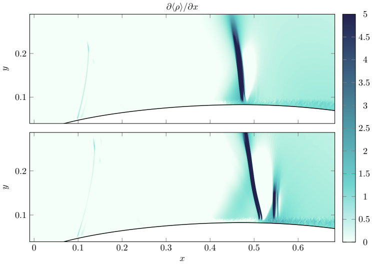
Spanwise forcing for drag reduction

Recent progresses at PoliMI:
applications and understanding

Maurizio Quadrio, Politecnico di Milano

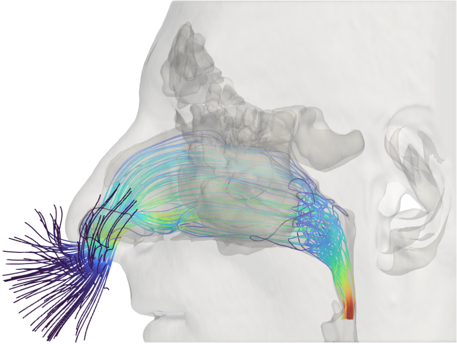
HITSZ, Oct 9 2023



A few words on another research topic

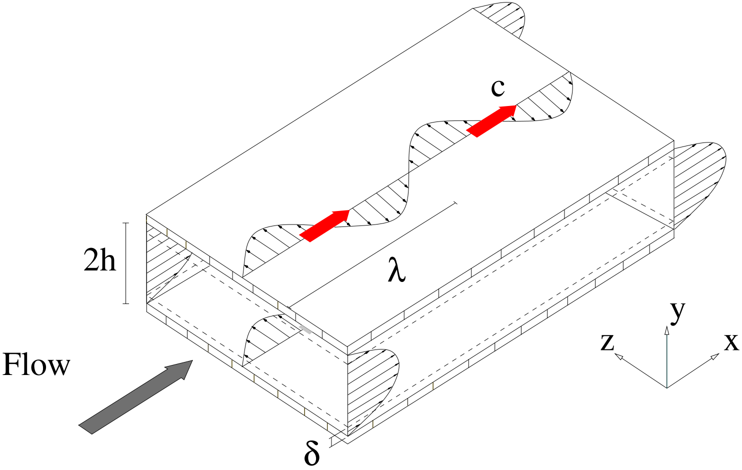
The flow in the human nose

- Highly multi-disciplinary topic
- Huge relevance, little research
- Large room for improvement



A primer on spanwise wall forcing for friction drag reduction

The streamwise-traveling waves

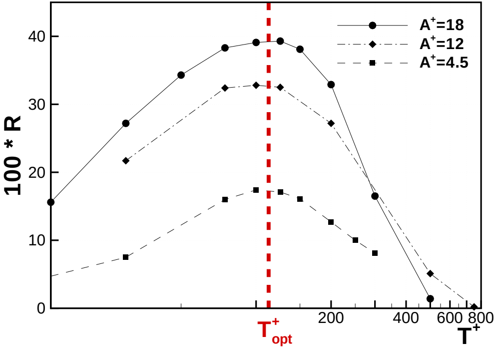


Quadrio, Ricco & Viotti, JFM 2009

The original idea: spanwise wall oscillation

$$\boxed{w(x, y = 0, z, t) = A \sin(\omega t)}$$

- Large reductions of turbulent friction
- Tiny net energy savings
- Unpractical



Quadrio & Ricco, JFM 2004

The traveling waves: a natural extension

Purely temporal forcing
The oscillating wall:

$$\boxed{w = A \sin\left(\omega t\right)}$$

Infinite phase speed

Purely spatial forcing
The steady waves:

$$\boxed{w = A \sin\left(\kappa x\right)}$$

Zero phase speed

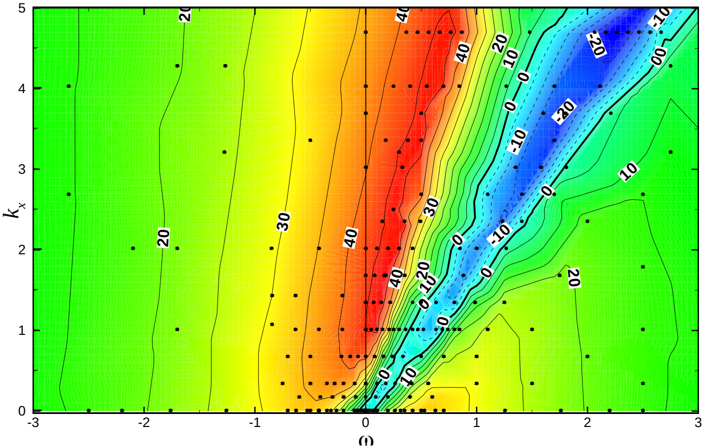
Combined space-time forcing

The traveling waves:

