DIRECT NUMERICAL SIMULATION OF TURBULENT FLOWS IN A VERTICAL ROTATING OPEN-CHANNEL

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Direct numerical simulation (DNS) is carried out to study turbulence characteristics in a vertical rotating open-channel with the rotation number $N_r = 0 - 0.12$ and the Reynolds number $Re = 180$ based on the wall friction velocity of non-rotating case and the channel depth. Here, two typical rotation regimes are identified. As $0 < N_r < 0.06$, the turbulence statistics correlated with the spanwise velocity fluctuation are enhanced since the shear rate of spanwise mean flow induced by Coriolis force increases; however, the other statistics are suppressed. As $N_r > 0.06$, the turbulence statistics are suppressed significantly because the effect of Coriolis force plays as a dominant role.

Keywords: Direct numerical simulation (DNS); vertical rotating channel flow; coherent structure.

1. Introduction

Turbulent flows in rotating frame exist in nature and industrial applications. The rotation induces additional body forces, i.e., centrifugal and Coriolis forces, acting on the turbulent flow, so that the momentum mechanism becomes more complex. Understanding the mechanism of turbulent flow in rotating system is of great importance in applications and fundamentals.

In a vertical rotating open-channel flow, since the mean vorticity component is perpendicular to the rotating axis, turbulent flow is more sensitive to the vertical rotation, even though a slight system rotation can induce a significant spanwise mean velocity $1$. As a result, the absolute mean flow deviates from the initial streamwise direction and redirects the mean shear and the turbulence structures. The interaction between the vorticity of coherent structures and the background vorticity due to imposed vertical rotation can significantly change the near-wall turbulence characteristics.

It is well established that direct numerical simulation (DNS) is effective to explore the mechanism of turbulent flow. Although the DNS has been applied extensively to investigation of turbulent channel flows, however, little work for a vertical rotating open-channel flow has been undertaken. In this study, the effects of rotation on the vertical rotating turbulent open-channel flow are studied by means of DNS.
2. Mathematical Formulation and Numerical Methods

The incompressible Navier-Stokes equations are used for direct simulation of fully developed turbulent flow in a vertical rotating open-channel. To normalize the governing equations, the friction velocity \( u_r \) of non-rotating channel flow is used as the velocity scale, the channel depth \( h \) as the length scale. The non-dimensional parameters in this problem are the rotation and Reynolds numbers, which are defined as \( N_r = 2\Omega h / u_r \) and \( Re = u_r h / \nu \), respectively, with \( \Omega \) being the angular speed of rotating frame and \( \nu \) the kinematic viscosity.

The turbulent open-channel flow is driven by a constant streamwise pressure gradient equal to that of the non-rotating case. Periodic boundary conditions are employed in the streamwise (\( x \)) and spanwise (\( z \)) directions. At the bottom wall (i.e., \( y = 0 \)), no-slip velocity condition is imposed. At the free-surface without deformation (i.e., \( y = 1 \)), a shear-free condition is used. In this study, a fractional-step method proposed by Verzicco and Orlandi \(^2\) is employed. Spatial derivatives are discretized by a second order central difference. Time advancement is carried out by the semi-implicit scheme using the Crank-Nicholson scheme for the viscous terms and the three-stage Runge-Kutta scheme for the convective terms. The Reynolds number \( Re \) is chosen as 180 and the rotation number \( N_r \) as 0–0.12. The mesh number is 193×193×193 with the corresponding computational domain \( 4\pi h \times h \times 2\pi h \) in the streamwise, vertical and spanwise directions, respectively. The relevant code and method used here have been verified extensively in our previous work \(^3\)–\(^7\).

3. Results and Discussion

The mean velocity in the streamwise and spanwise directions is shown in Fig. 1. As the vertical rotation is imposed, the streamwise mean velocity \( \langle u \rangle \) decreases monotonically with the increase of \( N_r \), indicating the reduction of the wall shear rate related to \( \langle u \rangle \). The spanwise mean velocity \( \langle w \rangle \) increases as \( N_r \) varies from 0 to 0.06; however, as \( N_r \) increases further, e.g., at \( N_r = 0.08–0.12 \), the spanwise mean flow is suppressed due to the effect of Coriolis force.

![Fig. 1. Profiles of the mean (a) streamwise and (b) spanwise velocity.](image-url)
The turbulence intensities are shown in Fig. 2(a)-(c). In pure shear channel flow, only the streamwise mean velocity exists. However, in the vertical rotating channel flow, since the Coriolis force induces the spanwise mean velocity shown in Fig. 1(b), there exist both the streamwise and spanwise mean shear effects. Thus, the production of the streamwise
velocity fluctuation comes from both processes. One is the shear process related to \( \langle u \rangle \), which is the major source to generate the streamwise velocity fluctuation in weakly rotating case, and the other the splattering effect associated with \( \langle w \rangle \). So does the spanwise velocity fluctuation, and the shear process of the spanwise mean flow will take the dominating responsibility to generate the spanwise velocity fluctuation in strong rotation case due to the presence of large spanwise mean velocity.

As \( \tau N \) increases, the near-wall shear rate related to \( \langle u \rangle \) reduces significantly. Thus, a decrease of \( u'_{w} \) is observed. As \( \tau N \) varies from 0 to 0.06, the spanwise velocity fluctuation \( w'_{w} \) is enhanced remarkably due to increasing the spanwise mean shear rate. The high near-wall peak value of \( w'_{w} \) at \( \tau N = 0.06 \), compared with other rotating cases, is attributed to strong shear rate of the spanwise mean flow. As \( \tau N = 0.08–0.12 \), the mechanism for turbulence fluctuation generation is suppressed by the effect of Coriolis force, which causes the reduction of turbulence intensities.

The shear stresses are shown in Fig. 2(d)-(f). Both \( u'v' \) and \( u'w' \) are observed to be negative near the wall region, while \( v'w' \) to be positive, which is associated to the ejection and sweep events near the wall. \( u'v' \) is mainly related to the change of \( \langle u \rangle \) and subsequently decreases with the increase of \( \tau N \). At \( \tau N = 0.02 \), a slight alteration of the shear stress occurs. However, at \( \tau N = 0.12 \), \( u'v' \) becomes nearly zero over the channel, indicating a poor correlation between the streamwise and vertical velocity fluctuations. The \( v'w' \), which is related to the change of \( \langle w \rangle \), is enhanced as \( \tau N \) varies from 0 to 0.06 and suppressed as \( \tau N \) from 0.06 to 0.12. Similar behavior of \( u'w' \) is also observed. The near-wall alterations of \( v'w' \) and \( u'w' \) are attributed to the shear rate of the spanwise mean flow, because \( \partial \langle w \rangle / \partial y \) contributes directly to the production rate of both the shear stresses based on the analysis of the transport equation of Reynolds stresses.

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References