TOWARD SMART CONTROL OF SEPARATION AROUND A WING
-Development of an Active Separation Control System-

Akira Nishizawa , Shohei Takagi
National Aerospace Laboratory of Japan, Chofu, Tokyo, 182-8522
Hiroyuki Abe, Ryutaro Maeda, Hiro Yoshida
National Institute of Advanced Industrial Science & Technology, Namiki, Tsukuba, 305-8564

Abstract

In this study an active control system for separation was constructed. The system was composed of a flow-direction discriminator, a controller and an actuator with ejection. By using the system, laminar boundary layer was automatically prevented from separation on a downward slope. Through the control experiment, the discriminator fabricated by the MEMS technology was found to work well as a reverse-flow detector even in the unsteady flow. Prevention of the separation was made by disturbing the laminar boundary layer upstream of the slope using a speaker as a jet type actuator. A computer controlled those elements based on a simple feedback algorithm. Results of the present control system for unsteady separation flow gave us various important hints toward the smart control of flow separation around a wing.

1. INTRODUCTION

Control of flow separation has been obviously one of the most noticeable fluid engineering subjects. The potential advantages of applying separation control are expected to be great for various systems such as air, land, and sea vehicles; turbomachines; diffusers; and a variety of other technologically important systems involving fluid flow (Gad-el-Hak 2000). There are large numbers of investigations on actuation methods of control of flow separation. Ahuja and Burrin (1984) and Hsiao et al (1990) used acoustic excitation for control. Neuburger and Wygnanski (1987) used vibrating ribbon to delay separation. By using synthetic jet technique, Glezer's group (1999, 2001) has carried out separation control and virtual-shaping of airfoils. For practical applications in civil aircraft, the attempting of pneumatic flow control to high-lift systems is predicted to have the greatest impact by McLean et al (1999). In such a case, feedback control methods may not necessarily be required, however, other new types of air vehicles such as unmanned aerial vehicles and micro aerial vehicles are becoming to be in the limelight as application objects using flow control recently. As stated by Greenblatt and Wygnanski (2000), these aerial vehicles possibly give various new subjects involving flow control. McCormick et at (2001) pointed out that packaging of a self-contained actuator inside the confined leading edge of the airfoil represented a significant challenge.

In the recent AIAA Conference held in Reno in January 2003, various new results relating separation control were reported. Narayanan and Banaszuk (2003) made a control experiment on the wall-bounded separation by using a jet with zero mass flux and examined proper frequency condition for separation control. McQuilling et al. (2003) studied experimentally an active separation control in a low pressure turbine blade cascade with ejector nozzles. By numerical simulation, Hamdani et al. (2003) made systematic study of separation control by varying various flow parameters, where the alternating tangential suction and blowing was applied. Jiang and Liu (2003) carried out the direct numerical simulation for separation control with pulsed jets. They stated the role of the Kelvin-Helmholtz instability mechanism in the wing separation. The instability was described to dominate from the leading edge and to the trailing edge. Their comment may be helpful to seek precursory pressure fluctuation signals in the leading edge area for constructing a control algorithm. They also examined the effect of the pulsed jet on the separation. So far, attempts to establish self-contained, closed loop control system for wings seem to be not reported yet. We consider that those attempts above mentioned become more important and interesting.

One of the goals in the MEMS subgroup is to establish the basis of smart control system of the flow separation around wings. So far, the subgroup has developed control devices mainly, i.e. sensors (Takagi et al. 2001, Takagi et al. 2002, Matsunuma et al. 2001) and actuators (Abe et al 2001). In the present study, we aim to establish a closed loop control system, which is composed of the separation detector (Ozaki et al, 2000), actuator and control algorithm.

