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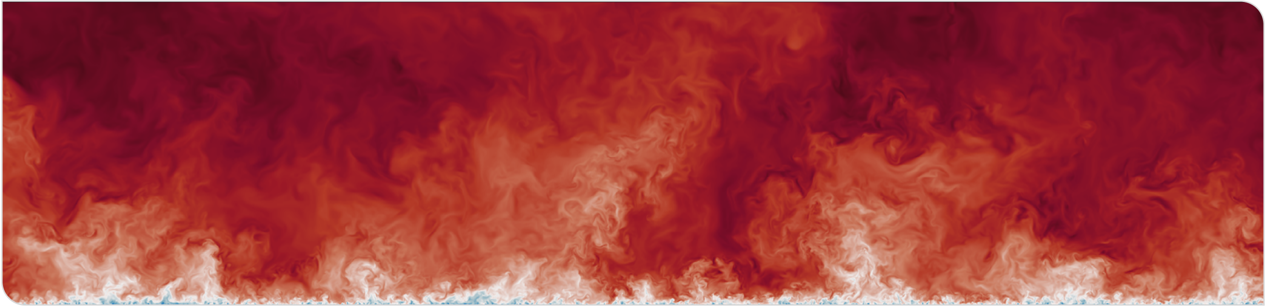
Numerical Study of turbulent skin-friction drag reduction via spanwise forcing at large Reynolds numbers

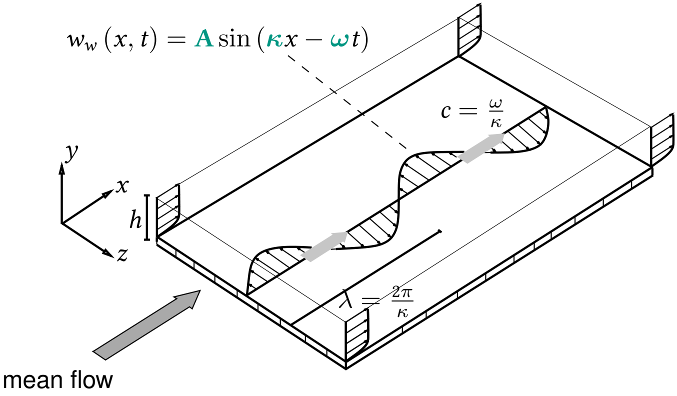
European Drag Reduction and Flow Control Meeting 2024, Turin, Italy

D. Gatti, M. Quadrio, F. Gattere, A. Chiarini, S. Pirozzoli | 10^{th} September 2024



Streamwise-travelling waves of spanwise wall velocity

Quadrio, Ricco & Viotti, JFM (2009)



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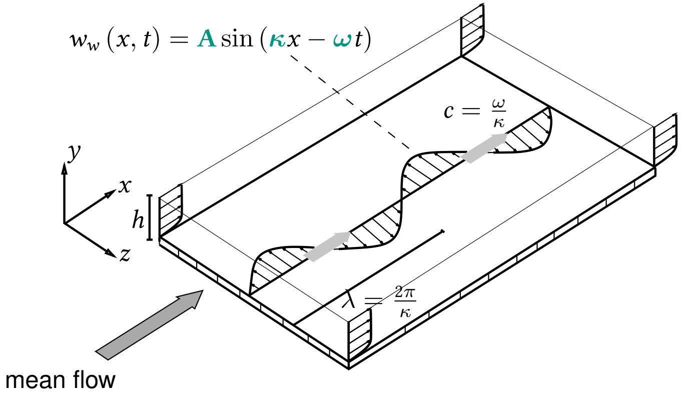

Pumping power: P_p

Drag reduction rate:

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

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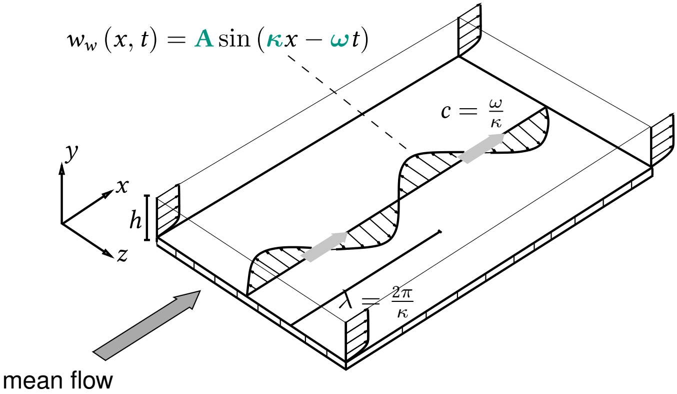

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Control input power: P_{in}

Net power saving rate:

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

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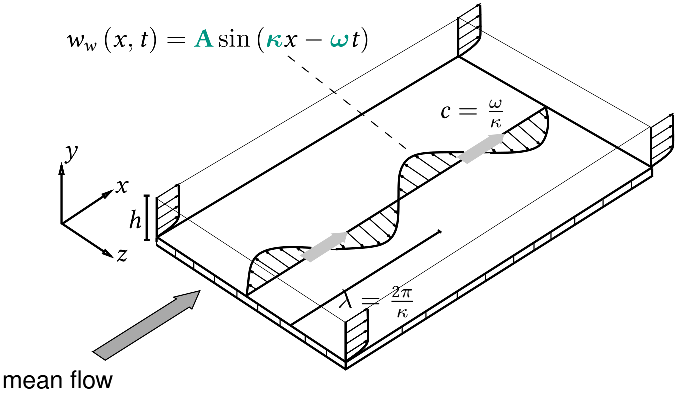

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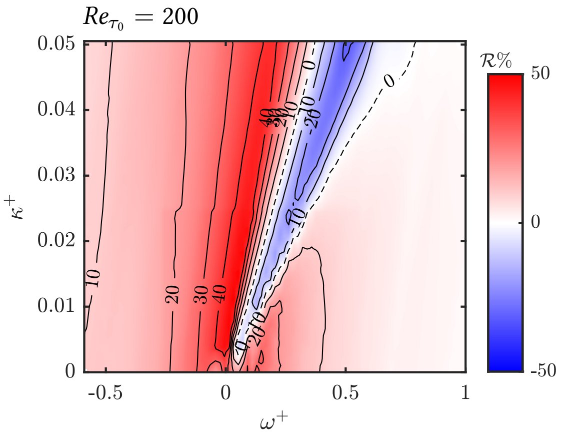
$\mathcal{R}$ and $\mathcal{S}$ depend on A, κ, ω and Reynolds number Re!

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

Data by Gatti & Quadrio, JFM (2016)



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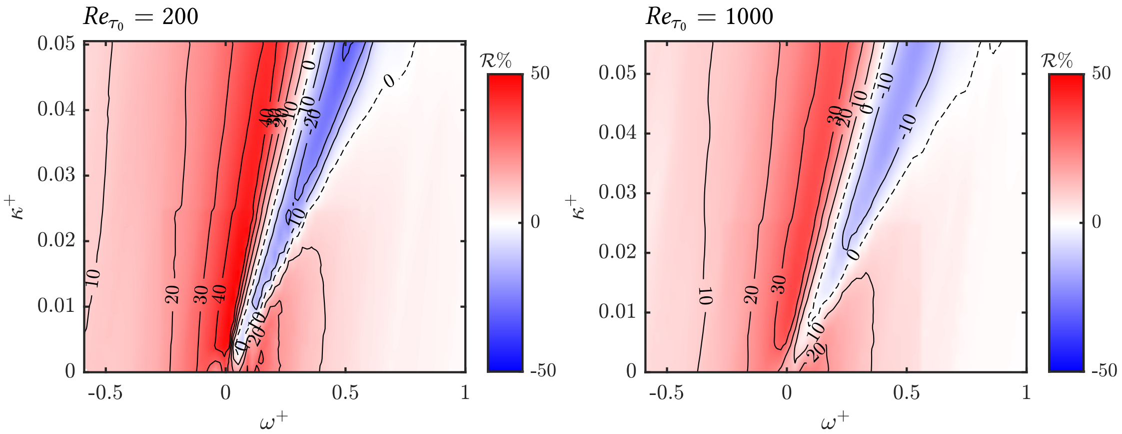

The Re-dependency of drag reduction

Twenty years of research, and counting...

