Turbulent drag reduction by spanwise forcing

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Outline

Control of turbulent flows

Focus on skin-friction turbulent drag reduction

Challenges in:

- physical understanding;
- technological developments;
- control-theoretical methods.

Passive vs. open-loop vs. closed-loop approach

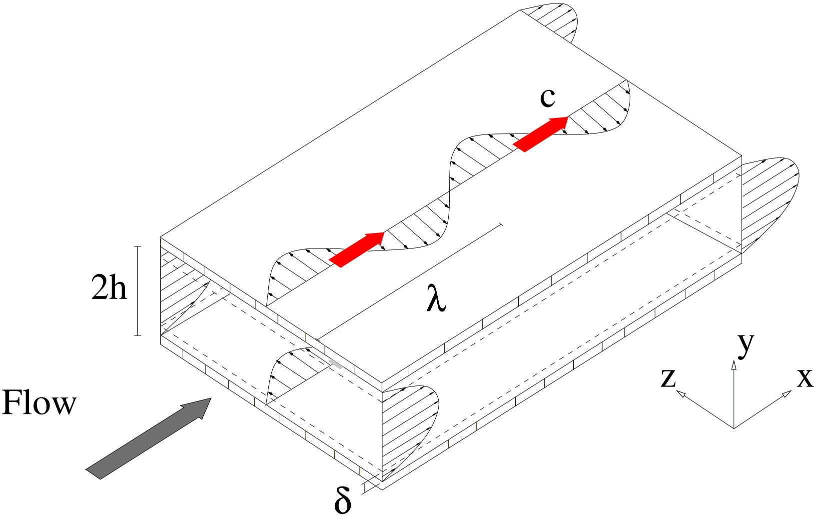
Outline

Streamwise-traveling waves of spanwise velocity

Experiment

Open questions

The streamwise-traveling waves

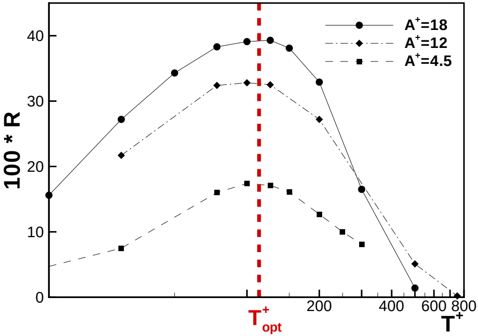


The original idea: spanwise wall oscillation

Quadrio & Ricco, JFM '04

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

- Large reductions of turbulent friction
- Unpractical

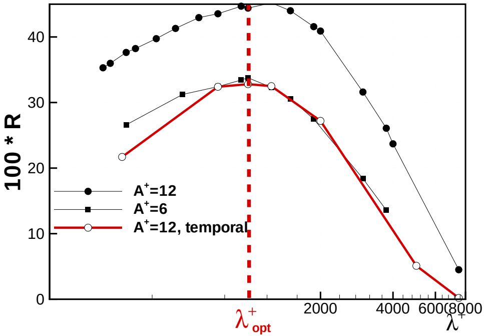


The oscillating wall made stationary

Viotti, Quadrio & Luchini, PoF 2009

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

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



The 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

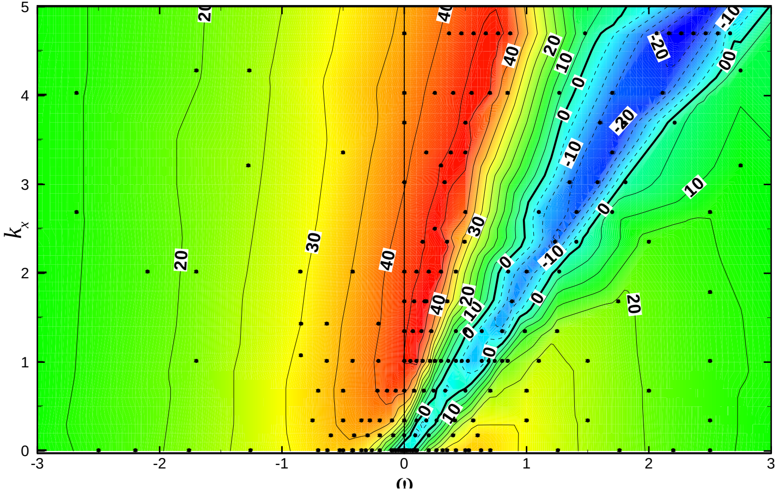
The traveling waves:

