Control of Turbulent Wall Flows

A survey of strategies explored at Politecnico di Milano

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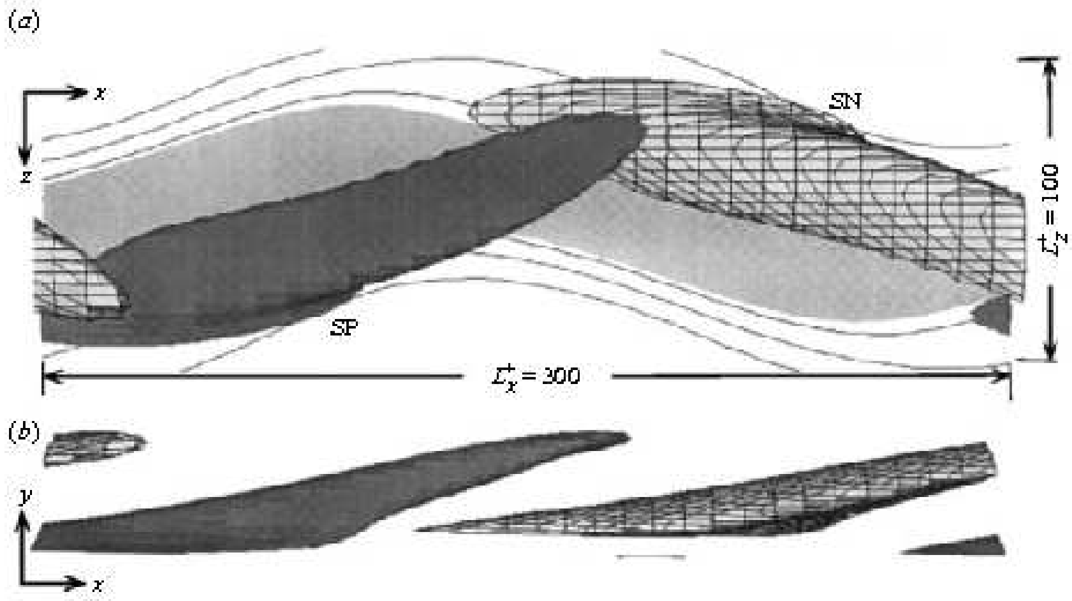
Contents

- Turbulent wall flows and control (friction drag)
- Numerical tool (DNS) & computing machines
- Wall transpiration (wall roughness?)
- Spanwise-oscillating wall (and future developments)
- Linear impulse response of the turbulent channel flow
- Adjoint Navier–Stokes
- Conclusions

Wall turbulence

Near-wall dynamics of turbulence structures: low-speed streaks and quasi-streamwise vortices (Schoppa & Hussain, JFM 2002)



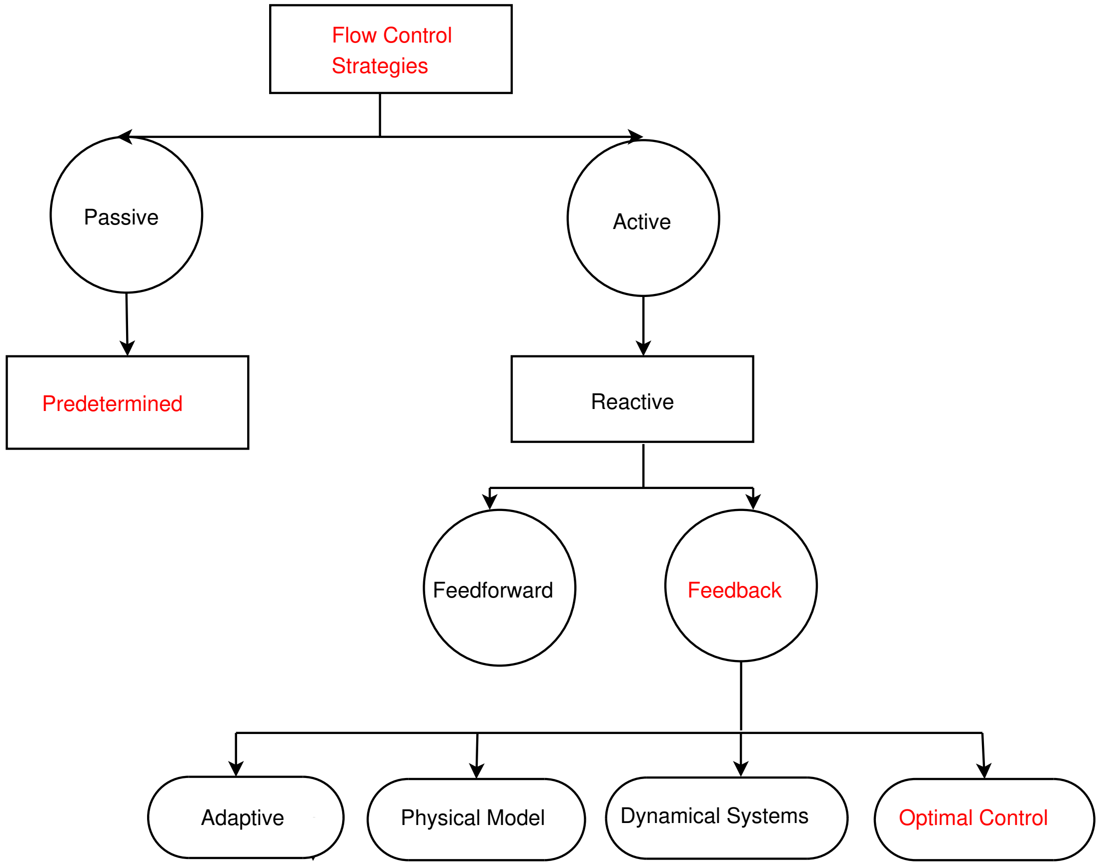
Control objectives

Interact with wall turbulence and its structures for:

- reduction of turbulent (friction) drag
- enhancement of turbulent mixing
- enhancement / reduction of heat exchange

Strong applicative interest: high potential benefits.

