SPACE-TIME CHARACTERISTICS OF COMPLIANT WALL IN TURBULNET CHANNEL FLOW

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Summary The interaction of compliant wall with turbulent channel flow is investigated using direct numerical simulation. The frequency/wave-number spectra and convection velocities of wall-pressure fluctuations and wall deformation are calculated from the database obtained by direct numerical simulation. When the compliant wall is sufficiently soft, the wall acts as large-amplitude two-dimensional traveling wave and its interaction with the flow is strong. The convection velocity of the pressure fluctuations on a soft compliant wall is lower than that on the rigid wall.

INTRODUCTION

The compliant wall has been suggested as a means to delay laminar to turbulent transition, to reduce the skin friction in turbulent boundary layer, or to suppress the flow induced noise [1], [2]. Although many studies on the compliant wall have been performed, the possibility of drag reduction in turbulent boundary layer by the compliant wall has been under debate and the interaction of compliant wall with turbulent boundary layer flow has not been clearly understood. Therefore, in the present study, we investigate the interaction between the compliant wall and near wall turbulence in a boundary layer using direct numerical simulation. From the database generated, we compute the three dimensional spectra of the wall pressure fluctuations and wall displacement, and their convection velocities.

NUMERICAL METHODS

We perform the direct numerical simulation of turbulent channel flow at Re_τ = 140, with the compliant surface at lower wall and the rigid surface at upper wall. We solve the Navier-Stokes equations for fluid motion, and the compliant wall is modeled as a plate supported by the spring and damper and is constrained to move only in the wall-normal direction [3]. The equation governing the wall motion is given as

$$\left[C_M \frac{\partial^2}{\partial t^2} + C_d \frac{\partial}{\partial t} + C_B \left(\frac{\partial^4}{\partial x^4} + 2\frac{\partial^4}{\partial x^2 \partial z^2} + \frac{\partial^4}{\partial z^4} \right) - C_{T_x} \frac{\partial^2}{\partial x^2} - C_{T_z} \frac{\partial^2}{\partial z^2} + C_K \right] \eta = -p_w, \tag{1}$$

where η is the wall displacement, C_M is the plate mass per unit area, C_d is the wall damping coefficient, C_B is the flexural rigidity of the plate, C_{Tx} and C_{Tz} are the longitudinal and horizontal tension coefficients per unit width, C_K is the spring stiffness, and x and z are the streamwise and spanwise directions. The hydrodynamic forcing on the wall is given by the pressure fluctuations p_w. We use a time-varying coordinate transformation [4] to handle the boundary condition at the moving compliant wall. Three-dimensional power spectra and convective velocities of the wall pressure fluctuations, wall displacement and wall velocity (v_w) are computed as in [5].

RESULTS

We consider the plate is a thin membrane, C_B = 0 and choose C_M = 1. We perform simulations by changing the values of other parameters, C_d, C_K, C_{Tx} and C_{Tz}. When the wall is ‘hard’ (large values of these parameters), there is little change in the drag on the wall and flow structures. When the values of these parameters are small, the wall acts like quasi two-dimensional wave, whose shape is similar to the ‘static divergence wave’ [6]. This wave induces form drag and enhances turbulence above the wall. Detailed results will be shown in presentation.

After performing direct numerical simulations and generating database on the wall pressure and movement, we compute the wave number/frequency spectra of wall pressure fluctuations and wall deformation. Figure 1 shows the streamwise wave number/frequency spectra $\Phi(k_x, \omega)$ for wall pressure fluctuations. When the wall is rigid, (Fig. 1(a)) the contours have narrow aspect ratio which represents strong convective nature of the wall pressure fluctuations. For compliant walls, a new branch in the contour plot appears. The frequency where the branch is located is related the natural frequency of the wall meaning that the branch is the result of wall motion. When the wall becomes softer (smaller C_K), the wall deformation significantly affects the flow and changes the shape of contours.

