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

XX AIDAA Conference – Milano
June 30, 2009

Outline

Outline

1. Background
2. The traveling waves
3. Experimental setup
4. Results

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

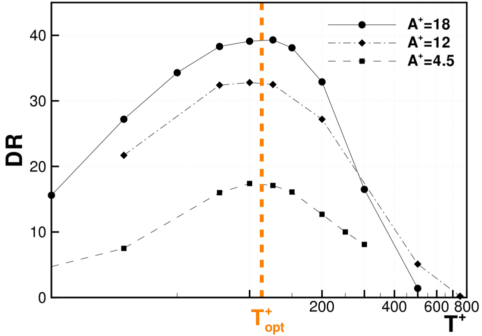
1993- many papers on the oscillating-wall technique

Spanwise wall oscillation: the essentials

Quadrio & Ricco, JFM 04

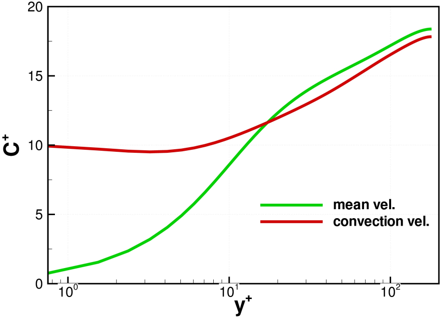
$$\boxed{w(x,y=0,z,t)=A\sin\left(\omega t\right)}$$

- Large reductions of turbulent friction
- Basic mechanism still elusive
- Does an optimum period T_{opt} exist?
- Unpractical



An important concept: the convection velocity

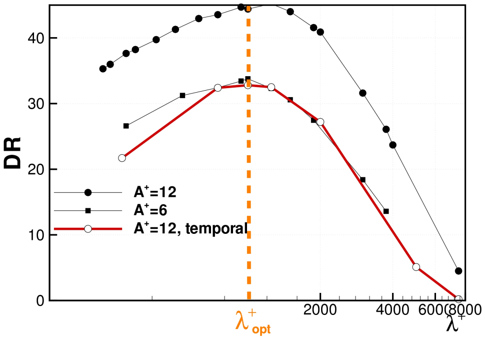
- Turbulent fluctuations at the wall possess a convection velocity
- Known concept (Kreplin & Eckelmann) in the '70
- Re-discovered (!) by Kim & Hussain '93
- Re-re-discovered (!!) by Quadrio & Luchini '03



The oscillating wall made stationary

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

- 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)



Outline

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 $c = \omega / \kappa$

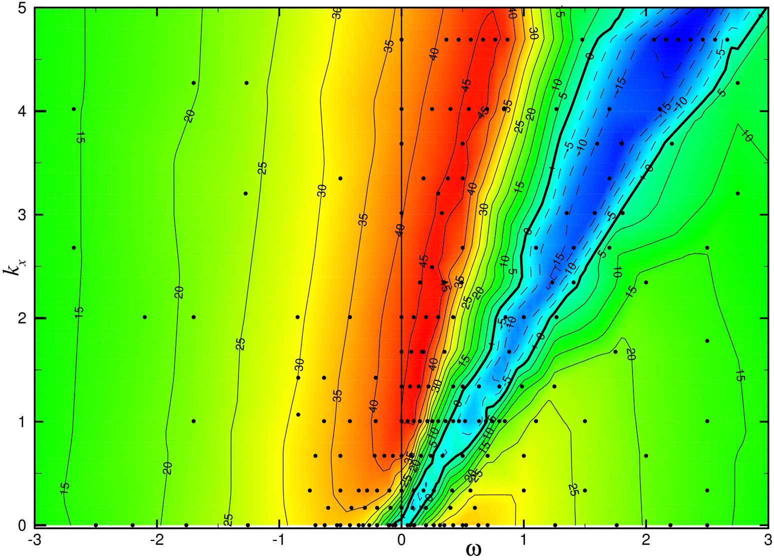
First results: a DNS study

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)

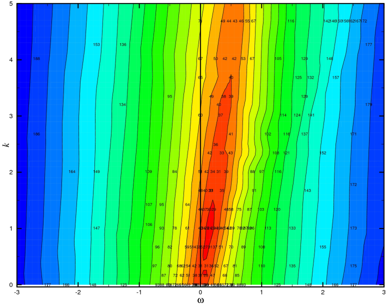
Unexpected results!

