ACTIVE CONTROL OF WALL TURBULENCE BY AN ACTUATOR ARRAY PRODUCING SPANWISE PERTURBATIONS

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ABSTRACT

Turbulent flow control using an actuator array and related modification of the turbulent spatial structure were experimentally examined using a channel system. Measurements by a particle image velocimeter (PIV) revealed that the actuator array can interact with the low-speed streaks near the wall and the regularity of streak-like coherent structures tends to decrease when the frequency of the wavy motion is more than 12.5 Hz. The critical frequency does not depend on the typical frequency of the burst interval, but may depend on the frequency introduced by the time scale of averaged burst duration.

INTRODUCTION

The control of turbulent flows using a micro electro-mechanical system (MEMS) is one of the most challenging recent topics in fluid engineering. In this study we tried to clarify 3-dimensional flow structures at the near-wall region when they are stimulated by artificial disturbances. Recent developments in flow visualization techniques using laser technology enable us to observe perspective views of the coherent structures in the wall turbulence, such as horseshoe vortices or streamwise vortices. Moreover, recent studies have provided hopeful results for controlling 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 could be in fact regulated to a certain degree.

Although active control technologies using actuator devices are under development, few examples of turbulent drag reduction by utilizing 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) used a numerical simulation to show the effect of spanwise oscillation on drag reduction. Laadhari et al. (1994) confirmed experimentally the significant effect of spanwise oscillation. Recently, Choi et al. (1998) carried out precise measurements of channel turbulent flow with spanwise oscillation and discussed 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 spanwise oscillation, Nakamura et al. (1998) indicated experimentally that wall oscillation in the direction normal to the wall 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 in 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 near the wall oscillation corresponds to the cross-flow in the channel.

During the last three decades, extensive efforts have been made to clarify the ordered or coherent motion in wall turbulence. An important finding 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 and sweep which is the in-rushing movement of high-speed fluid to the wall.

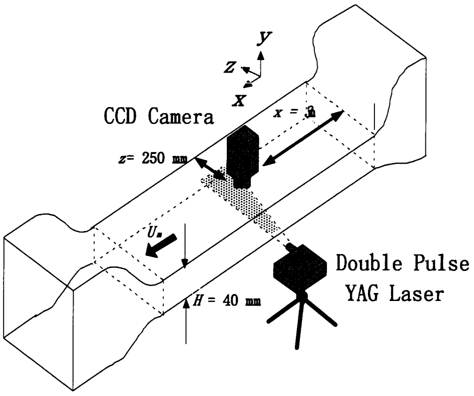

Figure 1: The closed-loop water channel system.

This gives us some clues about how to control turbulent flow drag with regard to this movement. If we can produce a proper artificial disturbance, or control input, to cancel the aforementioned near-wall coherent structures, it may be possible to manage flow drag more efficiently. This strategy can be called a "controlled active method" as opposed to conventional active methods.

For the purpose of optimizing the design and drive condition of the actuator array, information on the spatial structure of the near-wall turbulence is necessary. Although LDV is applicable to the near-wall region, the measurement is limited to 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 greater understanding of turbulent flow and how to reduce turbulent frictional drags.

EXPERIMENTAL SETUP

Water channel

A schematic drawing of the closed loop water channel is shown in Fig. 1. The channel is made of transparent acrylic plates to allow the flow to be visualized by a laser sheet, and filled with bubble-free water which is kept at a temperature T of 30°C by a cooling-heating system. The test section was 40 mm high (H), 500 mm wide (W), and 6000 mm long (L). A series of experiments was carried out at Reynolds number, Re = 7500. The bulk mean velocity, u_m, and the height of channel, H, are chosen for the reference scales. The actuator array is set in the top wall of the channel at $x = 5$ m downstream of the test section inlet. The flow shows a fully developed turbulent flow around the measuring point.

The averaged interval (λ) of low-speed streaks, which exist in the vicinity of the wall, is known to be estimated by:

$$\lambda \approx 100 \frac{\nu}{u_\tau}, \qquad (1)$$

where ν is the kinematic viscosity and u_τ the frictional velocity. The low-speed coherent structures can be found at 8 mm intervals at Re = 7500 using our water channel system.

