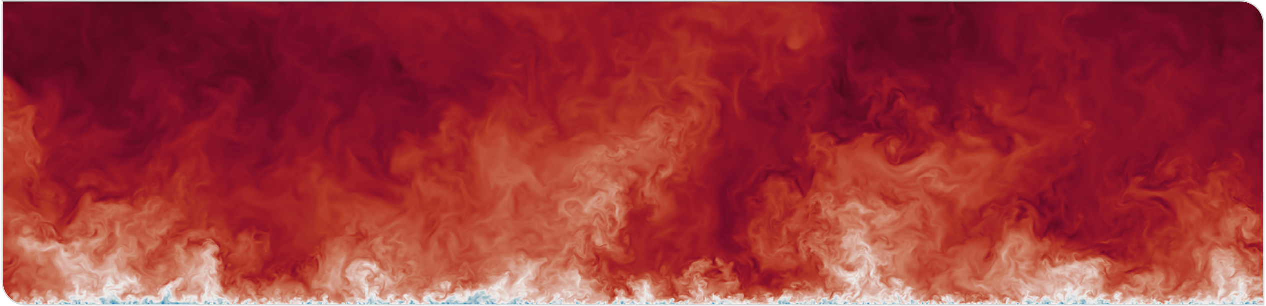
Karlsruhe Institute of Technology

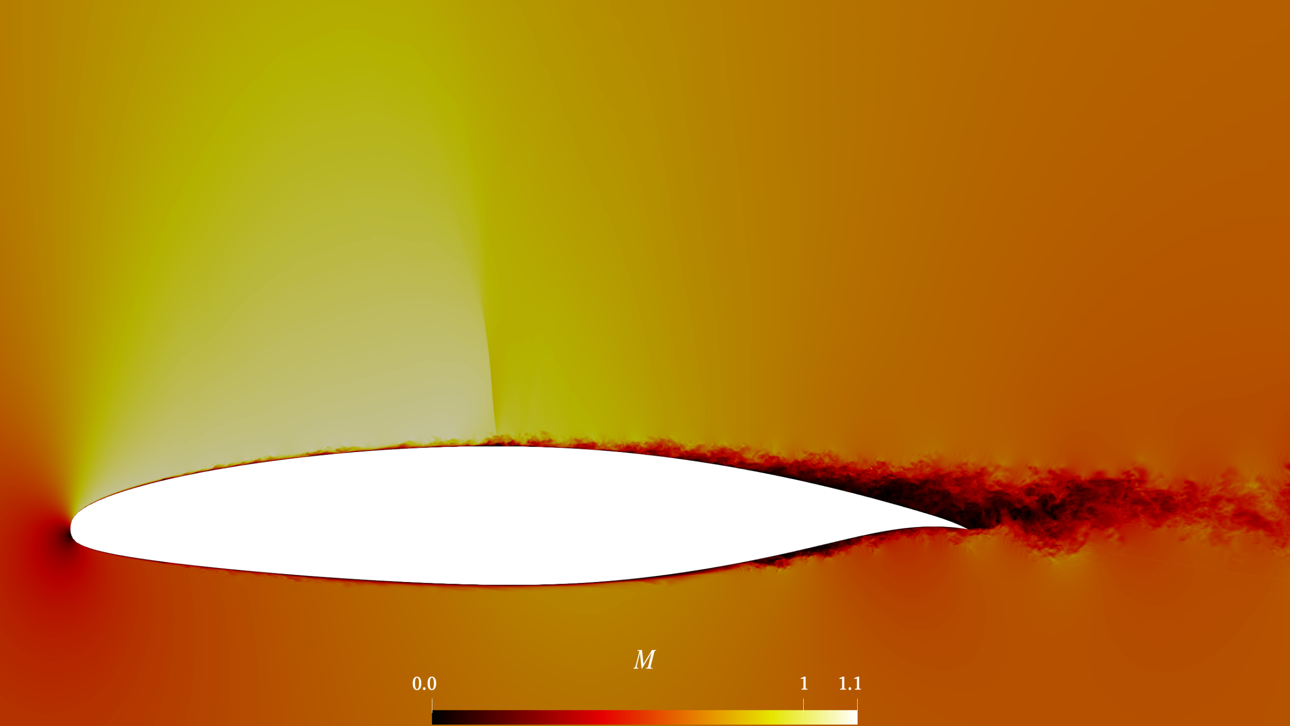
Institute of Fluid Mechanics

Turbulent drag reduction: what we do know, and what we don't

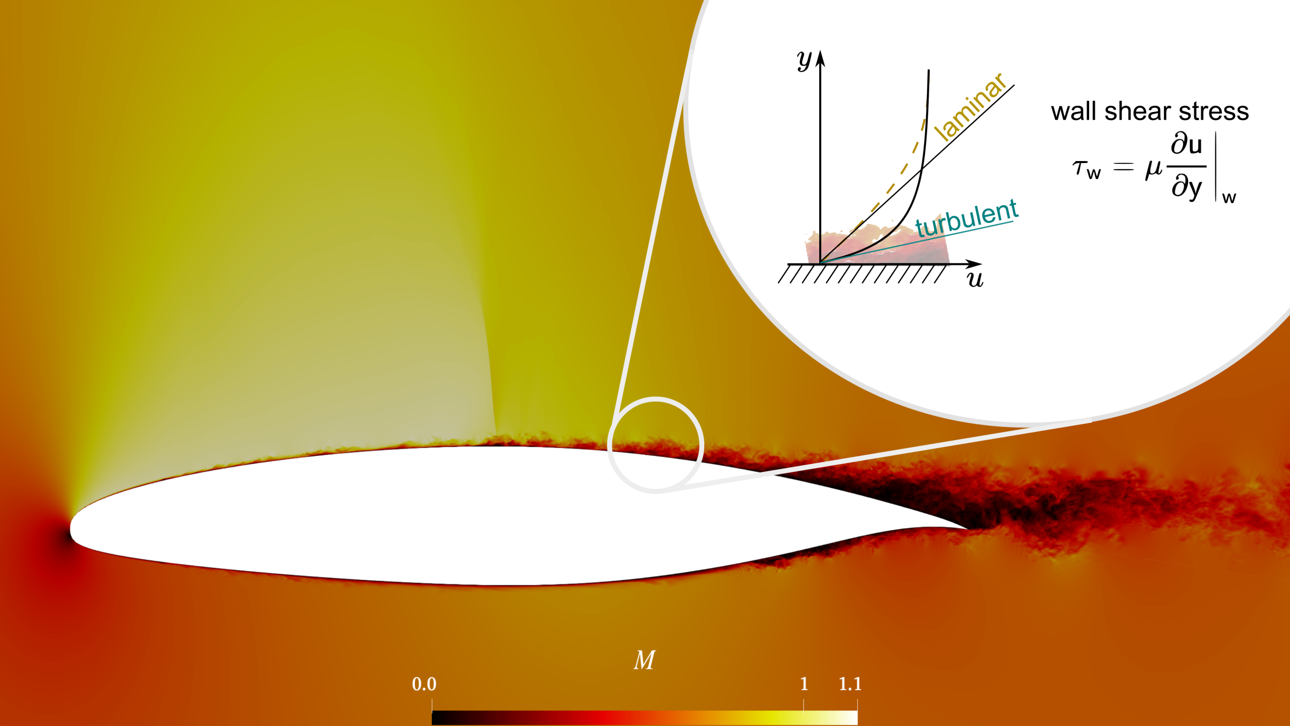
GAMM 95th annual meeting, Poznań, Poland

