zbMATH Open
THE FIRST RESOURCE FOR MATHEMATICS

Hearst, R. Jason; **de Silva, Charitha M.**; **Dogan, Eda**; **Ganapathisubramani, Bharathram**
Uniform-momentum zones in a turbulent boundary layer subjected to freestream turbulence. (English) Zbl 07345557
J. Fluid Mech. 915, Paper No. A109, 28 p. (2021).

Summary: The instantaneous structure of a turbulent boundary layer that has developed beneath freestream turbulence (FST) was investigated with planar particle image velocimetry. Measurements were performed in the streamwise-wall-normal plane at a position $Re_x = U_\infty x/\nu = 2.3 \times 10^6$ downstream of the boundary layer origin. FST was generated with an active grid placed upstream of a boundary layer plate. Three cases were investigated with FST intensity increasing from approximately zero to 12.8%. It is shown that internal interfaces, separating areas of approximately uniform momentum, are present for all cases and show a dependence on the FST. In particular, the number and length of the uniform-momentum zones (UMZs) decrease with increasing FST. The modal velocities associated with the UMZs are distributed in approximately the same way regardless of the condition of the outer flow, suggesting a degree of resilience of the instantaneous structure to the freestream. Tracking the top edge of the upper-most UMZ revealed that this contour approaches the wall for increasing FST. Finally, it is demonstrated that the observed first-order phenomena in a turbulent boundary layer subjected to FST can be modelled by superimposing an isotropic turbulence field on a turbulent boundary layer field, which supports the hypothesis that the underlying structure of the boundary layer appears to remain largely intact if the naturally occurring fluctuations in the turbulent boundary layer exceed the energy of the FST.

MSC:

76F40 Turbulent boundary layers
76F05 Isotropic turbulence; homogeneous turbulence

Keywords:

homogeneous turbulence; turbulent boundary layers; boundary layer structure

Full Text: DOI

References:

[1] Adrian, R.J., Meinhart, C.D. \& Tomkins, C.D.2000Vortex organization in the outer region of the turbulent boundary layer. J. Fluid Mech.422, 1-53. · Zbl 0959.76503

[2] Anderson, W. \& Salesky, S.T.2021Uniform momentum zone scaling arguments from direct numerical simulation of inertia-dominated channel turbulence. J. Fluid Mech.906, A8. · Zbl 07274707

[3] Baidya, R., et al.2019Simultaneous skin friction and velocity measurements in high Reynolds number pipe and boundary layer flows. J. Fluid Mech.871, 377-400. · Zbl 1419.76300

[4] Bautista, J.C.C., Ebadi, A., White, C.M., Chini, G.P. \& Klewicki, J.C.2019A uniform momentum zone-vortical fissure model of the turbulent boundary layer. J. Fluid Mech.858, 609-633. · Zbl 1415.76329

[5] Borrell, G. \& Jiménez, J.2016Properties of the turbulent/non-turbulent interface in boundary layers. J. Fluid Mech.801, 554-596.

[6] Cao, N., Chen, S. \& Doolen, G.D.1999Statistics and structures of pressure in isotropic turbulence. Phys. Fluids11 (8), 2235-2250. · Zbl 1147.76352

[7] Chauhan, K., Philip, J. \& Marusic, I.2014bScaling of the turbulent/non-turbulent interface in boundary layers. J. Fluid Mech.751, 298-328.

[8] Chauhan, K., Philip, J., De Silva, C.M., Hutchins, N. \& Marusic, I.2014aThe turbulent/non-turbulent interface and entrainment in a boundary layer. J. Fluid Mech.742, 119-151.

[9] Chen, X., Chung, Y.M. \& Wan, M.2020Unfirom-momentum zones in a turbulent pipe flow. J. Fluid Mech.884, A25. · Zbl 07150067

[10] Dogan, E., Hanson, R. \& Ganapathisubramani, B.2016Interactions of large-scale free-stream turbulence with turbulent boundary layers. J. Fluid Mech.802, 79-107.

[11] Dogan, E., Hearst, R.J. \& Ganapathisubramani, B.2017Modelling high Reynolds number wall-turbulence interactions in laboratory experiments using large-scale free-stream turbulence. Phil. Trans. R. Soc. A375 (2089), 20160091.

© 2021 FIZ Karlsruhe GmbH

[12] Dogan, E., Hearst, R.J., Hanson, R.E. \& Ganapathisubramani, B.2019Spatial characteristics of a zero-pressure-gradient turbulent boundary layer in the presence of free-stream turbulence. Phys. Rev. Fluids4, 084601.

