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

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# Outline

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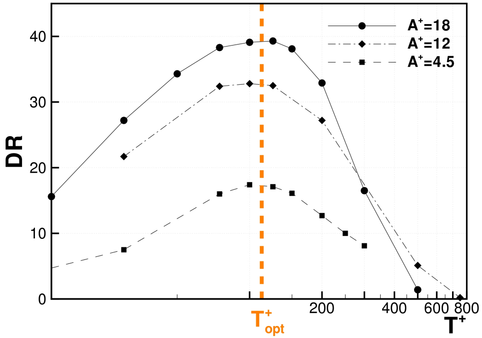
# Spanwise wall oscillation

## Quadrio & Ricco, JFM ’04

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

- Large reductions of turbulent friction
- Unpractical

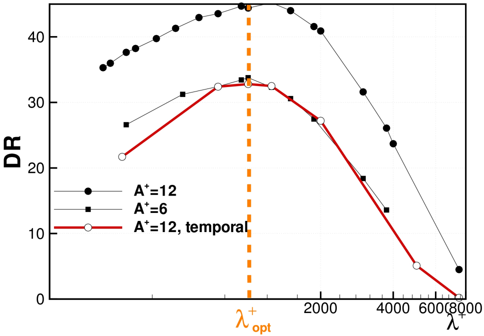


# The oscillating wall made stationary

Quadrio & Viotti, ETC XI

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

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

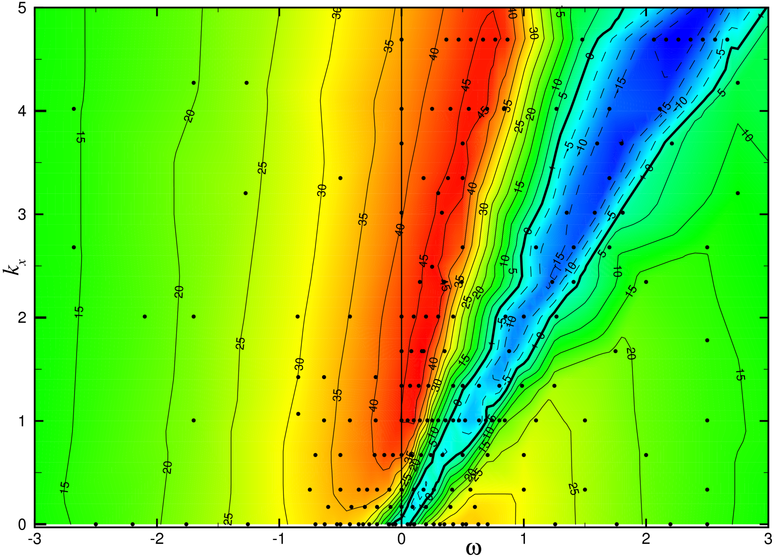
The traveling waves:

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

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

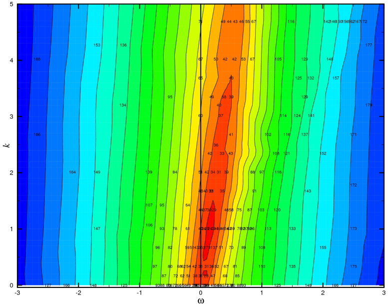
# Results from DNS (plane channel)

Quadrio et al., JFM 2009



# How much power to generate the waves?

- 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 phenomenon
- improve understanding of the traveling waves
- explore further the parameter space (*Re*, *A*)

# Outline

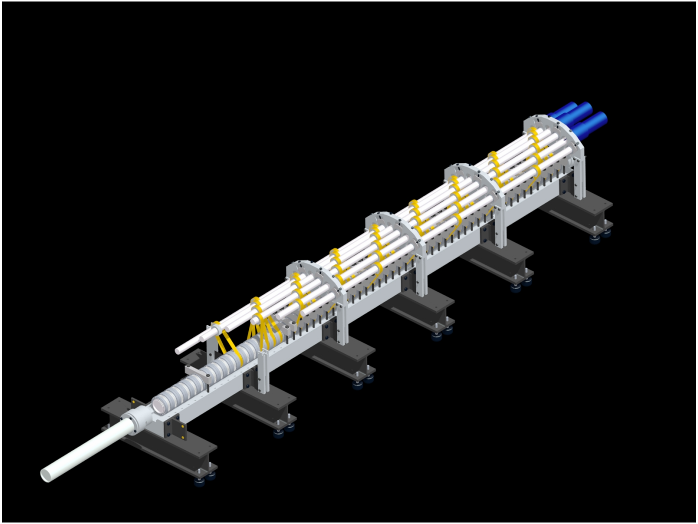
1. Background
2. Experimental setup
3. Results