2. EXPERIMENTAL APPARATUS

2.1 Wind tunnel and data acquisition

A wind tunnel as shown in Fig.1 was used for the present experiment. The tunnel has a cross section of 200mm by 200mm at the exit following the nozzle with a contraction ratio 9 in area. The turbulence intensity at the entrance to the test section is about 0.7% at a free stream velocity of 10m/s. In a test section, a flat plate of 200mm in width and 180mm in length made of 5mm thick Plexiglas was installed 50mm above the exit wall in order to avoid oncoming boundary layer. New laminar boundary layer developing on the plate encounters adverse pressure gradient downstream and separates somewhere on the constant slope region with an angle of 16°. The sloping plate was joined with the end of flat plate through a circular arc of 90mm in diameter in order to avoid fixing the separation line at the joint part. Under the ceiling board of the test section, a flexible plate was attached to adjust the direction of streamlines above the sloping plate: lowering the downstream end of the flexible plate can suppress the flow separation while the fitting of the plate to the ceiling has no effect on the separation. Raising and lowering of the flexible plate enabled us to check the operation of feedback flow control system for unsteady separation.

Profiles of the mean and fluctuating velocities in boundary layers developing on the plate were measured by means of a conventional constant-temperature hot-wire anemometer. The anemometer output was analogously linearized using a high sensitive pressure transducer connected to a Pitot static tube in uniform flow. The hot-wire sensor mounted on a 2-D traversing mechanism was manually moved. The outputs from the anemometer and a separation detector as mentioned below were acquired by 16 bit A/D board installed in a computer.

2.2 Separation detector

A cantilever sensor (CS) as shown in Fig.2 was used as a reverse-flow detector. This sensor made use of MEMS technology consists of five independent cantilevers of in line, which are perpendicularly extruded from the test plate, but three sensors are active with a length of 0.4, 0.8 and 1.2mm, a width of 0.23mm and a thickness of 0.01mm. It was installed at about 40mm downstream from the entrance of the slope, where flow separation apparently occurs according to preliminary hot-wire anemometer measurements when boundary layer is laminar. Each element has a strain gauge at the root near the base so as to interpret flow direction: the sensor output for reverse flow indicates the negative sign, and verse versa. In this experiment, the longest cantilever in three was used together with an amplifier (TEAC Model SA-59) with an excitation voltage of 10V and a DC gain of 2000. The effect of thermal drift due to variation of the ambient temperature was eliminated by observing the output at no wind before and after the measurements. More details on the gauge are given by Ozaki et al. (2000).

2.3 Control system

To examine an active control of the laminar separation, the laminar boundary layer on the flat plate was disturbed by small jets. Three holes of 1mm in diameter were drilled at a spacing of 40mm in spanwise direction on the flat plate at 50mm downstream from the leading edge. Each hole was connected to a speaker with tube. The driving pulse was set at sinusoidal wave with the cycle of 100Hz. Figure 3 shows the time traces of the speaker driving pulse and hot-wire output measured above the hole for no wind. The cyclic driving of speaker generates turbulent wedges from the holes and the development and merging of the wedges prevent the separation. For much larger angle of the slope, this method could not prevent the separation on the slope. The feedback-control system was consists of three simple procedures as shown in Fig.4; acquisition of CS output, discrimination of the flow direction and excitation of the boundary layer. For the discrimination of the reverse flow, time averaged voltage of the CS output was used: if it is positive the speaker is not driven and vice versa. The durations of acquisition and excitation can be independently adjusted.

3. RESULT AND DISCUSSION

3.1 Characteristics of basic flow

Profiles of velocities and turbulence intensities in the boundary layer were compared at the free-stream velocity of 10m/s for natural case without excitation and excited case with speaker driving. In both cases, the flexible wall was fixed on the ceiling. Figure 5 shows that the boundary layer at x=170mm is almost laminar for the natural case while a turbulent boundary layer is apparently formed for the excitation case. At a downstream location on the slope of x=215mm, an inflectional velocity profile is observed for the case of natural state in Fig.6 (a), which implies the laminar boundary layer separates on the slope. The large amplitude of velocity fluctuation at the height corresponding to the inflection point indicates the instability of inflectional shear layer on the separation bubble. On the other hand, the turbulent boundary layer has its maximum value of turbulence intensity close to the wall for the case of excited state as shown in Fig.6 (b) different from the natural case. There is no inflection point in the velocity profile. These facts suggest that the separated flow is swept away and eventually forward flow becomes dominant even on the slope due to the excitation.

