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ERCOFTAC

European Research Community On Flow, Turbulence And Combustion

Coherent near-wall structures and drag reduction by spanwise forcing

E. Gallorini[1], M.Quadrio[1], D.Gatti[2]

[1] Dept. of Aerospace Science and Technology (DAER), Politecnico di Milano, Italy

[2] Institute of Fluid Mechanics (ISTM), Karlsruhe Institute of Technology, Karlsruhe, Germany

Aim of the work

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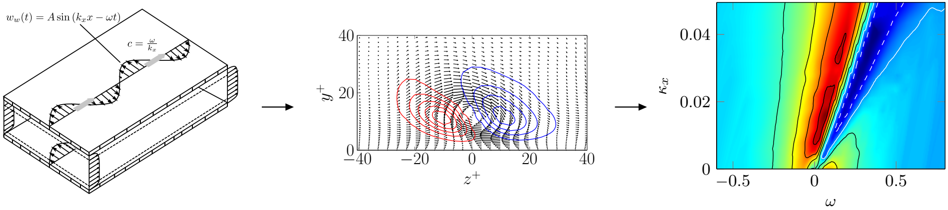


- Yakeno et al., PoF 2014 → oscillating walls (OW)
- What happens for streamwise travelling waves of spanwise wall velocity (TW)?

The database

5 high-resolution DNS (CPG) for turbulent channel flow at $Re_\tau = 200$, the control maximum wall velocity is $A^+ = 7$:

1. REF: No control applied
2. OW1: $\Delta U_b^+ = +2.43 \rightarrow$ High DR ($k_x^+ = 0.00$, $\omega^+ = 0.0840$);
3. OW2: $\Delta U_b^+ = +1.15 \rightarrow$ Low DR ($k_x^+ = 0.00$, $\omega^+ = 0.0250$) ;
4. TW1: $\Delta U_b^+ = +4.07 \rightarrow$ High DR ($k_x^+ = 0.01$, $\omega^+ = 0.0238$) ;
5. TW2: $\Delta U_b^+ = -1.44 \rightarrow$ DI ($k_x^+ = 0.01$, $\omega^+ = 0.1200$) ;

- The effect of the control is known (drag variation)
- How this happens?

Active control of a channel flow

When pressure gradient is constant (CPG) drag reduction result in an increase in the bulk velocity U_b:

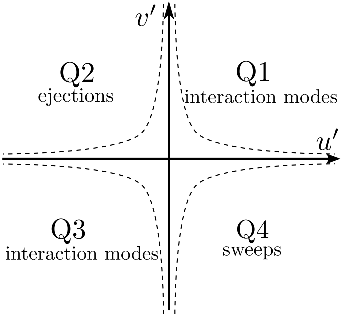
$$\Delta U_b = U_b - U_{b,REF} = \frac{1}{2h}\int_0^{2h} \overline{u} - \overline{u}_{REF}\, dy$$

From Marusic et al., JFM 2007:

$$U_b = \frac{Re_\tau}{3} + \int_0^{Re_\tau} (1 - \frac{y}{Re_\tau})(-\overline{u'v'})\, dy^+ = \frac{Re_\tau}{3} + \sum_{i=1}^{4} Q_i$$

Being Q_i the $i-$th quadrant contribution of the Reynolds shear stresses. As a consequence:

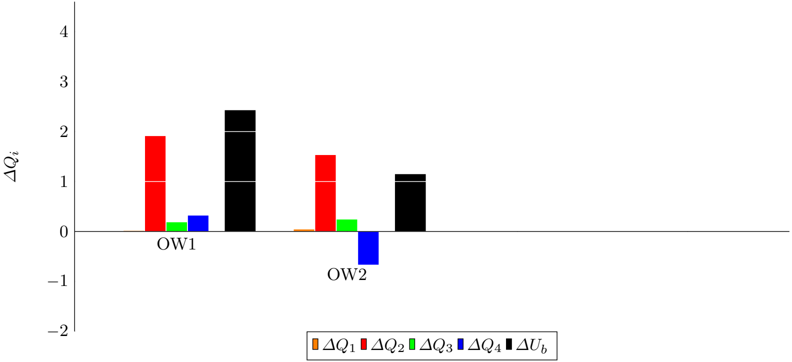
$$\Delta U_b = \sum_{i=1}^{4} \Delta Q_i$$



