Spanwise generalized Stokes layer and turbulent drag reduction

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Outline

Turbulent drag reduction with streamwise-travelling waves

Laminar Generalized Stokes Layer (GSL)

Putting things together
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
Outline

Turbulent drag reduction with streamwise-travelling waves

**Laminar Generalized Stokes Layer (GSL)**

Putting things together
Laminar flow: the GSL equation

Quadrio & Ricco JFM 2010, in press

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

- 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

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

Turbulent drag reduction with streamwise-travelling waves

Laminar Generalized Stokes Layer (GSL)

Putting things together
Turbulent spanwise flow agrees with laminar GSL!
Using the GSL solution

\( R \) vs analytical \( \delta_{GSL} \)

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 $\delta_{GSL}$ (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

\[ \mathcal{T} = \frac{\lambda}{U_c - c} \]
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