SKIN-FRICTION CONTRIBUTIONS MODIFIED BY A LARGE-EDDY BREAK-UP DEVICE

C. I. Chan[1], R. Örlü[2], P. Schlatter[2] and R. C. Chin[1]

[1] ***School of Mechanical Engineering, University of Adelaide, South Australia 5005, Australia***
[2] ***Linné FLOW Centre, KTH Mechanics, SE-100 44 Stockholm, Sweden***

chiip.chan@adelaide.edu.au

Abstract

Research on skin-friction drag reduction in wall-bounded flows is of great importance for practical interests. In the present study, the performance of a large-eddy breakup device (LEBU) mounted in a spatially evolving zero-pressure-gradient turbulent boundary layer (ZPG TBL) is investigated using large-eddy simulations up to $Re_\tau = 1350$. The LEBU are mounted at a distance of 0.1, 0.5 and $0.8\,\delta_{99}$ (99% boundary layer thickness) from the wall. Results show that the LEBU dampens the mean flow and turbulent fluctuations, and is coupled with a skin friction reduction rate. The dynamical contributions to the skin friction are computed using the Fukagata-Iwamoto-Kasagi (FIK) identity (Fukagata et al., 2002).. Results show that the Reynolds shear stress has an important role in the skin friction contribution. The skin friction reduction can be viewed as a combined effect through the reduced contribution of spatial development, mean convection and Reynolds shear stress.

1 Introduction

One of the fundamental interests in flow control is by manipulation of wall-bounded turbulence to achieve skin-friction reduction. The difficulties of obtaining accurate measurements in turbulent flow, particularly for high Reynolds numbers have limited the experimental investigations to provide much detailed information of the flow dynamics. With the advancement in numerical simulations, numerical studies in flow controls based on direct numerical simulation (DNS) and large-eddy simulation (LES) have provided information that was not previously available. Despite the vast number of experimental investigations of LEBUs, there is, however, a lack of numerical investigations to this aspect. The present study aims to re-examine the modification of skin friction and turbulence by a large-eddy break-up (LEBU) device in a spatially developing zero-pressure-gradient turbulent boundary layer (ZPG TBL) via LES. With the LES data, it is also possible to investigate in much more detail, the skin-friction contribution, by a skin-friction decomposition (FIK identity) proposed by proposed by Fukagata et al. (2002).

2 Methodology

An incompressible turbulent boundary layer is simulated in a computational box of streamwise, wall-normal and spanwise lengths of $x_L \times y_L \times z_L = 6000\delta_0^* \times 200\delta_0^* \times 240\delta_0^*$ respectively, where δ_0^* is the inlet displacement thickness. (Chevalier et al., 2007). Quantities non-dimensionalised by inner units of the uncontrolled TBL, are denoted by superscript '$+$' unless otherwise indicated (i.e. scaling with ν/u_τ and u_τ, respectively, where $u_\tau = \sqrt{\tau_w/\rho}$ is the friction velocity, ρ and ν are the fluid density and kinematic viscosity, respectively). An over-bar indicates an ensemble-averaged quantity, and a prime indicates the fluctuation component from it. In the present study, a numerical LEBU is implemented in a ZPG TBL at $x/\delta_0^* = 1000$ and at a distance 0.1, 0.5 and $0.8\,\delta_{99}$ (99% boundary layer thickness) from the wall, respectively, hereafter referred to as LB-01, LB-05 and LB-08. The implementation of the LEBUs via an immersed boundary method has been introduced by Chin et al., 2017.

The decomposition of c_f is given by the triple integral of the mean streamwise momentum equation over wall-normal (Fukagata et al., 2002):

$$c_f(x) = \underbrace{\frac{4(1-\delta^\star)}{Re_\delta}}_{\text{DT}} + \underbrace{4\int_0^1 (1-y^\star)(-\bar{u}\bar{v}^\star)\, dy^\star}_{\text{MC}} + \underbrace{4\int_0^1 (1-y^\star)(-\overline{u'v'}^\star)\, dy^\star}_{\text{RS}} - \underbrace{2\int_0^1 (1-y^\star)^2\, \bar{I}_x^\star\, dy^\star}_{\text{SD}} \tag{1}$$

where δ^* is the displacement thickness and $y^\star = y/\delta_{99}$, $u^\star = u/U_\infty$. The four terms in equation (1) represent: laminar contribution from the mean effect of evolving boundary layer thickness (DT), the mean convection (MC), the turbulent contribution from the weighted Reynolds shear stress (RS), and the contribution from the spatial-derivatives of the streamwise velocity component (SD).

