Turbulence Drag Reduction by In-Plane Wall Motion

Wenxuan Xie, Maurizio Quadrio

Department of Aerospace Engineering
Politecnico di Milano

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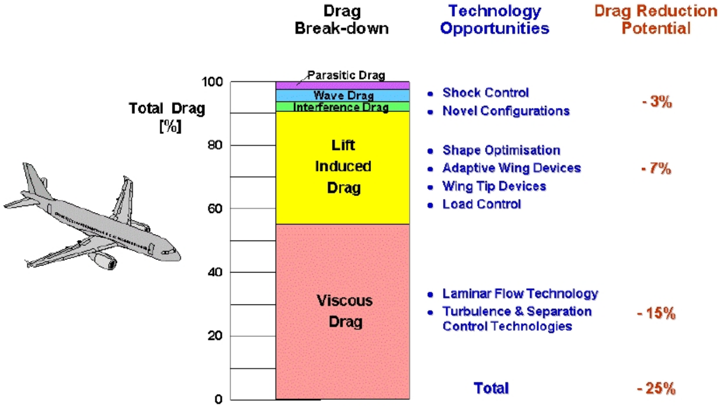
Why turbulence drag reduction?

Turbulence drag plays an important role in:

- Air transportation
- Ground transportation
- Water transportation
- Pipeline oil transportation
- ...

Why turbulence drag reduction? (cont.)

The breakdown of the drag on an aircraft (Schrauf, Community Aeronautics Days 2006)



Flow control techniques

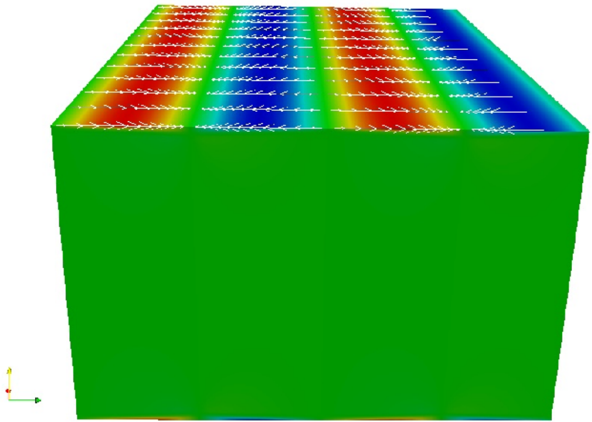
- Passive control
  no actuators, e.g.riblets (simple, less efficient)
- Active control
  - open-loop
    with actuators but no sensors (relatively simple, efficient)
  - closed-loop
    with both actuators and sensors (complex, efficient)

Flow control techniques (cont.)

Turbulent drag reduction by in-plane wall motion:

1. Spanwise-oscillating wall (Quadrio et al 2004 JFM)
   relatively large drag reduction, low net energy saving
2. Streamwise travelling waves (Quadrio et al 2009 JFM)
   large drag reduction, higher net energy saving
3. Spanwise travelling waves
   - wall motion
   - body forcing

Spanwise travelling waves (of spanwise velocity)



Spanwise travelling waves

- body forcing:
  $$F_z = Ie^{-y/\Delta}\sin(\kappa_z z - \omega t)$$
  Drag reduction 30% based on very limited observations, net savings unknown. (Du et al JFM 2002)
- wall motion:
  $$w = A\sin(\kappa_z z - \omega t)$$

Two methods give similar results in turbulence statistics and drag reduction. (Zhao et al Fluid Dyn Res 2004)

If $\kappa_z = 0$, wall oscillation

Method

Aim

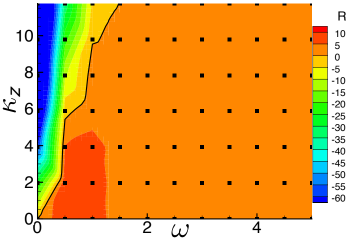
find the optimal point in the 3d parametric space $(A - \omega - \kappa_z)$ with the best energetic performance.

