The response of wall turbulence to streamwise-traveling waves of spanwise wall velocity

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iTi 2008, Bertinoro, Oct 12-15

Outline

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Spanwise wall forcing of turbulence

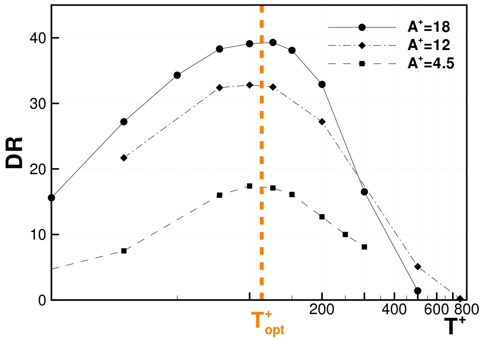
A long story made short

- 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

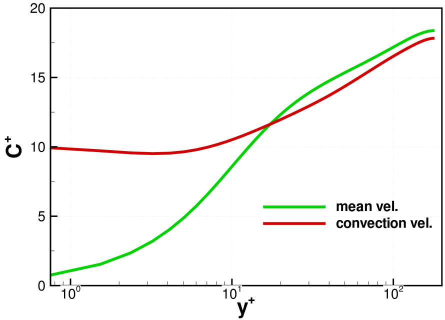
$$w(x, y = 0, z, t) = A \sin(\omega t)$$

- High levels of turbulent friction drag reduction
- Basic mechanism still elusive
- Existence of an optimum period T_{opt}
- Unpractical because of moving parts



An important concept: the convection velocity

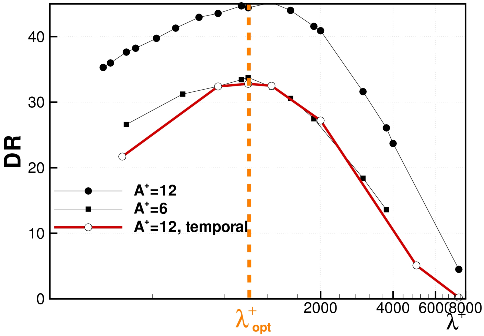
- Turbulent fluctuations at the wall possess a convection velocity
- Known concept (Kreplin & Eckelmann) in the '70
- Re-discovered (!) by Kim & Hussain '93
- Re-re-discovered (!!) by Quadrio & Luchini '03



The oscillating wall made stationary

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

- 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, other roughness)



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The traveling waves: an obvious curiosity

$w = A\sin(\omega t)$

Oscillating wall

- Infinite phase speed

$w = A\sin(\kappa x)$

Steady waves

- Zero phase speed

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

Traveling waves

- Phase speed $c = \omega / \kappa$

A numerical DNS study

- DNS pseudo-spectral code
- Parallel strategy to exploit commodity hardware (Luchini & Quadrio JCP 2006)
- Powerful dedicated system with 268 dual-core Opteron CPUs, 280GB RAM, 40TB disk space

A large parametric study

- Turbulent channel flow at $Re_\tau = 200$
- Standard domain size: $L_x = 6\pi h$, $L_y = 2h$ and $L_z = 3\pi h$
- Standard spatial resolution: $N_x = 320$, $N_y = 160$ and $N_z = 320$
- Long averaging time
- More than 250 simulations
- Approx. 4 centuries of CPU time

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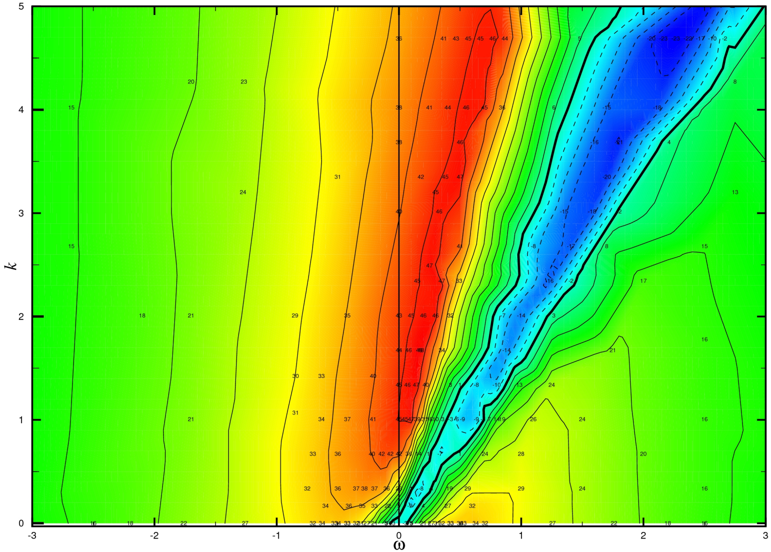
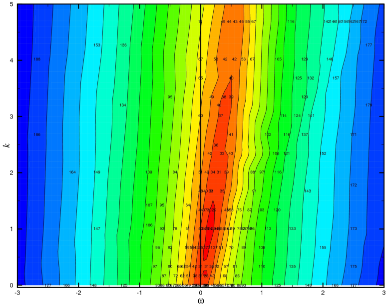
Unexpected results!

