SENSITIVITY STUDY OF TURBULENCE CONTROL WITH WALL BLOWING AND SUCTION

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ABSTRACT

Turbulence control for drag reduction is investigated using direct numerical simulations (DNS) of a turbulent boundary layer. Wall blowing and suction are applied using the opposition control strategy proposed by Choi *et al.* (1994). The sensitivity and robustness of the wall blowing and suction control are investigated. The effect of the blowing and suction strength is found less important than the phase information. The wall blowing and suction control is robust against moderate random modulation. It is found that the opposition control is very sensitive to the spanwise alignment of the wall blowing and suction. Turbulence characteristics affected by various wall blowing and suction parameters are also discussed.

INTRODUCTION

Control of turbulent flows for drag reduction has been studied for the past several decades. Various control strategies have been developed based on understanding of underlying physical mechanism and physical intuition. The near-wall streamwise vortices have been a target of turbulence control studies for the past several years because they are responsible for most turbulent kinetic energy production (Robinson, 1991). Several control strategies have been proposed using direct numerical simulations (DNS) of the Navier-Stokes equations: for example, wall blowing and suction, spanwise wall oscillation, wall deformation, external electro-magnetic field and transverse travelling wave. Extensive reviews on turbulence control are available in Bewley and Moin (1994), Pollard (1997), Kasagi (1998) and Gad-el-Hak (1994, 1996, 2000).

Among various methodologies, active control using wall blowing and suction has attracted significant interest in relation to micro-electro-mechanical systems (MEMS) based boundary layer control (Ho, 1997; Lofdahl and Gad-el-Hak, 1999; Mittal and Rampunggoon, 2002). It is shown that turbulence drag reductions can be obtained by simple closed loop control using wall blowing and suction. Choi *et al.* (1994) proposed opposition control (or V-control), in which wall blowing and suction are in opposition to the wall-normal velocity in the buffer layer. They reported that this control weakens effectively the streamwise vortices and, at $Re_\tau = 180$, approximately 25 % of drag reduction was observed.

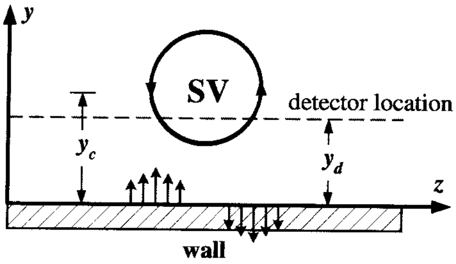

Figure 1: A schematic diagram of opposition control.

It is found that the wall blowing and suction control is effective and the required input energy is much less than the energy saved by the control. Recently, control algorithms are applied to determine the blowing and suction strength based on only wall information (Lee *et al.*, 1997, 1998, 2001;, Bewley *et al.*, 2001; Rebbeck and Choi, 2001). Later, opposition control is applied to higher Reynolds number flow (up to $Re_\tau = 650$) to see the Reynolds number effect (Collis *et al.*, 2000; Iwamoto *et al.*, 2002). It was found that the opposition control is as effective at higher Reynolds numbers as in the original low Reynolds number case.

In the present study, direct numerical simulations are performed to investigate the wall blowing and suction condition for effective drag reduction control. The main focus of the study is the sensitivity and robustness of the blowing and suction control.

DNS METHODS

DNS is performed for a turbulent flow channel with wall blowing and suction. In the DNS, the numerical code developed by Yang and Ferziger (1993) is used. The second-order accurate finite difference scheme is used for the convective and viscous terms. The solution procedure consists of a semi-implicit approach. A low storage, third-order Runge-Kutta method is used for time integration for the nonlinear convective terms, and a second-order Crank-Nicholson method for the viscous terms. The fractional-step method of Kim and Moin (1985) is used to enforce the solenoidal condition. The resulting discrete Poisson equation for the pressure is solved using a discrete Fourier transformation in the spanwise direction and a penta-diagonal direct matrix solver in the wall normal direction.

