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Turbulent Drag Reduction at Moderate Reynolds Numbers via Spanwise Velocity Waves

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Turbulent skin-friction Drag Reduction

Motivation

- **Economical** benefits
- **Environmental** benefits
- Better **understanding** of turbulence

Our focus

- The effects of $Re$ on a particular control strategy
A promising strategy

Streamwise-traveling waves of spanwise wall velocity (Quadrio et al., JFM 2009)

\[ w_w(x, t) = A \sin(\kappa_x x - \omega t) \]

\[ c = \frac{\omega}{\kappa_x} \]

Flow Unit for Drag Reduction

Results

Conclusions
High performances

Drag reduction rate:

\[ R = \frac{P_0 - P}{P_0} \]

Input power:

\[ P_{in} = \frac{1}{L_x L_z T} \int_0^{L_x} \int_0^{L_z} \int_0^T w w \frac{\partial w}{\partial y} \, dt \, dx \, dz \]

Power saving rate:

\[ S = R - \frac{P_{in}}{P_0} \]
High drag reduction achievable

(Quadrio et al., JFM 2009)
What happens at high $Re$?

Two possible scenarios

![Graph showing two zones: "Well-known" and Unknown Zone, with data points for Numerical and Experimental methods.](image-url)
What happens at high $Re$?

Two possible scenarios
Several means of investigation

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Our approach

Up to \( Re_T = 2000 \) with DNS of channels of reduced size

Pros

- No modeling errors
- No resolution errors

Cons

- Discretization errors at the large scales
Neither minimal nor full

\[ L_z^+ = 1000 \]

\[ L_x^+ = 2000 \]
Neither minimal nor full

$L_z^+ = 1884$

$L_x^+ = 3768$
Neither minimal nor full

$L_z^+ = 100$

$L_x^+ = 250$
Larger fluctuations of the space-averaged wall shear ($\Omega$)

$\Omega$ treated as a measure: $\sigma_{\Omega} = C \frac{\sigma_{\Omega}}{\sqrt{T_{sim}}}$

optimal compromise between space and time average

Jiménez & Moin, JFM 1991
Effects on drag reduction

$\kappa_x = 0$ (oscillating wall)
Effects on drag reduction

$\kappa_x = 0$ (oscillating wall)
Wave parameters

\[ \lambda_x^+ = 1256 \]
Drag reduction

\[ \lambda^+_x = 1256 \]
$\lambda_x^+ = 1256$

![Graph showing input power $100 \frac{P_{in}}{P_0}$ vs. $\omega^+$ for different $Re_T$ values including 200, 1000, and 2000.](image)
Reynolds effect

\[ R_{\text{max}} \sim Re^{-0.22} \]

Reduced
Reynolds effect

\[ R \sim Re^{-0.08} \]

\[ 100 R \]

\[ \omega^+ \]

\[ Re_\tau \]

\[ \omega^+ \]

\[ 100 R \]

\[ \omega^+ \]

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Reynolds effect

\[ R \sim Re^{-0.08} \]
Conclusions

$R \sim Re^{-0.22}$
“Conclusions”

...or even better!

\[ R \sim Re_{\tau}^{-0.08} \]

S increases with \( Re \)
A broader result

Need for extensive parametric studies

focusing on optimal parameters gives a limited view!
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Box size

\[ L_x^+ = \frac{1000}{2000} \quad L_z^+ = \frac{L_x^+}{2} \]

Criteria:

- “Healthy” turbulence up to \( y_d \) apart from wall if \( L_z^+ = 3y_d^+ \) and \( L_x^+ \approx h^+ \)
  (Florez and Jiménez, PoF 2010)
- At least one wavelength long \( L_x = \frac{2\pi}{\kappa_x} \)
Simulation data

Simulation time: \( T_{sim}^+ = 12000 \div 24000 \)

Resolution: \( \Delta x^+ = \Delta z^+ = 10 \quad \Delta y^+ < 4 \)

Grid points: \( 128 \times Re_T/2 \times 64 \quad 192 \times Re_T/2 \times 96 \)
Effects on wall skin friction

Fixed wall

![Graph showing the effects on wall skin friction for different Reτ values. The graph plots $C_f \times 10^3$ against $L_x^+ \times L_z^+$, with data points for $Re_\tau = 200$, $Re_\tau = 1000$, and $Re_\tau = 2000$. The graph also includes a line for Dean's results.](image-url)
Effects on input power

\[ \kappa_x = 0 \]