Spanwise generalized Stokes layer and turbulent drag reduction

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Outline

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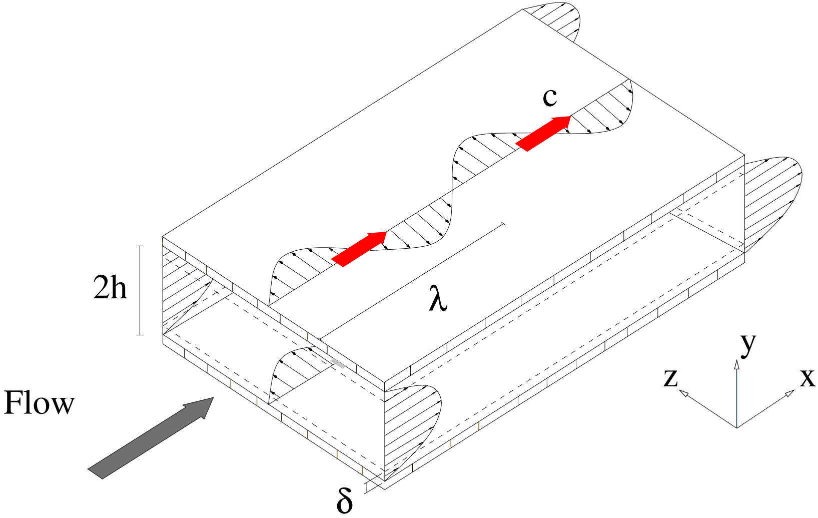
Turbulent drag reduction with streamwise-travelling waves

Laminar Generalized Stokes Layer (GSL)

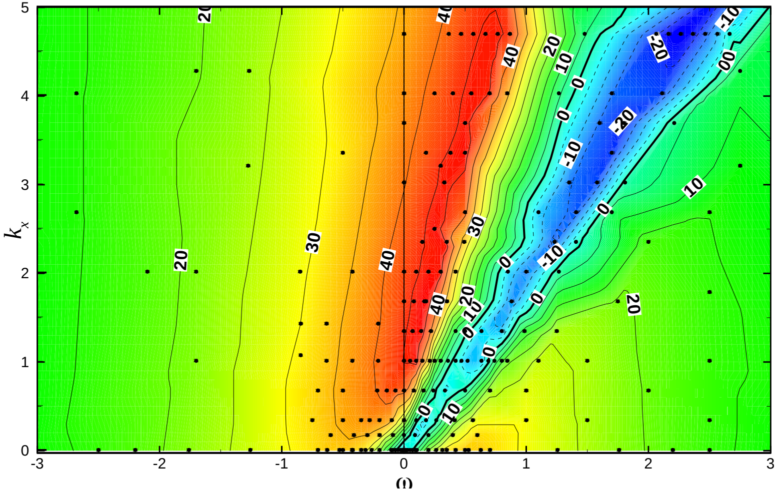
Putting things together

The travelling waves



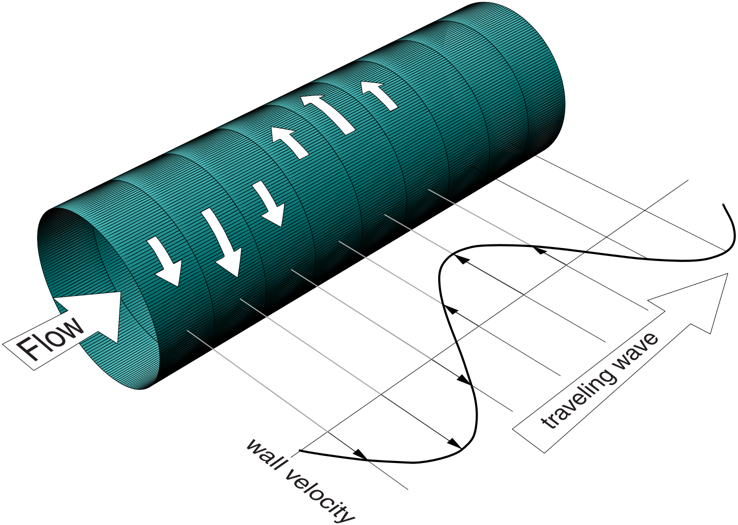
Results from DNS (plane channel)

