Visualization of wall turbulence under artificial disturbance by piezo actuator array

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ABSTRACT

A possibility of turbulent flow control by an actuator array was experimentally examined. A turbulent channel flow of water at *Re*=7500 in a rectangle channel (cross section: 500 mm x 40 mm) was used to clarify the optimum driving condition of the actuator array. Using a particle image velocimetry (PIV) system, we could visualize the low-speed fluid element penetrating into the outer layer from the inner layer. Six actuators are installed on the wall and aligned in spanwise direction. Each actuator element can be independently oscillated vertically at 100 μm amplitude. The mean spacing of streak-like structures existing in the vicinity of the wall are known to be in the order of 100 times the viscous length scale, 100*n*/ *u*. Suitable size of the actuator was determined to have half size of the mean spacing of low-speed streaks near the wall. Driving frequency was changed to find the condition of interactions between low-speed streaks and structures generated by actuators. In such a project, observation of instantaneous velocity distribution gives essential information and PIV is the only method usable to this purpose. The present PIV system allows to detect instantaneous velocity as well as vorticity concentrated near the wall in the interval of less than 0.1sec. As a result of analyzing spatial velocity distribution in *x*-*z* plane near the wall by PIV, the regularity of the velocity distribution in y^+=50 observed in plane channel flow becomes indistinct for the frequency (f_a) of actuator more than 12.5 Hz.

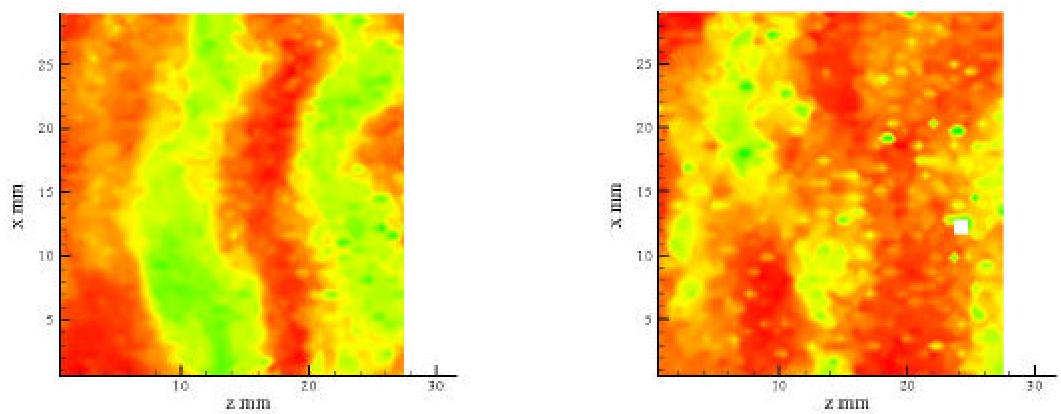


Figure 1 Spatial distributions of instantaneous velocity for *Re*=7500.

(a) f_a=0 Hz, (b)125 Hz. Fluid flows from bottom to top.

1. INTRODUCTION

The control of turbulent flows using a micro electro-mechanical system (MEMS) is one of the most challenging topics in recent fluid engineering research (for example, Kumar et al. (1999) and Kimura et al. (1999)). In this study we tried to clarify 3-dimensional flow structures at the near-wall region when they are stimulated by artificial disturbances.

In the past turbulent flows were believed to be completely random. However, after a sort of coherent structure was found in the turbulent boundary layers (Hama, et al. 1957, Kline, et al. 1967). This discovery indicated a possibility of controlling turbulence in attention with the coherent motion. Recent development in flow visualization techniques using laser technology enables us to observe perspective view of the coherent structures in the wall turbulence, such as horseshoe vortices or stream-wise vortices. Moreover, recent studies have provided hopeful results on control of turbulence. For example, Choi, et al. (1994) indicated numerically that drag in a turbulent channel flow could be decreased 30%, if local blowing/suction on the wall was properly arranged and controlled. Using MEMS devices, Stuart, et al. (1998) demonstrated in experiments that Reynolds stresses were in fact regulated to a certain degree.

Although active control technologies by actuator devices are under development, a few examples of turbulent drag reduction by active boundaries have been reported. In turbulent channel flows, spanwise wall oscillation is known to generate considerable reduction of the drag. Jung et al. (1992) showed the effect of spanwise oscillation on drag reduction by numerical simulation. Soon after, Laadhari et al. (1994) confirmed experimentally the significant effect of the spanwise oscillation. Recently, Choi et al. (1998) carried out a precise measurement of channel turbulent flow with spanwise oscillation and discussed on the mechanism of the drag reduction. They also found the same drag reduction effect in a circular pipe system. In addition to the effect of the spanwise oscillation, Nakamura et al. (1998) indicated experimentally that wall oscillation in wall normal direction in a rectangular channel had a drag-reducing effect like spanwise oscillation. Thus, oscillation of the channel wall does appear to have an effect on drag reduction. The flow configurations of the above studies are all related to rectangular or circular channels. More recently, Segawa et al. (2000) showed that a reduction of friction was observed by oscillating the bottom stationary disk in the rotating parallel disk system. It seems that the radial flow by the wall oscillation corresponds to the cross-flow in the channel.

