SMART CONTROL OF SEPARATION AROUND A WING
- Control Devices -

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Abstract

In order to construct a feedback control system for separation on an airfoil, continuous jet type vortex generator and cantilever flow sensor for discrimination of flow direction were developed. Jet type VG can generate single, longitudinal vortex with variable strength and extent. At certain driving conditions, VG actually brought appreciable improvement of airfoil performance. In addition, the present VG was found to suppress lift fluctuation, which is related to the aerodynamic noises. CFS could be utilized successfully in the feedback control system for separation.

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 (for example, Gad-el-Hak 2000, Hamdani et al. 2003). Nishizawa et al. (2004a) gave a brief review on this. However, feedback control system for separation is scarcely discussed. Our purpose in this project is to establish a sophisticated control system for separation (Nishizawa, et al. 2004a, 2004b)

. For this purpose, various actuators and sensors are newly developed (Pang, et al. 2004, Segawa, et al. 2003, 2005). In this section we will focus on a continuous jet type vortex generator (VG). The jet type VG developed in this project is designed to generate a single, longitudinal vortex with arbitrary strength and extent. In addition, a new flow direction discrimination sensor was developed through this project.

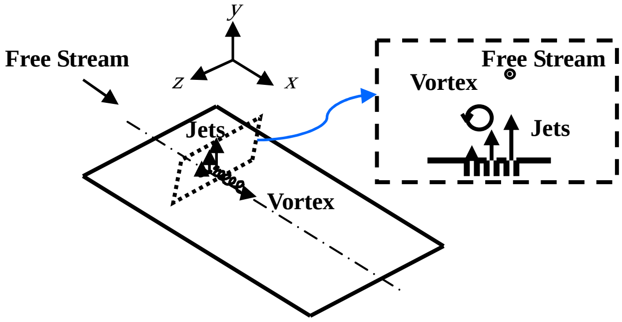
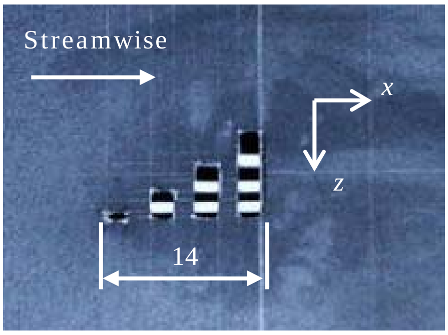
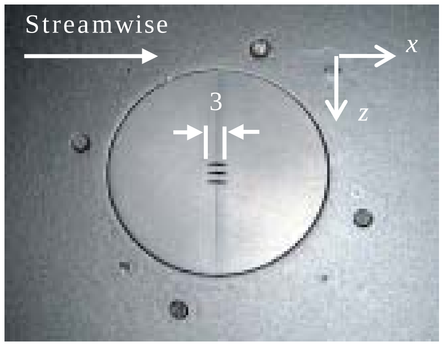


Fig.1 Principle of jet type VG.

2. Jet Type Vortex Generator

A brief review of developing the jet type VG throughout the project is described in the following. Figure 1 shows a concept of the present VG developed. Exit of the jets are mounted flush on the wall. Figure 2 shows the first model VG with multiple apertures (Abe, et al. 2001). Under the jet exits is a common reservoir connected with a compressor. Arrangement of the jet exit was decided empirically to generate small, longitudinal vortices. Figure 3 shows the second model (Abe, et al. 2004b). The second VG consists of three slits and each jet can be controlled separately by each regulator. Therefore, shear flow profile can be managed by regulating jets. However, when we utilize the multiple slit type VG on the airfoil, its piping system is too complicated to install it inside the airfoil. To overcome the problem, we designed the third





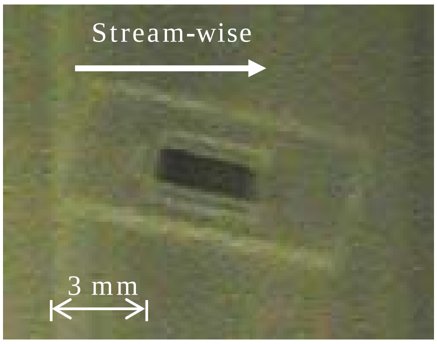


Fig.2 (top left) 1st model of VG, multiple aperture type. Fig.3 (top right) 2nd model, slit type. Fig.4 (bottom) Final model, single rectangular aperture.