Davide Gatti | 10th April 2025





M
0.0
1
1.1



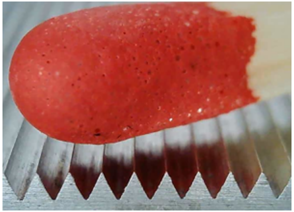
y
laminar
turbulent
u
wall shear stress
$\tau_w = \mu \frac{\partial u}{\partial y}\Big|_w$
M
0.0
1
1.1

Turbulent skin-friction drag reduction

some example applications

©Singletrack

drag reducing additives
in pipelines
$\sim$50% less drag



von Deyn, Gatti, Frohnapfel, JFM (2025)

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riblets
on airplanes and other vehicles
$\sim$8% less drag

fuel consumption reduction: $\sim$200kg/h
for a B777-300ER, Lufthansa Group, 2024

Main challenges

on the way from research to applications

- Reynolds number: Research at lower values of Re, applications at larger ones!
  - Does low-Re evidence transfer to high-Re flows?

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  - What is the effect of compressibility on drag reduction?

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- Flow complexity: Research in simple flows, applications in complex ones!
  - How does drag reduction affect lift and other sources of drag?

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  - How does drag reduction affect lift and other sources of drag?
- Physics: not fully understood! More on this in the next talk
  - What is the most realisable and efficient way of achieving drag reduction?

Main challenges

on the way from research to applications

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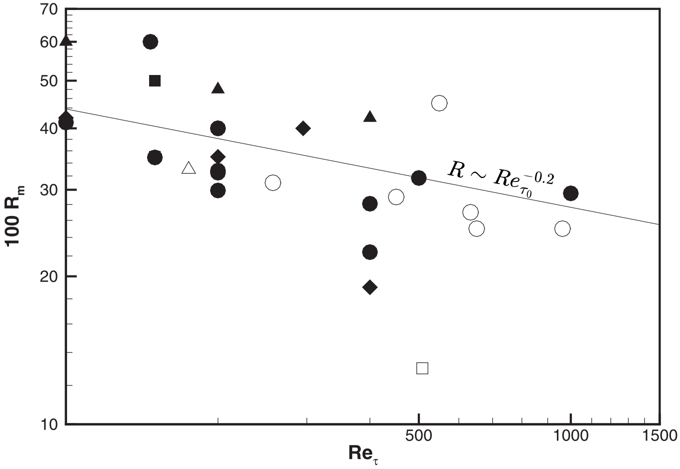
  - Does low-Re evidence transfer to high-Re flows?
- Mach number: Research in incompressible flows, applications also in compressible ones!
  - What is the effect of compressibility on drag reduction?

The Reynolds-number effect on turbulent skin-friction drag reduction

The *Re*-dependency of drag reduction

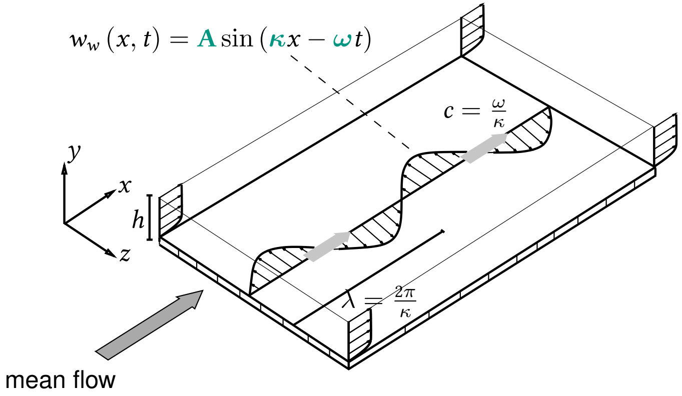
State of the art at GAMM 2012 in Darmstadt



Gatti & Quadrio, PoF (2013)

Streamwise-travelling waves of spanwise wall velocity

Quadrio, Ricco & Viotti, JFM (2009)



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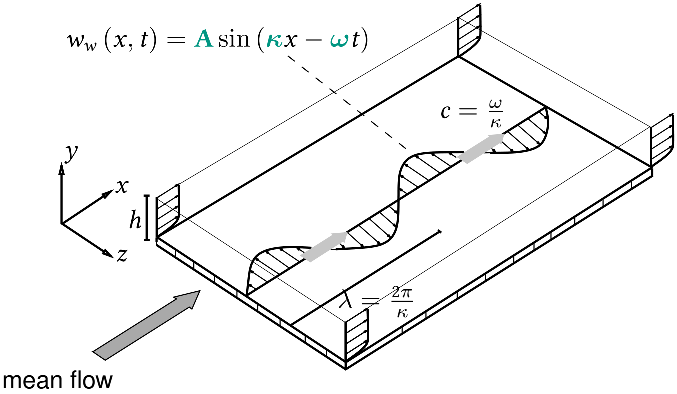

Pumping power: P_p

Drag reduction rate:

$$\mathcal{R} = 1 - \frac{P_p}{P_{p0}} = 1 - \frac{c_f}{c_{f0}}$$

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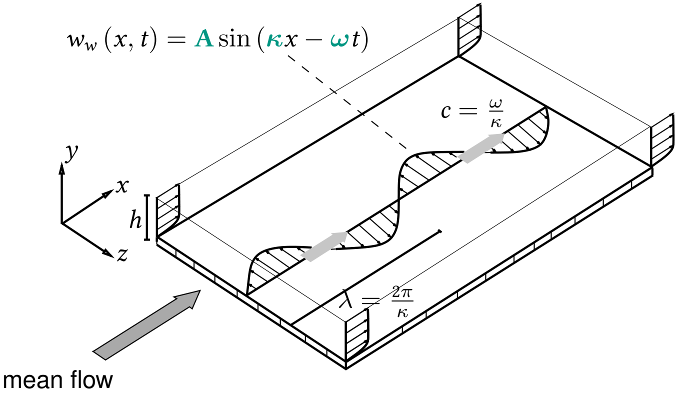

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Control input power: P_{in}

Net power saving rate:

$$\mathcal{S} = \mathcal{R} - \frac{P_{in}}{P_{p0}}$$

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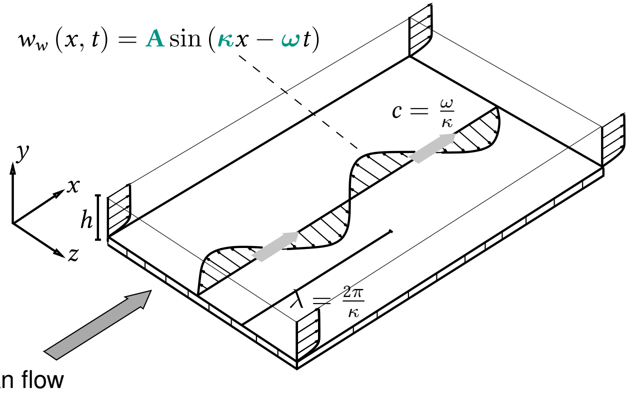