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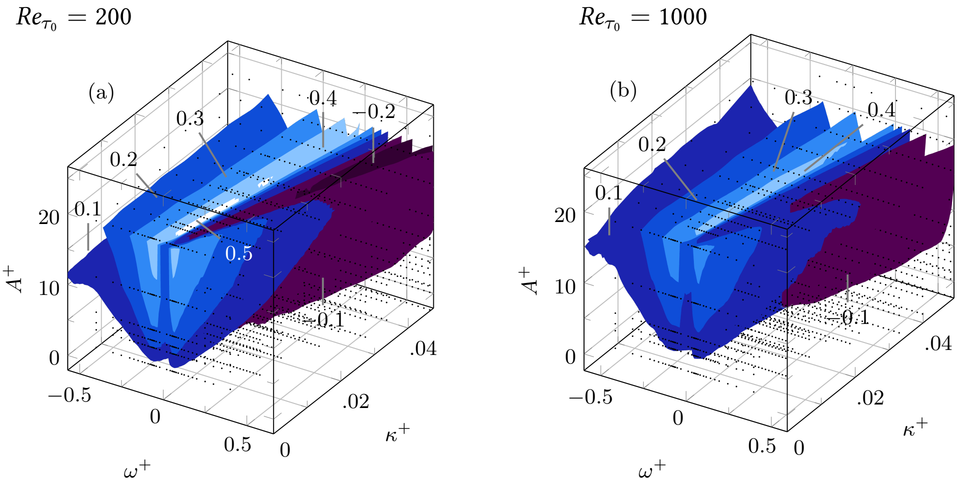
- Difficult to study: many parameters, difficulty to reach large Re
- $\mathcal{R}$ decreases with Re
- Early studies on wall oscillations ($\kappa = 0$):
  - $\mathcal{R}$ decreases rapidly with Re as $\mathcal{R} \sim Re_{\tau_0}^{\gamma}$

    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)

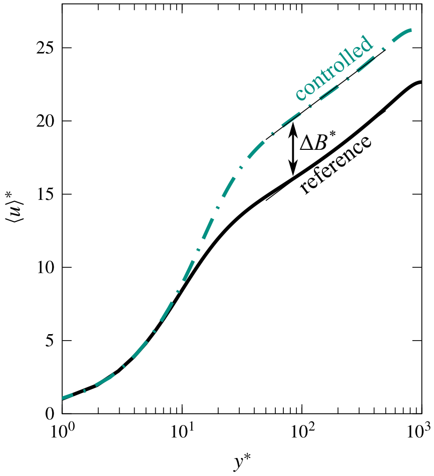
The GQ database

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^*

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

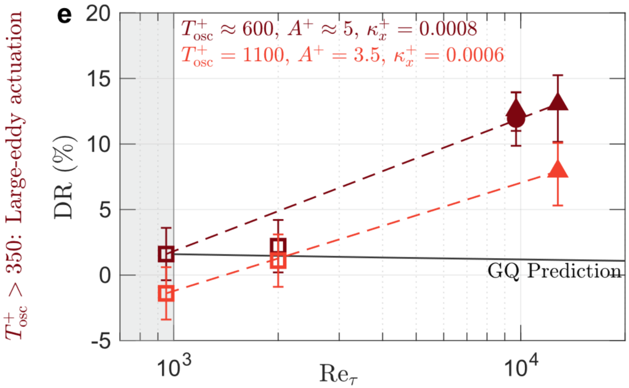
- $\Delta B^* = \Delta B^*(A^*, \kappa^*, \omega^*)$ is Re-independent
- A modified P-vK friction relation describes the Re-dependency of $\mathcal{R}$:

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

- $\mathcal{R}$ 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

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

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



$Re_{\tau_0} \leq 2000$:

- 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

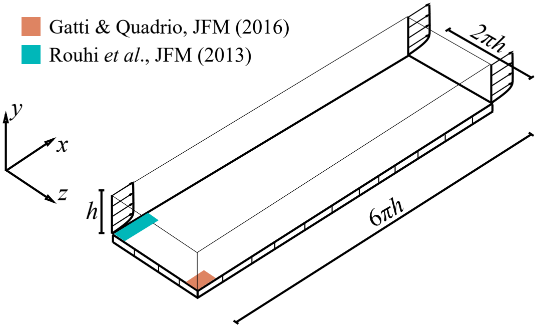
- Gatti & Quadro, JFM (2016) and Rouhi *et al.*, JFM (2023) utilised small domains and relatively small Re
- Marusic et al., Nature comm. (2021) compares results obtained with different flows and methods

motivate the present study

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

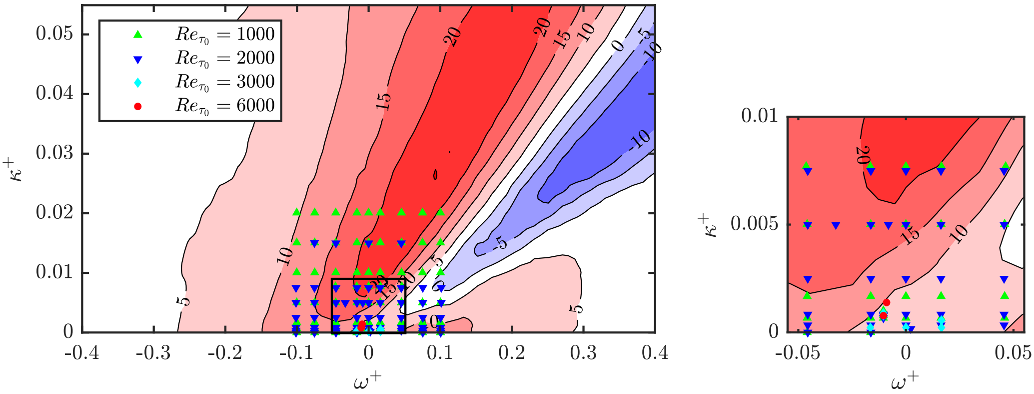
Methods

- 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)

