

Davide Gatti¹, Maurizio Quadrio²
Cameron Tropea¹, Bettina Frohnappel³

¹ Center of Smart Interfaces, Technische Universität Darmstadt, Germany

² Department of Aeronautical Sciences and Technologies, Politecnico di Milano, Italy

³ Institute of Fluid Mechanics, Karlsruhe Institute of Technology, Germany

ETC14, Lyon, 1-4 September 2013



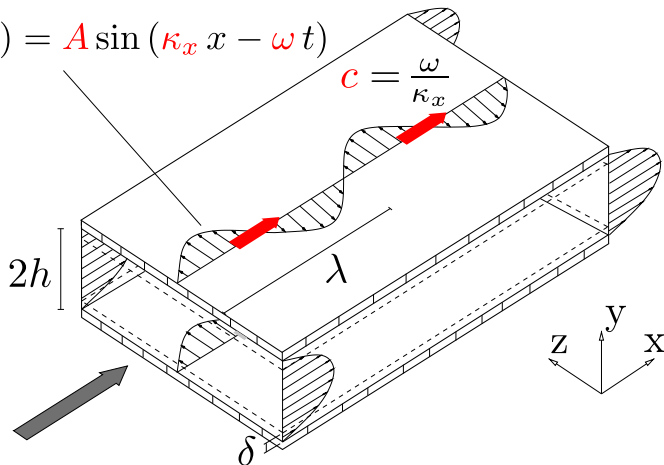
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Effectiveness of spanwise forcing for turbulent drag reduction at higher Re

A promising (general) spanwise forcing

streamwise-traveling waves of spanwise wall velocity

$$W_w(x, t) = A \sin(\kappa_x x - \omega t)$$



There are open issues!

- ▶ Two parameters (ω , κ_x) are studied
- ▶ Four parameters (Re_τ , A , ω , κ_x) are present
- ▶ R decays with Re
- ▶ Re -effect addressed mostly for the oscillating wall
 - ▶ Literature (Choi AIAA J.2002, Toubert JFM2012) proposes $R \sim Re_\tau^{-0.2}$
 - ▶ Recent results (Quadrio EFMC2012, Chung EFMC2012) show $R \sim Re_\tau^{-0.2}$ but also $R \sim Re_\tau^{-0.05}$
- ▶ Re -effect on energy efficiency to be investigated!

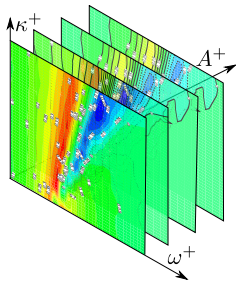
- ▶ Two Reynolds number
- ▶ Four Amplitudes
- ▶ Twelve wavenumbers
- ▶ Wide frequency range

$$Re_{\tau} = 200, 1000$$

$$A^{+} = 2, 4.5, 7, 12$$

$$\kappa^{+} \leq 0.055$$

$$-0.5 \leq \omega^{+} \leq 1$$



256 simulations for each (ω^{+}, κ^{+}) plane
Totally 2048+ simulations

Pumping with power P and controlling with power P_{in}

▶ drag reduction rate $R = \frac{P_0 - P}{P_0}$

▶ net power saving rate $S = R - \frac{P_{in}}{P_0}$

▶ gain $G = \frac{P_0 - P}{P_{in}}$

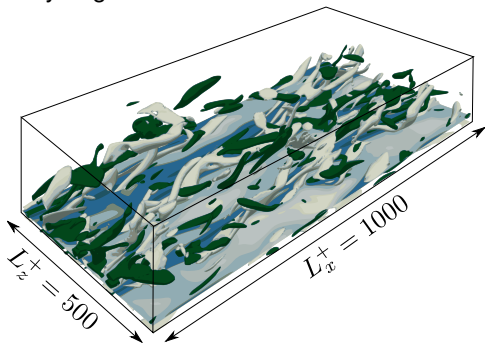
actuator efficiency $\eta > (1/G)$ to preserve positive power budget!

DNS of channels of **reduced** size:

- ▶ No modeling errors (like in full DNS)
- ▶ Discretization errors like in full DNS, but...
- ▶ ...truncation at large scales potentially larger!