Control techniques

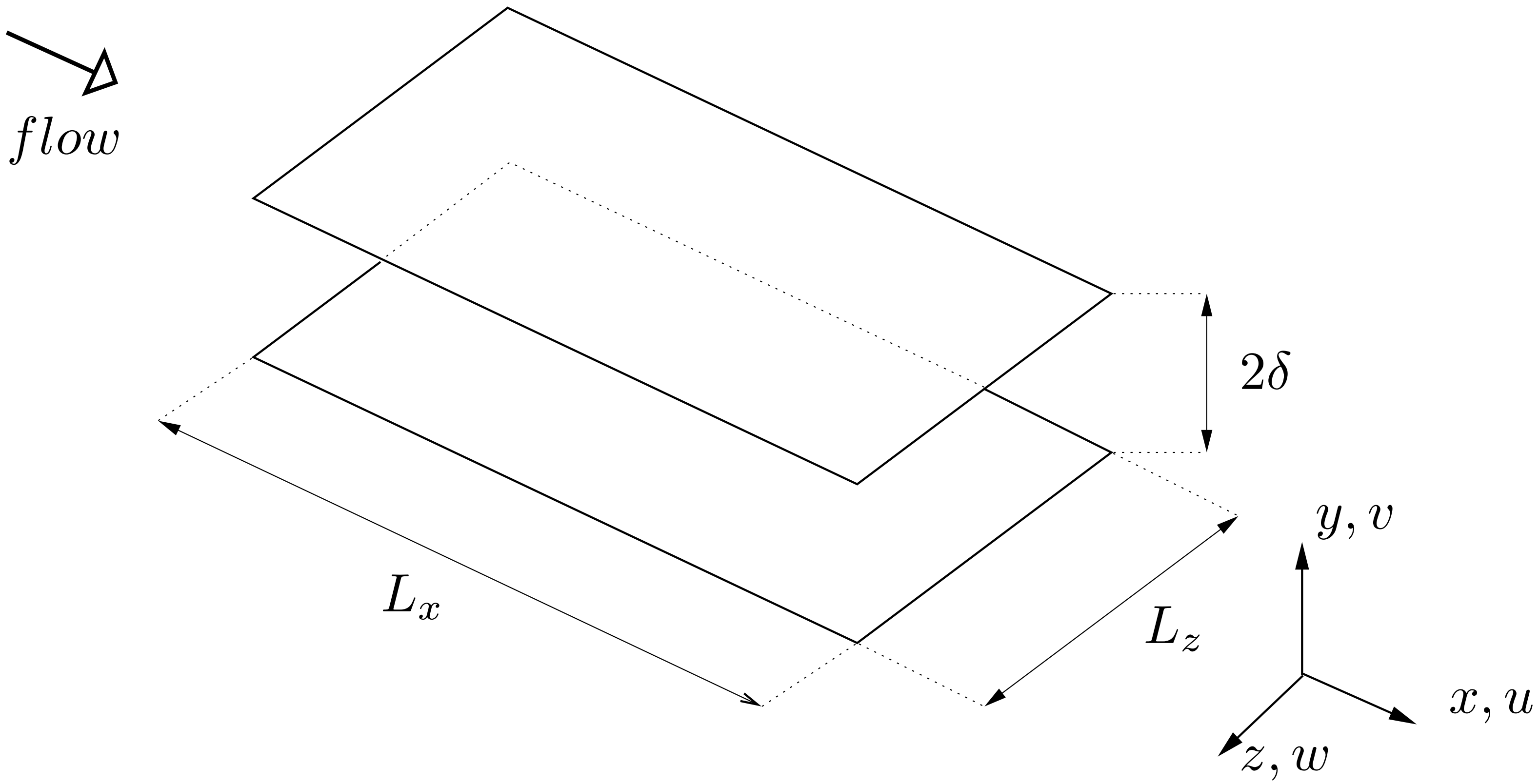


After Gad-el-Hak, J. Aircraft, 2001.

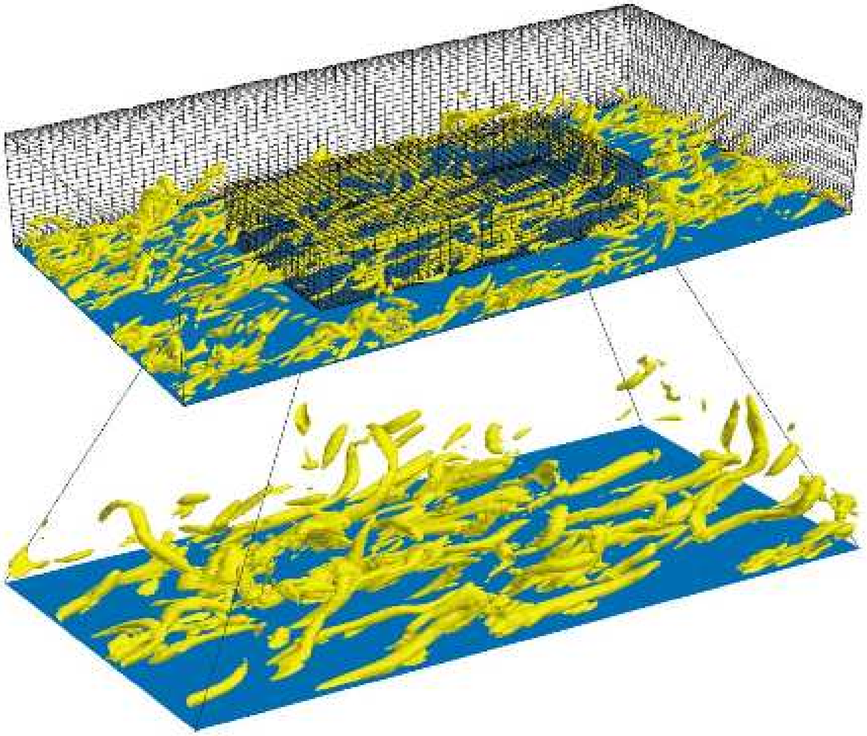
DNS: a research tool

- Numerical solution of turbulent flows without turbulence models
- Capture the basic physics of turbulence in simple flows
- Study of elementary turbulent flows of engineering interest (channel flow, pipe flow, boundary layer)
- Numerical experiments (unphysical ones can be conceived)
- Need for the highest computational efficiency

Turbulent flow in a plane channel



Complex dynamics in the simplest flow



Flow in the simplest geometry, yet with full range of space- and time-scales, many interacting coherent structures with intricated dynamics. After Bewley (Prog. Aerosp. Sc. 2001)

v-η formulation of the NS equations

Standard approach in DNS (Kim, Moin & Moser, JFM 1987): two uncoupled, scalar eqns for wall-normal velocity v and vorticity η

Periodic conditions $\Rightarrow$ Fourier discretization in the homogeneous directions: $\hat{v} = \hat{v}(y,t)$ and $\hat{\eta} = \hat{\eta}(y,t)$

- Minimal computational effort.
- Pseudospectral method, with de-aliasing.

Temporal integration: implicit time advancement for viscous terms, explicit for convective terms.

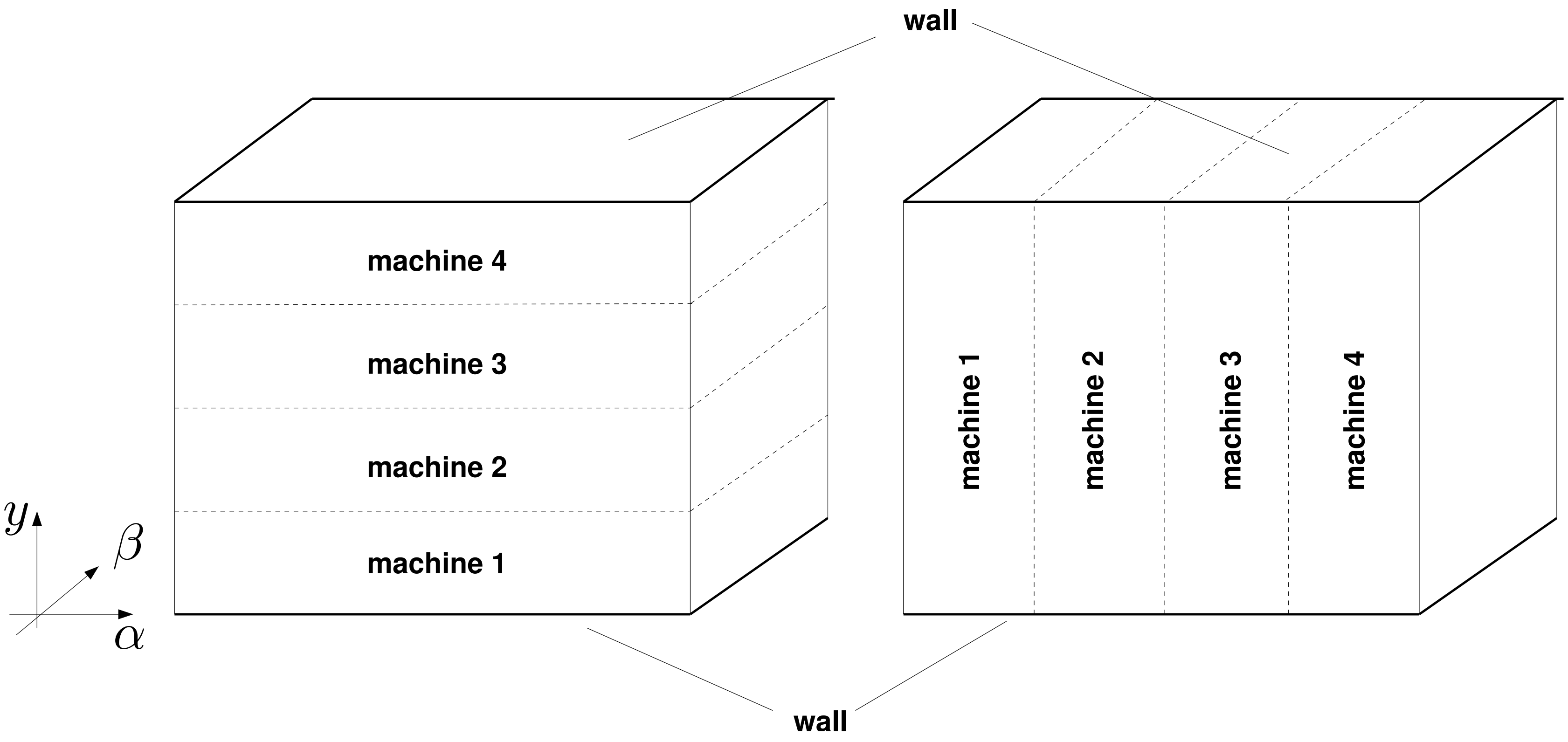
Wall-normal discretization & parallel computing

Computational efficiency does not call for any particular discretization in y.

Instead of spectral, we use high-order, compact finite difference schemes.

