Modification of turbulent friction drag by streamwise-traveling waves of spanwise wall velocity

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MOTIVATION AND TECHNIQUES

Motivation

- Understanding flow physics
- Flow modification for a better system efficiency

Turbulent friction drag reduction

- Active technique
- Net energy balance: $P_{net}(\%) = DR(\%) - P_{sp}(\%)$
- Accuracy is key to calculate net balance

Spanwise forcing of near-wall turbulence

- Spanwise wall oscillation below wall turbulence - *TIME*
- Standing wave of spanwise wall velocity - *SPACE*
- Traveling waves of spanwise wall velocity - *SPACE-TIME*

Channel flow: DNS Politecnico di Milano

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Spanwise wall oscillations

$$W = W_m \sin(2\pi t/T)$$

- W_m maximum wall velocity - T period of oscillation

Standing wave of spanwise wall velocity

$$W = W_m \sin(2\pi x/\lambda_x)$$

- λ_x streamwise wavelength

Streamwise-traveling waves of spanwise wall velocity

$$W = W_m \sin(\kappa_x x - \omega t)$$

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TURBULENT DRAG REDUCTION

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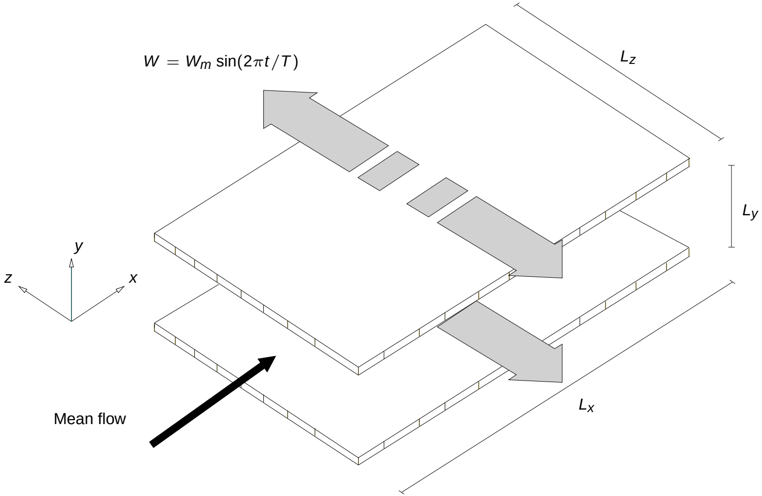
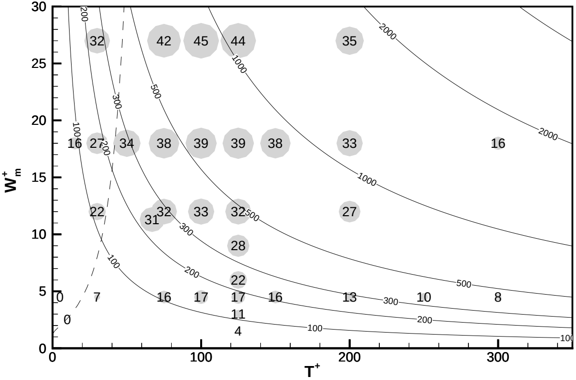
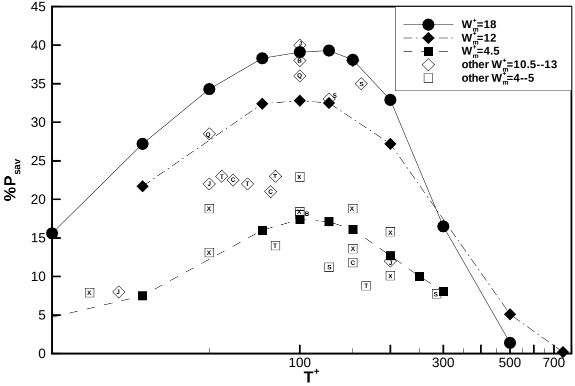
THE OSCILLATING-WALL FLOW