Waves may yield both DR and DI



How much power to generate the waves?

- Power $\sim w \partial w / \partial y|_{y=0}$
- 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*)

Outline

1. Background
2. The traveling waves
3. Experimental setup
4. Results

Our experimental setup

The main design choices

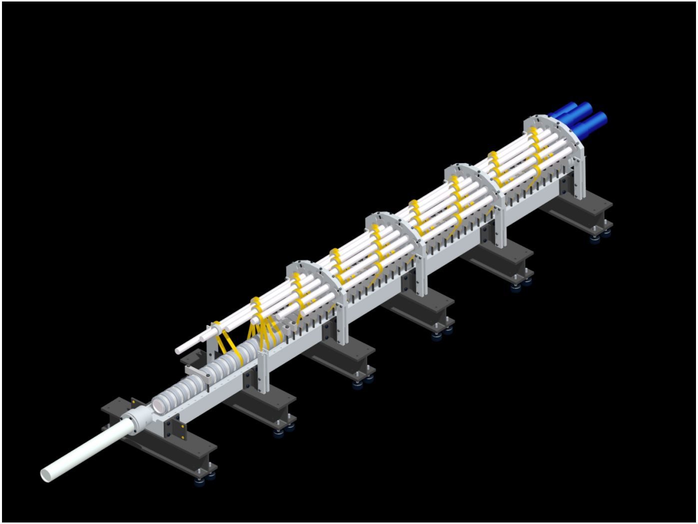
- Geometry of cylindrical pipe: naturally periodic in spanwise (azimuthal) direction
- Friction is measured through pressure drop
- Spanwise velocity at the wall is achieved by moving the wall
- Temporal variation is achieved by unsteady control of the wall velocity
- Spatial variation is achieved by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