Pumping power: $\boldsymbol{P_p}$

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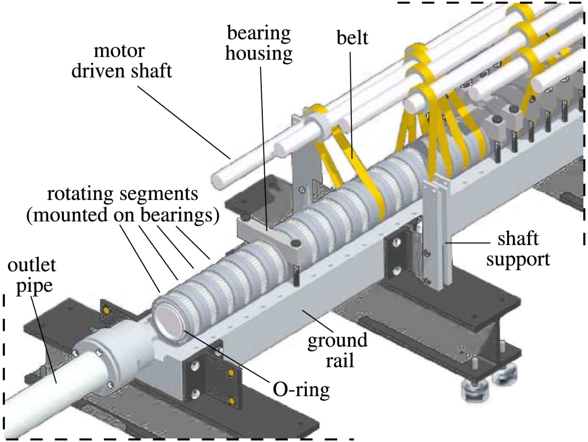
Control input power: $\boldsymbol{P_{in}}$

Net power saving rate:

$$\mathcal{S} = \mathcal{R} - \frac{P_{in}}{P_{p0}}$$

$\mathcal{R}$ and $\mathcal{S}$ depend on A, κ, ω and Reynolds number Re!

Experimentally verified!



Aueri *et al.*, PoF (2010)

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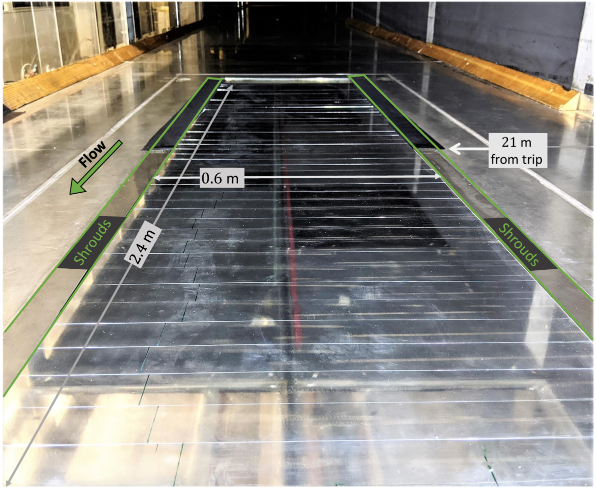
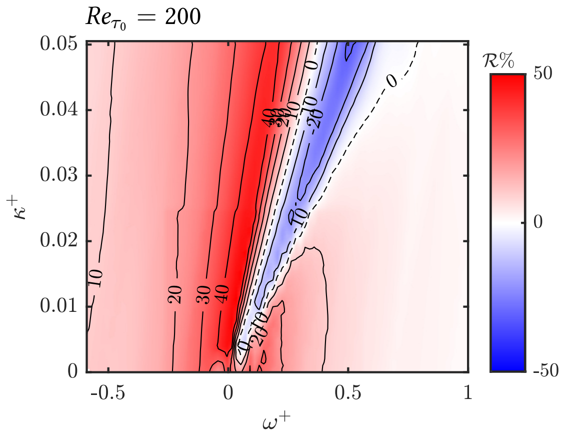


Marusic *et al.*, Nat.Comm. (2021)

The drag reduction map at $A^+ = 12$

Data by Gatti & Quadrio, JFM (2016)



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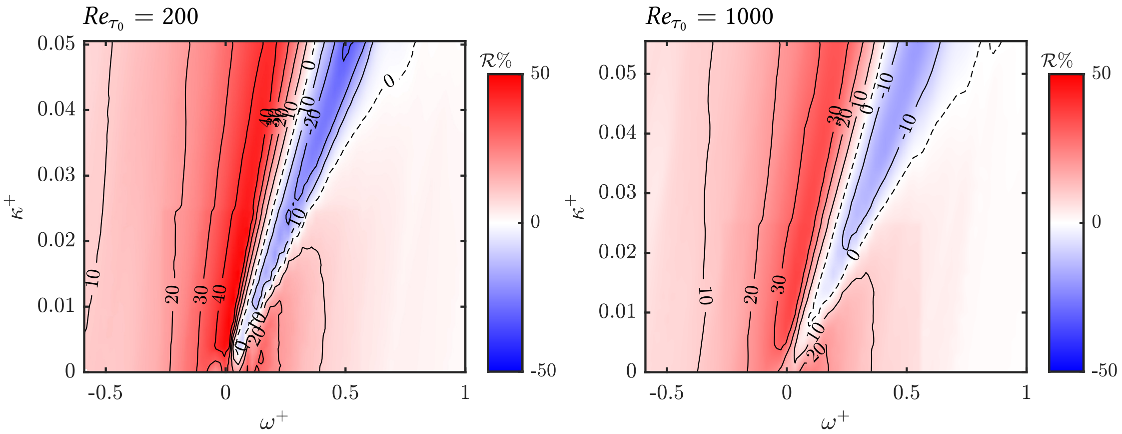


The Re-dependency of drag reduction

Twenty years of research, and counting...

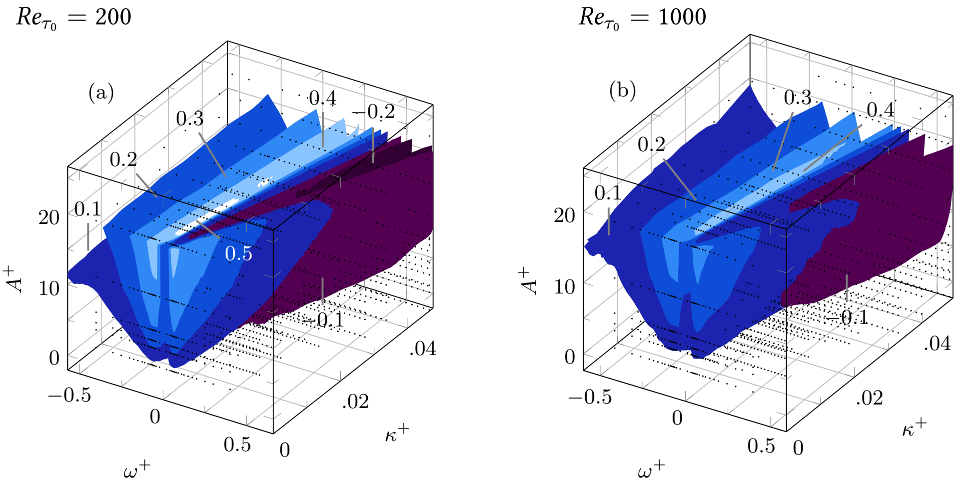
- Difficult to study: many parameters, difficulty to reach large Re
- $\mathcal{R}$ decreases with Re
- Early studies on wall oscillations ($\kappa = 0$):
  - $\mathcal{R}$ decreases rapidly with Re as $\mathcal{R} \sim Re_{\tau_0}^{\gamma}$