MAP OF DRAG REDUCTION

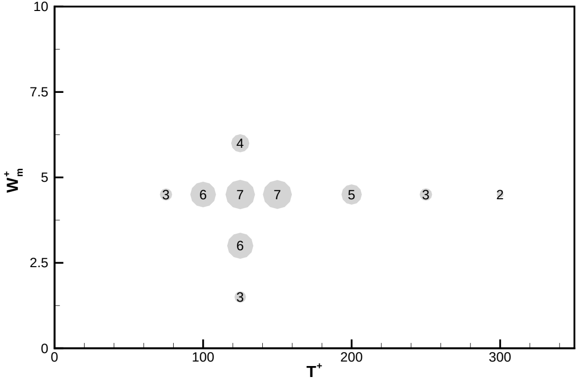


- $DR\%$ as function of W_m and T
- Optimal frequency - $DR\%$ grows with W_m



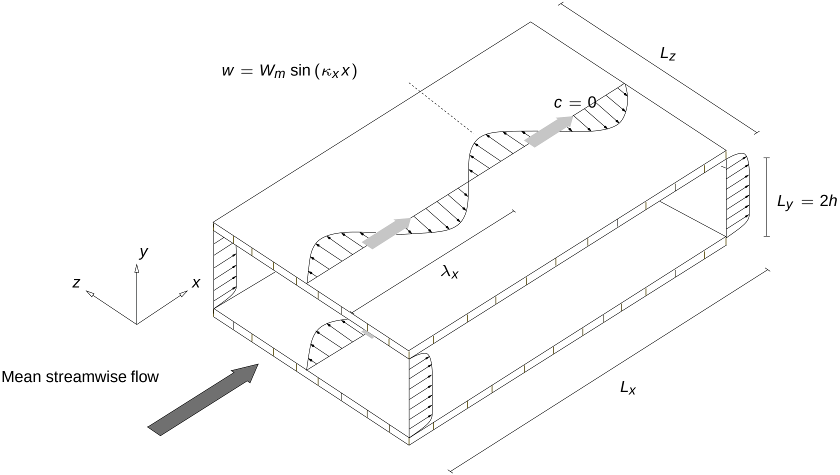
- Optimal frequency at fixed W_m
- It does not depend on W_m

MAP OF NET ENERGY SAVING

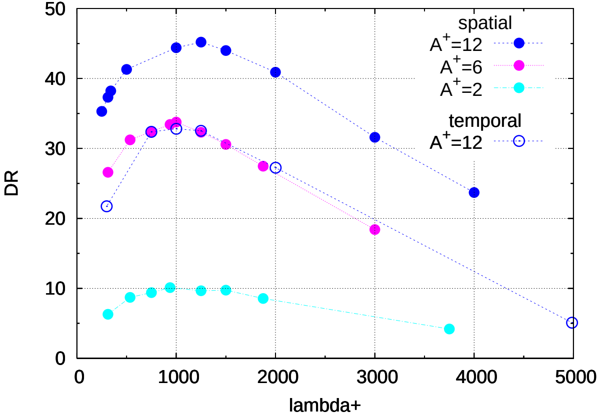


- Net energy balance: $P_{net}(\%) = DR(\%) - P_{sp}(\%)$
- Optimal T - Optimal W_m - unsteady $\rightarrow$ NOT practical

THE STANDING-WAVE FLOW



OPTIMAL WAVELENGTH



- **Optimal wavelength - U_W convection velocity**
- $U_W = \lambda_{x,opt} / T_{opt}$ - steady → roughness?

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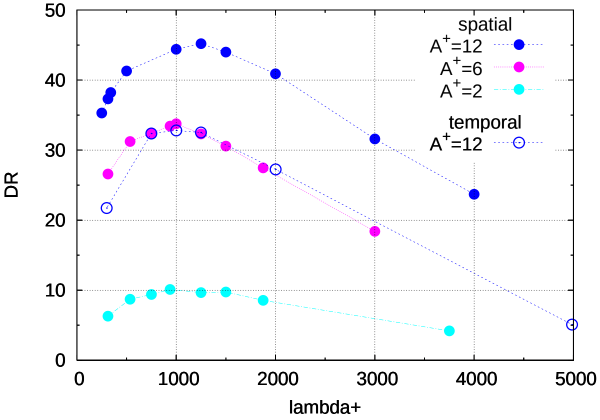