The time scale on the burst intervals should be estimated to change flows and control bursts or horseshoe vortices by active control. Luchik et al. (1987) reported on the averaged time between bursts, T_B. The non-dimensional time scale T of the burst interval is defined as:

$$T = \frac{u_m T_B}{\frac{1}{2} H}. \qquad (2)$$

For Re = 7500, we estimated that $T = 0.6$ and T_B = 0.8 second in our channel. Thus the averaged frequency of burst interval, f_B, was introduced as $f_B = 1/T_B = 1.25$ Hz.

Actuator array

To determine whether spanwise perturbations caused by an actuator array can interact with coherent structures in the vicinity of the wall, a laminated piezo-ceramic element was selected as the material. Figure 2 (a) shows a 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 an actuator is more than 100 μm at 160 volts. The frequency response ranges from 0 to 1 kHz. A layout drawing of an actuator array is shown in Fig. 2 (b). In the spanwise direction, eight actuators are arranged at $d = 4$ mm intervals, which corresponds to half of the typical length scale of streaking intervals. They can be oscillated independently at various phase differences from each other using six synchronized signal generators (NF Electric Instruments Co., NF1946). The actuator array is moved in various modes. In this experiment, "wavy mode", "gathering mode" and "alternating mode", as shown in Fig. 3, are tested to control coherent structures near the wall of channel turbulence.

PIV measurements

The system setup for visualizing the flow is illustrated in Fig. 1. 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 25 mJ per pulse was set over the channel system. By changing the combinations of the cylindrical lenses, the laser sheet thickness can be modified from 0.14 mm to 0.6 mm and the spread angle from 4.3 deg to 13.3 deg. The images were photographed with a CCD camera at 1008 x 1018 resolution (PIVCAM 10-30, TSI Model 630046) and the velocity vectors were also analyzed by PIV software (TSI, Insight NT). The maximum frequency of the pulse was 15 Hz. Thus the time series of velocity and vorticity distributions were acquired as shown within a 0.1 second interval using the PIV system. Globular aluminum oxide (Al_2O_3), which is 3 mm in diameter, was used as the seeding particle to obtain the images of the flow. By combining various lenses attached to the CCD camera, visualizations of the region from 2 x 2 mm to 40 x 40 mm were possible. The surface was covered with matte black film to prevent reflection of the laser light on the wall of the channel.

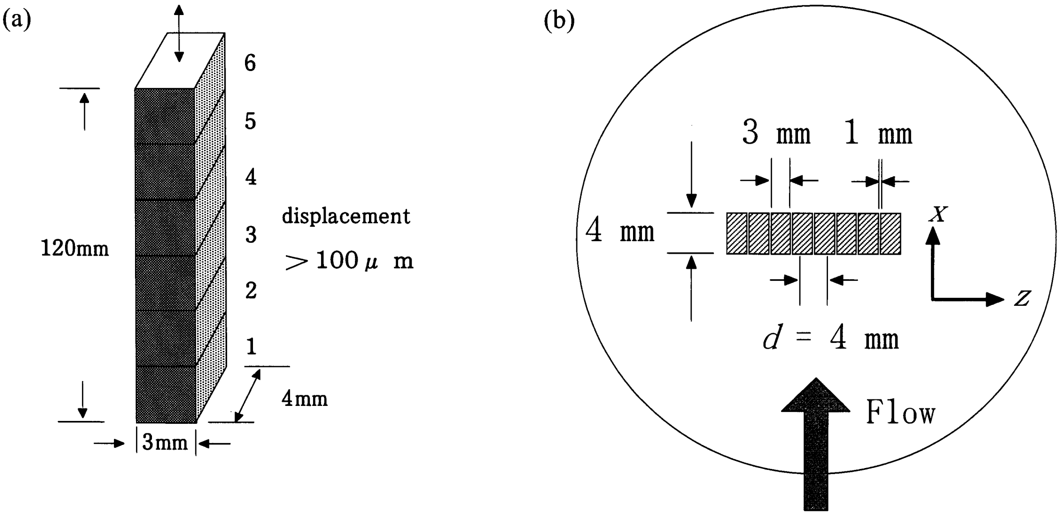

Figure 2: (a)Schematic drawing of an actuator which consists of six laminated piezo-ceramic elements. (b) Layout drawing of the actuator array. Eight actuators are arranged in spanwise direction.

