AN EXPERIMENTAL STUDY ON HIGHLY UNSTEADY SEPARATING FLOW

*1Seiichiro Izawa, Takuo Endo, Masaya Shigeta and Yu Fukunishi

*1Graduate School of Engineering, Tohoku University
6-6-01 Aramaki-Aoba, Aoba-ku, Sendai, 980-8579, Japan
izawa@fluid.mech.tohoku.ac.jp

ABSTRACT

A feedback control is attempted against an unsteady flow separation artificially generated on the plate surface by periodically moving the curved ceiling up and down at a constant frequency. The controlling system consists of a turbulence ejecting apparatus on the upstream side and several tufts on the downstream side. The movement of the tufts is monitored by a movie camera. When a separation is detected by processing the images of the tufts, a jet of turbulent fluid is ejected into the boundary layer through a slot in the plate. It is shown that the separation region shifts downstream and becomes smaller by the control.

1. INTRODUCTION

Flow separation is generally undesirable in fluid machinery. Once a separation takes place, the aerodynamic performance is degraded by the rapid increase in drag, and the intense pressure fluctuation synchronized with a periodic vortex shedding is likely to give rise to the fatigue fracture. A number of controlling methods to suppress separations have been proposed up to now and some of them have already been put into practical use. Wygnanski et al.[1, 2] provided a review on the control of flow separating from solid surfaces by periodic excitation. They reported that the separation can be significantly reduced by choosing the effective excitation frequencies, even when the amplitude of the synthetic jet is small, because the fluctuation is amplified by flow instability. They also pointed out that the periodic excitation is vastly superior to steady blowing in terms of performance efficiency and eliminates abrupt flow response. You and Moin [3] performed a Large-Eddy Simulation (LES) of separation control for flow over a NACA-0015 airfoil and evaluated the effectiveness of synthetic jets as a control technique. They discussed the detailed flow structures inside a synthetic jet actuator and the interaction between the synthetic jet and the cross flow.

Dynamic stall is a more severe problem, especially for helicopters, Micro Air Vehicles (MAV) with flapping wings, gas turbines and wind turbines. Woo and Glezer [4] reported that the brief actuation pulses generated by combustion-based actuators integrated into a NACA-

4415 airfoil can extend the flow attachment and enhance the global aerodynamic performance. Mulleners et al. [5] examined several vortex generators with different shapes attached near the leading edge as a passive controlling device. They found that the flow separation is delayed and separation vortices stay closer to the wall, owing to these devices.

These previous studies are based on the premise of steady flow separation or that the timing of actuation is uniquely determined by the known pitching motion of airfoil. On the other hand, in the present study, feedback control is attempted to prevent an unsteady flow separation, where the separation region moves largely as a function of time in the streamwise direction. The control effect is evaluated by measuring the flow field using a direction-sensitive probe [6].

2. EXPERIMENTAL SETUP

The experiment was carried out in a low speed in-draft wind tunnel at the Fluid Mechanics Laboratory of Tohoku University. The tunnel had a 1m long test section with a rectangle cross section of 170 mm $\times$ 588 mm at the inlet. A schematic view of experimental setup is shown in Fig. 1. An aluminum flat plate which is 900mm long, 580mm wide and 5 mm thick is horizontally mounted 50 mm away from the floor of the test section. The plate has an elliptical leading edge of major-to-minor axis ratio 20, together with a 150mm long adjustable trailing flap which used to prevent the flow separation at the leading edge. The coordinate system has its origin at the leading edge, where x , y and z denote the streamwise, wall-normal and spanwise directions, respectively.

The shape of the test section is a one-sided diffuser with a moderate curve of parabolic function on one side. A periodic unsteady flow separation can be generated on the plate surface by moving the ceiling by a crank mechanism connected to a motor. The angle of the ceiling is changed from 10 to 12 degrees at a constant frequency 1.5 Hz. Flow separation on the ceiling side was prevented by sucking flow through a large number of punched holes whose diameter was 2 mm, distributed at $x = 400$ through 550 mm. The freestream velocity U was set to be 3 m/s.