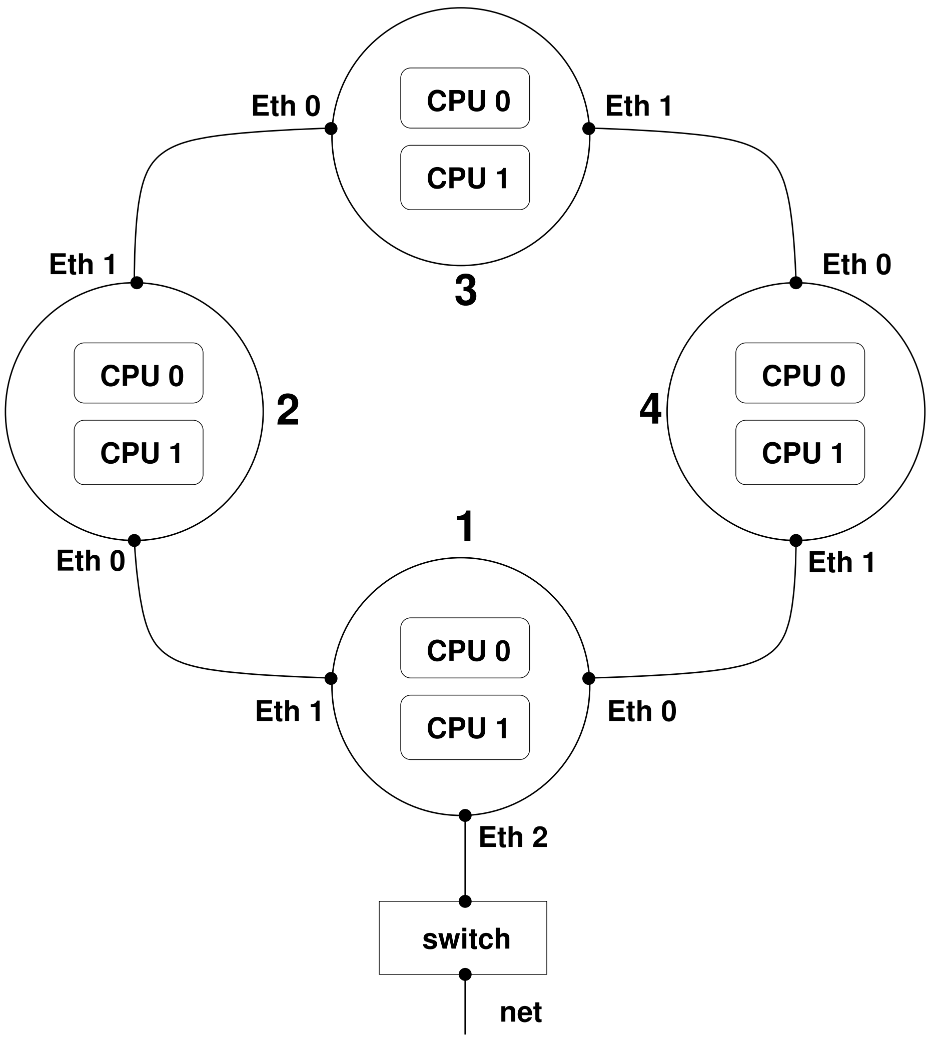
- Better resolution properties in wavenumber space (fewer Points Per Wavelength)
- Finite difference operators are local: key to our parallel strategy.
- Compact schemese are also known as implicit schemes (Lele, JCP 1992; Mahesh, JCP 1998).
- Eqns recast in a form where explicit compact schemes are possible, thanks to missing D_3

The parallel strategy (distributed memory)



When computing nonlinear terms, global transpose needed with spectral (Chebyshev) methods, but not with FD!

Connection topology: ring



Our first Personal Supercomputer

Low-cost, dedicated system: 2×8 Intel Pentium III CPUs and Fast Ethernet (2001).

Our current Personal Supercomputer

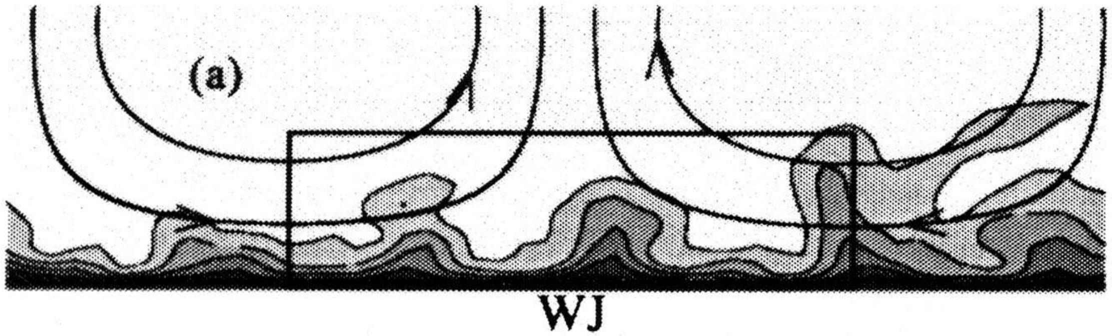
Low-cost, dedicated system: 2×10 Intel Xeon CPUs and Gigabit Ethernet (2004).

The language of marketing :-)

	Cray X1	Personal Supercomp.
clock speed	800 MHz	3 GHz
CPU Peak power	3.2 GFlop/s	6.0 GFlop/s
PE Peak Power	12.8 GFlop/s	12.0 GFlop/s
cost of 200 GFlop/s	$\approx$ \$ 2,500,000	$\approx$ \$ 50,000
floor space	2.3 m^2	0.25 m^2
compute density	356 GFlop/s / m^2	1740 GFlop/s / m^2
compute efficiency	13 GFlops/s / kW	45 GFlop/s / kW
weight	2090 kg	$\approx$ 150 kg
interconnect	400 GBit/s	1 GBit/s

Large-scale vortices through wall transpiration?

Starting point: recent findings by Schoppa & Hussain (PoF 1998):



In laminar flow, large-scale vortices can be created through zero-net mass flux distributed blowing/suction, via an instability mechanism active in a small window of $\mathrm{Re} - A - \lambda_t$ (Floryan, JFM 1997).

$$\boxed{v(x, 0, z, t) = A \sin(\lambda_t x)}$$

Drag-reducing wall roughness?

In laminar regime sinusoidal transpiration and wavy walls are equivalent (Floryan, JFM 2003).

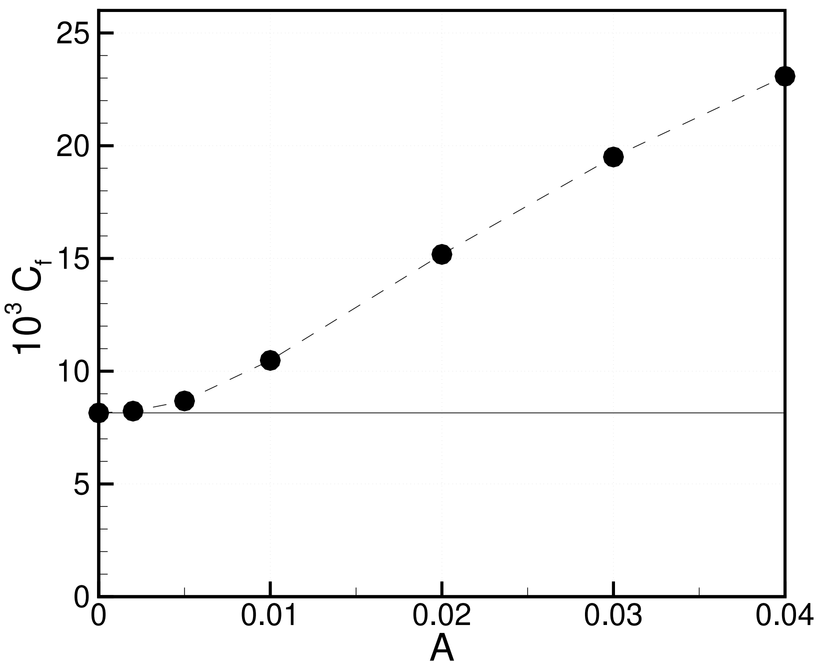
A rough wall would be the most appealing strategy!

