TURBULENCE CONTROL FOR SKIN-FRICTION DRAG REDUCTION: POTENTIALS AND LIMITATIONS

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ABSTRACT

Potentials and limitations of turbulence drag reduction control are investigated using direct numerical simulations (DNS) of a turbulent boundary layer. Wall blowing and suction are applied using the opposition control strategy. The optimal wall blowing and suction condition for effective drag reduction control is investigated. The sensitivity 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. It is found that the opposition control is very sensitive to the spanwise alignment of the wall blowing and suction. The effectiveness of MEMS devices for flow control has also been investigated using DNS. It is found that a loss of the control surface results in a substantial decrease of the drag reduction.

INTRODUCTION

More efficient aircraft are needed to meet the ambitious ACARE target of a 50% reduction in emission by 2020. Active control can help achieve a 50% reduction in fuel burn per passenger/km. 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. Many control methods have focused on the weakening of streamwise vortices, which are responsible for most of turbulent kinetic energy production (Robinson, 1991). 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. Several control strategies have been proposed using direct numerical simulations (DNS) of the Navier-Stokes equations: for example, wall blowing and suction (Choi *et al.*, 1994; Lee *et al.*, 1997, 1998; Hammond *et al.*, 1998; Bewley *et al.*, 2001), spanwise wall oscillation (Jung *et al.*, 1992; Choi and Graham, 1998), wall deformation (Endo *et al.*, 2000), external electro-magnetic field (Berger *et al.*, 2000; Lee and Choi, 2001) and transverse travelling wave (Du *et al.*, 2002). Extensive reviews on turbulence control are available in Bewley and Moin (1994), Pollard (1997), Kasagi (1998) and Gad-el-Hak (1994, 1996, 2000).

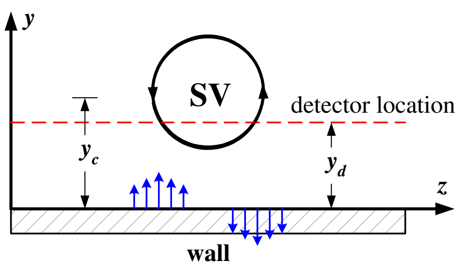

Figure 1: A schematic diagram of opposition control.

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.

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 almost 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

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^+ for $Re = 180$.

Case	y_d^+ (nominal value)	y_d^+ (real value)
Case 1	5	5.35
Case 2	10	10.46
Case 3	15	15.01
Case 4	20	20.69
Case 5	25	25.84

Table 2: 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^+ for $Re = 150$.

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

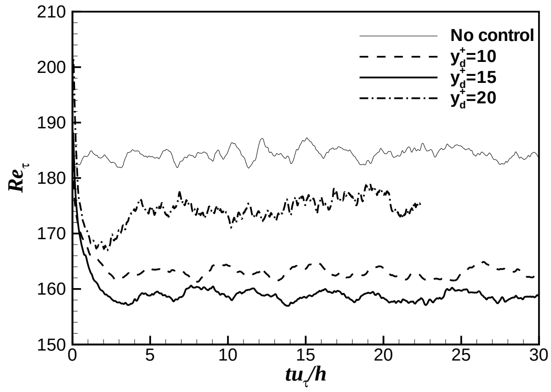

Figure 2: Time history of skin friction (Reynolds number) for various locations for the detection plane, y_d^+ for $Re = 180$.

DNS is performed for a turbulent flow channel with wall blowing and suction. The flow is assumed to be periodic in the streamwise and spanwise directions. For spatial discretisation, the second-order central differences are used. All flow variables are nondimensionalised by the friction velocity in the unperturbed 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. The computational domain is set $(4\pi \times 2 \times 2\pi)$ with a grid system $(128 \times 129 \times 192)$ in the x, y, z directions, respectively. The streamwise and spanwise grid resolutions are $\Delta x^+ = 17.7$ and $\Delta z^+ = 5.89$, respectively. The first grid point away from the wall is located at $y^+ = 0.2$. Here, a superscript + indicates the wall units of the unperturbed flow. Results for $Re = 150$ are also included.

