RELATIONSHIP BETWEEN STATISTICS AND TURBULENT STRUCTURES IN ROTATING PLANE POISEUILLE FLOW

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Abstract Direct numerical simulations are performed for plane Poiseuille flows with spanwise system rotation in the low Reynolds-number and rotation-number ranges. We discuss the very low rotation effects with emphasis on two transitional processes: the transition between laminar and turbulence; and that between the static state and the state in rotating system. The variations of the friction velocity and the friction coefficient are discussed in relation to dominant turbulent structures at each condition.

INTRODUCTION

In a shear flow under system rotation, the Coriolis force influences its flow stability and turbulent transition. Three important effects of a spanwise rotation on a turbulent channel flow are the stabilization (in the suction side) and destabilization (in the pressure side) of turbulence, and the generation of longitudinal roll cells (RC) [1]. In the suction side of the channel, the stable 'stratification' would attenuate turbulent motions. In the pressure side, the RC, which consists of large-scale streamwise vortices aligning in the spanwise direction regularity, may occur as an initial stage of laminar-turbulent transition and survive even with turbulent background at a high Reynolds number due to the Coriolis instability. Hence, in the rotating channel, both the stable and the unstable conditions coexist in the flow. An interesting phenomena relating to the transition regime is the turbulent stripe (TS), which is turbulent and quasi-laminar banded pattern and inclining with respect to the streamwise direction. According to the previous studies, TS would occur in the plane Poiseuille flow and Couette flow at transitional Reynolds numbers. Under the flow-stabilizing effect by body forces, TS can appear in a much wider parameter range [2]. In the rotating plane Poiseuille flow, an occurrence of TS has not been reported in any Reynolds- and rotation-numbers, because RC became dominant throughout the channel [3]. However, we have found TS occurring in the very low rotation numbers of $\mathrm{Ro}_\tau = 0.0$–0.2 (defined later) [4].

The present paper reports on a parametric DNS study on the transitional plane channel flow subjected to spanwise system rotation with a focus on the low-to-moderate rotation-number range. We investigate the variations of the bulk mean statistics (such as the friction coefficient and the flow rate), considering their relations to organized structures.

NUMERICAL CONDITIONS

In the literature, most researchers investigated rather high rotation-number ranges and focused mainly on the unstable condition. In this work, we performed a series of DNS for a low Reynolds number of $\mathrm{Re}_\tau = u_\tau\delta/\nu = 80$ (u_τ, the friction velocity; δ, half the channel width) and low rotation numbers for $\mathrm{Ro}_\tau = 2\Omega\delta/u_\tau = 0.01$–$1.5$ (Ω, system angular velocity). We employed a large domain of $102.4\delta \times 2\delta \times 51.2\delta$ with a grid of $2048 \times 192 \times 1024$ in the streamwise, wall-normal, and spanwise directions.

RESULTS

We identified various altered transition states from static- to rotating-system, and we observed a flow state, in which both TS and RC stably coexisted [4]. We found that TS occurred only in low Ro_τ and RC became dominant at high Ro_τ.

Figure 1 shows the dependency of the bulk Reynolds number, $\mathrm{Re}_\mathrm{m} = 2u_\mathrm{m}\delta/\nu$ (u_m, the bulk mean velocity), on the rotation number. The present data at $\mathrm{Re}_\tau = 80$ practically corresponds to an intermediate result between those at $\mathrm{Re}_\tau = 60$ and 100, showing a qualitative agreement with DNS by another group [3]. It is found that, at $\mathrm{Ro}_\tau = 0.2$, Re_m attains its maximum value at $\mathrm{Re}_\tau = 80$. In the results of Iida et al. [3], Re_m at $\mathrm{Ro}_\tau = 0.25$ and 0.75 seem to give the maximum values for $\mathrm{Re}_\tau = 60$ and 100, respectively, but the true maximum values are unfortunately still unknown. Although further DNS on other Re_τ are required, $\mathrm{Ro}_\tau = 0.2$ must be the critical point, at which Re_m becomes maximum and decreases from this point. Interestingly, this rotation number is equivalent to the upper bound of the range, where TS occurs in the present rotating channel flow. The variation of Re_m and its relation to TS in the low rotation-number range have been unclear in the literature, because of the limited DNS test ranges. The present result has successfully revealed those whole stories from static to rotating system.

The normalized friction velocities of $u_{\tau\mathrm{p}}/u_\tau$ and $u_{\tau\mathrm{s}}/u_\tau$ ($u_{\tau\mathrm{p}}$, the friction velocity at the pressure side; $u_{\tau\mathrm{s}}$, the friction velocity at the suction side) with respect to each wall of the channel are given in Fig. 2. The value of $u_{\tau\mathrm{p}}$ increases for Ro_m ($= 2\Omega\delta/u_\mathrm{m}$) ≤ 0.036 ($\mathrm{Ro}_\tau \leq 0.5$), and there is no significant change for higher Ro_m. Similarly, $u_{\tau\mathrm{s}}$ keeps changing (but decreasing) until $\mathrm{Ro}_\mathrm{m} = 0.036$. Our results for $\mathrm{Ro}_\mathrm{m} = 0.01$–$0.05$ are in good agreement with the experimental results at $\mathrm{Re}_\tau = 79$ [5]. As for different Reynolds numbers, the maximum Ro_m point shifts to higher values (of $\mathrm{Ro}_\mathrm{m} > 0.036$), although the Ro_m dependency of the friction velocities exhibits the same trend irrespectively of the Reynolds number.