3.2 Detection of reverse flow

In order to make sure of the results from the hot-wire measurements which do not indicate the flow direction, CS output signals were observed. Figure 7 compares the instantaneous waveforms of CS output for the cases of natural and excited states. For natural case, the sensor output is always negative in Fig.7 (a), which means that the flow is reverse, while the averaged sensor output becomes almost positive in Fig.7 (b) for the excited case. These results support the result by hot-wire measurements. The reason why instants of negative output occur sometimes in the excited case seems to be that the boundary layer transition is not completed on the flat plate. Furthermore there is a significant difference in the amplitude of the CS signals between the natural and excited cases. Figure 6 indicates that this difference depends on the amplitude of the velocity fluctuation at the height where the tip of CS is placed: the turbulence intensity close to the wall for the natural separation case is much lower than that for the excited case. This dependency of the CS amplitude on the relation between its length and the profile scale of the velocity fluctuation also suggests that the selection of the sensor length is required complying with the height of the separation bubble: for the thinner bubble, shorter-length sensor must be used although the sensitivity is lower than that of the longer sensor. It is important to consider this competitive condition to optimize the sensing process. The limitation of the sensitivity to velocity gradient also should be verified for each sensor in future.

Figure 8 shows the time-averaged output of CS for various free-stream velocities. For the natural case, the voltage decreases as the free-stream velocity increases, which means that the velocity of the reverse flow increases corresponding to the increase of the free stream. It is also found that the excitation method becomes effective when the free-stream velocity exceeds about 10m/s. This velocity depends on the critical Reynolds number for the small disturbances in the laminar boundary layer. In the present experiment, the Reynolds number based on the free-stream velocity and displacement thickness is about 460 at the free-stream velocity of 10m/s and x=170mm. This value is slightly higher than the critical Reynolds number of 420 for the Blasius boundary layer. Under the lower Reynolds number condition corresponding to the free-stream velocity in the rage of 6 to 8 m/s, the excitation even emphasizes the reverse flow although the driving condition of the speaker is not optimized. The ejection without boundary layer transition seems to facilitate the separation because the upwash possibly forms an inflection point on the velocity profile.

3.3 Operation of feedback control system

To demonstrate the feedback control system it was operated when the unsteady flow was formed by raising and lowering of the flexible wall attached to the ceiling. Figure 9 shows the time traces of CS output signal and speaker driving pulse in both cases without and with excitation. In this demonstration, the durations of sensing reverse flow and driving speaker in a control loop are 50ms and 500ms, respectively. The forward and reverse flows are repeated corresponding to the position of the flexible wall in the case without excitation as shown in Fig.9 (a). On the other hand, Fig.9 (b) shows that the reverse flow almost disappears in the case with excitation except the short duration of sensing and discrimination. It is also found that the speaker is not driven when the flow direction is forward. These results indicate optimum operation of the control system even for the unsteady flow.

To check the time response of the system the flexible wall was abruptly moved from the bottom to top. Figure 10 shows the CS output signal and speaker driving pulse for the cases with and without excitation. When the speaker driver is off the flow direction changes nearly stepwise from the forward to reverse as shown in Fig.10 (a). Figure 10 (b) shows the case with excitation and the flow direction becomes forward after a slight delay from the occurrence of the driving pulse. The delay comes from the distance between excitation holes and CS. The duration between the occurrence of reverse flow and start of speaker driving depends on the data acquisition time. The acquisition time was set at 32ms in Fig.10(b), where the reverse flow ia repeatedly accepted even after the first detection of reverse flow. To avoid this acceptance the acquisition time was decreased to 3.2ms in Fig.10 (c). It is found that the reverse flow almost disappears. Because the time response of CS is quite fast as shown by Takagi et al.(2002), it might be used for the system which has much shorter time constant.