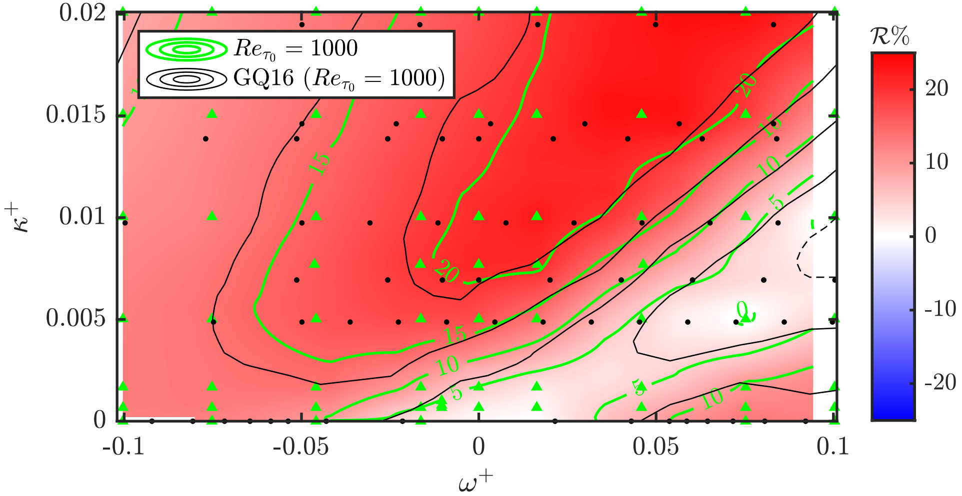


The new numerical database

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



Drag reduction rate $\mathcal{R}$



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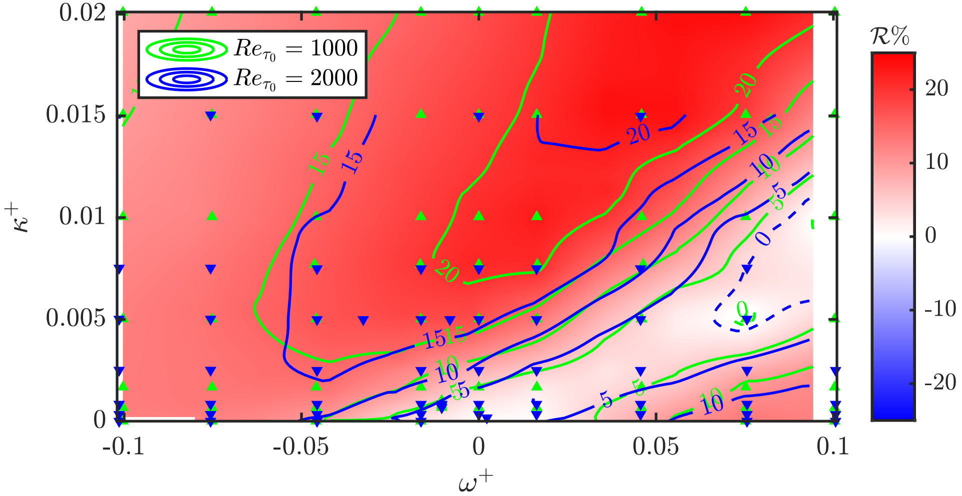
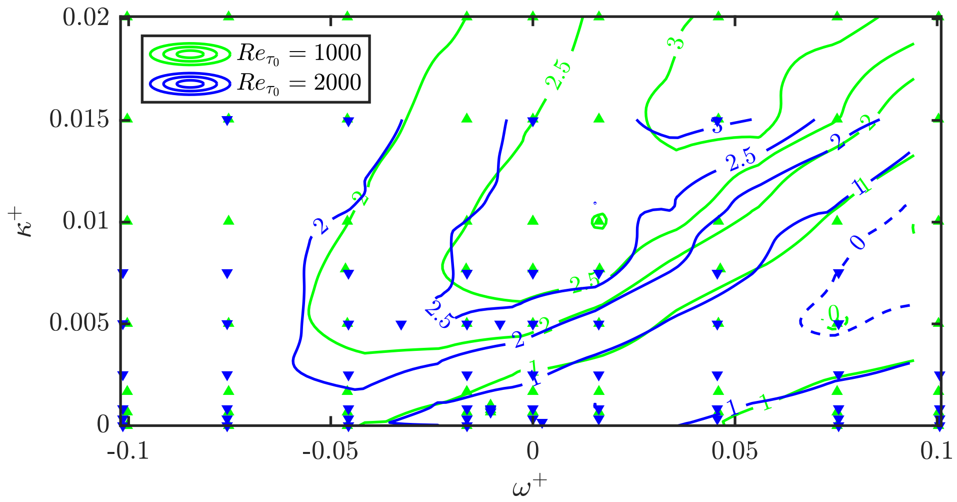