    Choi, Xu & Sung, AIAA (2002); Touber & Leschziner, JFM (2012)
- Later studies on travelling waves:
  - $\mathcal{R}$ can decrease slowly with Re
  - $\gamma = \gamma(A, \kappa, \omega)$

    Gatti & Quadrio, PoF (2013); Hurst, Yang & Chung, JFM (2014)
- First predictive model by Gatti & Quadrio, JFM (2016)

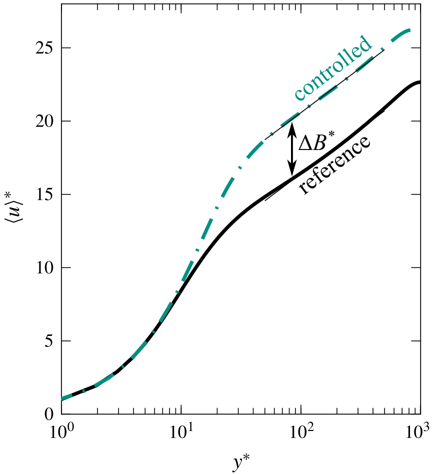
The GQ database

4020 Direct Numerical Simulation (DNS) in small domains, 20 DNS in large domains



The GQ model

A simple predictive model for the Re-dependency of drag reduction



- Near-wall manipulation induces a "roughness function" ΔB^*

$$U^*(y^*) = \frac{1}{k} \ln y^* + B_0^* + \Delta B^*$$

- $\Delta B^* = \Delta B^*(A^*, \kappa^*, \omega^*)$ is Re-independent
- A modified P-vK friction relation describes the Re-dependency of $\mathcal{R}$:

$$\Delta B^* = \sqrt{\frac{2}{C_{f\,0}}}\left[(1-\mathcal{R})^{-1/2} - 1\right] - \frac{1}{2k}\ln(1-\mathcal{R})$$

- $\mathcal{R}$ decreases with Re due to Re-dependency of $C_{f\,0}$
- Rouhi *et al.*, JFM (2023) confirm the GQ model up to $Re_{\tau_0} = 4000$ using LES in small domains

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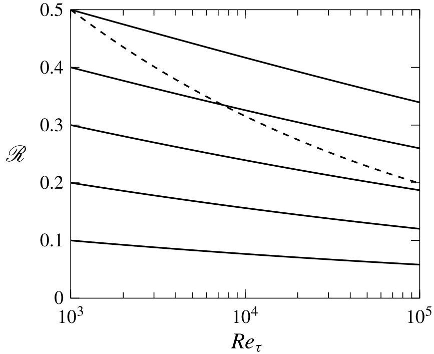

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A contrasting evidence: can $\mathcal{R}$ increase with Re?

A recent study by Marusic et al., Nature comm. (2021)

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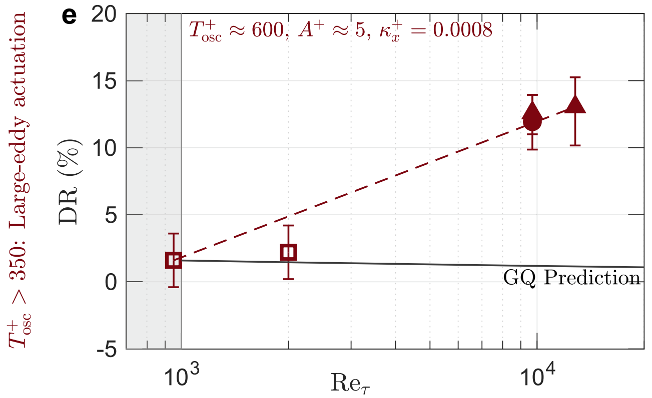

$Re_{\tau_0} \leq 2000$:

- Large Eddy Simulation
- Turbulent open channel flows in small domains
- Ideal forcing

$6000 \leq Re_{\tau_0} \leq 12800$:

- Laboratory experiment
- Turbulent boundary layers
- Discrete forcing

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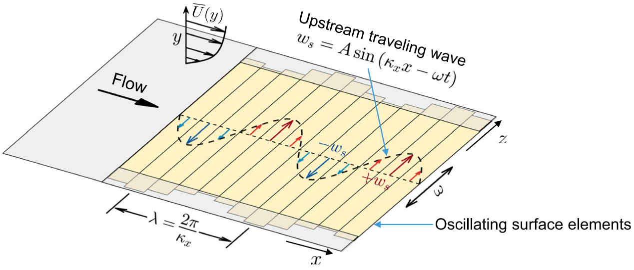

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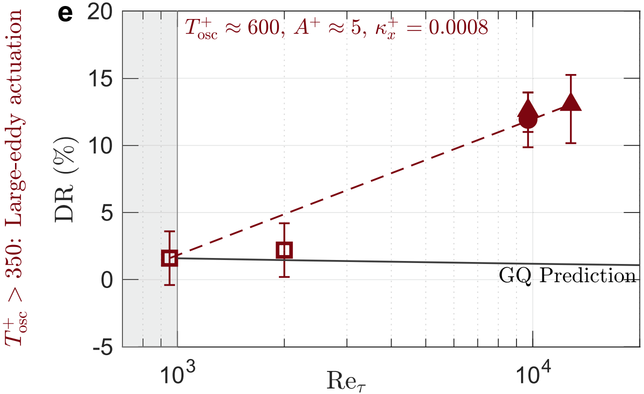

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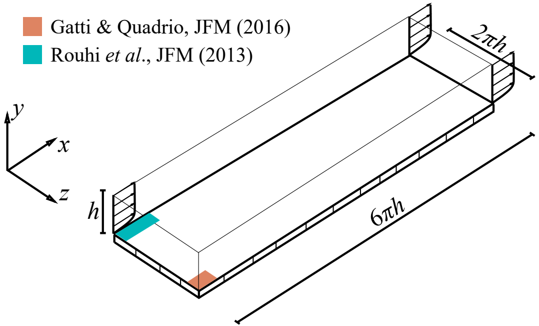
The new numerical database

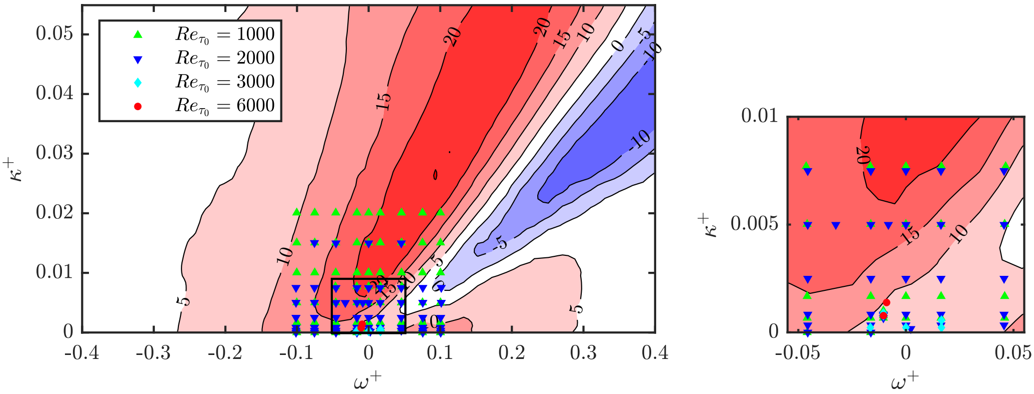
Setup

- Direct numerical simulation of turbulent open channel flows
- $Re_{\tau_0} = \{1000, 2000, 3000, 6000\}$
- Domain size: $L_x = 6\pi h$, $L_z = 2\pi h$
- Resolution: $\Delta x^+ \sim 8.5$, $\Delta z^+ = 4$
- Natural grid stretching by Pirozzoli & Orlandi, JCP (2021) in wall-normal direction
- GPU-accelerated second-order finite difference solver
- Uncertainty on C_f always below 1% with method by Russo & Luchini, JCP (2017)