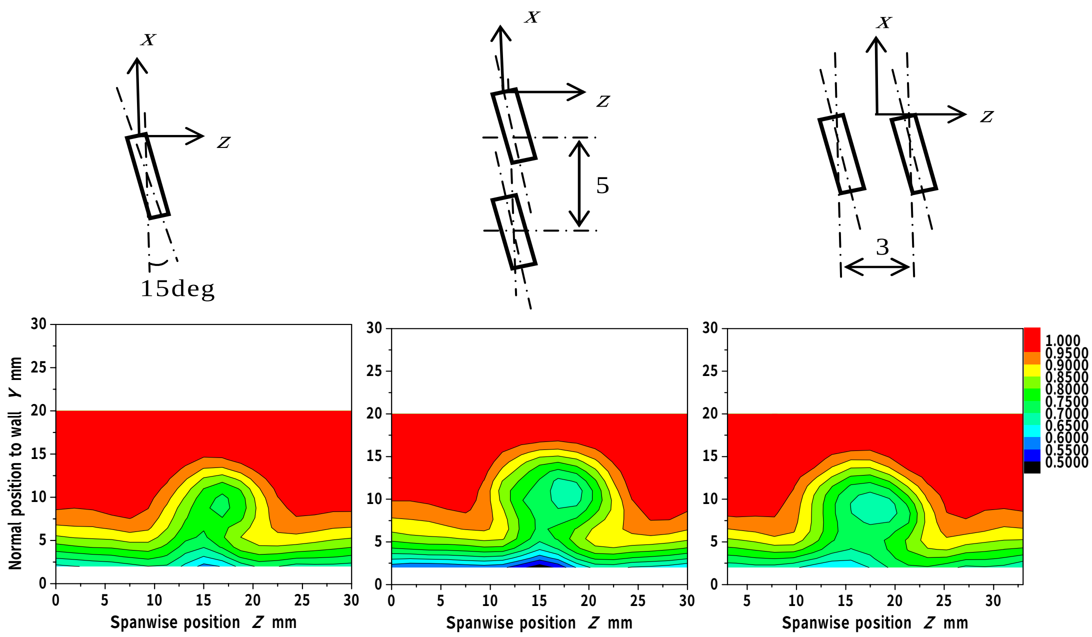


Fig.5 (a) (left) Contour of boundary layer velocity by 1 aperture. (b) (middle) 2 apertures set stream-wise with 5 mm pitch. (c) (right) 2 apertures set spanwise with 3 mm pitch.

(final) model.

Figure 4 shows the final model of the jet type VG (Abe, et al. 2004a). A single aperture for the jet is placed in the wall or airfoil surface. Most distinctive feature of this type VG is that it can produce single, longitudinal vortex with arbitrary strength and extent through controlling the jet velocity distribution across the aperture (Abe, 2002). 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.

Co-ordinate x, y, and z in the experiment are defined as streamwise-, normal to the wall-, and spanwise-directions, respectively. Velocity profiles of the boundary layer at x = 50 mm were measured by using the I-type hot wire anemometer. Velocity contours of the boundary layer at x = 50 mm and z = 50 mm are shown in Figure 5. Velocities are normalized by the free stream velocity, 5 m/sec. Figure 5(a) shows a vortex generated by the single jet aperture. It can be seen that single clockwise vortex is formed clearly. Direction of the rotation is discriminated because boundary layer of the right hand side rolls up. It was confirmed by the flow visualization using a smoke wire also. Figures 5(b) and 5(c) show vortices generated by two jet apertures with 5 and 3 mm pitches, respectively. By comparing Figures 5(a), 5(b), and 5(c), it is found that the strength and the size of the vortex generated by the two jet aperture system are higher and larger, respectively, than those of the vortex by the single aperture system. That is, the two aperture system can enhance the vortex. In case of Figure 5 (c), processes are not shown here, the vortex is formed by combining two vortices from two apertures. Through a series of experiments, it is summarize that intensity and size of the longitudinal vortex is controlled by varying the number and pitch of the jet apertures.