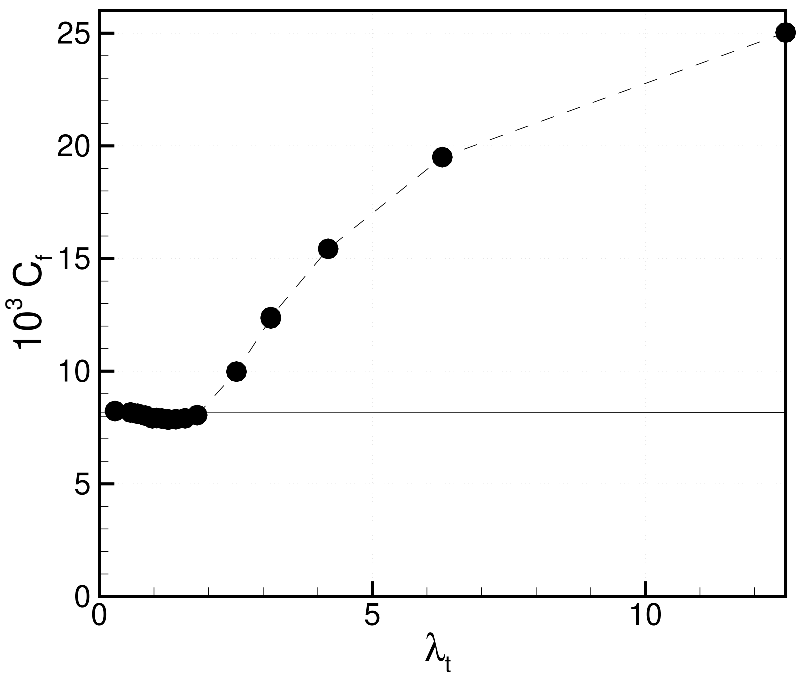
It is known that drag-reducing surfaces (other than riblets) may exist (Jiménez, Ann. Rev. Fluid Mech. 2004)

Numerical experiments (Quadrio, Floryan & Luchini, JFM 2004 subm.):

- No large-scale vortices...

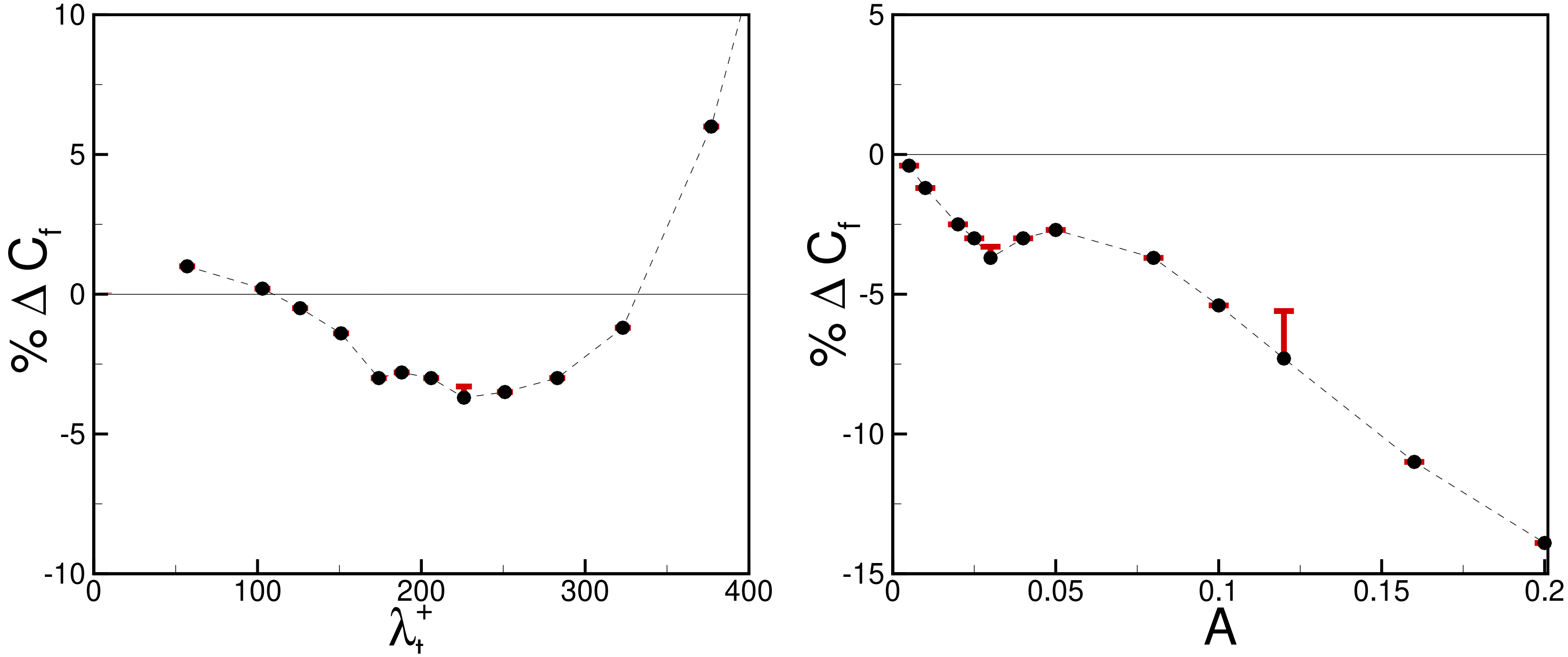
Friction changes





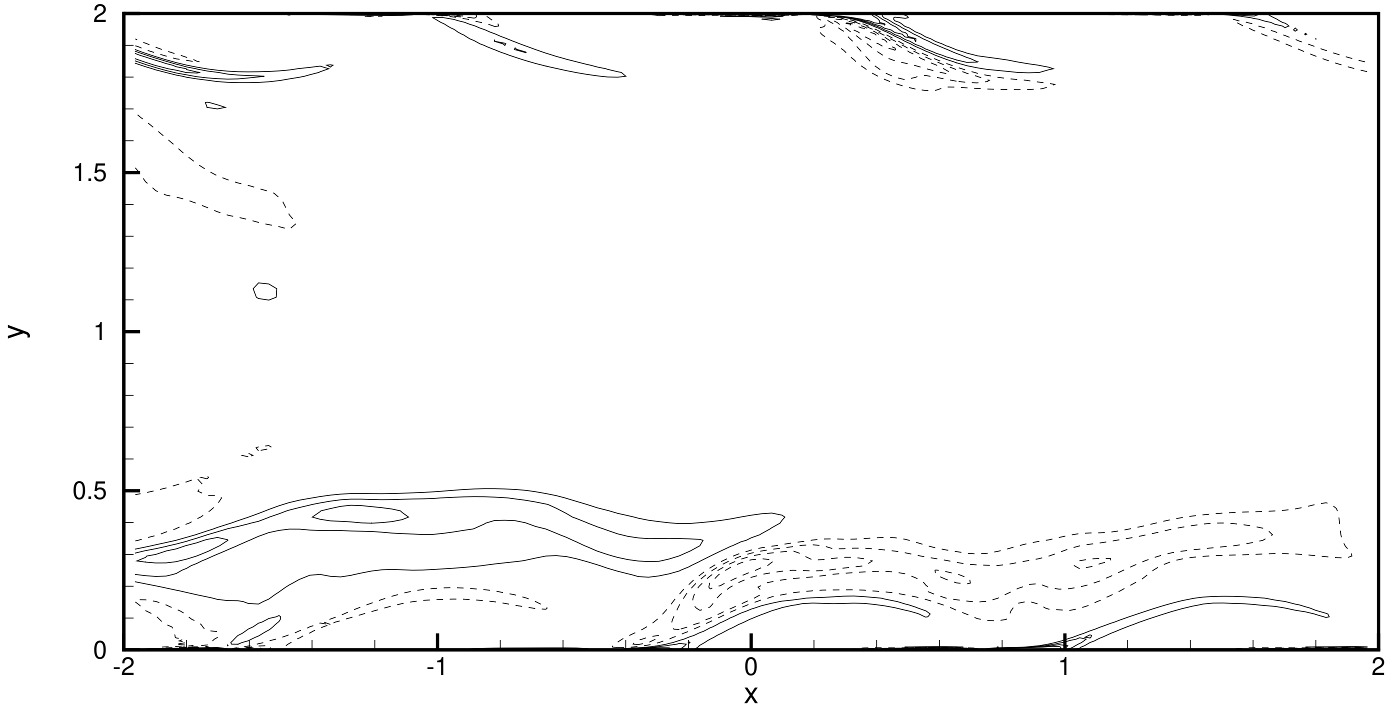
Large friction increase.

Unexpected effect of wavelength!



Significant, unexpected DR (not related to large-scale vortices, though).

Physical mechanism?



The wall is shielded from streamwise vorticity by properly-arranged transpiration.

