RELAMINARIZATION MECHANISM IN TURBULENT CHANNEL FLOW BY STREAMWISE TRAVELING WAVE-LIKE BLOWING AND SUCTION

Hiroya Mamori, Kaoru Iwamoto*, and Akira Murata
Department of Mechanical Systems Engineering
Tokyo University of Agriculture and Technology
2-24-16 Koganei City Naka Town Tokyo
*Corresponding Author: iwamotok@cc.tuat.ac.jp

ABSTRACT

Direct numerical simulation of fully developed channel flow under controlled by traveling wave-like blowing and suction is presented. Similar to a result in traveling wave-like wall deformation, a transition from a turbulent flow into a laminar flow due to downstream traveling wave is found. According to the visualization of the flow field, the negative Reynolds shear stress appears (it is ordinary positive) and develops with time advance, then a turbulent fluctuation disappears.

INTRODUCTION

Since 1990s, a feedback control is found to be effective to decrease the skin-friction drag in wall turbulence, while a major drawback of the feedback control is to require sensor to detect the flow field. In contrast, Min *et al.*(2006) performed the wall-normal blowing and suction from the wall in the form of the streamwise traveling wave in the fully developed turbulent channel flow. The traveling wave control does not require any sensors and decreases the skin-friction drag below that of the corresponding laminar flow (so-called the sub-laminar drag), when the wave travels in the opposed direction to the base flow (i.e., upstream traveling wave). The sub-laminar drag is sustained by the negative RSS in the region near the wall (it is ordinary positive) and the mechanism of the generation of the RSS has been explained by a detailed phase analysis (Mamori *et al.*, 2010).

Recent investigation by Nakanishi *et al.*(2012), the traveling wave-like wall deformation (instead by the blowing and suction) induces the relaminarization of the turbulent channel flow when the wave travels in the downstream direction on some parameter sets. The relaminarization is significant advantage itself, since not only the drag reduction but also the large control efficiency can be obtained. According to these findings, the traveling wave-like blowing and suction in the form of the traveling wave is expected to also induce the relaminarization, because the displacement of the wall deformation is as small as the wall-deformation control.

The objective of the present study is to exemplify the relaminarization of the fully developed turbulent channel flow by the traveling wave-like blowing and suction. The wider range of the parameter of the wave are examined in numerous case by means of direct numerical simulation. The visualization of the flow field clarifies the process of the relaminarization due to the traveling wave.

DIRECT NUMERICAL SIMULATION

Direct numerical simulation is done in the fully developed two-dimensional channel flow, where a mean pressure gradient is kept constant. Figure 1 shows the channel flow and the traveling wave-like blowing and suction. The governing equations are continuity and Navier-Stokes equations of an incompressible flow. The Reynolds number, based on the skin-friction velocity and channel half width, is examined at $\mathrm{Re}_\tau = 110$. All simulation starts from the fully developed turbulent channel flow. The periodic condition is imposed for homogeneous directions. On the wall, the streamwise and spanwise velocities are zero, while the wall-normal velocity, v_w, is the traveling wave, defined as

$$v_w^+ = a^+ \cos\left(\frac{2\pi}{\lambda^+}\left(x^+ - c^+t^+\right)\right), \tag{1}$$

where a, λ, and c are an amplitude, a wavelength, and a wavespeed of the wave, respectively. The present study is examined only the varicose mode i.e., the surface wall-normal velocities are in phase with opposed sign. In the present study, x, y, and z are coordinates for the streamwise, wall-normal, and spanwise directions, respectively. The velocities are u, v, and w and the time is denoted as t.

The skin-friction drag reduction rate, R_D, and the net saving rate, R_W, are the control performances, defined as

$$R_D = \frac{W_{p,\ \mathrm{Dean}}(\mathrm{Re}_b) - W_p(\mathrm{Re}_b)}{W_{p,\ \mathrm{Dean}}(\mathrm{Re}_b)}, \tag{2}$$

$$R_W = \frac{W_{p,\ \mathrm{Dean}}(\mathrm{Re}_b) - \left(W_p(\mathrm{Re}_b) + W_a\right)}{W_{p,\ \mathrm{Dean}}(\mathrm{Re}_b)}, \tag{3}$$

where W_p and W_a are the pumping power to drive the base flow and the actuation power of the traveling wave, respectively. And, $W_{p,\ \mathrm{Dean}}$ is the pumping power calculated by using an empirical formula of skin-friction drag coefficient (Dean, 1987).

