zbMATH Open
THE FIRST RESOURCE FOR MATHEMATICS

Jooss, Yannick; Li, Leon; Bracchi, Tania; Hearst, R. Jason

Spatial development of a turbulent boundary layer subjected to freestream turbulence. (English) Zbl 07319125

J. Fluid Mech. 911, Paper No. A4, 28 p. (2021).

Summary: The spatial development of a turbulent boundary layer (TBL) subjected to freestream turbulence (FST) is investigated experimentally in a water channel for friction Reynolds numbers up to $Re_\tau = 5060$. Four different FST intensities are generated with an active grid, ranging from a low-turbulence reference case to $u'_\infty / U_\infty = 12.5\%$. Wall-normal velocity scans are performed with laser doppler velocimetry at three positions downstream of the grid. There are two combating influences as the flow develops: the TBL grows while the FST decays. Whilst previous studies have shown the wake region of the TBL is suppressed by FST, the present measurements demonstrate that the wake recovers sufficiently far downstream. For low levels of FST, the near-wall variance peak grows as one moves downstream, whereas high FST results in an initially high variance peak that decays with streamwise position. These results are mirrored in the evolution of the spectrograms, where low FST results in the emergence of an outer spectral peak as the flow evolves, while high FST sees an initially high outer spectral peak decay in space. This finding is significant as it suggests the FST does not permanently mature the TBL ahead of its natural evolution. Finally, it is explicitly demonstrated that it is not sufficient to characterize the TBL solely by conventional parameters such as Re_τ, but that the level of FST and the evolution of the two flows must also be considered.

MSC:

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

Keywords:

homogeneous turbulence; turbulent boundary layers

Full Text: DOI

References:

[1] Adrian, R. J. \& Yao, C. S.1986Power spectra of fluid velocities measured by laser Doppler velocimetry. Exp. Fluids5 (1), 17-28.

[2] Anderson, J. D.2010Fundamentals of Aerodynamics. McGraw-Hill Education.

[3] Baars, W. J., Hutchins, N. \& Marusic, I.2016Spectral stochastic estimation of high-Reynolds- number wall-bounded turbulence for a refined inner-outer interaction model. Phys. Rev. Fluids1 (5), 054406.

[4] Blair, M. F.1983aInfluence of free-stream turbulence on turbulent boundary layer heat transfer and mean profile development, part ii—analysis of results. Trans. ASME: J. Heat Transfer105 (1), 41-47.

[5] Blair, M. F.1983bInfluence of free-stream turbulence on turbulent boundary layer heat transfer and mean profile development, part i—experimental data. Trans. ASME: J. Heat Transfer105 (1), 33-40.

[6] Boyer, L. \& Searby, G.1986Random sampling: distortion and reconstruction of velocity spectra from fast Fourier-transform analysis of the analog signal of a laser Doppler processor. J. Appl. Phys.60 (8), 2699-2707.

[7] Castro, I. P.1984Effects of free stream turbulence on low Reynolds number boundary layers. Trans. ASME: J. Fluids Engng106 (3), 298-306.

[8] Chauhan, K. A., Monkewitz, P. A. \& Nagib, H. M.2009Criteria for assessing experiments in zero pressure gradient boundary layers. Fluid Dyn. Res.41 (2), 021404. · Zbl 1286.76007

[9] Coles, D.1956The law of the wake in the turbulent boundary layer. J. Fluid Mech.1 (2), 191-226. · Zbl 0070.42903

[10] Comte-Bellot, G. \& Corrsin, S.1966The use of a contraction to improve the isotropy of grid-generated turbulence. J. Fluid Mech.25 (4), 657-682.

[11] Devinant, P., Laverne, T. \& Hureau, J.2002Experimental study of wind-turbine airfoil aerodynamics in high turbulence. J. Wind Engng Ind. Aerodyn.90 (6), 689-707.

[12] Dogan, E., Hanson, R. E. \& Ganapathisubramani, B.2016Interactions of large-scale free-stream turbulence with turbulent

boundary layers. J. Fluid Mech.802, 79-107.

[13] 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.

[14] 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 (8), 084601.

[15] Eitel-Amor, G., Örlü, R. \& Schlatter, P.2014Simulation and validation of a spatially evolving turbulent boundary layer up to \(Re_{\theta }=8300\). Intl J. Heat Fluid Flow47, 57-69.

[16] Ertunç, Ö., Özyilmaz, N., Lienhart, H., Durst, F. \& Beronov, K.2010Homogeneity of turbulence generated by static-grid structures. J. Fluid Mech.654, 473-500. · Zbl 1193.76006

[17] 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.

[18] Ferrante, A. \& Elghobashi, S.2004On the physical mechanisms of drag reduction in a spatially developing turbulent boundary layer laden with microbubbles. J. Fluid Mech.503, 345-355. · Zbl 1116.76368

[19] Ganapathisubramani, B.2018Law of the wall for small-scale streamwise turbulence intensity in high-Reynolds-number turbulent boundary layers. Phys. Rev. Fluids3 (10), 104607.

[20] Hancock, P. E. \& Bradshaw, P.1983The effect of free-stream turbulence on turbulent boundary layers. Trans. ASME: J. Fluids Engng105 (3), 284-289.