4. CONCLUDING REMARKS AND NEAR FUTURE PLAN

In the present study, the flow field on the downward slope simulating an upper wing surface was employed to establish the feedback control system of the laminar boundary layer separation. The system is composed of the flow direction sensor, the actuator to disturb the boundary layer and the computer controlling these elements. The discriminator made use of MEMS technology works well as a reverse-flow detector even in the unsteady flow. It is found that the new sensor as direct indicator of flow direction has excellent characteristics unlike a single hot-wire anemometer and it has a lot of advantages as follows; quite small volume having no influence on the flow as a disturbance generator, good response to the unsteadiness of the flow, high resolution in space, available for the very low speed and easy to use. The feedback control system was demonstrated for the unsteady flow and the system integration was established for the simple flow field. The robustness and optimization of the control system will be considered as a future work and several devices such as micro jet vortex generator, electric actuators, separation detector and warning device of separation are being investigated to be integrated in a wing model.

ACKNOWLEDGEMENTS

An air-flow sensor used as separation detector in this study was given by courtesy of Professor Isao Shimoyama, Department of Mechano-Informatics, the University of Tokyo. The authors would like to express their appreciation.

REFERENCES

Abe, H., Segawa, T., Matsunuma, T., Yoshida, H., 2001, “Vortex generator composed of micro jet array for flow separation control”, *Proc. 2nd Symp. Smart Control of Turbulence*, Univ. Tokyo, March 4-6, pp.117-120.

Abe, H., Segawa, T., Matsunuma, T., Yoshida, H., 2001, “Micro jet vortex generator for active control of flow separation", *Proc. International Conference on Power Engineering*, Oct.8-12, 2001, Xi'an China.

Ahuja, K.K., Burrin, R.H., 1984, "Control of flow separation by sound", *AIAA paper*, 84-2298.

Chatlynne, E., Rumingny, N., Amitay, M., Glezer, A., 2001, "Virtual aero-shaping of a Clark-Y airfoil using synthetic jet actuators", *AIAA paper*, 2001-0732.

Gad-el-Hak, M., 2000, *Flow control*, Cambridge Univ. Press.

Glezer, A., 1999, invited lecture, "Shear flow control using fluidic actuator technology", invited lecture in the *1st Symposium on Smart Control of Turbulence*, Dec.2-3, 1999, Tokyo, pp.39-45.

Greenblatt, D., Wygnanski, I.J., 2000, " The control of flow separation by periodic excitation", *Progress in Aerospace Sciences*, 36, pp. 487-545.

Hamdani, H., Baig, A., Zahir, S., 2003, "A systematic study of separation control by varying various parameters during alternative tangential blowing/suction", *AIAA paper,* 2003-422.

Hsia, F-B., Liu, C-F., Shyu, J-Y., 1990, "Control of wall-separated flow by internal acoustic exciteation", *AIAA J.* 28(8), pp.1440-1446.

Jiang, L., Liu, C., 2003, "Direct numerical simulation for flow separation control with pulsed jets", *AIAA paper*, 2003-0611.

Matsunuma, T., Kikushima,Y., Segawa, T., Maeda, R., 2001, "A novel double lever vibration sensor", reported in the ORCS project meeting on June 12, 2001 (unpublished).

McCormick, D.C., Lozyniak, S.A., MacMartin, D.G., Lorber, P.F., 2001, "Compact, high-power boundary layer separation control actuation development", *ASME paper* FEDSM2001-18279.

McLean, J.D., Crouch, J.D., Stoner, R.C., Sakurai, S., Seidel, G.E., Feifel, W.M., Rush, H.M., 1999, "Study of the application of separation control by unsteady excitation to civil transport aircraft", *NASA/CR*-1999-209338, pp.1-59.

