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Viscoelasticity-induced pulsatile motion of 2D roll cell in laminar wall-bounded shear flow

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ABSTRACT

For the clarification of the routes to elasto-inertial turbulence (EIT), it is essential to understand how viscoelasticity modulates coherent flow structures including the longitudinal vortices. We focused on a rotating plane Couette flow that provides two-dimensional (2D) roll cells for the steady laminar Newtonian-fluid case, and we investigated how the steady longitudinal vortices are modulated by viscoelasticity at different Weissenberg numbers. The viscoelasticity was found to induce an unsteady flow state where the 2D roll-cell structure was periodically enhanced and damped with a constant period, keeping the homogeneity in the streamwise direction. This pulsatile motion of the roll cell was caused by a time lag in the response of the viscoelastic force to the vortex development. Both the pulsation period and time lag were found to be scaled by the turnover time of cell rotation rather than by the relaxation time, despite the viscoelasticity-induced instability. We also discuss the counter torque on the roll cell and the net energy balance, considering their relevance to polymer drag reduction and EIT.

1. Introduction

Viscoelasticity not only causes turbulent drag reduction (DR), but also enhances disordered motions at higher additive concentration. In drag-reducing wall turbulence, the elastic force due to the additive tends to suppress the secondary motions of the near-wall coherent structures and, therefore, the near-wall structures are modulated to be apparently streamwise-independent streaks (Sureshkumar et al., 1997; Stone et al., 2002; 2004; Kim et al., 2007). The other aspect of the viscoelastic effect that yields an instability at high additive concentrations has also been subject of many studies since Giesekus's discovery of elasticity-induced instabilities (Giesekus, 1972). Larson et al. (1990) predicted that viscoelasticity gives rise to an oscillating mode by analyzing the linear stability of an inertia-less flow of Oldroyd-B fluid. Moreover, in flows at the state of maximum drag reduction (MDR), the viscoelasticity promotes a transition to chaotic flow state even at very low Reynolds numbers, which is known as elasto-inertial turbulence (EIT) (Hoyt, 1977; Groisman and Steinberg, 1998; Dubief et al., 2013; Samanta et al., 2013; Pan et al., 2013; Terrapon et al., 2015).

Recently, the possible connection between EIT and MDR has been pointed out. Once DR occurs, weakened streamwise vortices disappear temporarily for a certain period, during which the velocity profile approaches the MDR asymptote (Virk, 1975). Such temporal behavior, called hibernation, is known to occur even in the Newtonian wall turbulence; however, its frequency increases in the viscoelastic drag-reducing turbulence (Xi and Graham, 2010). The hibernating turbulence and the aforementioned viscoelastic effect to modulate the near-wall structures are commonly observed in both MDR and EIT flows (Xi and Graham, 2010; Samanta et al., 2013; Dubief et al., 2013; Terrapon et al., 2015). Recent studies have suggested the MDR phenomenon as a part of the EIT at the significant large Weissenberg number. Sid et al. (2018) demonstrated through numerical simulation that at high enough additive concentration a two-dimensional and chaotic flow can be sustained after sufficient perturbations have been introduced. This flow state was characterized by an energy injection from the additive to flow at medium and small scales. According to another work by Choueiri et al. (2018), such two-dimensional structures would appear when the additive concentration exceeds the MDR asymptote, whereas in the regime before the MDR asymptote the streamwise vortices are still observed with hibernating behaviors. These observations imply that the influence of viscoelasticity would be dominant in the EIT and change its role from that for the MDR. Because of the complexity of background turbulence, the route to EIT is still not well understood, in particular, regarding the transition process from the longitudinal vortices in DR to other forms that can be observed only in MDR or EIT. In this context, we can consider the elasticity-induced modulation of the coherent structures as a key phenomenon to understand the transition mechanism from DR to MDR and EIT.