The flow is assumed to be periodic in the streamwise and

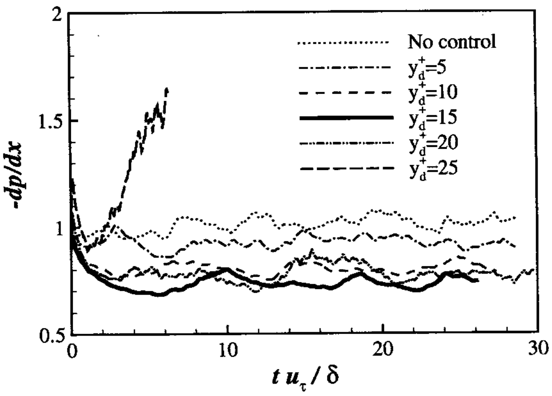

Figure 2: Time history of pressure gradient for various locations for the detection plane, y_d^+.

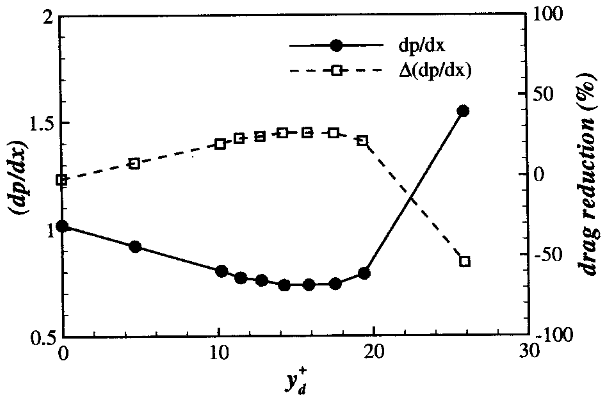

Figure 3: Time-mean pressure gradient and drag reduction for various y_d^+ locations.

Table 1: Numerical parameters used in direct numerical simulations. y_d^+ is y^+ location for the detection plane and $v_{rms}(y_d^+)$ is rms wall normal velocity fluctuation at y_d^+.

Case	y_d^+ (nominal value)	y_d^+ (real value)	$v_{rms}(y_d^+)$
Case 1	5	4.67	0.11082
Case 2	10	10.23	0.17248
Case 3	11	11.46	0.17689
Case 4	13	12.80	0.17930
Case 5	15	14.26	0.17980
Case 6	16	15.84	0.17853
Case 7	18	17.55	0.17567
Case 8	20	19.41	0.17567
Case 9	25	25.91	0.15364

spanwise directions. The flow rate in the streamwise direction is kept constant and the drag is measured by the mean pressure gradient necessary to maintain the flow rate. All flow variables are nondimensionalized by the friction velocity in the uncontrolled channel, u_τ and the channel half-width h. The Reynolds number is defined as $Re = u_\tau h/\nu$, where ν is the kinematic viscosity of the fluid. In the present study, $Re_\tau = 150$. The computational domain is set $(3\pi \times 2 \times \pi)$ in the x, y and z directions, respectively. A 64×97×96 grid system is used in the x, y and z directions. The grid spacings are $\Delta x^+ = 20.3$, $\Delta y^+_{min} = 0.3$, $\Delta y^+_{max} = 6.6$ and $\Delta z^+ = 4.5$.