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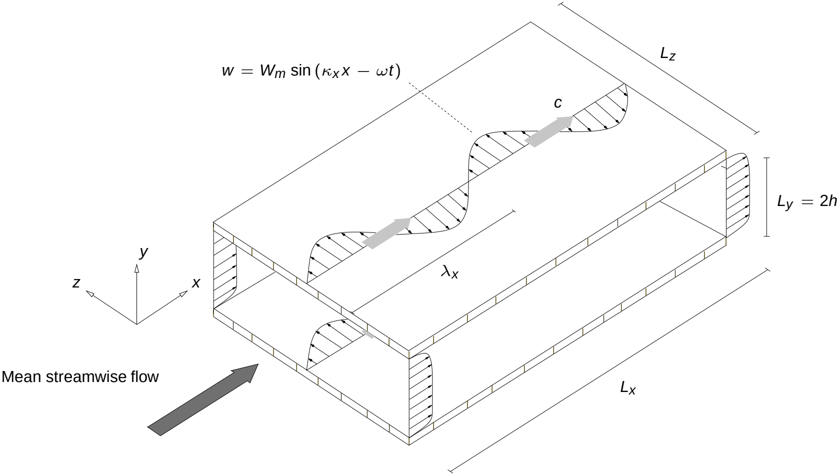
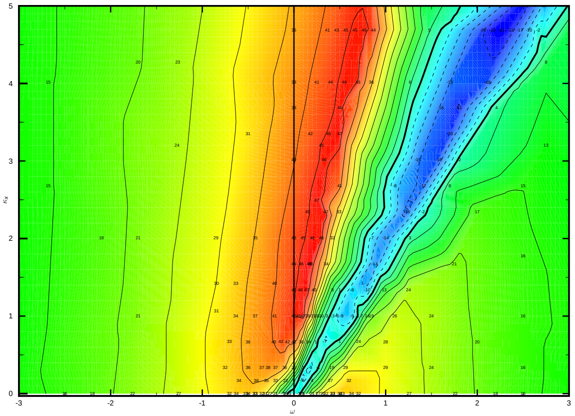
THE TRAVELING-WAVE FLOW

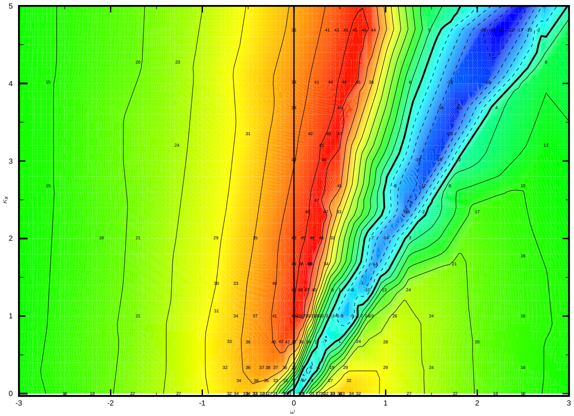


MAP OF DRAG MODIFICATION - W_m^+=12



- Blue: ***Drag increase*** $\sim$ ***20%*** - $c \approx U_w$
- Red: ***Drag reduction*** $\sim$ ***45%***

MAP OF DRAG MODIFICATION - $W_m^+=12$



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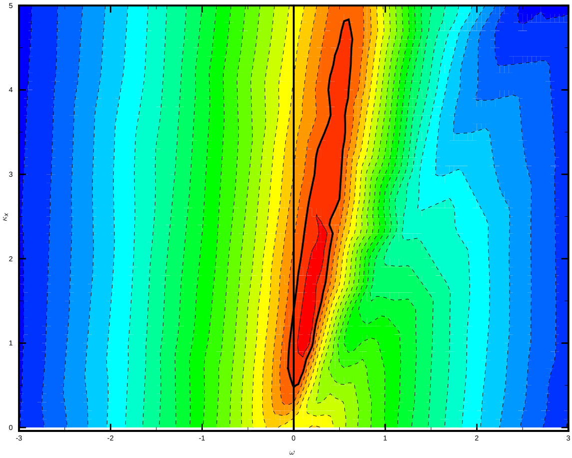