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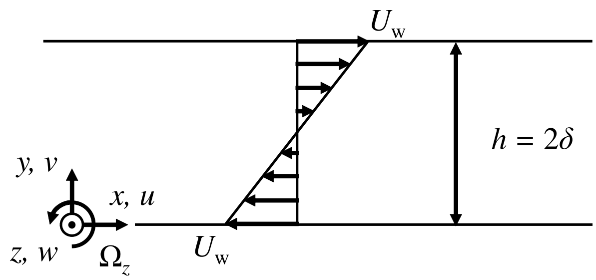

Fig. 1. Configuration of the rotating plane Couette flow.

Now, let us introduce the plane Couette flow subjected to spanwise system rotation (rotating plane Couette flow, RPCF), the definition of which is schematically shown in Fig. 1. This flow is known to bring distinct coherent streamwise roll cells and can therefore be a good test bench to study the effect of viscoelasticity on longitudinal vortices in a wall-bounded shear flow. Given an anti-cyclonic system rotation, where the system rotates in the opposite direction to the wall shear, the flow is linearly unstable owing to the Coriolis-force effect, which gives rise to the streamwise-elongated roll-cell structure. Depending on the Reynolds number $\mathrm{Re_w}$ and the rotation number Ω (the definitions are given in the next section), the coherent roll cells can take various forms, such as two-dimensional (2D) steady roll cells and three-dimensional (3D) wavy roll cells (Tsukahara et al., 2010; Kawata and Alfredsson, 2016a; 2016b). Comparing the flow structures in the RPCFs of Newtonian and viscoelastic fluids, one may gain physical insights into how the viscoelasticity modulates the longitudinal vortices in shear flow and why it leads to DR or EIT.

In this work, we performed direct numerical simulations (DNSs) to study the laminar RPCF of viscoelastic fluid at a Reynolds number of $\mathrm{Re_w} = 25$ and a rotation number of $\Omega = 10$ (the definitions of these parameters are given in the next section) over a wide range of Weissenberg numbers. This set of control-parameter values is chosen as a typical flow case that gives a steady and streamwise-independent roll cells in the Newtonian case, to better understand how the increase in viscoelasticity affects the instabilities of a streamwise vortical structure. We show that the increase in the viscoelasticity effect gives rise to an unsteady flow state where the 2D roll cells are periodically strengthened and suppressed, the time scale of which is on the same order as the hibernation period in the drag-reduced turbulence that was found by Xi and Graham (2010). We also discuss the energy exchange between the flow and the additive, and show that, in the pulsatile flow state, there is a certain time lag between the change in the flow structure and the energy exchange. Through these analyses, we demonstrate a negative torque on the roll cell in relation to the DR as well as the onset of unsteadiness that could be linked with EIT.

2. Numerical method

2.1. Flow configuration and governing equations

The coordinate system is defined as shown in Fig. 1: the x-, y-, and z-axes are taken in the streamwise, wall-normal, and spanwise directions, respectively. The top and bottom walls are located at $y = h$ and $y = 0$, respectively, and they move in opposite directions with a speed of U_w. The Reynolds number $\mathrm{Re_w}$ and the rotation number Ω are defined, on the basis of the wall speed U_w and the half channel height δ (=$h/2$), as $\mathrm{Re_w} = U_\mathrm{w}\delta/\nu$ and $\Omega = 2\Omega_z\delta^2/\nu$, respectively, where ν is the kinematic viscosity at zero shear rate.

The governing equations solved numerically in the present DNS are the nondimensional continuity and the non-Newtonian momentum equations written in a frame of reference rotating with the system:

$$\frac{\partial u_i^*}{\partial x_i^*} = 0, \tag{1}$$

and

$$\frac{\partial u_i^*}{\partial t^*} + u_j^*\frac{\partial u_i^*}{\partial x_j^*} = -\frac{\partial p^*}{\partial x_i^*} + \frac{\beta}{\mathrm{Re_w}}\frac{\partial^2 u_i^*}{\partial x_j^{*2}} - \frac{\Omega}{\mathrm{Re_w}}\epsilon_{i3k}u_k^* + \frac{1-\beta}{\mathrm{Wi_w}}\frac{\partial c_{ij}}{\partial x_j^*}. \tag{2}$$