McQuilling, M., Hollon, B., Jacob, J., 2003, "Active separation flow control in a low pressure turbine blade cascade model", *AIAA paper*, 2003-0615.

Narayanan, S., Banaszuk, A., 2003, "Experimental study of a novel active separation control approach", *AIAA paper*, 2003-60

Neuburger, D., Wygnanski, I., 1988, "The use of a vibrating ribbon to delay separation on two dimensional airfoils: Some preliminary observations", in Proc. Workshop II on Unsteady Separated Flow, ed. J.M. Walker, Frank J. Seiler Research Laboratory Report No.TR-88-0004.

Ozaki, Y., Ohyama, T. Yasuda, T. and Shimoyama, I., 2000, "An air flow sensor modeled on wind receptor hairs of insects", in Proc. MEMS 2000, Miyazaki, Japan, Jan. 23-27.

Takagi,S., Tokugawa, N., Yoshida, H., Abe, H., Atobe, T., Yamamoto, K., 2001, "Observation and control of separation from bluff bodies", *Proc. 2nd Symp. Smart Control of Turbulence*, Univ. Tokyo, March 4-6, pp.121-176.

Takagi,S., Tokugawa, N., Nishizawa, A., Abe, H., Kikushima, Y., Maeda, R., Yoshida, H., 2002, "Toward smart control of separation around a wing", *Proc. 3rd Symp. Smart Control of Turbulence*, Univ. Tokyo, March 3-5, pp.9-14.

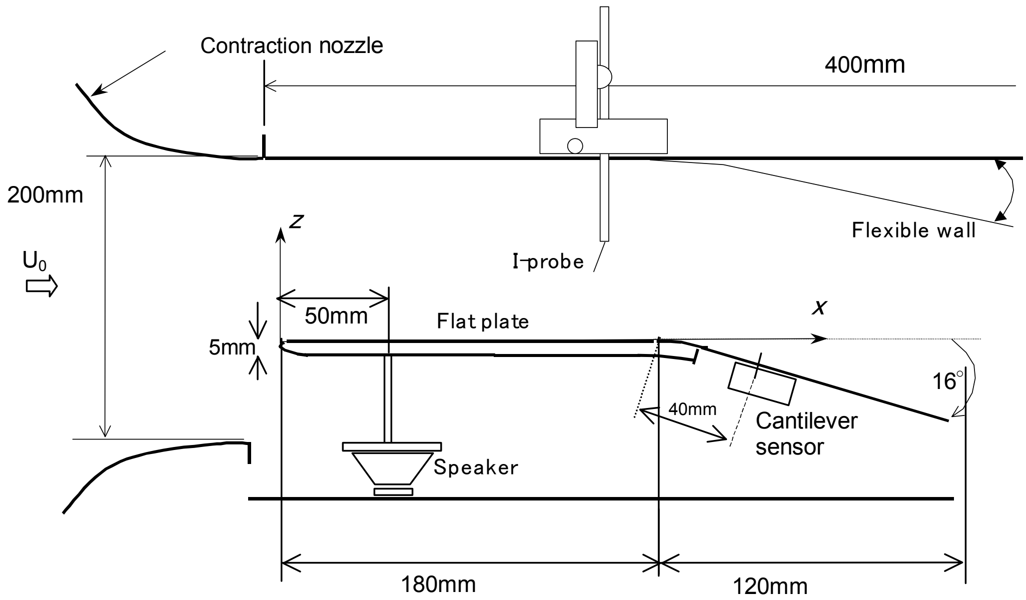

Fig.1 Experimental setup.

