Active and passive in-plane wall fluctuations in turbulent channel flows

Jozsa, Tamas

http://hdl.handle.net/10026.1/17683

10.1017/jfm.2019.145
Journal of Fluid Mechanics
Cambridge University Press (CUP)

All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.
Supplementing materials
Active and passive in-plane wall fluctuations
in turbulent channel flows

T. I. Józsa\textsuperscript{1,2†}, E. Balaras\textsuperscript{3}, M. Kashtalyan\textsuperscript{4}, A. G. L. Borthwick\textsuperscript{5},
and I. M. Viola\textsuperscript{2}

\textsuperscript{1}Department of Engineering Science, Institute of Biomedical Engineering,
University of Oxford, Oxford OX1 3PJ, UK
\textsuperscript{2}School of Engineering, Institute for Energy Systems, University of Edinburgh,
Edinburgh EH9 3FB, UK
\textsuperscript{3}Department of Mechanical and Aerospace Engineering, The George Washington University,
Washington DC 20052, USA
\textsuperscript{4}School of Engineering, Centre for Micro- and Nanomechanics (CEMINACS),
University of Aberdeen, Aberdeen AB24 3UE, UK
\textsuperscript{5}School of Engineering, Institute for Infrastructure and Environment, University of Edinburgh,
Edinburgh EH9 3FB, UK

(Received xx; revised xx; accepted xx)

\begin{tabular}{llllll}
\hline
\multicolumn{6}{c}{Drag reduction ($DR$) [%]} \\
\multicolumn{3}{c}{$u'_{1,a}$-control} & \multicolumn{3}{c}{$u'_{3,a}$-control} \\
\hline
\hline
$\frac{x}{c}$ & $Re_{\tau} \approx 180$ & $Re_{\tau} \approx 1000$ & $Re_{\tau} \approx 180$ & $Re_{\tau} \approx 1000$ \\
\hline
1 & 3.48 & 4.02 & 4.78 & 4.38 \\
2 & 4.19 & \textendash & 8.95 & \textendash \\
3 & 5.23 & \textendash & 12.20 & \textendash \\
5 & 6.51 & 6.65 & 17.18 & \textendash \\
7 & 7.84 & \textendash & \textendash & \textendash \\
8 & 7.97 & 7.03 & \textendash & 19.30 \\
9 & 7.73 & \textendash & 23.06 & \textendash \\
10 & 6.87 & \textendash & 23.85 & \textendash \\
11 & \textendash & \textendash & 24.15 & \textendash \\
12 & \textendash & 3.57 & 24.29 & 18.16 \\
13 & \textendash & \textendash & 23.90 & \textendash \\
15 & 0.63 & \textendash & 21.91 & 13.22 \\
\hline
\end{tabular}

Table 1: Drag reduction measured with active streamwise ($u'_{1,a}$) and spanwise ($u'_{3,a}$) controls.

\textsuperscript{†} Email address for correspondence: tamas.jozsa@eng.ox.ac.uk
| #  | $Re_r$ | $A_m$ | $A_d$ | $A_s$ | DR [%] | Comment                  |
|----|--------|-------|-------|-------|--------|--------------------------|
| 1  | $\approx$ 180 | 4     | 0.0   | 0.0625 | 2.87   |                          |
| 2  | $\approx$ 180 | 4     | 0.0   | 0.125  | 2.25   |                          |
| 3  | $\approx$ 180 | 4     | 0.0   | 0.25   | 3.39   |                          |
| 4  | $\approx$ 180 | 4     | 0.0   | 0.50   | 3.11   |                          |
| 5  | $\approx$ 180 | 4     | 0.0   | 1.00   | 3.68   | Lo0Lo, max drag reduction|
| 6  | $\approx$ 180 | 4     | 0.0   | 2.00   | 3.41   |                          |
| 7  | $\approx$ 180 | 4     | 0.0   | 4.00   | 3.33   |                          |
| 8  | $\approx$ 180 | 4     | 0.0   | 8.00   | 2.56   |                          |
| 9  | $\approx$ 180 | 4     | 0.0   | 16.00  | 1.80   |                          |
| 10 | $\approx$ 180 | 4     | 0.0   | 32.00  | 1.28   |                          |
| 11 | $\approx$ 180 | 4     | 0.0   | 64.00  | 0.61   |                          |
| 12 | $\approx$ 180 | 4     | 0.0   | 96.59  | 0.86   | Lo0Hi, optimised for max $RC\{\tau_{i,rms}'\}$ |
| 13 | $\approx$ 180 | 4     | 0.0   | 128.00 | 0.66   |                          |
| 14 | $\approx$ 180 | 4     | 0.0   | 256.00 | 0.16   |                          |
| 15 | $\approx$ 180 | 4     | 0.0   | 512.00 | -0.07  |                          |
| 16 | $\approx$ 180 | 4     | 0.0   | 1024.00| -0.17  |                          |
| 17 | $\approx$ 180 | 16    | 0.0   | 1.00   | 2.87   |                          |
| 18 | $\approx$ 180 | 64    | 0.0   | 1.00   | 1.77   |                          |
| 19 | $\approx$ 180 | 256   | 0.0   | 1.00   | 0.36   |                          |
| 20 | $\approx$ 180 | 1024 | 0.0   | 1.00   | 0.06   |                          |
| 21 | $\approx$ 180 | 4     | 1.0   | 1.00   | 3.54   |                          |
| 22 | $\approx$ 180 | 4     | 4.0   | 1.00   | 3.19   |                          |
| 23 | $\approx$ 180 | 4     | 16.0  | 1.00   | 2.47   |                          |
| 24 | $\approx$ 180 | 4     | 64.0  | 1.00   | 1.78   |                          |
| 25 | $\approx$ 180 | 4     | 256.0 | 1.00   | 0.66   |                          |
| 26 | $\approx$ 180 | 8     | 1.0   | 1.00   | 3.32   |                          |
| 27 | $\approx$ 180 | 16    | 1.0   | 1.00   | 2.71   |                          |
| 28 | $\approx$ 180 | 32    | 1.0   | 1.00   | 2.21   |                          |
| 29 | $\approx$ 180 | 8     | 2.0   | 2.00   | 3.08   |                          |
| 30 | $\approx$ 180 | 8     | 4.0   | 2.00   | 2.89   |                          |
| 31 | $\approx$ 180 | 8     | 8.0   | 2.00   | 2.87   |                          |
| 32 | $\approx$ 180 | 8     | 16.0  | 2.00   | 2.52   |                          |
| 33 | $\approx$ 180 | 8     | 32.0  | 2.00   | 1.95   | LoHiLo                  |
| 34 | $\approx$ 180 | 8     | 4.0   | 0.25   | 2.66   |                          |
| 35 | $\approx$ 180 | 8     | 4.0   | 0.50   | 2.92   |                          |
| 36 | $\approx$ 180 | 8     | 4.0   | 1.00   | 3.18   |                          |
| 37 | $\approx$ 180 | 8     | 4.0   | 2.00   | 2.89   |                          |
| 38 | $\approx$ 180 | 8     | 4.0   | 4.00   | 2.64   |                          |
| 39 | $\approx$ 180 | 4     | 0.1   | 0.10   | 3.16   |                          |
| 40 | $\approx$ 180 | 4     | 1.0   | 0.50   | 3.61   | LoLoLo, same as #44      |
Active and passive in-plane wall fluctuations in turbulent channel flows