$$\boxed{w = A \sin\left(\kappa x - \omega t\right)}$$

Finite phase speed $c = \omega / \kappa$

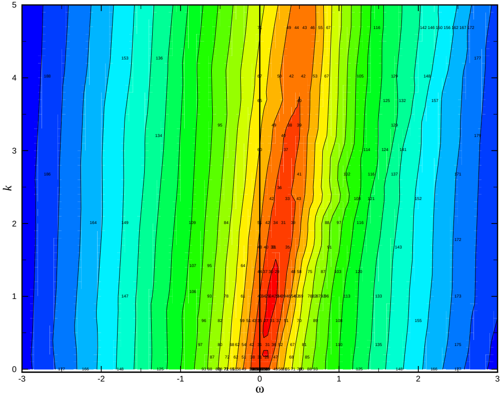
Results from DNS (plane channel)



Quadrio et al JFM 2009

How much power to generate the waves?

- Map of P_{in} is similar to map of R!
- S and G may get very high

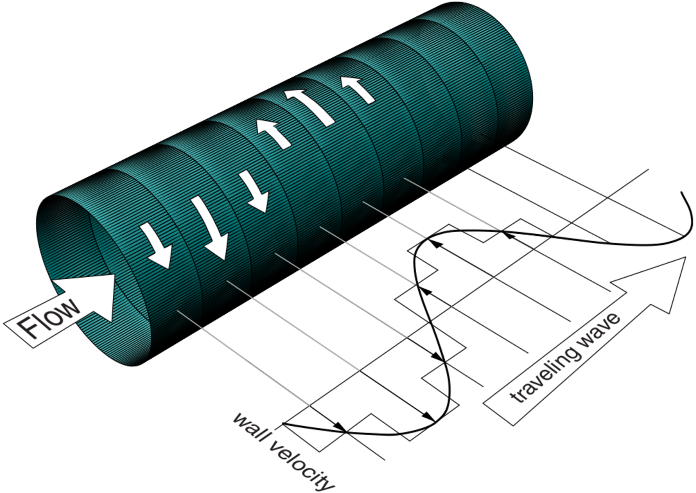


Experimental verification

- Cylindrical pipe
- Friction is measured through pressure drop
- Spanwise wall velocity: wall movement
- Temporal variation: unsteady wall movement
- Spatial variation: the pipe is sliced into thin, independently-movable axial segments

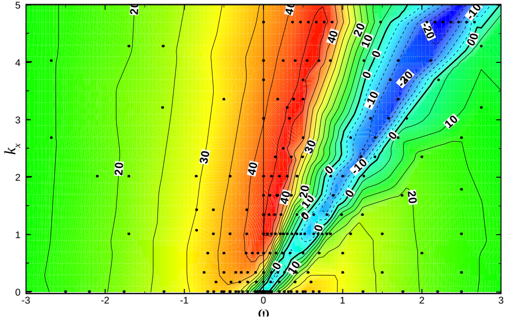
Auteri et al PoF 2010

The concept



We have answers to several questions, but ...

- Performance



Quadrio et al JFM09

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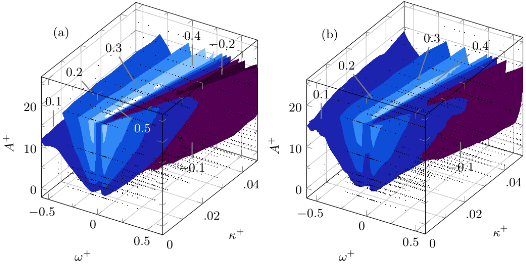
- Reynolds number



Quadrio & Gatti JFM16

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- Compressibility

Gattere et al. JFM submitted

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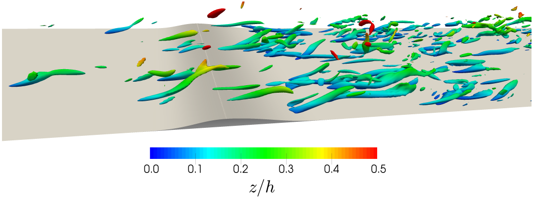
- Performance
- Reynolds number
- Compressibility
- Complex geometries



Banchetti et al JFM20

We have answers to several questions, but ...

