Smart Control of Flow Separation around an Airfoil*

Hiroyuki ABE**, Takehiro NOMURA***, Yoshihiro KIKUSHIMA** and Hiro YOSHIDA**

**National Institute of Advanced Industrial Science and Technology,
Namiki 1-2-1, Tsukuba, Ibaraki, 305-8564, Japan
E-mail: abe.hiroyuki@aist.go.jp
***University of Tsukuba,
Tennodai 1-1-1, Ibaraki, 305-8571, Japan

Abstract
In order to construct a control system for flow separation around an airfoil, continuous jet type vortex generator and optical cantilever sensor for discriminating flow condition were developed. Blowing jet apertures of the vortex generator are placed in airfoil surface at 0 and 30 % chord. The jet apertures were aligned span-wise on the suction surface. Locations and interval of the apertures were decided according to the previous data on the flow separation at low and high attack angles of the MEL001 airfoil. Most distinctive feature of the present jet vortex generator is that it can produce single, longitudinal vortex with arbitrary strength and extent by controlling the jet velocity distribution across the aperture. The optical cantilever sensor was developed. It was installed at the trailing edge. The sensor has two functions: discrimination of flow direction and compensation of temperature fluctuation of flow. The flow around the airfoil is controlled by actuating of the vortex generator and information from the optical cantilever sensor. The vortex generator can be used not only as an actuator but also sounding flow condition. The longitudinal vortices are discharged as tracer for the flow monitoring. The discharged tracer vortices accumulate information on the flow around the airfoil as they travel downstream. Thus the flow condition is monitored by the sensor at the trailing edge. The monitored signals were sent to the computer and analyzed and then feedback control signal is sent to the actuator.

Key words: Aerodynamics, Flow Separation, Control, Airfoil, Optical Fiber Sensor, Longitudinal Vortex, Jet

1. Introduction

Separation of flow causes striking losses and limits the performance of various flow-related devices, such as, airfoils, diffusers, duct system, and so on. Through separation control, flow pattern becomes close to that given by inviscid theory. As a result, large lift and small drag can be attained. To date, much research has been done concerning how to suppress the separation (1), (2). Nishizawa et al. (3) gave a brief review on the separation control. However, feedback control system for separation is scarcely discussed. Our purpose is to establish a sophisticated control system for separation. In this study we will focus our attention on the possibility of flow separation control by using MEL001 airfoil developed for the wind turbine, a closed loop control system composed of the novel actuator and sensor, where the Reynolds numbers are 1×10^5-2×10^5.
2. Experimental Facility

2.1 Wind tunnel

A series of experiments were performed in the open-circuit blower type wind tunnel. The test section is 1.0 m high, 0.5 m wide and 2.0 m long. The free stream velocity in the test section is variable from 1 to 30 m/sec. The test section is placed after the contraction duct. The contraction rate is 8 to 1. The turbulence intensity in the test section is under 0.4 % for free streams over 10 m/sec.

2.2 Measurement instrumentation

Constant-temperature hot-wire (HW) anemometry of I types were used for the velocity measurement. The I type HW (TSI model 1218-T1.5) was used to examine the boundary layer formed by the vortex generator. The static pressures along the airfoil surface were measured by the pressure transducers (SCANIVALVE model PDCR23D). The pressure transducer has pressure range of ±254 mmAq, nonlinearity of below ±0.2 %FS and hysteresis of below ±0.2 %FS. The three components load cell (NISSHO ELECTRIC WORKS model LMC-3531) was used to detect the lift and drag forces and pitching moment working on the airfoil. The three components load cell has allowable overload of 200 N, allowable moment of 20 Nm, nonlinearity of below ±0.2 %FS and hysteresis of below ±0.2 %FS. The optical sensing interrogator (MICRON OPTICS model si425) was used for analyzing optical signal of the Fiver Bragg Grating (FGB) cantilever sensor. The interrogator has wavelength range of 1520-1570 nm, wavelength resolution of 1 pm, and sampling frequency of 250 Hz.

3. Jet Type Vortex Generator

3.1 Vortex generator

Figure 1 shows an aperture of vortex generator (4). The aperture for the jet is installed on the boundary layer plate in the test section. Most distinctive feature of the present VG jet (VGJ) is that it can produce single, longitudinal vortex with arbitrary strength and extent through controlling the jet velocity distribution across the aperture (5). The jet aperture has a guide with 3-dimensional structure beneath the wall, which enhances to form favorable cross sectional jet velocity distribution. The jet formed by such manner interacts with the cross flow (in the boundary layer of the free stream) to produce an arbitrary longitudinal vortex.