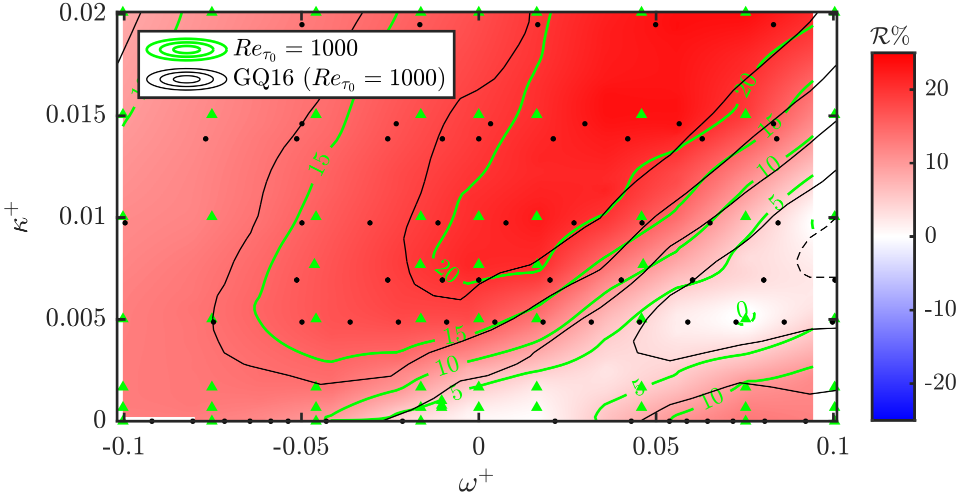


The new numerical database

147 simulations at $A^+ = 5$ up to $Re_{\tau_0} = 6000$



Drag reduction rate $\mathcal{R}$



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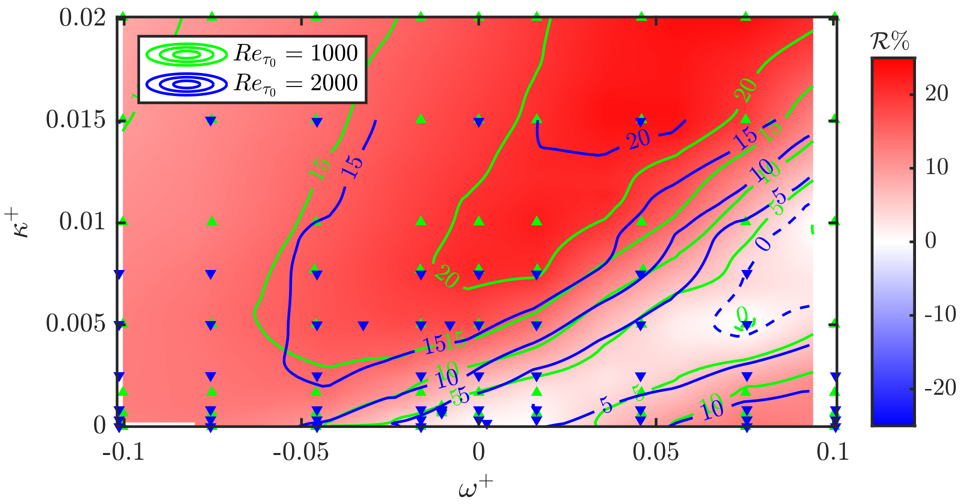
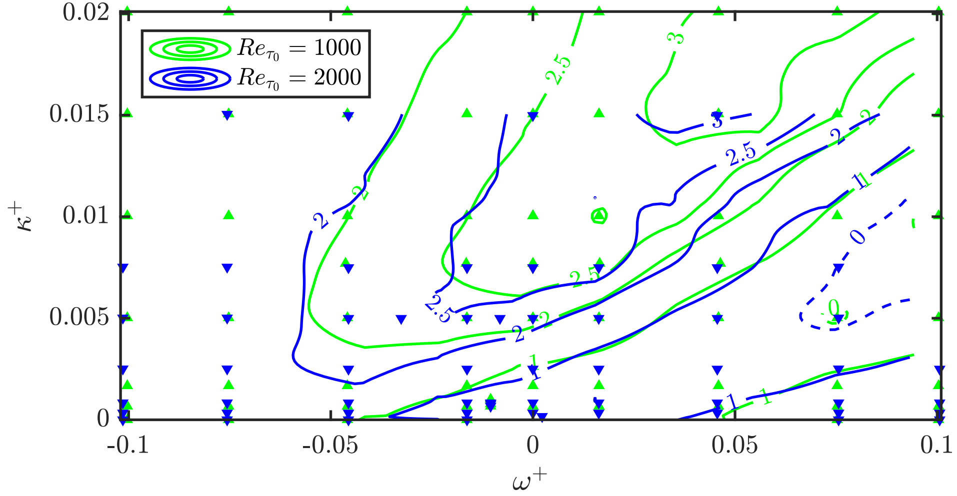
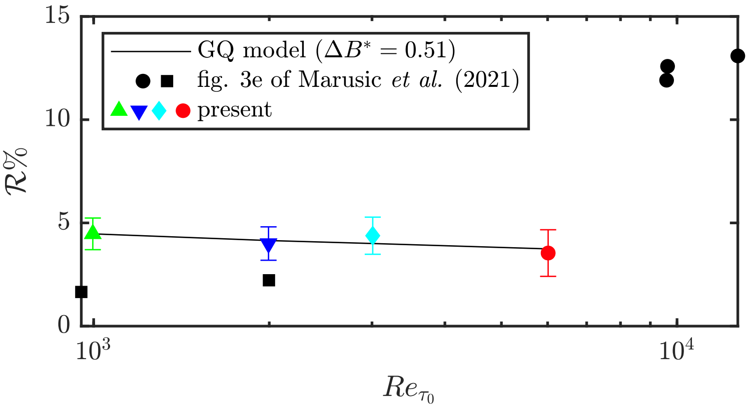


Roughness function ΔB^*



Does $\mathcal{R}$ increase with Re?

