Drag-reducing characteristics of the generalized spanwise Stokes layer: experiments and numerical simulations

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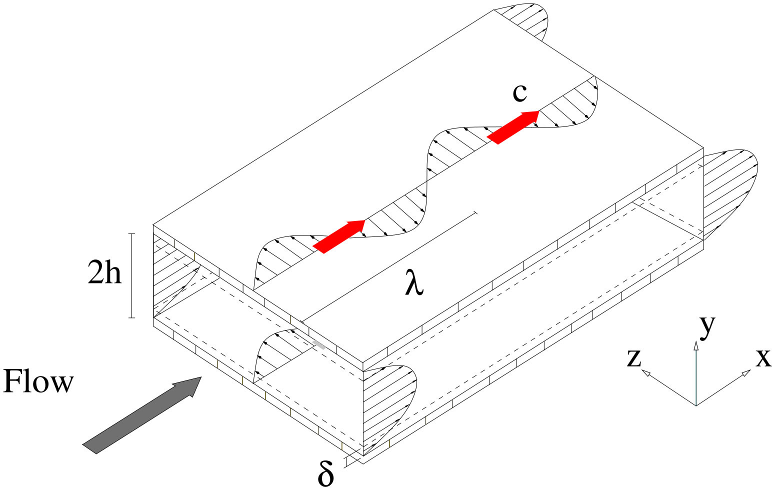
Tokyo, March 18th, 2010

Outline

Outline

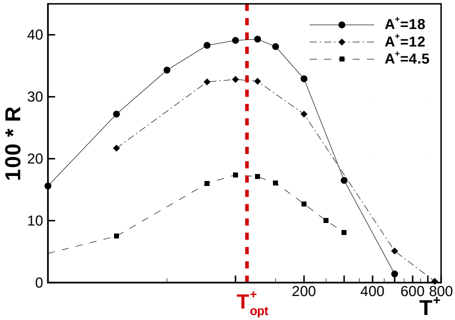
The travelling waves



The original idea: spanwise wall oscillation
Quadrio & Ricco, JFM '04

$$w(x, y = 0, z, t) = A \sin(\omega t)$$

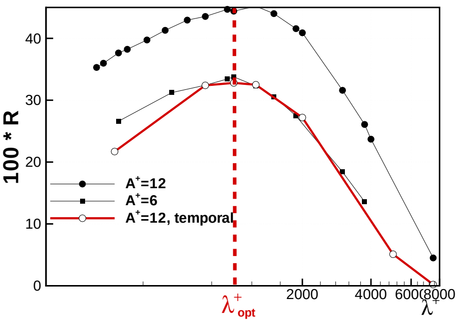
- Large reductions of turbulent friction
- Unpractical



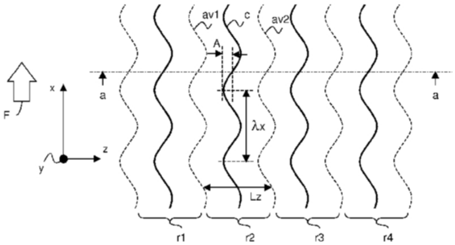
The oscillating wall made stationary
Viotti, Quadrio & Luchini, ETC 2007

$$w(x, y = 0, z, t) = A \sin(\kappa x)$$

- Existence of an optimal wavelength $\lambda_{opt} = U_c T_{opt}$
- Can be implemented as a passive device (sinusoidal riblets)



- Promising roughness distribution
- Better than straight riblets?



The traveling waves: a natural extension

Purely temporal forcing

The oscillating wall:

$$w = A \sin(\omega t)$$

Infinite phase speed

Purely spatial forcing

The steady waves:

$$w = A \sin(\kappa x)$$

Zero phase speed

Combined space-time forcing

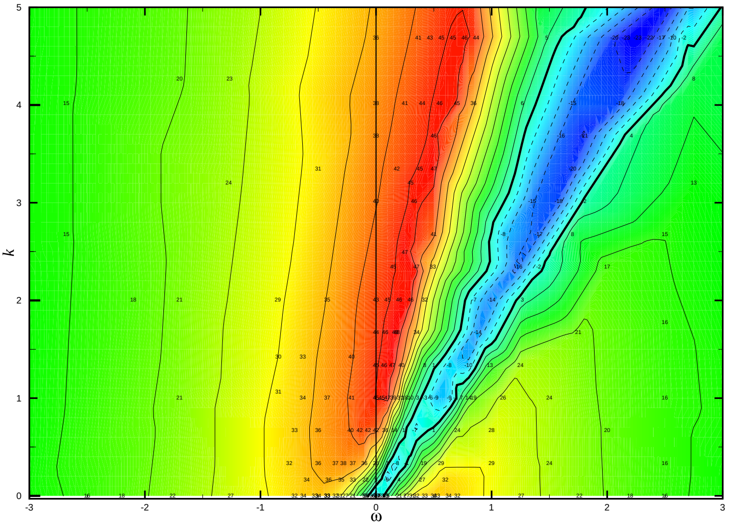
The traveling waves:

$$w = A \sin(\kappa x - \omega t)$$

Finite phase speed $c = \omega / \kappa$

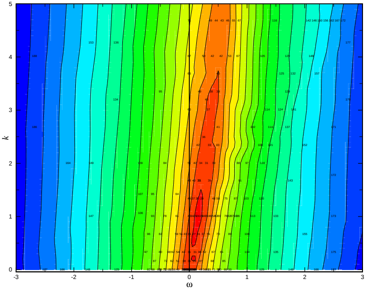
Results from DNS (plane channel)

Quadrio et al., JFM 2009

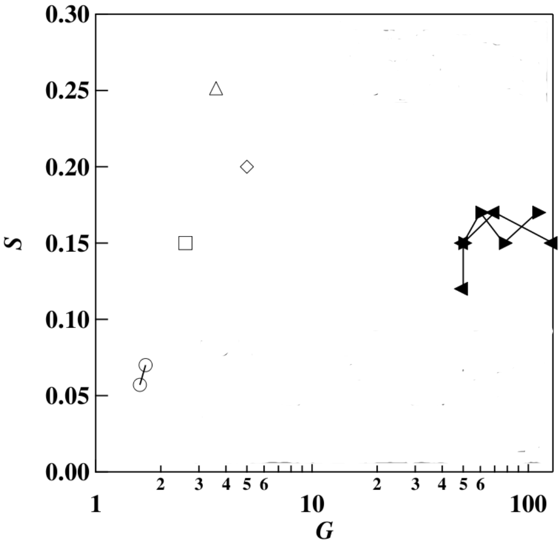


How much power to generate the waves?

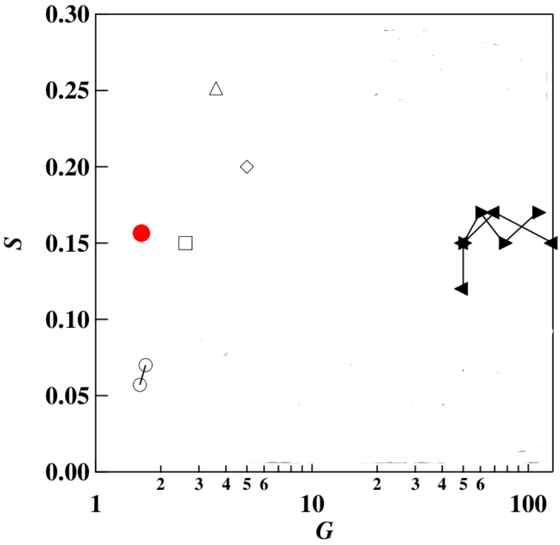
- Map of P_{in} is similar to map of R!
- S and G may get very high



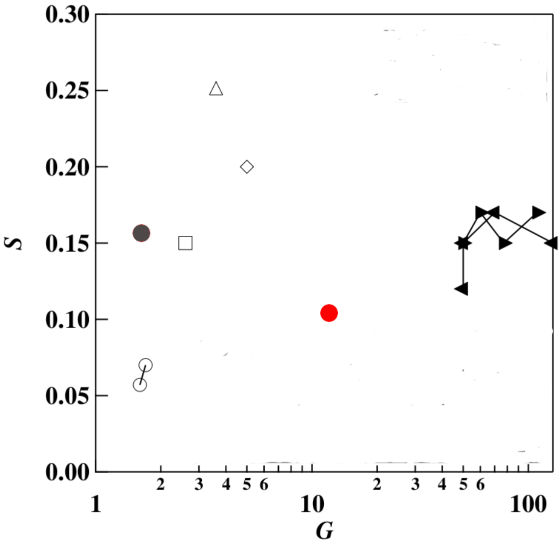
Power efficiency



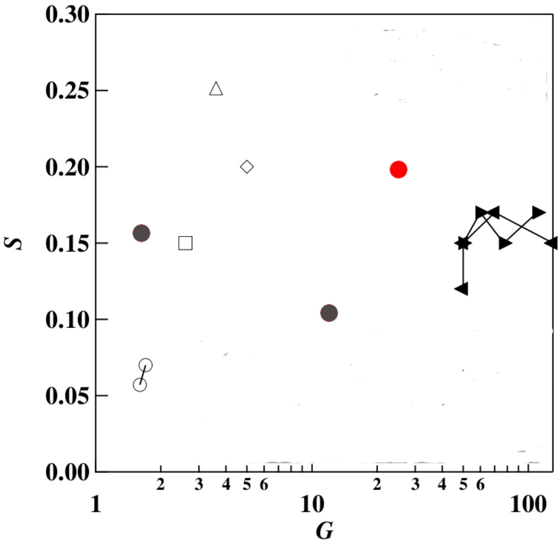
Power efficiency



Power efficiency



Power efficiency



Outline

Why?

