DIRECT MEASUREMENT OF WALL-SHEAR STRESS OF PLANE SHEAR LAYER WITH PLASMA SYNTHETIC JET ACTUATOR

Kakuji OGAWARA*, Shinsuke MOCHIZUKI*, Takehiro HIGUCHI*
***Yamaguchi University, Faculty of Engineering**

Keywords: *Wall Shear Stress, Flow Control, Direct Measurement, Plasma Synthetic Jet Actuator*

Abstract

One of the useful ways to measure the effect of the flow control devise is to use the wall-shear stress sensor to measure the wall-shear stress directly. The sensor used in this study measures the force produced by the wall-shear stress, which is reduced by the flow control devise. In this paper, the wall-shear stress of the plane turbulent shear layer with the plasma synthetic jet actuator (PSJA) is investigated. PSJA is a flow control device composed of electrodes with A.C. signal. The actuator uses electrohydrodynamic (EHD) effect and induces flow around the electrodes. Plasma synthetic jet actuator has great advantage such as the miniaturization, maintenance free, and easy to control compared to other actuators. In this paper, the wall-shear stress of the flow in a low-speed wind tunnel is observed to experiment the effect of the PSJA to the plane turbulent shear layer. The results show that the PSJA changes the flow condition of shear layer by accelerating the flow in the shear layer.

1 Introduction

The synthetic jet actuators are studied as the flow control devise. The PSJA is one of these actuators with the plasma actuator, which induces jet with the A.C. glow discharge. As studies related to PSJA, Sherman et al. has shown the drag reduction on a flat plate with plasma actuator [1]. Corke et al. has presented the suitable electrodes shape of plasma actuator for flow control on airfoil [2][3][4].

The authors have been studying the PSJA with electrode shape to induce 3-D jet for separation control. In experimental investigation of this PSJA, the NACA0012 airfoil had effect of drag reduction up to 29% [5]. In numerical study, the optimum position of electrode and the combination of PSJA was studied [6][7][8].

Various studies are held about the PSJA, but none has measured the wall-shear stress of the PSJA directly by the wall-shear stress sensor. In this paper, the wall-shear stress sensor directly measures the wall-shear stress and the effect of the PSJA to the wall-shear stress is investigated.