During these three decades, extensive efforts have paid to clarify the ordered or coherent motion in wall turbulence. One of the important findings relating to the mechanism of turbulent friction is that turbulent skin friction is mainly generated by the so-called ejection of lower speed clusters in the near-wall region into a higher stream region away from the wall (Kline et al. 1967) and sweep which is the inrush motion of high-speed fluid to the wall. This fact gives us some clues about controlling the turbulent flow drag in conscious with this motion. If we can produce a proper artificial disturbance, or control input, to cancel the aforementioned near-wall coherent structure, it may be possible to manage the flow drag more efficiently. This strategy can be called "controlled active method" in distinction of conventional active methods.

In the purpose of optimization of design and drive condition of actuator array, information of spatial structure of near wall turbulence is necessary. Although LDV is applicable to near wall region, the measurement is limited only one point at a time. Thus we used particle image velocimetry (PIV), which has been recently recognized as a powerful tool for precise flow observation. Structure analyses of turbulent flow using PIV should lead to understanding turbulent flow and how to deduce turbulent frictional drags.

2. EXPERIMENTAL METHOD and PROCEDURES

2.1 Closed-loop Water channel System

The experimental set up including water channel and PIV is basically the same with Li et al. (2000). Thus, in this section, essential and specific matter on the present study will be described. The closed loop water channel system we used in this study is shown in Fig. 2. The channel is made of transparent acrylic plates to allow visualizing the flow by laser sheet. The channel is filled with bubble-free water and kept at temperature T = 30°C by a cooling system. The test section is 40 mm in height, H, 500 mm in width, W, and 6000 mm in length, L. A series of experiment was carried out at the Reynolds number 7500. The Reynolds number (Re) is defined as:

$$Re = \frac{HU}{n},$$

where U is the mean velocity averaged over the duct cross-section and n is the kinematic viscosity of the water. In this experiment, the bulk mean velocity U equals 0.15 m/s. The flow control by means of actuators is carried out in the top or bottom wall of the channel at x=3000 mm downstream of the test section inlet. As the Reynolds number is much larger than 3000, the flow develops turbulence. For turbulence, it is well known that the hydrodynamic entrance length (l_e) can be introduced experimentally as:

$$l_e = 0.639d \times Re^{0.25}.$$

Because l_e is estimated at about 250 mm in this experiment, it becomes fully a developed turbulent flow around the measuring point.

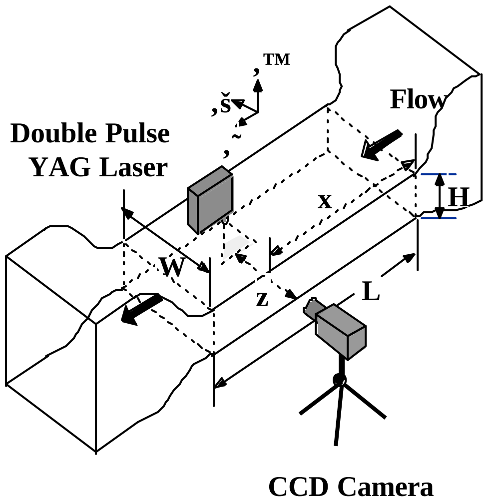


Figure 2 The closed-loop water channel system.

2.2 Actuator Array and Scales

According to the finding that turbulent friction is mainly contributed by coherent motion near the wall, a strategy called "controlled active method" focusing to coherent motion will be efficient to manipulate turbulent friction. To establish controlled active method, sensor of coherent motion, actuator and control algorithm are essential components. Especially, the key of development is an actuator driven by computer command. Because of the coherent motion spreads in space and moves time by time, the actuator must have spatial distribution and sufficient temporal response. Other important factors are enough amplitude and durability in the fluid. Thus, in this study, a laminated piezo-ceramic element was selected as the material of actuator array.

Figure 3 shows the picture and schematic drawing of an actuator which consists of six laminated piezo-ceramic elements (Tokin Co., AE0203D16). Each element stretches 17 μm at 160 volts. Therefore the stroke of the actuators is more than 100 μm at 160 volts. The frequency response is ranging from 0.1 to 1 kHz. A layout drawing of the actuator array is shown in Fig. 4(a) and is composed of six laminated piezo-ceramic actuators.

They can also oscillate from f_a=1 to 1kHz in the phase difference of 60 degrees each other using six synchronized signal generators (NF Electric Instruments Co., NF1946). To control a coherent structure in a turbulent flow, the actuators are moved in various modes, for example the wavy mode shown in Fig. 4(b).