Figure 2 shows the near wall velocity contour at $x = 50$ mm caused by the single jet aperture on the wall. Free stream velocity was 5 m/sec and jet velocity was set to be twice the free stream, 10 m/sec. The flow velocity was measured by using the I-type hot wire anemometer. Numerical values of the contours are normalized velocities by the free stream velocity. It can be seen in Fig.2 that a single clockwise vortex clearly modifies the boundary layer. That is, Direction of the rotation is discriminated because the boundary layer of the right hand side rolls up. It was confirmed by the flow visualization using a smoke wire also.

3.2 Characteristics of MEL001 airfoil

Figure 3 shows the section profile of MEL001 airfoil. It was developed for a wind turbine blade at Mechanical Engineering Laboratory (former institute of AIST). In the experiment, an end plate was fitted with the airfoil to minimize the effect of the wing tip-vortex. The chord length and the span of the airfoil were 150 mm and 500 mm, respectively. Figure 4 shows lift-to-drag ratio $L/D$ of the airfoil at various chord Reynolds numbers $Re$. In order to see the level of the hysteresis effect, $L/D$ data observed for increasing and decreasing the attack angle $\alpha$ are superimposed (same as in Figs. 7, and 8). The lift and drag forces were calculated from the static pressure distribution along the
Fig. 1  The aperture of vortex generator on the wall. The jet is ejected to direction of y axis.
\(x\): Stream-wise, \(z\): Span-wise

Fig. 2  Contour of normalized velocity at \(x = 50\) mm

airfoil surface. In Fig. 4, it is found that for the attack angles \(-5^\circ < \alpha < +12^\circ\), the ratio \(L/D\) for smaller Reynolds numbers \(Re = 50,000\) and \(100,000\) are remarkably smaller than that for \(Re = 200,000\). On the other hand, in the attack angles \(\alpha < -5^\circ\) and \(\alpha > +12^\circ\), \(L/Ds\) for all \(Re\) coincide with each other. Figure 5 shows the pressure coefficients \(C_p\) for the same flow Reynolds numbers, \(Re = 50,000, 100,000,\) and \(200,000\). The attack angle was set to be \(\alpha = 6^\circ\). In Fig. 5 it is seen that at the lowest Reynolds number \(Re = 50,000\) the \(C_p\) on the suction side becomes almost constant downwards after chord-wise position \(x/c = 0.4\), i.e. no pressure recovery. This is considered to be due to the laminar separation. The pressure recovery in the region \(x/c > 0.4\) becomes more appreciable as the Reynolds number increases from \(Re = 100,000\) to \(200,000\). Generally, it is said that airfoils stall when the attack angle becomes larger. In the low Reynolds number flows, however, the stall occurs even at lower attack angles and then it recovers at higher attack angles. This is a peculiar separation behavior in the low Reynolds number flows.

3.3 Effect of the vortex generator

Under the adverse pressure gradients, the turbulent boundary layer has higher ability to convey flows without the separation than the laminar boundary layer does. This is because of the wall normal momentum mixing caused by the turbulent boundary layer. The vortex generator is considered to have an equivalent effect to the turbulent mixing process. Figure 6 shows a schematic diagram of VGJ locations, chord-wise position \(x/c = 0, x/c = 0.3\), on the MEL001 airfoil for the control system, which consists of blowing jet apertures aligned span-wise on the suction surface, air tanks and some sensors. The chord length and
the span of the airfoil were 300 mm and 490 mm, and an end plate was fitted with the airfoil to minimize the effect of the wing tip-vortex. Locations and interval of VGJs were decided properly based on the previous experimental data. In this sense, they are optimized. The airfoil is supported by a cantilever with a load cell. Compressed air for VGJ is supplied.
Fig. 6  Arrangement of the vortex generator on the MEL001 airfoil