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

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

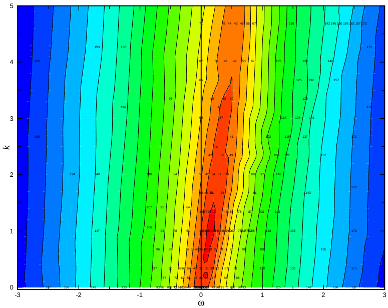
Results from DNS (plane channel)

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



The many variants of spanwise forcing

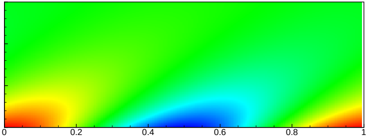
$$w = A \sin(\kappa_x x - \omega t) \qquad StTW - w$$

$$w = A \sin(\kappa_z z - \omega t) \qquad SpTW - w$$

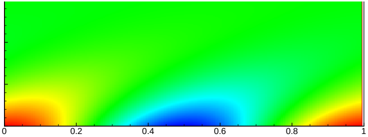
$$f_z = A e^{-y/\Delta} \sin(\kappa_x x - \omega t) \qquad StTW - Fz$$

$$f_z = A e^{-y/\Delta} \sin(\kappa_z z - \omega t) \qquad SpTW - Fz$$

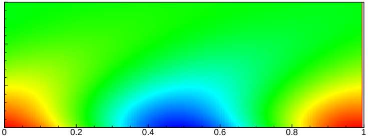
The spanwise laminar flow (StTW-w)



$w(t/T, y)$, TSL ($\kappa = 0$)

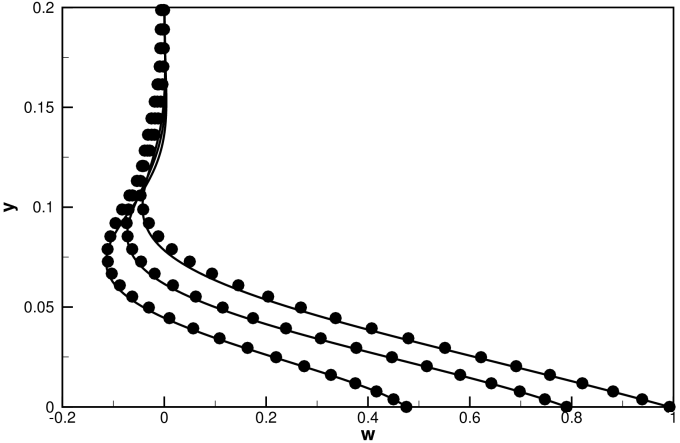


$w(x/\lambda, y)$, SSL ($\omega = 0$)



$w((x - ct)/\lambda, y)$, GSL

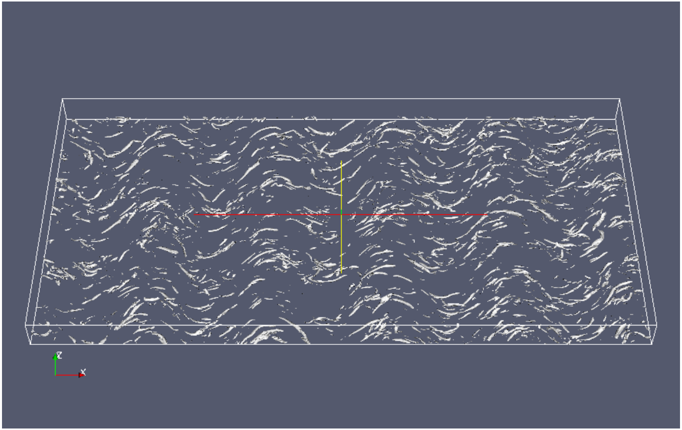
Spanwise turbulent flow agrees with laminar GSL



