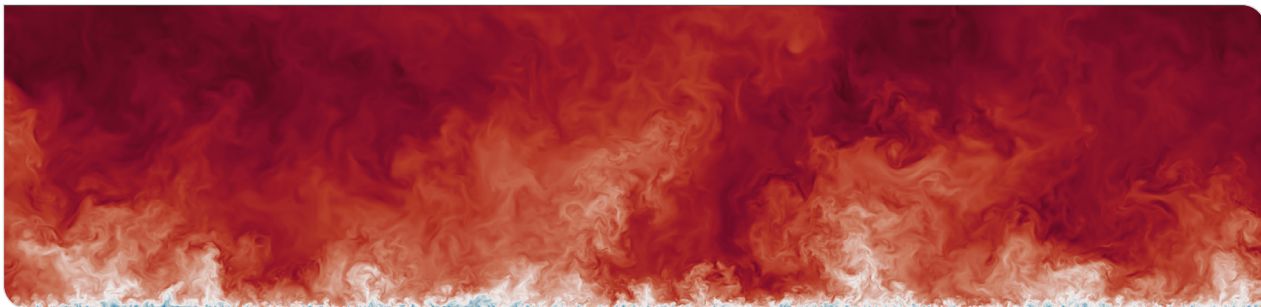


Numerical Study of turbulent skin-friction drag reduction via spanwise forcing at large Reynolds numbers

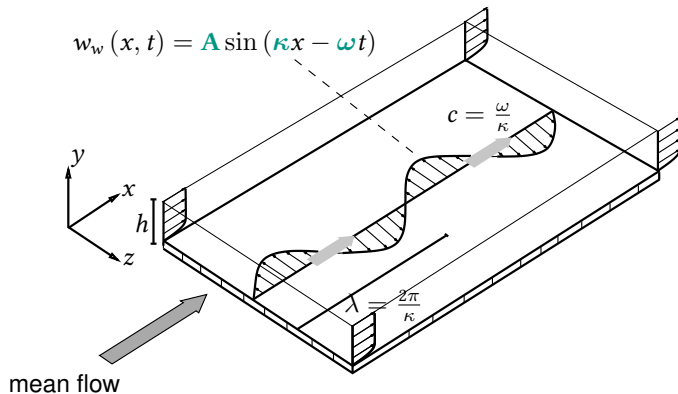
2nd European Fluid Dynamics Conference 2025, Dublin, Ireland

D. Gatti, M. Quadrio, F. Gattere, A. Chiarini, S. Pirozzoli | 29th Augusts 2025



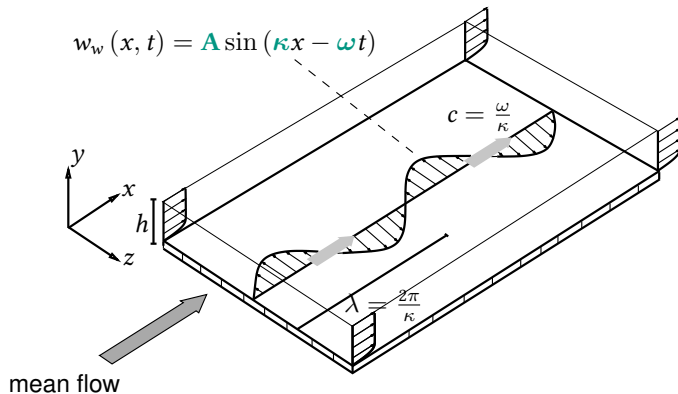
Streamwise-travelling waves of spanwise wall velocity

Quadrio, Ricco & Viotti, JFM (2009)



Streamwise-travelling waves of spanwise wall velocity

Quadrio, Ricco & Viotti, JFM (2009)



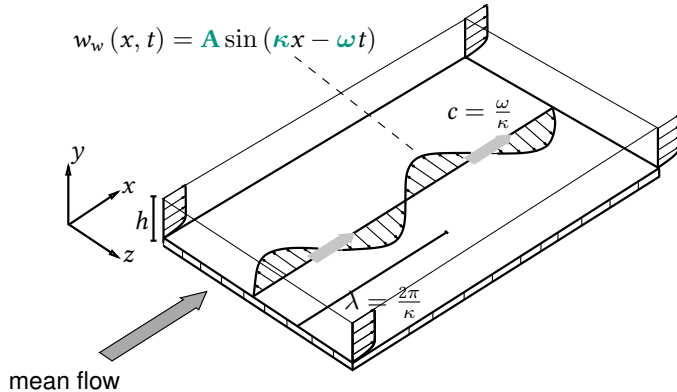
Pumping power: P_p

Drag reduction rate:

