Do outer-layer structures affect the $Re$-dependence of drag reduction by wall actuation?

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Active drag reduction by in-plane wall motion

- Combination of oscillatory spanwise motion and streamwise waves
  \[ W(x,t) = W_m \cos\left(2\pi \frac{t}{T} + 2\pi \frac{x}{\lambda}\right) \]
  - Actuation defined by:
    \[ W_m^+ = \frac{W_m}{u_*} \quad T^+ = \frac{u_*^2}{v} \quad \lambda^+ = \frac{u_*}{v} \lambda \]

Drag reduction up to 47% at low Reynolds number

Question is pertinent to other control scenarios:
- Wall-normal travelling waves (spanwise/streamwise)
- Mass-less micro-blowing/suction
- Passive methods: riblets, wavy surfaces….

Much lower drag-reduction levels
Motivation

- DNS shows significant decline of drag-reduction effectiveness with $Re$.
- For given actuation parameters, log-law appears to asymptote to a near-constant upward shift:
  \[ \Delta B^+ \rightarrow \text{const} \neq f(Re) \]
- Log-law can be manipulated (Gatti & Quadrio, 2017) to give:
  \[ DR = f(C_{f_o}, \Delta B^+) , \text{ but } C_{f_o} = f(Re) \]
- But scenario looks more complicated.
- Unclear what happened at much higher $Re$. 

Unactuated skin friction:

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Rising $Re$
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\[ y^+ \]
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\[ Re^+ \]
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Experiments: canonical boundary layers at $Re_\tau = 2800 - 19000$

- Streamwise energy has outer peak
- Energy increases progressively with Reynolds number
- Suggests presence of energetic outer structures

Key question: What is the role of energetic outer structures?
  - Distortion of turbulence in viscous wall layer?
  - Reduced effectiveness of actuation?
Outer large-scale structures

- DNS: Streamwise intensity, canonical channel flow $Re_\tau = 4200 \& 5300$

(Lozano-Duran & Jimenez, 2014; Lee & Moser, 2015)

$y^+ = 3.9 \sqrt{Re_\tau}$

Marusic et al’s correlation of location of structures
How do outer structures affect the near-wall layer?

- "Footprinting": convective ‘quasi-steady’ shift of small-scale turbulence
- "Modulation": attenuation and amplification of small-scale turbulence

\[
W(x, t) = W_m \cos\left(2\pi \frac{t}{T} + 2\pi \frac{x}{\lambda}\right)
\]

\[
Re_\tau = 1020 \\
T^+ = Tu_\tau^2 / \nu = 100 \\
DR = 27\%
\]
Conceptual representation of LS-SS interaction

Large-scale structure

Small scale

Superposition “Footprinting”

Modulation

Splatting / Anti-splatting

Large-scale sweeps & ejections

Side view

Top view

Side view

Top view
Skin-friction modulation by outer structures

Visible correlation:
- Positive LS motions streak amplification
- Negative LS motions streak attenuation

\[ \text{Cf (Stokes strain < 0)} \]

\[ u_{LS} \text{ at } y^+ \approx 200 \]
Correlation maps

- Correlation between $u_{LS}$ fluctuations

- Correlation of $C_f$ fluctuations with $u_{LS}$ fluctuations

Spatial lag

$y^+ = 3$

$y^+ = 150$
Large-scale/small-scale splitting

- Hilbert-Huang *Empirical Mode Decomposition (EMD) – 2D spatial implementation*
- Splits signal into chosen number of *Intrinsic Modes*
- No Fourier cut-offs or explicit filtering; energy conserving
- Mode-wise split of pre-multiplied spanwise spectra of streamwise velocity fluctuations; 6 modes; $T^+ = 100$

\[
\lambda_z^+ \approx 100 \quad \lambda_z^+ \approx 700 - 1500
\]
Modal decomposition of streamwise energy at $y^+ = 13$