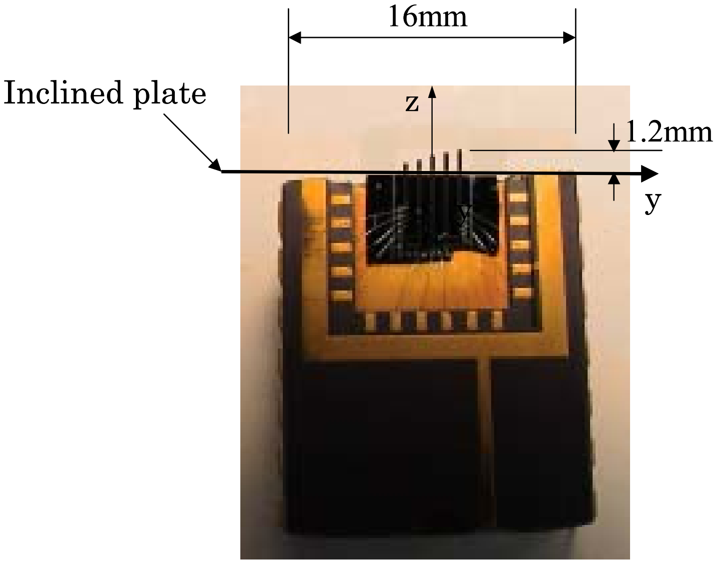

Fig.2 Cantilever sensor (Ozaki et al. 2000).

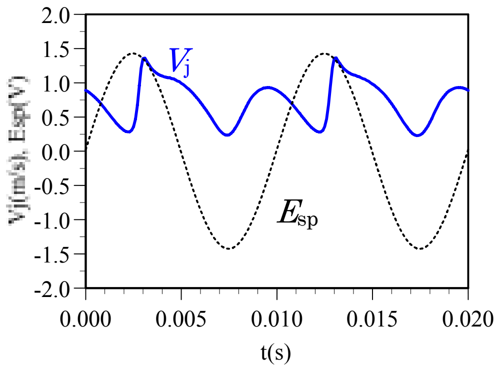

Fig.3 Time traces of the speaker driving pulse, E_{sp}, and hot-wire output, V_j, measured above the hole (z=1mm) for no wind.

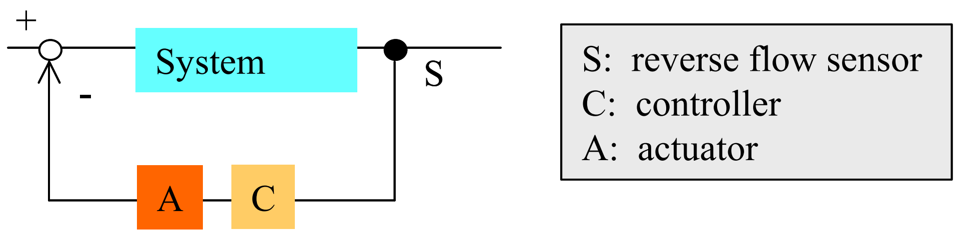

Fig.4 Schematic of the control system.

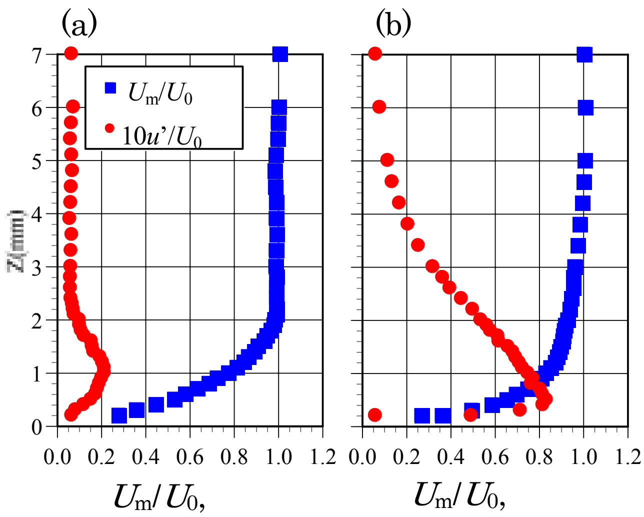

Fig.5 Profiles of mean velocity, U_m, and turbulence intensity, u'/U_0, at x=170mm and U_0, =10m/s. (a)Natural , (b)Excited