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



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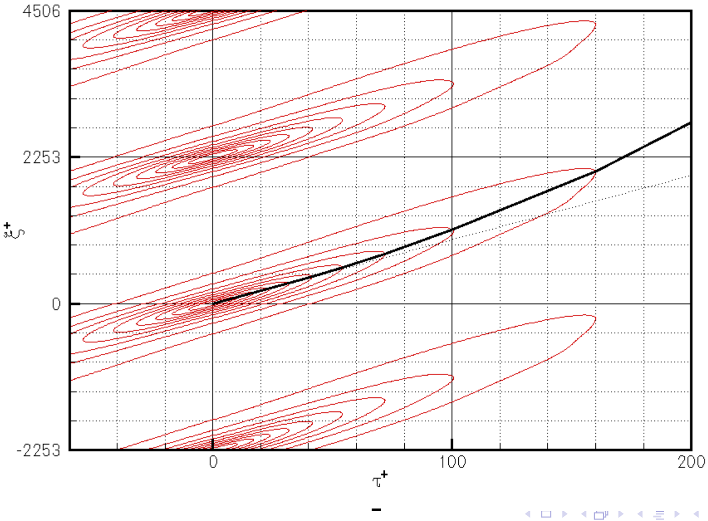
Understanding the physics

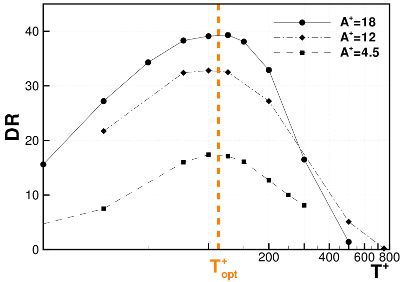
The lifetime T_ℓ of turbulent structures



Unsteadiness in the convecting reference frame

Oscillating wall

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



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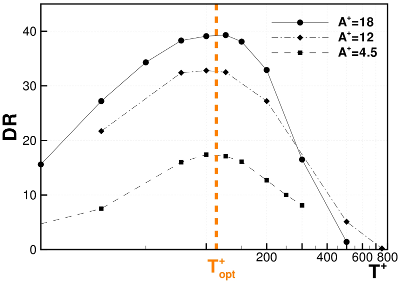


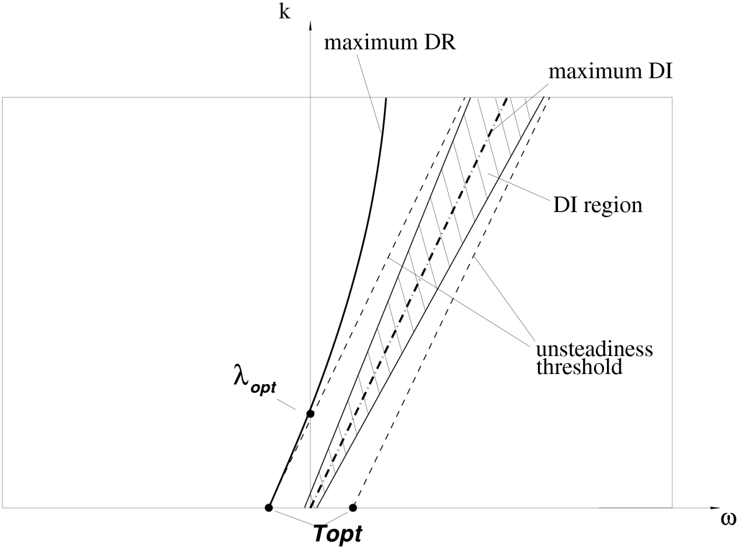
Traveling waves

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

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

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

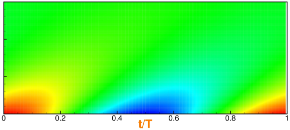
How spanwise forcing really works (1)