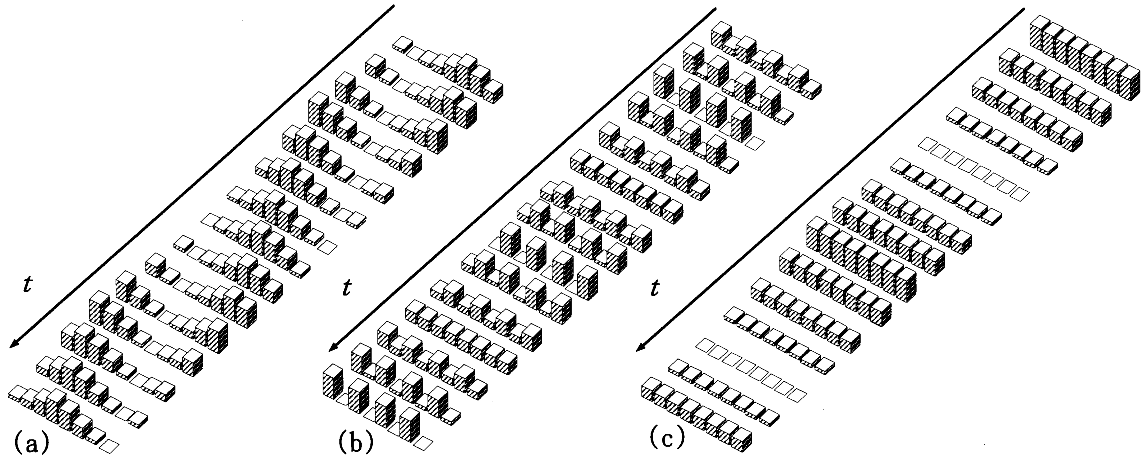

Figure 3: Schematic drawings of time evolution of surface shapes. (a) Wavy mode, (b) Alternative mode, and (c) Gathering mode.

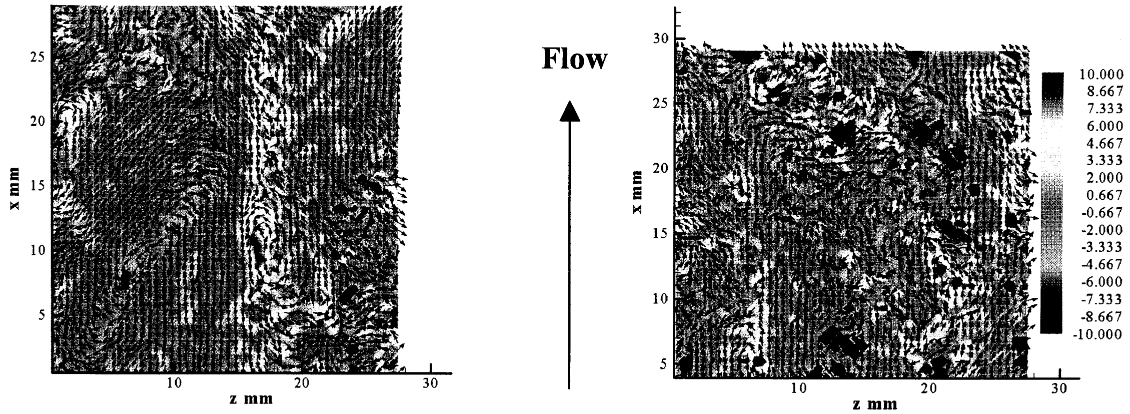

Figure 4 Instantaneous velocity (vectors) and vorticity (color contours) distributions of x-z plane at $y = 5$ mm to ($y^+ = 50$) visualized by PIV. (a) No control. (b) $f_a = 125$ Hz. Actuator array is set 15 mm upstream. Velocities corresponding to mean value of visualized area have been subtracted from all vectors.

