The Effects of System Rotation on Kinematics of Vortical Structure in Turbulent Channel Flow

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Abstract Direct numerical simulations (DNSs) of rotating turbulent Poiseuille flows are performed to study the effects of system rotation on the kinematics of the quasi-streamwise vortices. By using the second invariant of the deformation tensor, a number of streamwise vortices are detected and averaged in the wall vicinity. As observed in the homogeneous shear flow(1), with the increase in the system rotation the streamwise vortical structures tend to be aligned and elongated in the streamwise direction, and their shape in the cross streamwise plane becomes more circular rather than elliptic. In the case of smaller angular frequency, the streamwise vortices tend to be accompanied by the vortices of opposite streamwise vorticity in both ejection and sweep sides of the vortex, where inrush motion of fluids toward the wall, and outward motion from the wall are observed, respectively. With increase in the system rotation, vortices in the sweep side are attenuated, though those in the ejection side are enhanced. Enhancement of vortices in the ejection side is found to be attributed to the alignment of vortical structure and low- speed streak in the streamwise direction.

INTRODUCTION

Previously, we made a study on a homogeneous shear flow, and the effect of system rotation on the longitudinal vortical structure. Without system rotation, vortex shape is elliptic in the cross streamwise section, and the vortex is accompanied by the opposite sign of the streamwise vorticity. When the system rotation is imposed in the way to enhance the vorticity of the mean shear, the vortex is more stretched in the spanwise direction, and the opposite sign of the vorticity around the vortex is more enhanced. In contrast, when the system rotation is imposed in the way to reduce the mean spanwise vorticity, the shape of the vortex becomes circular and the opposite sign of vorticity becomes weak. In this study on rotating Poiseuille flow, we detect the number of the streamwise vortices as the isosurfaces of the second invariant of the deformation tensor, and average them. Moreover, the vortices with the opposite streamwise vorticity around the educed vortices are also detected. Then, the effect of the system rotation on the kinematics of the streamwise vortices, and the vortices of opposite vorticity around them are studied in detail. The Reynolds number, in this study, is set to be very low to see the effect of system rotation on the vortices in the near-wall region, where the mean shear effect is very intense and the body force effect is usually negligible at the high-Reynolds number. Because of a small Reynolds number, the suction side of the flow becomes almost relaminarized. Hence, our attention is on the pressure side of a channel where the system rotation reduces the effects of mean spanwise vorticity.

NUMERICAL PROCEDURE

Poiseuille flow under spanwise system rotation is numerically simulated by the spectral method. Flow is driven by a constant mean pressure gradient in the x-direction, and is assumed to be homogeneous in the x- and z-directions, so that periodic boundary conditions are imposed in these directions; x(x1), y(x2) and z(x3) are set to be streamwise, wall-normal and spanwise directions, respectively. The no-slip boundary condition is imposed on the velocity components at the two walls. Moreover, the entire flow rotates in the counterclockwise direction with angular frequency 2Ω. In all cases, a spectral method is adopted with Fourier series in the x- and z-directions and a Chebyshev polynomial expansion in the y-direction. 512 x 65 x 288 grid points are used for the computational domain of $22\pi\delta$ x2δ x$10\ \pi\delta$ in the x-, y- and z-directions, respectively. In the calculations, Reynolds number Re defined by the pressure gradient, channel half width is set to be 60, while rotation number Ro defined by the pressure gradient, channel half width, and 2Ω is changed as 0, 0.1, 0.25,0.75,1.5 and 3.