How the waves increase drag

Key parameter: phase speed

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



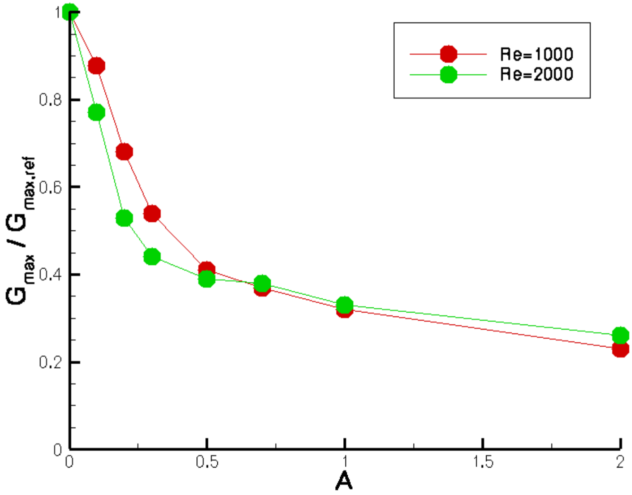
How the waves decrease drag

Key parameter: alternate spanwise shear

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

A by-product: the waves increase flow stability

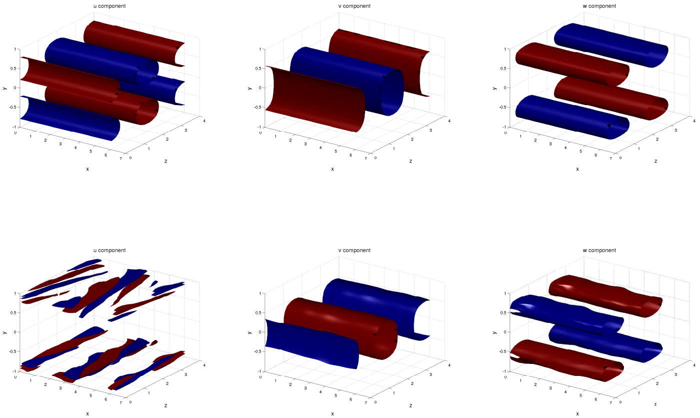
Changes in maximum transient growth for $\kappa = 1$, $\beta = 1.5$



Optimal input

$\kappa = 1$, $\beta = 1.5$, $A = 0$ (top) vs $A = 1$ (bottom)

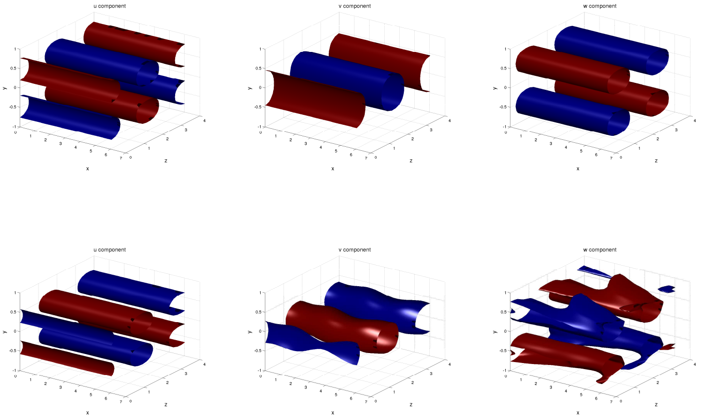
u	v	w
0.11 - 0.74	2.68 - 2.63	3.28 - 3.79