Reynolds stresses balance

For OW two mechanisms were highlighted, considering the quadrant contribution of $\overline{u'v'}$:

- Q_2 suppression;
- Q_4 enhancement-suppression;



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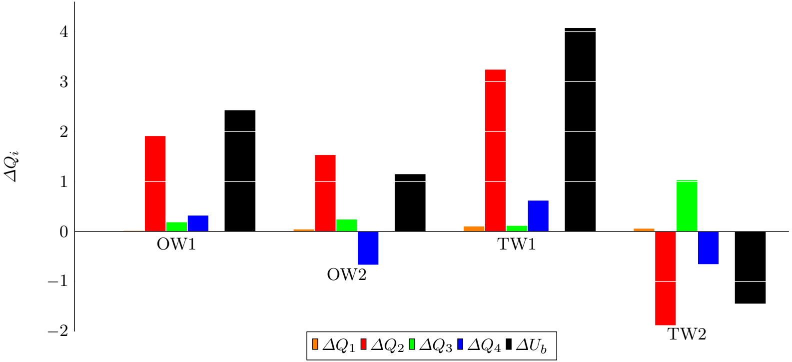
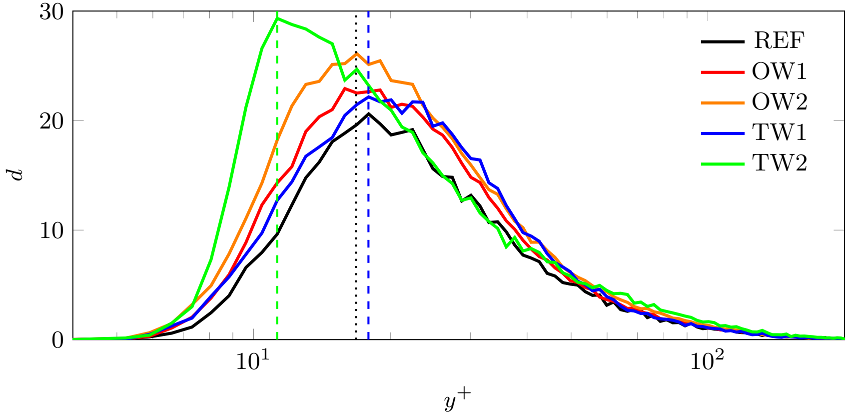


Vortices extraction

(QSV) are extracted using the swirling-strenght (Zhou et al., JFM 1999).

- Swirling-strenght: intensity of the imaginary part of the complex eigenvalues of $\nabla \boldsymbol{u}$.
- Control $\rightarrow$ Modification of QSV number and distribution in wall-normal direction:

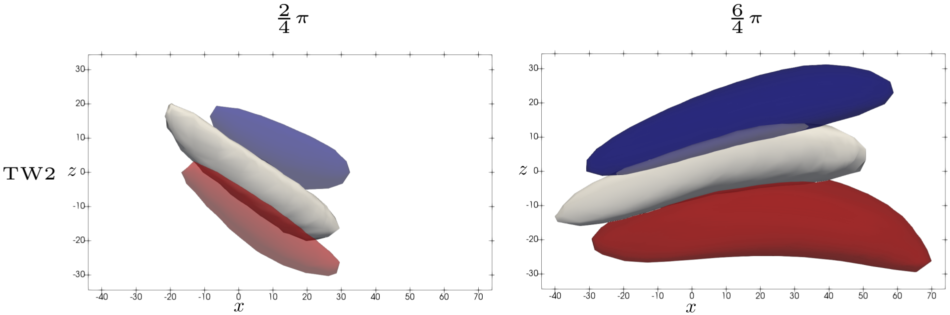


Conditional average

After the extraction, QSV

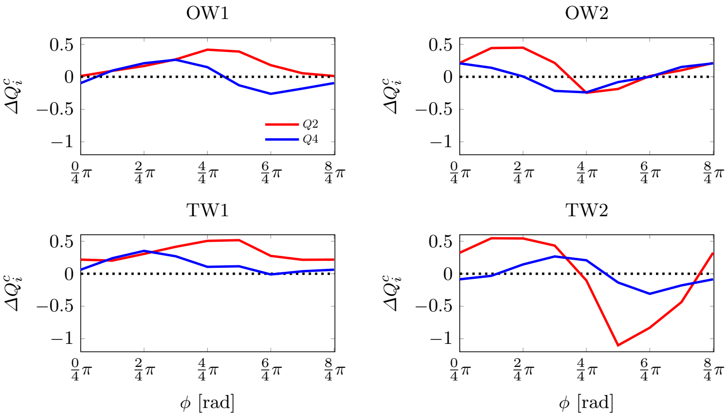
- at the same control phase;
- with the same sense of rotation;
- located at the same distance from the wall;

are averaged together obtaining conditionally-averaged structures.



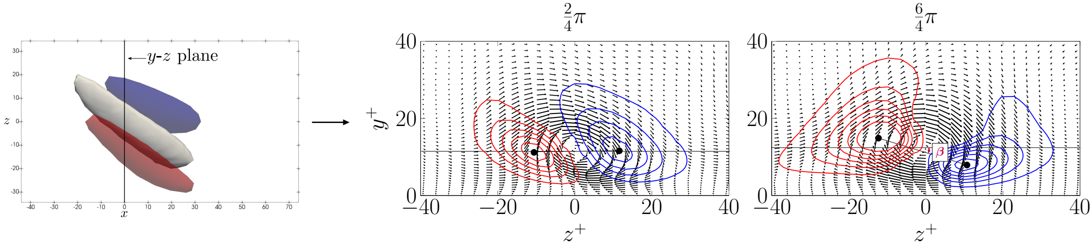
Variation of Reynolds stresses

$$Q_i^c(\phi) = -d \int_{V_c} \left(1 - \frac{y^+}{Re_\tau}\right) \left(-\overline{u^c v^c}(\phi)\right)_i dV. \quad (1)$$



Bouncing (1/2)

We observe a "bouncing" of Q_2 and Q_4 events for TW$\rightarrow \beta$:



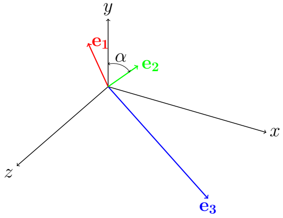
The bouncing is:

- high when drag increase (TW2) is present,
- low for drag reduction (TW1).

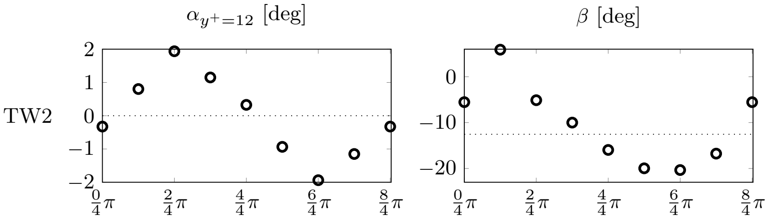
▶ We link this phenomenon with the modification to the stress state due to $x-$dependency of $\tilde{w}$ for TW.

Bouncing (2/2)

Principal stresses for TW:



α and β shows a similar phase evolution:

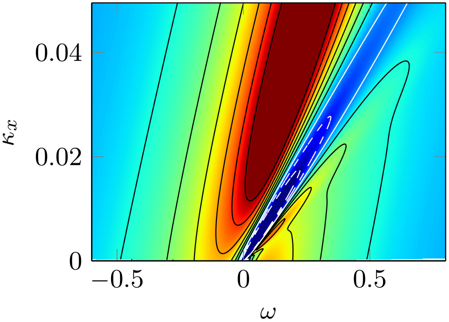


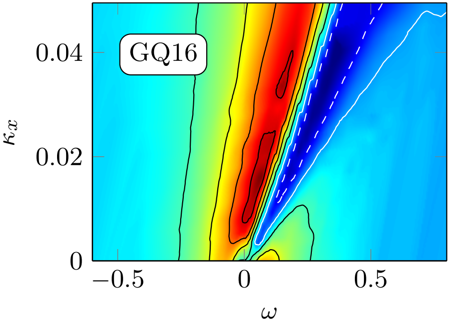
Scaling of drag Reduction (1/2)