- **Small-scale (SS)**
- **Large-scale (LS)**

### Large-scale/small-scale splitting

- **Mode 1**
- **Mode 2**
- **Mode 3**

- **Mode 4**
- **Mode 5**
- **Mode 6**
Mode-wise correlation map

Correlation between skin friction and streamwise fluctuation modes

\[
\max R(\Delta x))
\]

Correlation pronounced for mode 4
Contributions of modes to streamwise energy

- Mixed-mode contributions weak
- $\sum$ modal contributions = total

\[ u_i u_j = 2u_{SS} u_{LS} + 2u_{SS} u_{AE} + 2u_{LS} u_{AE} \]
Contributions of modes to shear stress and skin friction

- Contribution of turbulent shear stress to $C_f$ (Fukagata-Iwamoto-Kasagi relation)

$$C_f = \frac{12}{Re_b} + 12 \int_0^1 \left(1 - \frac{y}{h}\right) \left(-\frac{\overline{uv}}{4U_b^2}\right) d\left(\frac{y}{h}\right)$$

$$\overline{u_iu_j} = \begin{bmatrix} u_{SS}u_{SS} & u_{SS}u_{AE} & u_{SS}u_{LS} \\ u_{AE}u_{SS} & u_{AE}u_{AE} & u_{AE}u_{LS} \\ u_{LS}u_{SS} & u_{LS}u_{AE} & u_{LS}u_{LS} \end{bmatrix}$$

But contributions do not reflect indirect modulation interactions.
Focus on 5%.... 50% sub-ranges of extreme events in large-scales PDF

Addition of central band of PDF – absence of large-scale motions
Small-scale stress profiles

- Effect on small-scale shear and normal stress in extreme 5% positive and negative large-scale fluctuations

Large positive LS fluctuations:
- thin viscous sublayer & increase viscous stress
- Increase turbulent SS stress near the wall

Large negative LS fluctuations:
- thicken viscous sublayer & reduce viscous stress
- reduce turbulent SS stress near the wall

Effect asymmetric!
Conditional sampling of $C f_x$ fluctuations

- **Conditional sampling within**
  - 5% weakest LS events
  - 5% strongest LS events
  - 5% “no” LS events

- Strongly asymmetric modulation
- **Positive** LS motions cause much strongest modulation (large variance of PDF)
- **Negative** LS motions cause weaker modulation
  - streaks are already weak due to actuation
Joint PDFs of small-scale motions

- Conditional sampling within
  - 5% weakest LS events
  - 5% strongest LS events

- Drastic differences in
  - intensity
  - correlation

\[ \Delta u_{LS}^+ \approx 4 \]

\[ uv \quad y^+ = 16 \]

Ejections

Sweeps - splatting
Conditional sampling of $Cf_x$ fluctuations

- Conditional sampling within 5% segments of LS PDF

- Strongly asymmetric modulation
- Positive LS motions cause strongest modulation
  - large variance
  - Large skewness

Modulation cannot be described by variance alone!
Illustration of skewness of SS fluctuations

- Small scales: modes 1+2+3; Large scales: modes 4+5+6
- Hilbert transform: envelope of magnitude of small-scale motions

$$Cf_{x,LS} + A$$
$$Cf_{x,SS}$$
$$-(Cf_{x,LS} + A)$$
Concluding observations

Do outer-layer structures affect the $Re$-dependence of drag reduction by wall actuation?

- No quantitative answer (yet), on contribution of modulation but.....
  - Direct large-scales contribution to skin friction is order 30%
  - Maximum large-scale skin-friction fluctuations around 30%
  - Maximum skin-friction fluctuations around 100%
  - Strong differences between effects of positive and negative large-scale footprints

- Strong modulation of near wall small-scale motions and skin friction by positive large-scale motions; much weaker modulation by negative motions

- Positive large-scale fluctuations cause strong increase in energy and shear stress close to the wall.

- Negative large-scale fluctuations cause moderate decrease in energy and shear stress.