3 Results

The skin friction coefficient $c_f = \bar{\tau}_w/\frac{1}{2}\rho U_\infty^2$, and $\bar{\tau}_w(x) = \mu\, \partial\bar{u}/\partial y|_{y=0}$ of the LEBU flows is plotted in Appendix figure 1(a), together with the uncontrolled TBL. Three distinct differences can be identified. The magnitude of local drag reduction rate, its peak value and the recovery rate, are depended on the wall-normal distance where the LEBU is positioned. The similar trend is observed in previous experimental studies (e.g. Lynn et al. 1995) and may be related to wake-sublayer interaction suggested by Savill & Mumford (1988). The mean velocity profile and Reynolds stresses profile at normalized downstream distance $\xi = 5$ are shown in Appendix figure 1(b,c). It can be seen that in the case LB-01, a relative downward shift in the log-law region are obtained, and the slopes of the log-law remain nearly the same as that of the uncontrolled TBL. A similar downward shift is also observed for LB-05 and LB-08 at further downstream and is significant when the skin friction reduction rate is increased. Choi et al. (1994) related the log-law shift as a result of increasing thickness of the viscous sublayer in their active flow control study. As shown in figure 1(c), LB-08 and LB-05 clearly suppress the r.m.s and Reynolds shear stress at $\xi = 5$ downstream of the LEBU, while LB-01 exhibits an opposite trend. The streamwise evolution of the FIK terms in equation (1) are shown in Appendix figure 2. Except the DT term, which is related to the laminar contribution, remains constant for all cases, LEBU initially suppresses the RS term and enhances the SD and MC term, which acts as the key mechanism to reduce skin friction drag. Further downstream, opposite trends are observed for these terms, i.e. ΔRS > 0 and Δ(SD, MC) < 0. Also note that variation in LB-01 is more rapid than LB-05 and LB-08.

4 Conclusions

Simulations of ZPG TBL with LEBUs mounted at $y/\delta_{99} = 0.8$, 0.5 and 0.1 (correspond to $y^+ = yu_\tau/\nu = 354$, 221 and 44) were performed. The LEBU was modelled using an immersed boundary method. Reduction in local skin friction was found in all cases. The results showed that, when the LEBU is placed closer to the wall, the peak skin friction reduction is increased, however, only sustained for a shorter downstream distance. Streamwise evolution of the mean velocity and turbulent statistics were computed and compared with the unmanipulated flow. Mean velocity profile showed that the velocity experiences a shift in the log-law region, which had been observed in previous drag-reduced flow studies. All Reynolds stresses are suppressed downstream of the LEBU, which is coupled with a similar rate of skin-friction reduction. From the FIK identity, the RS is significantly attenuated. However, in general, the skin-friction reduction in LEBUs flow is not proportional to the change of RS, but rather a combined effect resulting from RS, MC and SD.

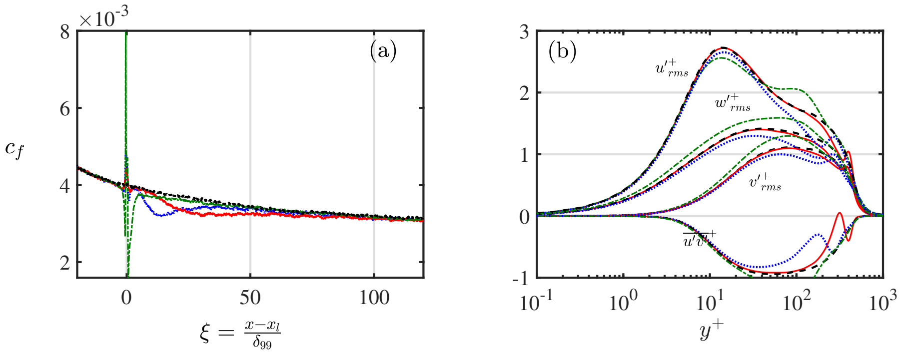

Figure 1: (a) Skin friction coefficient, (b) Reynolds stresses profile at $\xi = 5$, (black - - -) no control; (red ——) LB-08; (blue ······) LB-05; (green -·-·) LB-01.