3. Effect of the Vortex Generator on the Lift of MEL001 Airfoil

Figure 6 shows a schematic diagram of VG locations, x/c = 0, x/c = 0.3, on the airfoil, which consists of blowing jet apertures aligned span-wise on the suction surface, air tanks and some sensors. CFSs are aligned along the center line of the airfoil. Locations and interval of VGs were decided properly based on the data accumulated. In this sense, they are optimized. The airfoil is supported by a cantilever with a load cell. Compressed air for VG is supplied from outside.

Figure 7 shows lift coefficient C_L as a function of attack angle α with VG at x/c = 0. Chord Reynolds number Re is 1.0×10^5. V/U is the jet velocity normalized by the free stream U. First we realized that C_L was remarkably influenced by the existence of the jet apertures. In the case without VG (■), no jet apertures, C_L is relatively low at lower attack angles up to 6º due to laminar separation at near x/c = 0.4. C_L decreases again at the higher attack angles of 18º to 20º, this is because laminar separation at leading edge, i.e. stall, occurs. By applying VGs, such C_L behavior at lower and higher attack angles is remarkably improved. At those attack angles, C_L is remarkably improved at proper jet velocity. On the contrary, in the middle attack angles of 8º to 16º, VG is not so effective. Though all attack angles considered, it is seen that too strong jet, $V/U > 2$, does not bring high C_L.

Figure 8 shows the velocity contours of the boundary layer on suction side of the airfoil at the trailing edge. Attack angle is α = 4º. The cases V/U=0 and 2 in Figure 8 correspond, respectively, to the results of ● and ◆ at α = 4º in Fig. 7. Velocity is normalized by the free stream velocity U. Comparing the results of V/U=0 and 2 in Fig. 8, it is seen that low speed area in the case of V/U=0, where separation occurs, is suppressed by applying VG like in the case of V/U=2. The boundary layer becomes wavy with small height