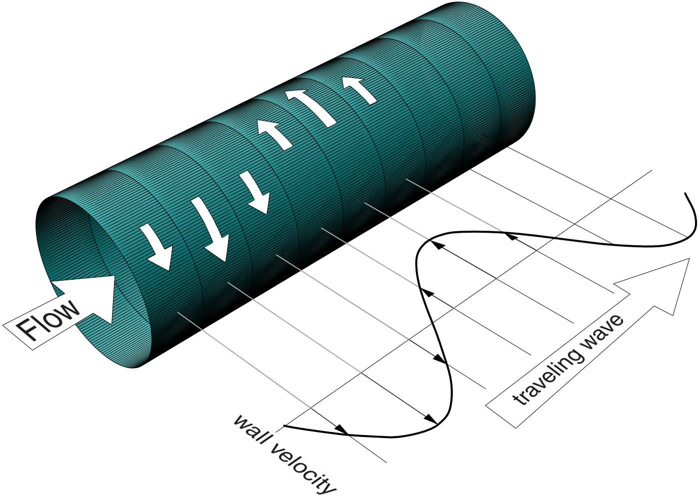
A proof-of-principle experiment to:

- confirm drag reduction
- improve understanding of the travelling waves

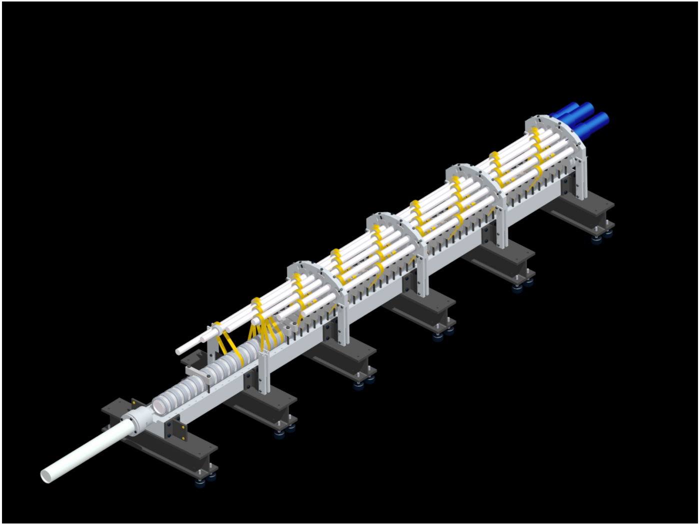
Main design choices

- Cylindrical pipe
- Friction is measured through pressure drop
- Spanwise wall velocity: wall movement
- Temporal variation: unsteady wall movement
- Spatial variation: the pipe is sliced into thin, independently-movable axial segments

