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Receptivity of plane Poiseuille flow to local micro-vibration disturbance on wall

Wei-dong Cao*, Qi-xiang Hu, Bing Liu

Research Center of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang 212013, PR China

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Abstract

The receptivity of plane Poiseuille flow to local single-period micro-vibration disturbances with different phases at the top and bottom walls was investigated through direct numerical simulation of three-dimensional incompressible Navier-Stokes equations. Results show that the disturbance presents a symmetrical distribution in the spanwise direction when the micro-vibration on the wall ends, and the initial disturbance velocities and spatial distribution of the disturbance structure are different at the top and bottom walls. The disturbance's velocity, amplitude, and high- and low-speed streaks increase with time, and the amplitude of streamwise disturbance velocity is larger than those of spanwise and vertical disturbance velocities. However, no significant Tollmien-Schlichting wave was found in the flow field. The number of disturbance vortex cores gradually increases with the disturbance area. High-speed disturbance fluid concentrates near the wall and its normal velocity largely points to the wall, while low-speed disturbance fluid largely deviates from the wall. Furthermore, the streamwise velocity profiles near the top and bottom walls both become plump because of the existence of the disturbances, and the streamwise velocity profiles show a trend of evolving into turbulent velocity profiles. The shear stress near the wall increases significantly. The local micro-vibration disturbance on the wall in plane Poiseuille flow can induce the development of a structure similar to turbulent spots.

Keywords: Poiseuille flow; Disturbance; Velocity profile; Vortex; High- and low-speed streaks

1. Introduction

Due to the significant influence of laminar-turbulent transition on heat transfer, mass transfer, momentum transfer, and wall friction near the wall, a large number of scholars have focused their research on the laminar-turbulent transition and control of the boundary layer in recent years. The three processes of transition include receptivity, linear disturbance evolution, and nonlinear evolution. Transition is a complex process relating to the Reynolds number, wall temperature, the wall shape, wall roughness, fluid compressibility, the pressure gradient, external noise, and external disturbance. Various flow structures are found under various conditions, especially in channel flow, pipes, and other simple shear flows. Transition at the initial stage is usually characterized by distortions in the local flow field caused by local micro-disturbance, and unstable high- and low-speed strip areas emerging near the wall, leading to complex vortices with gradually increasing vortex intensity downstream. The dynamic characteristics of disturbance are similar to those of coherent structures in fully developed turbulent boundary layers, whereas they are significantly different from the classical transition process, which is characterized by Tollmien-Schlichting waves showing linear growth, nonlinear instability, secondary instability, and, finally, a three-dimensional nonlinear effect.

Ellingsen and Palm (1975) first put forward a probable growth mechanism in the sense of a non-natural transition. As

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* Corresponding author.
E-mail address: cwd@ujs.edu.cn (Wei-dong Cao).