Optimal output

$\kappa = 1$, $\beta = 1.5$, $A = 0$ (top) vs $A = 1$ (bottom)

u	v	w
481x - 44x	0.47x - 0.51x	0.40x - 0.46x



Outline

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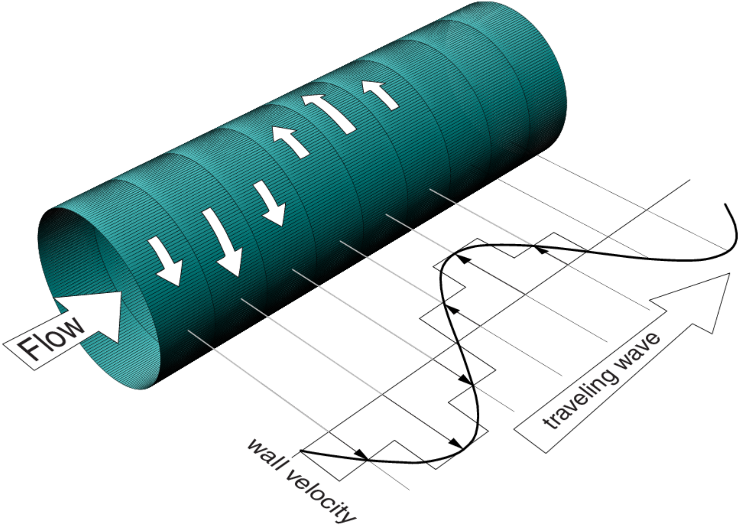
Experimental verification

Auteri et al PoF 2010

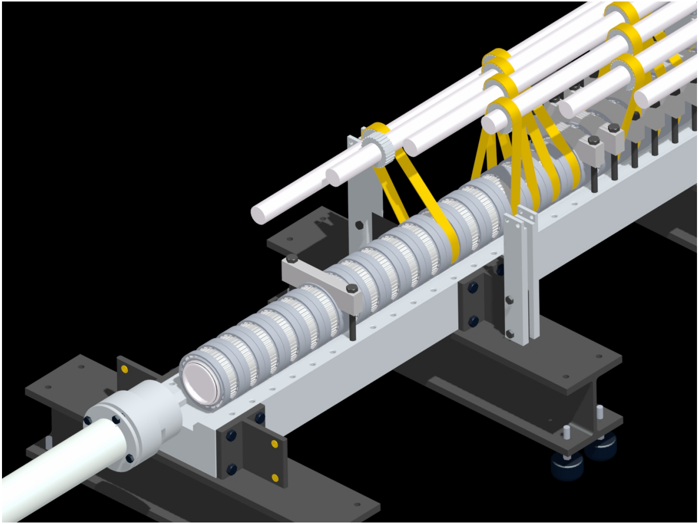
- Cylindrical pipe
- Friction is measured through pressure drop
- Spanwise wall velocity: wall movement
- Temporal variation: unsteady wall movement
- Spatial variation: the pipe is sliced into thin, independently-movable axial segments