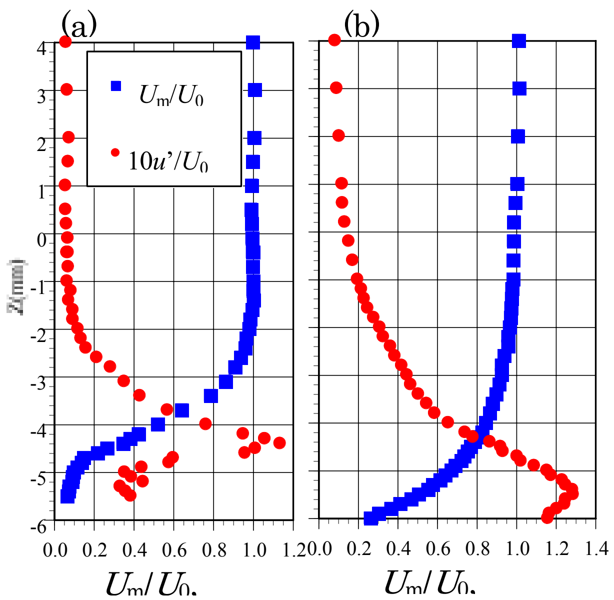

Fig.6 Profiles of mean velocity, U_m, and turbulence intensity, u'/U_0, at x=215mm and U_0, =10m/s. (a)Natural , (b)Excited

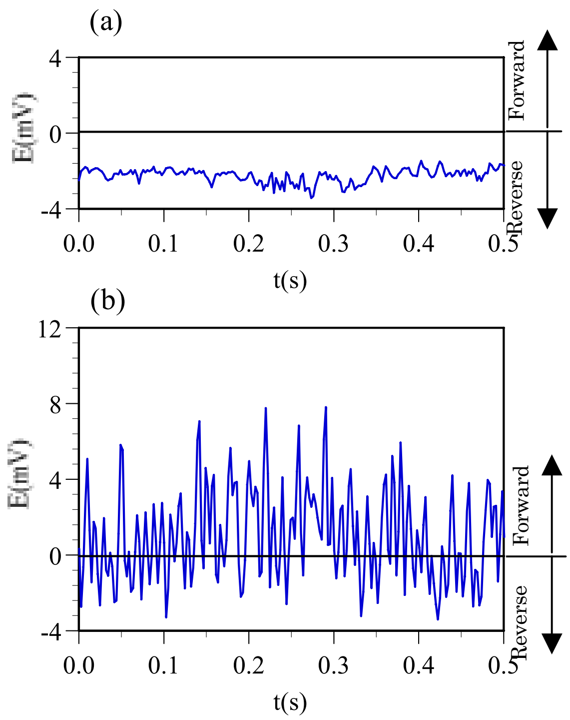

Fig.7 Instantaneous waveforms of Cantilever sensor output at U_0, =10m/s. (a)Natural , (b)Excited

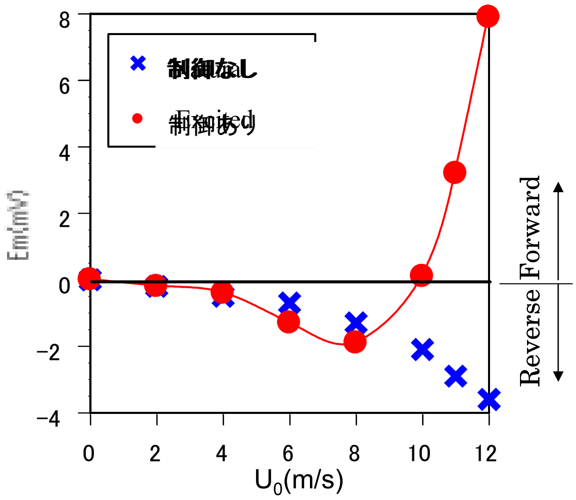

Fig.8 Time-averaged CS output for various free-stream velosity.