Here we introduce the length scale of the streak-like structure at y=2 mm from the upper or bottom wall from which flow visualization is

$$U_t = \sqrt{t_w / r} \approx 0.0092 ,$$

where r is the density at T=30^{o}C. Therefore u_t is roughly estimated at 0.01 m/s. The most typical scale length l of the streaks is known to be 100 times the viscous length scale, 100n/ u_t. Thus a streak-like coherent structure of about 8 mm can be found at Re =7500. We chose actuators with a width less than a half of the streak's length scale (l) and arranged them at 4 mm intervals for controlling the fluid at 1/2 l. For example, it is possible to produce the disturbance in spanwize direction by operating actuators by wavy mode.

Concerned with structure analyses, the area where vorticity and time evolutions of their low-speed ordered structures concentrate could be acquired within a 0.1 second interval. They will aid in our understanding of turbulent flow and establishment of a control method for it. To change flows and control bursts or horseshoe vortexes by active control, the time scale on the burst was estimated. Luchik et al. (1987) introduced the averaged time between bursts, T_B. The non-dimensional timescale T of the bursting interval is defined as:

$$T = \frac{UT_B}{\frac{1}{2}H} .$$

For Re=7500, we estimated that T=0.6 and T_B equals 0.8 second using our channel. T_B corresponds to the averaged occurring frequency of bursts, f_T=1.25Hz. Thus the actuators were oscillated in frequency higher than T_B.

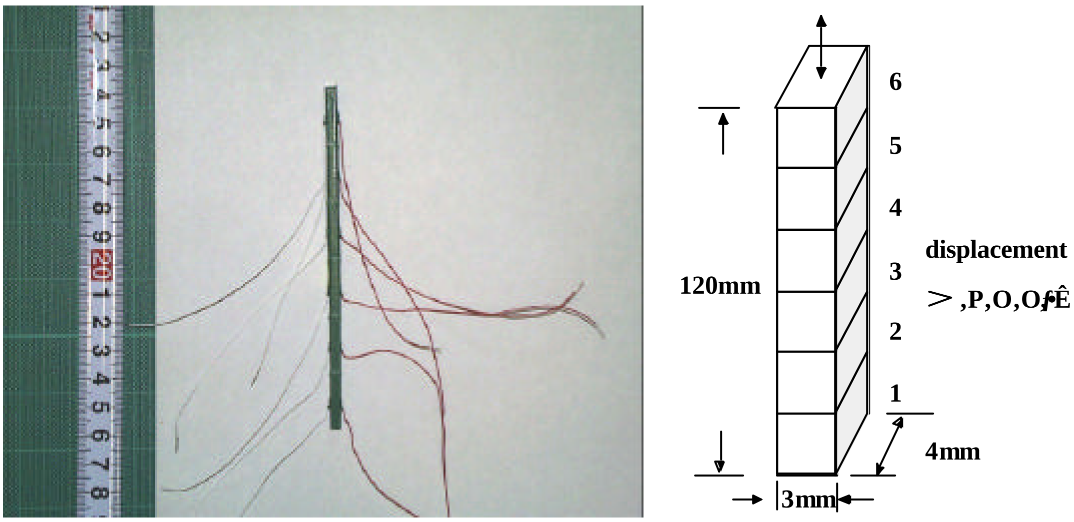


Figure 3 Picture and schematic drawing of an actuator which consists of six laminated piezo-ceramic elements.

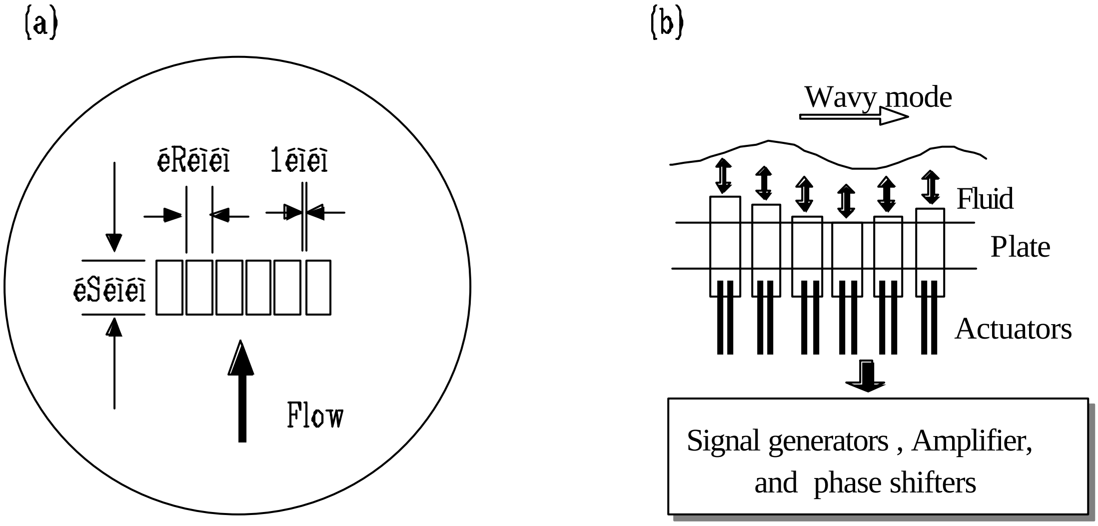


Figure 4 Actuator array. (a) Layout of 6 piezo-ceramic actuators. (b) Sectional view of *y*-*z* plane.