The concept



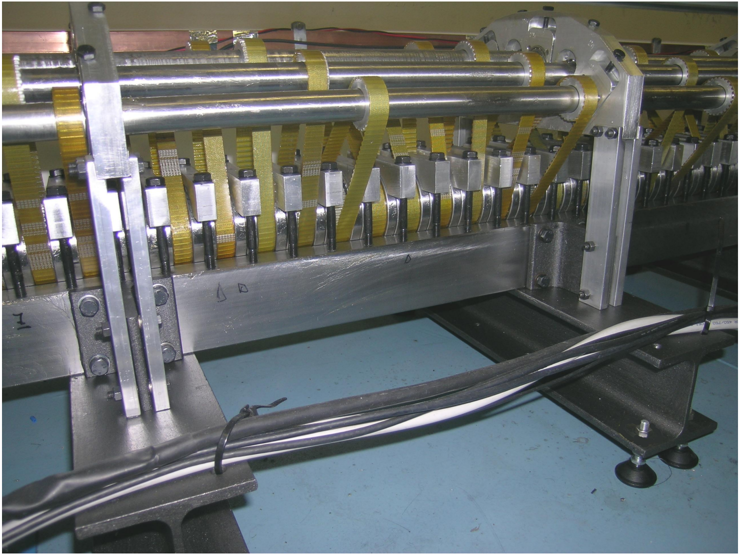
Closeup of the rotating segments

60 slabs with 6 independent motors



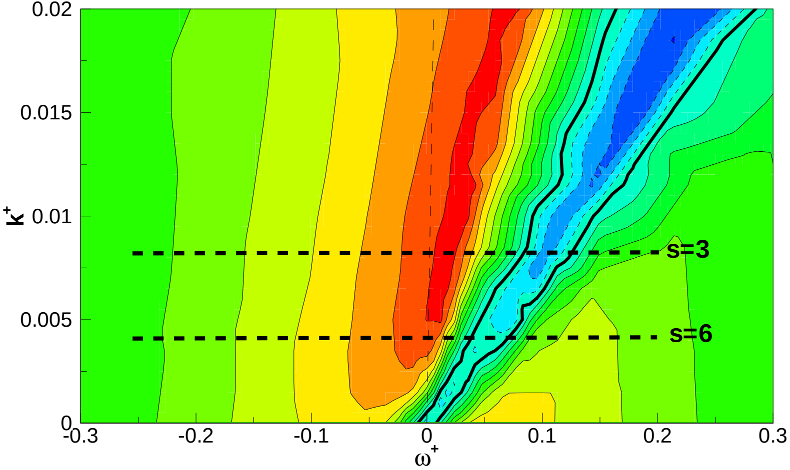
The transmission system

Shafts, belts and rotating segments

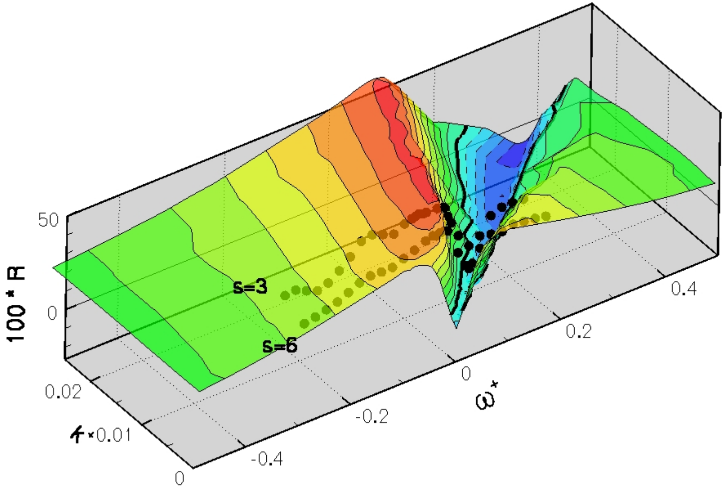


Experimental conditions as in DNS

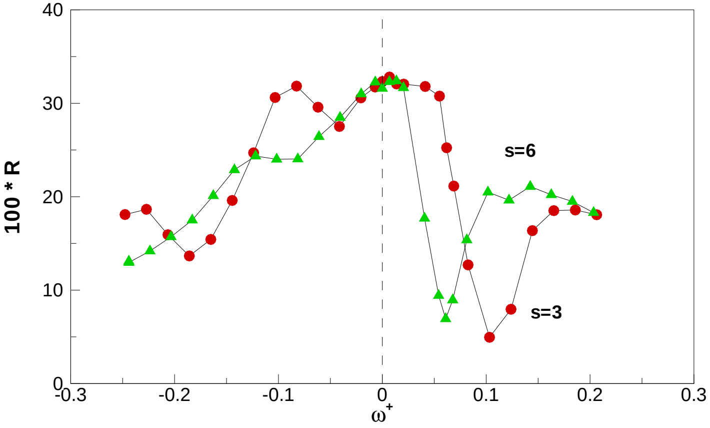
Water, $R^+ = 175$



Drag variation (1)



Drag variation (2)