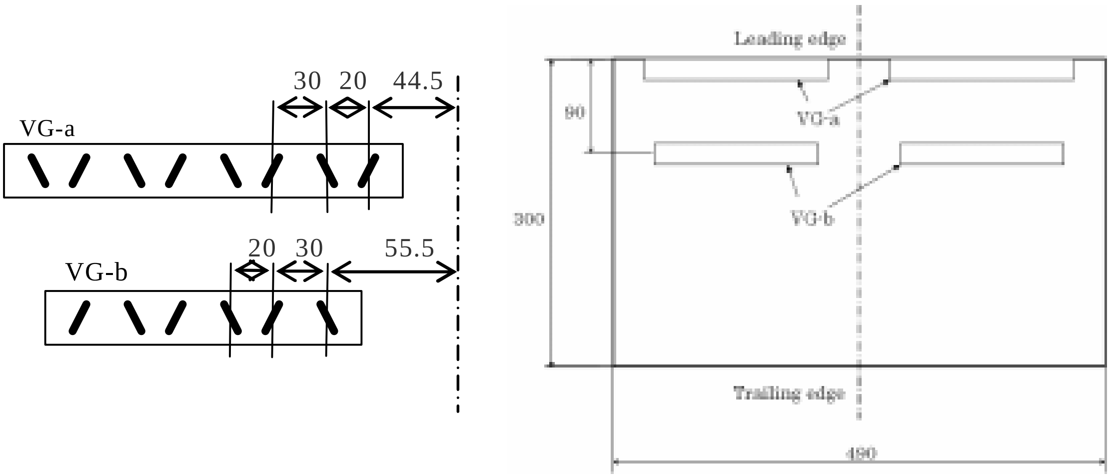


Fig. 6 Arrangement of the vortex generator on the wing

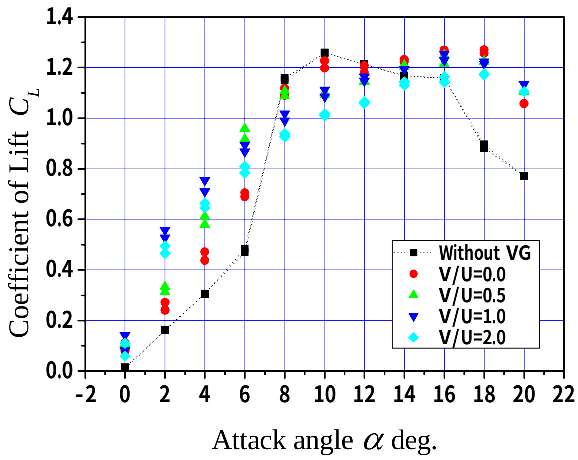


Fig.7 Effect of the VG at leading edge on C_L

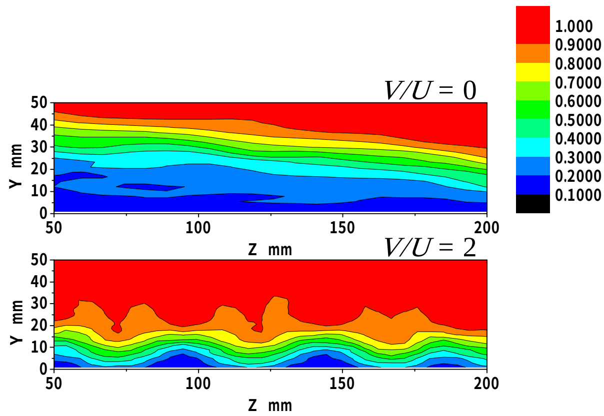


Fig.8 Velocity contour of boundary layer at trailing edge $\alpha = 4^{o}$

when VG is acted. The wavy structure is produced by interaction of longitudinal vortices discharged from the VG array set at the leading edge.

4. Numerical Simulation

In order to examine the effect of the continuous jet VG, a few numerical simulations were carried out. At certain VG driving conditions, a meaningful improvement of airfoil performance was observed (Yoshida, et al. 2005), i.e. 3 - 16 % increase in C_l/C_d at α = 6° and Re = 5X10^4 – 2X10^5. Figures 10 and 11 show, respectively, the flow fields without and that with VG at leading edge. Comparing them, it is found that vorticity structure is actually suppressed by VG. It is more clearly shown in the insets of the figures, which plot time variation of lift coefficient. Continuous jet type VG remarkably suppresses fluctuation of the aerodynamic force unlike the synthetic jet. Less fluctuation effect seems to be favorable to minimize aerodynamic noises.