- Performance
- Reynolds number
- Compressibility
- Complex geometries
- Working mechanism

- Several studies and reviews
- Statistics are either unchanged or consequence of drag reduction
- No convincing explanation for the drag reduction mechanism
- The mechanism should be known before searching for an actuator

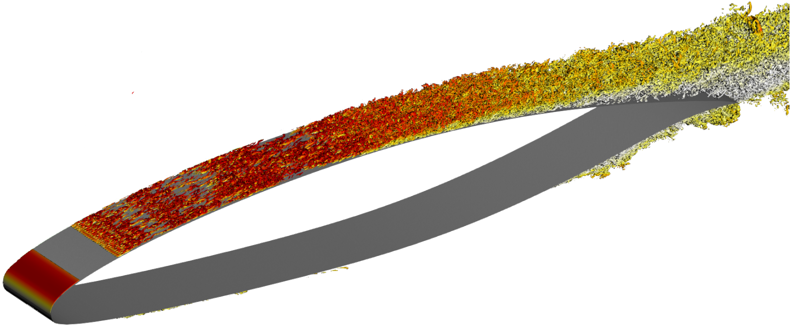
Spanwise forcing on complex geometries

A simple question for the drag reduction community

- Skin-friction drag reduction (DR) is often studied in simple geometries
- For a complex body, skin-friction DR should be extrapolated to total DR
- The standard answer is: in proportion!

Turbulent flow over a transonic airfoil

- Direct Numerical Simulation (up to 1.8 billions cells)
- Supercritical V2C airfoil
- $Re_\infty = 3 \times 10^5$, $M_\infty = 0.7$, $\alpha = 4^\circ$
- Control by spanwise forcing (steady StTW)
- Only a portion of the suction side is controlled



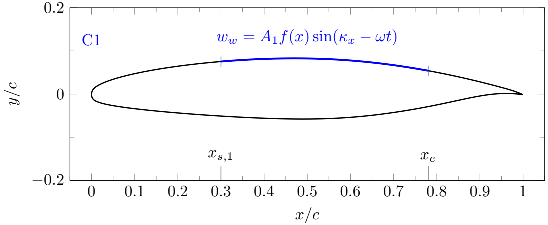
Two control layouts

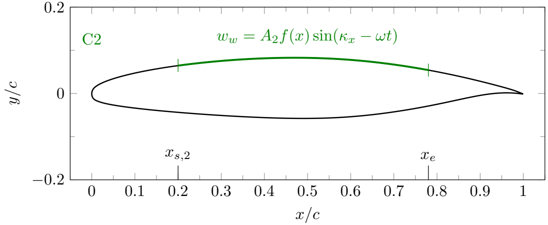
For C1:

- $A_1 = 0.5$, $\omega = 11.3$, $\kappa_x = 161$
- $x_{s,1} = 0.3c$, $x_{e,1} = 0.78c$

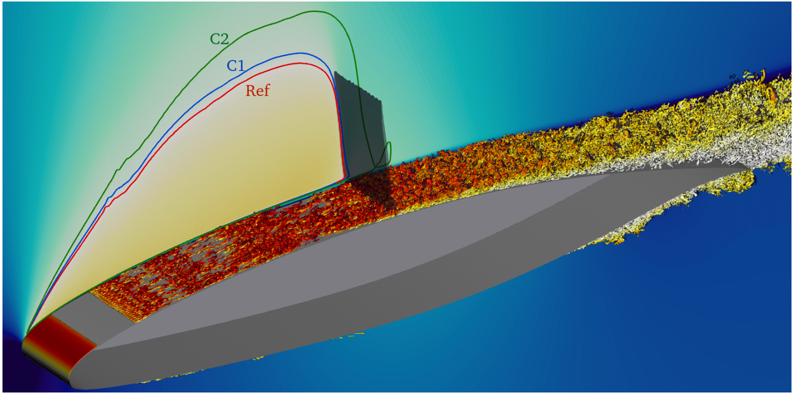
For C2:

- $A_2 = 0.68$, $\omega = 11.3$, $\kappa_x = 161$
- $x_{s,2} = 0.2c$, $x_{e,2} = 0.78c$



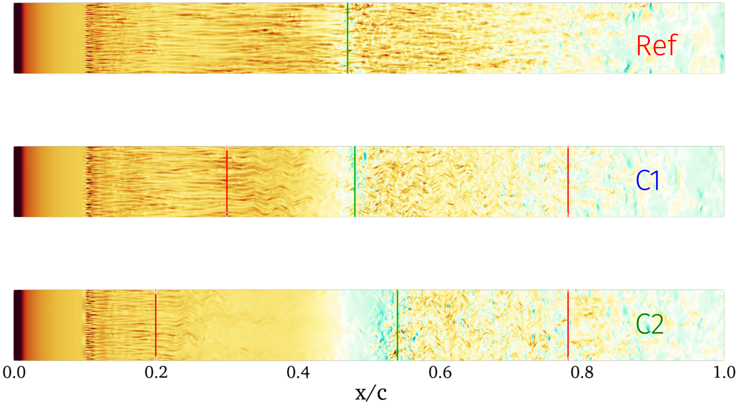


The mean flow



— $M = 1$ (Ref)
— $M = 1$ (C1)
— $M = 1$ (C2)