<u>2.3 Visualization Technique</u>

A view of system setup for visualizing the flow is illustrated in Fig. 2. The actuator array is mounted on a circular plate set in the top wall of the channel at *x*=3000 mm downstream of the test section inlet. To visualize the near-wall flow, a pair of YAG laser sheets with the power of 25mJ per pulse was set over the channel system. By changing the combinations of the cylindrical lenses, the laser sheet thickness can be modified in a range of 0.14 mm to 0.6 mm and a spread angle in the range of 4.3 deg to 13.3 deg. The images were photographed with a CCD camera with a 1008x1018 resolution (PIVCAM 10-30, TSI Model 630046) and those velocity vectors are also analyzed by PIV software (TSI, Insight NT). The maximum frequency of the pulse was 15Hz. Thus the time series of velocity and vorticity distributions are acquired within a 0.1 second interval as shown when using the PIV system. Globular aluminum oxide (Al_2O_3), which is 3 μm in diameter, was used as the seeding particle to obtain the image of the flow. By combining various lenses attached to the CCD camera, the visualization of the region from 2x2 mm to 40x40 mm was possible. Matte black film was stuck on the surface to prevent reflection of the laser light on the wall of the channel.

We tried to control turbulent flow by operating actuators in various modes, for example a wavy mode by phase-shifting each actuator (Fig. 4(b)). If we detected these coherent structures by PIV and provided them with some appropriate disturbance, there is a possibility to manipulate the frictional drag in the wall turbulence.

3. EXPERIMENTAL RESULTS and DISCUSSION

Figure 7 shows the velocity and vorticity distributions in *x-y* plane at *Re*=7500. The laser was irradiated at *z*=250 mm, the midpoint between the sidewalls. In this paper, velocity and vorticity are described as color contour legends which are shown in Fig. 5. The low-speed structures are near the wall, though time averaged velocity and vorticity distributions did not have any characteristic spatial structure in this plane (Fig. 6). These coherent structures are called a “horseshoe-like vortex”. Rapid ejection of these low-speed structures from the plate is also well known as “bursts”. Thus the frictional drag was generated between the low- and high-speed structures. Therefore, it was considered that the vortex by the friction is likely to form in places near the top and bottom wall. In Fig. 7 we can see brilliant blue and red fields where the friction concentrates and the increase in vorticity was caused. Since bursts occur intermittently, to elucidate the bursting phenomena it is useful to capture the time evolutions of velocity and vorticity. Figure 7 also shows that the spatial structures were preserved for a short time and flow when riding on the main stream.

Figure 8 illustrates the signal of velocity fluctuations in comparison with the displacement of an actuator. As the typical time scale T_B of the bursting interval is estimated that T_B equals 0.8 second using our channel. T_B corresponds to the averaged occurring frequency of bursts, f_T=1.25Hz. On the other hand, it is known that the frictional drag of turbulence is reduced by the compliant wall. The effective frequency of the compliant wall for drag reduction is considered to be higher than 10 of T_B (Choi, private communication). It can be interpreted since the effect appears when the wall’s eigenfrequency synchronizes not the bursting period but the bursting duration with 1/10 of T_B. Therefore the actuators should be oscillated in frequency higher than T_B. For this reason, the frequencies of the actuators, f_a, were set at multiples of 1.25Hz, for example 6.25, 12.5, and 125Hz.

Actuators are oscillated in the phase difference of 60 degrees each and moved in the wavy modes as shown in Fig. 4(b). Figures 10 also shows an outlook chart of the structures generated by the wavy mode in the vicinity of the wall. Spotted fields, where high and low speed streaks are mixed in together, will be formed. As a result, sine wave velocity fluctuations are caused in spanwize direction. In Choi, et al.’s (1998) experiment using a rectangular channel, 20% of the frictional drag was reduced by spanwise oscillation of a channel wall. This research is similar to their experiment in the meaning of inducing flow in spanwise direction.

Figures 9 show the snapshot of velocity distributions at *y*=5 mm from the bottom plate for Reynolds number, *Re*=7500. CCD camera was set in 15mm upstream from the actuator array and images were acquired in 30 mm x 30 mm of *x-z* plane. *y*=5 corresponds to 50 times of well unit, y^+=50 where mean velocity is about *U*=0.15 m/sec (Red zone in Fig. 9(a).) The special scale length between streaks was found as about 10 mm, which is close to empirical value *l*, for *Re*=7500. We can see in Fig. 9(a) that fine spatial structures stay in the *x-z* plane. On the other hand, the low-speed streaks are blurred for the frequency of actuators more than f_a=125Hz as shown in Fig. 9(d). Their shapes indicate that the spatial structures can be made to disappear by an active control.