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

Streamwise-travelling waves of spanwise wall velocity

Quadrio, Ricco & Viotti, JFM (2009)



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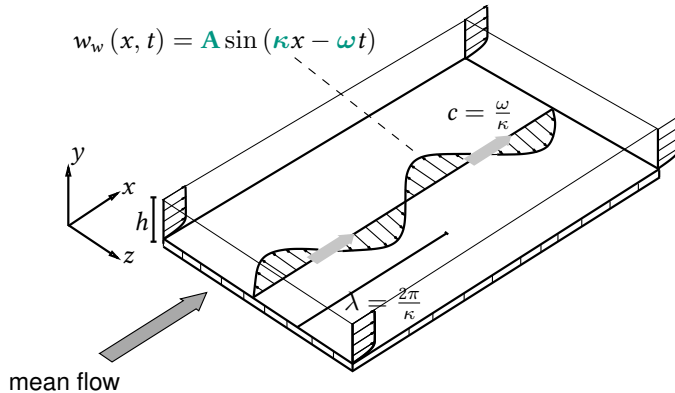
Control input power: P_{in}

Net power saving rate:

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

Streamwise-travelling waves of spanwise wall velocity

Quadrio, Ricco & Viotti, JFM (2009)



Pumping power: P_p

Drag reduction rate:

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

Control input power: P_{in}

Net power saving rate:

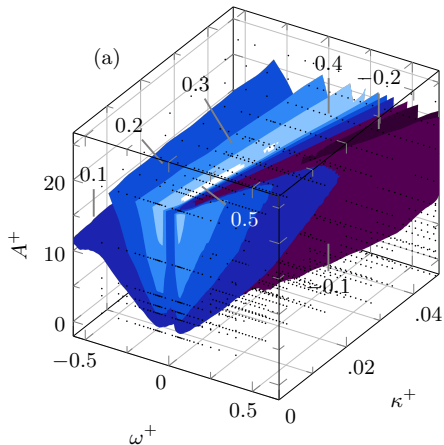
$$\mathcal{S} = \mathcal{R} - \frac{P_{in}}{P_{p0}}$$

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

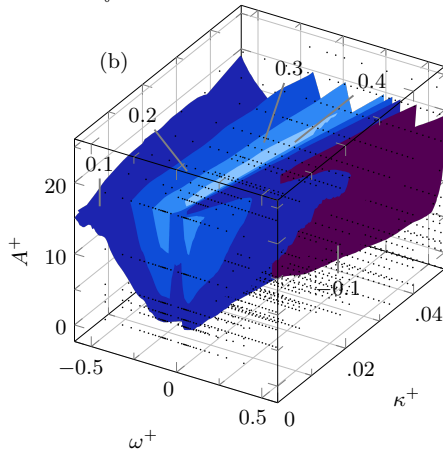
The GQ database (Gatti & Quadrio, JFM 2016)

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

$Re_{\tau_0} = 200$



$Re_{\tau_0} = 1000$



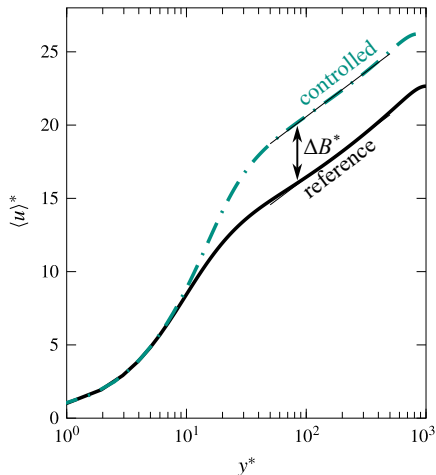
The *Re*-dependency of drag reduction

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 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} :

