Shekar, Ashwin; **McMullen, Ryan M.**; **McKeon, Beverley J.**; **Graham, Michael D.**
Self-sustained elastoinertial Tollmien-Schlichting waves. (English) Zbl 07210552
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Summary: Direct simulations of two-dimensional plane channel flow of a viscoelastic fluid at Reynolds number $Re = 3000$ reveal the existence of a family of attractors whose structure closely resembles the linear Tollmien-Schlichting (TS) mode, and in particular exhibits strongly localized stress fluctuations at the critical layer position of the TS mode. At the parameter values chosen, this solution branch is not connected to the nonlinear TS solution branch found for Newtonian flow, and thus represents a solution family that is nonlinearly self-sustained by viscoelasticity. The ratio between stress and velocity fluctuations is in quantitative agreement for the attractor and the linear TS mode, and increases strongly with Weissenberg number, Wi. For the latter, there is a transition in the scaling of this ratio as Wi increases, and the Wi at which the nonlinear solution family comes into existence is just above this transition. Finally, evidence indicates that this branch is connected through an unstable solution branch to two-dimensional elastoinertial turbulence (EIT). These results suggest that, in the parameter range considered here, the bypass transition leading to EIT is mediated by nonlinear amplification and self-sustenance of perturbations that excite the TS mode.

MSC:

76F06 Transition to turbulence
76A10 Viscoelastic fluids
76F20 Dynamical systems approach to turbulence
76F65 Direct numerical and large eddy simulation of turbulence

Keywords:

drag reduction; turbulent transition

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References:

[1] Chaudhary, I., Garg, P., Shankar, V. \& Subramanian, G.2019Elastoinertial wall mode instabilities in viscoelastic plane Poiseuille flow. J. Fluid Mech.881, 119-163. · Zbl 1430.76037

[2] Chaudhary, I., Garg, P., Subramanian, G. \& Shankar, V.2020 Linear instability of viscoelastic pipe flow. Preprint, arXiv:2003.09369v1.

[3] Choueiri, G. H., Lopez, J. M. \& Hof, B.2018Exceeding the asymptotic limit of polymer drag reduction. Phys. Rev. Lett.120 (12), 124501.

[4] Dallas, V., Vassilicos, J. \& Hewitt, G.2010Strong polymer-turbulence interactions in viscoelastic turbulent channel flow. Phys. Rev. E82 (6), 066303.

[5] Drazin, P. G. \& Reid, W. H.2004Hydrodynamic Stability, 2nd edn. . Cambridge University Press. · Zbl 1055.76001

[6] Dubief, Y., Terrapon, V. E. \& Soria, J.2013On the mechanism of elastoinertial turbulence. Phys. Fluids25 (11), 110817.

[7] Duguet, Y., Pringle, C. C. T. \& Kerswell, R. R.2008aRelative periodic orbits in transitional pipe flow. Phys. Fluids20 (11), 114102. · Zbl 1182.76222

[8] Duguet, Y., Willis, A. P. \& Kerswell, R. R.2008bTransition in pipe flow: the saddle structure on the boundary of turbulence. J. Fluid Mech.613, 255-274.

[9] Eckhardt, B., Faisst, H., Schmiegel, A. \& Schneider, T. M.2008Dynamical systems and the transition to turbulence in linearly stable shear flows. Phil. Trans. R. Soc. Lond. A366 (1868), 1297-1315.

[10] Eckhardt, B., Schneider, T. M., Hof, B. \& Westerweel, J.2007Turbulence transition in pipe flow. Annu. Rev. Fluid Mech.39, 447-468.

[11] Garg, P., Chaudhary, I., Khalid, M., Shankar, V. \& Subramanian, G.2018Viscoelastic pipe flow is linearly unstable. Phys. Rev. Lett.121 (2), 024502.

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

[13] Graham, M. D.2014Drag reduction and the dynamics of turbulence in simple and complex fluids. Phys. Fluids26, 101301.

[14] Hameduddin, I., Gayme, D. F. \& Zaki, T. A.2019Perturbative expansions of the conformation tensor in viscoelastic flows. J. Fluid Mech.858, 377-406. · Zbl 1415.76015

[15] Hof, B., Van Doorne, C. W. H., Westerweel, J., Nieuwstadt, F. T. M., Faisst, H., Eckhardt, B., Wedin, H., Kerswell, R. R. \& Waleffe, F.2004Experimental observation of nonlinear traveling waves in turbulent pipe flow. Science305 (5690), 1594-1598.

[16] Jiménez, J.1990Transition to turbulence in two-dimensional Poiseuille flow. J. Fluid Mech.218, 265-297.

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

[18] Kim, K., Li, C.-F., Sureshkumar, R., Balachandar, S. \& Adrian, R. J.2007Effects of polymer stresses on eddy structures in drag-reduced turbulent channel flow. J. Fluid Mech.584, 281-299. · Zbl 1175.76069

[19] Kurganov, A. \& Tadmor, E.2000New high-resolution central schemes for nonlinear conservation laws and convection-diffusion equations. J. Comput. Phys.160 (1), 241-282. · Zbl 0987.65085

[20] Lee, S. J. \& Zaki, T. A.2017Simulations of natural transition in viscoelastic channel flow. J. Fluid Mech.820, 232-262. · Zbl 1383.76288

[21] Li, W. \& Graham, M. D.2007Polymer induced drag reduction in exact coherent structures of plane Poiseuille flow. Phys. Fluids19 (8), 083101. · Zbl 1182.76452

[22] Li, W., Stone, P. A. \& Graham, M. D.2005Viscoelastic nonlinear traveling waves and drag reduction in plane Poiseuille flow. Fluid Mech. Appl.: Proceedings of the IUTAM Symposium on Laminar-Turbulent Transition and Finite Amplitute Solutions77, 285-308.