RESULTS AND DISCUSSIONS

Uncontrolled mode

Figure 3 (a) shows an instantaneous velocity distribution in the *x-z* plane at $Re = 7500$. The CCD camera was set at 15 mm downstream from the actuator array and images were acquired in 30 mm x 30 mm of the *x-z* plane. The laser was irradiated at $y = 5$ mm. $y = 5$ mm corresponds to 50 wall units, $y^+ = 50$, where mean velocity is $u_m = 0.15$ m/s. Two streaks are arranged at 10 mm intervals. Although we obtained 500 pairs of pictures in an experiment, the typical length scale of streaking intervals was found to be close to 100 wall units. We also found that the vorticity in the *x-z* plane concentrates in the edges of streaks. Since bursts occur intermittently, it is useful to capture the time evolutions of velocity and vorticity for elucidating the bursting phenomena using PIV. By analyzing the time series of velocity distributions, it is found that several coherent structures ride on the main stream and are preserved for a short time. This indicates that feed-forward active control of coherent structures can be performed if we can detect the bursting and sweeping by sensors and prevent such bursting and sweeping.

Wavy mode

For investigating whether artificial disturbances can interact with the streaks in the vicinity of the wall, variations of the velocity distributions in the *x-z* plane were tested using the actuator array. In "wavy mode", eight actuators oscillate from $f_a = 0$ to 1 kHz with the phase difference of 45 degrees to each other as shown in Fig. 3 (a). Thus the wavelength in this mode is set to be 400 wall units. Because the actuators are arranged in the spanwise direction, spanwise perturbations are applied to the fluid near the wall. From eq. (2), the typical time scale T_B of the burst interval was estimated to be 0.8 second using our channel. T_B corresponds to the averaged frequency of occurrence of bursts, $f_B = 1.25$ Hz. In this study, the frequencies of the actuators, f_a, were set at multiples of f_B, for example at 6.25, 12.5, and 125 Hz, which correspond to $5\,f_B$, $10\,f_B$ and $100\,f_B$.

There are streaks for the frequency of the wavy mode less than $f_a = 10$ Hz, as same with the uncontrolled case. However, the low-speed streaks are blurred for actuator frequencies over $f_a = 12.5$ Hz as shown in Fig. 4 (b), which is instantaneous velocity and vorticity distributions at $f_a = 125$ Hz. This shape indicates that the spatial structures can be made to disappear by active control. The critical frequency, $f_a = 12.5$ Hz at which the coherent structures were destroyed, seems to correspond to $10\,f_B$. At present, we assume that the critical frequency $f_a = 12.5$ is not of the same order as $1/T_B$, but the typical time scale of the burst duration, T_D. If this is true, the averaged burst duration should be 1/10 of T_B ($=10\,f_B$). We will measure the time series of the velocity fluctuations using a hot-wire anemometer or laser Doppler velocimeter (LDV) to clarify the mechanism of destruction.

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

$$\delta \approx 5\sqrt{\frac{x\nu}{u_f}}, \qquad (3)$$

where u_f is the free stream velocity and is 0.18 m/s in this experiment. Therefore the length scale of growth is estimated as $\delta = 4.5$ mm for $Re = 7500$. As δ is comparable to the length scale of streaks, disturbances can interact with streaks sufficiently.

In this study, the spanwise perturbations may be generated by the wavy mode in the vicinity of the wall. Spotted fields, where high- and low-speed streaks are mixed together, are formed. As a result, sine wave velocity fluctuations can be caused in the spanwise direction. Figure 5 (a) shows the averaged velocity distribution of 500 pictures in wavy mode. The actuator array is set at the edge of the right side. We can find several ordered structures even if averaged, which also indicates that the spanwise perturbations are caused by the wavy motion of the actuator array.

Alternating and gathering modes

We tried to generate the spanwise flow by oscillating the actuator array in two other modes, alternating and gathering modes, which are distinct from the wavy one. In alternating mode, actuators oscillate with the phase difference of 180 degrees from the next one. All actuators move without phase difference in gathering mode.

The alternative mode can give spanwise perturbations to downstream flows from the actuator array. The length scale of active control is 8mm, which is equal to 100 wall units. Therefore the special resolution is 4 times higher than in case of the wavy mode. Figures 5 (c) and (d) show the averaged velocity distribution in the *x-z* plane in the case of alternating mode. We can also find several structures the same as with the case of wavy mode.

On the other hand, the gathering mode does not give spanwise perturbations, but streamwise. There is no special structure in the case of gathering mode as shown in Fig. 5 (b). This may show that the cross-flow generated by the spanwise perturbations is effective to interact with the coherent structures. At present, we are trying to measure the velocity distribution in the vicinity of the wall by PIV and LDV and analyze the statistical quantities of them to find whether spanwise flow is generated by these modes.