- Red-thick line - ***Positive net balance: MAX*** $\approx$ ***18%***
- Oscillating wall give *negative* balance at this W_m^+

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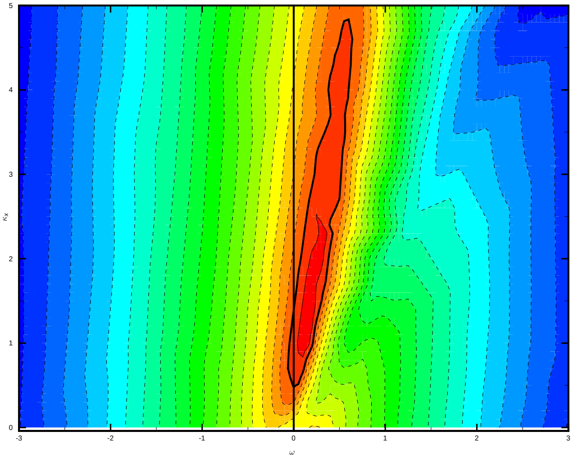

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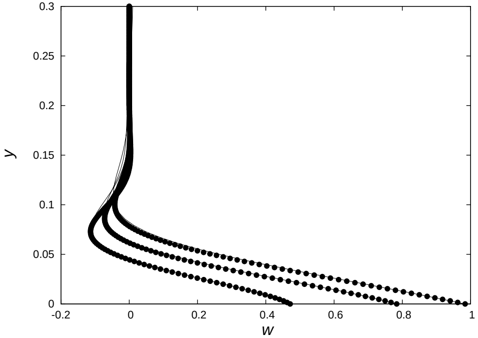
TURBULENT AND LAMINAR SPANWISE FLOW



- $w = W_m \Re\{C e^{2\pi i(x-ct)/\lambda_x} \mathbf{Ai}\left[e^{\pi i/6}\left(2\pi\tau^*/(\lambda_x \nu)\right)^{1/3}(y - c/u_\tau)\right]\}$
- Good agreement despite simplifications small δ - long λ_x
- Major advantage for further analysis DR scaling

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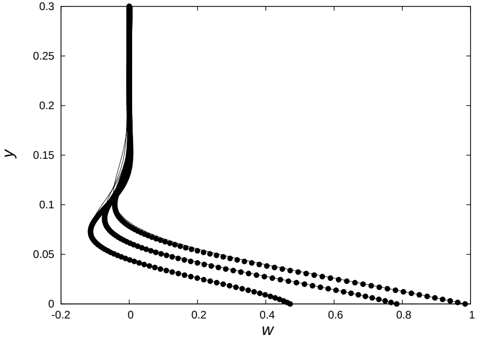

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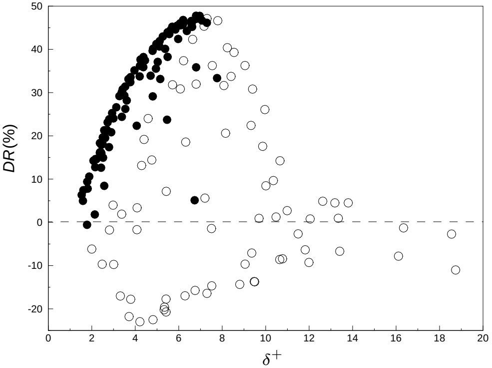

$$\mathcal{T} \equiv \frac{\lambda_x}{\mathcal{U}_w - c} = \frac{2\pi}{\mathcal{U}_w \kappa_x - \omega}$$

Equivalent period of forcing - MINIMAL CONDITIONS $\delta^+ \approx 1$

SUMMARY AND FUTURE WORK

Summary

- **Oscillating wall**: nice, instructive, **not** practical
- **Standing wave**: **steady** - roughness?
- **Traveling wave**: highly efficient!

Future work

- Physics: near-wall turbulence
- Scaling of drag modification
- Experiments on traveling waves!