Here we consider how a disturbance of 0.1mm ejected from the stationary plate by the actuator grows at 15 mm upstream in the *x* direction. The growth size *d* of disturbance is introduced as:

$$d \approx 5\sqrt{\frac{xn}{U_f}}$$

where U_f is the free stream velocity and 0.18 m/sec in this experiment. Therefore the length scale of growth is estimated as *d* =4.5 mm for *Re*=7500. As *d* comparable to the length scale of streaks, disturbances can interact with streaks sufficiently.

It is considered not to be nontrivial that the low-speed streaks disappear by such periodic inputs because the motions of turbulent structures are not stationary and don’t always synchronize with the periodic motion of disturbances by actuators. In one case, an actuator can move by synchronizing phase with the coherent structures and with the opposite phase in the other case. The former will activate the systematic structure, and the latter inhibit them, if the phenomenon near wall responses linearly. Therefore it seems that these phenomena is nonlinear and the disturbances always diffuse the coherent structures.

It is also well known that some artificial streaks with the regular interval on the wall, called riblets, can reduce the flow drag (For example Walsh et al. (1984)). It is considered that the similar nonlinear phenomenon occurs near the riblets because the convexes of the riblets don’t always agree with the positions where low-speed streaks stay. It is also same about the concaves. To restricting the motion of streaks and tidy them up along the riblets seems the reason why the riblets have the effect of the drag reduction. The control method, enumerating artificially, in this study is similar to the riblets but seems to be smart for flexible corresponding for the various flow conditions.

The velocity of the progressive wave generated by wavy mode of actuator array is U_s=0.30 m/s at f_a=12.5 Hz in spanwize direction. As the free stream velocity is U_f=0.18 m/sec, Thus the ratio of the spanwise velocity to the free stream velocity is U_s/U_f=1.7. On the other hand, the amplitude of the spanwise velocity component in Choi et al.'s experiment is estimated to be U_s=1.5 m/sec at maximum as against U_f=2.5 m/sec. Thus the ratio of the spanwise velocity to the free stream velocity is U_s/U_f=0.6. Because U_s/U_f is much larger than that of Choi et al. (1992), the frictional drag can be reduced in this experiment though it has not been observed yet.

In these circumstances, it was proven that the coherent structures existing in the vicinity of the wall can be interacted with the disturbance by actuator array, and an experiment for actively control of turbulent flow was shown in this study.

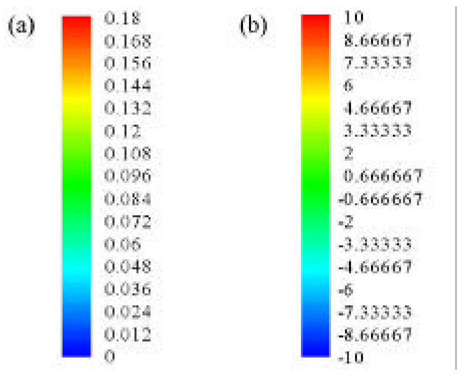


Figure 5 (a) Contour legend of velocity. (b) Contour legend of vorticity.

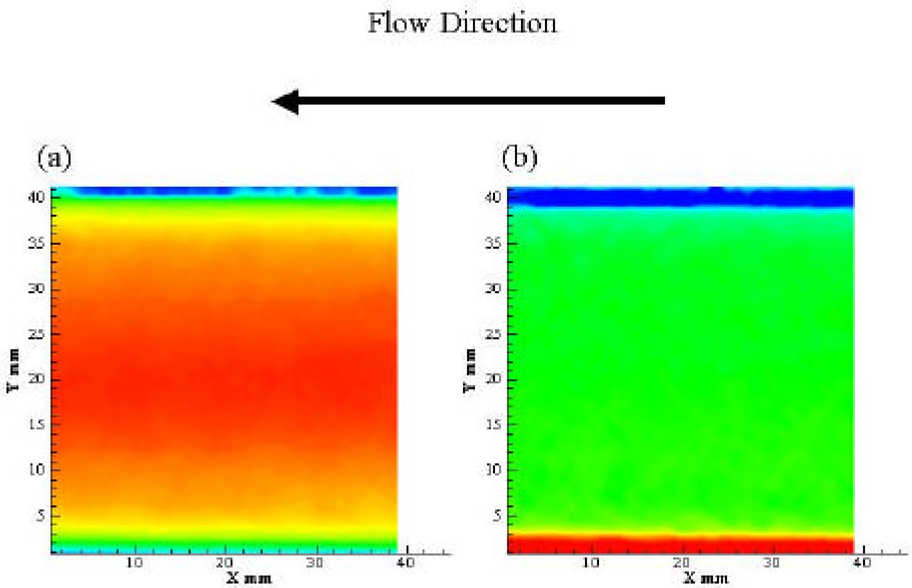


Figure 6 (a) Averaged velocity distributions in *x-y* plane at *Re* =7500. Vectors 48 pictures. Actuators are placed at *x*=20 mm.