# Main design choices

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

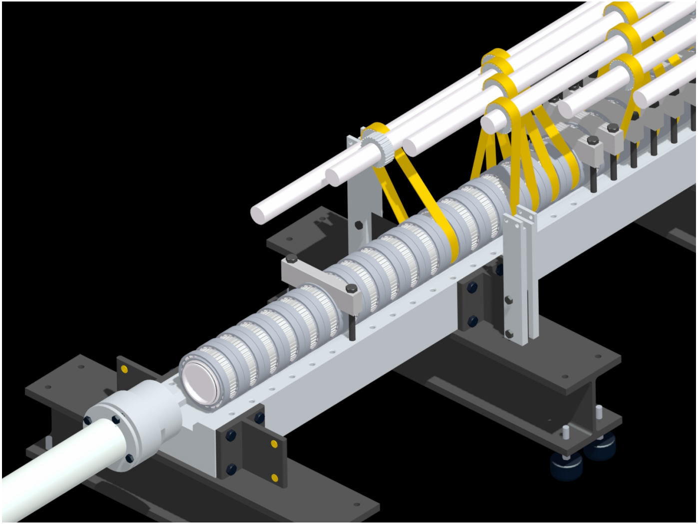
# SHOW MOVIE HERE!

# The pipe
## A closed-circuit water pipe



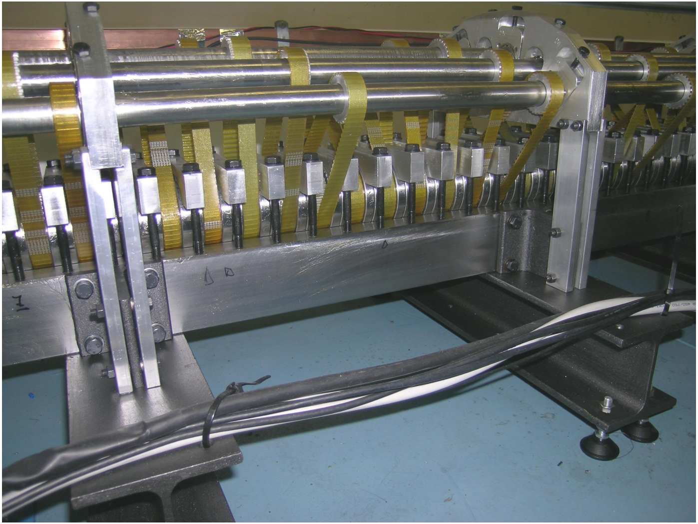
# The rotating segments

## 60 slabs with 6 independent motors



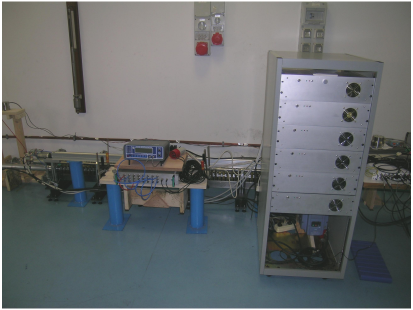
# The transmission system

## Shafts, belts and rotating segments



# The control system

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



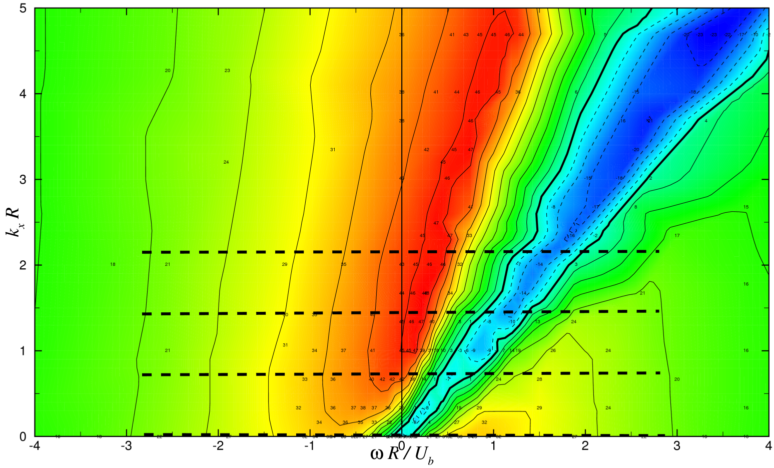
# Flow parameters

- Working fluid is water
- $U_b = 0.085$ m/s
- $R = 0.025m$
- $Re = 4900$
- $Re_\tau = 180$

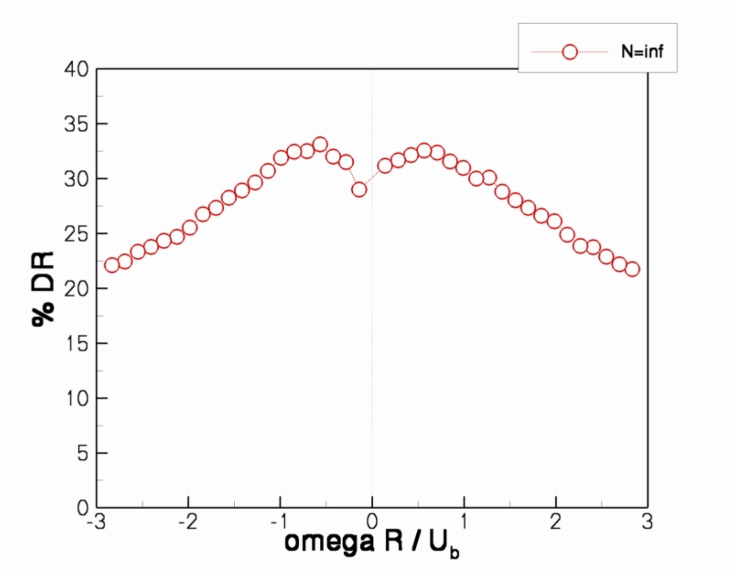
- System degassed after filling
- Temperature and flow rate are continuously monitored
- Reference pressure drop $\approx 7$ Pa!