Fig. 1 Experimental setup

A direction-sensitive probe [6] was used to judge the flow direction. The probe consists of a single hot wire connected to a Constant Temperature Anemometer (CTA) circuit and two cold wires connected to a Constant Current Thermometer (CCT) circuit. Each wire is a $5\ \mu\text{m}$ diameter tungsten wire. Two cold wires 2 mm long are set vertically up- and downstream of the 1.4 mm long hot wire. The distance between the hot wire and the cold wires are 0.7 mm each. The cold wires detect the heated wake of the hot wire. Since the output signal of CCT increases in proportion to the temperature of the flow, the flow direction can be judged by comparing the CCT output with a proper threshold. However, these output voltages of CCT are very weak and accompanies undesirable noise. So, a low-pass filter with a cutoff frequency of 45 Hz was used. An indicator named "direction coefficient" C_{dir} which represent the reverse-flow rate was introduced. C_{dir} could be obtained by a conditional sampling and ensemble averaging technique using the ceiling angle as a reference signal. $C_{\text{dir}} = 1$ indicates that only a forward flow existed during one cycle of period, while $C_{\text{dir}} = -1$ indicates a reverse flow. So, the negative C_{dir} region can be regarded as a separation region.

Figure 2 shows a schematic view of the main unit of the controlling device. The device was installed on the backside of the flat plate. The main unit consisted of a turbulence generating box and a loudspeaker. A square mesh was rotated at a constant speed of 20 rpm inside the box generating turbulence. When a separation occurs downstream, this pre-generated turbulent fluid is pushed out through a slot in the plate surface into the boundary layer by operating the loudspeaker. The slot of 4 mm width and 60 mm length was placed at $x = 435$ mm upstream of the reverse flow region and the jet velocity was less than 1 m/s measured at the outlet of the slot. An occurrence of reverse flow was detected by using three tufts attached on the plate 115 mm ~ 165 mm downstream of the slot. Their motion was always monitored by an USB camera, outside of the test section, and was processed real time by the Lucas-Kanade optical-flow algorithm. The loudspeaker was driven 0.15 s each time the reverse flow was detected, where pulse width modulation (PWM) method was used to control the loudspeaker. The average time required for the im-

(a) Top view

(b) Main unit of controlling device

Fig. 2 Schematic view of controlling device

age processing was approximately 17.5 ms.

3. RESULTS AND DISCUSSION

First, the capability of a direction-sensitive probe in finding a reverse flow was evaluated and the results were compared with those of a single hotwire probe.

Figure 3 shows the time-averaged velocity when the ceiling angle is fixed at 10 or 12 degrees, where only the velocity larger than $0.4U (= 1.2\text{ m/s})$ is shown in the figure. It is because the hotwire measurement becomes unreliable below this velocity. Low-speed region spreading wide in the vertical direction can be found, especially in the downstream region. The low-speed region moves upstream when the angle of one-sided diffuser changed from 10 degrees to 12 degrees.

The direction coefficients obtained by the direction-sensitive probe are shown in Fig. 4. Separation regions are clearly captured by the direction-sensitive probe. When the ceiling angle is 10 degrees, the upstream and the downstream edges of separation region are 513 mm and 606 mm at $y = 1.5$ mm, and the separation region reaches 4.7 mm away from the plate surface. The generated separation bubble moves upstream at larger ceiling angles. The reverse flow area covers from 480 mm to 530 mm at $y = 1.5$ mm in the freestream direction, and up to 2.94 mm in the wall-normal direction. It can be found that the actual separation region accounts for a small

Fig. 3 Time-averaged velocity map at fixed ceiling angles.

Fig. 4 Direction coefficient map at fixed ceiling angles.

proportion of the low-speed region, as shown in Fig. 3.

When the ceiling oscillates at a constant frequency 1.5Hz, the separation region on the flat plate is no more stationary. Figure 5 shows the time variation of leading and trailing edges of a separation region at $y = 1.5\text{mm}$ when the control device is installed. The dotted lines in the figure indicate those for the flows at fixed ceiling angles of $\alpha = 10$ or 12 degrees. The result was obtained by a conditional sampling and ensemble averaging technique after low-pass filtering at a cut-off frequency 45Hz.