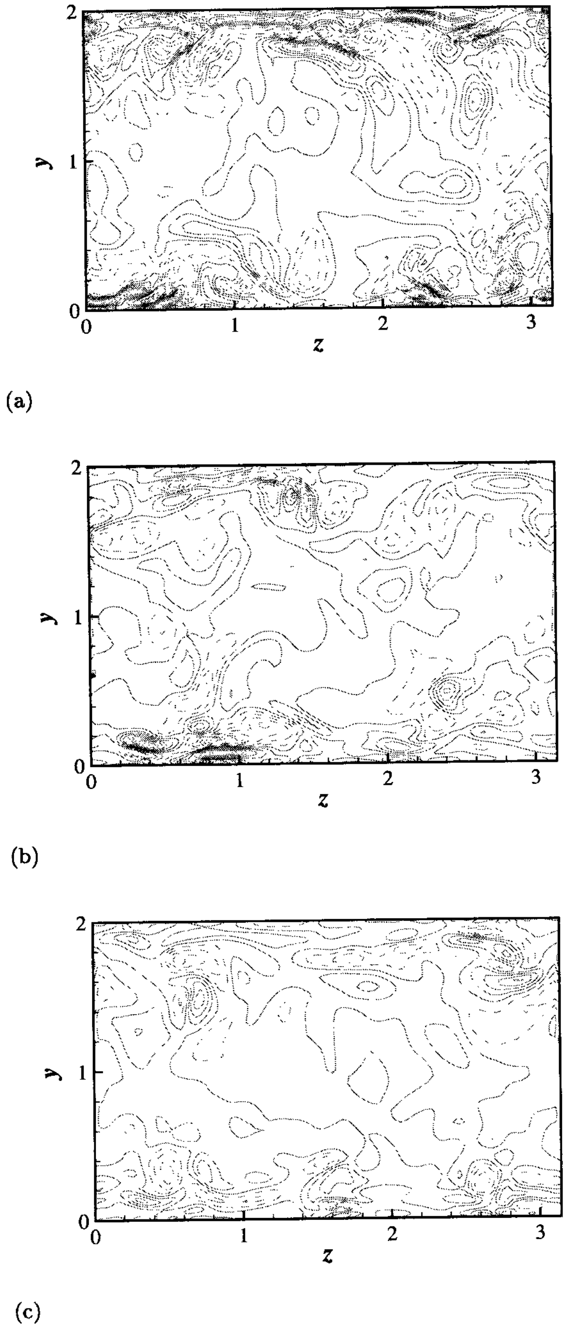

Figure 4: Instantaneous velocity vector plots in $y - z$ plane. (a) no control, (b) $y_d^+ = 10$, (c) $y_d^+ = 15$ and (d) $y_d^+ = 25$.

RESULTS AND DISCUSSION

In opposition control, wall blowing and suction are applied to suppress the sweep and ejection events in the near-wall turbulence, which are responsible for most skin-friction drag (Choi *et al.*, 1994). The magnitude of blowing and suction is determined as the opposite to the wall-normal velocity at a detection plane located at a small distance (y_d) from the wall (see Fig. 1).