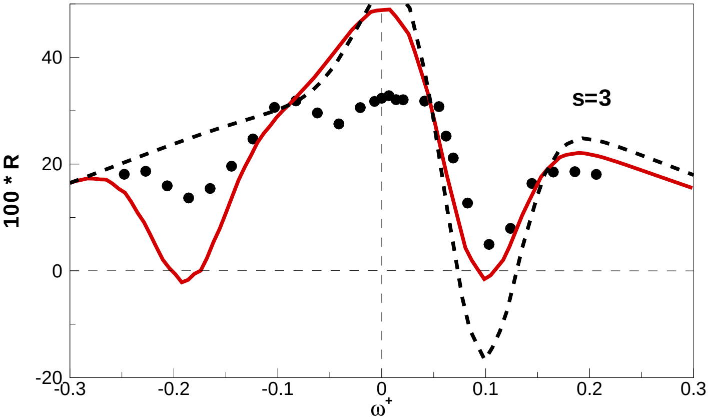


Comments

Quantitative agreement between DNS and experiment is not expected:

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

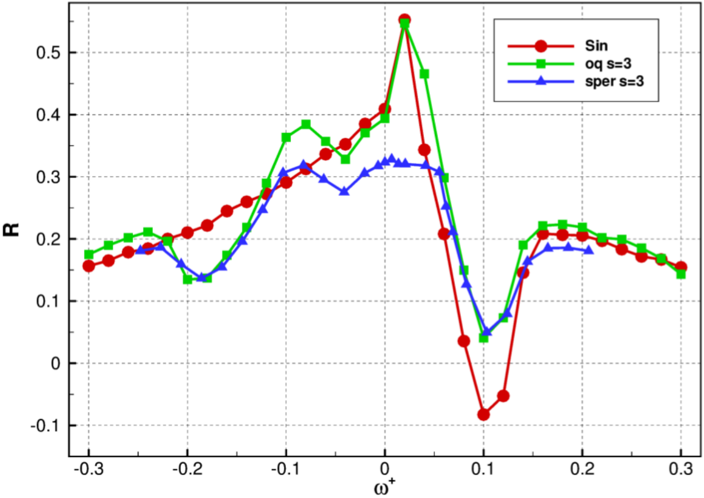
Wiggles can predicted!



- Wiggles in the experimental data are discretization effects

DNS of the experiment

Ad-hoc code to avoid clustering of points near the axis



DNS of the experiment

MOVIE

Outline

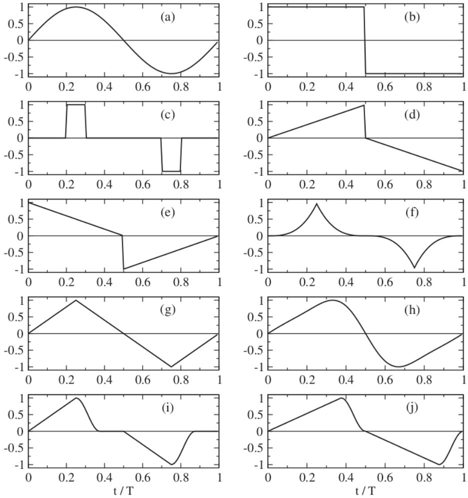
(1) What is an effective notation?

- Confusing notation might lead to poor reception of our research
- Often confusing for ourselves!
- My proposal: StTW-w, SpTW-y, StTW-v, etc

(2) What happens for non-sinusoidal waveform?

Cimarelli et al, PoF 2013

Sinusoid is global optimum, but can be outperformed locally



(3) What happens at high *Re*?