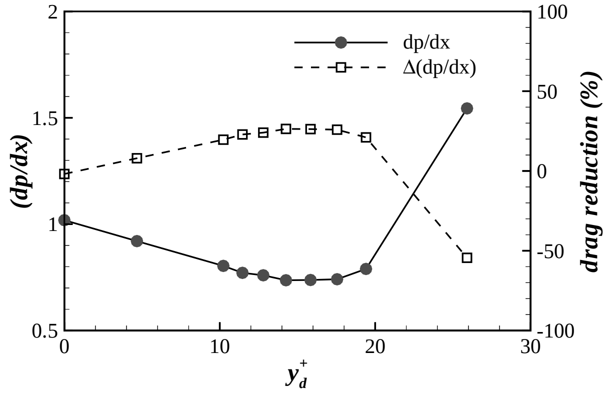

Figure 3: Time-mean pressure gradient and drag reduction for various y_d^+ locations.

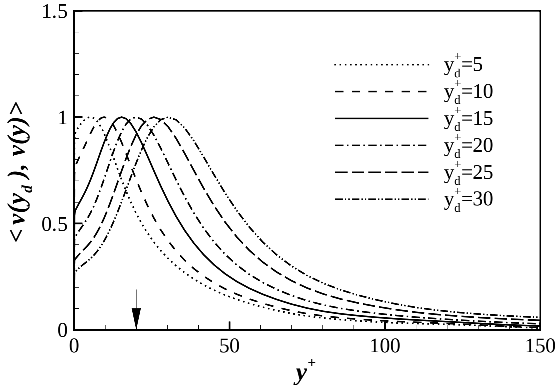

Figure 4: Correlation coefficient $< v(x, y_d, z), v(x, y, z) >$.

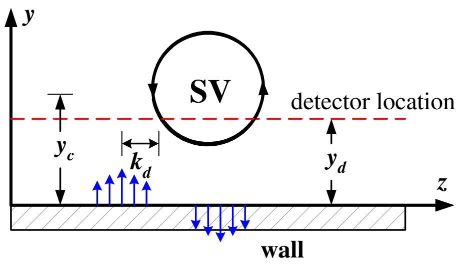

Figure 5: A schematic diagram of mis-aligned wall blowing and suction

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).

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

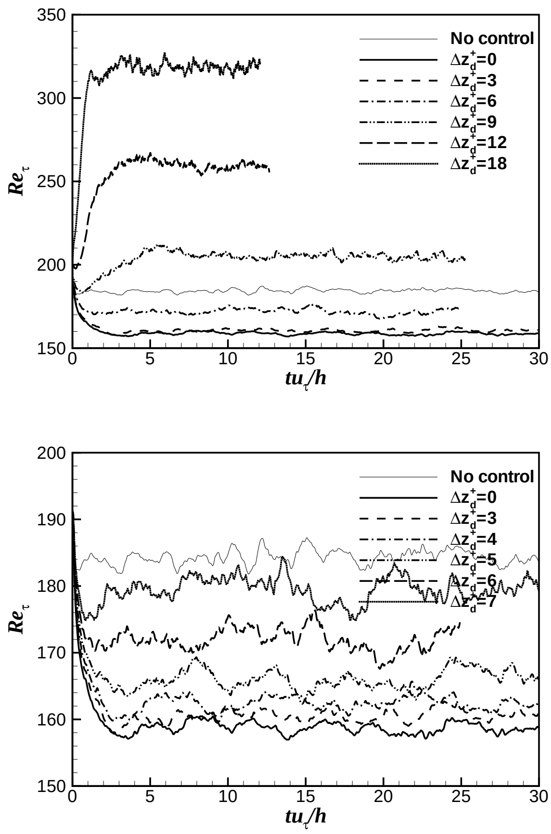

Figure 6: Effect of Δz_d on drag reduction at $y_d^+ = 15$.

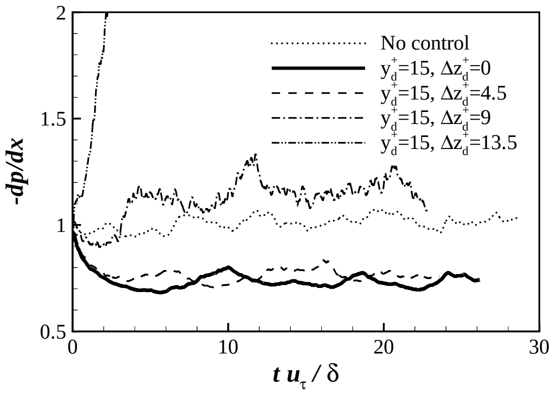

Figure 7: Effect of Δz_d on drag reduction at $y_d^+ = 15$ for $Re = 150$.