Marusic et al. (2021) parameters: $A^+ = 5,\ \kappa^+ = 0.00078,\ \omega^+ = -0.0105$



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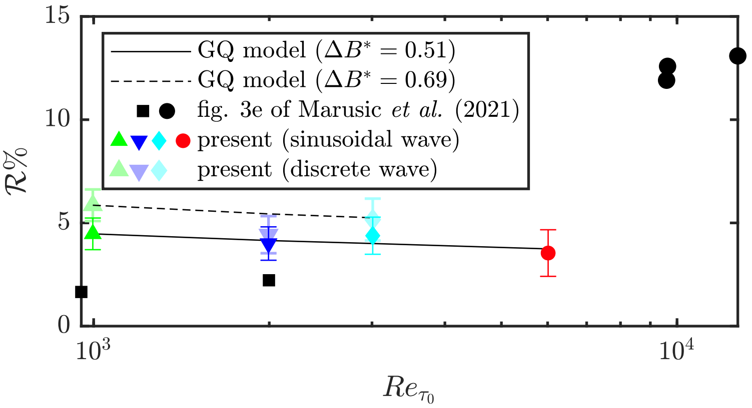
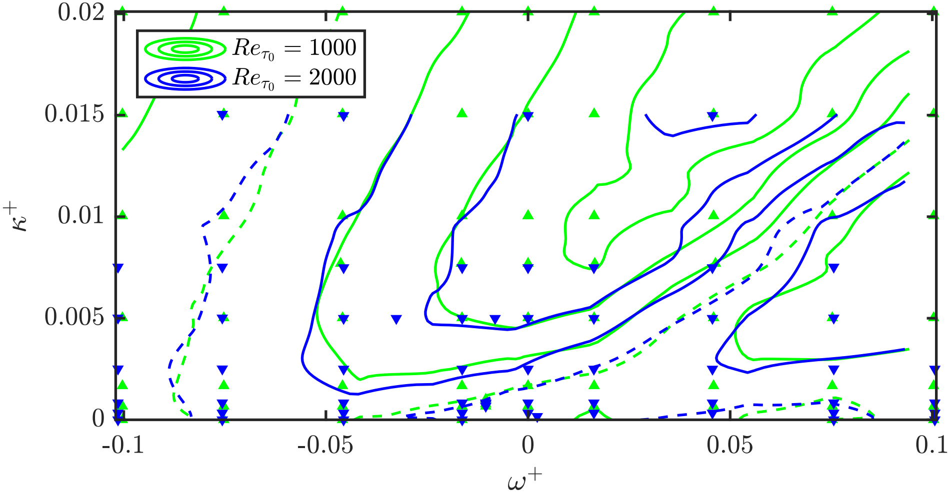


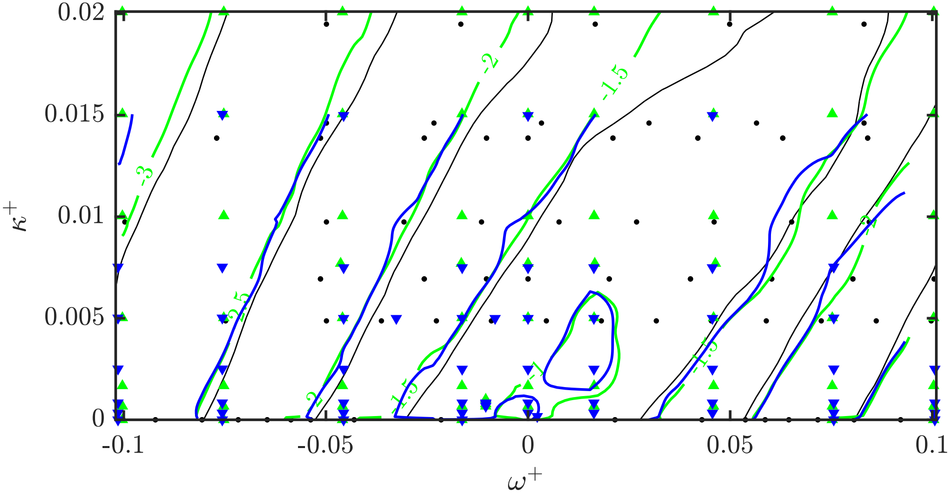
Net power saving $\mathcal{S}$

$\mathcal{S} = \mathcal{R} - P_{in}/P_{p_0} = \mathcal{R} - P_{in}^+/U_{b_0}^+$



Control input power P_{in}^{+}

Constant with Re in viscous units



Reynolds-number dependence of $\mathcal{S}$

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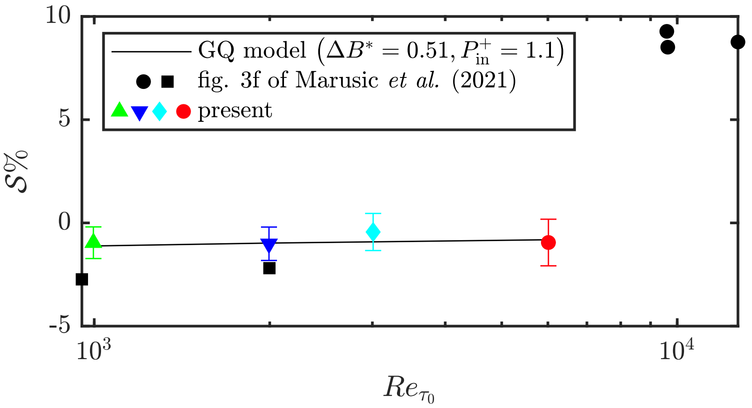

The Re-dependency of drag reduction

What do we know now?

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- Increase of $\mathcal{R}$ with Re observed by Marusic *et al.*, Nat. Comm. (2021) not confirmed

The Re-dependency of drag reduction

What do we know now?

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- 🙁 GQ model confirmed: $\mathcal{R}$ decreases with Re
- $\mathcal{S}$ also predictable, decay is slower than $\mathcal{R}$
- Increase of $\mathcal{R}$ with Re observed by Marusic *et al.*, Nat. Comm. (2021) not confirmed
- 🙂 GQ model predicts only mild decay of $\mathcal{R}$ with Re

Some still open question:

- Would other flows behave similarly?
- What is the reason for the discrepancy?
  - e.g. $\mathcal{R}$ at $A^+ = 2.5, \kappa^+ = 0.0014, \omega^+ = -0.009, Re_{\tau_0} = 6000$
  - 6% Chandran *et al.*, JFM (2023)
  - 2.3% $\pm$ 1.1 present

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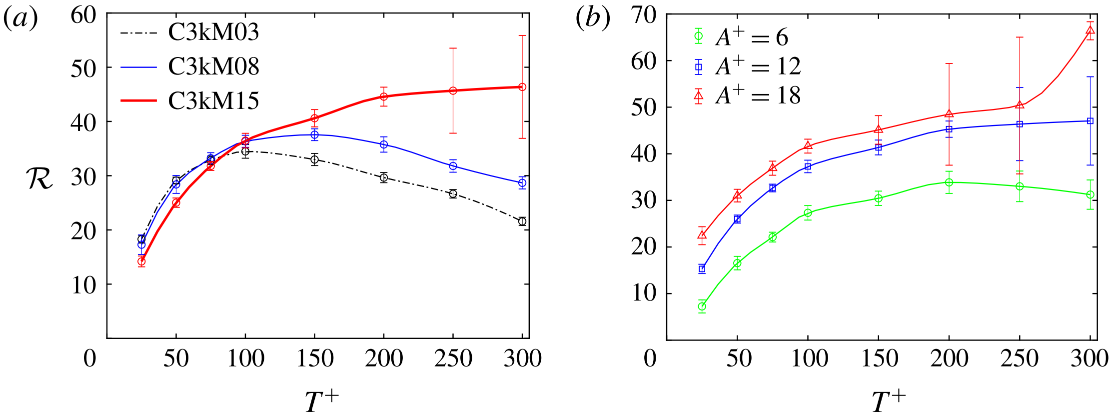
The Mach-number effect on turbulent skin-friction drag reduction