# Outline

# Experimental conditions



# Drag variation



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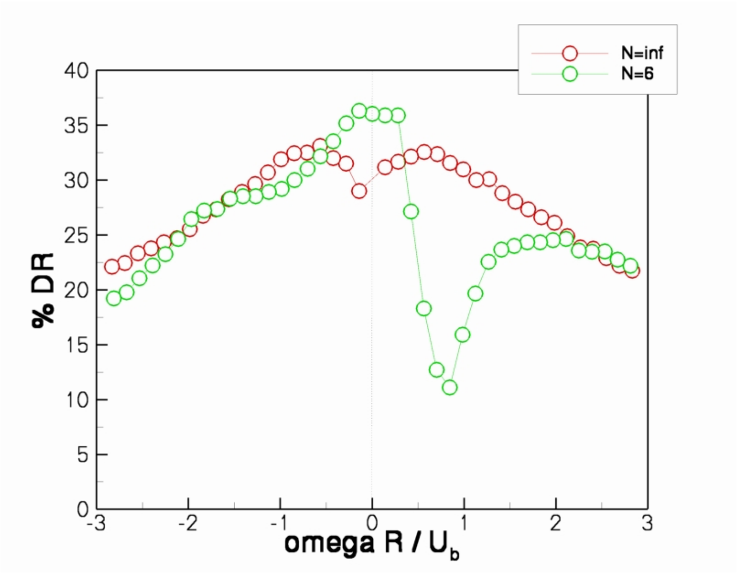
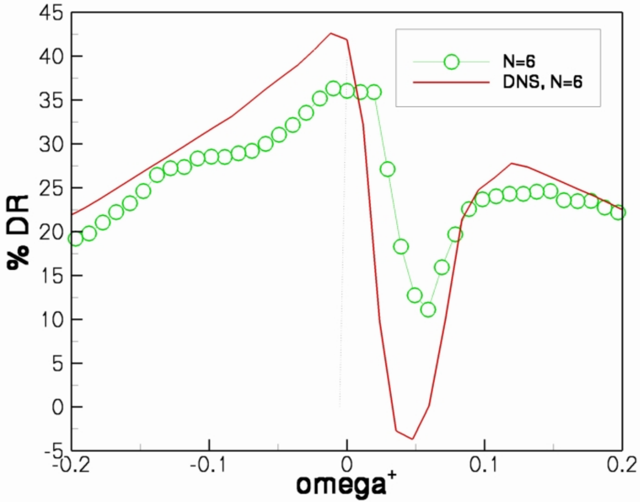
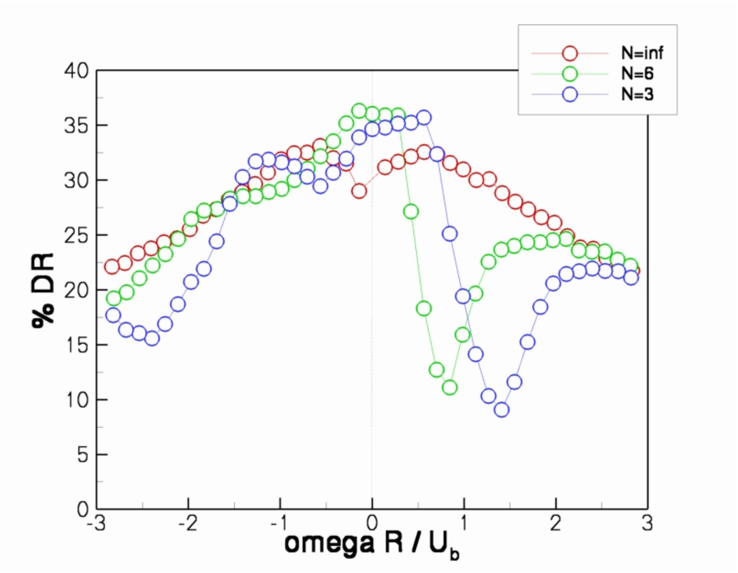


# Comparison with DNS (plane channel)

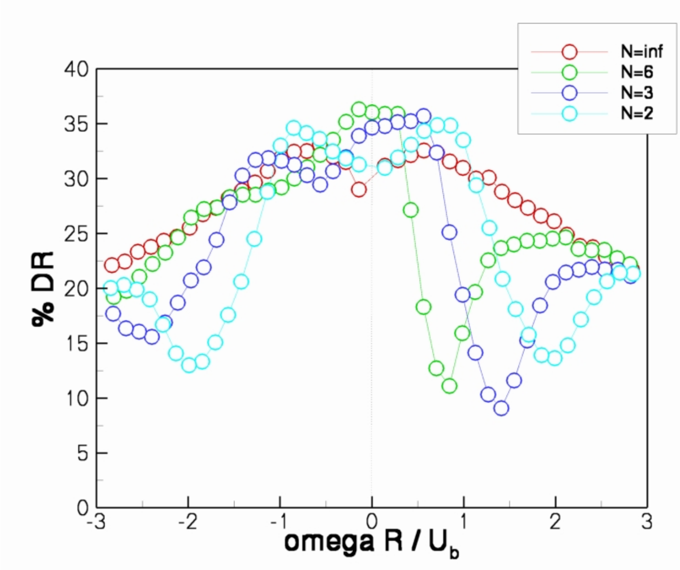
