Universal Threshold of Bypass Transition in Shear Flows

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Jianjun Tao*, Shiyi Chen, Weidong Su

* SKLTCS and CAPT, Department of Mechanics and Aerospace Engineering
College of Engineering, Peking University, 100871 Beijing, China
e-mail: jjtao@pku.edu.cn

ABSTRACT

The difficulty to predict laminar-turbulent transition is mainly brought by the sensitivity of shear flows to external perturbations. subcritical instability induced by finite-amplitude disturbances may trigger the bypass transition such as in linearly stable pipe flows and plane Couette flows. It has been shown that at the initial stage of transition the localized turbulent motions, e.g. spots in channel flows and puffs in pipe flows, share some common features. For example, they all include streamwise streaks and vortices, and the amplitude of some tolerable disturbances decreases as the Reynolds number increases with a scaling law of Re^{-1} as observed in experiments of pipe flows [1,2] and theoretical analysis of plane Couette and plane Poiseuille flows [3]. The similarities between these shear flows suggest that they may follow the same route to turbulence [4]. However, checking such idea by a direct comparison among their Reynolds-number thresholds is obstructed because different conventions are used in non-dimensionalization.

By building a disturbed shear-flow model and scaling analysis of the corresponding governing equations, we propose a local Reynolds number Re_M to characterize the threshold of the bypass transition. Based on this model, it is deduced easily that the critical disturbance amplitude scales in proportion to Re^{-1}. More importantly, since Re_M is defined by examining local flow field, different shear flows can be analyzed within the same model and the influence on the definition brought by different conventions used in non-dimensionalization is excluded. For large amplitude disturbances, the critical Re_M observed in experiments of plane Poiseuille flow, pipe Poiseuille flow and plane Couette flow are all close to 325. This surprising agreement indicates quantitatively that there exists a underlying universality of shear flow dynamics at the onset of localized turbulence, and the proposed local Reynolds number Re_M seems a proper universal parameter to characterize such bypass transition in different viscous shear flows.

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