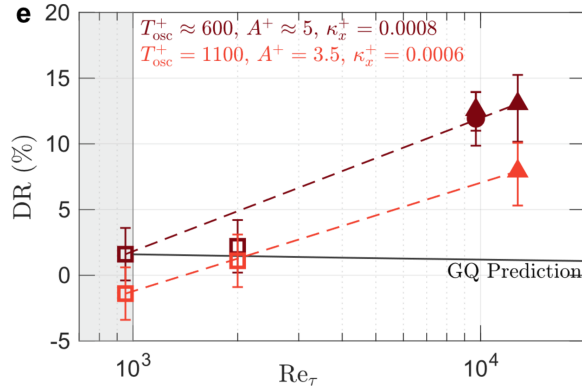
$$\Delta B^* = \sqrt{\frac{2}{C_{f_0}}} \left[(1 - \mathcal{R})^{-1/2} - 1 \right] - \frac{1}{2k} \ln(1 - \mathcal{R})$$

- \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

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

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

$T_{osc}^+ > 350$: Large-eddy actuation



$Re_{\tau_0} \leq 2000$:

- 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

Motivation

overcome some limitations of the present studies

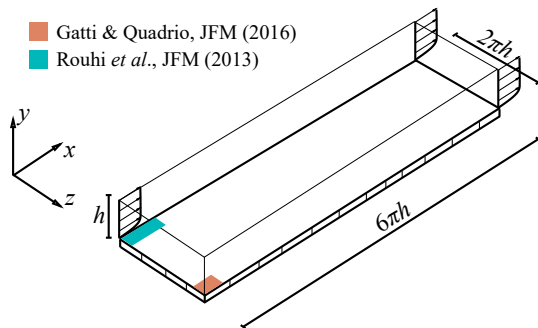
Limitations of the studies so far

- Gatti & Quadro, JFM (2016) and Rouhi *et al.*, JFM (2023) utilised **small domains and relatively small Re**
- Marusic *et al.*, Nature comm. (2021) compares results obtained with **different flows and methods**

motivate the present study

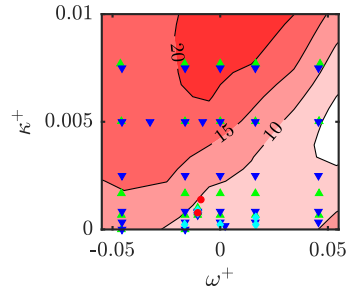
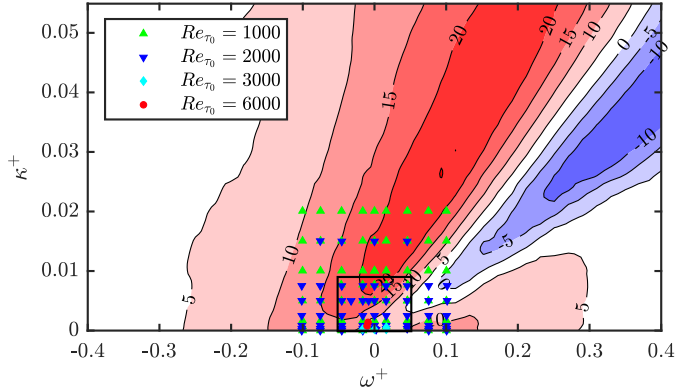
- produce a new numerical database of drag reduction data in **domains and higher Re**
- utilising a **single method**

- 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)