DRAG REDUCTION RATE

Figure 2 shows the time traces of R_D and R_W for different wavespeed at $a^+ = 3$, $\lambda^+ \approx 432$, and $\mathrm{Re}_\tau = 110$, where

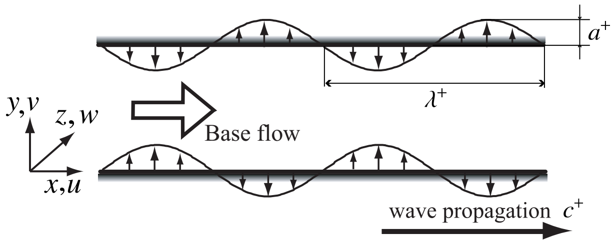

Figure 1. Channel flow with blowing and suction from the wall in the form of the traveling wave.

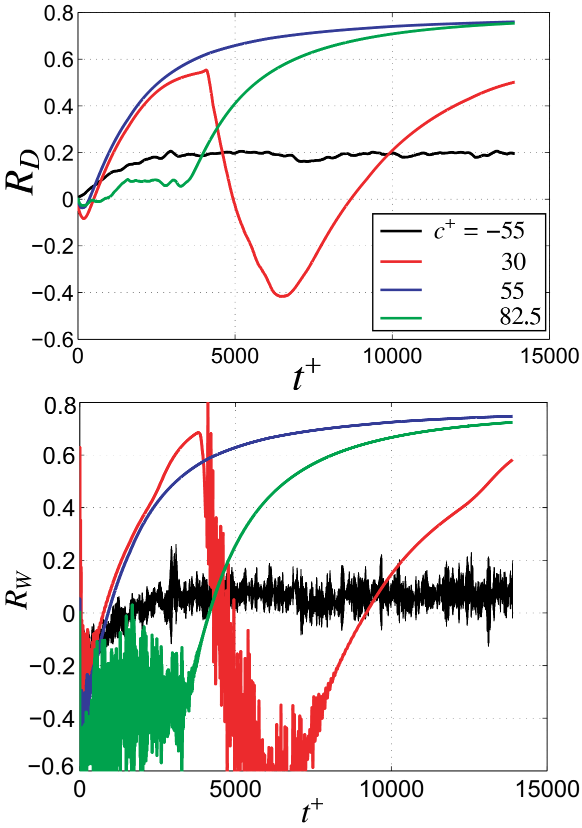

Figure 2. Time history of the drag reduction rate (top) and the net saving rate (bottom) for different wavespeeds of the traveling wave at $a^+ = 3$ and $\lambda \approx 432$ ($\mathrm{Re}_\tau = 110$).

the superscript of plus denotes a nondimensional variable in wall unit. For the upstream traveling wave at $c^+ = -55$, the drag decrease and the positive efficiency are obtained ($R_D \approx 0.2$ and $R_W \approx 0.1$). This wave can sustain the sub-laminar drag when the amplitude is large, while few efficiency is obtained due to remain the turbulence. The downstream traveling wave at $c^+ = 30$ induces the cyclic behavior: R_D and R_W increase, rapidly decrease and increase again. This behavior is identical to that observed in the case the traveling wave-like wall deformation. In contrast, the drag reduction rate and the net saving rate are large at $c^+ = 55$ ($R_D > 0.7$ and $R_W > 0.7$) due to the relaminarization. At $c^+ = 82.5$, the relaminarization is also found while the turbulence remains at $t^+ < 3000$.

Figure 3 summarizes the control effect for different amplitudes of the waves at $\mathrm{Re}_\tau = 110$. The relaminarization occurs for the downstream wave at $\lambda^+ > 100$. As a slower wavespeed or a shorter wavelength than that on relaminarization, the cyclic behavior is found. For the wavespeed is nearly equal to zero but positive, the skin-friction dramatically increases due to the critical layer effect. The upstream traveling wave at $\lambda^+ > 400$ and $a^+ = 3$ or $\lambda^+ > 200$ and $a^+ = 5$, the skin-friction drag decreases ($R_D > 0.2$) without relaminarization. For the shorter wavelength $\left(\lambda^+ < 200\right)$, the drag decreases slightly or increases.