The concept

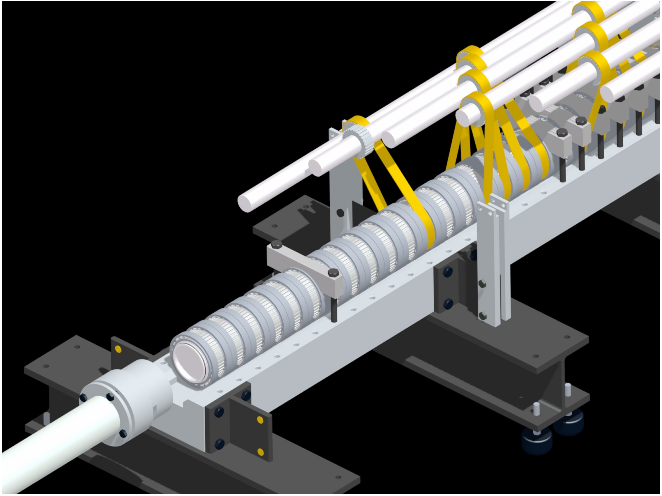


A global view

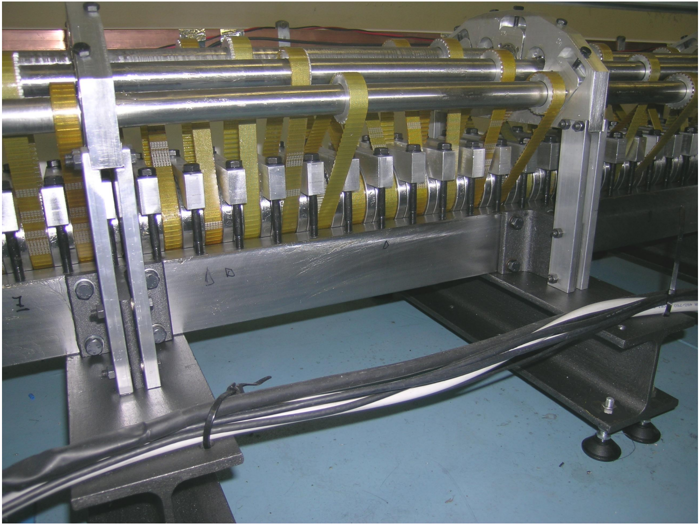


Closeup of the rotating segments

60 slabs with 6 independent motors



The transmission system
Shafts, belts and rotating segments



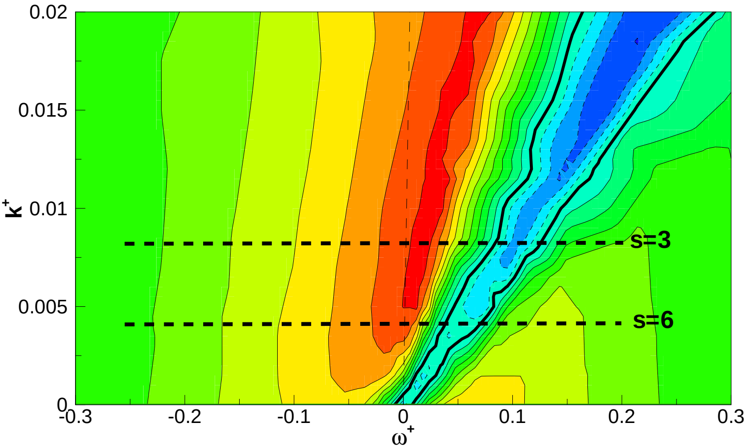
The control system

- Slab motion is feedback-controlled
- Tachimetric sensors
- Vertically-moving reservoir

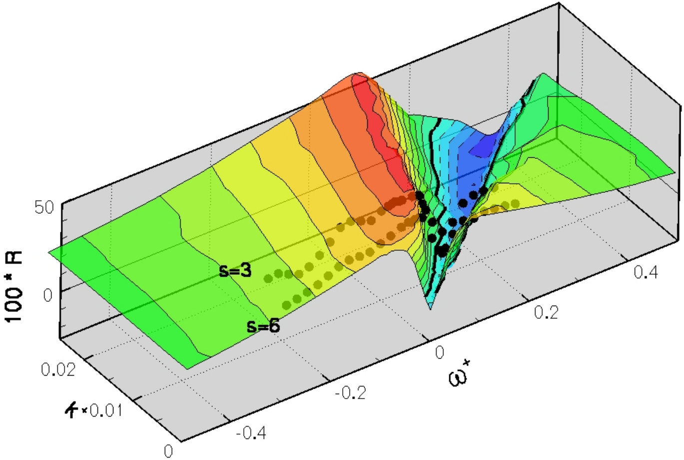
Flow parameters

- Water, $Re = 4900$ or $Re_\tau = 175$
- Reference pressure drop $\approx$ 10 Pa!
- Anticorrosion device
- Pressure sensors flooded in water
- Friction factor verifies Prantl's empirical correlation

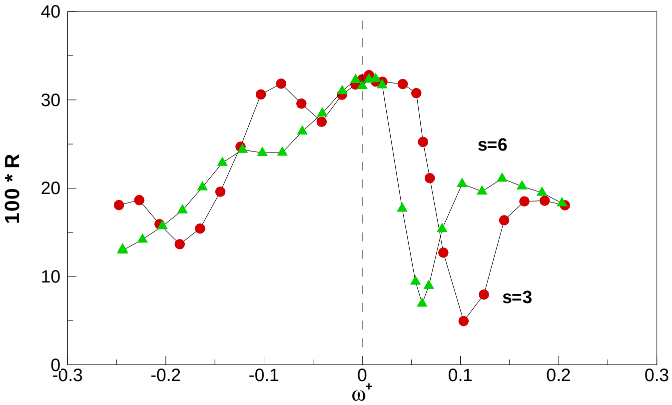
Experimental conditions



Drag variation (1)



Drag variation (2)