Quadrio et al., JFM 2009

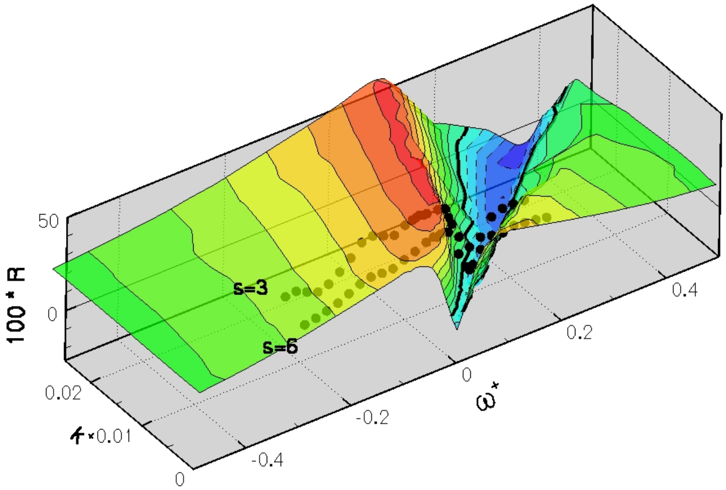


Laboratory experiment (cylindrical pipe)

Auteri et al, Phys. Fluids (2010), in press



Drag variation



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Laminar flow: the GSL equation

Quadrio & Ricco JFM 2010, in press

$$\boxed{\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} = \nu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right)}$$

- TSL (Stokes)
- SSL
- All together: GSL
- one-way coupling with streamwise flow

The analytical solution

1. $\delta \ll h$ (translates into $\lambda/h \ll Re_b$)
2. Linear u profile

$$w(x, y, t) = A \Re \left\{ C e^{2\pi i (x - ct)/\lambda} \mathrm{Ai} \left[e^{\pi i/6} \left(\frac{2\pi u_{y,w}}{\lambda \nu} \right)^{1/3} \left(y - \frac{c}{u_{y,w}} \right) \right] \right\}$$

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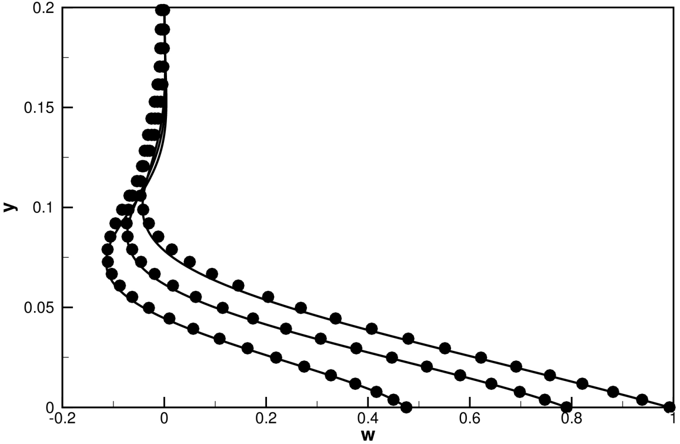
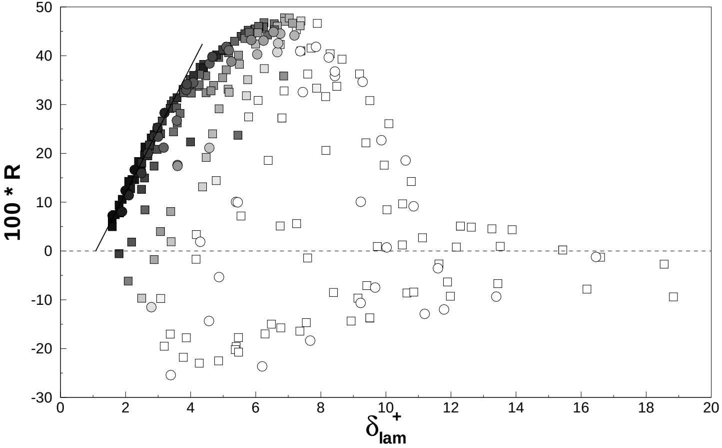
Turbulent spanwise flow agrees with laminar GSL!