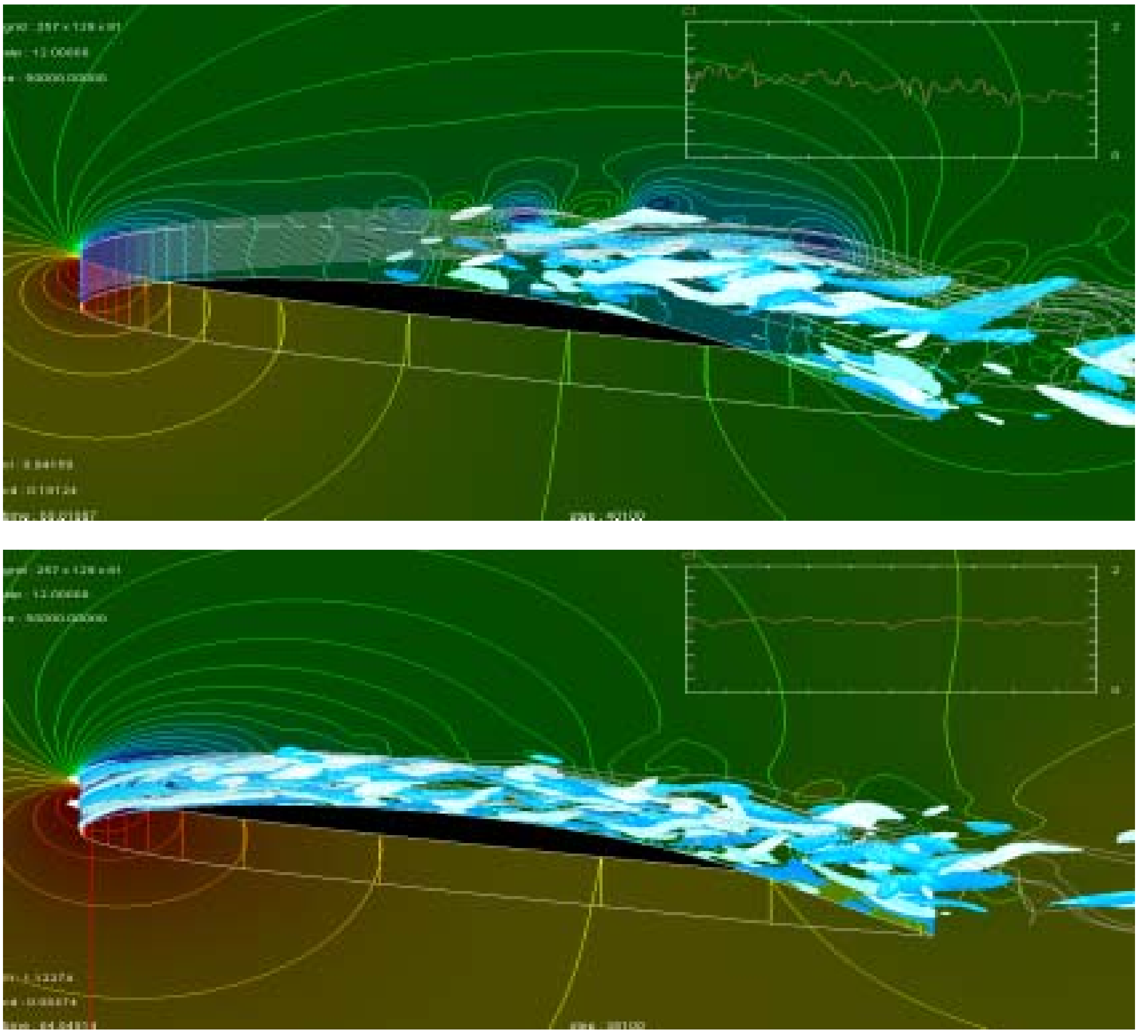


Fig. 9 Flow field around MEL001 airfoil. Re=50,000, α=6º. (a) (top) without VG. (b) (bottom) with VG at the leading edge. V_{jmax}/U=1. Inset: lift coefficient as a function of time, full scale is about 1 sec (Yoshida, et al. 2005).

5. Cantilever Flow Sensor and Others

In order to detect reversed flow, double cantilever sensor was developed (Pang, et al. 2004). The double cantilever system enables us to monitor not only local flow velocity but also velocity gradient, i.e. shear stress. For evaluation of skin friction of a plate, optical fiber Bragg grating system was developed (Segawa, et al.2003) and successfully applied to observe laminar and turbulent skin frictions (Segawa, et al. 2005).

Besides, Matsunuma (2001) developed a miniature resonance sensor, which was designed to detect peculiar fluctuation frequency in the flow. However, this was not used in the control system.

6. Conclusions

In order to construct a feedback control system for separation on an airfoil, continuous jet type vortex generator (VG) and cantilever flow sensor (CFS) for direct discrimination of flow direction were newly developed. The jet type VG can generate single, longitudinal vortex with variable strength and extent. At certain driving conditions, VG actually brought appreciable improvement of airfoil performance. In addition, the present VG was found to suppress lift fluctuation, which is intimately related to the aerodynamic noises. CFS could be utilized successfully in the feedback control system for separation. Although results are not shown here, Segawa et al. (2002, 2005) confirmed that, by using local actuator array, near wall turbulent structure was modified and, under some conditions, drag reduction was observed. The actuators used were array of piezo-ceramic elements and alternating suction / blowing jet array. They were supposed to give an equivalent effect to the spanwise wall oscillation.

So far, we have prepared devices for a feedback control system for an airfoil separation. Although the basic performance of the control system was confirmed by Nishizawa et al (2004a, 2004b), further optimization of components, actuator and sensor remain for future study.

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