$$v(x, 0, z : t) = -v(x, y_d, z : t). \qquad (1)$$

Detection Plane Location

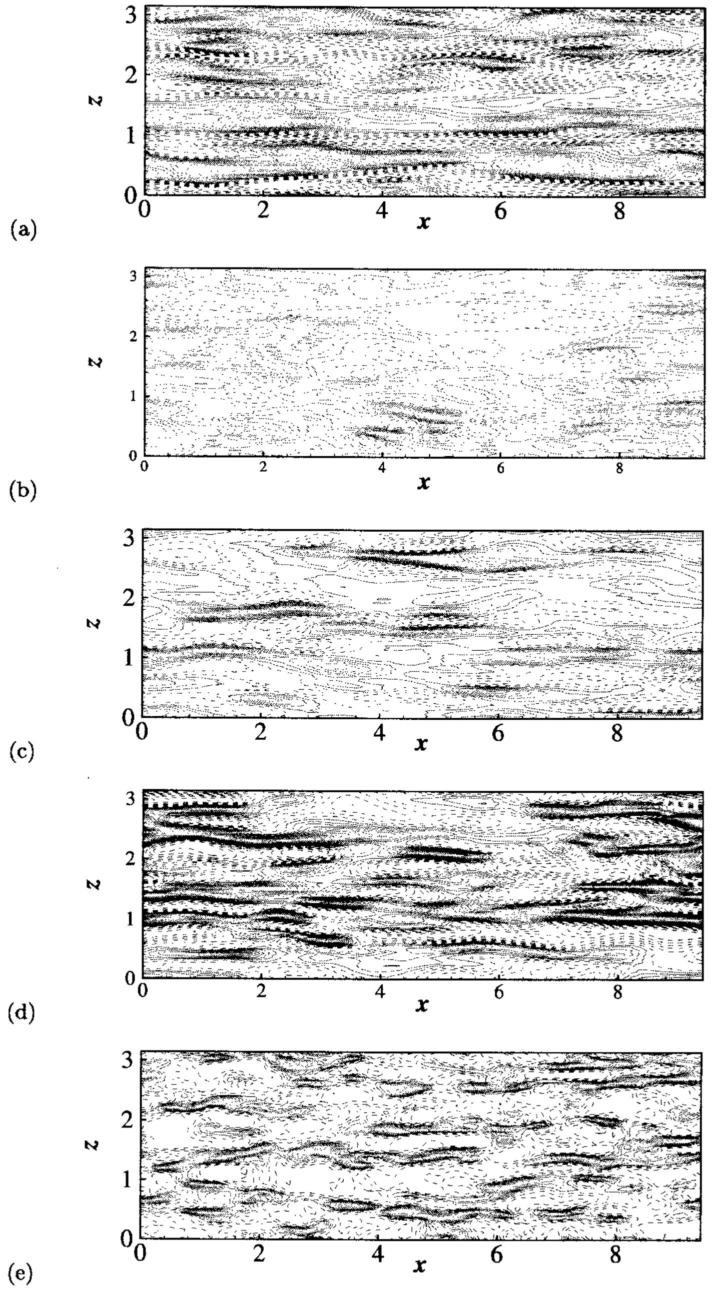

Figure 5: Low-speed streaks. (a) no control, (b) $y_d^+ = 5$, (c) $y_d^+ = 10$, (d) $y_d^+ = 15$, and (e) $y_d^+ = 20$. Increments are 0.01 in (a), (b), (c) and (d), and 0.05 in (e).

The drag reduction with the various locations for the detection plane is shown in Fig. 2. It is found that the overall success of opposition control is very sensitive to the location of the detection plane. The optimal wall blowing and suction are from $y_d^+ \approx 15$, consistent with Hammond *et al.* (1998). Note, detection planes at $y_d^+ = 10$ or 20 also give reasonably good results. For $y_d^+ > 20$, however, the opposition control becomes unstable and the drag is increased substantially, consistent with the previous studies (Choi *et al.*, 1994; Hammond *et al.*, 1998).

The sensitivity of the opposition control is investigated in terms of the detection plane location and the wall blowing and suction strength. First, opposition control is applied with several detection plane around the optimal location $y_d^+ \approx 15$ (Fig. 2). The detailed parameters are summarised in Table 1. The effect to drag reduction of small changes in the detection plane location is found to be small for $10 \leq y_d^+ \leq 20$. The time-averaged pressure gradient and drag reduction are shown in Fig. 3. Negative values of drag reduction indicate a drag increase. For $10 \leq y_d^+ \leq 20$, the drag reduction is about 25%. The effects of the detection plane location y_d on turbulence structures are clearly seen in Figs. 4 and 5, which show streamwise vorticity and low-speed streaks, respectively.