Spanwise-oscillating wall

Technique known from early ’90 (Jung *et al.*, PoF 1991), both experiments and DNS.

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

- DR of the order of 40% is reported by many (not all) investigators (at low Re)
- Optimum period of oscillation $T^+ = 2\pi/\omega^+ \approx 100$ (no general agreement)
- Working mechanism not fully understood
- Interaction between near-wall streaks and vortices altered

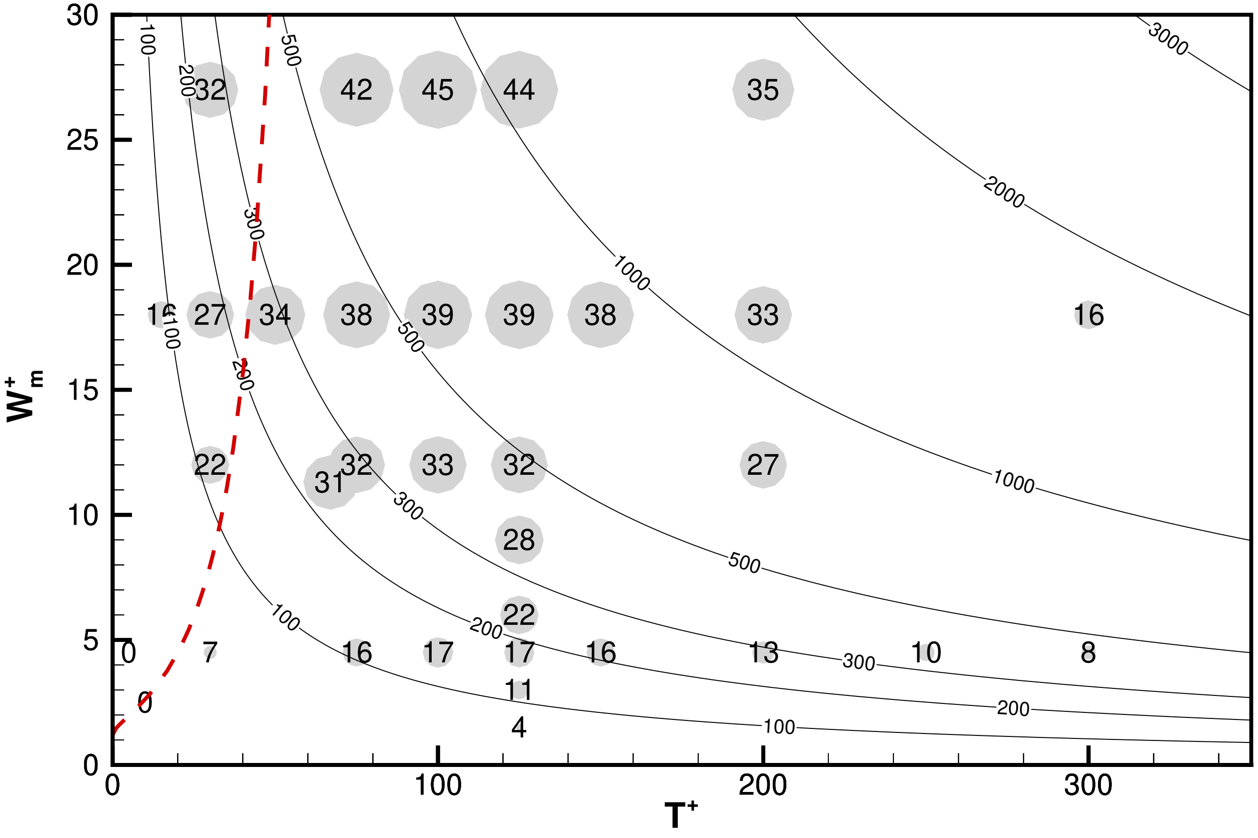
Movie from Quadrio & Ricco, J. Turbulence 2003 (initial transient).

Open questions

- maximum drag reduction? (discrepancies between experiments and DNS results)
- energy budget? (saved energy must be compared to the energy spent to move the wall)
- scaling of drag reduction? (one parameter relating to DR is not available)
- (what happens at higher Re?) (small range of Re explored to date)

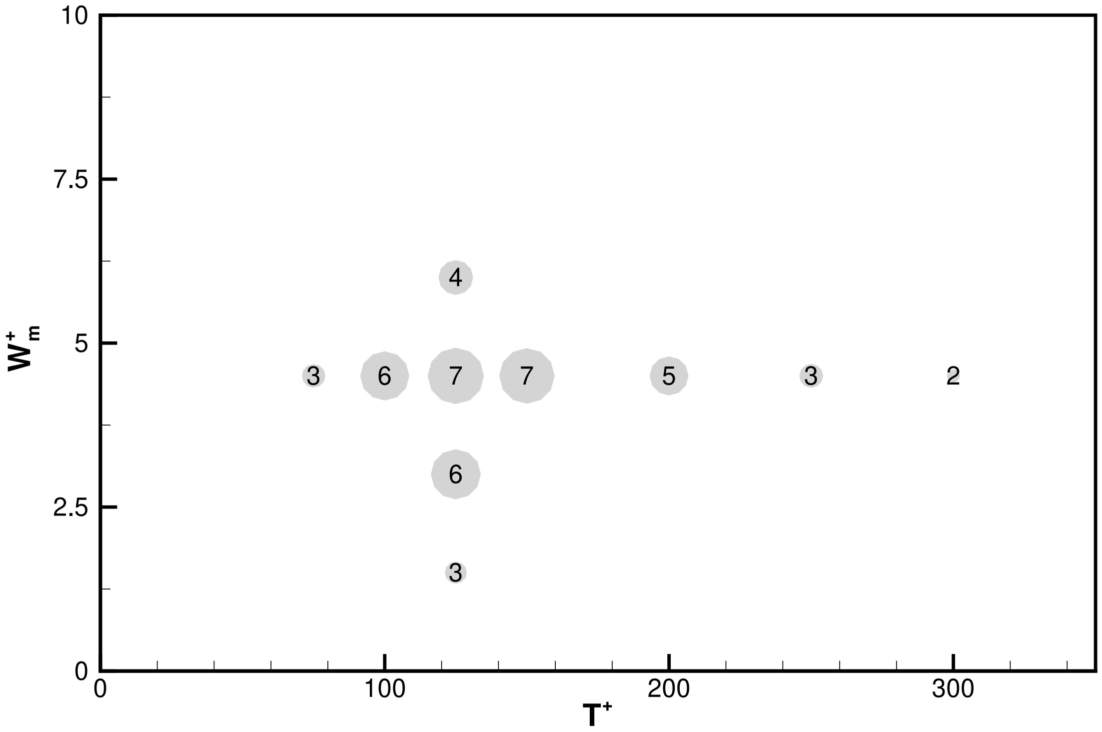
Answers with $\mathcal{O}(100)$ large DNS, at $\mathrm{Re}_\tau = 200$, each with more than 2×10^7 d.o.f. and 5×10^4 time steps. Quadrio & Ricco, JFM 2004 to appear.

Maximum drag reduction



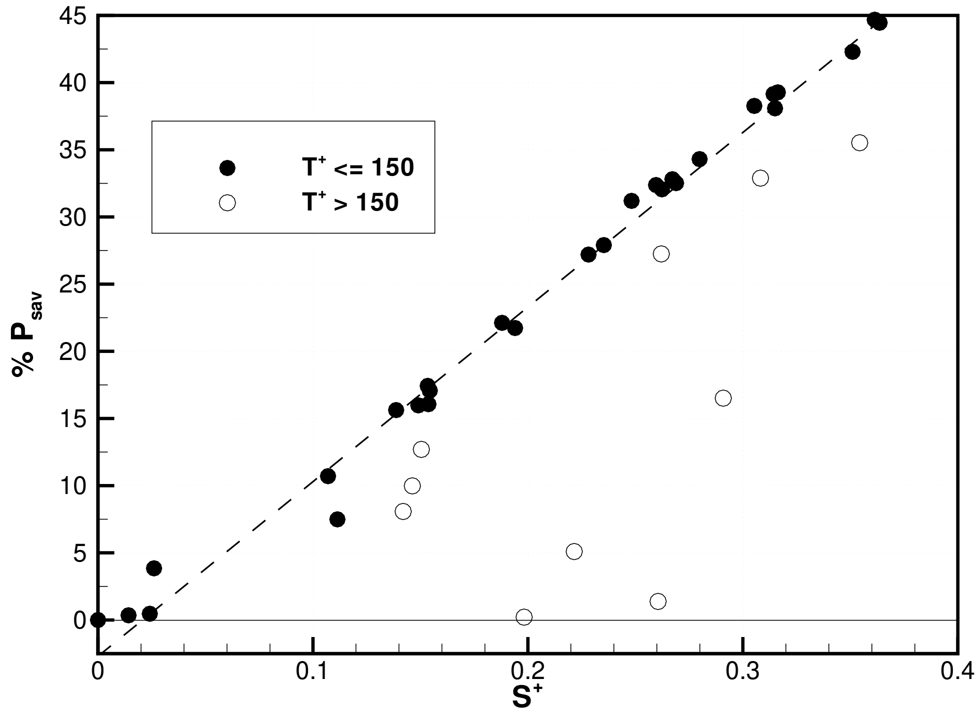
Reason for conflicting results explained.