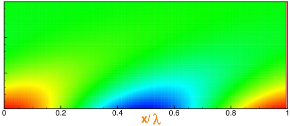
One step back

Extending the laminar Stokes solution

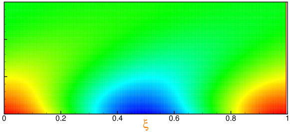
- Laminar case
- Transverse, alternating boundary layer
- Qualitative similarity



$w(y, t)$



$w(y, x)$

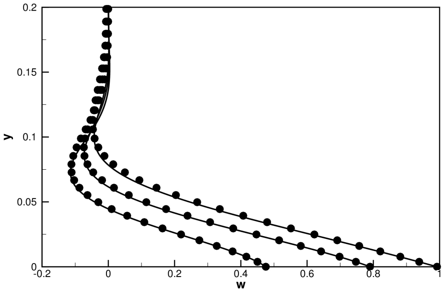


$w(y, x - ct)$

The generalized Stokes layer

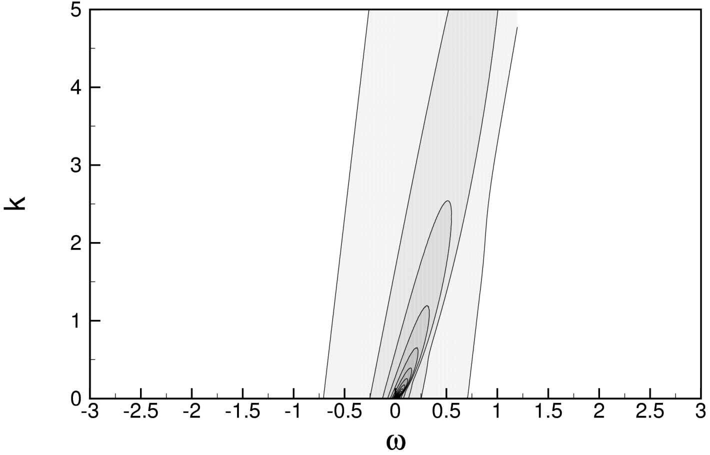
An analytical approximate solution

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

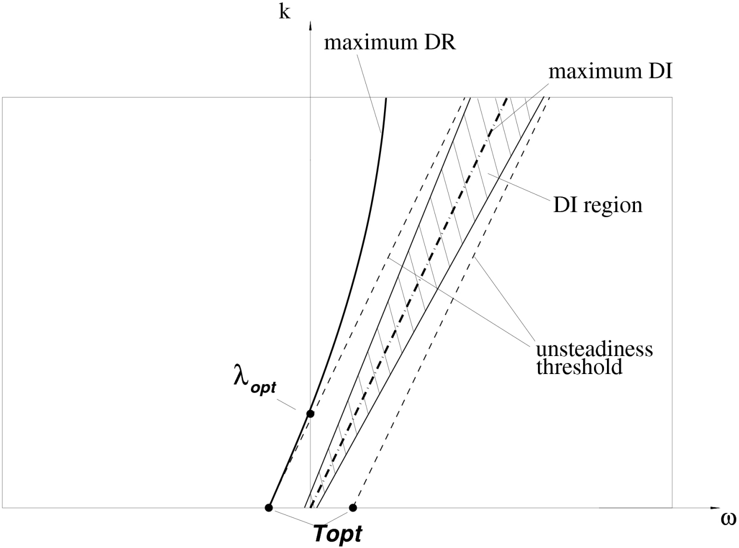


- $\delta_{GSL} \ll h$
- Neglect streamwise viscous diffusion
- Threshold velocity to discriminate flow regimes

Using the GLS solution
Thickness of the GLS



How spanwise forcing really works (2)



Future work

- Understanding scaling properties of DR (laminar solution available!)
- Really understanding how spanwise forcing really works
- Real device?