Detection Plane Location

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 $y_d^+ = 10$ also give reasonably good results. This finding is somewhat different from the previous study at a lower Reynolds number ($Re_\tau = 150$), where the sensitivity of drag reduction to y_d^+ did not appear very segnificant (see Fig. 3). 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 can be calculated from the results. Negative values of drag reduction indicate a drag increase. For $10 \leq y_d^+ \leq 15$, the drag reduction is about 25%. The effects of the detection plane location y_d on turbulence structures are clearly seen in the streamwise virticity contour plot (not shown here).

To examine the relationship between velocity signals at various detection planes around $y_d^+ = 15$, two-point correlation of the wall normal velocity is examined.

$$R_{vv}(y : y_d) =< v(x, y_d, z), v(x, y, z) > . \tag{2}$$

As shown in Fig. 4 the correlation is generally high in the near the wall region ($y^+ < 30$). For $y_d^+ = 15$, R_{vv} has high values for $10 \leq y^+ \leq 20$.

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 (see Fig. 5).

$$v(x, 0, z : t) = v(x, y_d, z + \Delta z_d : t). \tag{3}$$

The detection point is misaligned by Δz_d in the z-direction. Several values of Δz_d are considered: $\Delta z_d^+ = 3, 4, 5, 6, 7, 8, 9, 12$ and 18. While slightly mis-aligned wall blowing and suction give as an effective drag reduction as the aligned case, control with $\Delta z_d^+ > 8$ increases the drag (Fig. 6). Turbulence characteristics affected by spanwise mis-alignment of wall blowing and suction are clearly seen in low-speed streaks and vector plots. It is found that the opposition control is very sensitive to the spanwise alignment of the wall blowing and suction. In real applications, $\Delta z_d^+ = 3$ is rather small, especially when the Reynolds number is high. This makes the opposition control quite difficult to apply to high Reynolds number flow.

MEMS actuator simulation

Recently, MEMS devices have been used in active flow control (Suzuki *et al.* 2005). We performed numerical simulations to test this idea. The actuator size used in the MEMS experiments was $2.4mm$ ($29\ \nu/u_\tau$) and $14mm$ ($168\ \nu/u_\tau$) in the streamwise and spanwise directions, respectively. In this study, the width of the longitudinal slots is $36\ \nu/u_\tau$, and the length is the same as the computational domain size ($2260\ \nu/u_\tau$). The gaps between the slots are $12\ \nu/u_\tau$. So, about 75% of the wall area is being used for flow control. As shown in Fig. 8, the use of slot results ($\Delta z_d = 0$) in a smaller drag reduction, mainly due to the loss of the control area. When the spanwise shift of the detection plane was applied, the drag reduction becomes much worse, as expected. When the detection plan was moved in the spanwise direction, the deterioration of the drag reduction is very evident. The $\Delta z_d^+ = 6$ case shows almost the same level of skin-friction drag as the no control case, resulting in a zero drag

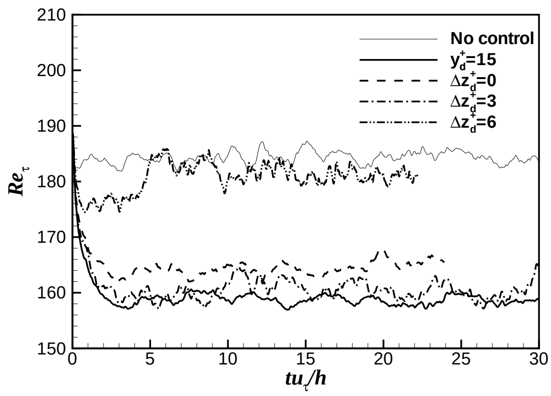

Figure 8: Effect of Δz_d on drag reduction with slots at $y_d^+ = 15$.

reduction. Instantaneous w velocity contour plots in $x - y$ plane are shown in Fig. 11. Turbulence activity becomes stronger with the spanwise shift.