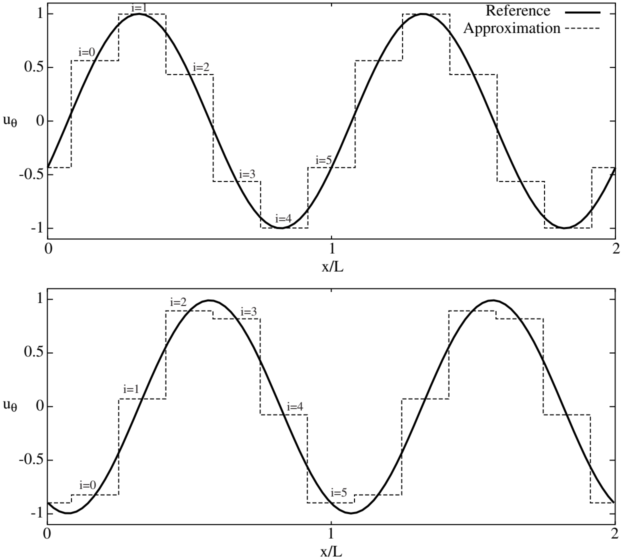


Comments

Quantitative agreement between DNS and experiment is not expected:

- Spatial transient
- Cylindrical vs planar geometry
- Difference (small) in *Re* and *A*
- Waveform effects

The discrete waveform



Fourier expansion of the discrete wave

s=3

$$\tilde{w} = \frac{3\sqrt{3}}{2\pi} A \left\{ \sin\left(\omega t - \kappa x\right) + \frac{1}{2} \sin\left(\omega t + 2\kappa x\right) + \ldots \right\}$$

s=6

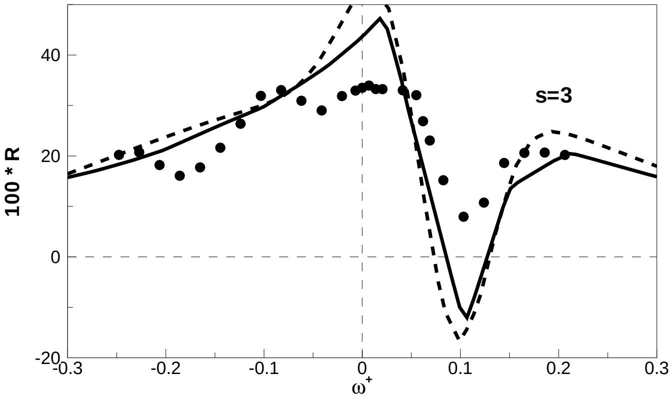
$$\tilde{w} = \frac{3}{\pi} A \left\{ \sin\left(\omega t - \kappa x\right) + \frac{1}{5} \sin\left(\omega t + 5\kappa x\right) + \ldots \right\}$$

Integral representation of the R map

$$R(\omega,\kappa)=\int\int K(\tau,\xi)f_{\omega,\kappa}(\tau,\xi)\,d\tau d\xi$$

- $f_{\omega,\kappa}(\tau,\xi)$ is the sinusoidal wave (monocromatic)
- Kernel K empirically determined by fitting DNS results

The monocromatic R map

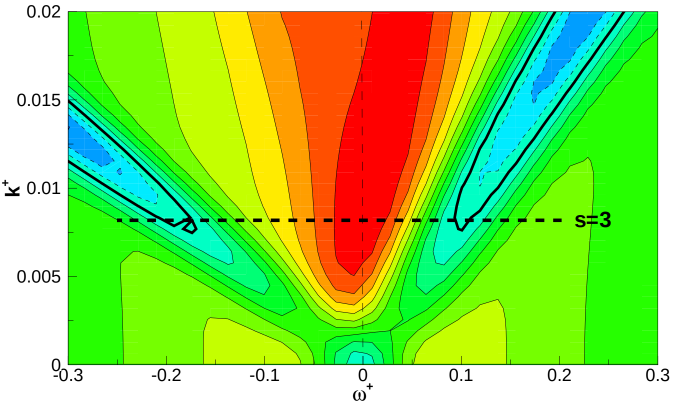


The non-monocromatic wave

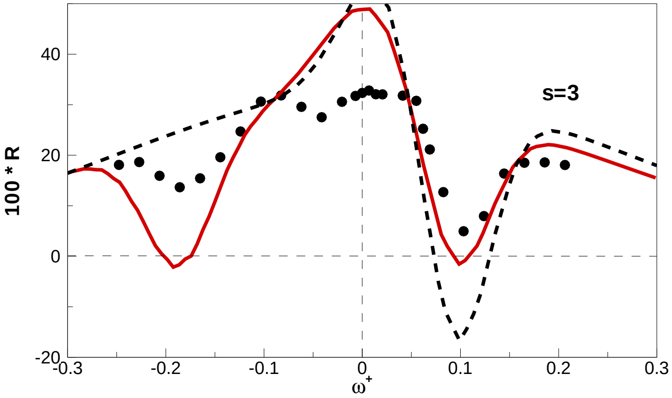
The generating wave does not need be monocromatic
Suppose linear superposition:

$$\tilde{R}(\omega,\kappa) = \int\int K(\tau,\xi)\left[f_{\omega,\kappa} + \frac{1}{2} f_{\omega,-2\kappa}\right] \mathrm{d}\tau \mathrm{d}\xi$$