Domain size constant in wall units:

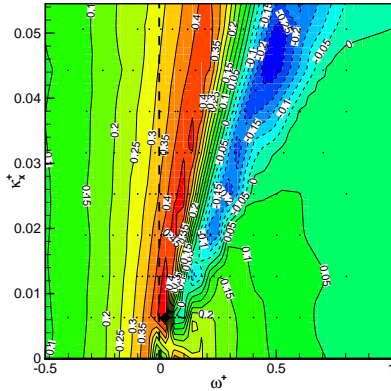
- ▶ decreasing size with Re
- ▶ Del Alamo *et al.* JFM
 $Re_\tau \approx 1000$
 $3000 < L_x^+ < 23800$



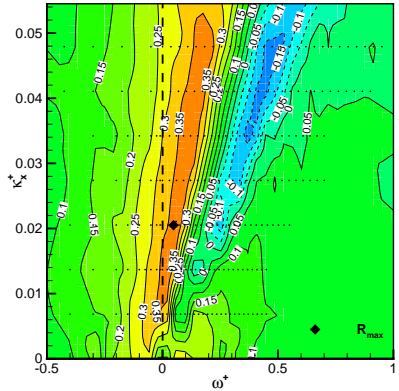
Effect of Re : R

$$A^+ = 12$$

$Re_\tau = 200$



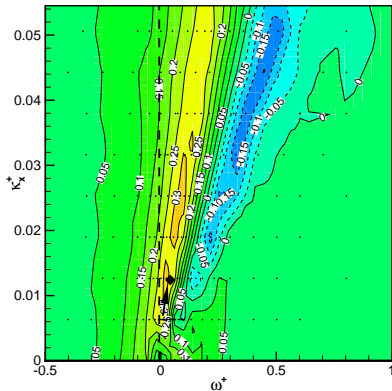
$Re_\tau = 1000$



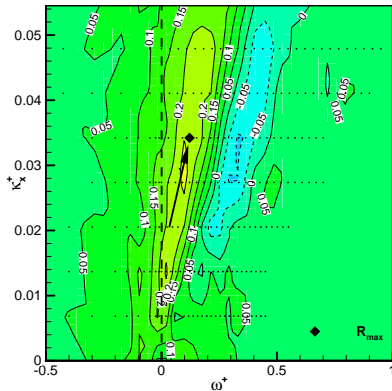
Effect of Re : R

$A^+ = 4.5$

$Re_\tau = 200$



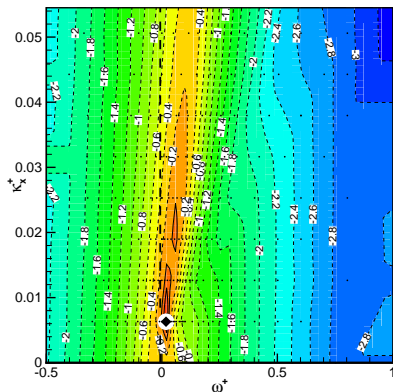
$Re_\tau = 1000$



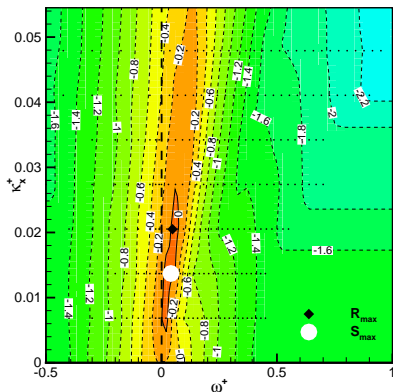
Effect of Re : S

$A^+ = 12$

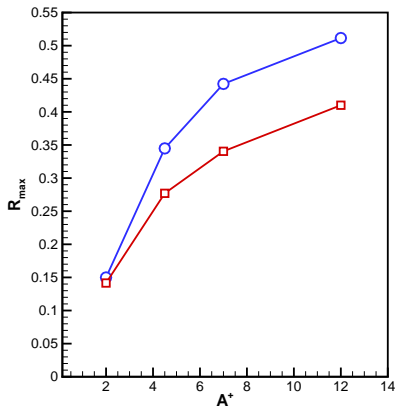
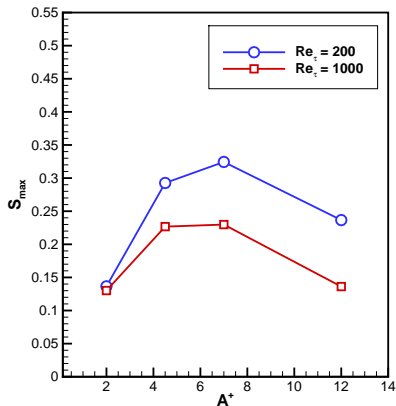
$Re_\tau = 200$



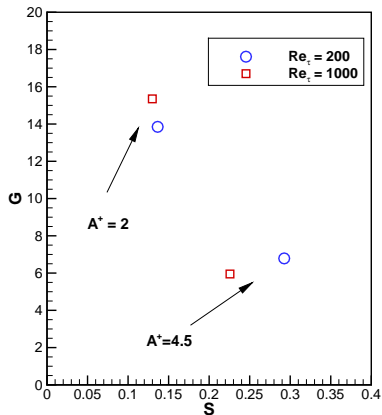
$Re_\tau = 1000$



Re-effect depends on A too



What about the Gain?



- ▶ Suggestive values
- ▶ At $A^+ = 2$ low Re -sensitivity
- ▶ At $A^+ \geq 4.5$ high Re -sensitivity