Notable difficulties

- Low-budget experiment
- Small pressure drop
- Water

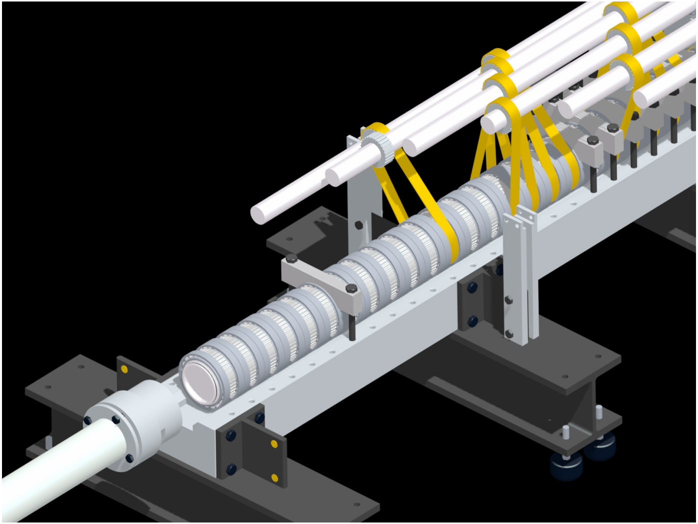
The pipe

A closed-circuit water pipe



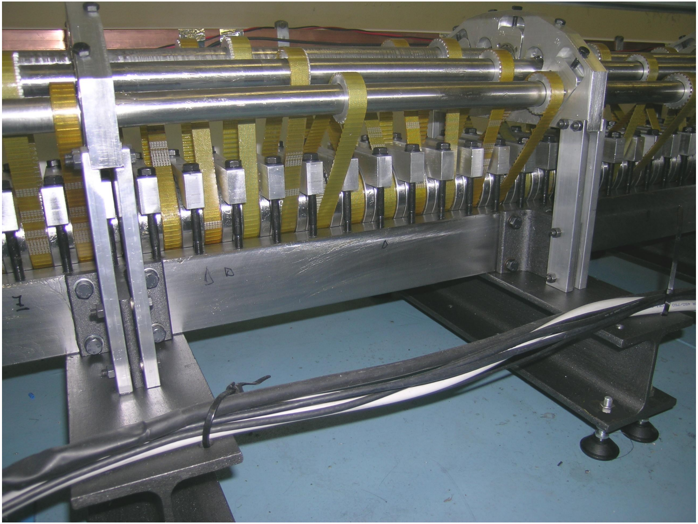
The rotating segments

60 slabs with 6 independent motors



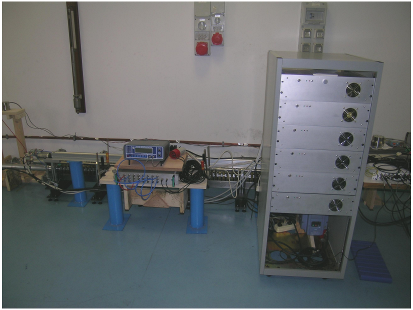
The transmission system

Shafts, belts and rotating segments

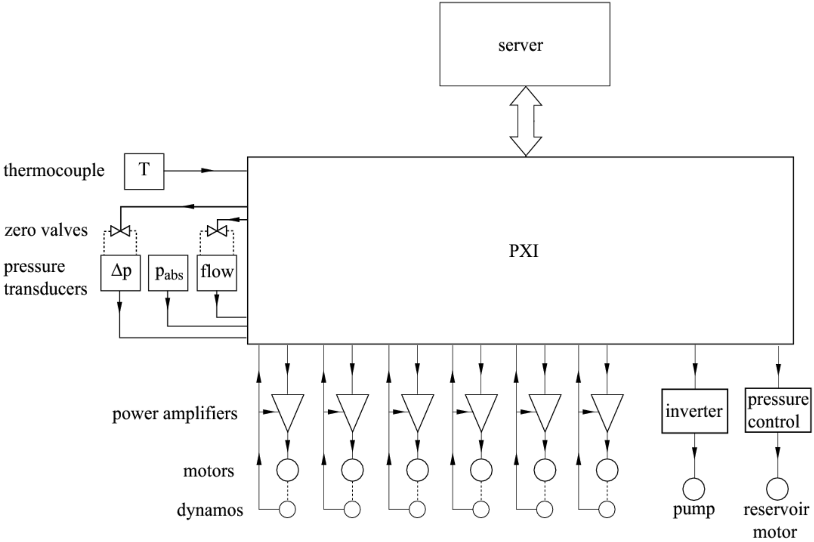


The control system

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



Schematic


server
PXI
thermocouple
T
zero valves
pressure transducers
Δp
p_{abs}
flow
power amplifiers
motors
dynamos
inverter
pressure control
pump
reservoir motor

Flow parameters and procedure

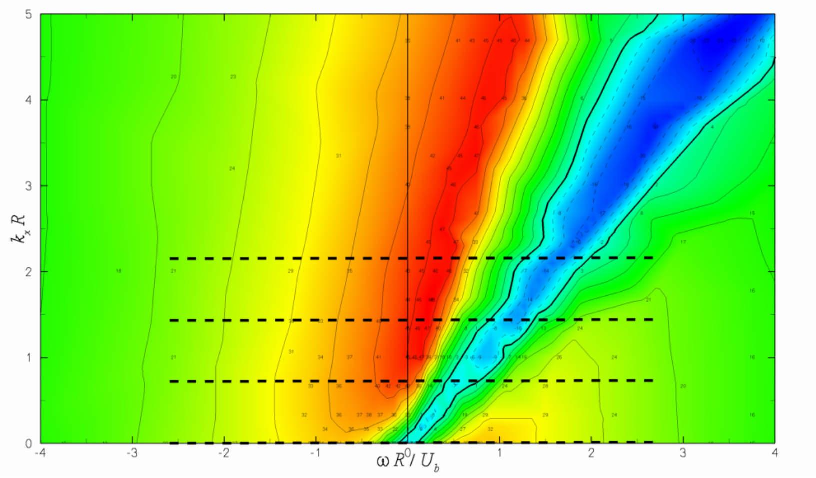
- Working fluid is water
- $U_b = 0.9$ m/s
- $Re = 4900$
- $Re_\tau = 180$

- System degassed after filling
- Temperature is continuously monitored
- Flow rate is continuously monitored
- Re is adjusted at every measurement point by changing U_b