## Inner units



# Drag variation



# Drag variation



# Comments

We do not expect quantitative agreement between DNS and experiment:

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

# Conclusions and outlook

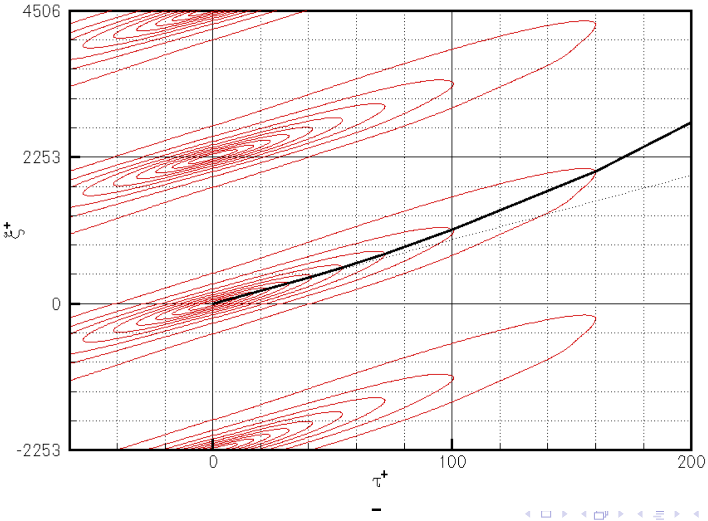
- DR is confirmed
- A large 37% is measured at intermediate intensity