Wall Blowing and Suction Strength

Secondly, the sensitivity connected with the blowing and suction strength is investigated. The amplitude of the wall blowing and suction is determined as follows:

$$v(x, 0, z : t) = -Av(x, y_d, z : t). \qquad (2)$$

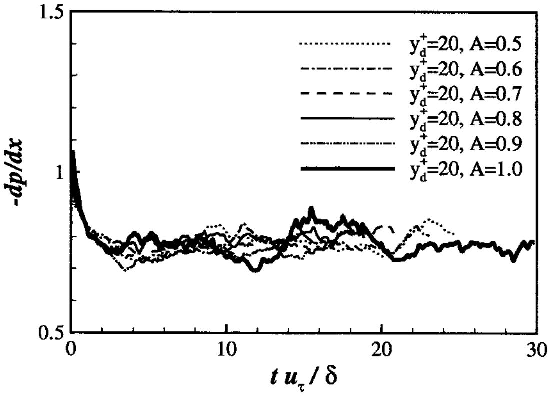

Figure 6: Effect of various blowing and suction strengths at $y_d^+ = 20$.

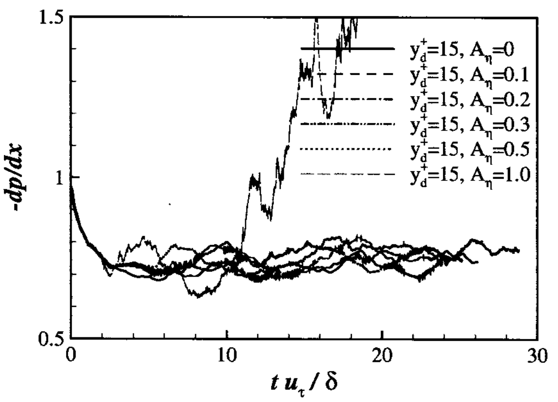

Figure 7: Effect of random modulation on drag reduction at $y_d^+ = 15$.

Here, A is a constant and $y_d^+ = 20$ is chosen, where the centre of the streamwise vortex, y_c is located on average (Kim *et al.*, 1987). Several values for A are applied to find an optimal value and the results are shown in Fig. 6. It is found that the opposition control with $y_d^+ = 20$ is not very sensitive to the wall blowing and suction strength as long as the strength is not too high ($A \leq 1$). When $A > 1$, significant drag increases are obtained. Overall, the detection plane at $y_d^+ = 20$ does not seem to be the optimal location for the maximum drag reduction.

Random Modulation

For practical implementation, the robustness of the opposition control is also examined.

$$v(x, 0, z : t) = (1 + \eta) v(x, y_d, z : t). \qquad (3)$$

Here, η is a random number with a standard deviation of A_η. Five values of A_η are considered: $A_\eta = 0.1, 0.2, 0.3, 0.5$ and 1.0. In the robustness study, $A = 1$ and $y_d^+ = 15$ is chosen because it gives the best drag reduction without any amplitude modulations. It is found that moderate random modulations have little effect on drag reduction as shown in Fig. 7. However, large random modulations reduce the drag reduction significantly.

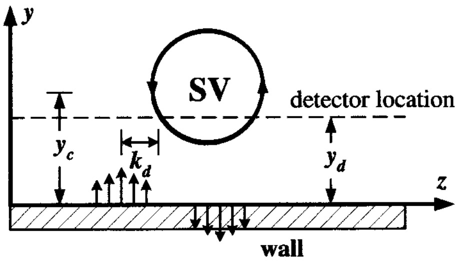

Figure 8: A schematic diagram of mis-aligned wall blowing and suction

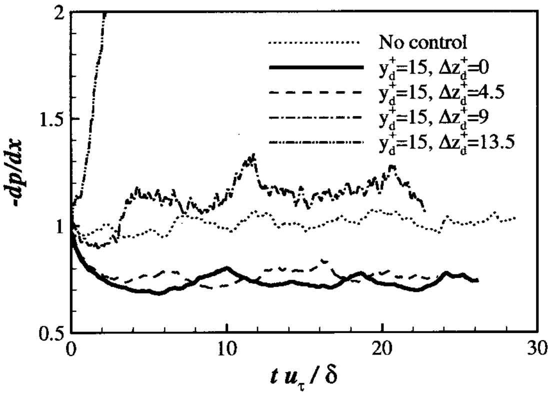

Figure 9: Effect of Δz_d on drag reduction at $y_d^+ = 15$.