The Ma-dependency of drag reduction

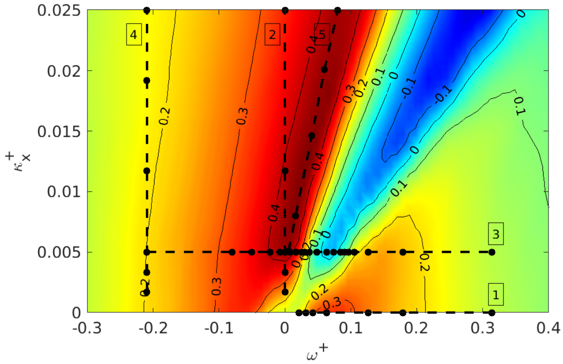
Yao & Hussain, JFM (2019): $\mathcal{R}$ increases with Ma



The compressible numerical database

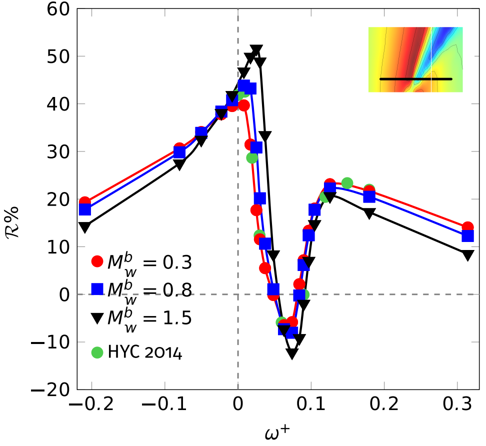
Setup

- Direct numerical simulation of turbulent channel flows
- STREAmS solver by Bernardini *et al.*, CPC (2021)
- Domain size: $L_x = 6\pi h$, $L_z = 2\pi h$
- Resolution: $\Delta x^+ \sim 8.5$, $\Delta z^+ = 4$
- Constant flow rate (CFR) : $U_b = const$
- $Re_{\tau_0} = 400$
- $M_w^b = U_b/c_w = U_b/\sqrt{\gamma R T_w} = 0.3, 0.8, 1.5$ (as Yao & Hussain, JFM 2019)
- Control: $A^+ = 12$, 42 combinations of (ω^+, κ_x^+)



Drag reduction $\mathcal{R}$

$\kappa_x = 0.005$



$\mathcal{R}_{M=0.3} \approx$ 40 % $\mathcal{R}_{M=1.5} \approx$ 52 %

Compressibility effect ($M_w^b \uparrow$):

- Large positive effect at small ω
- Small negative effect at large $|\omega|$

Drag reduction $\mathcal{R}$

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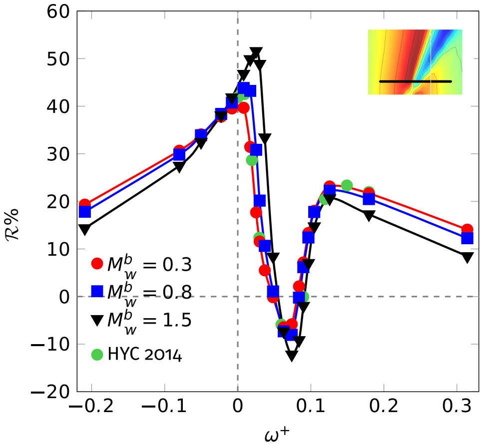

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Compressibility effect ($M_w^b \uparrow$):

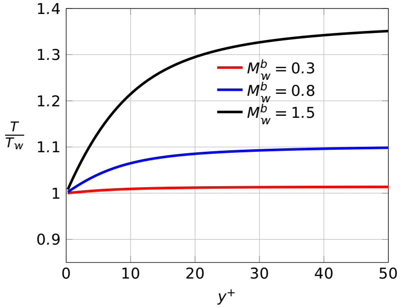
- Large positive effect at small ω
- Small negative effect at large $|\omega|$

Is the increase of $\mathcal{R}$ really due to compressibility?

The effect of the temperature

- $T_b \uparrow$ with Ma and $\mathcal{R}$ depending on (ω, κ_x)

$$T_b = \frac{1}{2h\rho_b U_b} \int_{-h}^{h} \langle \rho u T \rangle \, dy$$



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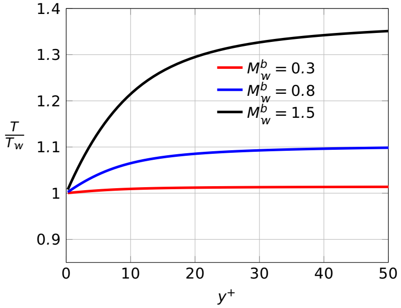
Compressibility or indirect effect of $T_b \uparrow$?



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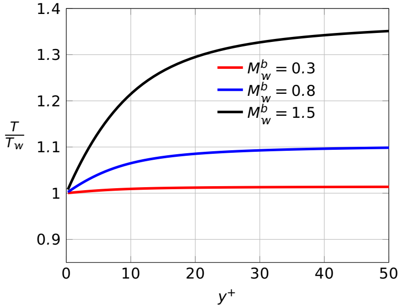
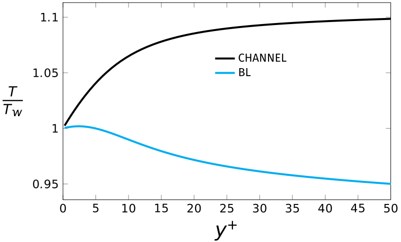
Compressibility or indirect effect of $T_b \uparrow$?

- T profile not representative of external flows





New comparison strategy

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$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho (e + p/\rho) u_j}{\partial x_j} = \frac{\partial \sigma_{ij} u_i}{\partial x_j} - \frac{\partial q_j}{\partial x_j} + f u_1$$

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Zero Bulk Cooling (ZBC)

$$\Phi = 0$$

T_b/T_w varies with Ma and $\mathcal{R}$

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Zero Bulk Cooling (ZBC)

$$\Phi = 0$$

T_b/T_w varies with Ma and $\mathcal{R}$

Constrained Bulk Cooling (CBC)

$$\Phi = f(\Theta = const = 0.75)$$

Diabatic Parameter (Θ)

$\Theta =$ Fraction of the available kinetic energy transformed into thermal energy at the wall

$$\Theta = \frac{T_w - T_b}{T_r - T_b}, \quad \frac{T_r}{T_b} = \left(1 + \frac{\gamma - 1}{2} r (M_w^b)^2\right)$$