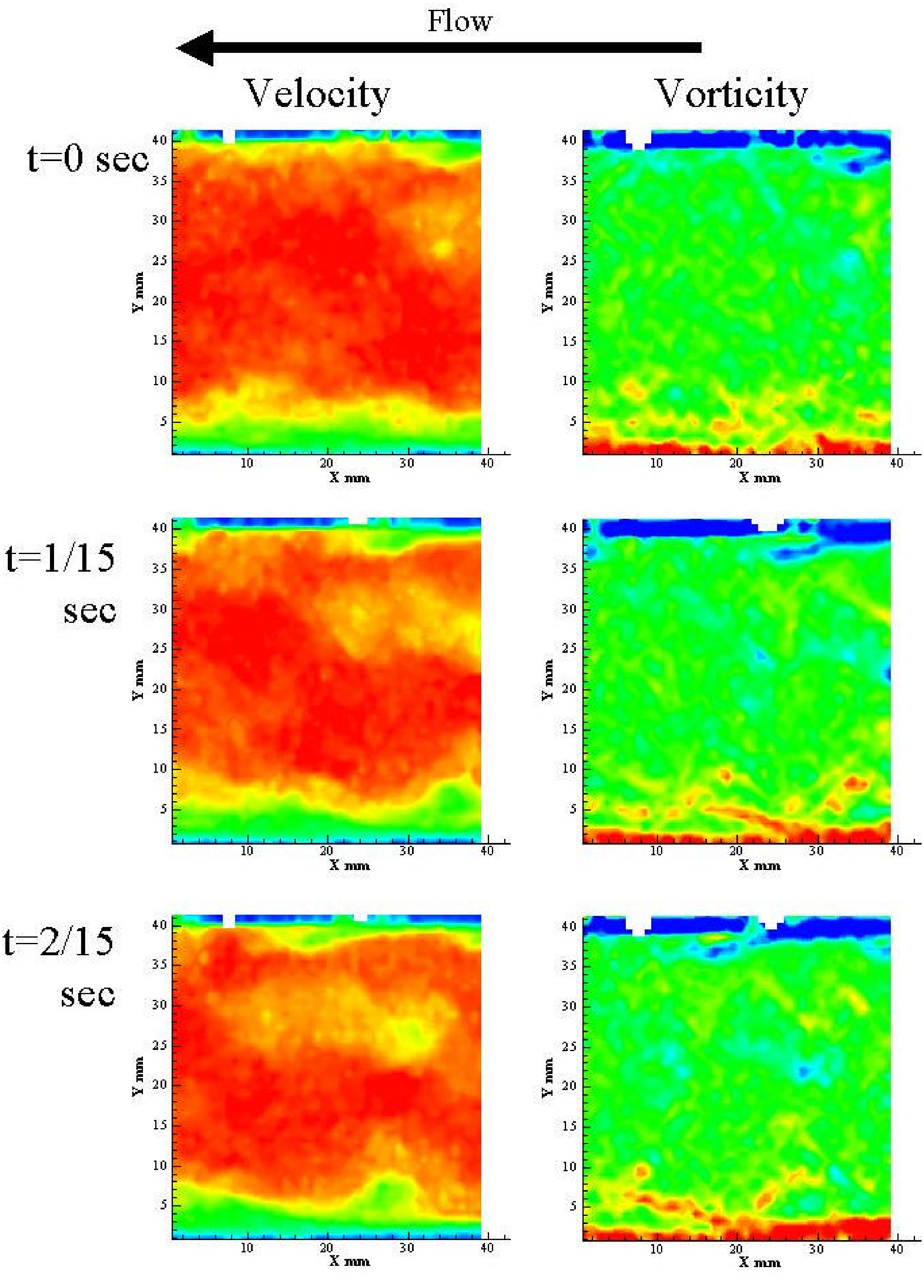


Figure 7 Time series of velocity and vorticity distribution in *x-y* plane. *Re*=7500. It flows from right to left. (a) Velocity. (b) Vorticity. Actuators are also placed at *x*=20 mm.