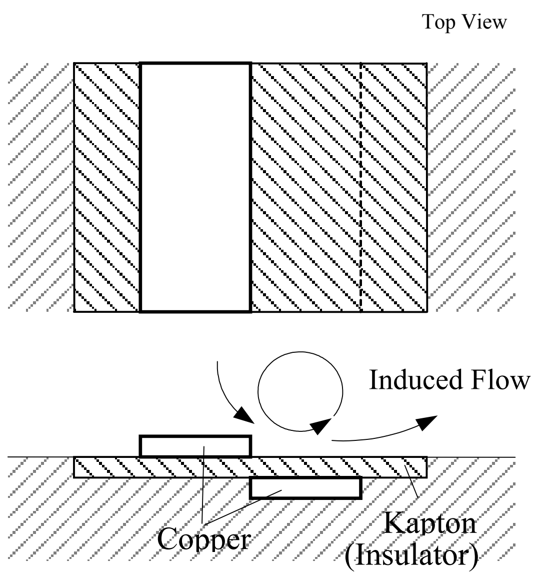

Fig.1 S – S type PSJA

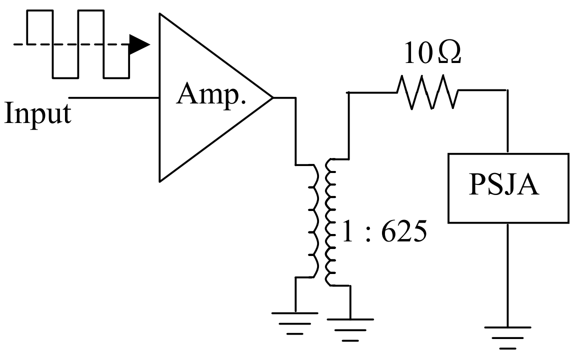

Fig.2 Schematic view of circuit

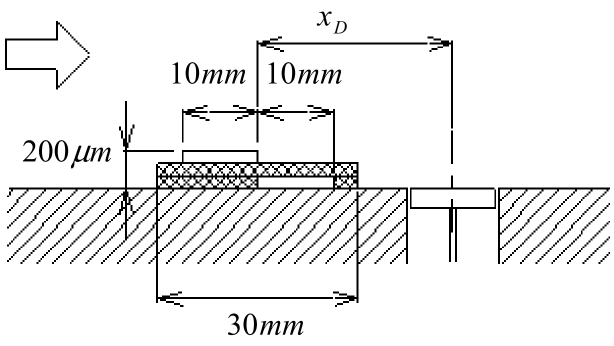

Fig.3 Schematic view of experimental setup

2 Plasma Synthetic Jet Actuator

Schematic view of PSJA for 2-D jet proposed by Corke et al. is shown in figure 1. This actuator is composed of anode and cathode with 50 [μm] thick copper tape and polyimide film for insulator between anode and cathode. This is called Strip - Strip type (S-S type) PSJA. The electrodes and insulator are arranged perpendicular to the flow direction, and anode is set in the upper side of the flow. Figure 2 is schematic view of circuit to operate PSJA. This actuator is supplied by high voltage A.C. input of rectangle wave using a signal generator (Hewlett Packard, 3312A Function Generator). The input voltage is amplified by power amplifier (Sony, Integrated Stereo Amplifier TA-V7700) and transformer (UNION, 1 : 625) is used to operate PSJA. In the experiment, the input voltage to PSJA is around 2500 [*V*] and the frequency is 500 [*Hz*].

Mechanisms to induce flow including electric force is shown in equation (1) ,

$$\mathbf{F}_b = \frac{1}{2}\varepsilon_0 \nabla \mathbf{E}^2 \qquad (1)$$

where $\mathbf{F}_b$ is the body force per volume, ε_0 is the permittivity of the free space, and $\mathbf{E}$ is the electric field strength[2]. This body force enables PSJA to produce the flow shown in figure 1. The PSJA actuates without mechanical devices, so there are no deterioration. Also, the devise is simple so the miniaturization is possible and since the input is simple, the active control on the flow is easy to conduct.

3 Wind Tunnel and Wall-Shear Stress Sensor

Wall-shear stress is measured in the low speed wind tunnel with the size of 6000, 310, 900 [*mm*] (length, height, width). This wind tunnel is especially made for the measurement of the wall-shear stress of plane shear layer. The wind tunnel has ability to produce 25[*mm*] of turbulent boundary layer. Wall-shear stress sensor is placed on the plane wall of the wind tunnel and PSJA is embedded on upstream of the wall-shear stress sensor. Figure 3 shows the schematic view of the PSJA embedded in the low speed wind tunnel. The edge of the PSJA is treated smoothly to reduce the vortex produced by the shape of PSJA itself.

Wall-shear stress is measured by the wall-shear stress sensor shown in figure 3. The sensor measures the displacement of the floating element by the fluid friction force of the flow. The voltage is given as the displacement of the floating element. Figure 4 shows the schematic view of the wall-shear stress sensor and figure 5 is actual photo of the wall-shear stress sensor. The sensor has 100[*mm*] diameter flat plate to measure the wall-shear stress of the flow. The displacement sensor (Iwatsu Electronics, ST-0532A probe) works with the digital multi-meter (Advantest, R6411A) and a filter (NF Electronics Instrument, Dual Channel Programmable Filter 3624) to measure the