T_b/T_w constant

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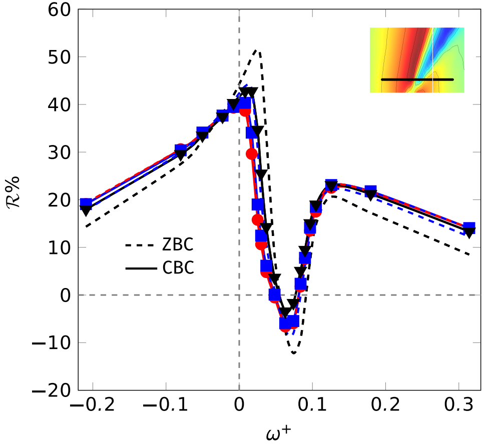
Drag reduction $\mathcal{R}$

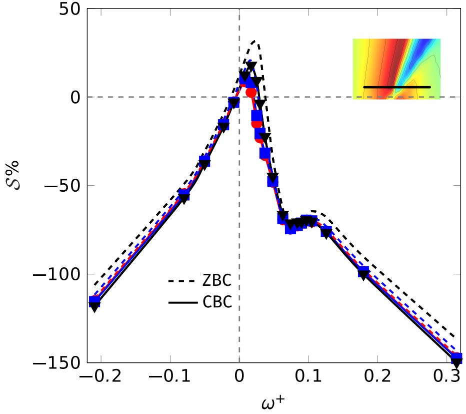
ZBC versus CBC



$\mathcal{R}_{M=0.3} \approx 40\ \%$ $\quad \mathcal{R}^{ZBC}_{M=1.5} \approx 52\ \%$ $\quad \mathcal{R}^{CBC}_{M=1.5} \approx 43\ \%$

Net power saving $\mathcal{S}$

ZBC versus CBC



$$\mathcal{S} = \mathcal{R} - \frac{P_{in}}{P_0}$$

$\mathcal{S}_{M=0.3} \approx$ 10 %

$\mathcal{S}^{ZBC}_{M=1.5} \approx$ 31 %

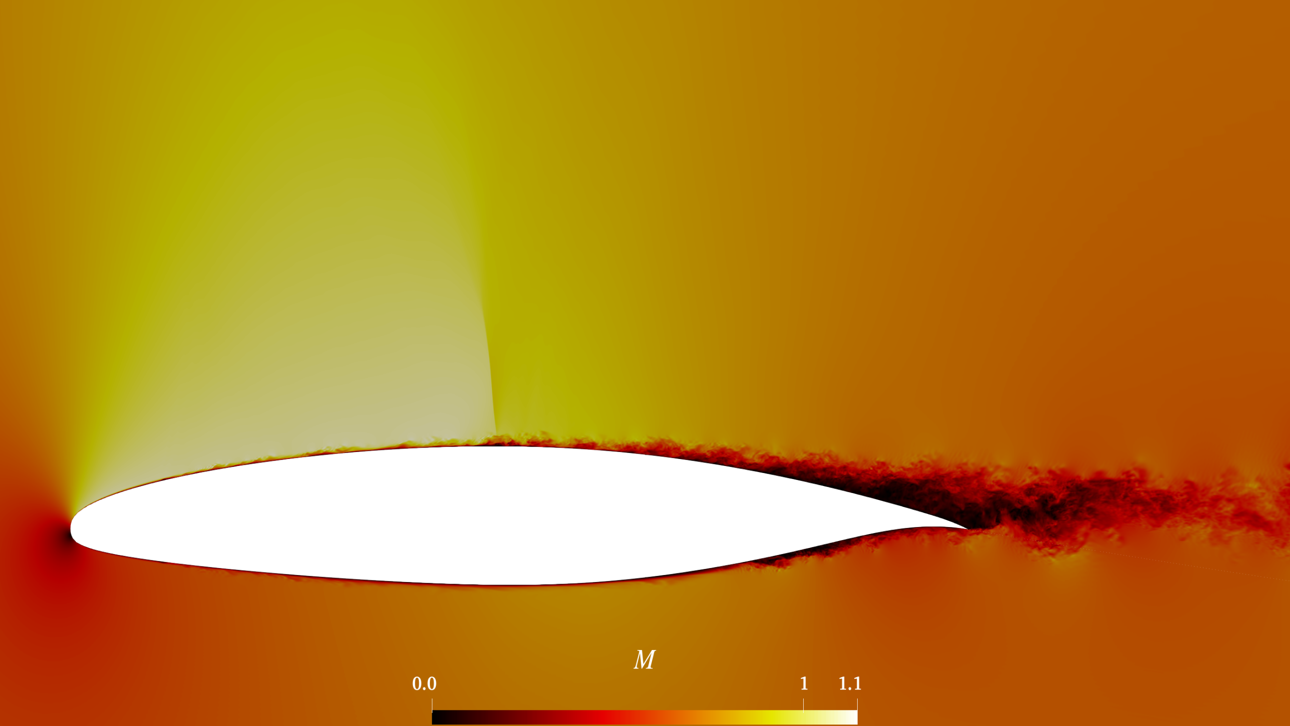
$\mathcal{S}^{CBC}_{M=1.5} \approx$ 18 %

The Ma-dependency of drag reduction

What do we know now?

- The effects of compressibility (Ma) and temperature should be addressed separately
- Two different comparison strategies:
  - Zero Bulk Cooling ($\Theta =$variable)
  - Constrained Bulk Cooling ($\Theta =$const.): decouples compressibility and temperature
- Compressibility has little effects on $\mathcal{R}$
- Temperature has large effects on $\mathcal{R}$
- Results published in Gattere *et al.*, JFM (2024)

What is still left
to be done?

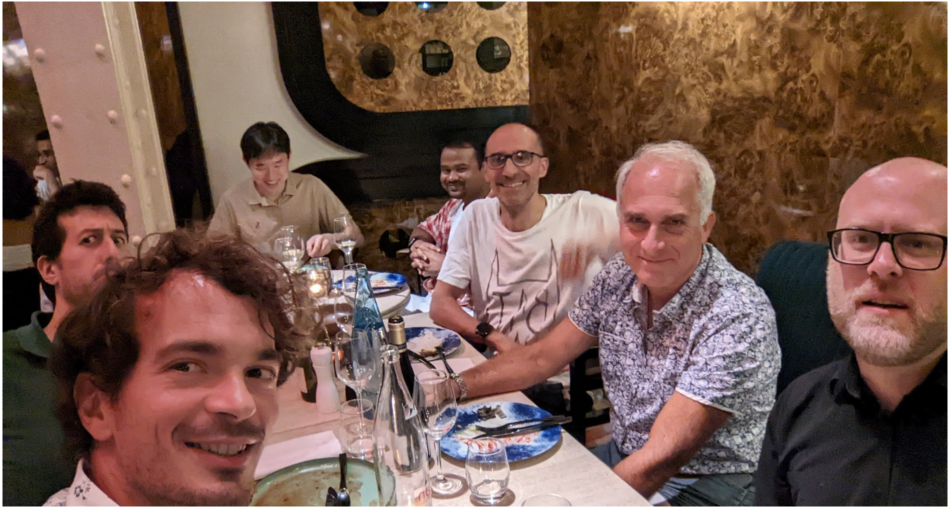


M
0.0
1
1.1

Thanks!

Karlsruhe Institute of Technology

Thanks!



Parameters of Chandran et al., JFM 2023

Not constant in viscous units!