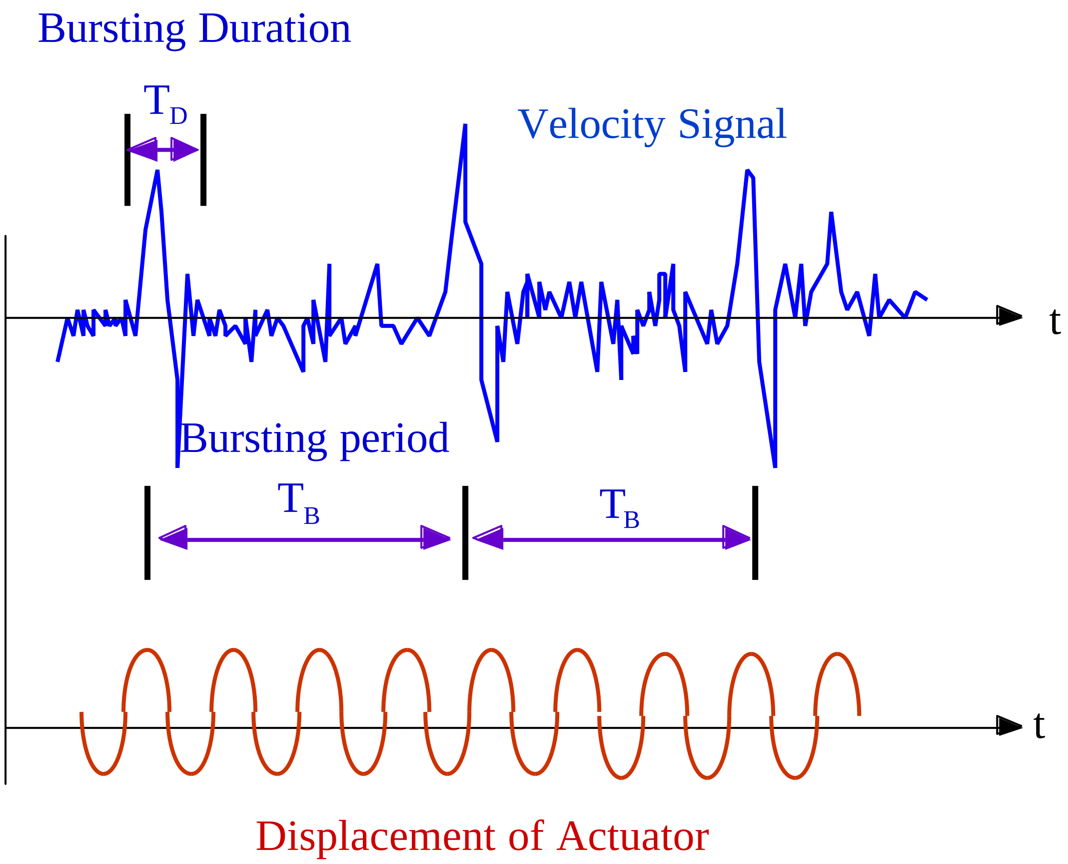
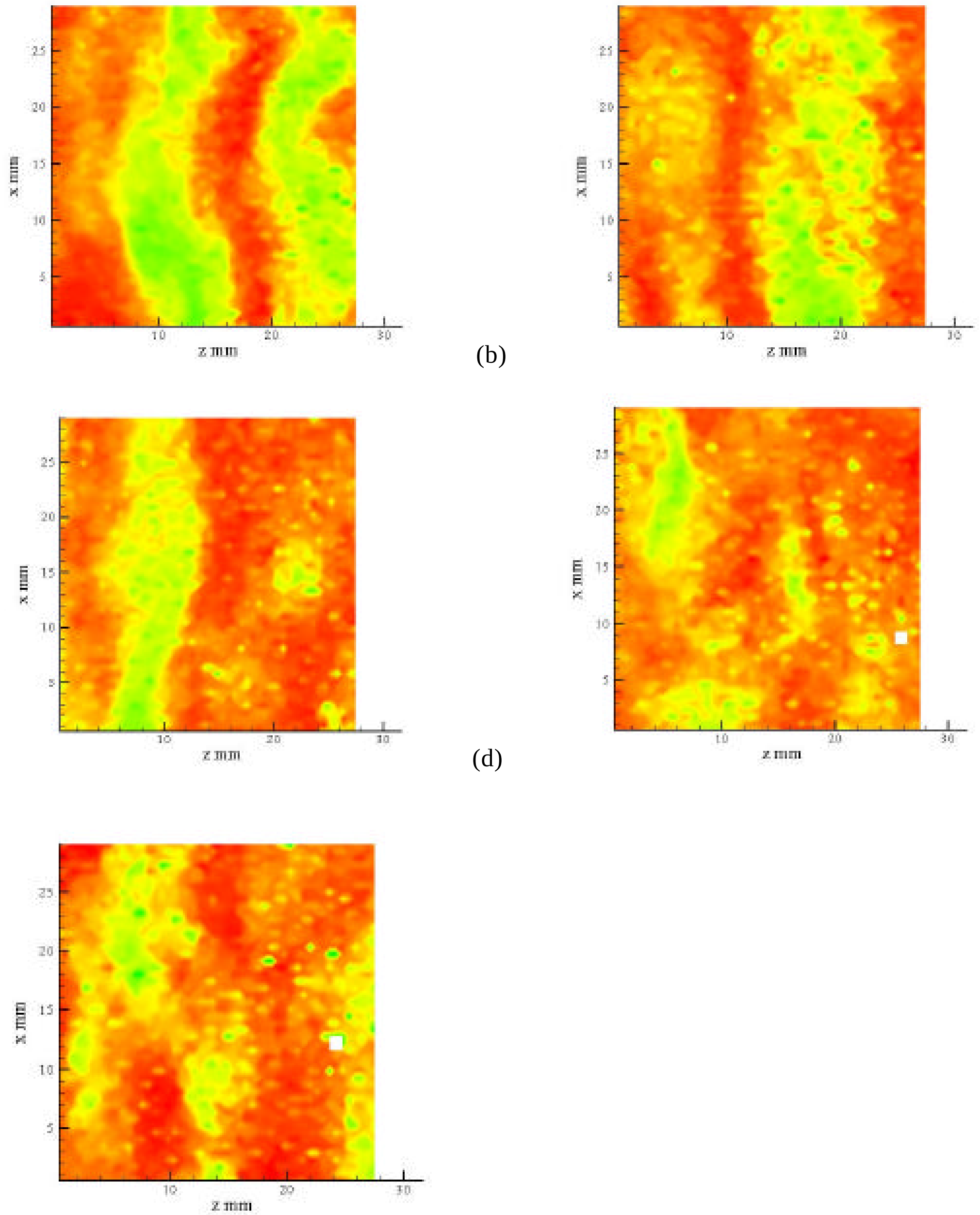