Instantaneous flow: near-wall fluctuations

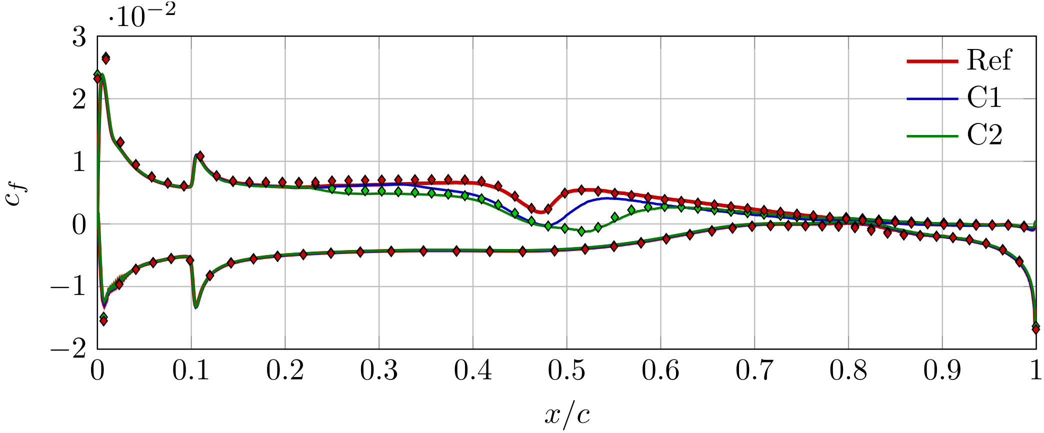


🟩 shock position

🟥 x_s and x_e

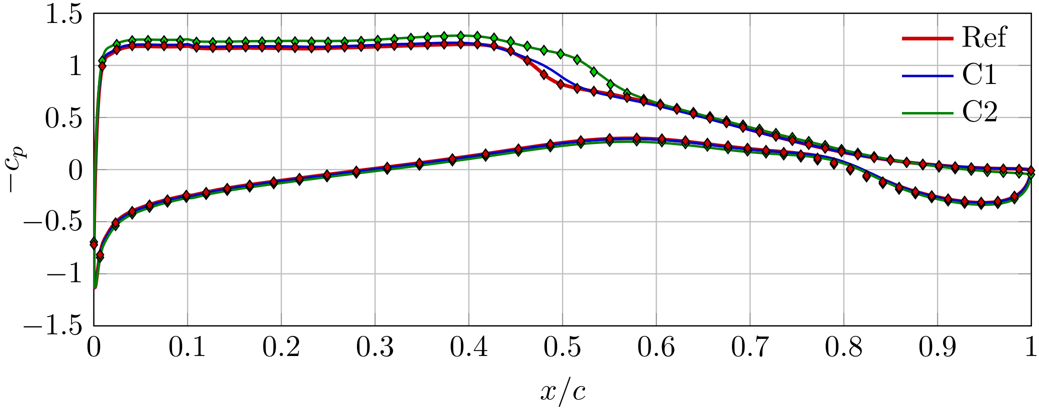
Friction coefficient

$$c_f = \frac{2\tau_w}{\rho_\infty U_\infty^2}$$



Pressure coefficient

$$c_p = \frac{2(p_w - p_\infty)}{\rho_\infty U_\infty^2}$$



Aerodynamic forces

At the same incidence angle $\alpha = 4°$

	Reference	C2	Δ_2	C2 ($\alpha = 3.45°$)	Δ_2
C_ℓ	0.740	0.825	+11.3%	0.730	-1.3%
C_d	0.0247	0.0245	-0.8%	0.0210	-15.0%
$C_{d,f}$	0.0082	0.0071	-13.4%	0.0074	-9.7%
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How does it scale to a full aircraft?

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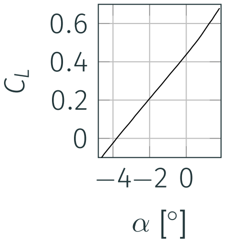
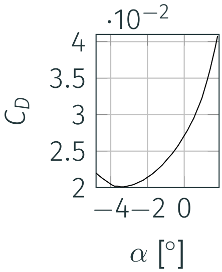
Assumptions:

- The wing is responsible for the entire lift and 1/3 of the non-lift-induced drag
- ΔC_ℓ and ΔC_d induced by control do not change along the wing span
- ΔC_ℓ and ΔC_d induced by control do not change with α, Re_∞ and M_∞

How does it scale to a full aircraft?

- DLR-F6 (Second AIAA CFD drag prediction workshop)
- Data from `https://aiaa-dpw.larc.nasa.gov`
- Control C2 in flight conditions: $M_\infty = 0.75$, $Re_\infty = 3 \times 10^6$





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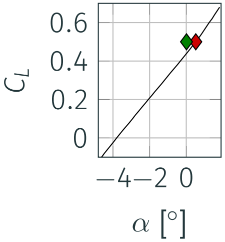
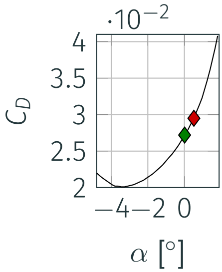
	Uncontrolled	Controlled
C_L	0.5	0.5
α	0.52°	0.0125°
C_D	0.0295	0.0272





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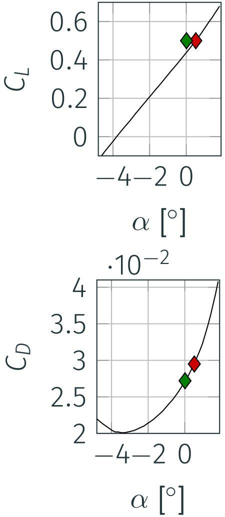


$\Delta C_D \approx 9.0\%$

actuation power ≈ 1% of the overall power expenditure

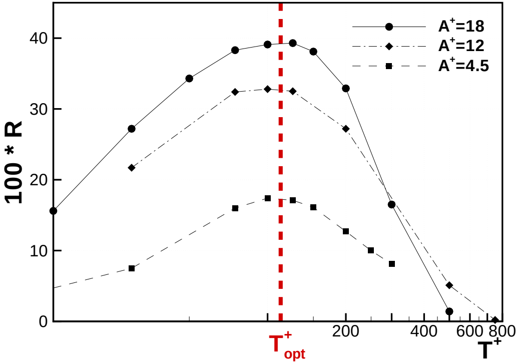
Friction drag reduction is more than a goal

- The global aerodynamic performance of the wing is improved by locally reducing skin friction over a portion of the suction side
- We measure $\Delta C_d \approx 15\%$ and $\Delta C_D \approx 9\%$ (but more is possible!)
- Skin-friction drag reduction should be considered as a tool and not only as a goal