In Yakeno et al., PoF 2014, Q_2 suppression and Q_4 enhancement has been linked with the spanwise shear at $y^+ = 10$ and $y^+ = 15$:

$$\Delta U_b = a \left(\frac{\partial \tilde{w}}{\partial y} \Big|_{y^+=10} \right)_{rms} - b \left(\frac{\partial \tilde{w}}{\partial y} \Big|_{y^+=15} \right)_{rms} \qquad (2)$$

Since similar phenomena were observed for TW, we extend the relation to the new control:





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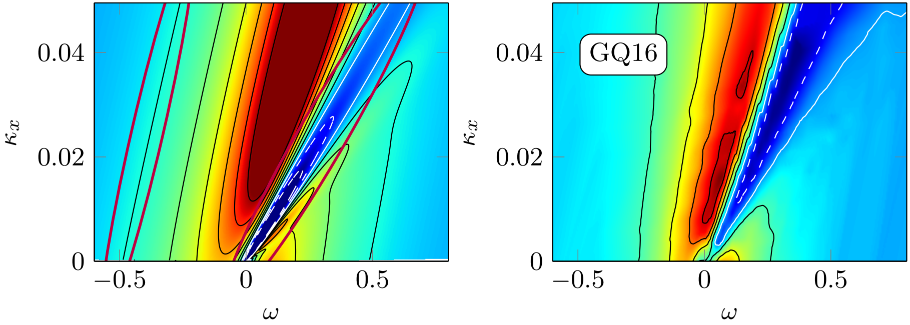
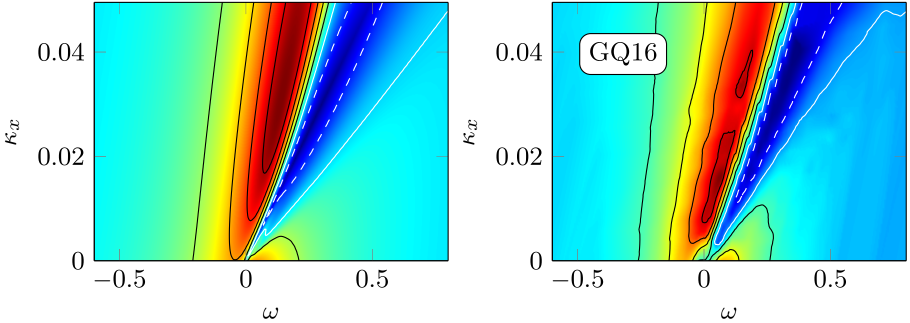


Scaling of drag Reduction (2/2)

$$\Delta U = S' \left(a\tau_z|^{rms}_{y^+=10} + b\tau_z|^{rms}_{y^+=15} \right) - c\alpha^{rms}_{y^+=12}. \quad (3)$$

being:

- τ_z: spanwise component of the principal stress state associated with the phase-averaged strain-rate tensor $\langle \mathcal{S} \rangle$;
- S': mean acceleration in the Generalized Stokes Layer, $S' = a'_m \frac{\ell}{A}$ and $a'(\omega, \kappa_x) = \frac{1}{\ell}\int_0^\ell a_m(\omega_{eq}, \kappa_x, y)dy$;
- α: represents the "bouncing".