Roughness function ΔB^*



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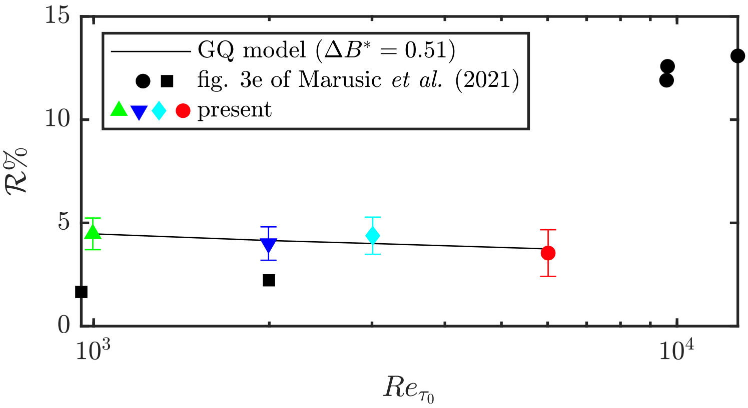
Does $\mathcal{R}$ increase with Re?

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



Conclusion

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- 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

Net power saving $\mathcal{S}$

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

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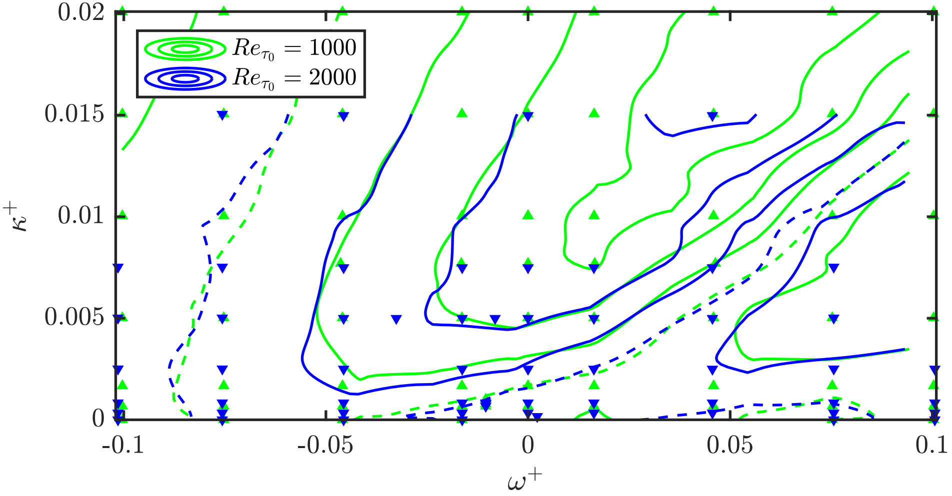

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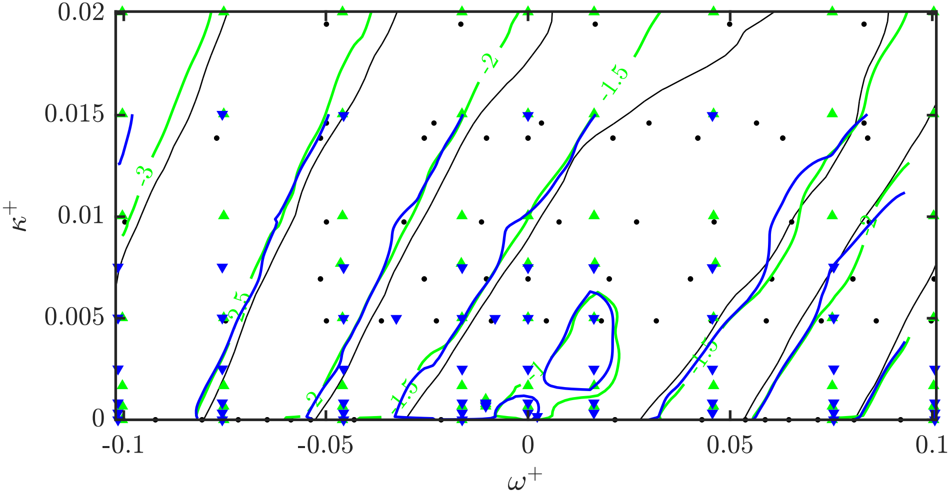
Control input power P_{in}^{+}

Constant with Re in viscous units



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

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