ACTIVE SEPARATION CONTROL SYSTEM IMPROVED FOR CONTROL TIME AND SUPPRESSION EFFECT

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Abstract

Longitudinal (streamwise) vortices are produced by the interaction between the jets and the freestream. This technique is known as the vortex generator jet method because it controls separation in the same general way as the well-known method using solid vortex generators. The vortex generator jet method is an active control technique which provides a time-varying control action to optimize performance under a wide range of flow conditions. The vortex generator jets can adjust the strength of longitudinal vortices by varying the jet speed. Therefore, they can achieve the adaptive control by properly adjusting the jet speed. Furthermore, for flow situations where separation control is not needed, parasitic drag can be avoided with the jet flow turned off. Hasegawa et al. developed an active separation control system using vortex generator jets. In this study, the original control system has been improved in order to attain a faster response and make separation control more effective. The improved system can be practically applied to the flow separation control of a two-dimensional diffuser. In the improved system, a vortex generator jet method with suction control has been developed in order to make effective the suppression of flow separation and as a result the suppression is attained for large divergence angle of the two-dimensional diffuser.

1 Introduction

Pitched and skewed jets issuing through small holes in a wall into a freestream have proven effective in the control of boundary layer separation [1],[2]. Longitudinal vortices are produced by the interaction between jets and the freestream. In this method, the fluid particles which have large energy of the freestream are supplied to decelerated fluid particles in the boundary layer by longitudinal vortices. This technique is known as the vortex generator jet method because it controls separation in the same general way as the well-known method using solid vortex generators. The passive control technique with solid vortex generators (rectangular, ramp, delta-shaped winglets, etc.) has advantages such as simplicity, ruggedness, and low cost. Their disadvantages are that 1) they do not have the ability to provide a time-varying control action and therefore they cannot be adopted for highly maneuverable aircraft and 2) they add parasitic drag in flow situations where stall suppression is not needed (e.g., an airfoil operating near its design condition). It is desirable for the control devices to be operated only when flow separation occurs. However, solid vortex generators are always exposed in the flow and they have increased drag.

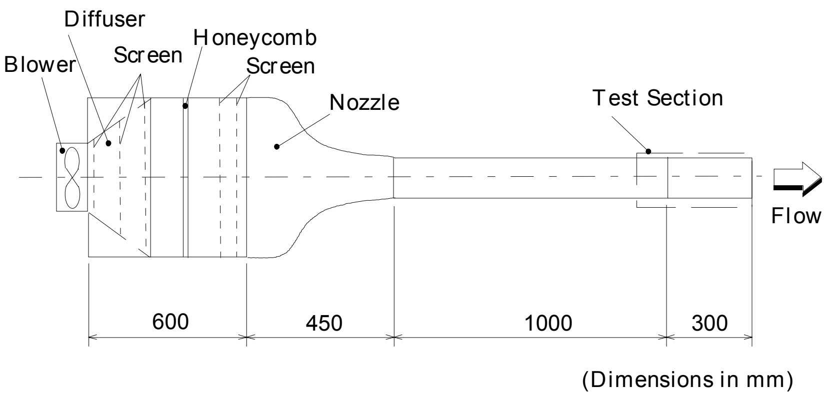


Fig. 1 Schematic diagram of experimental facility.

The vortex generator jet method is an active control technique which provides a time-varying control action to optimize performance under a wide range of flow conditions. The vortex generator jets can adjust the strength of longitudinal vortices by varying the jet speed. Therefore, they can achieve the adaptive control by properly adjusting the jet speed corresponding to flow parameters such as the angle of attack of an airfoil, the diffuser's divergence angle, and the freestream velocity. Furthermore, for flow situations where separation control is not needed, parasitic drag can be avoided with the jet flow turned off. The vortex generator jet method may accomplish separation control only when it is necessary and therefore it is useful for both design and off-design conditions. Stall control with airplane or fluid machinery is not needed in usual operations because they are designed to produce no separation. If the control device operates only when it is necessary and can adaptively suppress flow separation, the ideal flow corresponding to the flow under its design condition is always attained without any changes in design of airfoils or diffusers.

The study of airfoil performance using vortex generator jets has been reported in recent years [3]. Longitudinal vortices have the ability to convect kinetic and thermal energy in the lateral plane and this ability could be utilized to enhance film cooling efficiency [4]. Furthermore, applications of vortex generator jets to control of dynamic stall produced by changing the angle of attack of the airfoil have been reported [5]. However, the control system does not have the ability to adaptively suppress flow separation caused by changing in the flow fields.

Hasegawa et al. developed an active separation control feedback system and confirm the effectiveness of the system for the flow fields caused by change of freestream velocity and the diffuser's divergence angle [6]. The objective of this study was to improve the original control system in order to attain a faster response and make separation control more effective.