The non-monocromatic $\tilde{R}$ map



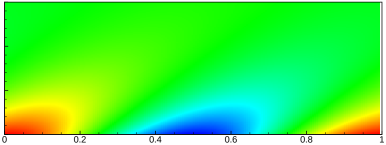
Wiggles are predicted!



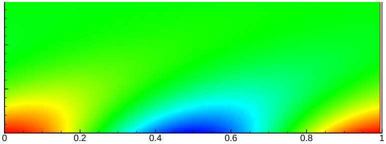
- Wiggles in the experimental data are discretization effects

Outline

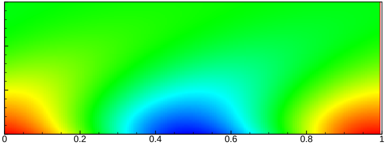
The spanwise laminar flow



$w(y, t)$



$w(y, x)$



$w(y, x - ct)$

Laminar: the GSL equation

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

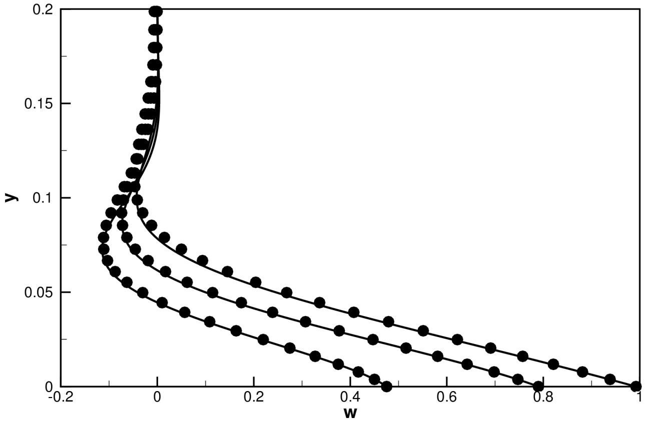
- TSL (Stokes)
- SSL (Viotti et al, PoF 2009)
- one-way coupling with streamwise flow

The analytical solution

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

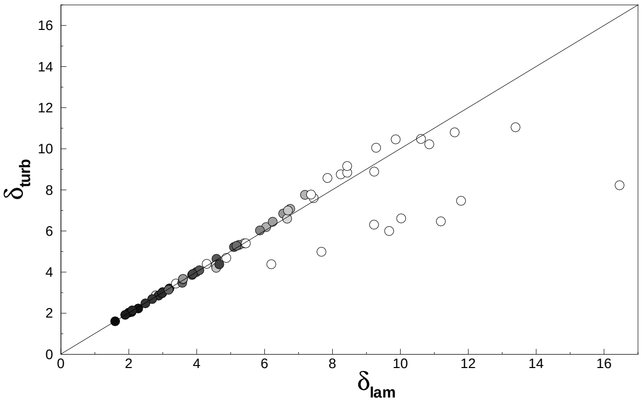
$$w(x,y,t) = A\Re\left\{Ce^{2\pi i(x-ct)/\lambda}\,\mathrm{Ai}\left[e^{\pi i/6}\left(\frac{2\pi u_{y,w}}{\lambda\nu}\right)^{1/3}\left(y-\frac{c}{u_{y,w}}\right)\right]\right\}$$

Spanwise turbulent flow agrees with the GSL



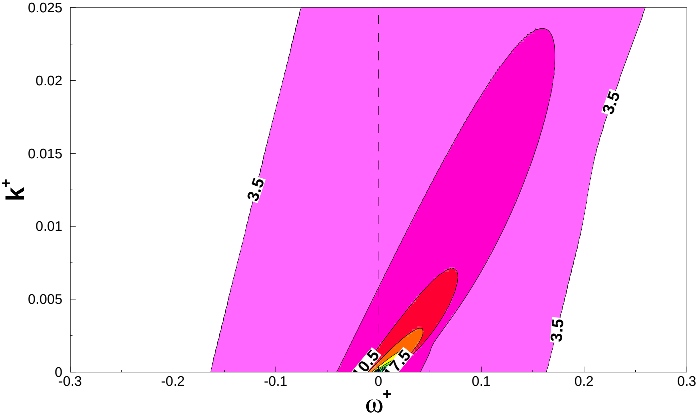
Using the GSL solution (1)
Turbulent (DNS) vs laminar (analytical) δ_{GSL}

