Skin-friction drag reduction via steady streamwise oscillations of spanwise velocity

Claudio Viotti[1], Maurizio Quadrio[1] & Paolo Luchini[2]

[1]Dip. di Ingegneria Aerospaziale, Politecnico di Milano (I)
[2]Dip. di Ingegneria Meccanica, Università di Salerno (I)

11th European Turbulence Conference 2007
25-28 June 2007
Porto, Portugal

Obivious requirements

- Simple $\Rightarrow$ feasible
- Energy efficient $\Rightarrow$ net saving

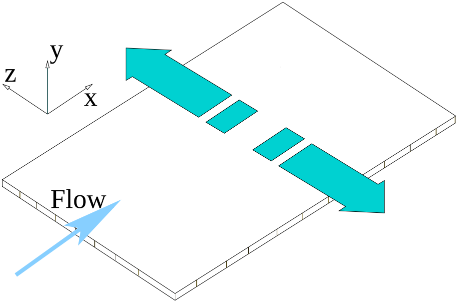
Additional requirement

- Steady $\Rightarrow$ convertible into passive device ??

Temporal-oscillating wall

Jung, Mangiavacchi & Akhavan (PoF, 1992)

$$W_w = A \sin\left(\frac{2\pi}{T} t\right)$$



- Stokes layer interacts with wall structures
- DR up to 40%
- optimal period $T^+_{opt} \approx 100 - 125$
- net energy saving up to 7%
- unsteady!!

Spanwise forcing

Further studies and variants

W_w	*Temporal-oscillating wall*
$A\sin(\frac{2\pi}{T}t)$	Jung *et al.* (1992), Laadhari *et al.* (1994), J. I. Choi *et al.* (2002), Quadrio & Ricco (2003, 2004)
$A\sin(\frac{2\pi}{\lambda}z - \frac{2\pi}{T}t)$	Zhao *et al.* (2004)
F_z	*Spanwise body force*
$Ae^{-y/\Delta}\sin(\frac{2\pi}{T}t)$	Du *et al.* (2002), Berger *et al.* (2000), Breuer *et al.* (2004)
$Ae^{-y/\Delta}\sin(\frac{2\pi}{\lambda}z)$	Du *et al.* (2002)
$Ae^{-y/\Delta}\sin(\frac{2\pi}{\lambda}z - \frac{2\pi}{T}t)$	Du *et al.* (2002), Zhao *et al.* (2004), Pang & K.S. Choi (2004)
$Ae^{-y/\Delta}\sin(\frac{2\pi}{\lambda}x)$	Berger *et al.* (2000)

Time vs. space

Question

Can a temporal oscillation be converted into a spatial oscillation?

Possible answer

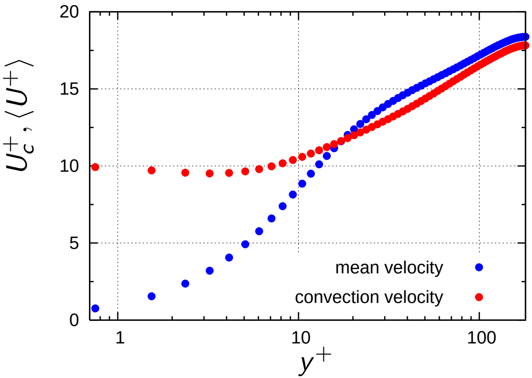
Yes, by exploiting the convective nature of the flow

Convection velocity in turbulent wall flows

Quadrio & Luchini, Pof 2003

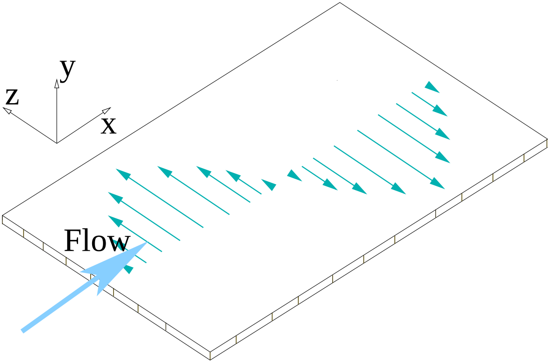
Channel flow,
DNS at $Re_\tau = 180$

- convection velocity of turbulent fluctuations
- convection is not zero at the wall!
- near wall: $U_c^+ \approx 10$