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

[22] Hearst, R. J., Buxton, O. R. H., Ganapathisubramani, B. \& Lavoie, P.2012Experimental estimation of fluctuating velocity and scalar gradients in turbulence. Exp. Fluids53 (4), 925-942.

[23] 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

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

[25] Hutchins, N. \& Marusic, I.2007Evidence of very long meandering features in the logarithmic region of turbulent boundary layers. J. Fluid Mech.579, 1-28. · Zbl 1113.76004

[26] Isaza, J. C., Salazar, R. \& Warhaft, Z.2014On grid-generated turbulence in the near- and far field regions. J. Fluid Mech.753, 402-426.

[27] Kang, H. S., Chester, S. \& Meneveau, C.2003Decaying turbulence in an active-grid-generated flow and comparisons with large-eddy simulation. J. Fluid Mech.480, 129-160. · Zbl 1063.76507

[28] 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

[29] Larssen, J. V. \& Devenport, W. J.2011On the generation of large-scale homogeneous turbulence. Exp. Fluids50 (5), 1207-1223.

[30] 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

[31] Lavoie, P., Djenidi, L. \& Antonia, R. A.2007Effects of initial conditions in decaying turbulence generated by passive grids. J. Fluid Mech.585, 395-420. · Zbl 1118.76008

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

[33] Maldonado, V., Castillo, L., Thormann, A. \& Meneveau, C.2015The role of free stream turbulence with large integral scale on the aerodynamic performance of an experimental low Reynolds number S809 wind turbine blade. J. Wind Engng Ind. Aerodyn.142, 246-257.

[34] Marusic, I., Chauhan, K. A., Kulandaivelu, V. \& Hutchins, N.2015Evolution of zero-pressure-gradient boundary layers from different tripping conditions. J. Fluid Mech.783, 379-411. · Zbl 1382.76125

[35] Marusic, I., Mckeon, B. J., Monkewitz, P. A., Nagib, H. M., Smits, A. J. \& Sreenivasan, K. R.2010Wall-bounded turbulent flows at high Reynolds numbers: recent advances and key issues. Phys. Fluids22 (6), 065103. · Zbl 1190.76086

[36] Marusic, I., Monty, J. P., Hultmark, M. \& Smits, A. J.2013On the logarithmic region in wall turbulence. J. Fluid Mech.716, R3. · Zbl 1284.76206

[37] Mohamed, M. S. \& Larue, J. C.1990The decay power law in grid-generated turbulence. J. Fluid Mech.219, 195-214.

[38] Monkewitz, P. A., Chauhan, K. A. \& Nagib, H. M.2008Comparison of mean flow similarity laws in zero pressure gradient turbulent boundary layers. Phys. Fluids20 (10), 105102. · Zbl 1182.76530

[39] Perry, A. E., Marusic, I. \& Jones, M. B.1998New evolution equations for turbulent boundary layers in arbitrary pressure gradients. Sadhana23 (5), 443-457. · Zbl 1075.76552

[40] Prandtl, L.1905 über Flüssigkeitsbewegung bei sehr kleiner Reibung. In Proceedings of the 3rd International Congress of Mathematicians, Heidelberg, 1904, Leipzig, pp. 485-491. B. G. Teubner. · Zbl 36.0800.02

[41] Raushan, P. K., Singh, S. K. \& Debnath, K.2018Grid generated turbulence under the rigid boundary influence. J. Wind Engng Ind. Aerodyn.182, 252-261.

[42] Rodríguez-López, E., Bruce, P. J. K. \& Buxton, O. R. H.2015A robust post-processing method to determine skin friction in turbulent boundary layers from the velocity profile. Exp. Fluids56 (4), 68.

[43] Sharp, N. S., Neuscamman, S. \& Warhaft, Z.2009Effects of large-scale free stream turbulence on a turbulent boundary layer. Phys. Fluids21 (9), 095105. · Zbl 1183.76470

[44] 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 (10), 105102.

[45] Smits, A. J. \& Marusic, I.2013Wall-bounded turbulence. Phys. Today66 (9), 25.

[46] Stefes, B. \& Fernholz, H. H.2004Skin friction and turbulence measurements in a boundary layer with zero-pressure-gradient under the influence of high intensity free-stream turbulence. Eur. J. Mech. B/Fluids23 (2), 303-318. · Zbl 1058.76520

[47] Thole, K. A. \& Bogard, D. G.1996High freestream turbulence effects on turbulent boundary layers. Trans. ASME: J. Fluids Engng118 (2), 276-284.

[48] 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 (12), 1629.

[49] Wang, S., Zhou, Y., Alam, M. M. \& Yang, H.2014Turbulent intensity and Reynolds number effects on an airfoil at low Reynolds numbers. Phys. Fluids26 (11), 115107.

[50] Wu, X. \& Moin, P.2009Direct numerical simulation of turbulence in a nominally zero-pressure-gradient flat-plate boundary layer. J. Fluid Mech.630, 5-41. · Zbl 1181.76084

[51] Wu, X., Moin, P., Wallace, J. M., Skarda, J., Lozano-Durán, A. \& Hickey, J.-P.2017Transitional-turbulent spots and turbulent-turbulent spots in boundary layers. Proc. Natl Acad. Sci.114 (27), E5292-E5299.

[52] 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 (4), 045104.

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