Modification of Turbulent Flow using Distributed Suction

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Use of wall-normal blowing/suction is very effective for turbulence control.

Sumitani & Kasagi, AIAA J. 1995: constant blowing (suction) is known to affect significantly the friction drag and the heat transfer.

Choi et al. JFM 1994: use of time- and space-dependent blowing/suction (difficult to implement in practice!) is known to allow 25% turbulence drag reduction.

Jiménez et al JFM 2001: active/passive porous walls, increase in drag.
**MOTIVATION I**

Study the effect of a steady, longitudinal distribution of suction at the wall, with *low amplitude and zero net mass flux*.

Tool: **DNS** of the turbulent plane channel flow.

\[
v(x, y = \pm h, z, t) = A \sin (\alpha_s x)
\]
MOTIVATION II

Schoppa & Hussain, PoF 1998: large-scale streamwise vortices are known to produce a significant drag reduction.

In laminar regime, Floryan JFM 2003 has shown that sinusoidal suction creates such vortices.

Result from stability analysis with mean turbulent profile as base flow:
$Re = 3300, A = 0.004U_c$
Floryan JFM 2003: the laminar case is qualitatively analogous to the flow over a wavy wall.

Many papers exist on turbulent flow over wavy walls. It is currently believed that the wavelength of the wavyness by itself does not play any role, von Röhr, JFM 2003.

The same is assumed by Jiménez et al (suction). Does the wavelength matter?
THE NUMERICAL METHOD

Our solver of the incompressible Navier–Stokes equations has:

- II-order equation for the normal vorticity and IV-order equation for the normal velocity, without pressure
- Fourier discretization in the homogeneous directions
- Fourth-order compact finite-differences over a 5-point unevenly spaced computational molecule in the wall-normal direction
- Three-substeps Runge–Kutta partially implicit time advancement
- Parallel execution on both shared-memory and distributed-memory computers
Numerical issues

PARAMETERS OF THE SIMULATIONS

Computational parameters: the same as Kim, Moin & Moser in JFM, 1987 (longer integration time). $8 \cdot 10^6$ d.o.f.

Plane turbulent channel flow at $Re_\tau = 180$.

- Periodic-box dimensions: $L_y = 2h$ $L_x = 4\pi h$ $L_z = 2\pi h$
- Spatial discretization: $N_x = 193$ $N_z = 129$ $N_y = 161$
- Spatial resolution: $\Delta x^+ = 11.7$ $\Delta y^+ = 0.8$ to 4.5 $\Delta z^+ = 7.0$
- Temporal resolution: $\Delta t^+ \approx 0.15$
- Total integration time: $T \approx 600h/U_c$

Calculations run on Itanium II machines of the SHARCNET Computing Center at the University of Western Ontario. Approx. 40 cases plus some accuracy checks.
Results

**Friction vs. Suction Amplitude**

\[ C_f = \frac{2\tau}{\rho U_b^2} \]. Reference: \( C_f = 8.15 \cdot 10^{-3} \), within 0.3 % from KMM

\[ \alpha_s = 1/h \]
Results

Friction vs. suction wavelength

$10^3 C_f$

$\alpha_s h$

$A = 0.03 U_p$
Results

**DISCUSSION**

1. The effect is proportional to $A$ at fixed $\alpha_s$. The threshold of minimum $A$ depends on $\alpha_s$.
2. A better parameter could be the product $A\lambda_s$ (flow rate).
3. Suction wavelength does matter!
4. When $\lambda_s \rightarrow \infty$ the limit of uniform blowing + uniform suction is recovered. Agreement with $\lambda_s^+ \approx 4000$ from Jiménez, and with results from Sumitani & Kasagi.

Is the flow over a wavy wall really independent on the wavelength of the corrugation? Probably not...
**Unexpected Result: Small Drag Reduction**

![Graph showing drag reduction](image)

- **$C_f$** vs. $\alpha_s h$
- **A = 0.03 \(U_p\)**
Turbulence statistics

**MEAN PROFILE**

![Graph showing mean profiles with different values of $\alpha h$.](image)

- **ref**
- $\alpha h = 5$
- $\alpha h = 1$

The graph illustrates the mean velocity profile $U/U_P$ against the normalized distance $y/h$, with different values of $\alpha h$.
Turbulence statistics

**MEAN PROFILE IN WALL UNITS**

![Graph showing mean profile in wall units with curves for different values of $\alpha h$.]
Turbulence statistics

VELOCITY FLUCTUATIONS

$U^+, V^+, W^+$ vs $\gamma^+$

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1D STREAMWISE SPECTRA

$S^3$ vs $\alpha$

- **ref**
- $\alpha_h=1$
- $\alpha_h=5$

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**STREAMWISE DIRECTION IS NOT-HOMOGENEOUS!**

![Graph showing velocity profiles](image)

- **$U/U_P$** vs. **$y/h$**
- **$\alpha h = 1$**
- **$\lambda = 0$**
- **$\lambda = 1/4$**
- **$\lambda = 1/2$**
- **$\lambda = 3/4$**
- **Mean**

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TRANSVERSAL CORRELATIONS, \( u \) AT \( y^+ \approx 10 \)

\( \alpha h = 5 \)

\( \alpha h = 1 \)
Turbulence statistics

STREAMWISE FRICTION

\( \alpha h = 5 \)

\( \alpha h = 2 \)
CONCLUSIONS

Suction wavelength $\lambda_s$ plays a fundamental role.

**Dramatic drag increase** at wavelengths $\lambda_s^+ > 350$, towards the asymptotic value of uniform blowing and uniform suction. Usual turbulence structure (elongated low-speed streaks) disappear.

**Small drag reduction** below the threshold $\lambda_s^+ = 350$. Critical wavelength is related to the typical size of near-wall turbulent structures.

No evidence of large-scale vortices. Basic flow structure is a pair of large-scale spanwise rolls.