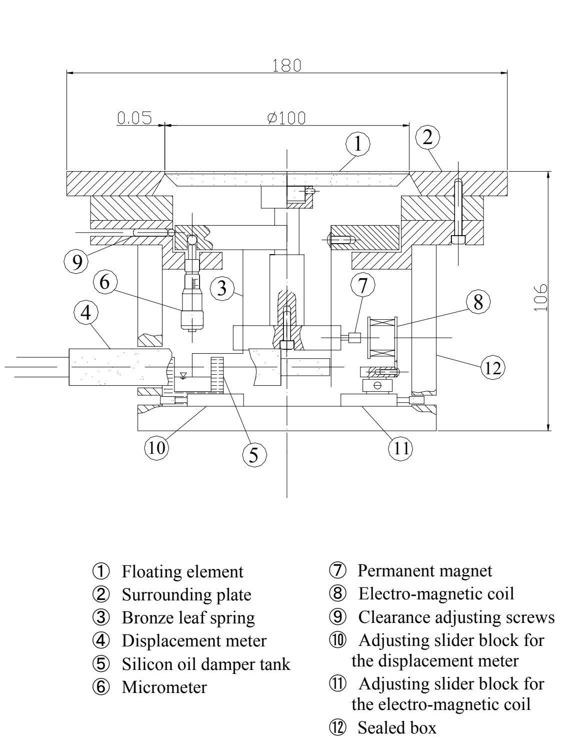

Fig.4 Schematic view of wall-shear stress sensor

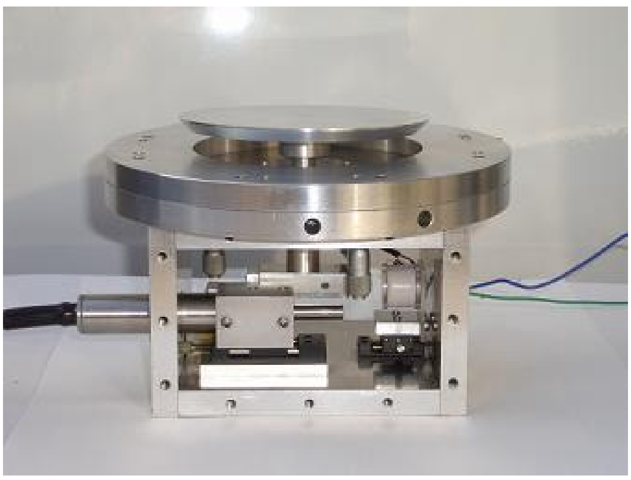

Fig.5 Photo of wall-shear stress sensor

displacement of the element, which is calibrated with the weight before the experiment gives the direct force of the wall-shear stress. The minimum measurement resolution is 0.002[μm] and the accuracy is ±1[%]. The gap between the floating element and the surrounding plate is

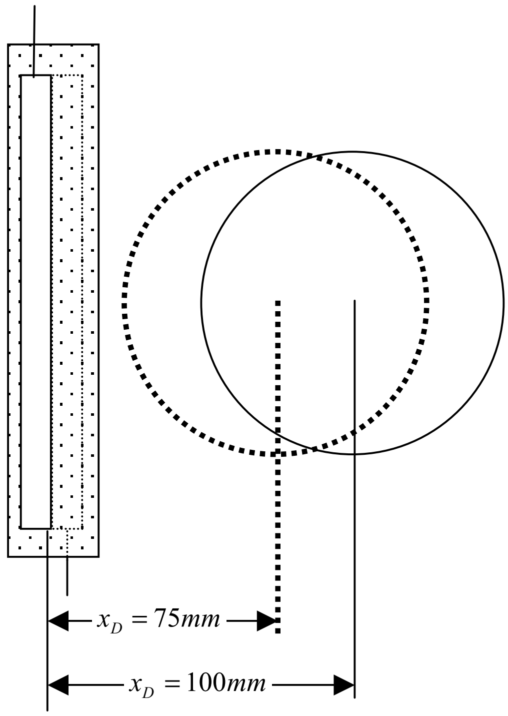

Fig.6 Top view of configuration

0.05[*mm*], which is small enough not to make any effect to the flow condition.

The mean flow velocity of the experiment is 12[*m/s*]. The Reynolds number is 1.59×10^6 and the kinematic viscosity coefficient is 1.572 $\times10^{-5}$[m^3/s] in the experiment.