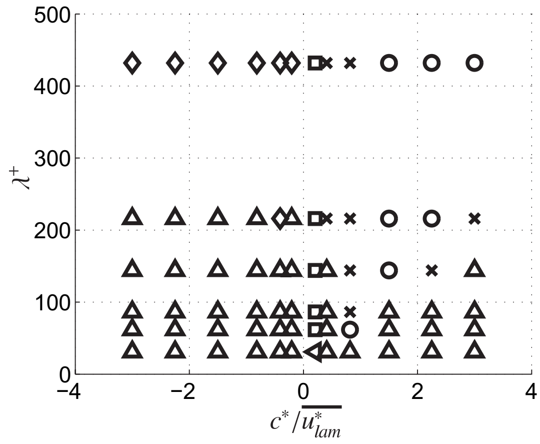

Figure 3. Skin-friction drag change due to the traveling wave-like blowing/suction: $\circ$, relaminarization; $\times$, cyclic motion; $\square$, critical layer effect; $\diamond$, ordinary drag decrease with the upstream wave ($R_D > 0.1$); $\triangleleft$, drag decrease with downstream wave ($R_D > 0.1$); $\triangle$, drag increase or slight drag decrease ($R_D < 0.1$). $\bar{u}_{lam}$ is the bulk mean flow rate corresponding laminar flow.

In order to clarify the relaminarization effect, the three-component decomposition is defined for the arbitrary function, f, as

$$f = \bar{f} + \tilde{f} + f''. \quad (4)$$

On the RHS of the equation, the bar denotes the averaged value for spatially and temporally and the tilde denotes the phase average of the traveling wave. The double prime denotes the random component which represents the ordinary turbulent component.

Figure 4 shows the change of the periodic and random RSSs under the control of the downstream traveling wave with time advance, of which parameter induces the relaminarization. At the beginning of the control, the periodic-RSS does not appear while the random-RSS dominates the flow field. At $t^+ \approx 200$, the periodic-RSS is produced due to the traveling wave and alternates in the streamwise direction in the region near the wall. The positive and negative periodic-RSS alternates in the streamwise direction, we refereed it as the cellular structure. The random-RSS is found while the channel. But the negative (positive) random-RSS appears above the suction part of the traveling wave in the lower (upper) half region of the channel. At $t^+ = 300$, the cellular structure of the periodic-RSS is found clearly, whereas the random-RSS is found to be decrease.

After the long time advance, the periodic-RSS is produced without fluctuation in the region center of the channel. The non-quadrature is observed in the region near the wall. According the phase analysis for the laminar flow controlled by the traveling wave, the non-quadrature is due to the viscous effect and determined by the direction of the traveling wave: the distribution of the periodic-RSS contributes to produce the drag. On the other hand, the random-