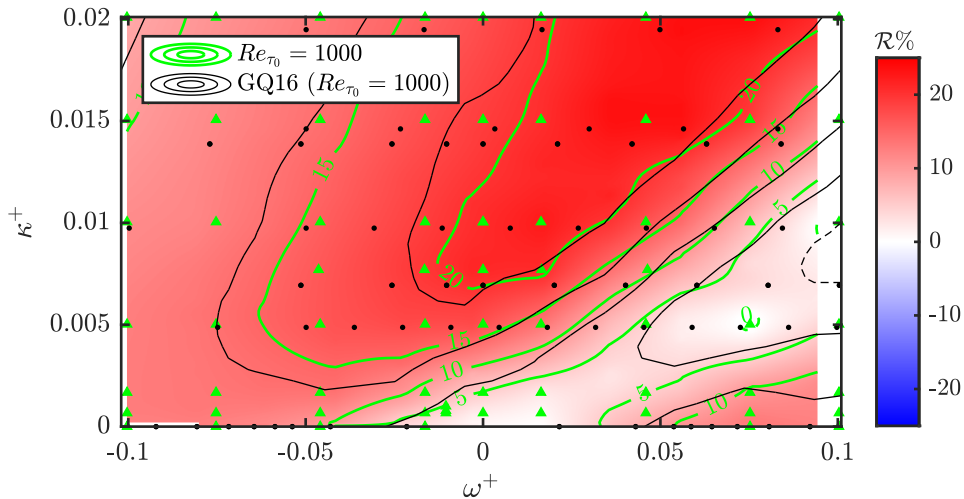


The new numerical database

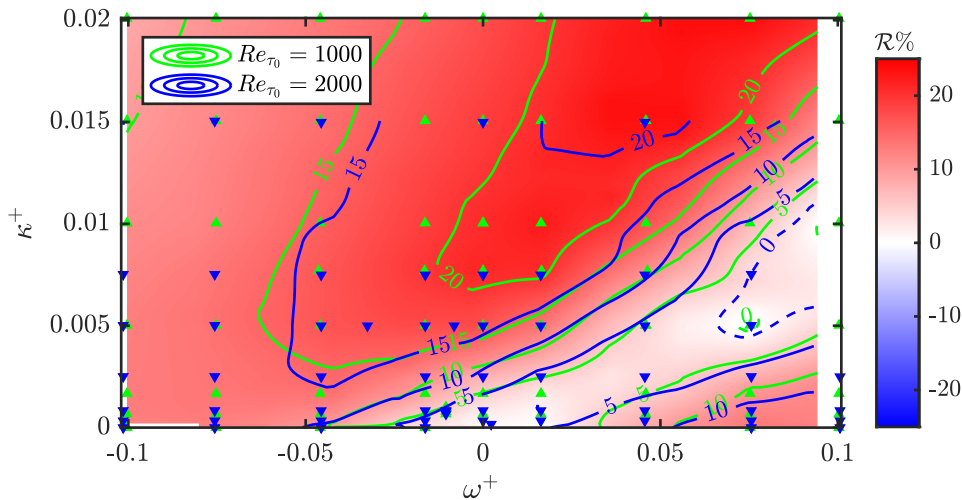
143 simulations at $A^+ = 5$ up to $Re_{\tau_0} = 6000$



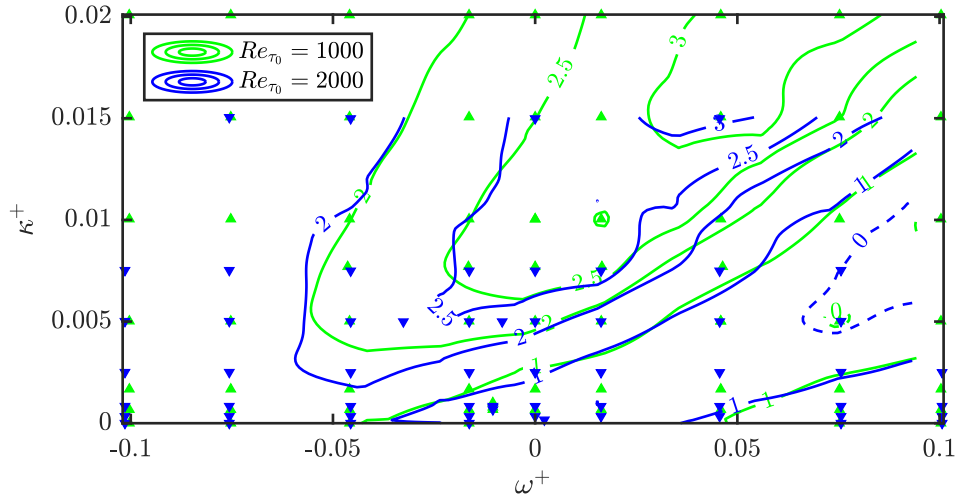
Drag reduction rate \mathcal{R}



Drag reduction rate \mathcal{R}

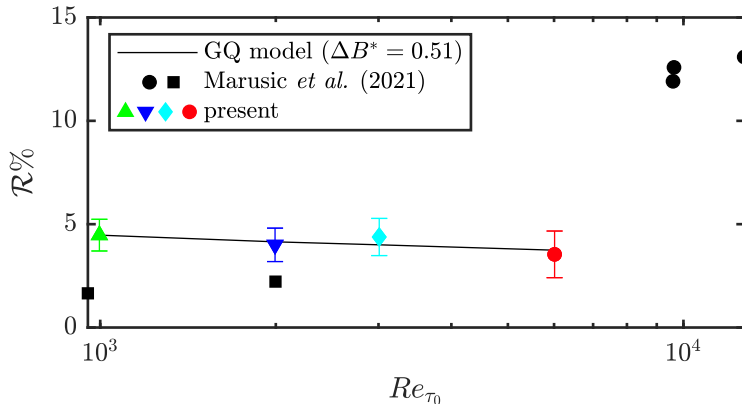


Roughness function ΔB^*



Does \mathcal{R} increase with Re ?