RESULTS AND DISCUSSION

Figures 1 shows the rotational effect on the mean velocity. With increase in the system rotation, mean velocity decreases and the region of zero absolute vorticity appears in the unstable side; mean velocity gradient becomes almost equal to the two times of rotation frequency in the pressure side. In the stable side of a channel, flow is relaminarized with a system rotation. Figure 2 shows the effects of rotation on the kinematics of vortical structure, which are averaged after detecting the streamwise vortices at $y/\delta=0.16$ (approximately $y^+=10$) by the second invariant of deformation tensor. First, the circular motion is clearly observed at $y^+=10$ in the center of the figure. In the case of Ro=025, vortex at the center is accompanied by the vortices of opposite streamwise vorticity in both sweep and ejection sides where inrush motion of fluids toward the wall, and outward motion from the wall are observed, respectively. In the case of Ro=1.5, however, enhanced are vortices in the ejection side, while those in the sweep side are attenuated. Probability distribution function counting the number of vortices with opposite vorticity also shows the above-mentioned tendency. In the conference, we will show that the enhancement of the vortices in the ejection side is attributed to the alignment of vortical structure and low-speed streaks in the streamwise direction. Moreover, the association between the Reynolds shear stress and opposite streamwise vorticity around the detected vortex will be discussed.

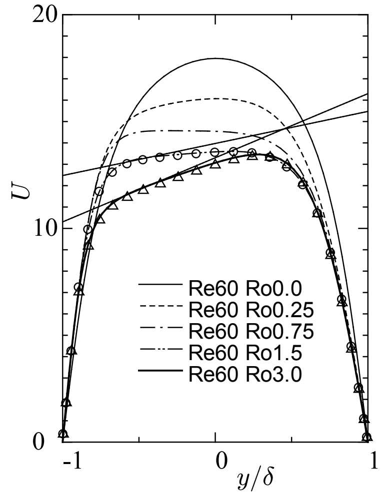

Figure 1. Mean velocity profiles. Mean velocity is normalized by the mean pressure gradient and channel half width. Symbols represent the numerical simulations of 512 x 129 x 288 grid points. Tangent lines are included to show the region of zero absolute vorticity.

(a)

(b)

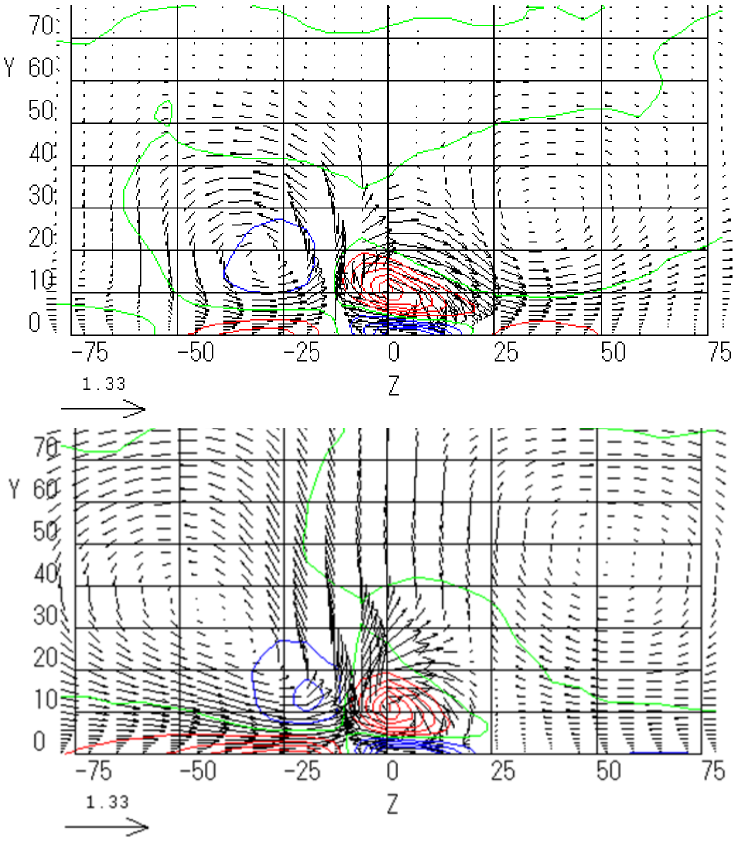

Figure 2. Averaged velocity vectors v and w and contours of streamwise vorticity in the cross streamwise plane; Red and blue contours represent positive and negative vorticity, while green represents zero vorticity. All quantities are non-dimensionalized by mean pressure gradient, channel half width and viscosity. Y and Z are nondimensinalized by the viscosity and friction velocity. (a) Ro=0.25, (b)Ro=1.5.

References

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