Wall Turbulence Control by spanwise-traveling waves

Wenxuan Xie, Maurizio Quadrio

Department of Aerospace Science and Technology
Politecnico di Milano

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Various flow control techniques have been proposed. The spanwise-traveling wave concept was first studied by Du and Karniadakis (*JFM* 2002, *Science* 2003)

- Large drag reduction (up to more than 30%)
- Modified near wall turbulence structure

Some interesting part in the parametric space is not covered by the existing simulation cases

- The energetic performance is not presented
Two types of spanwise-traveling wave

spanwise body forcing
\[ F_z = A_f \sin(\kappa_z z - \omega t) e^{-y/\Delta} \]
- Acts directly on the bulk fluid
- Oriented in the spanwise direction
- Varies sinusoidally
- The wave travels along the spanwise direction
- Decays exponentially with the wall normal distance

spanwise wall velocity (EFMC 2012)
\[ w = A_{vel} \sin(\kappa_z z - \omega t) \]
- In-plane wall deformation
- Oriented in the spanwise direction
- Varies sinusoidally
- The wave travels along the spanwise direction
- One parameter less!

How is the performance of the traveling wave of body forcing? (Drag and Energetic)

Key conclusion: spanwise wall oscillation \((\kappa_z = 0)\) outperforms all other waves in the parametric space
Purpose and Method

Aim

- Explore the 4-D \((\omega - \kappa_z - A_f - \Delta)\) parametric space more exhaustively
- Find the best **drag reduction and energetic performance**

Approach

- Near 800 turbulent channel flow DNS simulations at \(Re_T = 200\)
  \[\omega \in [0.5, 10], \quad \kappa_z \in [0, 9.8], \quad A_f \in [0.1, 2], \quad \Delta \in [0.01, 1]\]
- Constant Flow Rate

**Definition:**

\[
R(\%) \equiv \frac{P_0 - P}{P_0} \times 100 \quad S(\%) \equiv \frac{P_0 - (P + P_{in})}{P_0} \times 100
\]

in which

\[
P_{in} = \frac{1}{t_f - t_i} \int_{t_i}^{t_f} \int_0^{L_x} \int_0^{L_z} \int_0^{2h} \rho f_z w \, dy dz dx dt
\]
Modification of Near Wall Turbulence

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Results: $R$

\[ \Delta = 0.01 \]

\[ \Delta = 0.02 \]

\[ \Delta = 0.04 \]

\[ \Delta = 0.1 \]
The iso-surfaces of R (%)
$\Delta = 0.01$

$\Delta = 0.02$

$\Delta = 0.04$

$\Delta = 0.1$
The iso-surfaces of $S (%)$
Comparison with wall based forcing

<table>
<thead>
<tr>
<th></th>
<th>Body Forcing</th>
<th>Wall Motion</th>
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</thead>
<tbody>
<tr>
<td>$R_{max}$</td>
<td>$47$ ($\omega = 1$, $\kappa_z = 0$, $A_f = 2$, $\Delta = 0.04$)</td>
<td>$38$ ($\omega = 0.5$, $\kappa_z = 0$, $A_{vel} = 0.5$)</td>
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<tr>
<td>$S_{max}$</td>
<td>$12$ ($\omega = 0.75$, $\kappa_z = 0$, $A_f = 0.5$, $\Delta = 0.04$)</td>
<td>$10$ ($\omega = 0.5$, $\kappa_z = 0$, $A_{vel} = 0.2$)</td>
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- 1 more parameter ($\Delta$) enables the Body forcing to be better tuned
- The gain in $R$ is largely cancelled out by the power required to manipulate the flow ($P_{in}$)
- Both $R_{max}$ and $S_{max}$ are always found to be at $\kappa_z = 0$ in both cases
Conclusion

- Body forcing and wall motion behave similarly
- Both R and S reach the optimal at $\kappa_z = 0$
- The spanwise traveling wave concept is outperformed by the spanwise oscillatory body forcing
- Even the Spanwise oscillatory body forcing/wall oscillation isn’t particularly appealing in the sense of S compare to other techniques.
  e.g. Streamwise traveling wave of transverse wall velocity ($S_{max} > 25$)