Our control law: streamwise steady waves

$$W_w = A \sin\left(\frac{2\pi}{\lambda_x} x\right)$$



TWO PARAMETERS

- Amplitude A
- Wavelength λ_x

Numerical study with DNS

- Turbulent channel flow at $Re_\tau = 200$
- Domain size: $L_x = 6\pi h$, $L_y = 2h$, $L_z = 3\pi h$
- Spatial resolution: $N_x \times N_y \times N_z = 320 \times 160 \times 320$
- Averaging time: 10^4 viscous time units
- Number of simulations: 35

Computing tool

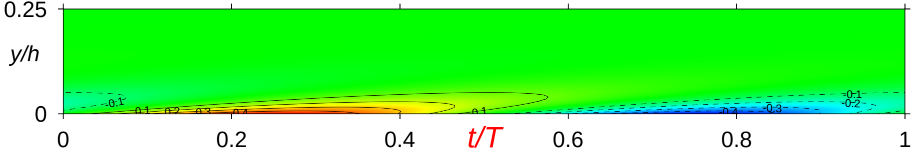
- DNS pseudo-spectral code
- Parallel computing on commodity hardware (Luchini & Quadrio JCP-2006)
- The "Personal Supercomputer": Powerful dedicated system with 128 Opteron CPUs, 100GB RAM, 4TB disk

Spanwise flow (1)

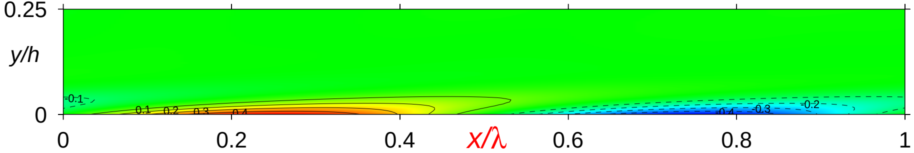
The laminar case

Contour of spanwise velocity W

Temporal oscillation



Spatial oscillation

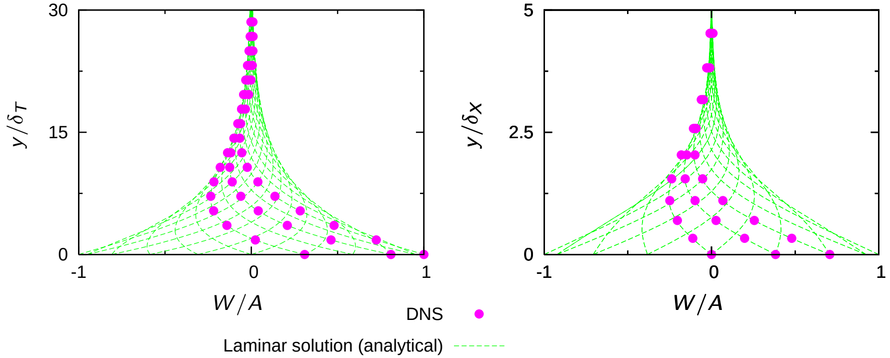


Spanwise flow (2)

Laminar solution vs. turbulent DNS data

$$\delta_T = \nu^{1/2} T^{1/2} \qquad \delta_X = \nu^{1/3} \lambda_x^{1/3} \frac{dU}{dy}^{-1/3}$$

▸ details



Spanwise-averaged turbulent flow cohincides with analytical solution in both cases

A natural question

TEMPORAL OSCILLATION

$T^+_{opt} \approx 100 - 125$

$U_c^+ = 10$

$\Longrightarrow$

SPATIAL OSCILLATION

$\lambda^+_{opt} \approx 1000 - 1250$??