The working mechanism

Focus on spanwise wall oscillation

$$\boxed{w(x, y = 0, z, t) = A \sin\left(\frac{2\pi}{T} t\right)}$$



- An optimal oscillation period exists
- Its value is $T^+_{opt} \approx 100$

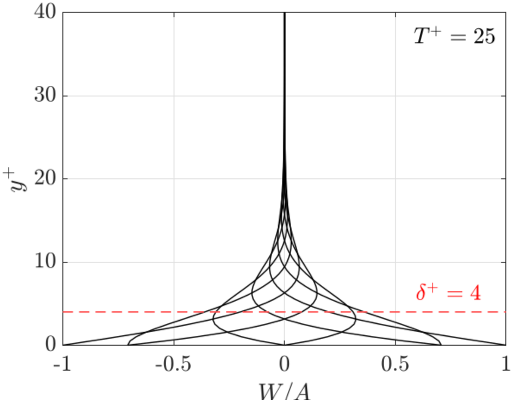
The transversal Stokes layer

It is well described by the laminar solution:

$$W_{SL}(y,t) = A \exp\left(\frac{-y}{\delta}\right) \sin\left(\frac{2\pi}{T}t - \frac{y}{\delta}\right)$$

with

$$\delta(T) = \sqrt{\frac{\nu T}{\pi}}$$



Possible interpretations of T_{opt}

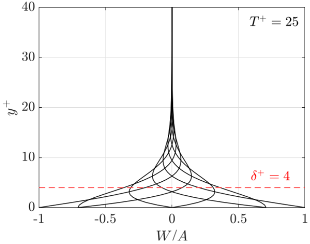
- a wall-normal length scale (thickness of the Stokes layer)?
- a turbulence time scale (lifetime of wall structures)?
- a streamwise length scale (a convection distance)?
- a streamwise length scale (the length of low-speed streaks)?
- a spanwise length scale (the displacement of the moving wall)?
- none of the above?

A thought experiment

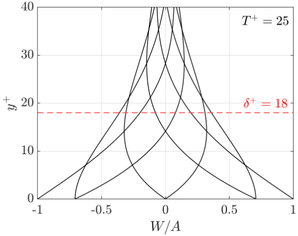
In a DNS, an artificial Stokes layer can be prescribed: T and δ can be decoupled!

The profile $W_{SL}(y, t)$ is enforced, instead of computed

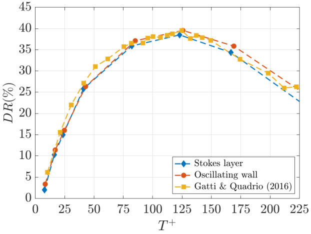
True W_{SL}:



Artificial W_{SL}:



Check:



Parameter study of $DR = DR(\delta, T)$

Channel flow DNS at $Re_\tau = 200$

Domain size $4\pi h \times 2\pi h$

$A^+ = 12$ is fixed

$\approx$ 100 DNS are carried out by varying T and δ independently

Parameter study of $DR = DR(\delta, T)$

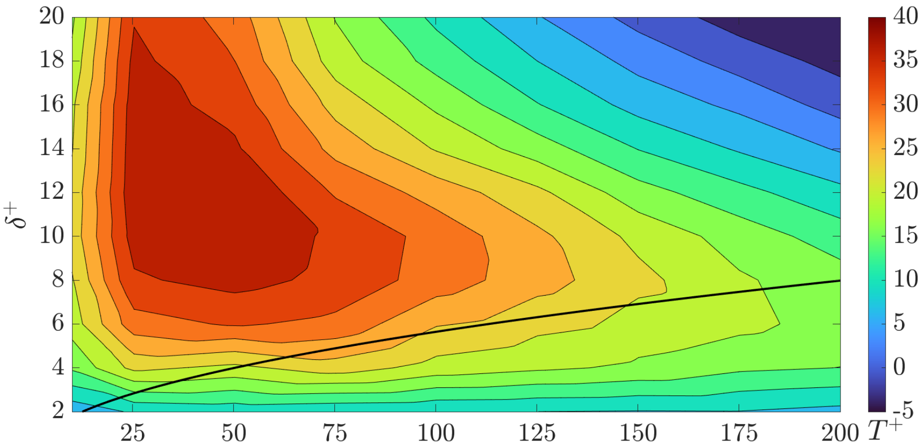
Channel flow DNS at $Re_\tau = 400$

Domain size $4\pi h \times 2\pi h$

$A^+ = 12$ is fixed

$\approx$ 100 DNS are carried out by varying T and δ independently

Drag reduction map at $Re_\tau = 400$



Lesson learned

- The ‘magic’ value $T^+_{opt} = 100$ carries no special meaning
- Potential for much larger drag reduction (!)
- Understanding spanwise forcing requires more work