4 Experimental Results

Figure 7 shows the output voltage from the direct measurement of the wall-shear stress sensor at the x_D=75[*mm*] downstream of the PSJA. Although the center of the sensor is 75[*mm*] downstream of PSJA, the radius of the sensor is 50[*mm*], so the sensor is measuring circular region from 25[*mm*] to 125[*mm*] as shown in figure 6. The horizontal axis of figure 7 is data number taken every 40[*sec*]. The bold line shows the condition of the PSJA, where on while the line is up and off while the line is down. Three different cases are shown in the graph with the same configuration. From this graph, in every case, the voltage lowers when the PSJA is on and the voltage enlarges when the PSJA is off.

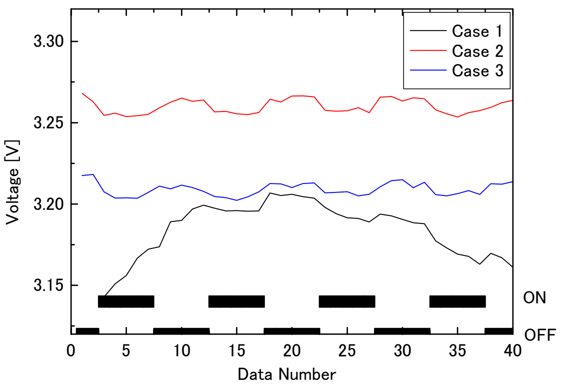

Fig.7 Output voltage by PSJA on/off
x_D=75*mm*, *u*=12*m/s*

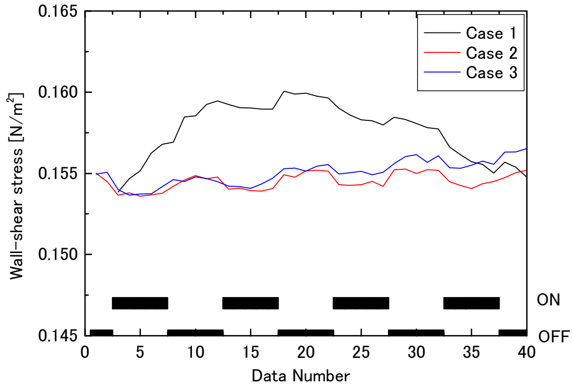

Fig.9 Wall-shear stress by PSJA on/off
x_D=75*mm*, *u*=12*m/s*

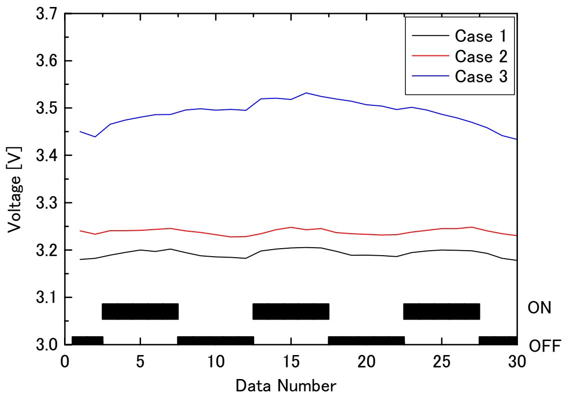

Fig.8 Output voltage by PSJA on/off
x_D=100*mm*, *u*=12*m/s*

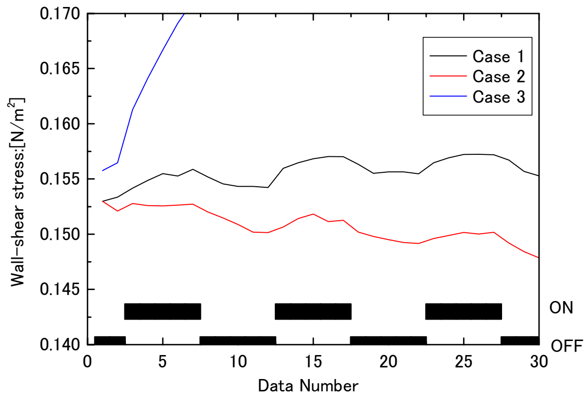

Fig.10 Wall-shear stress by PSJA on/off
x_D=100*mm*, *u*=12*m/s*

Figure 8 shows the same output voltage in case of x_D=100[*mm*]. The circular region of the floating element is 50[*mm*] to 150[*mm*]. The flow velocity is also 12[*m/s*]. In this graph, the output voltage enlarges when the PSJA is on and lowers when the PSJA is off. This leads to the result that the effect of the PSJA differs according to measurement place.