Drag reduction by spanwise oscillations

In the experiment of Choi et al. (1998) using a rectangular channel, 20% of the frictional drag was reduced by spanwise oscillation of a channel wall. Our research is similar to their experiment with regards to inducing flow in the spanwise direction. It is also well known that some artificial streaks with regular intervals on the wall, called riblets, can reduce the flow drag (for example, as reported by Walsh et al. (1984)). It is considered that a similar nonlinear phenomenon occurs near the riblets because the convex parts of the riblets do not always agree with the positions where low-speed streaks are seen. This is also the same for the concave parts.

Restricting the motion of the streaks and tidying them up along the riblets seems to be the reason why the riblets have the effect of reducing drag. Our control method, enumerating artificially, is similar to the riblets but seems to be smart to flexibly correspond to various flow conditions. Endo et al. (2000) carried out direct numerical simulations of an active flow control using a sensor array and an actuator unit. The actuator that they proposed in their simulation can deform and create disturbances to cancel the vorticities of streaks in the vicinity of the wall. Using their method, it was found that streak structures near the wall could be ordered along the flow direction and could decrease the frictional drag as well as riblets.

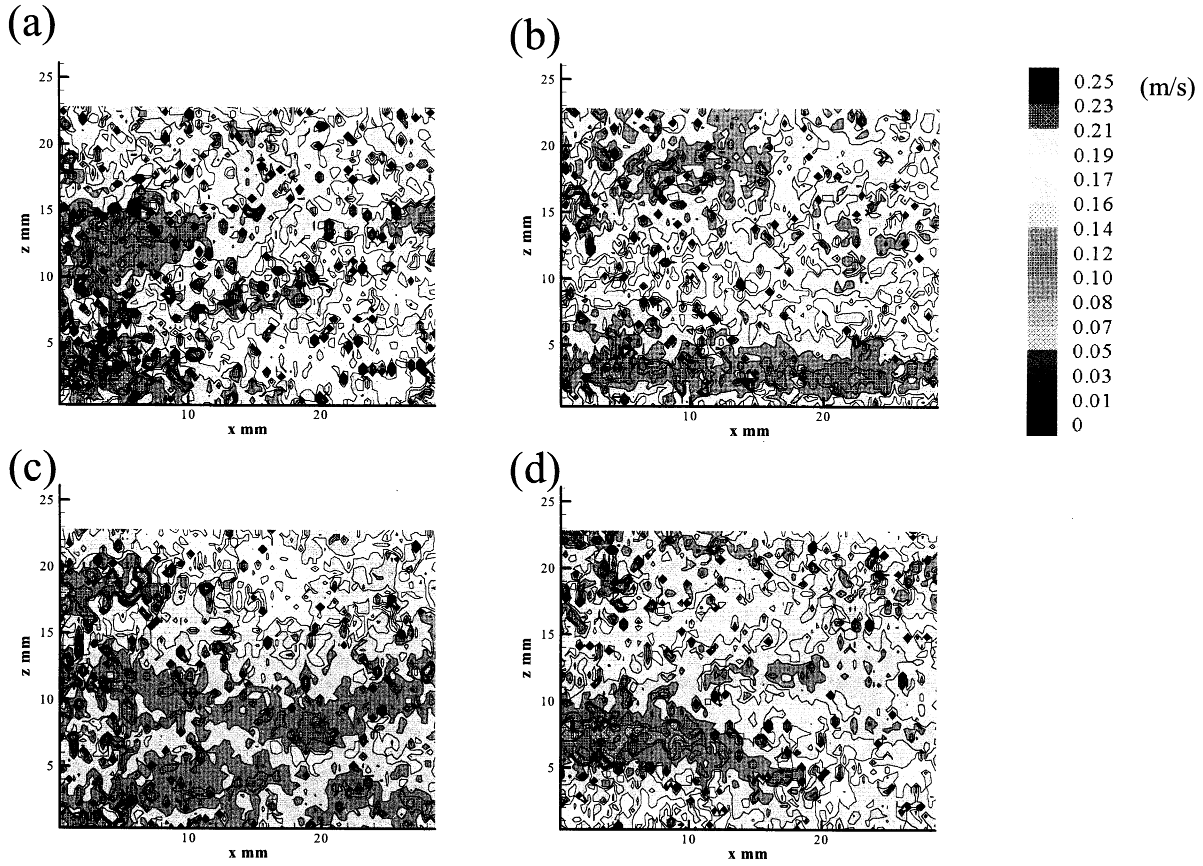

Figure 5: Contour legend of velocity. (a) Wavy 200, (b) gatheing 200 Hz, (c) alternative 100 Hz, and (d) alternative 25 Hz.