- Current assumption is $DR \sim Re_\tau^\gamma$ with $\gamma = -0.2$
- DR at flight *Re* would be negligible
- We claim that the outlook is much better

Huge computational study, 4020 DNS

Gatti & Quadrio, JFM to be submitted

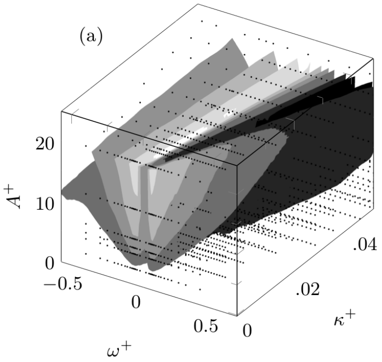
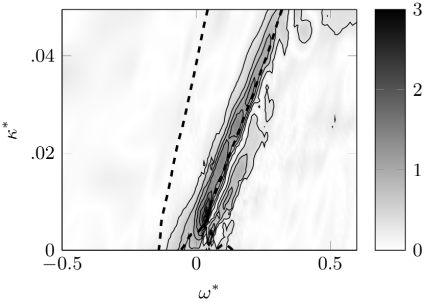


FIGURE 4. Overview of the results as isosurfaces of drag reduction R in the three-dimensional parameter space $(\omega^+, \kappa_x^+, A^+)$ for $Re_\tau = 200$ (a) and $Re_\tau = 1000$ (b). The cloud of dots represents the 2010 data points where, at each Re, a DNS has been carried out.

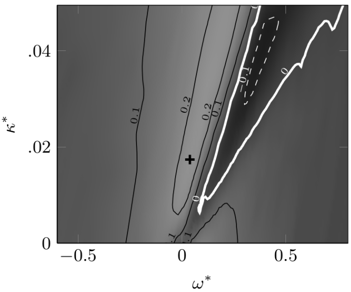
Loss of performance is localized and limited to low *Re*

This is really good news!

- Measuring drag reduction through ΔB^+ is robust w.r.t. *Re*
- In a sense, there is no *Re*-effect!



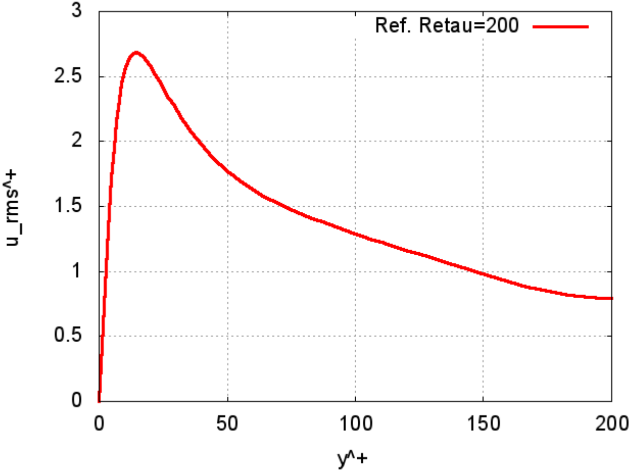
Change of ΔB from $Re_\tau = 200$ to $Re_\tau = 1000$



Extrapolation to $Re_\tau = 10^5$

(4) What is the right way to interpret results?

SOW: ”Turbulence intensity is destroyed”



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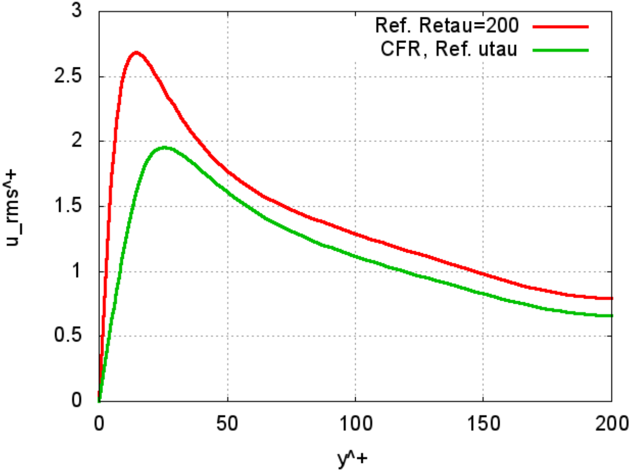