Spanwise Alignment

It was known that, in blowing and suction control, wave information in the spanwise direction is much more important than in the streamwise direction. The robustness of the control with mis-aligned wall blowing and suction is studied.

$$v(x, 0, z : t) = v(x, y_d, z + \Delta z_d : t). \qquad (4)$$

Three values of Δz_d are considered: $\Delta z_d^+ = 4.5$, 9 and 13.5. While slightly mis-aligned wall blowing and suction give as an effective drag reduction as the aligned case, control with $\Delta z_d^+ = 9$ increases the drag (Fig. 9). Turbulence characteristics affected by spanwise mis-alignment of wall blowing and suction are clearly seen in Figs. 10 and 11, which show low-speed streaks and vector plots, respectively. It is found that the opposition control is very sensitive to the spanwise alignment of the wall blowing and suction. In real applications, $\Delta z_d^+ = 4.5$ is very small, especially when the Reynolds number is high. This makes the opposition control difficult to apply to high Reynolds number flow.

CONCLUDING REMARKS

Direct numerical simulations have been performed to investigate the wall blowing and suction for turbulence skin-friction drag reduction. The opposition control is found to be rather insensitive to the location of detection plane for $10 \leq y_d^+ \leq 20$. The opposition control is also insensitive to the blowing and suction strength A. Almost the same drag reductions are obtained with $A = 0.5$. The wall blowing and suction control is robust against moderate random modulation. It is found that the opposition control is very sensitive to the spanwise alignment of the wall blowing and suction. The mis-aligned wall blowing and suction control increases the drag substantially.