| #  | $Re_{\tau}$ | $A_m$ | $A_d$ | $A_s$ | DR [%] | Comment                        |
|----|-------------|-------|-------|-------|--------|--------------------------------|
| 41 | $\approx 180$ | 4     | 1.0   | 2.00  | 3.47   |                                |
| 42 | $\approx 180$ | 4     | 0.5   | 1.00  | 3.45   |                                |
| 43 | $\approx 180$ | 4     | 2.0   | 1.00  | 3.23   |                                |
| 44 | $\approx 1000$ | 28    | 7.0   | 3.50  | 1.47   | LoHiLo, same as #40            |
| 45 | $\approx 1000$ | 8     | 1.0   | 1.00  | 2.35   | LoLoLo, max drag reduction     |
| 46 | $\approx 1000$ | 8     | 0.0   | 0.10  | -0.64  | max drag increase              |
| 47 | $\approx 1000$ | 8     | 0.0   | 1.00  | 2.04   |                                |
| 48 | $\approx 1000$ | 8     | 0.0   | 10.00 | 1.62   |                                |
| 49 | $\approx 1000$ | 8     | 0.0   | 100.00| 2.29   |                                |
| 50 | $\approx 1000$ | 8     | 0.0   | 1000.00| 0.18  |                                |

Table 2: Drag reduction measured with passive streamwise wall fluctuations ($u'_{1,p}$).

| #  | $Re_{\tau}$ | $A_m$ | $A_d$ | $A_s$ | DR [%] | Comment                        |
|----|-------------|-------|-------|-------|--------|--------------------------------|
| 51 | $\approx 180$ | 4     | 1.0   | 1.00  | -58.77 | max drag increase              |
| 52 | $\approx 180$ | 8     | 1.0   | 1.00  | -55.12 |                                |
| 53 | $\approx 180$ | 16    | 1.0   | 1.00  | -49.00 | LoLoLo                         |
| 54 | $\approx 180$ | 32    | 1.0   | 1.00  | -40.52 |                                |
| 55 | $\approx 180$ | 16    | 1.0   | 2.00  | -48.52 |                                |
| 56 | $\approx 180$ | 16    | 1.0   | 4.00  | -47.88 |                                |
| 57 | $\approx 180$ | 16    | 1.0   | 8.00  | -46.76 |                                |
| 58 | $\approx 180$ | 16    | 1.0   | 16.00 | -43.63 |                                |
| 59 | $\approx 180$ | 16    | 64.0  | 16.00 | -17.65 |                                |
| 60 | $\approx 180$ | 16    | 64.0  | 64.00 | -13.37 |                                |
| 61 | $\approx 180$ | 16    | 64.0  | 128.00| -10.26 |                                |
| 62 | $\approx 180$ | 16    | 128.00| 128.00| -7.18  |                                |
| 63 | $\approx 180$ | 4     | 0.0   | 646.93| -3.67  | Lo0Hi, optimised for max $RC\{\tau'_{3,rms}\}$ |
| 64 | $\approx 180$ | 4     | 0.0   | 1024.00| -1.77  | min drag increase              |

Table 3: Drag reduction measured with passive spanwise wall fluctuations ($u'_{3,p}$).
The Pearson Correlation Coefficient (PCC) between two variables with zero mean value ($q_1$ and $q_2$) based on spatial averaging is

$$\text{PCC}\{q_1, q_2\} = \frac{\langle q_1 q_2 \rangle_s}{\sqrt{\langle q_1^2 \rangle_s \langle q_2^2 \rangle_s}}.$$  (0.1)