Turbulent skin-friction reduction by oblique wavy surfaces

Sergei Chernyshenko, Sacha Ghebali, Michael Leschziner

Imperial College London London
It started 7 years ago …

1. The idea

2. Semi-empirical theory

3. Main effects

4. DNS

5. What next

There is a chance. Should we try?

A question (in confidence)

by Sergei Chernyshenko

to all involved in the EPSRC/Airbus/EADS project

Investigation of alternative drag-reduction strategies in turbulent boundary layers by using wall forcing

People: Michael A. Leschziner (ICL, Principal investigator), Sergei Chernyshenko (ICL), Emile Touber (ICL), Duncan Lockerby (Warwick), Faisal Baig (Warwick), Carlos Duque-Daza (Warwick), Christopher Davies (Cardiff), Jeremy Benton (Airbus), Jan Meyer (EADS IW), Sylvain Lareau (ICL), Olivier Blesbois (ICL), Yongmann Chung (Warwick), Edward Hurst (Warwick), Michael Togneri (Cardiff), Stephen Rolston (EADS IW), Richard Ashworth (EADS IW)

S.Ghebali, S.Chernyshenko, & M. Leschziner
Can large-scale oblique undulations on a solid wall reduce the turbulent drag? Phys. Fluids 29, 105102 (2017)

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How to replace the steady Stokes layer (SSL) with something feasible?

\[ W = A \sin(kx) \]

20% net drag reduction
The idea: a rigid oblique wavy wall, much smoother and with much larger wavelength than riblets.
The wavy wall will need only a gentle slope due to the triple-deck interaction mechanism.

\[ \Delta p \sim U \Delta U \]

\[ \Delta p \sim u \Delta u \]

\[ \Delta u \sim \frac{U}{u} \Delta U \gg \Delta U \]
A match between wavy wall and SSL by the spanwise shear

\[ w_w = \hat{w}_w \sin(k_x x) \]

\[ w_{ssl} = \hat{w}_{ssl}(y) \sin(k_x x) \]

\[ w_{ww} = \hat{w}_{ww}(y) \sin(k_x x + k_z z + C) \]

\[ p = \hat{p} \sin(k_x x + k_z z) \]

\[ \frac{dw_{ssl}}{dy} \approx \frac{dw_{ww}}{dy} \]

\[ \hat{p} \approx 0.9 \hat{w}_w k_z^{2/3}/k_x \]

* Phase shift between SSL and WW is ignored in this presentation, and wall units used

Talk by Sergei Chernyshenko
A wavy wall is a few times more energy expensive than a moving wall

\[ w_{ssl} = \hat{w}_{ssl}(y) \sin(k_xx) \quad \quad w_{ww} = \hat{w}_{ww}(y) \sin(k_xx + k_z z + C) \]

\[ u_{ssl} = U(y) \quad \quad u_{ww} = U(y) + \hat{u}_{ww}(y) \sin(k_xx + k_z z + C) \]

\[ r = \frac{\text{energy dissipated due to wall motion}}{\text{energy dissipated due to wall waves}} \]

\[ r = 3.122 + 2.323 \frac{k_x^2}{k_z^2} + 0.7986 \frac{k_z^2}{k_x^2} \]

\[ r_{\text{min}} = 5.846 \]

\[ \frac{k_x}{k_z}\bigg|_{\text{opt}} = 0.7657 \]
An assumption: when SSL and wavy wall match, the power saved by suppressing turbulence is the same 2.4% drag reduction by wavy wall.

DNS – Skewed flow

\[ \Delta x^+ = \Delta z^+ < 2 \]
\[ \Delta y^+ \in [0.6, 4.5] \]
\[ L_x^+ \times L_z^+ \approx 1900 \times 3700 \]
\[ \Delta t^+ = 0.02 \]

2 – 3 waves

700M cells, 1728 cores, \(~\) 10 days
There is drag reduction, but 1% only and at a different angle and wavelength from predicted.

\[ \theta = 75^\circ \]

\[ \theta = 70^\circ \]

\[ \theta = 80^\circ \]

\[ Re_\tau \approx 360 \]

\[ \lambda_x^+ \approx 2700 \]
Also, the drag reduction is observed at a smaller amplitude than predicted by the theory.

Friction reduction

Pressure drag
DNS: spanwise shear of SSL and a wavy wall are indeed close

Comparison of the shear strain

\[ Re_\tau \approx 360 \]

- wavy 70°, \( \lambda^+ \approx 2700 \) (rescaled)
- wavy 52°, \( \lambda^+ \approx 1500 \)
- SSL, \( \lambda^+ \approx 1250 \)

\[ 6.000 \frac{\partial W}{\partial y} \]
An assumption: when SSL and wavy wall match, the power saved by suppressing turbulence is the same, but the DNS says:

DNS: at this Re, a substantial part of the power is saved due to the change in the mean profile.

We can have the same suppression of turbulence but less power saved due to smaller change in the mean profile.

A fit to the data of Viotti et al. Phys. Fluids, 21(11):1–9, 2009
Longitudinal pressure gradient strongly affect turbulent fluctuations

Change in $\overline{u'^2}$ from the baseline
Conclusions

- The proof of concept is given: wavy wall produced drag reduction, although small (about 1%)

- The wavy wall does create a spanwise shear profile similar to that created by a steady Stokes layer

- The semi-empirical theory should be improved by taking into account the effect of wall forcing on the mean profile energy dissipation

- Drag reduction can be affected by the influence of the longitudinal pressure gradient. Hence, modifying wall shape to reduce the effect of the unfavourable pressure gradient can be beneficial

- Reducing the longitudinal component of the mean velocity induced by the waves can be beneficial