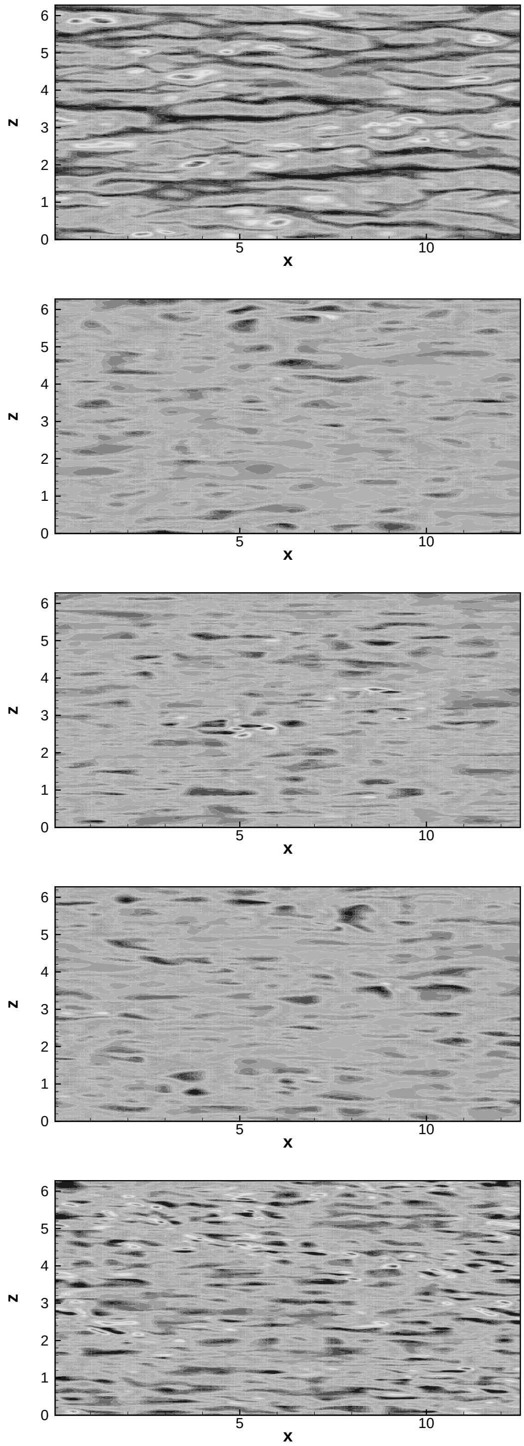

Figure 9: Instantaneous w velocity contour plots in $x - y$ plane. (a) No control, (b) $y_d^+ = 15$, (c) MEMS device with $\Delta z_d = 0$, (d) $\Delta z_d = 3$ and (e) $\Delta z_d = 6$.

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:

$$v(x, 0, z : t) = -Av(x, y_d, z : t). \tag{4}$$

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. 10. 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. The opposition control is found to be rather sensitive to the spanwise misalignment of detection plane. By changing (reducing) the blowing/suction strengths, it is possible to the $y_d^+ = 25$ case stable. The resulting drag reduction is not very great compared with the optimal case. However, it can provide an opportunity to make the whole control system stable.

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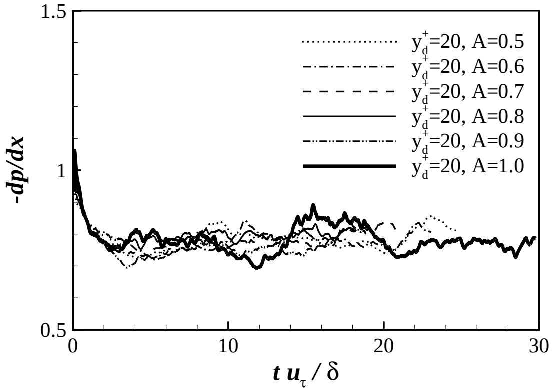

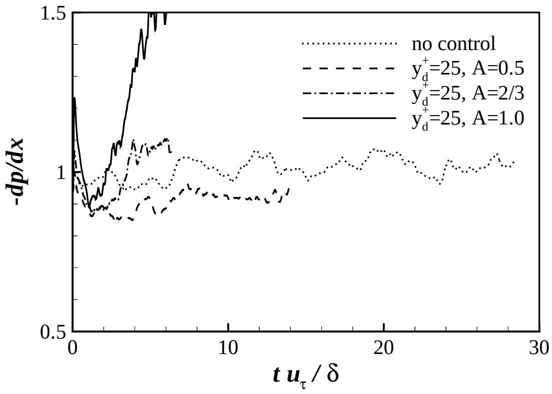

Figure 10: Effect of various blowing and suction strengths at a) $y_d^+ = 20$ (for $Re = 150$) and b) $y_d^+ = 25$.