Net drag reduction



Savings from wall oscillation may exceed added expenditure!

Scaling of drag reduction

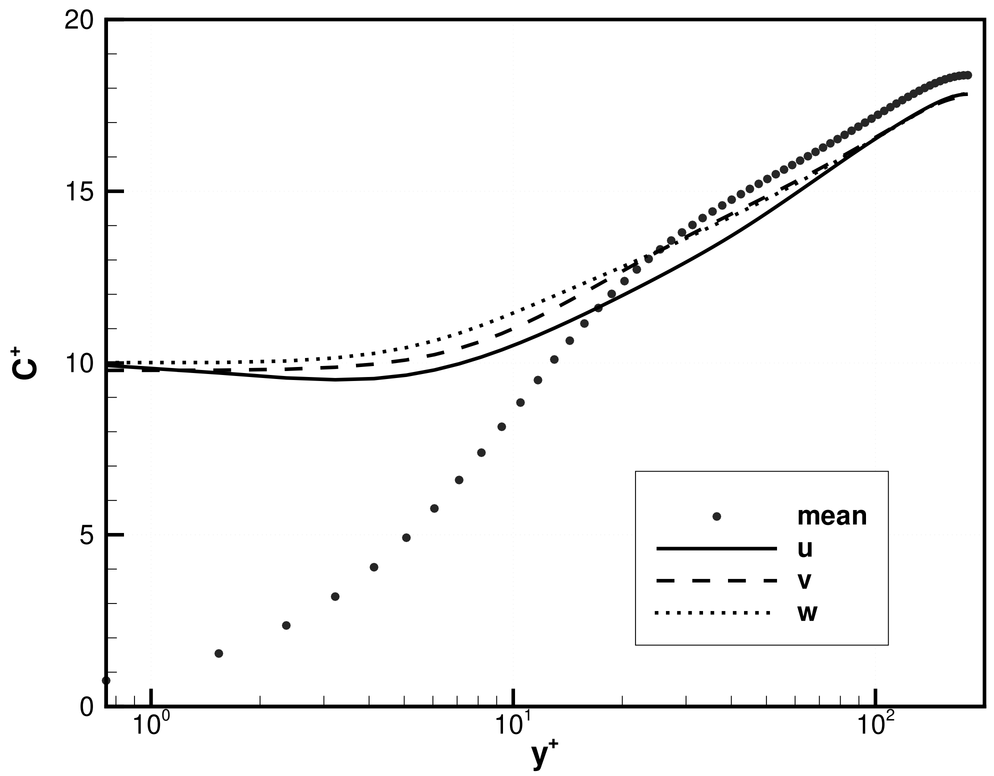


$$S^+ = \frac{a_m^+ \ell^+}{W_m^+} = 2\sqrt{\frac{\pi}{T^+}} \ln\left(\frac{W_m^+}{W_{th}^+}\right) \mathrm{e}^{-\overline{y}^+ \sqrt{\pi/T^+}}$$

Further developments

- Confirm the importance of local acceleration a_m^+ (see also Zhao *et al.*, Fluid Dyn. Res. 2004). This paves the way for:
  - using convection velocity and steady blowing
  - optimizing the temporal waveform
  - use of travelling waves
- Explore Re effects

Convection velocity near a wall



The “footprint” of turbulence... From Quadrio & Luchini, PoF 2003.

Impulse response

To characterize the dynamics of a turbulent channel flow through the statistically averaged linear response $\mathcal{H}$ of the velocity field to external (wall) perturbations:

$$\boxed{\mathcal{O}(x,y,z,t) = \int \mathcal{H}(x-x',y,z-z',t-t')\,\mathcal{I}(x',z',t')\,\mathrm{d}x'\,\mathrm{d}z'\,\mathrm{d}t'}$$

- Useful information for MEMS design: which effects are to be felt *here* at time t_1 if an actuator at the wall has been moved *there* at time $t_2 < t_1$?
- Very demanding experiments/simulations: full 4d characterization of $\mathcal{H}$ never attempted. Laminar response is being examined by Bamieh *et al.*, JFM 2004 subm.

Objective

Extract from Direct Numerical Simulation (DNS) the 4-d response function $\mathcal{H}(x, y, z, t)$ to the wall-normal velocity:

$$\boxed{v(x, 0, z, t) = \delta(x)\delta(z)\delta(t)}$$

The response function $\mathcal{H}$ in time and frequency domains

- In frequency domain: $\widehat{\mathcal{H}}(f)$ is the response to sinusoidal forcing of varying frequency f
- In time domain: $\mathcal{H}(t)$ is the response to a Dirac δ function at $t = 0$

The former is the Fourier transform of the latter.

Difficulties

Very low signal-to-noise (S/N) ratio:

- Turbulence is noisy
- Perturbation amplitude must be small for linearity

Phase-locking averages allow the extraction of the deterministic part of the response, at the expense of a very large statistical sample.

$\widehat{\mathcal{H}}(f)$ as the response to sinusoidal forcing

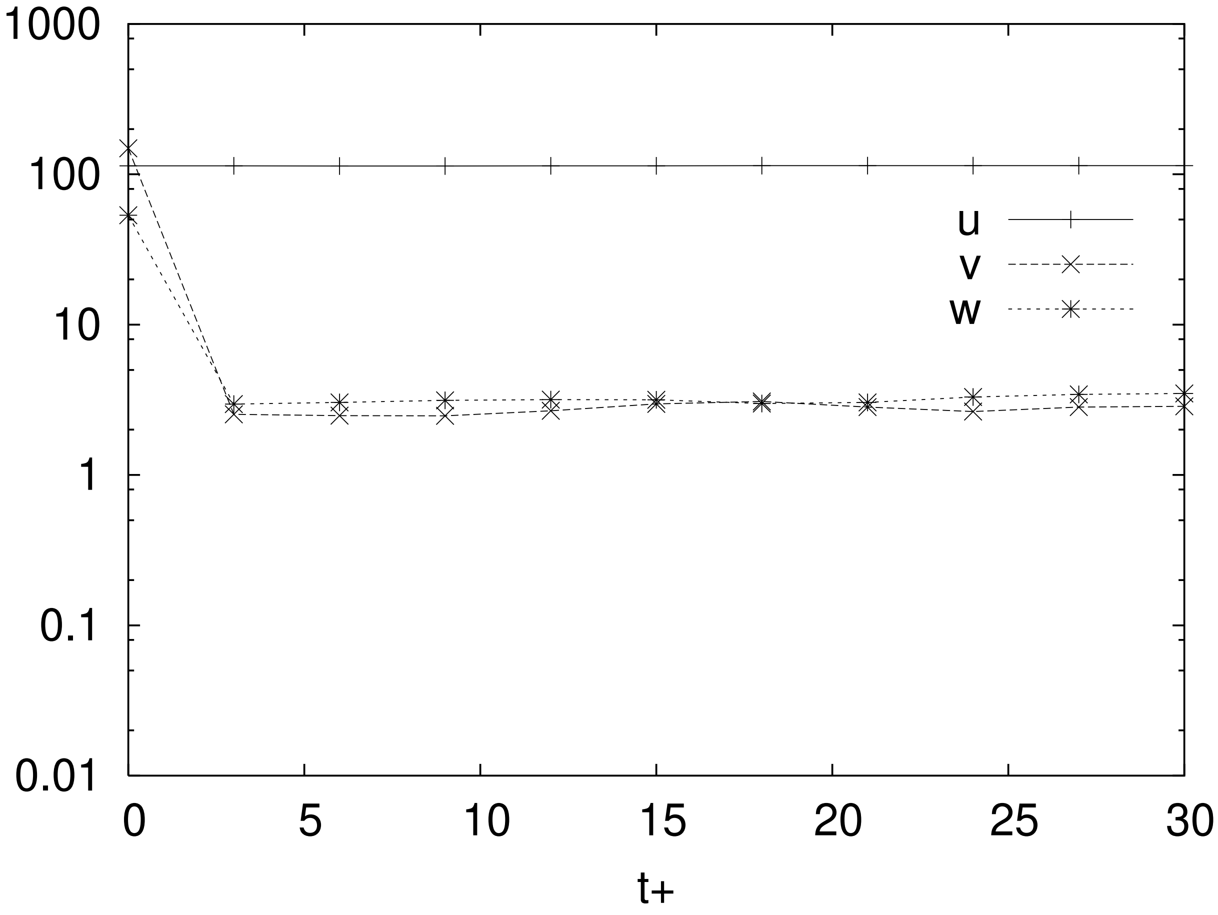
- Pro: the allowed forcing amplitude is larger and therefore the required averaging time is shorter
- Con: a number of simulation for different frequencies is required