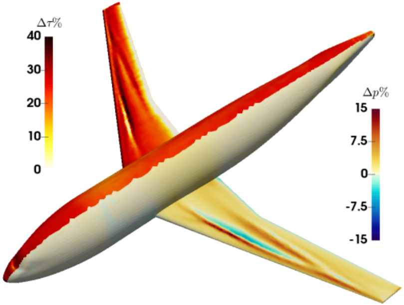
Conclusions

- Research on spanwise forcing is pretty much alive
- Steady progress in understanding various effects
- If just actuators were available...
- Potential exists for passive devices

Chap.1: EDRFCM 2017, Rome

Asking the question

- Preliminary study (coarse RANS, wall functions, DR model)
- Suggests that pressure distribution is affected
- Resemblance with similar studies for riblets

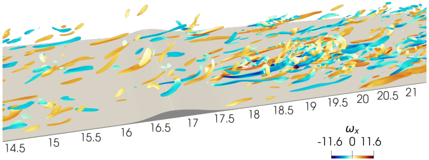


EDRFCM 2017: Drag reduction of a wing-body configuration via spanwise forcing, J.Banchetti, A.Gadda, G.Romanelli & M.Quadrio

Chap.2: EDRFCM 2019, Bad Herrenhalb

First answer, simple physics

- Reliable modelling (DNS, DR accounted for directly)
- Still simple physics
- Confirmation that skin-friction DR may led to pressure DR too



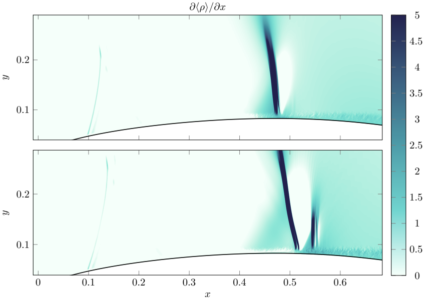
EDRFCM 2019

Paper: J.Banchetti *et al*: Turbulent drag reduction over curved walls. J. Fluid Mech. 2020, **896** A10.

Chap.3: EDRFCM 2022, Paris

Final answer, richer physics

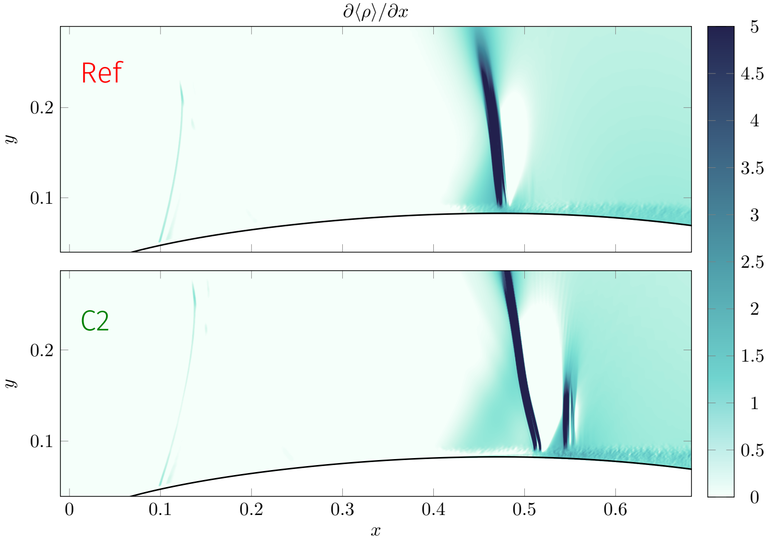
- Reliable modelling (DNS, DR accounted for directly)
- Richer physics (compressible flow over a transonic wing with shock wave)
- Extrapolation to the entire airplane



EDRFCM 2022

Paper: M.Quadrio *et al*: Drag reduction on a transonic airfoil. J. Fluid Mech. 2022, **942** R2.

Mean flow: downstream shift of the shock



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Computational details

- compressible NS solver for a calorically perfect gas: second-order FV method, with locally 3rd-order WENO numerical flux with Ducros sensor
- domain with spanwise width $0.1c$, mesh radius $25c$
- incoming laminar flow, periodic spanwise boundary conditions
- baseline mesh $4096 \times 512 \times 256$
- resolution after Zauner, De Tullio & Sandham (2019) (but at lower Re), then checked a posteriori to obey requirements set forth by Hosseini et al. 2016
- statistics accumulated for $40c/U_\infty$