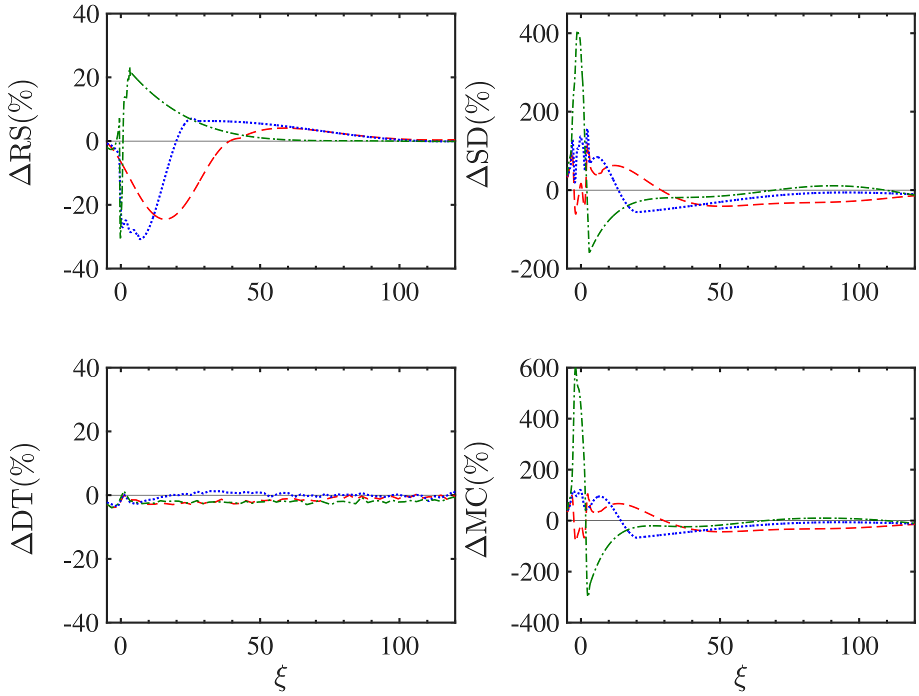

Figure 2: A comparison of FIK terms equation (1) in uncontrolled TBL and LEBUs flows, (red - - -) LB-08; (blue ······) LB-05; (green -·-·) LB-01. For example, $\Delta \mathrm{RS}\,(\%) = (\mathrm{RS} - \mathrm{RS}_0)/\mathrm{RS}_0 \times 100\%$ and the subscript '0' denotes the uncontrolled case..

References

Chevalier, M., Lundbladh, A. and Henningson, D. S. (2007), Simson–a pseudo-spectral solver for incompressible boundary layer flow. Tech. rep. TRITA-MEK 2007:07. KTH Mechanics,Stockholm, Sweden.

Chin, C., Örlü, R., Monty, J., Hutchins, N., Ooi, A. and Schlatter, P. (2017), Simulation of a large-eddy-break-up device (LEBU) in a moderate Reynolds number turbulent boundary layer, *Flow Turbul. Combust.*, 98(2), 445–460.

Fukagata, K., Iwamoto, K. and Kasagi, N. (2002), Contribution of Reynolds stress distribution to the skin friction in wall-bounded flows, *Phys. Fluids.*, 14(11), L73–L76.

Lynn, T. B., Bechert, D. W. and Gerich, D. A. (1995), Direct drag measurements in a turbulent flat-plate boundary layer with turbulence manipulators, *Exp. Fluids.*, 19(6), 405–416.

Savill, A. M. and Mumford, J. C. (1988), Manipulation of turbulent boundary layers by outer-layer devices: skin-friction and flow-visualization results. *J. Fluid Mech.*, vol. 191, pp. 389–418.