To measure actual wall-shear stress of plane shear layer with PSJA, the voltage measured in figure 7 and 8 is converted to the stress by following procedure. First the offset voltage (1.625[*V*]) is subtracted from the measured voltage. The difference is calculated by calibrated constant measured before the experiment, then the difference is calculated to the force on the flat plate.

The wall-shear stress in cases of x_D=75[*mm*] are shown in figure 9. In case 1, the result seemed to be smeared by environmental condition changes. The other 2 cases have similar results that wall-shear stress lowers when PSJA is on and returns to normal value when off. This shows that the PSJA has ability to reduce the wall-shear stress of plane shear layer in close region.

Figure 10 shows the wall-shear stress in the case of x_D=100[*mm*]. Different from the case of x_D=75[*mm*], the wall-shear stress rises when the PSJA is on. This shows that the PSJA is increasing the wall-shear stress in further regions.

Figure 11 and 12 is the average and errors of the wall-shear stress. Figure 11 clearly shows that the wall-shear stress decreases when the PSJA is on. The average stress lowers about 0.5[%] when the PSJA is on and off. Figure 12

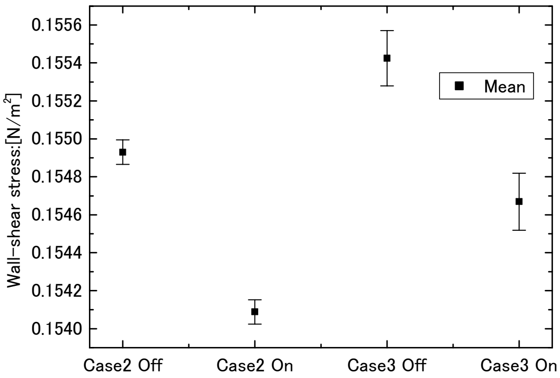

Fig.11 Average stress and errors
x_D=75*mm*, *u*=12*m/s*

Table.1 Effect of PSJA in different x_D

x_D	Average Wall-shear stress		Difference
	PSJA on	PSJA off	
[*mm*]	[mN/m^2]	[mN/m^2]	[%]
75	155.18	154.38	-0.51820
80	157.39	155.72	-1.07244
85	152.51	151.70	-0.53395
90	150.90	150.36	-0.35914
95	154.33	154.29	-0.02593
100	152.62	153.79	0.760778

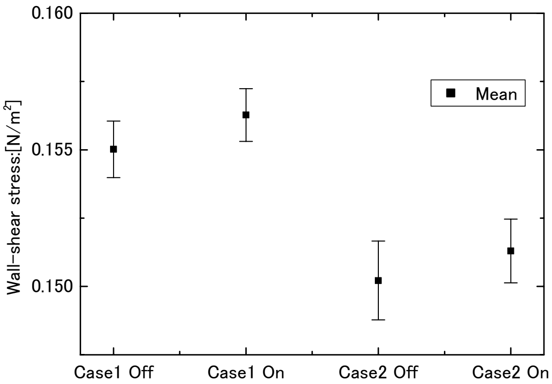

Fig.12 Average stress and errors
x_D=100*mm*, *u*=12*m/s*

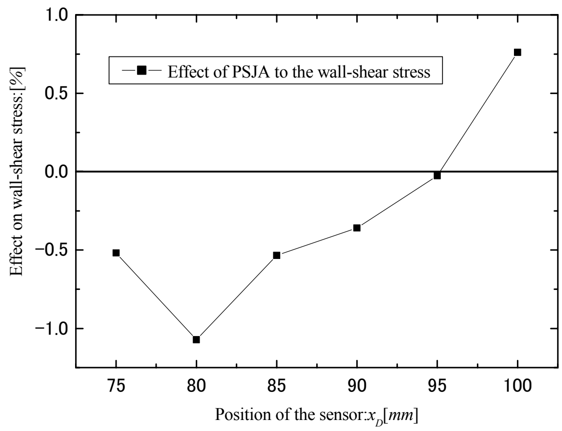

Fig.13 Effect of PSJA in different x_D

also shows the clear result that wall-shear stress increases when the PSJA is on which is totally different from case of x_D=75[*mm*]. The average stress increases about 0.7[%] when the PSJA is on and off.