- Describe effects of spatial discretization
- Cartesian vs cylindrical
- Explore parameter space
- Scaling of DR

# THE END...

# Understanding the physics

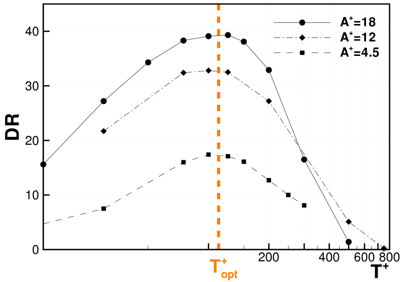
## The lifetime $T_\ell$ of turbulent structures



# Unsteadiness in the convecting reference frame

## Oscillating wall

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



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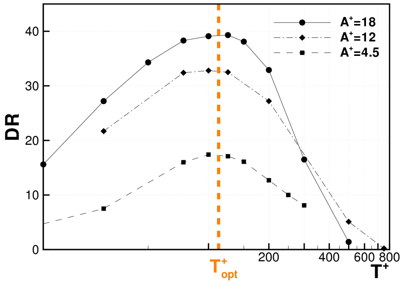


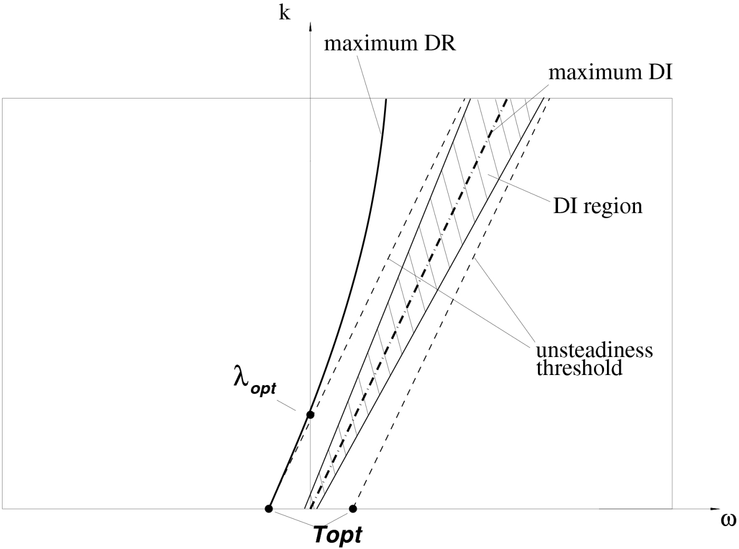

## Traveling waves

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

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

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

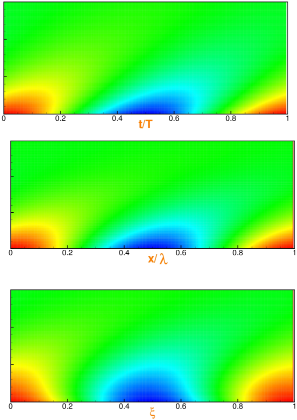
# How spanwise forcing really works
Quadrio et al., JFM 2009



# One step back

## Extending the laminar Stokes solution

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




$w(y, t)$

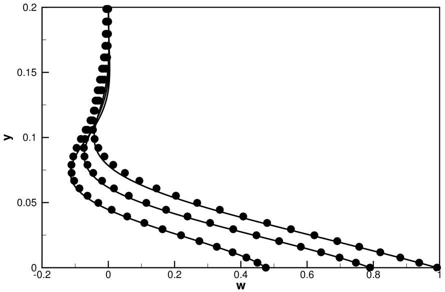
$w(y, x)$

$w(y, x - ct)$

# 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 GSL solution
## Thickness of the GSL