- ▶ Reduced domain allowed a higher- Re parametric study
- ▶ Low Re effects identified
- ▶ $R = f(Re_\tau, A, \omega, \kappa_x)$ $R \neq f(Re_\tau)g(A, \omega, \kappa_x)$
- ▶ Re -effect is less severe at low A^+
 - ▶ interesting for applications!
- ▶ S and G can increase with Re

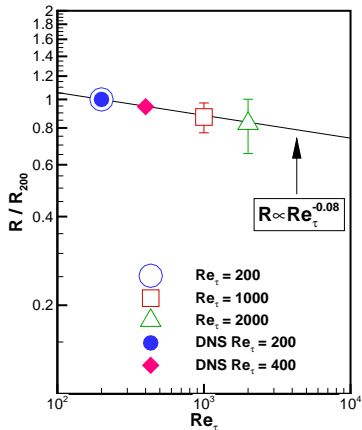
- ▶ *Low-Re* effect detected. What about *high-Re* ones?
- ▶ Are the results only suggestive? Preliminary study:
 - yes, they are: some (deterministic) biases present
 - no, they aren't: full DNS confirms the trends
- ▶ Gain understanding with the simplified tool
why it worked. It justifies simplified approaches



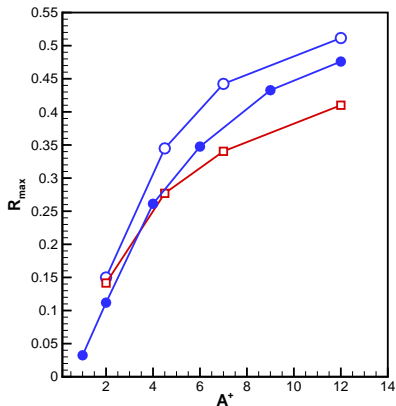
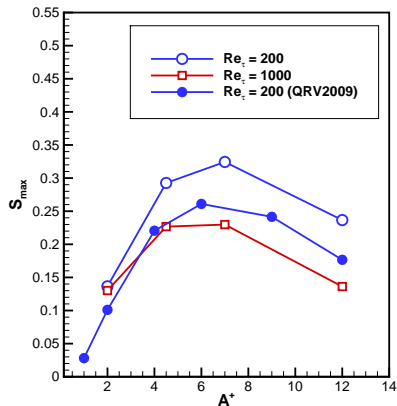
THANKS
for the kind attention!

gatti@csi.tu-darmstadt.de

Full DNS confirms the trend



Domain size: effect on R_{max} and S_{max}



Domain size: effect on C_f