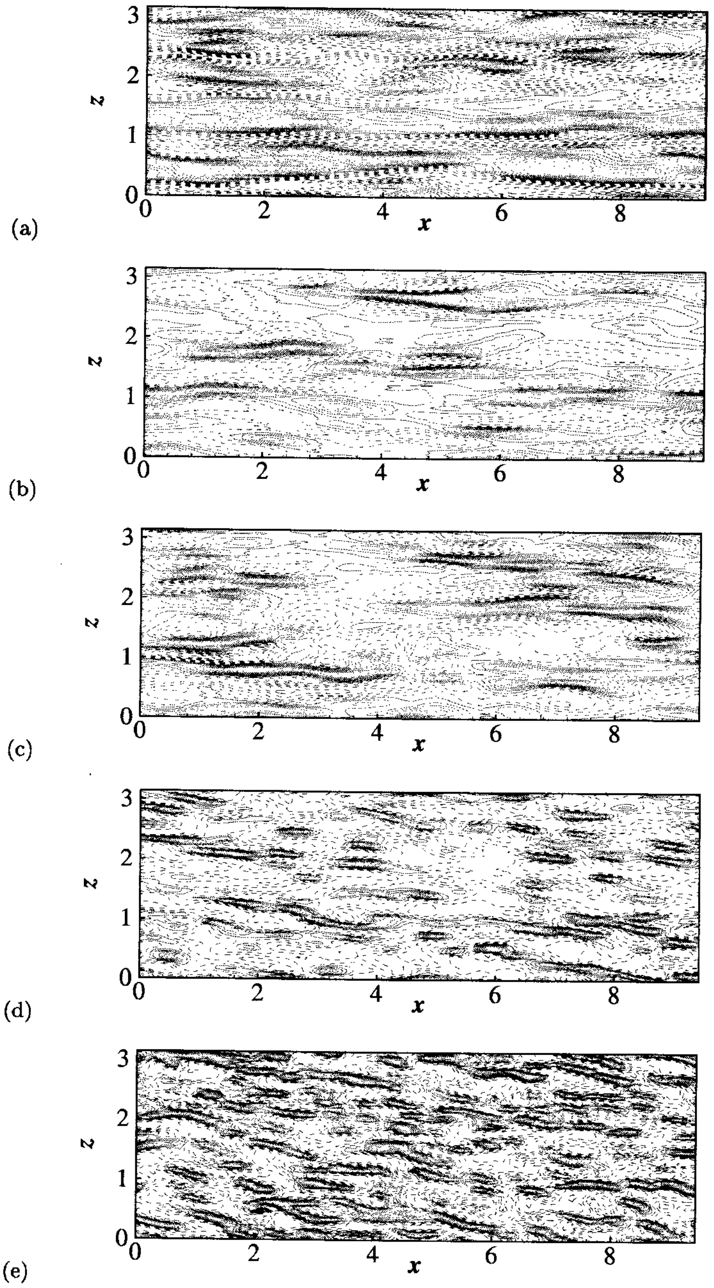

Figure 10: Low-speed streaks at $y^+ = 1.0$. (a) no control, (b) $\Delta z_d = 0$, (c) $\Delta z_d = 4.5$, (d) $\Delta z_d = 9.0$, and (e) $\Delta z_d = 13.5$. Increments are 0.01 in (a), (b) and (c), and 0.05 in (d) and (e).

ACKNOWLEDGEMENTS

This research was supported partially by a grant from the National Research Laboratory of the Ministry of Science and Technology, Korea.

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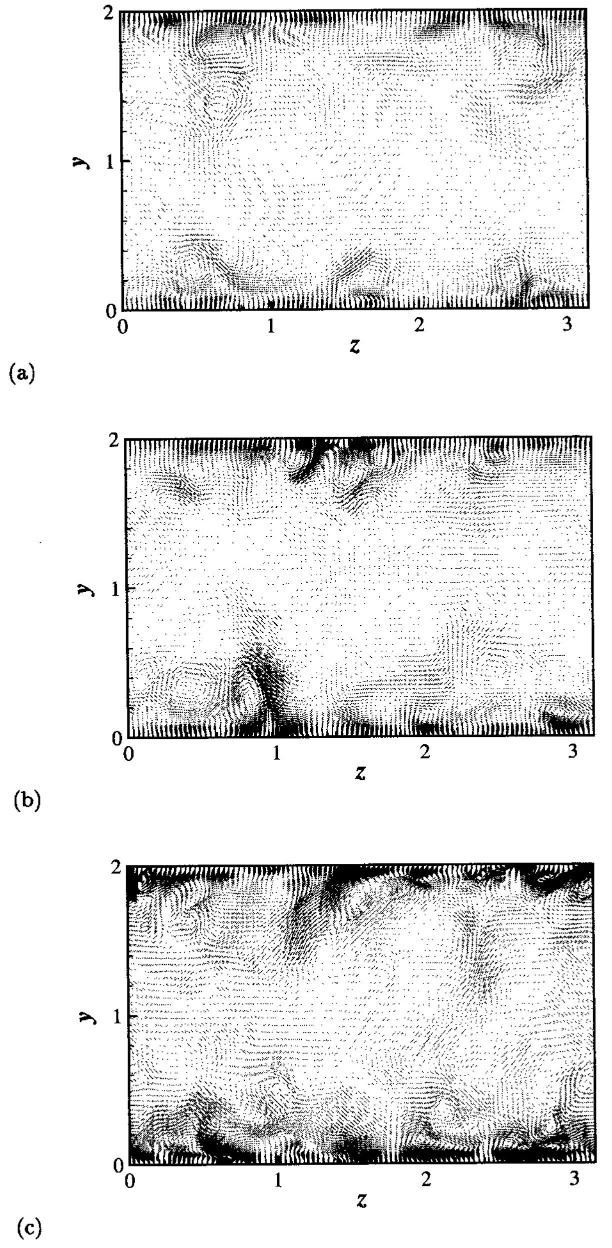

Figure 11: Instantaneous velocity vector plots in $y-z$ plane. (a) $\Delta z_d = 0$, (b) $\Delta z_d = 4.5$ and (c) $\Delta z_d = 9.0$.

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