Figure 3 displays the relation between the skin friction coefficient $C_f = 2\tau_w/\rho u_\mathrm{m}^2$ (τ_w is the wall shear stress at either suction- or pressure-side wall) and (i) Ro_τ or (ii) Re_m. Open and filled symbols represent the pressure-side and suction-side values, respectively. Note that, as shown in Fig. 1, Re_m undergoes a change because of the calculation that was performed under the constant Re_τ condition. Also shown in Fig. 3(ii) is the experimental result [5], and the different symbols indicate different system angular velocities (Ω). In our results, C_f increases in the pressure side with increasing of Ro_τ, while C_f decreases in the suction side with increasing of Ro_τ, but C_f alters to increase for $Ro_\tau \geq 0.2$. This rotation number ($Ro_\tau = 0.2$) of the alteration gives the maximum Re_m, as mentioned above. Moreover, the data point is settled in the relaminarization region for $Ro_\tau \geq 0.2$, where Re_m decreases and C_f increases even in the suction side.

These alterations of parameter dependencies are related to different kinds of turbulent structures that dominate in each flow field. The state of structure is dominated by RC in the pressure side for $Ro_\tau \geq 0.2$, and turbulent motion is attenuated in the suction side. According to visualized flow fields (figure not shown here), low- and high-speed streaks decrease and almost disappear with further increase of Ro_τ in the suction side. In conclusion, the turbulent channel flow subjected to the spanwise rotation provides various qualitative alternations in the rotation-number dependency around $Ro_\tau = 0.2$.

In the final paper, we will perform other Re_τ and discuss the dependency alterations in a wide range of Re_τ. Their alterations will be examined further in relation to the turbulent structures and statistics, in order to discover the whole story from static to rotating system in each region of the pressure and suction side.

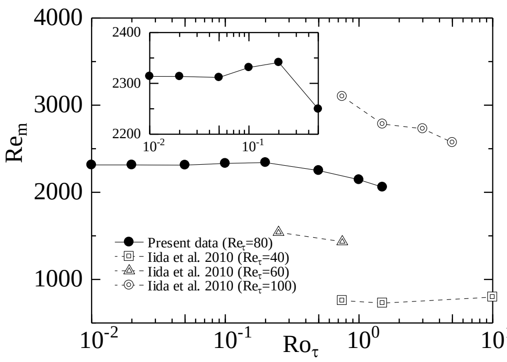

Figure 1. Bulk Reynolds number versus Ro_τ.

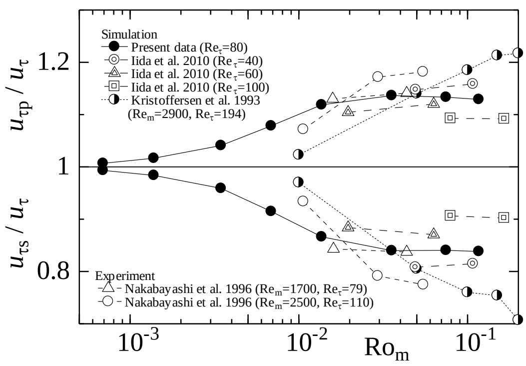

Figure 2. Friction velocity of each wall, $u_{\tau p}/\ u_\tau$ and $u_{\tau s}/\ u_\tau$ as a function of Ro_m.

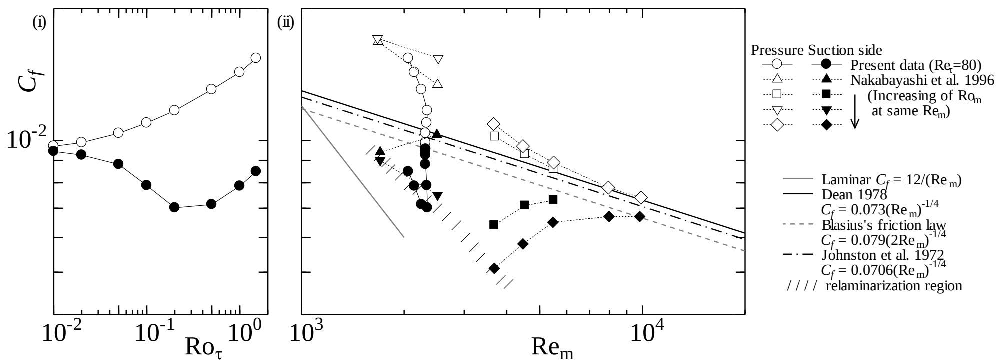

Figure 3. Skin friction coefficient as a function of (i) Ro_τ and (ii) Re_m.

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