Streamwise-traveling waves in a pipe flow: experimentally assessing the turbulent drag reduction

F.Auteri, A.Baron, M.Belan, A.Bertolucci, G.Gibertini, M.Quadrio

Dip. Ing. Aerospaziale Politecnico di Milano

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Outline

1. Background
2. The traveling waves
3. Experimental setup
4. Results
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Spanwise wall forcing of turbulence
A long story made short

Spanwise forcing may decrease turbulent friction drag:

1985  Bradshaw & Pontikos 1985: sudden spanwise pressure gradient

1992  Jung et al. 1992: harmonic spanwise wall oscillation

1993- many papers on the oscillating-wall technique
Spanwise wall oscillation: the essentials
Quadrio & Ricco, JFM 04

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

- Large reductions of turbulent friction
- Basic mechanism still elusive
- Does an optimum period \( T_{opt} \) exist?
- Unpractical
Turbulent fluctuations at the wall possess a convection velocity

Known concept (Kreplin & Eckelmann) in the ’70

Re-discovered (!) by Kim & Hussain ’93

Re-re-discovered (!!!) by Quadrio & Luchini ’03
The oscillating wall made stationary

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

- Convection allows translating the oscillation into a steady forcing
- Existence of an optimal wavelength \( \lambda_{opt} = U_w T_{opt} \)
- Easily implemented as a passive device (sinusoidal riblets)
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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 \( c = \omega / \kappa \)
First results: a DNS study
Quadrio et al., JFM 2009

- DNS pseudo-spectral code
- Powerful system with 268 dual-core Opteron CPUs, 280GB RAM, 40TB disk space
- Turbulent plane channel flow at $Re_\tau = 200$
- Approx. 4 centuries of CPU time (or 500MWh of power)
Unexpected results!
Waves may yield both DR and DI
How much power to generate the waves?

- Power $\sim w \frac{\partial w}{\partial y}|_{y=0}$
- Upper bound to energetic cost
- Similar to drag reduction map!
- Ratio of energy save to cost up to 30:1
- Up to 25% net energy save
Motivation for a laboratory experiment

Devise a proof-of-principle experiment to:

- confirm DR and DI
- improve our understanding of the traveling waves
- explore further the parameter space ($Re$, $A$)
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Our experimental setup
The main design choices

- Geometry of **cylindrical pipe**: naturally periodic in spanwise (azimuthal) direction
- Friction is measured through pressure drop
- Spanwise velocity at the wall is achieved by moving the wall
- Temporal variation is achieved by unsteady control of the wall velocity
- Spatial variation is achieved by **slicing the pipe into** thin, independently-movable **axial segments**
Notable difficulties

- Low-budget experiment
- Small pressure drop
- Water
The pipe
A closed-circuit water pipe
The rotating segments
60 slabs with 6 independent motors
The transmission system
Shafts, belts and rotating segments
The control system

- Motion of the slabs is feedback-controlled
- Dynamometric sensors to feed back angular speed
- Fully automated test management
Flow parameters and procedure

- Working fluid is water
- $U_b = 0.9 \text{ m/s}$
- $Re = 4900$
- $Re_\tau = 180$

- System degassed after filling
- **Temperature** is continuously monitored
- Flow rate is continuously monitored
- $Re$ is adjusted at every measurement point by changing $U_b$
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Experimental conditions
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SHOW MOVIE HERE?
Drag changes
Bulk units

![Graph showing drag changes](image)

- N=2
- N=3
- N=6
- N=inf

**Axes:**
- Horizontal: $\omega R / U_b$
- Vertical: %DR

**Legend:**
- N=2: Red solid line
- N=3: Green dashed line
- N=6: Blue dotted line
- N=inf: Pink square marker
Comparison with DNS & plane channel

Inner units
Discussion

Quantitative disagreement between DNS and experiment

- Spatial transient?
- Cylindrical vs planar geometry?
- Difference in GSL
- Difference (small) in $Re$ and $A$
Conclusions

- DR is confirmed
- 26% DR is one of the largest ever measured
- Quantitative uncertainty
- Demonstrated existence of $T_{opt}$ for oscillating pipe
Understanding the physics
The lifetime $T_\ell$ of turbulent structures
Unsteadiness in the convecting reference frame

Oscillating wall

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

\[ T_\ell = \frac{\lambda}{x} U_w - c U_w \]: convection velocity at the wall

\[ c = \frac{\omega}{\kappa} \]: phase speed
Unsteadiness in the convecting reference frame

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

**Traveling waves**
- Forcing on a timescale $\gg T_\ell$ does not yield DR
- Timescale: oscillation period $\mathcal{T}$ as seen in a convecting reference frame

\[
\mathcal{T} = \frac{\lambda_x}{U_w - c}
\]
- $U_w$: convection velocity at the wall
- $c = \omega/\kappa$: phase speed
How spanwise forcing really works
Quadrio et al., JFM 2009
One step back
Extending the laminar Stokes solution

- Laminar flow
- Transverse, alternating boundary layer
- Qualitative similarity

\[ w(y, t) \]
\[ w(y, x) \]
\[ w(y, x - ct) \]
The generalized Stokes layer
An analytical approximate solution

\[ w(x, y, t) = A \Re \left\{ Ce^{2\pi i(x - ct)/\lambda_x} \text{Ai} \left[ e^{\pi i/6} \left( \frac{2\pi u_y,0}{\lambda_x v} \right)^{1/3} \left( y - \frac{c}{u_y,0} \right) \right] \right\} \]

- \( \delta_{GSL} \ll h \)
- Neglect streamwise viscous diffusion
- Threshold velocity to discriminate flow regimes
Using the GLS solution
Thickness of the GLS