Black points are “good” waves



Using the GSL solution (2)

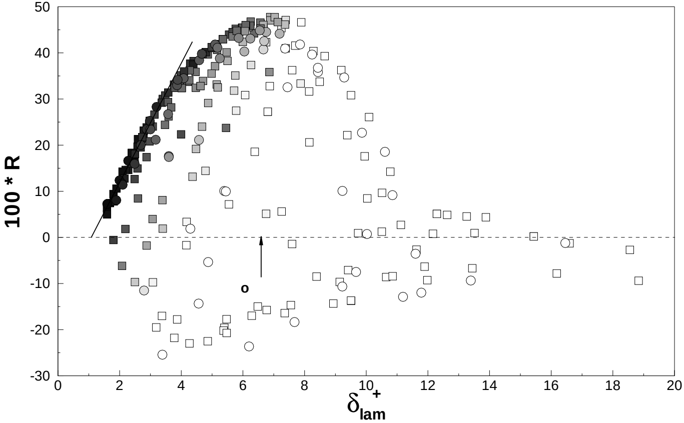
Map of analytical δ_{GSL}



Using the GSL solution (3)

R vs analytical δ_{GSL}

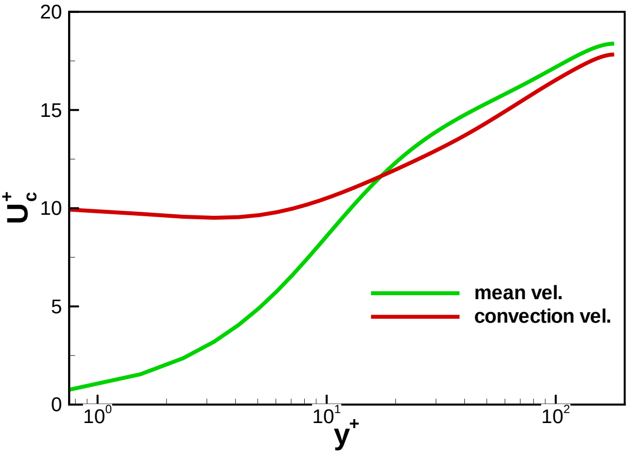
Black points are “good” waves



Outline

The near-wall convection velocity U_c

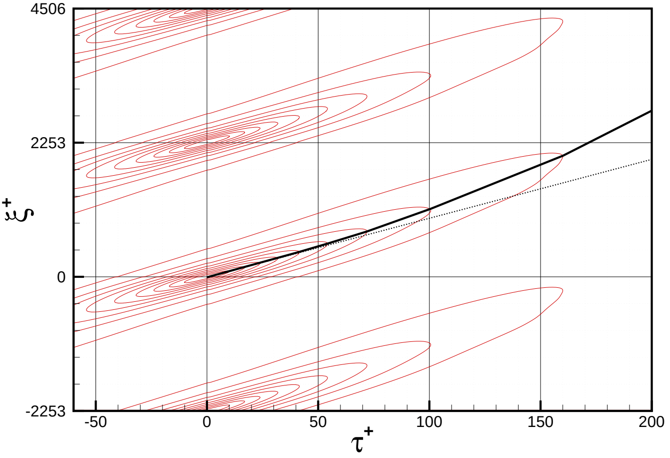
Quadrio & Luchini, PoF 2003



Near-wall physics 2: the turbulence lifetime T_ℓ

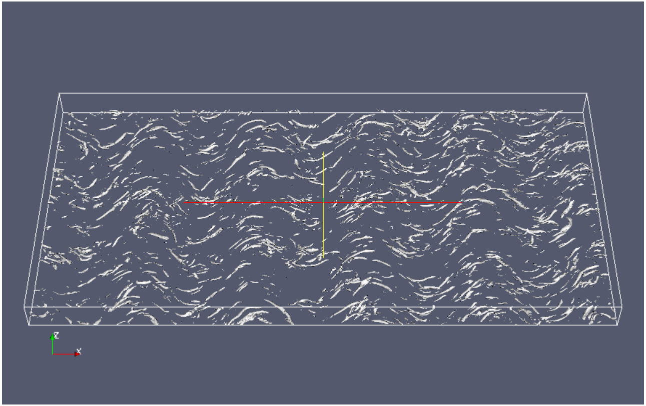
Quadrio & Luchini, PoF 2003

Space-time autocorrelation of wall friction



How the waves increase drag

- Waves lock with the convecting structures
- 'Steady' forcing: $c^+ \approx U_c^+$