A natural question

TEMPORAL OSCILLATION

$T^+_{opt} \approx 100 - 125$

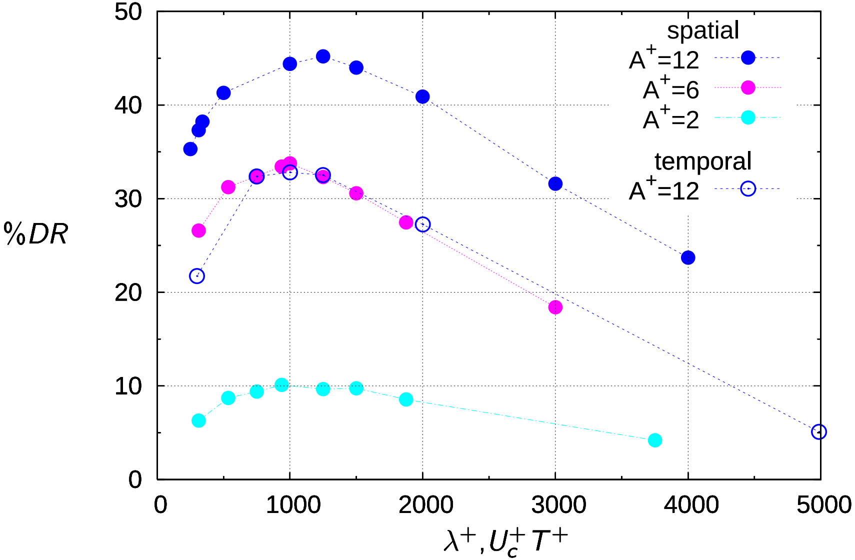
$U^+_c = 10$

$\Longrightarrow$

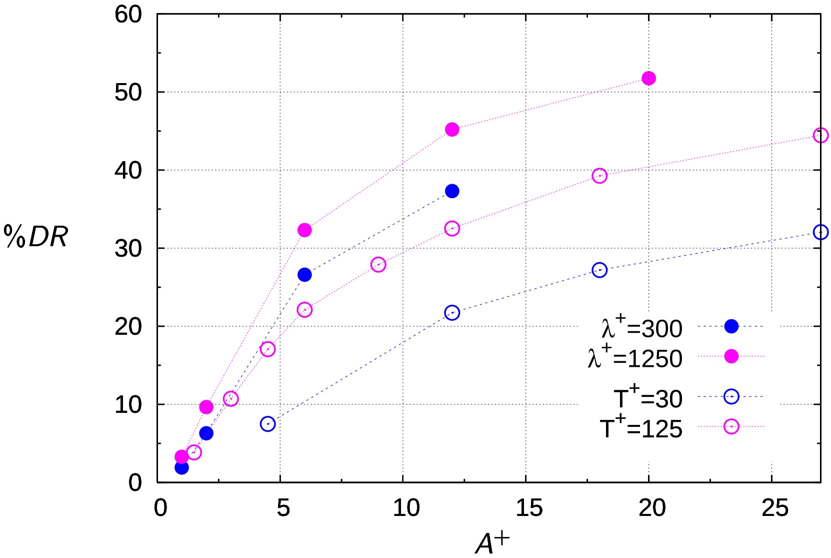
SPATIAL OSCILLATION

$\lambda^+_{opt} \approx 1000 - 1250$??

Drag reduction (1)



Drag reduction (2)



Power budget: definitions

- Power required to drive the flow:

$$P_{drive} = \mu \langle \frac{\partial U}{\partial y} \frac{Q_x}{h} \rangle$$

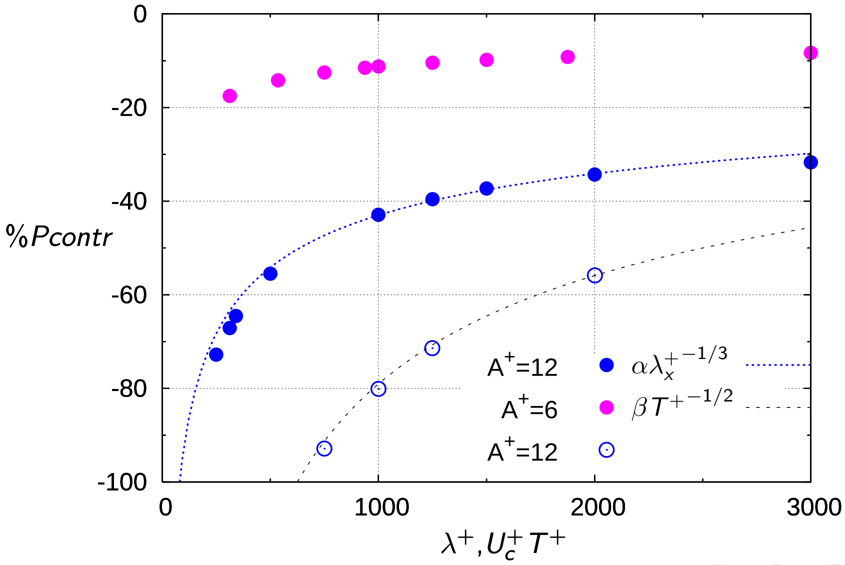
- Power required to control the flow:

$$P_{contr} = \mu \langle \frac{\partial W}{\partial y} W \rangle$$

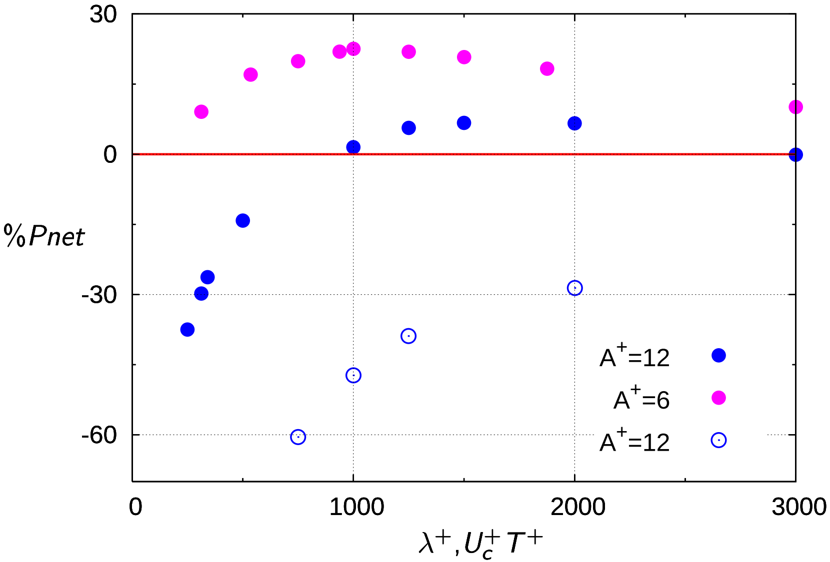
- Net power saved after DR:

$$P_{net} = \Delta P_{drive} + P_{contr}$$

Power budget (1)

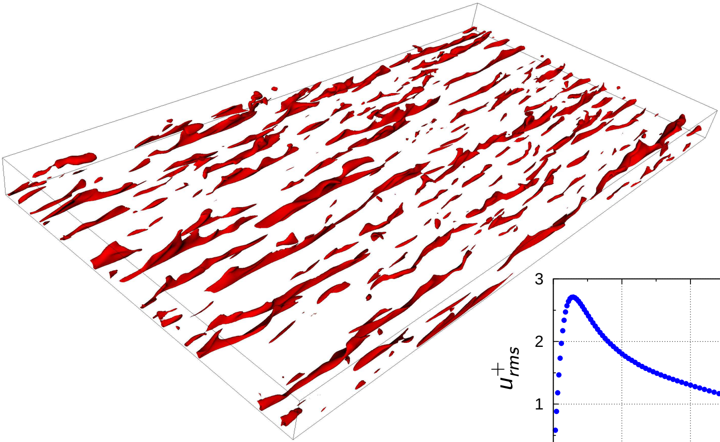


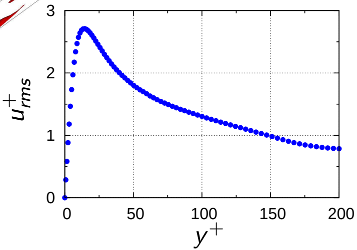
Power budget (2)