Using the GSL solution

R vs analytical δ_{GSL}

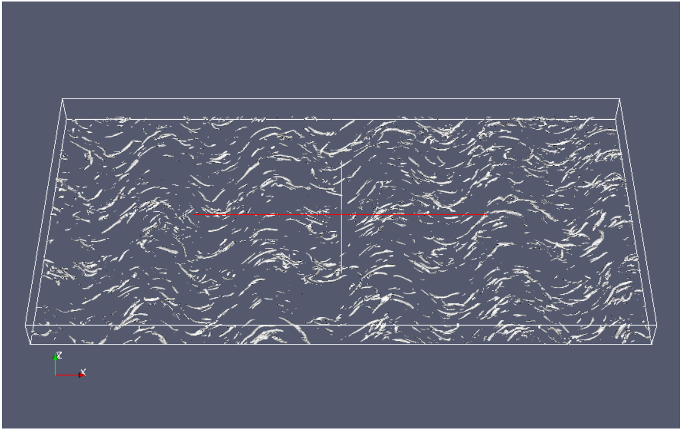
Black points are "good" waves



How the waves increase drag

Key parameter: phase speed

- Waves lock with the convecting structures
- Steady forcing in the convective reference frame: $c^+ \approx U_c^+$



How the waves decrease drag

Key parameter: unsteadiness

- Drag reduction is proportional to δ_{GSL} (WHY?)
- Large $\delta_{GSL} \Rightarrow$ large T
- Quasi-steady forcing when $T \gg T_\ell$

Limit to drag reduction

Forcing must be 'unsteady'

Forcing on a timescale $\gg T_\ell$ does not yield DR

Oscillating wall

- Forcing timescale: oscillation period T

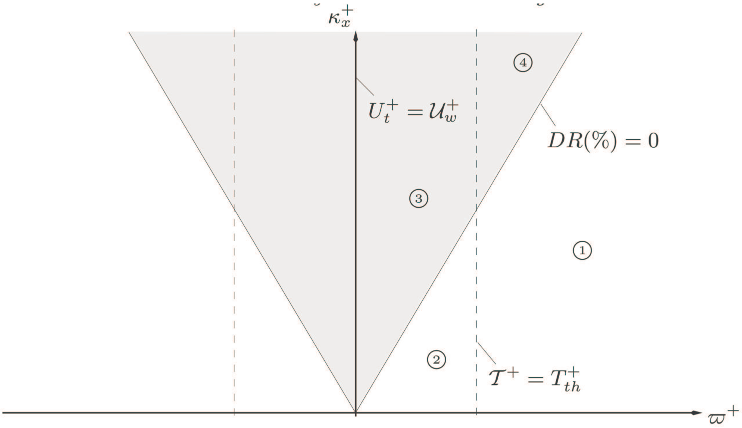
Travelling waves

- Forcing timescale: oscillation period $\mathcal{T}$ as seen by the convecting structures

$$\boxed{\mathcal{T} = \frac{\lambda}{U_c - c}}$$

Waves and turbulent friction

Waves in (1) and (2) are "good" waves



Conclusions

- Waves reduce drag and are energy-efficient
- Waves useful for understanding drag-reduction mechanism
- Still incomplete understanding of the physics
- Analytical solution for the GSL
- Relation between laminar GSL and turbulent drag reduction

Issues

- Further understanding (why is $\delta_{GSL} \sim R$?)
- Actuators
- Higher efficiency?
- *Re* effects

THANK YOU