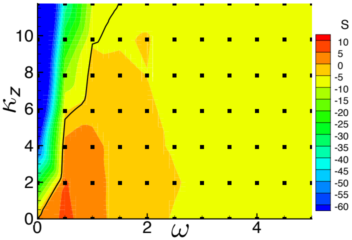
Around 250 Direct Numerical Simulation for the turbulent channel flow

- $L_x = 4.8,\ L_y = 2,\ L_z = 3.2$
  non-dimensionalized by h (half of the channel height)
- $nx = 64,\ ny = 100,\ nz = 128$
  $\Delta_x^+ = 10,\ \Delta_z^+ = 5$
- $Re_\tau = 200$ (corresponding to $Re = 4760$)

Map of Drag Reduction and Net Energy Saving

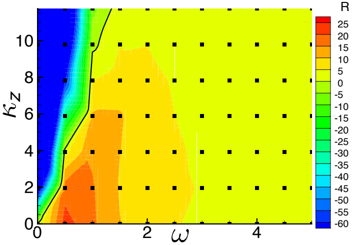
A=0.1





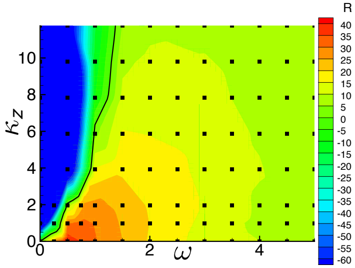
Map of Drag Reduction and Net Energy Saving (cont.)

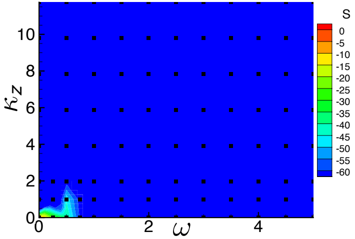
A=0.2



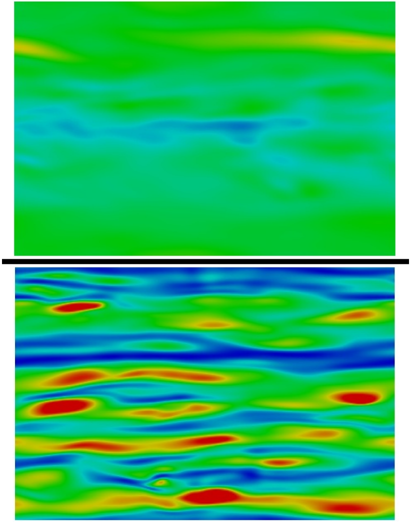
Map of Drag Recution and Net Energy Saving(cont.)

A=0.5



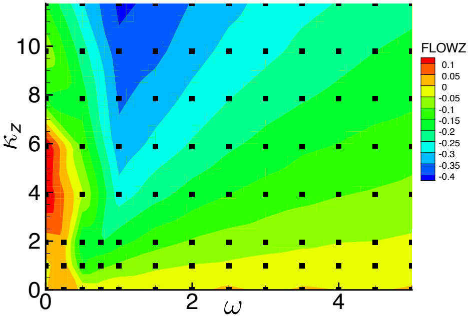


Modification of Near Wall Turbulence

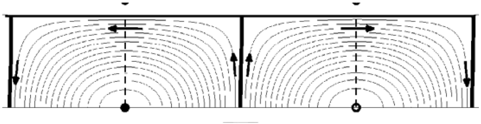


Spanwise flow rate

- $\nabla_z P = 0$ in all simulations
- spanwise flow rate arises for most of the simulations
- analogy to travelling wave of blowing and suction



"Streaming" effect from blowing/suction waves



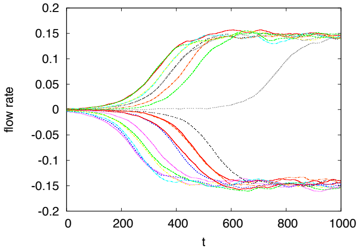
Suppose the blowing/suction wave is travelling from left to right. We look at a particle originally at distance y_0 from the wall:

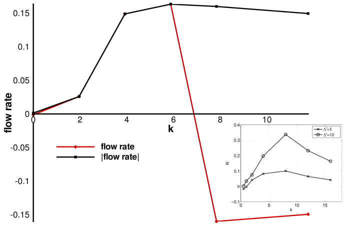
- In the first cell (the cell on the right), the particle is first pushed towards the wall and then blowed back to y_0, the particle is travelling in region $y < y_0$
- In the second cell, the particle is first blowed towards the center line and then sucked back to y_0, the particle is travelling in region $y > y_0$

Hoepffner and Fukagata JFM 2009

In the case of standing wave

- Different initial fields lead to different sign of the flow rate. The symmetry is kept on time average.
- The absolute values of the flow rate qualitatively agree with the drag reduction values from standing wave of blowing and suction. (Mamori and Fukagata ETC 2011)





Conclusion

From the global map:

- relatively large maximum drag reduction, but low net energy saving
- outperformed by the spanwise wall oscillation

From the flow statistics:

- near wall turbulence cycle is modified
- creation of spanwise flow rate (could be used?)

Thank you all!