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



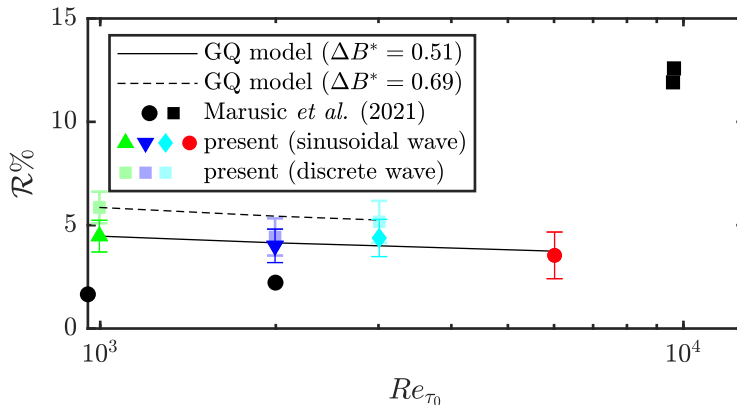
- New DNS database of skin-friction drag reduction up to $Re_{\tau_0} = 6000$
 - large domain size, single method
 - widest range considered numerically so far
- GQ model confirmed: \mathcal{R} decreases with Re
- Increase of \mathcal{R} with Re observed by Marusic *et al.*, Nat. Comm. (2021) not confirmed
- \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
- Loci of maximal \mathcal{S} and \mathcal{R} almost coincide as predicted by GQ13 and GQ16



D. Gatti, M. Quadrio, A. Chiarini, F. Gattere,
S. Pirozzoli, *Turbulent skin-friction drag
reduction via spanwise forcing at high
Reynolds number*, J. Fluid Mech. 1016:A58.
doi:10.1017/jfm.2025.10412

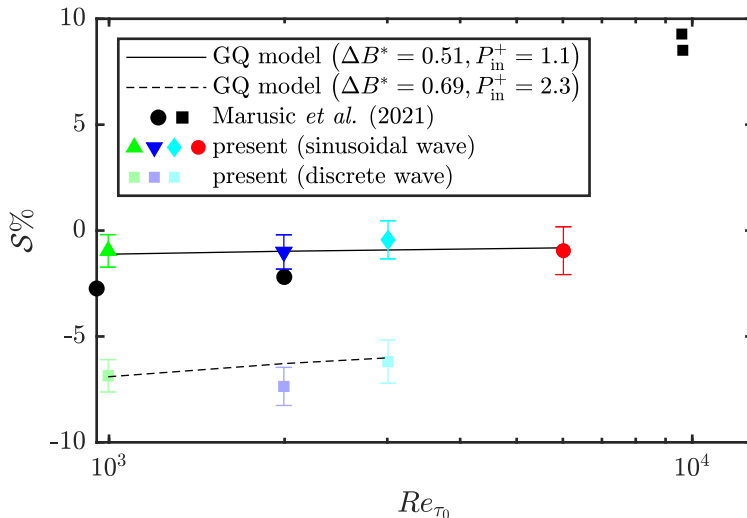
Reynolds-number dependence of \mathcal{R}