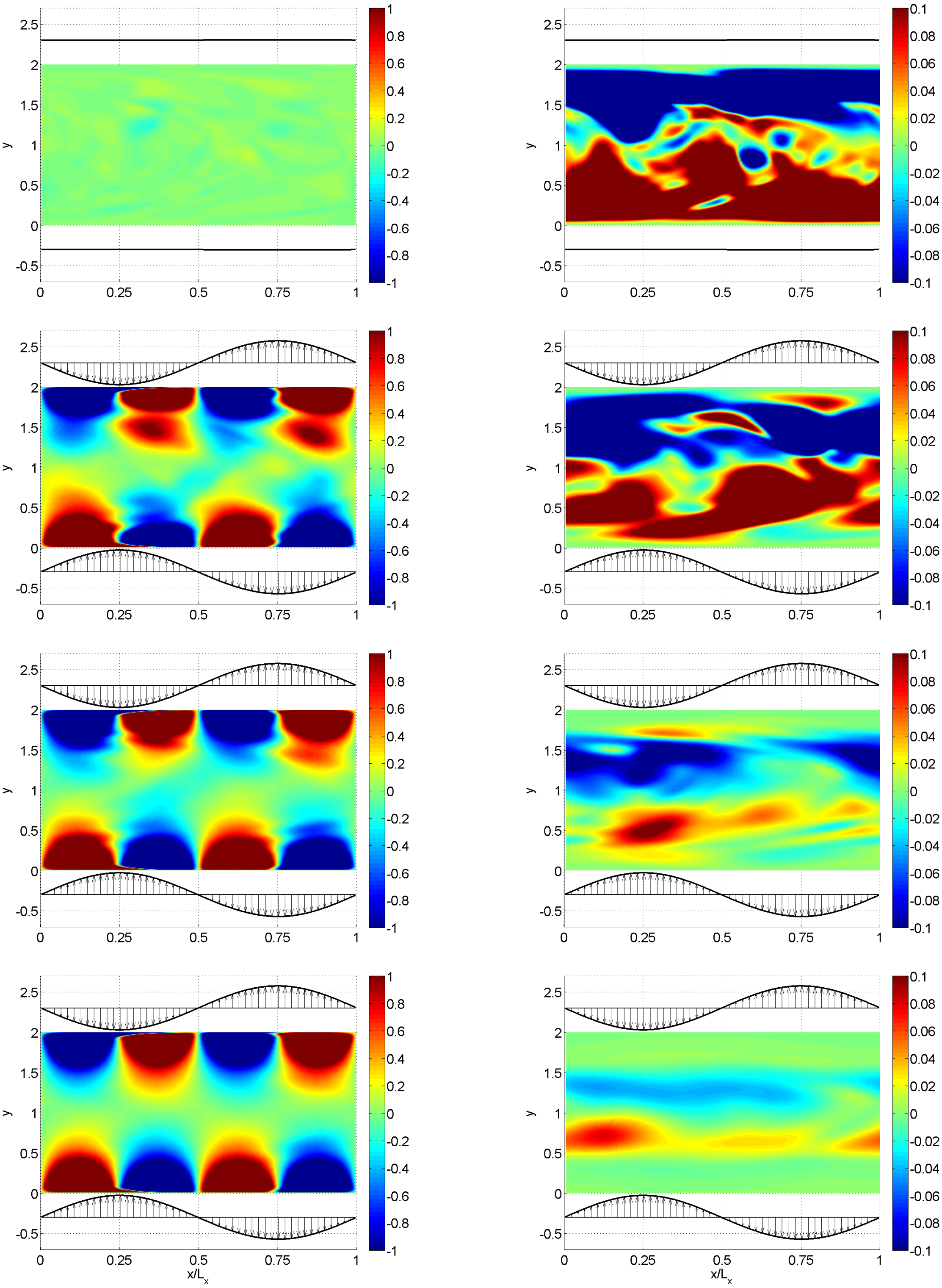

Figure 4. Visualization of the Reynolds shear stress distribution: left, the periodic-component; right, the random component ($a^+ = 3$, $\lambda^+ = 432$, and $c^+ = 55$). Top row, $t^+ = 0$. Second row, $t^+ \approx 200$. Third row, $t^+ \approx 300$. Bottom row, steady state.

RSS is found to decreases. According to the observation of modulation of the random-RSS, the negative random-RSS appears and develops with time advance, then the random-RSSs will disappear i.e., relaminarization.

CONCLUSION

The numerical simulation of the fully developed turbulent channel flow under the traveling wave-like blowing and suction is presented. On some set of control parameters, we confirm the relaminarization of the turbulent flow due to the wave. The controlled flow can be categorized into that pointed by the previous work for the traveling wave-like wall-deformation: the stable relaminarization, the unstable relaminarization, significant increase of the drag due to the critical layer effect and the slight drag decrease or drag increase. The observation of the change of the RSSs, the periodic-RSS is produced after the beginning of the control, immediately. The negative and positive random-RSS appears above the suction part of the traveling wave in the lower and upper half of the channel, respectively, and develops with time advance. Then, the relaminarization occurs.

REFERENCE

Min, T., Kang, S. M., Speyer, J. L., 2006, “Sustained sub-laminar drag in a fully developed channel flow”, Journal of Fluid Mechanics, Vol. 558, pp. 309-381.

Mamori, H., Fukagata, K., and Hoepffner, J., 2010, “The phase relationship in laminar channel flow controlled by traveling wave-like blowing or suction”, Physical Review E, Vol. 81, 046304.

Nakanishi, R., Mamori, H., and Fukagata, K., 2012,“Relaminarization of turbulent channel flow using traveling wave-like wall deformation,” International Journal of Heat and Fluid Flow, Vol. 35, pp. 152-159.

Dean, R.B., 1987, ”Reynolds number dependence of skin friction and other bulk flow variables in two-dimensional rextangular duct flow”, Journal of Fluids Engineering, Vol., 100, pp. 215-232.