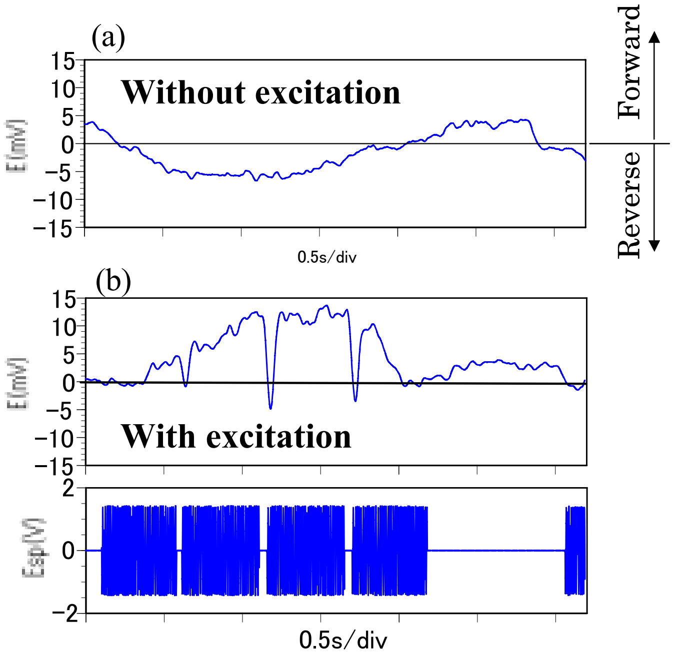

Fig.9 Demonstration of the control system. (a) CS output without excitation, (b) CS output and speaker driving pulse, E_{sp}, with excitation.

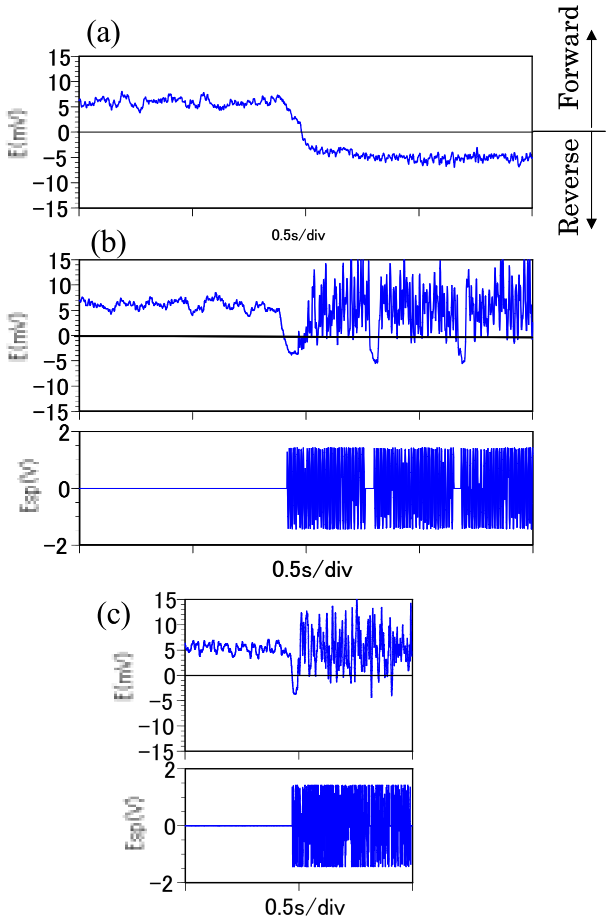

Fig.10 Demonstration of the control system for the stepwise changed flow field. (a) Without excitation, (b) With excitation, the acquisition time is 32ms, (c) With excitation, the acquisition time is 3.2ms,