Fig. 5 Time variation of leading edge (LE) and trailing edge (TE) of separation region at $y = 1.5\text{mm}$.

The signal of angle sensor attached to the ceiling oscillation mechanism was used as a reference signal and the ensemble averaging was performed by using the direction sensitive probe's data of 37 ~ 38 cycles. It can be found that the periodic motion of the ceiling makes the separation region to synchronously oscillate in the x direction. Small fluctuations can be observed in the trailing edge side profile. This is a reflection of the unsteady movement of the reattachment point owing to the small vortices formed in the separated shear layer. It should be noted that there is a certain phase difference between the ceiling angle and the separation region generated on the floor. Flow separation disappears for a while after the ceiling starts to open and reaches the maximum after the ceiling starts to close again.

Next, experiments to actively control the flow were carried out.

Figure 6 shows the distributions of direction coefficients before and after the control, at $2\pi ft = 1.5\pi$ ($\alpha = 11$ deg.). Large separation which covers the measurement region downstream of $x = 510\text{mm}$ is observed in the flow filed before control. However, by ejecting a disturbed jet through the slot at $x = 435$ mm based on the information obtained by observing the downstream tufts at $x = 500 \sim 600$ mm, the separation can be effectively suppressed, which is shown in the figure. The streamwise length of the separated area decreases from 453 mm^2 to 86 mm^2 , while moves upstream for about 30 mm. In order to evaluate the control effect quantitatively, the following new index is introduced.

$$R_a(t) = - \sum_i C_{\text{dir},i} \Delta S; i \in C_{\text{dir}} < 0, \quad (1)$$

where ΔS is the area of measurement grid, $10\text{mm} \times 1\text{mm}$. The value of R_a represents the area of separated flow in the measurement region at a certain phase. The results are plotted in Fig. 7. For comparison, the result without premixing is plotted in the figure. "Blowing" is

Fig. 6 Direction coefficient at $2\pi ft = 1.5\pi$ ($\alpha = 11$ deg.). Fig. 7 Time variation of reverse flow area R_a .

the case when the square mesh in the turbulence generating box shown in Fig. 2 (b) remained at rest and only the loud speaker was driven. It can be found that the dynamic flow separation can be effectively controlled by introducing the disturbances upstream of the separation region.

4. Conclusions

Active separation control of flow though a one-sided diffuser was attempted by a wind tunnel experiment. The target unsteady flow separation was artificially generated on the flat plate by periodically moving the curved ceiling up and down at constant frequency of 1.5Hz. A

controlling device which consisted of a turbulence generating chamber and an ejection pipe connected to a loud speaker was installed beneath the plate and activated when the downstream tufts detected the reverse flow. The results obtained by the conditional sampling technique shows that the present controlling method is effective in reducing the separation area.

REFERENCES

- [1] Greenblatt, D. and Wygnanski, I.J., The control of flow separation by periodic excitation, *Prog. Aerospace Sci.*, **36**, pp. 487-545 (2000).
- [2] Seifert, A., Greenblatt, D. and Wygnanski, I.J., Active separation control: an overview of Reynolds and Mach numbers effects, *Aerospace Sci. & Tech.*, **8**, pp. 569-582 (2004).
- [3] You, D. and Moin, P., Large-eddy simulation of flow separation over an airfoil with synthetic jet control, *Center for Turb. Res.*, **8**, pp. 337-346 (2006).
- [4] Woo, G.T.K., and Glezer, A., Transitory Control of Dynamic Stall, *Proc. 7th Int. Symp. Turb. & Shear Flow Phen. (TSFP-7)*, pp. 1-6 (2011).
- [5] Hine, B., Mulleners, K., Joubert, G. and Raffel, M., Dynamic Stall Control by Passive Disturbance Generators, *Proc. 29th AIAA Appl. Aero. Conf.*, pp. 1-14 (2011).
- [6] Wei, Q.-D. and Sato, H., An experimental study of the mechanism of intermittent separation of a turbulent boundary layer, *J. Fluid Mech.*, **143**, pp. 153-172 (1984).