[13] Dong, S., Lozano-Durán, A., Sekimoto, A. \& Jiménez, J.2017Coherent structures in statistically stationary homogeneous shear turbulence. J. Fluid Mech.816, 167-208. · Zbl 1383.76181

[14] Eisma, J., Westerweel, J., Ooms, G. \& Elsinga, G.E.2015Interfaces and internal layers in a turbulent boundary layer. Phys. Fluids27, 055103.

[15] Elsinga, G.E. \& Marusic, I.2010Universal aspects of small-scale motions in turbulence. J. Fluid Mech.662, 514-539. · Zbl 1205.76123

[16] Esteban, L.B., Dogan, E., Rodríguez-López, E. \& Ganapathisubramani, B.2017Skin-friction measurements in a turbulent boundary layer under the influence of free-stream turbulence. Exp. Fluids58 (9), 115.

[17] Ganapathisubramani, B., Longmire, E.K. \& Marusic, I.2003Characteristics of vortex packets in turbulent boundary layers. J. Fluid Mech.478, 35-46. · Zbl 1032.76500

[18] Gul, M., Elsinga, G.E. \& Westerweel, J.2020Internal shear layers and edges of uniform momentum zones in a turbulent pipe flow. J. Fluid Mech.901, A10. · Zbl 07256850

[19] Hancock, P.E. \& Bradshaw, P.1989Turbulence structure of a boundary layer beneath a turbulent free stream. J. Fluid Mech.205, 45-76.

[20] Head, M.R. \& Bandyopadhyay, P.1981New aspects of turbulent boundary-layer structure. J. Fluid Mech.107, 297-338.

[21] Hearst, R.J., Dogan, E. \& Ganapathisubramani, B.2018Robust features of a turbulent boundary layer subjected to high-intensity free-stream turbulence. J. Fluid Mech.851, 416-435. · Zbl 1415.76336

[22] Hearst, R.J. \& Ganapathisubramani, B.2015Quantification and adjustment of pixel-locking in Particle Image Velocimetry. Exp. Fluids56 (10), 191.

[23] Hearst, R.J. \& Ganapathisubramani, B.2017Tailoring incoming shear and turbulence profiles for lab-scale wind turbines. Wind Energy20, 2021-2035.

[24] Hearst, R.J., Gomit, G. \& Ganapathisubramani, B.2016Effect of turbulence on the wake of a wall-mounted cube. J. Fluid Mech.804, 513-530.

[25] Hearst, R.J. \& Lavoie, P.2015The effect of active grid initial conditions on high Reynolds number turbulence. Exp. Fluids56 (10), 185.

[26] Hunt, J.C.R. \& Carruthers, D.J.1990Rapid distortion theory and the 'problems' of turbulence. J. Fluid Mech.212, 497-532. · Zbl 0692.76054

[27] Hunt, J.C.R. \& Durbin, P.A.1999Perturbed vortical layers and shear sheltering. Fluid Dyn. Res.24, 375-404. · Zbl 1051.76520

[28] Hunt, J.C.R., Eames, I., Da Silva, C.B. \& Westerweel, J.2011Interfaces and inhomogeneous turbulence. Phil. Trans. R. Soc. A369, 811-832.

[29] Hutchins, N. \& Marusic, I.2007Large-scale influences in near-wall turbulence. Phil. Trans. R. Soc. A365, 657-664. · Zbl 1152.76421

[30] Jie, Y., Xu, C., Dawson, J.R., Andersson, H.I. \& Zhao, L.2019Influence of the quiescent core on tracer spheroidal particle dynamics in turbulent channel flow. J. Turbul.20 (7), 424-438.

[31] Jooss, Y., Li, L., Bracchi, T. \& Hearst, R.J.2021Spatial development of a turbulent boundary layer subjected to freestream turbulence. J. Fluid Mech.911, A4. · Zbl 07319125

[32] Klewicki, J.C.2010Reynolds number dependence, scaling, and dynamics of turbulent boundary layers. Trans. ASME: J. Fluids Engng132, 094001.

[33] Kozul, M., Hearst, R.J., Monty, J.P., Ganapathisubramani, B. \& Chung, D.2020Response of the temporal turbulent boundary layer to decaying free-stream turbulence. J. Fluid Mech.896, A11. · Zbl 07207858

[34] Kwon, Y.S., Philip, J., De Silva, C.M., Hutchins, N. \& Monty, J.P.2014The quiescent core of turbulent channel flow. J. Fluid Mech.751, 228-254. · Zbl 1416.76063

[35] Larssen, J.V. \& Devenport, W.J.2011On the generation of large-scale homogeneous turbulence. Exp. Fluids50, 1207-1223.

[36] Laskari, A., De Kat, R., Hearst, R.J. \& Ganapathisubramani, B.2018Time evolution of uniform momentum zones in a turbulent boundary layer. J. Fluid Mech.842, 554-590. · Zbl 1419.76318

[37] Makita, H.1991Realization of a large-scale turbulence field in a small wind tunnel. Fluid Dyn. Res.8, 53-64.