[23] Li, W., Xi, L. \& Graham, M. D.2006Nonlinear travelling waves as a framework for understanding turbulent drag reduction. J. Fluid Mech.565, 353-362. · Zbl 1177.76169

[24] Lopez, J. M., Choueiri, G. H. \& Hof, B.2019Dynamics of viscoelastic pipe flow at low Reynolds numbers in the maximum drag reduction limit. J. Fluid Mech.874, 699-719. · Zbl 1419.76040

[25] Mckeon, B. J. \& Sharma, A. S.2010A critical-layer framework for turbulent pipe flow. J. Fluid Mech.658, 336-382. · Zbl 1205.76138

[26] Min, T., Choi, H. \& Yoo, J. Y.2003Maximum drag reduction in a turbulent channel flow by polymer additives. J. Fluid Mech.492, 91-100. · Zbl 1063.76579

[27] Page, J. \& Zaki, T. A.2015The dynamics of spanwise vorticity perturbations in homogeneous viscoelastic shear flow. J. Fluid Mech.777, 327-363. · Zbl 1381.76020

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

[29] Patera, A. T. \& Orszag, S. A.1981Finite-amplitude stability of axisymmetric pipe flow. J. Fluid Mech.112, 467-474. · Zbl 0518.76037

[30] Pereira, A., Thompson, R. L. \& Mompean, G.2019a Beyond the maximum drag reduction asymptote: the pseudo-laminar state. Preprint, arXiv:1911.00439.

[31] Pereira, A. S., Thompson, R. L. \& Mompean, G.2019bCommon features between the Newtonian laminar-turbulent transition and the viscoelastic drag-reducing turbulence. J. Fluid Mech.877, 405-428. · Zbl 1430.76223

[32] Samanta, D., Dubief, Y., Holzner, M., Schäfer, C., Morozov, A. N., Wagner, C. \& Hof, B.2013Elastoinertial turbulence. Proc. Natl Acad. Sci. USA110 (26), 10557-10562.

[33] Schmid, P. J.2007Nonmodal stability theory. Annu. Rev. Fluid Mech.39, 129-162. · Zbl 1296.76055

[34] Shekar, A. \& Graham, M. D.2018Exact coherent states with hairpin-like vortex structure in channel flow. J. Fluid Mech.849, 76-89. · Zbl 1415.76137

[35] Shekar, A., Mcmullen, R. M., Wang, S.-N., Mckeon, B. J. \& Graham, M. D.2019Critical-layer structures and mechanisms in elastoinertial turbulence. Phys. Rev. Lett.122 (12), 124503.

[36] Sid, S., Terrapon, V. E. \& Dubief, Y.2018Two-dimensional dynamics of elastoinertial turbulence and its role in polymer drag reduction. Phys. Rev. F3 (1), 011301.

[37] Stone, P. A. \& Graham, M. D.2003Polymer dynamics in a model of the turbulent buffer layer. Phys. Fluids15 (5), 1247-1256. · Zbl 1186.76502

[38] Stone, P. A., Waleffe, F. \& Graham, M. D.2002Toward a structural understanding of turbulent drag reduction: nonlinear coherent states in viscoelastic shear flows. Phys. Rev. Lett.89 (20), 208301.

[39] Stone, P. A., Roy, A., Larson, R. G., Waleffe, F. \& Graham, M. D.2004Polymer drag reduction in exact coherent structures of plane shear flow. Phys. Fluids16 (9), 3470-3482. · Zbl 1187.76502

[40] Vaithianathan, T., Robert, A., Brasseur, J. G. \& Collins, L. R.2006An improved algorithm for simulating three-dimensional, viscoelastic turbulence. J. Non-Newtonian Fluid Mech.140 (1-3), 3-22. · Zbl 1143.76349

[41] Virk, P. S.1975Drag reduction fundamentals. AIChE J.21 (4), 625-656.

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

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

[44] Waleffe, F.2003Homotopy of exact coherent structures in plane shear flows. Phys. Fluids15 (6), 1517-1534. · Zbl 1186.76556

[45] Wang, J., Gibson, J. \& Waleffe, F.2007Lower branch coherent states in shear flows: transition and control. Phys. Rev. Lett.98 (20), 204501.

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

[47] White, C. M. \& Mungal, M. G.2008Mechanics and prediction of turbulent drag reduction with polymer additives. Annu. Rev. Fluid Mech.40, 235-256. · Zbl 1229.76043

[48] Zammert, S. \& Eckhardt, B.2014Streamwise and doubly-localised periodic orbits in plane Poiseuille flow. J. Fluid Mech.761, 348-359.

[49] Zhang, M., Lashgari, I., Zaki, T. A. \& Brandt, L.2013Linear stability analysis of channel flow of viscoelastic Oldroyd-B and FENE-P fluids. J. Fluid Mech.737, 249-279. · Zbl 1294.76119