from outside. Figures 7 and 8 show the coefficient of lift $C_L$ as a function of the attack angle $\alpha$ with and without VGJ forcing. In those figures are examined the effects of VGJs on $C_L$ when they are installed at $x/c = 0$ (VG-a in Fig. 6) and $x/c = 0.3$ (VG-b in Fig. 6), respectively. Chord Reynolds number $Re$ is $1.0 \times 10^5$. $V/U$ is the non-dimensional jet velocity normalized by the free stream velocity $U$. In Fig.7 we realized that $C_L$ was remarkably influenced by the existence of the jet apertures for VGJs. That is, for $\alpha < 6^\circ$, $C_L$ for no jet apertures is lower than that with VGJ apertures but no forcing due to the laminar separation at around $x/c = 0.4$. At higher $\alpha$ of $18^\circ - 20^\circ$, again $C_L$ for no apertures becomes lower than that for apertures. Those lower $C_L$ for no apertures is considered to be due to the separation characteristics for the flow Reynolds numbers considered peculiar to MEL001 airfoil, i.e. the turbulent separation at the trailing edge and laminar separation at the leading edge. By applying VGJs, such $C_L$ behavior at lower and higher $\alpha$ is remarkably improved as shown in Figs. 7 and 8. By comparing Figs 7 and 8, however, we realize that VGJs at the leading edge (VG-a) and at $x/c = 0.3$ (VG-b) have different effects. In Figs.7 and 8, the maximum $C_L$ s are almost the same, due to the typical airfoil characteristics under the low Reynolds number flows. Referring Fig.9, we can say that the present VGJs have the effect of suppressing laminar separation. In other words, under VGJ operation, the airfoil characteristics at $Re = 100,000$ move to those at higher $Re = 200,000$ in Fig.9. The most striking deference between $C_L$ s for the case of VG-a and VG-b appears at $\alpha = 0^\circ$. The $C_L$ for VG-a is remarkably lower than that for VG-b. This is considered to be due to the stagnant flow at the leading edge, where fully developed vortices are hard to be generated, because the direction of the jet from VG-a is against the free stream at $\alpha = 0^\circ$. In the lower attack angles $0^\circ < \alpha < 6^\circ$, $C_L$ is remarkably improved at proper jet velocity and location of VGJ. That is, VGJs with weak jet ($V/U = 1$) at $x/c = 0.3$ (VG-b) is more effective.
to improve $C_L$ than that with strong jet ($V/U = 2$) or at $x/c = 0$ (VG-a). On the contrary, for $8^\circ < \alpha < 16^\circ$, VG is not so effective. Moreover, it is found that the strong jet is not always more effective than the weak jet. At the higher attack angles $\alpha = 20^\circ$, influence of the VG
position on $C_L$ is distinguishable. VGJs at $x/c = 0$ (VG-a) is more effective than that at $x/c = 0.3$ (VG-b). Generally, present results suggest that VGJ placed just before the separation point is effective to control the airfoil separation.

4. FBG Cantilever Sensor

4.1 FBG cantilever sensor

In this study, a Fiber Bragg Grating (FBG) system is used as a cantilever sensor. FBG is an optical fiber that acts as an optical filter by gratings in the fiber core. The cantilever sensor consists of FBG of 0.125 mm diameter and a plastic plate of 0.3 mm thick. Figure 10 illustrates the cantilever sensors. Two types of cantilever sensors were made: the “T” shape is for discrimination of the flow direction (left in Fig.10) and the “I” shape is for compensation of temperature fluctuation in the flow (right in Fig.10). “I” shape was found to be less sensitive to the force than “T” shape. Therefore, “I” shape was used as the temperature compensation only.\(^7\)

4.2 Characteristics of the sensor at the trailing edge of the airfoil

Figures 12 and 13 show the MEL001 airfoil with the FBG cantilever sensor at the trailing edge. The trailing edge was chosen as the best place for the sensors to be installed, because at this position the flow is supposed to be less disturbed by the cantilever sensors. The optical sensing interrogator for FBG has sampling frequency of 250 Hz and can process
Figure 14 shows the wave length shift $d\lambda$ of FBG as a function of attack angle $\alpha$. VGJs are not acting. In Fig. 14 (and in Fig.15), $d\lambda$ is defined to be positive when the cantilever sensor is bent upward, and to be negative when it is bent downward (see Fig.13). For low Reynolds number flows of $100,000 < Re < 150,000$ and low attack angles $\alpha$ up to 6°, $d\lambda$ is larger than that for high Re of 175,000 and 200,000. For larger attack angles $\alpha > 10$°, on the other hand, higher Reynolds number flow brings higher $d\lambda$. Moreover, $d\lambda$ is more sensitive to Reynolds number than in the lower attack angles. Such behavior is quite natural considering that the laminar separation at low Reynolds number occurs in the suction side of the airfoil. Thus the flow at the trailing edge tends to roll up from the pressure side to the suction side of the airfoil. For attack angles $\alpha$ larger than 8°, $d\lambda$ increases with $\alpha$. The reason is that the cantilever sensor is influenced by free stream. For all Re flows considered, $d\lambda$ remains constant at $16^\circ < \alpha < 18^\circ$ and increases at $\alpha = 20^\circ$ again. The constant $d\lambda$ at $16^\circ < \alpha < 18^\circ$ is conjectured that influence of free stream to the cantilever sensor becomes weak because the cantilever sensor is totally embedded in a separation bubble at those attack angles.

