.
- No simple superposition of the drag reduction rates.
- Drag reduction is more robust with hybrid method.

References

1 Dean, Brian & Bhushan, Bharat 2010 Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **368** (1929), 4775–4806.

2 J., Szodruch 1991 Viscous drag reduction on transport aircraft. In *29th Aerospace Sciences Meeting* . American Institute of Aeronautics and Astronautics.

3 Koh, S.R., Meysonnat, P., Statnikov, V., Meinke, M. & Schröder, W. 2015 Dependence of turbulent wall-shear stress on the amplitude of spanwise transversal surface waves. *Computers & Fluids* **119**, 261–275.

4 Meysonnat, P. S., Roggenkamp, D., Li, W., Roidl, B. & Schröder, W. 2016 Experimental and numerical investigation of transversal traveling surface waves for drag reduction. *European Journal of Mechanics - B/Fluids* **55**, 313–323.