Outline

1. Background
2. The traveling waves
3. Experimental setup
4. Results

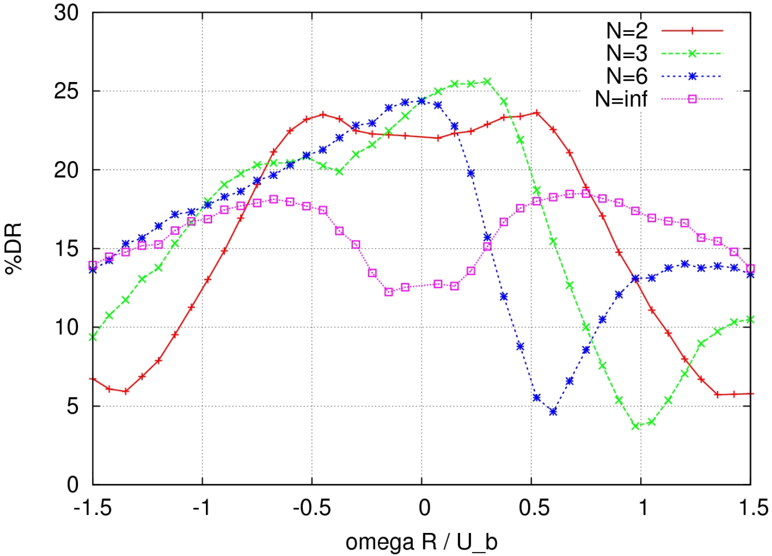
Experimental conditions



SHOW MOVIE HERE?

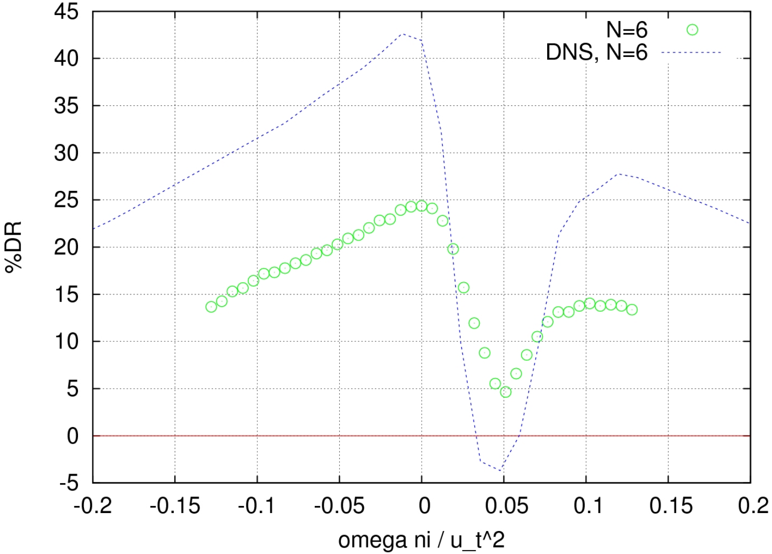
Drag changes

Bulk units



Comparison with DNS & plane channel

Inner units



Discussion

Quantitative disagreement between DNS and experiment

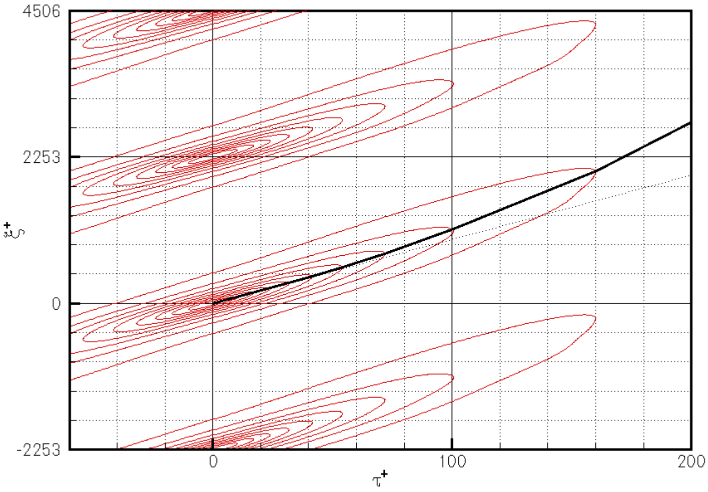
- Spatial transient?
- Cylindrical vs planar geometry?
- Difference in GSL
- Difference (small) in *Re* and *A*