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



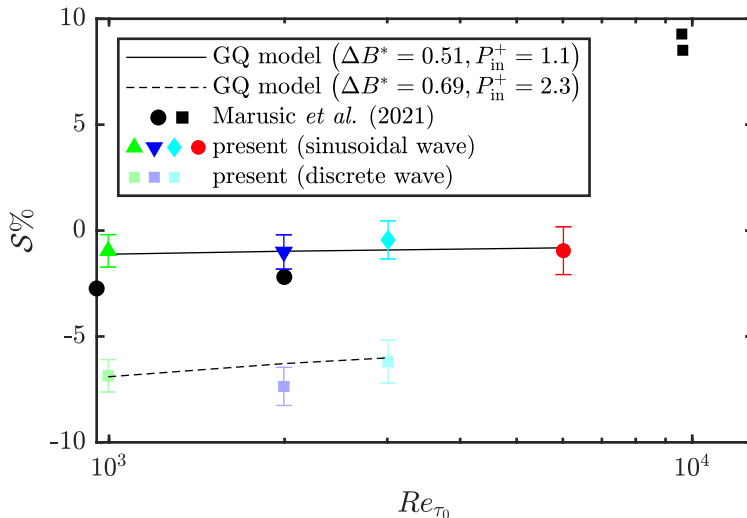
Reynolds-number dependence of S

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



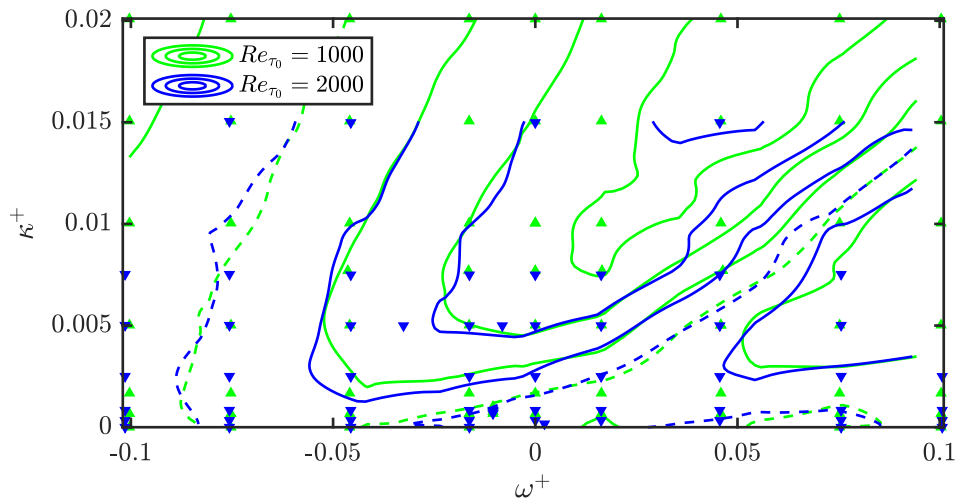
Reynolds-number dependence of S

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



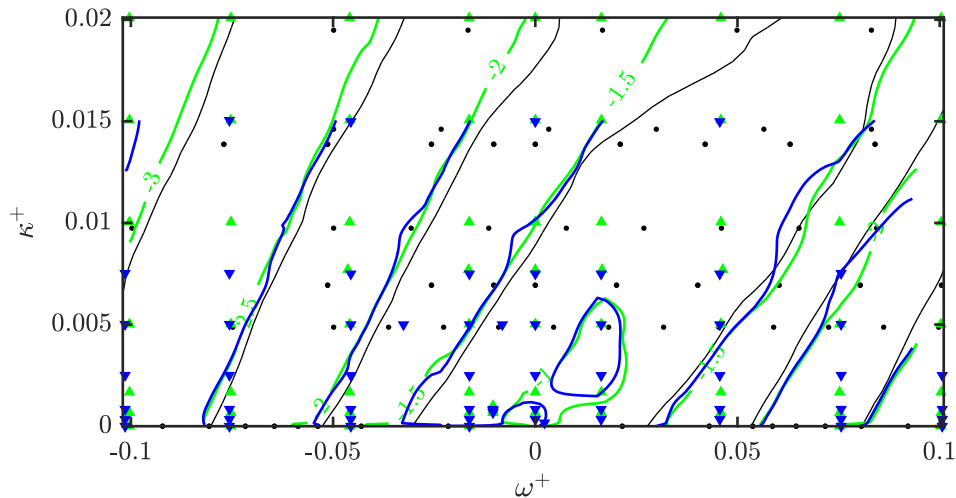
Net power saving \mathcal{S}

$$\mathcal{S} = \mathcal{R} - P_{in}/P_{p0} = \mathcal{R} - P_{in}^+/U_{b0}^+$$



Control input power P_{in}^+

Constant with Re in viscous units



Reynolds-number dependence of \mathcal{S}

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