How the waves decrease drag

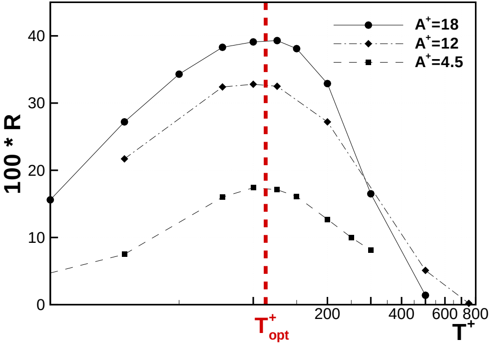
- Drag reduction is proportional to δ_{GSL} (WHY?)
- Large $\delta_{GSL} \Rightarrow$ large T
- Too large a T implies quasi-steady forcing

Limit to drag reduction

Forcing must be unsteady

Oscillating wall

- Forcing on a timescale $\gg T_\ell$ does not yield DR
- Forcing timescale: oscillation period T



Limit to drag reduction

Forcing must be 'unsteady'

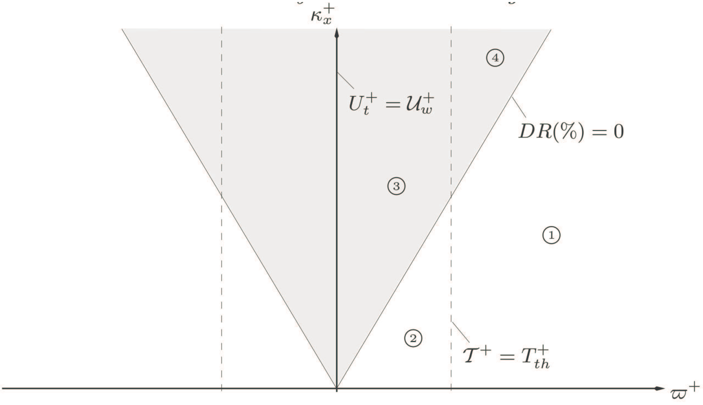
Travelling waves

- Forcing on a timescale $\gg T_\ell$ does not yield DR
- Timescale: oscillation period $\mathscr{T}$ as seen by the convecting structures

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

Waves and turbulent friction

Four regions in each half-plane:



Outline

Conclusions

Streamwise-travelling waves:

- Useful for understanding drag-reduction mechanism (Flatland)
- Extremely energy-efficient
- Still incomplete understanding ▸ Example
- Issue of spatial discretization

Outlook

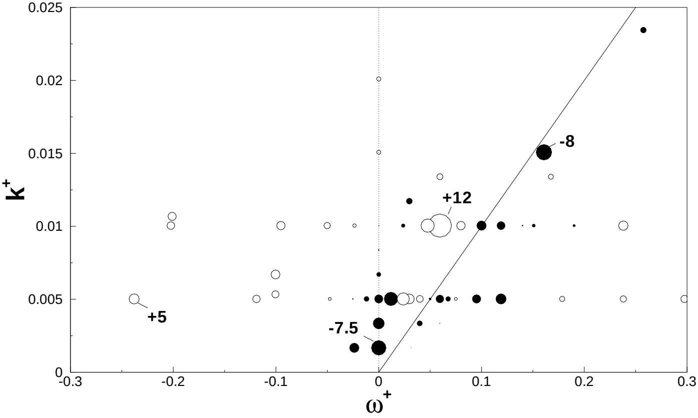
- Further understanding (why is $\delta_{GSL} \sim R$?)
- Further increase in efficiency
- Further development of actuators
- Explore *Re* effects

Credits

- Pierre Ricco
- Fulvio Martinelli
- Claudio Viotti
- Franco Auteri
- Arturo Baron
- Marco Belan
- Paolo Luchini

The scaling issue (1)

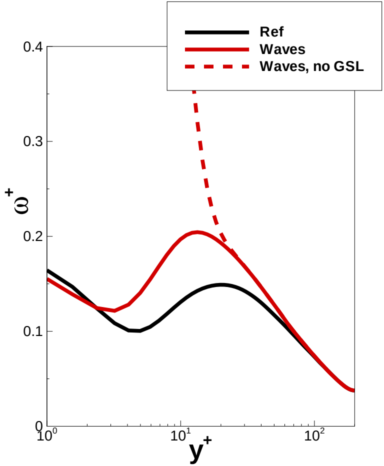
Drag reduction



The scaling issue (2)

Do streamwise vorticity fluctuations decrease?

"The streamwise vorticity fluctuation near the wall is reduced by the spanwise wall oscillation."



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