Figure 8　Schematic drawing of velocity fluctuation near the wall in comparison with displacement of actuator.



(a) (b) (c) (d) (e)

Figure 9 Typical velocity distribution in *x*-*z* plane, *Re*=7500.
(a) f_a=0 Hz, (b) 1.25 Hz, (c) 6.25 Hz, (d) 12.5 Hz, (e) 125 Hz.
Actuators are placed in 50 mm downstream.

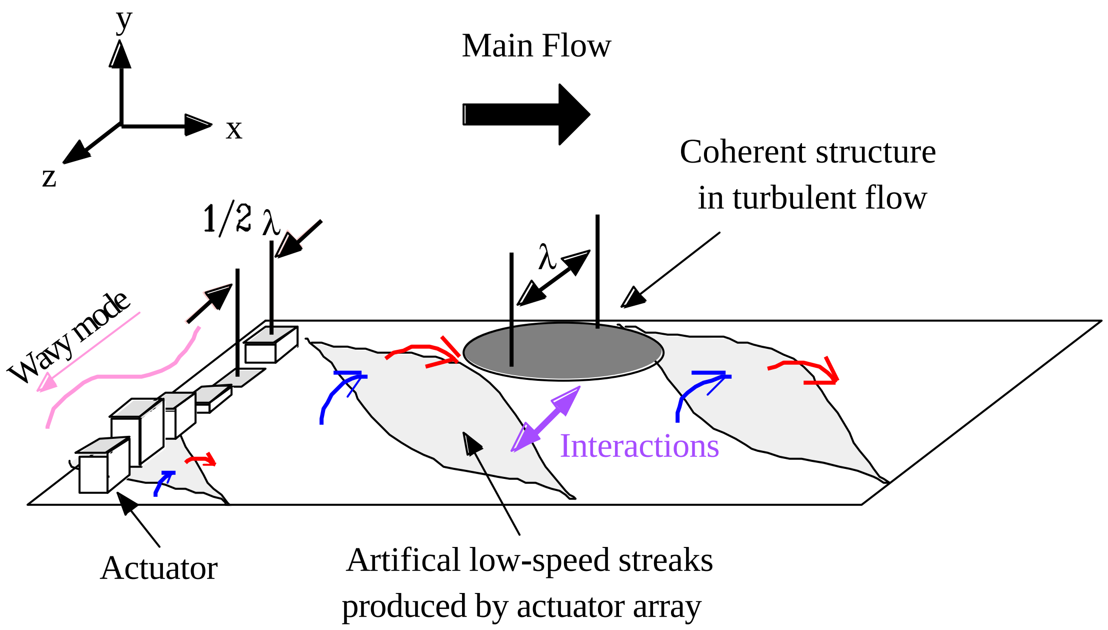


Figure 10 Schematic illustration of streaks.

4. CONCLUSIONS

The coherent structures of the turbulent flow in the channel flow for *Re*=7500 were analyzed using PIV. The main results are following as:

(1) The horseshoe-like structures and bursts which exist near the wall were visualized.
(2) The rapid separations of bursts from the wall caused local concentrations of vorticity and their spatial structures are preserved for a short time and flow while riding on the main stream.
(3) The regularity of the velocity distribution tended to decrease for the frequency of actuator more than f_a=12.5Hz, compared to when it was not controlled.
(4) . The length scale of growth of disturbances ejected from the wall by actuators is estimated as d =4.5 mm for *Re*=7500. These disturbances can interact with streaks sufficiently and the coherent structures can be made to disappear by an active control

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