Isosurfaces of streamwise velocity: $u^+ = -4$

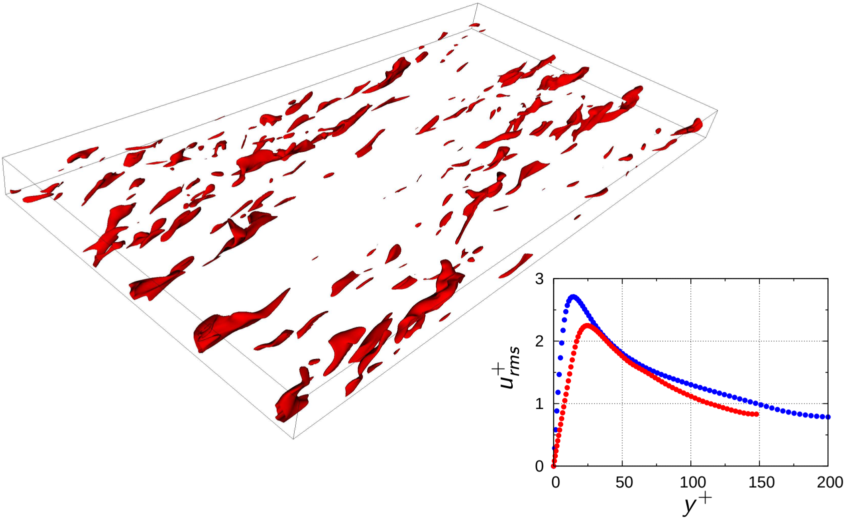
Uncontrolled



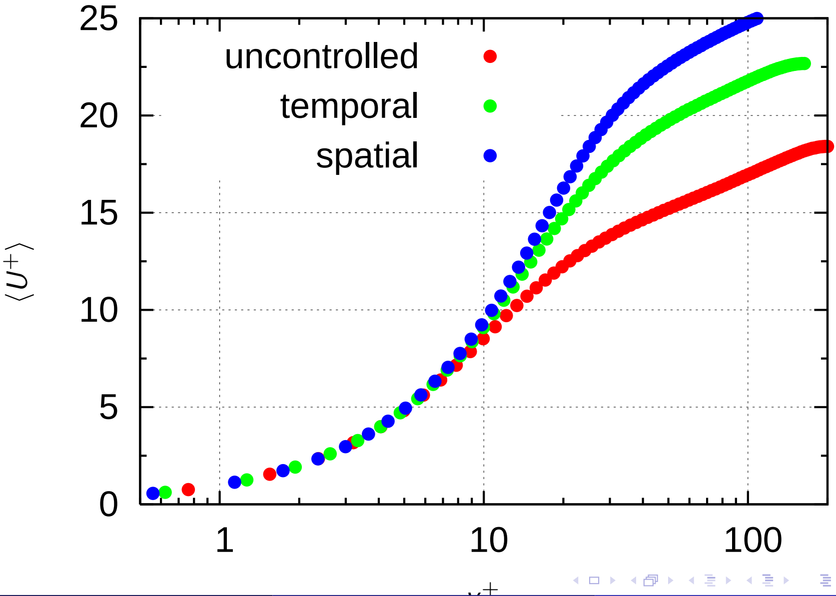


Isosurfaces of streamwise velocity: $u^+ = -4$

Controlled, *DR* 45%, actual wall units



Mean velocity profiles



Conclusions

1. U_c translates temporal into spatial forcing
2. Spatial forcing is more efficient
   - Higher DR (up to 52%)
   - Higher net saving (up to 23%)
3. Turbulent spanwise mean flow is based on laminar dynamics

- Passive device?

Spanwise flow (3)

Spatial oscillation - analytical results

Governing equation for z-component of velocity

$$U(y)\frac{\partial W}{\partial x} = \nu\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2}\right)$$

Hypothesis (δ_X thickness of the "spatial Stokes layer")

$$\delta_X \ll h, \quad \lambda = \mathcal{O}[h] \quad \Rightarrow \quad \frac{\partial^2 W}{\partial x^2} \ll \frac{\partial^2 W}{\partial y^2}, \quad U(y) \sim \left.\frac{dU}{dy}\right|_w y$$

Simplified governing equation:

$$\left.\frac{dU}{dy}\right|_w y\frac{\partial W}{\partial x} = \nu\frac{\partial^2 W}{\partial y^2}$$

It is possible to look for a solution in the form

$$W(x,y) = \Re\left[e^{i2\pi/\lambda x} F(y)\right]$$

obtaining a complex Airy equation for $F(y)$

$$i \left.\frac{dU}{dy}\right|_w y F(y) = \nu \lambda \frac{d^2 F(y)}{dy^2}$$

$$\overset{solution}{\Longrightarrow} F(y) = C\mathcal{A}\left(e^{-i2\pi/3} i \frac{y}{\nu^{1/3} \lambda^{1/3} \left.\frac{dU}{dy}\right|_w^{-1/3}}\right)$$

$$\boxed{\delta_X = \nu^{1/3} \lambda_x^{1/3} \left.\frac{dU}{dy}\right|_w^{-1/3}}$$