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

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Outline

1. Travelling waves (DNS)
2. Travelling waves (experiment)
3. The GSL
4. How do the waves work?
5. Conclusions
1 Travelling waves (DNS)

2 Travelling waves (experiment)

3 The GSL

4 How do the waves work?

5 Conclusions
The travelling waves

Travelling waves (DNS)
Travelling waves (experiment)
The GSL
How do the waves work?
Conclusions
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

![Graph showing the effect of spanwise wall oscillation on turbulent friction](image)
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)
The sinusoidal riblets
A new concept under experimental testing

- Promising roughness distribution
- Better than straight riblets?
The traveling waves: a natural extension

<table>
<thead>
<tr>
<th>Purely temporal forcing</th>
<th>Purely spatial forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>The oscillating wall:</td>
<td>The steady waves:</td>
</tr>
<tr>
<td>( w = A \sin(\omega t) )</td>
<td>( w = A \sin(\kappa x) )</td>
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<tr>
<td>Infinite phase speed</td>
<td>Zero phase speed</td>
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<th>Combined space-time forcing</th>
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<td>The traveling waves:</td>
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<tr>
<td>( w = A \sin(\kappa x - \omega t) )</td>
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<tr>
<td>Finite phase speed ( c = \omega / \kappa )</td>
</tr>
</tbody>
</table>
Results from DNS (plane channel)
Quadrio et al., JFM 2009

Travelling waves (DNS)
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How do the waves work?
Conclusions
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

Travelling waves (DNS)

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How do the waves work?

Conclusions
Power efficiency
Travelling waves (DNS)

How do the waves work?

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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

Travelling waves (DNS)

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How do the waves work?

Conclusions
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

Travelling waves (DNS)

Travelling waves (experiment)

The GSL

How do the waves work?

Conclusions
Drag variation (1)
Drag variation (2)

![Graph showing drag variation with different values of s=3 and s=6.](image)
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

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Fourier expansion of the discrete wave

Travelling waves (DNS)

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How do the waves work?

Conclusions

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

\[ s=3 \]

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

\[ s=6 \]
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:

\[ \tilde{R}(\omega, \kappa) = \int \int K(\tau, \xi) \left[ f_{\omega, \kappa} + \frac{1}{2} f_{\omega, -2\kappa} \right] d\tau d\xi \]
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The non-monocromatic $\tilde{R}$ map
Wiggles in the experimental data are discretization effects
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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

$$w(x, y, t) = \mathcal{A} \Re \left\{ Ce^{2\pi i(x-ct)/\lambda} Ai \left[ e^{\pi i/6} \left( \frac{2\pi u_{y,w}}{\lambda v} \right)^{1/3} \left( y - \frac{c}{u_{y,w}} \right) \right] \right\}$$
Spanwise turbulent flow agrees with the GSL
Using the GSL solution (1)
Turbulent (DNS) vs laminar (analytical) $\delta_{GSL}$

Black points are “good” waves

![Graph showing comparison between turbulent and laminar waves with black points indicating good waves.](image-url)
Using the GSL solution (2)
Map of analytical $\delta_{GSL}$
Using the GSL solution (3)

$R$ vs analytical $\delta_{GSL}$

Black points are “good” waves
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The near-wall convection velocity $U_c$
Quadrio & Luchini, PoF 2003
Near-wall physics 2: the turbulence lifetime $T_\ell$
Quadrio & Luchini, PoF 2003

Space-time autocorrelation of wall friction

![Graph showing space-time autocorrelation of wall friction](image-url)
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 $\delta_{GSL}$ (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 $T$

![Graph showing the effect of oscillation amplitude on drag reduction](image-url)
Limit to drag reduction
Forcing must be ‘unsteady’

Travelling waves

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

$$\mathcal{T} = \frac{\lambda}{U_c - c}$$
Waves and turbulent friction

Four regions in each half-plane:

\[ U_t^+ = U_w^+ \]

\[ DR(\%) = 0 \]

\[ T^+ = T_{th}^+ \]
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Conclusions

Streamwise-travelling waves:

- Useful for understanding drag-reduction mechanism (Flatland)
- Extremely energy-efficient
- Still incomplete understanding
- 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

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The scaling issue (2)
Do streamwise vorticity fluctuations decrease?

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