On the other hand, it is known that the frictional drag of turbulence is reduced by a compliant wall. Choi (2000) indicated that the effect appears when the wall's natural frequency synchronizes with not the burst period but with the burst duration. Although the typical time scale of the burst duration could not be reported in our experiment, it should be much shorter than T_B. Choi's interpretations provide clues for optimizing the control of streaks and thus reducing turbulent drag.

CONCLUSIONS

The coherent structures of turbulent flow in a channel flow for $Re = 7500$ were analyzed using PIV. The main results are as follows:

(1) The horseshoe-like structures in the vicinity of the wall were visualized by PIV.
(2) The rapid separations of bursts from the wall caused local concentrations of vorticity and their spatial structures were preserved for a short time and flow while riding on the main stream.
(3) The regularity of the velocity distribution tended to decrease at actuator frequencies over $f_a = 12.5$ Hz, compared to the uncontrolled case. It may be caused by not the burst interval, but by the burst duration.
(4) The averaged velocity distributions by wavy and alternating modes show that the cross-flows can be generated by the spanwise motion of the actuator array.

With these conditions, it was proven that the coherent structures in the vicinity of the wall can be made to interact with the disturbance using an actuator array, and an experiment for active control of turbulent flow was described in this study.

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REFERENCES

Choi, K.-S., DeBisschop, J.-R. and Clayton, B. R., 1998, "Turbulent boundary-layer control by means of spanwise-wall oscillation", AIAA Journal, vol. 36, pp. 1157-1163.

Choi, K.-S. and Graham, M., 1998, "Drag reduction of turbulent pipe flows by circular-wall oscillation", Phys. Fluids 10, pp. 7-9.

Choi, K.-S., 2000, "Turbulent drag-reduction mechanisms: strategies for turbulence management", Springer-Verlag Lecture Notes, to be published.

Choi, H., Moin, P. and Kim, J., 1994, "Active turbulence control for drag reduction in wall-bounded flows", Journal of Fluid Mechanics 262, pp. 75-110.

Endo, T., Kasagi, N. and Suzuki, U., 2000, "Control of wall shear turbulence with arrayed micro sensor/actuator units" Proc. 4th JSME-KSME Thermal Engineering Conference, vol. 3, pp. 493-498.

Jung, W. J., Mangiavacchi, N. and Akhavan, R., 1992, "Suppression of turbulence in wall-bounded flows by high frequency spanwise oscillations", Physics of Fluids A4, pp. 1605-1607.

Laadhari, F., Skandaji, L. and Morel, R., 1994, "Turbulence reduction in a boundary layer by a localspanwise oscillating surface", Physics of Fluids A6, pp. 3218-3220.

Luchik, T. S. and Tiederman, W. G., 1987, "Timescale and structure of ejections and bursts in turbulent channel flows", Journal of Fluid Mechanics 174, pp. 529-552.

Nakamura, M., Sakai, E., Igarashi, O. and Masaoka S., 1998, "Experimental study on the pressure distribution of a flow through a two-dimensional cannel with oscillating wall", Nagare 17, 444 (in Japanese).

Segawa, T., Yoshida, H., Kikushima, Y. and Tsutsui, Y., 2000, "An attempt of active flow control in rotating disk system", Proc. ASME Pressure Vessels and Piping Conference, Emerging Technologies in Fluids, Structures, and Fluid/Structure Interactions Vol. 2, pp. 133-118.

Stuart, A., Jacobson, A. and Reynolds C. W., 1998, "Active control of streamwise vortics and streaks in boundary layers", Journal of Fluid Mechanics 360, pp. 179-211.

Walsh, M. J. and Lindemann, A. M., 1984, "Optimization and application of riblets for turbulent drag reduction", AIAA paper 84-0347.