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

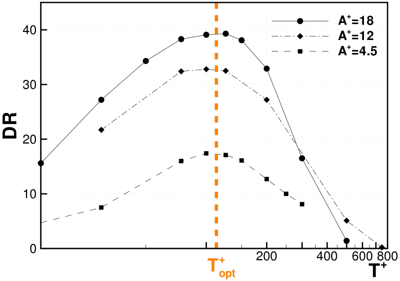
The lifetime T_ℓ of turbulent structures



Unsteadiness in the convecting reference frame

Oscillating wall

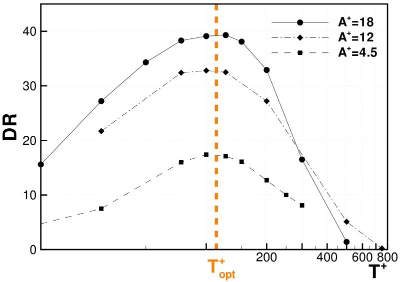
- Forcing on a timescale $\gg T_\ell$ does not yield DR
- Timescale: oscillation period T



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

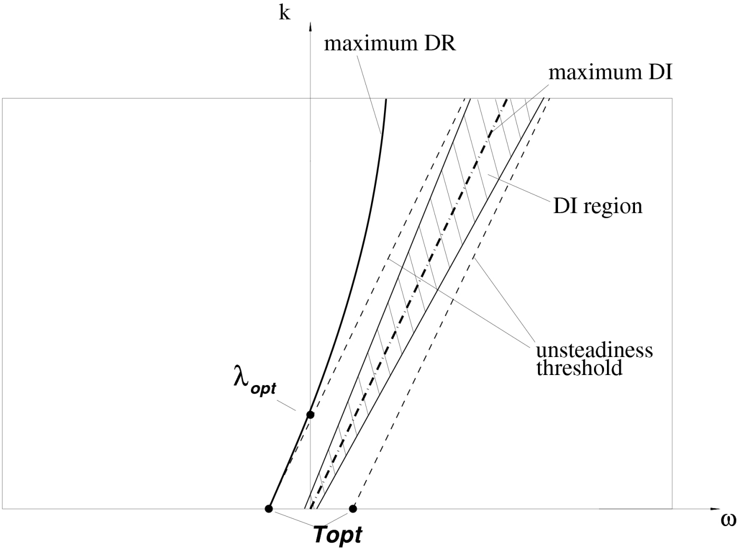
- Forcing on a timescale $\gg T_\ell$ does not yield DR
- Timescale: oscillation period $\mathscr{T}$ as seen in a convecting reference frame

$$\boxed{\mathscr{T} = \frac{\lambda_x}{U_w - c}}$$

- U_w: convection velocity at the wall
- $c = \omega/\kappa$: phase speed

How spanwise forcing really works

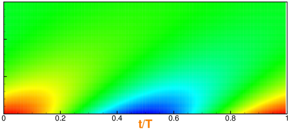
Quadrio et al., JFM 2009



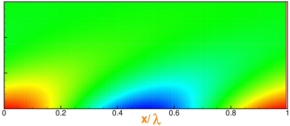
One step back

Extending the laminar Stokes solution

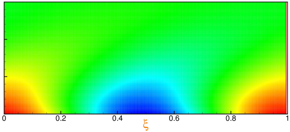
- Laminar flow
- Transverse, alternating boundary layer
- Qualitative similarity



$w(y, t)$



$w(y, x)$

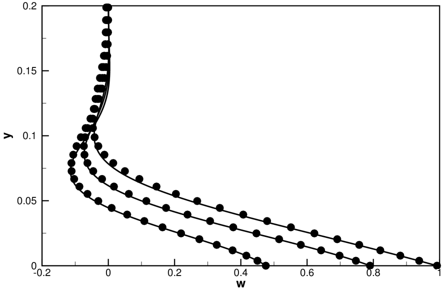


$w(y, x - ct)$

The generalized Stokes layer

An analytical approximate solution

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



- $\delta_{GSL} \ll h$
- Neglect streamwise viscous diffusion
- Threshold velocity to discriminate flow regimes

Using the GLS solution

Thickness of the GLS