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Exact coherent states with hairpin-like vortex structure in channel flow. (English)

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J. Fluid Mech. 849, 76-89 (2018).

Summary: Hairpin vortices are widely studied as an important structural aspect of wall turbulence. The present work describes, for the first time, nonlinear travelling wave solutions to the Navier-Stokes equations in the channel flow geometry – exact coherent states (ECS) – that display hairpin-like vortex structure. This solution family comes into existence at a saddle-node bifurcation at Reynolds number Re = 666. At the bifurcation, the solution has a highly symmetric quasi-streamwise vortex structure similar to that reported for previously studied ECS. With increasing distance from the bifurcation, however, both the upper and lower branch solutions develop a vortical structure characteristic of hairpins: a spanwise-oriented 'head' near the channel centreplane where the mean shear vanishes connected to counter-rotating quasi-streamwise 'legs' that extend toward the channel wall. At Re = 1800, the upper branch solution has mean and Reynolds shear-stress profiles that closely resemble those of turbulent mean profiles in the same domain.

MSC:

76D05 Navier-Stokes equations for incompressible viscous fluids
37N10 Dynamical systems in fluid mechanics, oceanography and meteorology
76D17 Viscous vortex flows
76F06 Transition to turbulence

Keywords:

boundary layer structure; nonlinear dynamical systems; turbulent flows

Software:

channelflow

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References:

[1] Adrian, R. J., Hairpin vortex organization in wall turbulence, Phys. Fluids, 19, 4, (2007) · Zbl 1146.76307

[2] Brand, E.; Gibson, J. F., A doubly-localized equilibrium solution of plane Couette flow, J. Fluid Mech., 750, R3, (2014)

[3] Chantry, M.; Willis, A. P.; Kerswell, R. R., Genesis of streamwise-localized solutions from globally periodic traveling waves in pipe flow, Phys. Rev. Lett., 112, 16, (2014)

[4] Cherubini, S.; Palma, P. D.; Robinet, J. C.; Bottaro, A., Edge states in a boundary layer, Phys. Fluids, 23, 5, (2011) · Zbl 1241.76246

[5] Duguet, Y.; Pringle, C. C. T.; Kerswell, R. R., Relative periodic orbits in transitional pipe flow, Phys. Fluids, 20, 11, (2008) · Zbl 1182.76222

[6] Duguet, Y.; Schlatter, P.; Henningson, D. S.; Eckhardt, B., Self-sustained localized structures in a boundary-layer flow, Phys. Rev. Lett., 108, (2012)

[7] Duguet, Y.; Willis, A. P.; Kerswell, R. R., Transition in pipe flow: the saddle structure on the boundary of turbulence, J. Fluid Mech., 613, 255-274, (2008) · Zbl 1151.76495

[8] Eckhardt, B.; Faisst, H.; Schmiegel, A.; Schneider, T. M., Dynamical systems and the transition to turbulence in linearly stable shear flows, Phil. Trans. R. Soc. Lond. A, 366, 1868, 1297-1315, (2008)

[9] Eckhardt, B.; Schneider, T. M.; Hof, B.; Westerweel, J., Turbulence transition in pipe flow, Annu. Rev. Fluid Mech., 39, 447-468, (2007) · Zbl 1296.76062

[10] Eitel-Amor, G.; Örlü, R.; Schlatter, P.; Flores, O., Hairpin vortices in turbulent boundary layers, Phys. Fluids, 27, 2, (2015)

[11] Gibson, J. F.2012 ChannelFlow: a spectral Navier-Stokes simulator in C$++$. \textit{Tech. Rep.}, University of New Hampshire.

[12] Gibson, J. F.; Brand, E., Spanwise-localized solutions of planar shear flows, J. Fluid Mech., 745, 25-61, (2014)

[13] Gibson, J. F.; Halcrow, J.; Cvitanović, P., Visualizing the geometry of state space in plane Couette flow, J. Fluid Mech., 611, 107-130, (2008) · Zbl 1151.76453

[14] Gibson, J. F.; Halcrow, J.; Cvitanovic, P., Equilibrium and travelling-wave solutions of plane Couette flow, J. Fluid Mech., 638, 243-266, (2009) · Zbl 1183.76688

[15] Hof, B.; Van Doorne, C. W.; Westerweel, J.; Nieuwstadt, F. T.; Faisst, H.; Eckhardt, B.; Wedin, H.; Kerswell, R. R.; Waleffe, F., Experimental observation of nonlinear traveling waves in turbulent pipe flow, Science, 305, 5690, 1594-1598, (2004)