Here, p is the pressure hydrostatic including both the static pressure and the centrifugal acceleration, ϵ_{ijk} is the Levi–Civita symbol, and the variables with the superscript * stand for the nondimensional quantities normalized by δ and/or U_w. The viscosity ratio and the Weissenberg number are defined as and $\mathrm{Wi_w} = U_\mathrm{w}^2\lambda/\nu$, where μ_s and μ_a are the viscosity of the solution and the additive, respectively, and λ is the relaxation time of the additive. The former β is a measure of the concentration of the additive, and the effect of the viscoelasticity becomes more significant with decreasing β. The Weissenberg number $\mathrm{Wi_w}$ physically represents the ratio of the relaxation time of the additive to the viscous time scale. The nondimensional conformation tensor c_{ij} of the last term in Eq. (2) is defined on the basis of the extra stress tensor by viscoelasticity τ_{ij} as $c_{ij} = \tau_{ij}\lambda/\mu_\mathrm{a} + \delta_{ij}$ (where δ_{ij} is the Kronecker delta) and is governed by a constitutive equation. We adopted the Giesekus model (Giesekus, 1982):

$$\frac{\partial c_{ij}}{\partial t^*} + \frac{\partial u_m^* c_{ij}}{\partial x_m^*} - \frac{\partial u_i^*}{\partial x_m^*}c_{mj} - \frac{\partial u_j^*}{\partial x_m^*}c_{mi} + \frac{\mathrm{Re_w}}{\mathrm{Wi_w}}[c_{ij} - \delta_{ij} + \alpha(c_{im} - \delta_{im})(c_{mj} - \delta_{mj})] = 0, \tag{3}$$

where α is the mobility factor, the value of which is between 0 and 1. The mobility factor α represents the strength of the nonlinearity effect in the Giesekus model and is known to be proportional to the inverse of the maximum polymer extension in the finitely extensible nonlinear elastic-Peterlin (FENE-P) model. Hence, the elastic scales are smaller with increasing α.

In the present study, the viscosity ratio and the mobility factor were fixed at $\beta = 0.8$ and $\alpha = 0.001$, respectively, as the DNS on a plane or an orifice channel flow performed with these values of α and β (Tsukahara et al., 2011; 2013) showed a qualitative agreement in terms of the DR effect with the experiment result using a drag-reducing surfactant.

2.2. Numerical procedures

We used the finite difference method for the spatial discretization. The fourth-order central difference scheme was used for the x- and z-directions, whereas the second-order central difference scheme was adopted in the wall-normal (y-) direction. For the time integration, the second-order Crank–Nicolson and the second-order Adams–Bashforth schemes were used for the wall-normal viscous term and the other terms, respectively. As for the constitutive equations with the Giesekus model, a flux limiter of the MINMOD scheme was adopted to approximate the spatial derivatives in the advective term without adding artificial diffusivity, as Yu and Kawaguchi (2004) proposed. As for the boundary condition, the periodic boundary conditions were imposed in the x- and z- directions and the no-slip condition was applied on the walls.

In the present study, we employed a computational domain size of $L_x \times L_y \times L_z = 7.5h \times 2\delta \times 2h$, to massively limit the degree of freedom artificially and thereby extract the essential influence of increasing $\mathrm{Wi_w}$ on the flow structure. The streamwise domain length $L_x = 7.5h$ corresponded to the streamwise wavelength of the 3D wavy roll cells experimentally observed in the Newtonian RPCF (Tsukahara et al., 2010), and the spanwise domain length $L_z = 2h$ was even smaller than the spanwise scale of the experimentally observed structure. In a computation with a smaller domain size, the 2D roll cells in the Newtonian case did not develop. In the computation with a larger domain size, on the other hand, the observed tendency of the Wi effect remained