Wall Turbulence Control by spanwise-traveling waves

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Turbulence Skin Friction Drag Reduction

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

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- 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

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

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!

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

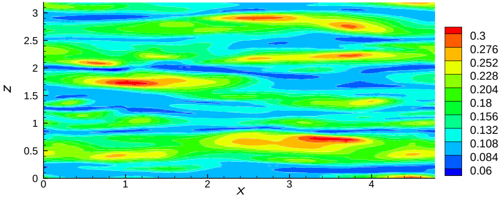
- Near 800 turbulent channel flow DNS simulations at $Re_\tau = 200$
  $\omega \in [0.5, 10],\ \kappa_z \in [0, 9.8],\ A_f \in [0.1, 2],\ \Delta \in [0.01, 1]$
- Constant Flow Rate

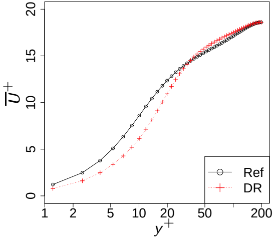
Definition:

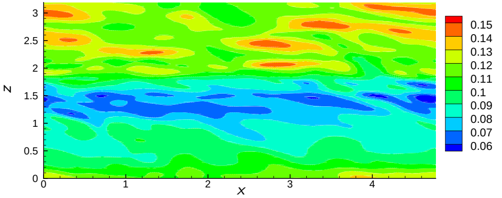
$$R(\%) \equiv \frac{P_0 - P}{P_0} \times 100 \qquad S(\%) \equiv \frac{P_0 - (P + P_{in})}{P_0} \times 100$$

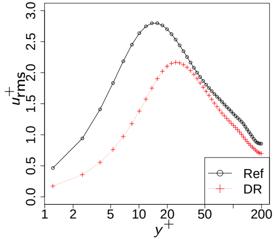
in which $P_{in} = \dfrac{1}{t_f - t_i} \displaystyle\int_{t_i}^{t_f} \int_0^{L_x} \int_0^{L_z} \int_0^{2h} \rho f_z w \ \mathrm{dydzdxdt}$

Modification of Near Wall Turbulence

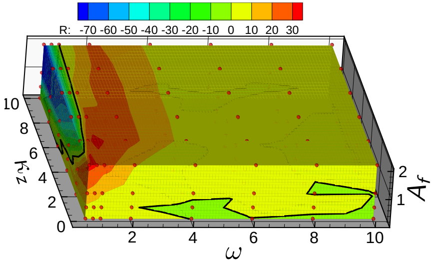




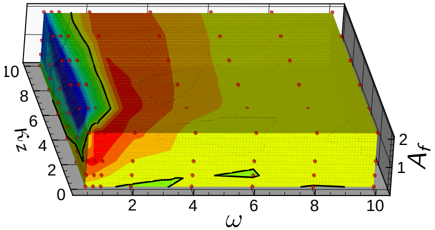




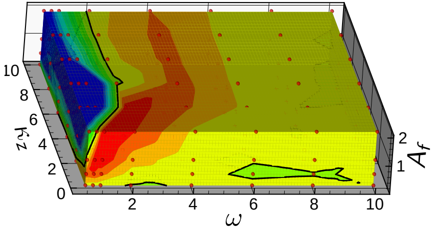
Results: R



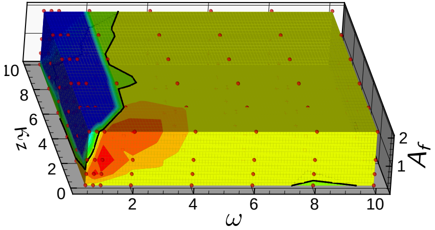
$\Delta = 0.01$



$\Delta = 0.02$



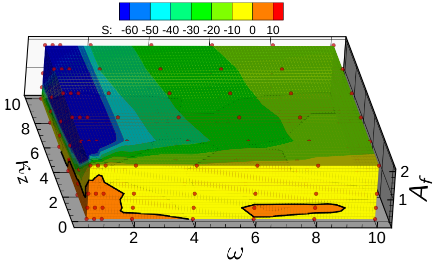
$\Delta = 0.04$



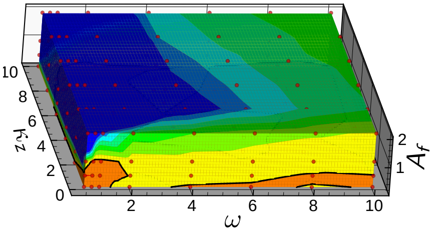
$\Delta = 0.1$

The iso-surfaces of R (%)

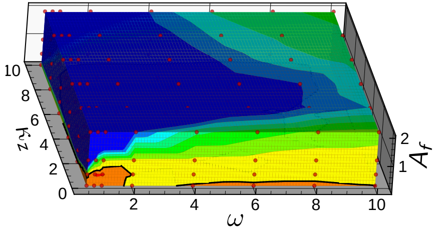
Results: S



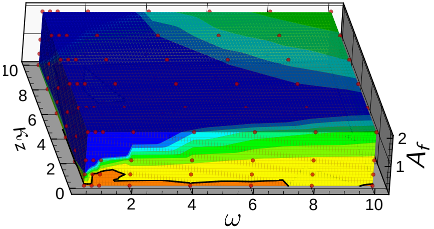
$\Delta = 0.01$



$\Delta = 0.02$



$\Delta = 0.04$



$\Delta = 0.1$

The iso-surfaces of S (%)

Comparison with wall based forcing

	Body Forcing	Wall Motion
R_{max}	47 ($\omega = 1$, $\kappa_z = 0$, $A_f = 2$, $\Delta = 0.04$)	38 ($\omega = 0.5$, $\kappa_z = 0$, $A_{vel} = 0.5$)
S_{max}	12 ($\omega = 0.75$, $\kappa_z = 0$, $A_f = 0.5$, $\Delta = 0.04$)	10 ($\omega = 0.5$, $\kappa_z = 0$, $A_{vel} = 0.2$)

- 1 more parameter (Δ) 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 ($S_{max} > 25$)