$\mathcal{H}(t)$ as the response to an actual impulse

- Pro: in a single shot the same amount of information as many sinusoidal simulations
- Con: the allowed forcing amplitude is smaller and therefore the required averaging time is longer

Periodic repetition of impulses, separated by $\Delta t^+ \sim 45$, with phase-locked averages.

Spatial maximum of $\mathcal{H}$ vs time. Results after 1.3KMM



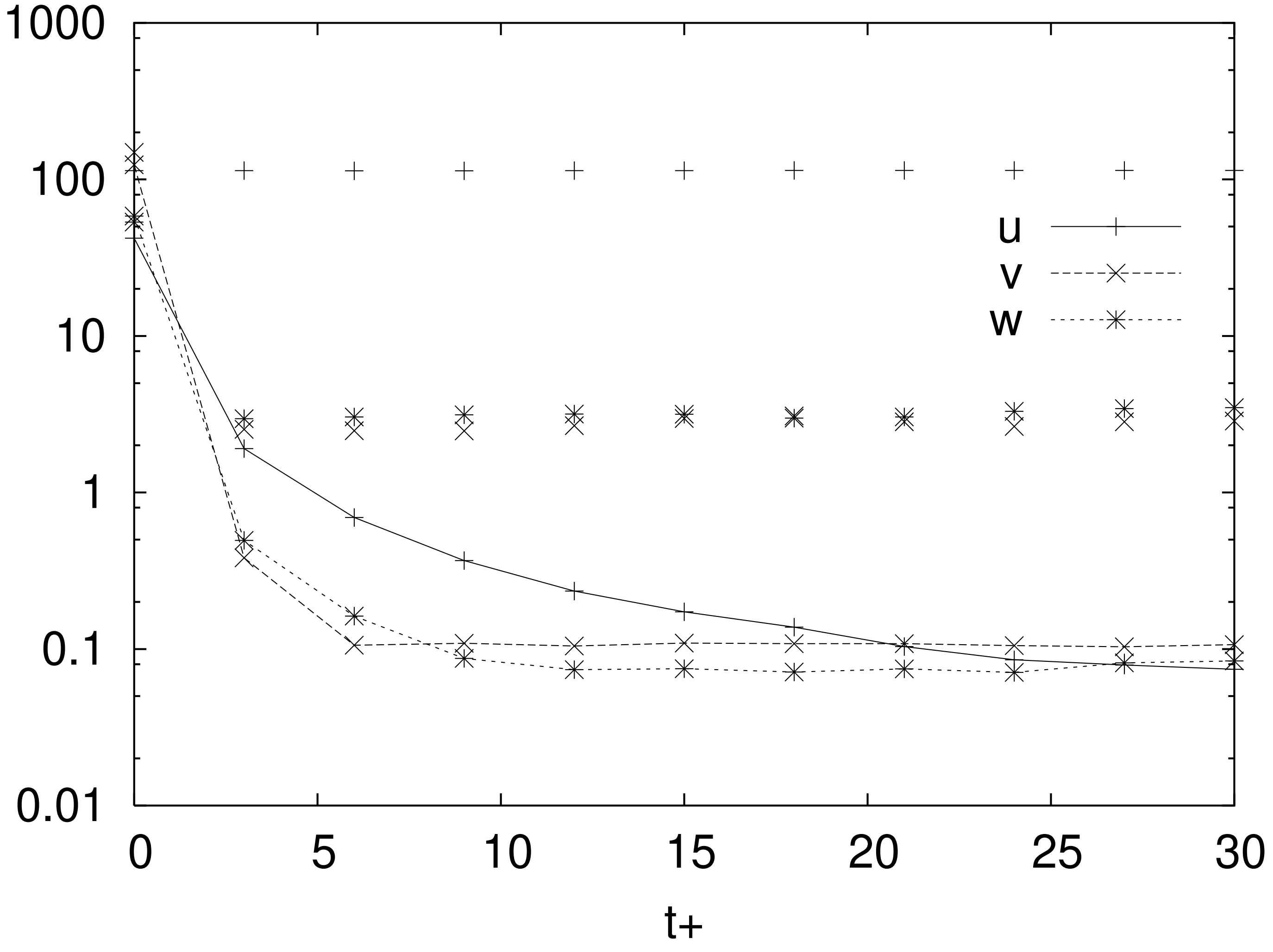
Idea: forcing with a random signal

From signal theory: when a white noise is passed through a linear filter, the correlation between input and output is proportional to the impulse response of the system.

$$\boxed{\begin{cases} R_{io}(t) &= \int \mathcal{H}(t-t')R_{ii}(t')\mathrm{d}t' \\ R_{ii}(t') &= \delta(t') \end{cases} \qquad \Rightarrow R_{io}(t) = \mathcal{H}(t)}$$

Turbulent fluctuations will be averaged out just as in phase-locking.