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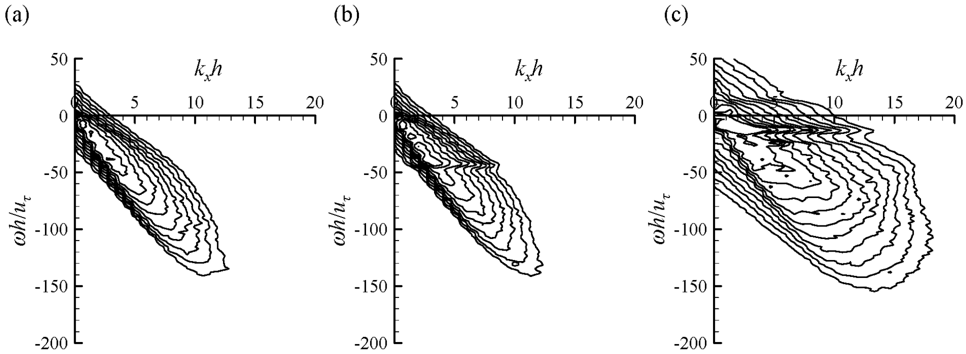

Figure 1 Contours of two-dimensional streamwise wave-number/frequency spectra $\Phi(k_x\ \omega)$ for wall pressure fluctuations: (a) rigid wall; (b) C_K = 9.0; (c) C_K = 1.0. Other parameters are C_M = 1.0, C_d = 0.5, $C_B = C_{Tx} = C_{Tz}$ = 0. Contour levels are logarithmically distributed from $10^{-4.8}$ to $10^{-1.8}$ with exponent increments of 0.3.

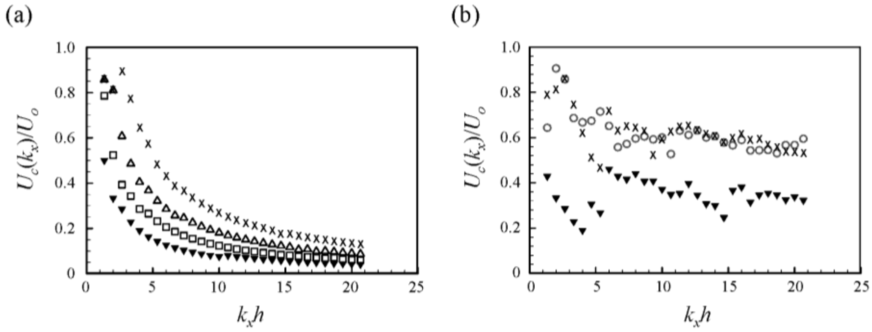

Figure 2 Convection velocities of (a) wall displacement and (b) wall pressure fluctuations. In (a), ▼, C_K = 1; □, 2; △, 4; ×, 9. In (b), ○, Rigid wall; ▼, C_K = 1.0; ×, 9.0. Other parameters are C_M = 1.0, C_d = 0.5, $C_B = C_{Tx} = C_{Tz}$ = 0.

Figure 2 shows the convection velocities of wall deformation and wall pressure fluctuations as a function of the streamwise wave number. The convection velocity of wall displacement decreases with the wave number k_x, but increases with increasing C_K. The convection velocity of wall pressure fluctuations with C_K = 9 is similar to that of the rigid wall, whereas that with C_K = 1.0 is much smaller than that of the rigid wall.

CONCLUSIONS

In the present study, the interaction of compliant wall with a turbulent channel flow was investigated using direct numerical simulation at Re_τ = 140. The compliant wall was modeled as a spring supported plate and was constrained to move only in the vertical direction. With the soft compliant wall, quasi two-dimensional waves with large amplitude appeared. These waves induced form drag and enhanced turbulence near the wall. In the wall pressure spectrum, a new branch appeared due to the movement of compliant wall. As the wall became softer, the convection velocity of wall displacement decreased, and that of wall pressure fluctuations is smaller than that of rigid wall.

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References

[1] Riley JJ., Gad-el-Hak M., Metcalfe RW.: Compliant coatings. *Annu. Rev. Fluid Mech.* **20**: 393-420, 1988.
[2] Gad-el-Hak M.: Compliant coatings for a drag reduction. *Prog. Aerosp. Sci.* **38**: 77-99, 2002.
[3] Carpenter P.W., Garrad A.D.: The hydrodynamic stability of flow over Kramer-type compliant surfaces. Part 1. Tollmien-Schlichting instabilities. *J. fluid Mech.* **155**: 465-510, 1985.
[4] Kang S., Choi H.: Active wall motions for skin-friction drag reduction. *Phys. Fluids* **12**: 3301-3304, 2000.
[5] Choi H., Moin P.: On the space-time characteristics of wall-pressure fluctuations. *Phys. Fluids* **2**: 1450-1460, 1990.
[6] Gad-el-Hak M., Blackwelder R.F., Riley J.J: On the interaction of compliant coating with boundary layer flows. *J. Fluid Mech.* **140**: 257--280, 1984.