Conclusion and future developments

The effect of OW and TW on QSV has been analyzed:

- Q_2 and Q_4 variation are the dominant mechanism of drag variations;
- The control affects QSV's distribution and intensity;
- TW involves phenomena ("bouncing", different velocities of structures and control wave) that, when correctly scaled, are in agreement with the drag-reduction map;

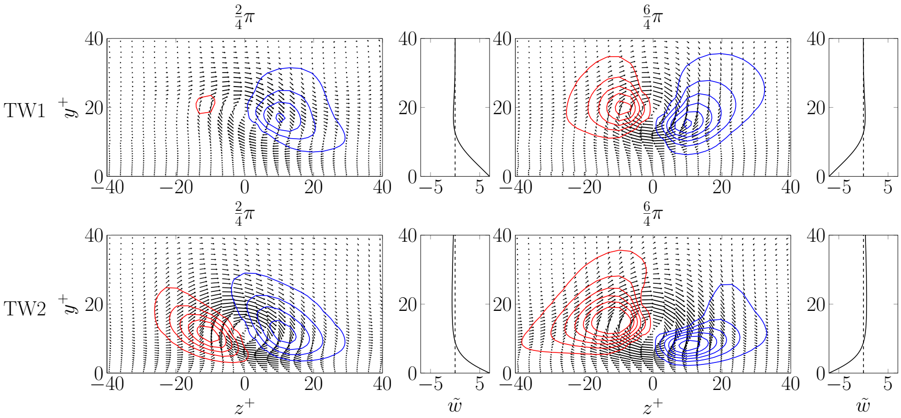
What has to be done?

- This work is based on observations of physical phenomena;
- empirical scaling $\rightarrow$ physical interpretation.

Thank you for your attention!

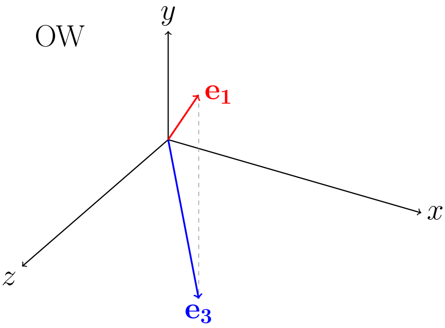
contact: emanuele.gallorini@polimi.it

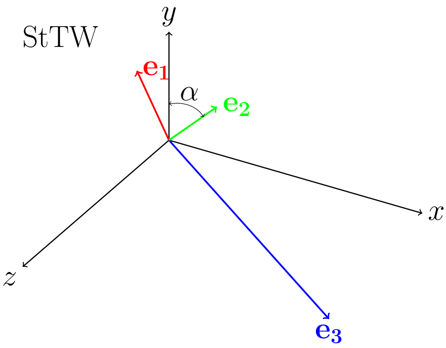
Phase-evolution of conditionally averaged QSV



Stress state

$$\langle \mathcal{S} \rangle = \begin{bmatrix} 0 & \partial\langle u\rangle/\partial y & \partial\tilde{w}/\partial x \\ \partial\langle u\rangle/\partial y & 0 & \partial\tilde{w}/\partial y \\ \partial\tilde{w}/\partial x & \partial\tilde{w}/\partial y & 0 \end{bmatrix} \quad (4)$$

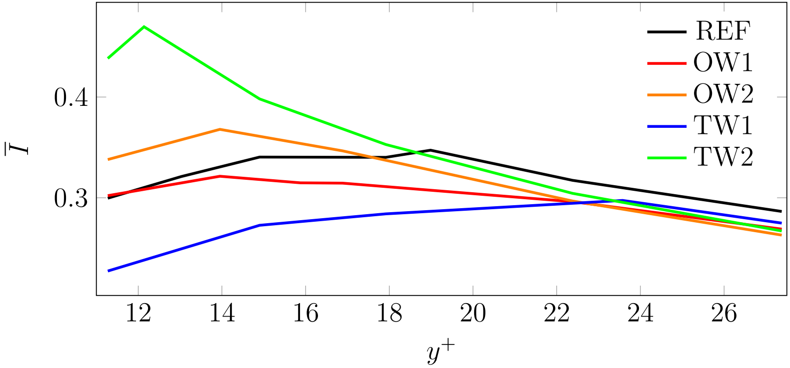




Vertex intensity

TW2 involves high phase shifts of Q_2 and Q_4 , this can be explained by the high intensity of the structures:

$$\overline{I}(y^+) = \int\int_{\omega_x > 0.5\omega_{x,max}(y^+,\phi)} \omega_x \, dV \, d\phi \tag{5}$$



Tilt angle