Figure 15 shows $d\lambda$ as a function of attack angle $\alpha$ under VGJ operation. VGJ is placed at VG-b position in Fig.6. Appreciable improvement appears for $\alpha < 8^\circ$. Moreover, it is interesting to note that $d\lambda$ seems to be roughly a linear function of $\alpha$. The reason is
considered as follows: The cantilever sensor is stuck out trailing edge. Therefore, the cantilever sensor is influenced by not only the wake of the airfoil but free stream. If there are no separations in the flow around the airfoil, the cantilever sensor tends to be bent upward (i.e. pressure side to suction side of the airfoil) by the free stream as $\alpha$ increases.

5. Control of Flow Separation

5.1 Control system

For establishing the closed loop control algorithm for the present sensor and actuator, relationship between $d\lambda$ and $\alpha$ and a map of $Re$-$\alpha$ indicating separation/non-separation regime are required. The following equations for $Re$ and $d\lambda$ are defined by using data in Fig. 15 by the least square method.

\[\alpha = A \times d\lambda + B \quad (1)\]

\[A = 928.45 - 5.82 \times 10^{-3} \times Re + 1.03 \times 10^{-8} \times Re^2 \quad (2)\]

\[B = 232.07 - 1.56 \times 10^{-3} \times Re + 3.02 \times 10^{-9} \times Re^2 \quad (3)\]

Fig. 14 Wave length shift without driving VGJs

Fig. 15 Wave length shift with driving VGJs
Figure 16 shows the $Re$-$\alpha$ map decided empirically.

The control algorithm is as follows: First, actuator is operated to sound the flow condition around the airfoil, i.e. $d\lambda$. The ambient flow speed and the kinematic viscosity are evaluated separately to calculate $Re$. Then corresponding $\alpha$ can be decided by Eq. (1). Knowing $\alpha$ and $Re$, the map tells whether or not the point $(\alpha, Re)$ is in the separation regime. If the point is in the separation regime, actuator is operated to suppress the separation. The sampling frequency of the controller is 250 Hz and time required for judgment of the flow condition is 20 sec. In this control algorithm, VGJ is used not only to suppress the separation but to detect $d\lambda$ variation. Thus, there is no need to stop the actuator for monitoring the flow condition. In the previous study by Nishizawa et al.\(^3\), the actuator had to be stopped during the monitoring of the ambient flow. By using the present control system, the airfoil was able to be kept without flow separation successfully.

5.2 Result of closed loop control

The control test was conducted under the condition of attack angle $\alpha$ from 0° to 20°, free stream velocity $U$ of 7.5 m/sec, jet velocity $V \approx 2U$ and Reynolds number $Re$ of 150,000. The $Re$ value was chosen according to the sensitivity of the sensor and experimental convenience. Figure 17 shows the result of the closed loop control. The coefficient of lift $C_l$ is clearly improved for $\alpha < 4$° due to the control. In the region of $8$° < $\alpha$ < 16°, “Control” case brings slightly larger $C_l$ than “No-control” case. This is due to the
sounding process in the former case, which is not included in the later case. In the sounding process, vortices are shedding and this process causes slight improvement of $C_L$. The demonstration of the control system was conducted at $Re = 150,000$ instead of $100,000$ due to the limitation of sensitivity of the present sensor. The effect of VGJs on $C_L$ is more enhanced in lower Reynolds number flows. But it is not remarkable in higher Reynolds number flow as shown in Fig.17.

In Fig. 18, the separation control system is checked at $\alpha$ of $0^\circ$. In this figure, we see that the control started automatically at 240 sec and stopped compulsorily at 400 sec after a designated time period (160 sec). It is found that the control system automatically detects the separation and starts operation of the actuator to bring improved $C_L$.

6. Concluding Remarks

A closed loop control system for separation around the MEL001 airfoil was established successfully. The system is composed of the vortex generator jets (VGJ), the optical fiber sensor (FBG), signal processor and personal computer. For the closed loop control, an empirical data map on the Reynolds number and the attack angle $Re-\alpha$ was used. In this control system, the vortices generated by VGJs are used for both sounding flow condition around the airfoil and suppressing flow separation.

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References

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