[16] Itano, T.; Generalis, S., Hairpin vortex solution in planar couette flow: a tapestry of knotted vortices, Phys. Rev. Lett., 102, (2009)

[17] Kawahara, G.; Uhlmann, M.; Van Veen, L., The significance of simple invariant solutions in turbulent flows, Annu. Rev. Fluid Mech., 44, 203-225, (2012) · Zbl 1352.76031

[18] Khapko, T.; Kreilos, T.; Schlatter, P.; Duguet, Y.; Eckhardt, B.; Henningson, D. S., Localized edge states in the asymptotic suction boundary layer, J. Fluid Mech., 717, R6, (2013) · Zbl 1284.76106

[19] Nagata, M.; Deguchi, K., Mirror-symmetric exact coherent states in plane Poiseuille flow, J. Fluid Mech., 735, R4, (2013) · Zbl 1294.76115

[20] Neelavara, S. A.; Duguet, Y.; Lusseyran, F., State space analysis of minimal channel flow, Fluid Dyn. Res., 49, 3, (2017)

[21] Park, J. S.; Graham, M. D., Exact coherent states and connections to turbulent dynamics in minimal channel flow, J. Fluid Mech., 782, 430-454, (2015) · Zbl 1381.76097

[22] Perry, A. E.; Chong, M. S., On the mechanism of wall turbulence, J. Fluid Mech., 119, 106-121, (1982) · Zbl 0517.76057

[23] Rawat, S.; Cossu, C.; Rincon, F., Travelling-wave solutions bifurcating from relative periodic orbits in plane Poiseuille flow, Comptes Rendus Mécanique, 344, 6, 448-455, (2016)

[24] Robinson, S. K., Coherent motions in the turbulent boundary-layer, Annu. Rev. Fluid Mech., 23, 1, 601-639, (1991)

[25] Schlatter, P.; Li, Q.; Örlü, R.; Hussain, F.; Henningson, D. S., On the near-wall vortical structures at moderate Reynolds numbers, Eur. J. Mech. (B/Fluids), 48, 75-93, (2014) · Zbl 06931934

[26] Skufca, J. D.; Yorke, J. A.; Eckhardt, B., Edge of chaos in a parallel shear flow, Phys. Rev. Lett., 96, 17, (2006)

[27] Smits, A. J.; Mckeon, B. J.; Marusic, I., High-Reynolds number wall turbulence, Annu. Rev. Fluid Mech., 43, 1, 353-375, (2011) · Zbl 1299.76002

[28] Theodorsen, T.1952Mechanism of Turbulence. In Second International Midwest Conference on Fluid Mechanics, pp. 1-19. Ohio State University.

[29] Toh, S.; Itano, T., A periodic-like solution in channel flow, J. Fluid Mech., 481, 67-76, (2003) · Zbl 1034.76014

[30] Townsend, A. A., Equilibrium layers and wall turbulence, J. Fluid Mech., 11, 1, 97-120, (1961) · Zbl 0127.42602

[31] Waleffe, F., On a self-sustaining process in shear flows, Phys. Fluids, 9, 4, 883-900, (1997)

[32] Waleffe, F., Three-dimensional coherent states in plane shear flows, Phys. Rev. Lett., 81, 19, 4140-4143, (1998)

[33] Waleffe, F., Exact coherent structures in channel flow, J. Fluid Mech., 435, 93-102, (2001) · Zbl 0987.76034

[34] Waleffe, F., Homotopy of exact coherent structures in plane shear flows, Phys. Fluids, 15, 6, 1517-1534, (2003) · Zbl 1186.76556

[35] Wall, D. P.; Nagata, M., Exact coherent states in channel flow, J. Fluid Mech., 788, 444-468, (2016) · Zbl 1381.76093

[36] Wang, J.; Gibson, J.; Waleffe, F., Lower branch coherent states in shear flows: Transition and control, Phys. Rev. Lett., 98, 20, (2007)

[37] Wedin, H.; Kerswell, R. R., Exact coherent structures in pipe flow: travelling wave solutions, J. Fluid Mech., 508, 333-371, (2004) · Zbl 1065.76072

[38] Woodcock, J. D.; Marusic, I., The statistical behaviour of attached eddies, Phys. Fluids, 27, 1, (2015)

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

[40] Zammert, S.; Eckhardt, B., Harbingers and latecomers – the order of appearance of exact coherent structures in plane Poiseuille flow, J. Turbul., 18, 2, 103-114, (2016)