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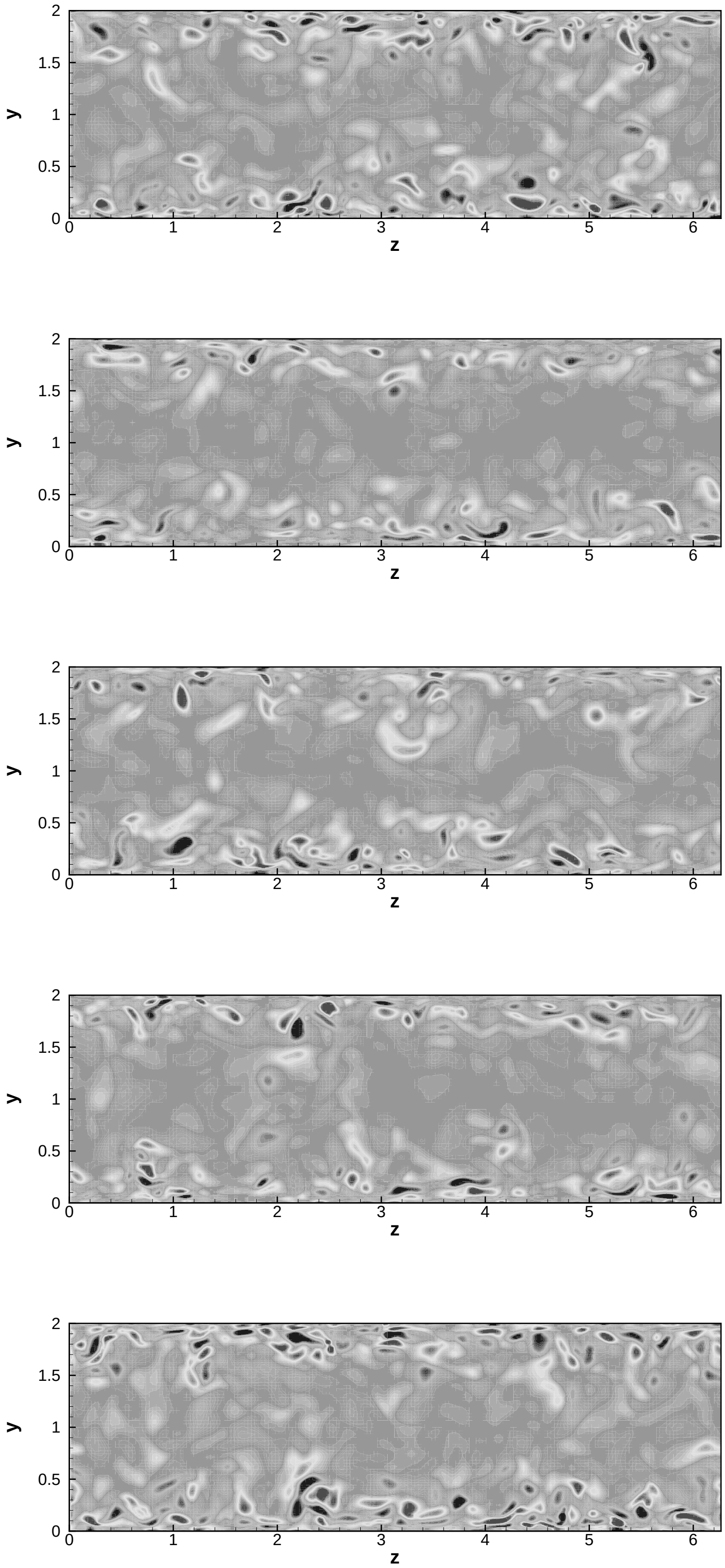

Figure 11: Vector plot in $y-z$ plane. (a) No control, (b) $y_d^+ = 15$, (c) MEMS device with $\Delta z_d = 0$, (d) $\Delta z_d = 3$ and (e) $\Delta z_d = 6$.