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micro-disturbance of spanwise vortices occurs in the shear layer, the streamwise disturbance velocity grows linearly with time, and high- and low-speed streaks appear in non-viscous ideal fluid. Landahl (1980) also obtained a similar conclusion that constantly lifting fluid particles with horizontal momentum in shear flow cause the disturbance of stream velocity, which means that there is a transient growth mechanism where non-viscous growth coexists with viscous damping. Blackwelder (1983) found that vortex dynamics of reverse streamwise vortices in the turbulent boundary layer and in the laminar-turbulent transition zone of the boundary layer are similar and their scales are also similarly represented by the viscous length. Acarlar and Smith (1987) found that artificial disturbance near the wall of the laminar boundary layer led to lateral vortex line deformation and the disturbance developed into a hairpin vortex. Henningson et al. (1987) investigated the characteristics of vortex structures in Poiseuille flow and the boundary layer through numerical methods by designing an initial local disturbance near the wall. Testing results of the hot-wire anemometer proved that the vortex structures exist as one kind of multi-eddy structure. Haidari and Smith (1994) examined the generation and growth of single hairpin vortices created by controlled surface fluid injection within a laminar boundary layer over a range of the Reynolds number. Rosenfeld et al. (1999) proposed a general model to describe the evolution of local three-dimensional disturbance, which showed that the size of disturbance was much smaller than the characteristic length of the external shear flow. Using this model, the spanwise vortex was pulled to the outer region due to the effect of the disturbance jet, and the disturbance extended in the normal direction, while it was also stretched by the shear flow of the outer region and re-rotated into the inner region; these processes promoted the growth and enlargement of streamwise vortices, which directly caused the increase of the normal velocity as well as the intensity of upper jet-flow (Rosenfeld et al., 1999). Andersson et al. (1999) found that, owing to the effect of viscous dissipation, there was considerable linear growth in three-dimensional disturbance before attenuation. Streamwise vortices can induce instantaneous maximum growth in space in a non-parallel flat plate boundary layer. If the amplitude of streaks reaches a sufficiently large value, secondary instability will occur and induce the primeval breakdown and transition (Andersson et al., 1999). Li (2001) experimentally investigated the generation mechanism of streamwise vortices in the transition region and examined the physical process, caused by the axial vortex instability induced by the interaction of the Λ-vortex and secondary vortex rings. Svizher and Cohen (2001) used a continuous injection to generate hairpin vortices in subcritical plane Poiseuille flow. Zhang and Tang (2006) simulated the generation and development of turbulent spots with the local streamwise velocity pulse of fluid as the initial disturbance near the wall in channel flow, and analyzed the characteristics of nonlinear evolution of turbulent spots. Lu et al. (2008) researched the evolutionary mechanisms and characteristics of the vortex structure stimulated by the local constant wall velocity pulse during a period of time in the boundary layer with the pressure gradient. Lee and Wu (2008) presented direct comparisons of experimental results of transition in wall-bounded flows obtained by flow visualizations, hot-film measurement, and particle-image velocimetry, along with a brief mention of relevant theoretical progresses, based on a critical review of about 120 selected publications. Despite somewhat different initial disturbance conditions used in experiments, the flow structures were found to be practically the same.

Although there has been some progress, through experiments and numerical simulations, improving our understanding of the temporal and spatial evolution characteristics of disturbance in laminar shear flow, further research is needed to investigate the effect and mechanisms of basic flow deformation on the disturbance growth, as well as the receptivity problems induced by initial disturbance differences at the walls in simple shear flow. Currently, wall disturbance is a common method of investigating receptivity problems such as the evolution of disturbance and mean flow profile changes in Poiseuille flow in experiments and numerical calculations. In this study, local single-period micro-vibrations with opposite phases were applied to the top and bottom walls in plane Poiseuille flow.

2. Numerical methods

2.1. Governing equations and numerical method

The governing equations adopted were the incompressible, non-dimensional Navier-Stokes equations, and continuity equation:

$$\frac{\partial \boldsymbol{u}}{\partial t}+(\boldsymbol{U}\cdot\nabla)\boldsymbol{u}+(\boldsymbol{u}\cdot\nabla)\boldsymbol{U}+(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=-\nabla p'+\frac{1}{Re}\nabla^2\boldsymbol{u} \tag{1}$$

$$\nabla\cdot\boldsymbol{u}=0 \tag{2}$$

where Re is the Reynolds number; $\boldsymbol{U}$ is the numerical solution of Poiseuille basic flow, and $\boldsymbol{U}=(u_0,v_0,w_0)$, where u_0, v_0, and w_0 are the streamwise, vertical, and spanwise velocities, respectively; $\boldsymbol{u}$ is the three-dimensional disturbance velocity vector, and $\boldsymbol{u}=(u',v',w')$, where u', v', and w' are the streamwise disturbance velocity, vertical disturbance velocity, and spanwise disturbance velocity, respectively; and p' is the three-dimensional disturbance pressure. In this paper $Re=U_\infty h/\upsilon=5\ 000$, where U_∞ is twice the maximum velocity of Poiseuille basic flow, h is 0.5 times the width of the two-dimensional channel, and υ is the kinematic viscosity. The procedures of direct numerical simulation of Eqs. (1) and (2) were as follows: the third-order mixed explicit-implicit scheme was used for time discretization, the Fourier spectral expansion was used in the spanwise direction, the fifth-order upwind compact finite difference scheme was used for the nonlinear terms, the five-point central non-equidistant difference scheme was used for the Helmholtz equations, the fifth-order symmetrical compact finite difference scheme was used for the viscous terms, and the time step was 0.01. The numerical method is described in detail in Lu et al. (2006).