Turbulent drag reduction by spanwise forcing

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Outline

Streamwise-traveling waves of spanwise velocity

Experiment

Open questions
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

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Experiment

Open questions
The streamwise-traveling waves
Streamwise-traveling waves of spanwise velocity

The original idea: spanwise wall oscillation
Quadrio & Ricco, JFM '04

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

- 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

\[ w = A \sin(\kappa_x x - \omega t) \quad \text{StTW} - w \]

\[ w = A \sin(\kappa_z z - \omega t) \quad \text{SpTW} - w \]

\[ f_z = A e^{-y/\Delta} \sin(\kappa_x x - \omega t) \quad \text{StTW} - Fz \]

\[ f_z = A e^{-y/\Delta} \sin(\kappa_z z - \omega t) \quad \text{SpTW} - Fz \]
The spanwise laminar flow (StTW-w)

\[ w(t/T, y), \text{TSL (}\kappa = 0\text{)} \]

\[ w(x/\lambda, y), \text{SSL (}\omega = 0\text{)} \]

\[ w((x - ct)/\lambda, y), \text{GSL} \]
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 $\delta_{GSL}$
- 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)

$U$

0.11 - 0.74

$V$

2.68 - 2.63

$W$

3.28 - 3.79
Optimal output

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

- \( U \):
  - 481x - 44x

- \( V \):
  - 0.47x - 0.51x

- \( W \):
  - 0.40x - 0.46x
Streamwise-traveling waves of spanwise velocity

Experiment

Open questions
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
Streamwise-traveling waves of spanwise velocity

Experiment

Open questions

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)
Quantitative agreement between DNS and experiment is \textbf{not} expected:

- Spatial transient
- Cylindrical vs planar geometry
- Difference (small) in $Re$ and $A$
- \textbf{Waveform effects}
Wiggles can be 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

Streamwise-traveling waves of spanwise velocity

Experiment

Open questions
(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 $DR \sim Re^{\gamma}$ 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 $\Delta B^+$ is robust w.r.t. $Re$.
- In a sense, there is no $Re$-effect!

Change of $\Delta B$ 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"
Streamwise-traveling waves of spanwise velocity

Experiment

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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.Frohnepfel)

\[ E_p = \frac{\tau_w V}{A} = \frac{MU_b^2 C_f}{2A} \]

\[ E_p \propto (U_b)^{7/4} \]

CPI line (Constant Power Input)

CPG line

laminar (uncontrolled)

Turbulent (uncontrolled)

CFR line

\[ C_f \propto U_b^{-1} : \text{laminar} \]
\[ C_f \propto U_b^{-1/4} : \text{turbulent} \]
(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