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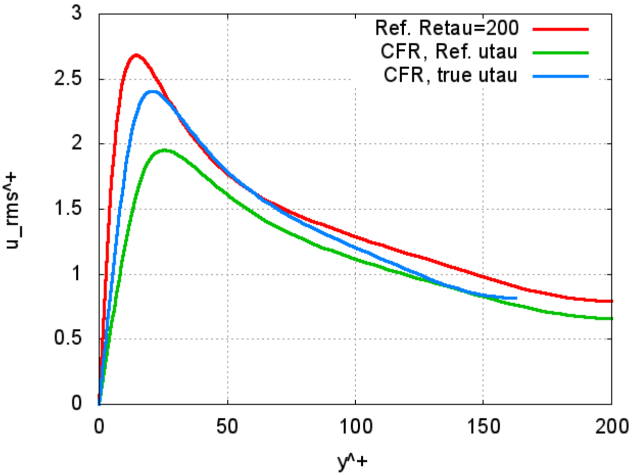

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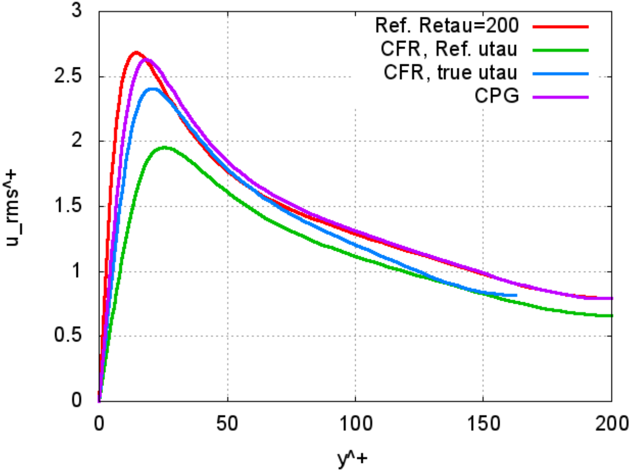


The need for a (arbitrary) forcing term in DNS

- NS equations alone cannot push fluid through the duct
- Popular choices are constant flow rate (CFR) and constant pressure gradient (CPG)
- Often equivalent on physical grounds
- Known difference on practical grounds

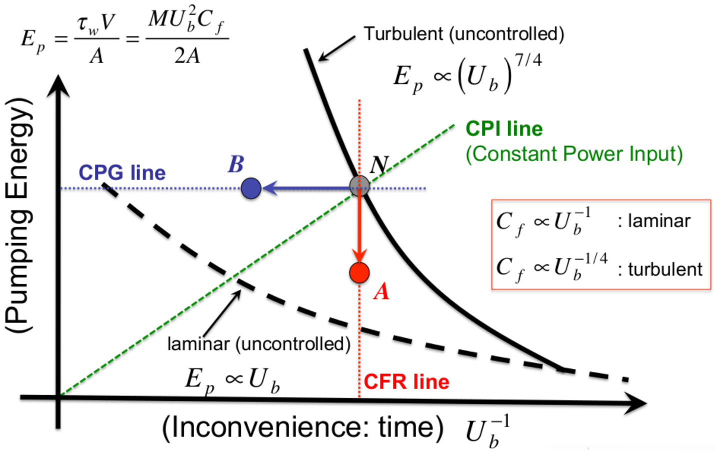
CFR or CPG?

Pre-determines the global energy budget for drag reduction

- Potential source of confusion
- Concerns both DNS and experiments
- CFR: pumping power is reduced with drag reduction
- CPG: pumping power is increased with drag reduction

A further option: CPI

The Money-vs-Time plane (JFM 2012, 2014 with Y.Hasegawa & B.Frohnapfel)



(5) What is the working mechanism of spanwise forcing?

(Too) many answers are available...

- There is a definite beneficial effect (on drag at CFR; on flow rate at CPG)
- All other claims are affected by either i) the scaling problem; ii) the chicken-egg problem

Conclusions

- Spanwise forcing is an effective way to interact with wall turbulence
- Interesting net energy savings can be achieved
- Performance does not degrade significantly with *Re*
- Understanding its true potential requires full understanding of the working mechanism