- Pro: like in sinusoidal forcing, power is uniformly distributed over time and space
- Pro: like in impulsive forcing, in a single shot the same amount of information as many sinusoidal simulations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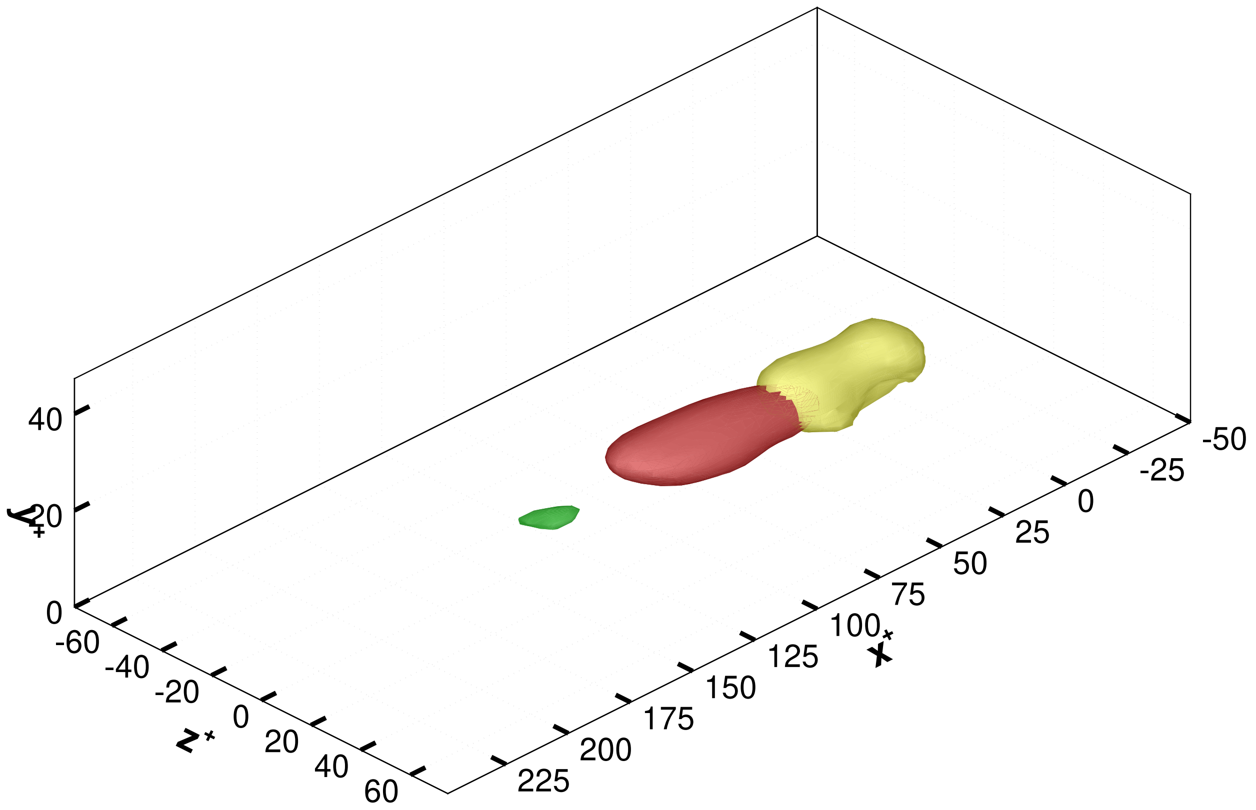
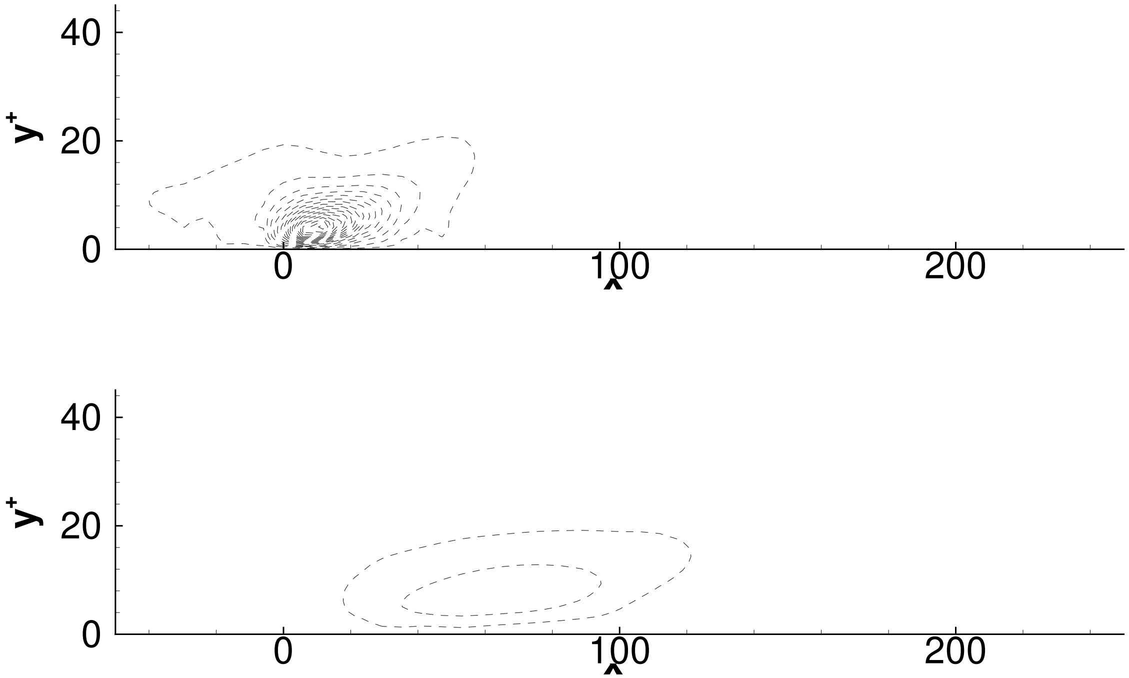
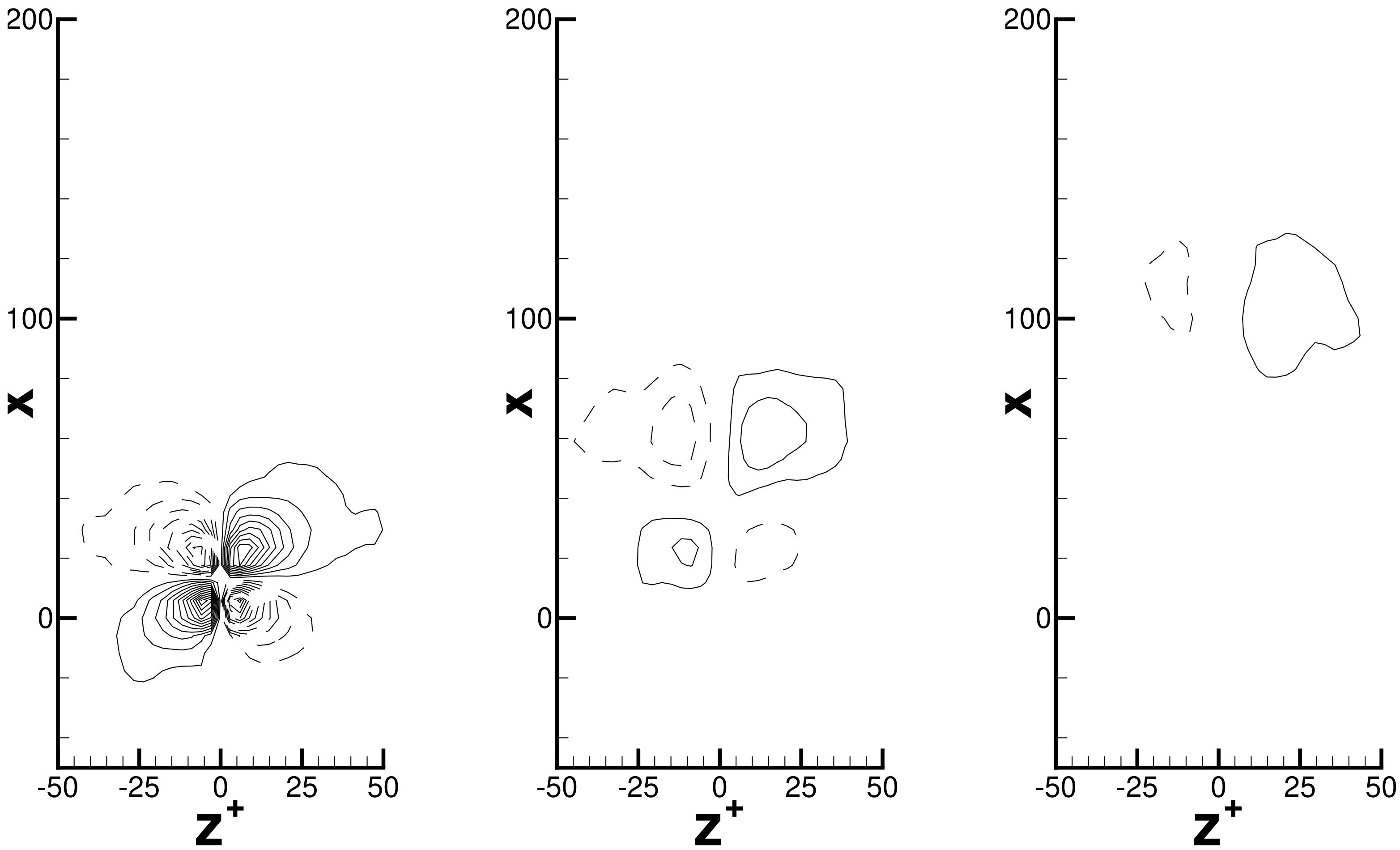


$x - y$ plane at $z^+ = 0$, u component



$x - z$ plane at $y^+ \sim 8$, w component



Adjoint DNS

Compute the control law in the idealized situation of:

- arbitrary blowing/suction distribution at the wall $v_i(x, 0, z, t)$
- full-field information available
- plenty of on-line computational resources

Tool: non-linear, adjoint-based gradient optimization strategies.

Adjoint: tool to compute derivatives of an arbitrary objective function with respect to the control parameters.

A numerical challenge

Adjoint computations must be efficient

- derivatives of the objetcive function w.r.t. all control variables are needed simultaneously
- control variables are the discrete counterpart of $v_i(x, 0, z, t)$, up to 10^8

Back and forward in time. Huge storage requirements: to compute adjoint in $[0, T]$ the complete direct field in $[0, T]$ must be available

Results: computing time is 2 times the direct code.

The adjoint field at the wall

Adjoint field provides non-trivial information.

Movies from Luchini & Quadrio, ASME 2002.

We have found divergence of the adjoint computation:

- unexpected
- reasonable (turbulence is a chaotic system!)

Future work: let statistical analysis enter the picture, to move towards realistic situations.

Conclusions

- Many approaches to turbulent friction drag reduction are being explored
- A few of them are promising
- Most of them help understanding the near-wall turbulence dynamics
- Studies are at a preliminary stage. We are far from building devices for real-world applications
- Huge amount of work in the near future!