[38] Mckeon, B.J.2019Self-similar hierarchies and attached eddies. Phys. Rev. Fluids4, 082601.

[39] Meinhart, C.D. \& Adrian, R.J.1995On the existence of uniform momentum zones in a turbulent boundary layer. Phys. Fluids7 (4), 694-696.

[40] Nickels, T.B., Marusic, I., Hafez, S. \& Chong, M.S.2005Evidence of the \(k_1^{-1}\) law in a high-Reynolds-number turbulent boundary layer. Phys. Rev. Lett.95, 074501.

[41] Nickels, T.B., Marusic, I., Hafez, S., Hutchins, N. \& Chong, M.S.2007Some predictions of the attached eddy model for a high Reynolds number boundary layer. Phil. Trans. R. Soc. A365, 807-822.

[42] Perry, A.E. \& Li, J.D.1990Experimental support for the attached-eddy hypothesis in zero-pressure-gradient turbulent boundary layers. J. Fluid Mech.218, 405-438.

[43] Philip, J., Meneveau, C., De Silva, C.M. \& Marusic, I.2014Multiscale analysis of fluxes at the turbulent/non-turbulent interface in high Reynolds number boundary layers. Phys. Fluids26, 015105.

© 2021 FIZ Karlsruhe GmbH

[44] Reuther, N. \& Kähler, C.J.2018Evaluation of large-scale turbulent/non-turbulent interface detection methods for wall-bounded flows. Exp. Fluids59, 121.

[45] Saxton-Fox, T. \& Mckeon, B.J.2017Coherent structures, uniform momentum zones and the streamwise energy spectrum in wall-bounded turbulent flows. J. Fluid Mech.826, R6. · Zbl 1430.76279

[46] Sharp, N., Neuscamman, S. \& Warhaft, Z.2009Effects of large-scale free stream turbulence on a turbulent boundary layer. Phys. Fluids21, 095105. · Zbl 1183.76470

[47] Sillero, J.A., Jiménez, J. \& Moser, R.D.2013One-point statistics for turbulent wall-bounded flows at Reynolds numbers up to \(\delta^+ \approx 2000\). Phys. Fluids25, 105102.

[48] Sillero, J.A., Jiménez, J. \& Moser, R.D.2014Two-point statistics for turbulent boundary layers and channels at Reynolds numbers up to \(\delta^+ \approx 2000\). Phys. Fluids26, 105109.

[49] De Silva, C.M., Hutchins, N. \& Marusic, I.2016Uniform momentum zones in turbulent boundary layers. J. Fluid Mech.786, 309-331. · Zbl 1381.76106

[50] De Silva, C.M., Philip, J., Hutchins, N. \& Marusic, I.2017Interfaces of uniform momentum zones in turbulent boundary layers. J. Fluid Mech.820, 451-478. · Zbl 1383.76257

[51] Theodorsen, T.1952 Mechanism of turbulence. In Proceedings of the Second Midwestern Conference on Fluid Mechanics, pp. 1-18. Ohio State University.

[52] Vincenti, P., Klewicki, J., Morrill-Winter, C., White, C.M. \& Wosnik, M.2013Streamwise velocity statistics in turbulent boundary layers that spatially develop to high Reynolds number. Exp. Fluids54, 1629.

[53] Watanabe, T., Zhang, X. \& Nagata, K.2018Turbulent/non-turbulent interfaces detected in DNS of incompressible turbulent boundary layers. Phys. Fluids30, 035102.

[54] Wu, X., Wallace, J.M. \& Hickey, J.-P.2019Boundary layer turbulence and freestream turbulence interface, turbulent spot and freestream turbulence interface, laminar boundary layer and freestream turbulence interface. Phys. Fluids31, 045104.

[55] Yang, J., Hwang, J. \& Sung, H.J.2016Structural organization of the quiescent core region in a turbulent channel flow. Intl J. Heat Fluid Flow62, 455-463.

[56] You, J. \& Zaki, T.A.2019Conditional statistics and flow structures in turbulent boundary layers buffet by free-stream turbulence. J. Fluid Mech.866, 526-566. · Zbl 1415.76413

[57] Zhou, J., Adrian, R.J., Balachandar, S. \& Kendall, T.M.1999Mechanisms for generating coherent packets of hairpin vortices in channel flow. J. Fluid Mech.387, 353-396. · Zbl 0946.76030

This reference list is based on information provided by the publisher or from digital mathematics libraries. Its items are heuristically matched to zbMATH identifiers and may contain data conversion errors. It attempts to reflect the references listed in the original paper as accurately as possible without claiming the completeness or perfect precision of the matching.