From these results, the PSJA lowered the wall-shear stress in closer location of the actuator and enlarged the stress in further downstream positions. Since the PSJA is inside the turbulent shear layer, main cause of the stress is the Reynolds stress. This shows that the PSJA accelerates the flow in closer region and due to this acceleration the flow decelerates in the further downstream region, which lead to the decreasing and increasing of the wall-shear stress. The acceleration reduces the burst appears in turbulence shear layer in the closer regions to the PSJA[9].

To examine more detail of the PSJA effects on the wall-shear stress of the plane shear layer, the wall-shear stress is measured in different positions. The actuator was moved 5[*mm*] each between x_D=75[*mm*] and x_D=100[*mm*]. Table 1 shows the calculated results of every position. From these results, the PSJA lowers the wall-shear stress in the closer region up to x_D=95[*mm*]. Figure 13 shows the plotted data of difference in each x_D when the PSJA is on and off. The graph shows some tendency to lower its effect as goes downstream. The PSJA does not have strong ability to produce the flow to change the whole flow velocity, so as PSJA gets far, the effect of PSJA should decrease. But, effect of the PSJA is large in case of x_D=100 [*mm*], which clearly shows that the PSJA is increasing the flow velocity in close region and decreases due to the increased velocity in the further regions.

Conclusion

The wall-shear stress of plane turbulent shear layer with PSJA is measured directly by the wall-shear sensor in low turbulence wind tunnel. The results have shown that the PSJA reduces the wall-shear stress in the vicinity of PSJA and increases the stress in the further downstream region. This is due to ability of PSJA to blow the jet onto shear layer and increases flow velocity that lead to lowering the Reynolds stress as well as bursts appeared in turbulent shear layer.

PSJA is already known as the flow control devise to change the conditions of wakes of wing in high angle of attack. In this paper, we demonstrated another effect on the shear layer to change the wall-shear stress itself.

References

[1] Daniel M. Sherman, et al, "Electrohydrodynamic Flow Control with a Glow-Discharge Surface Plasma", AIAA J., Vol. 38, No. 7, July 2000

[2] Corke, T.C., Jumper, E., Post, M., Orlov, D. and McLaughlin, T. 2002. "Application of weakly – ionized plasmas as wing flow – control devices", AIAA paper, 2002 – 0350, 2002

[3] Post, M. and Corke, T.C., "Separation Control on high angle of attack airfoil using plasma actuator", AIAA paper, 2003 – 1024, 2003

[4] Post, M., Corke, T.C., "Separation Control using plasma actuators stationary and oscillating airfoils", AIAA paper, 2004 – 0841, 2004

[5] Kakuji Ogawara, Naoki Nakatani, Souichi Saeki, "Flow Control to the Surface on Airfoil with Plasma Synthetic Jet Actuator", JSME B, 2237-2242, Oct 2003

[6] Tadao Ueda and Kakuji Ogawara, "Numerical 3 – D Simulation for Control of Flow around an Airfoil Using Plasma Synthetic Jet Actuator", JSME, 03 – 0853, 2004

[7] Tadao Ueda and Kakuji Ogawara, "Numerical Simulation of Flow Induced by Plasma Synthetic Jet Actuator", JSME, 04 – 0297, 2004

[8] Tadao Ueda and Kakuji Ogawara, "Study on Optimum Location of Plasma Synthetic Jet Actuator Using Pseudo Viscosity Model", JSME, 04 – 0298, 2004

[9] S.J.Kline, et al., "The structure of turbulent boundary layers", Journal of Fluid Mechanics, vol 30, part 4, pp. 741-773, 1967