2 Experimental Apparatus and Method

2.1 Experimental Apparatus

Experiments were conducted in a low speed wind tunnel. A schematic diagram of the wind tunnel is shown in Fig. 1. The freestream velocity was varied from 0 to 13 m/s. The test section inlet dimensions are 250×120 mm (W×H). The test section had the function of variable diffuser. More details of the test section were given in Hasegawa et al. [6]. The jet flow was delivered through a metering valve after accumulating the air to a tank by a compressor. A rotameter was placed downstream from the metering valve. The vortex generator jet method could adjust the strength of longitudinal vortices by varying the jet speed. Adaptive control was achieved by adjusting the jet speed corresponding to the degree of separation. The jet speed was controlled by the valve which was actuated by an electric signal from a personal computer. In this study, in order to attain the effective suppression for large divergence angle of a two-dimensional diffuser, the vortex generator jet method with suction control has been developed. Location of static pressure holes and the suction slot are shown in Fig. 2. Static pressure meas-

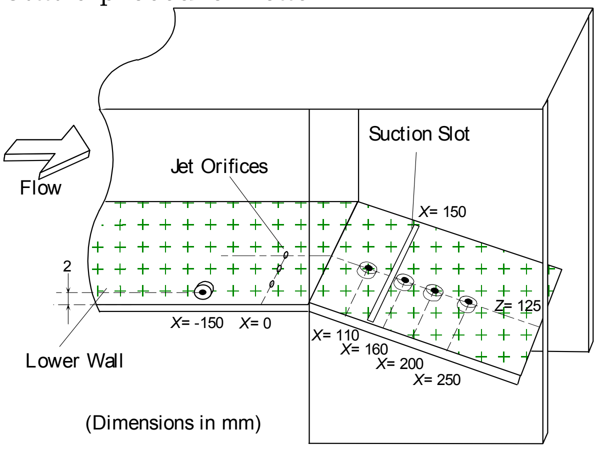


Fig. 2 Location of static pressure holes.

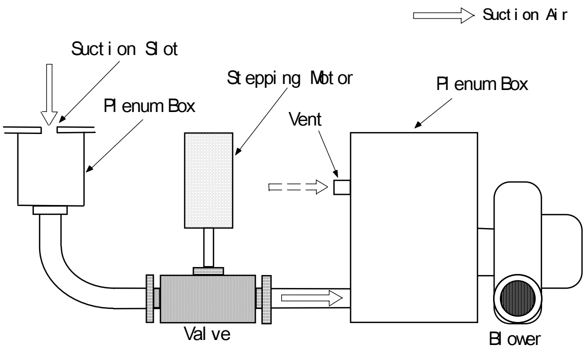


Fig. 3 Schematic diagram of suction system.

urements were carried out at several stations in the downstream direction using a differential pressure transducer which had the ability to measure very small differential pressure (0.01 mmAq). The width of suction slot was 3 mm (Ws =3 mm). The suction system was driven by an electric blower. In the suction system, the flow rate was controlled by a computer-controlled valve unit which was set between the suction slot and the blower. A detailed diagram of the suction system is shown in Fig. 3.

2.2 Experimental Method

Figure 4 shows the configuration of the jets and the coordinate system used to describe the flowfield. Three jet orifices were placed at the upstream of the divergent lower wall and they were configured on the right-hand side of the lower wall in the test section (viewed from upstream). The jets in this study were skewed at 90 deg (θ =90 deg) with respect to the freestream direction (0 deg being downstream). The jet pitch angle (ϕ) was selected

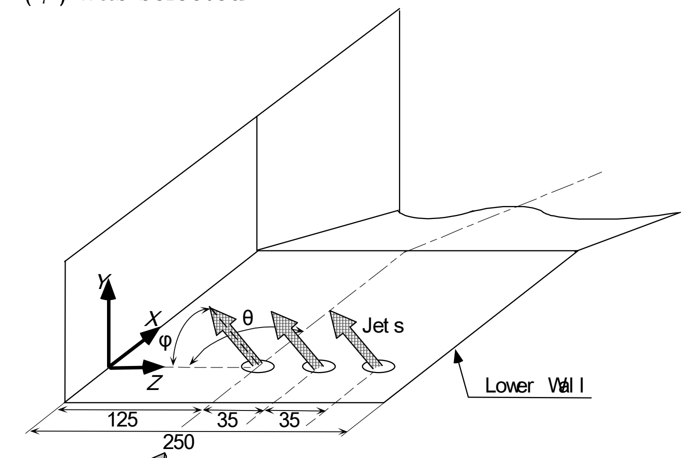


Fig. 4 Jets configuration in test section

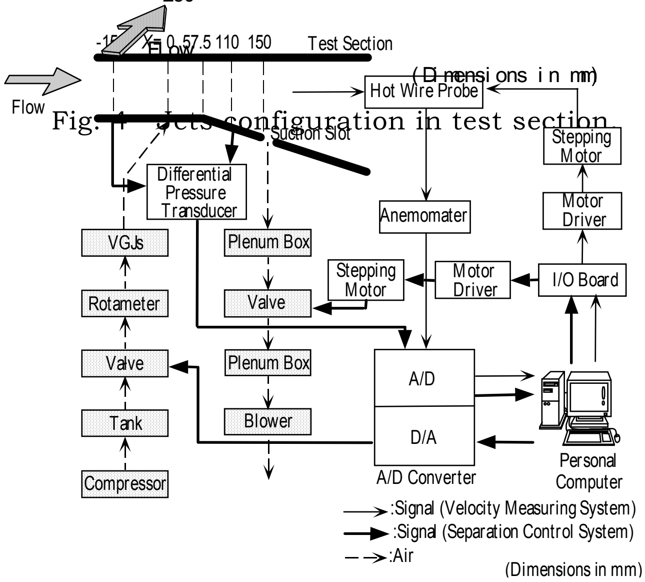


Fig. 5 Schematic diagram of active separation control system.

as ϕ =30 deg or ϕ =45 deg by changing the jet orifice unit. The jet orifice diameter was a circular one of 2 mm (Dj=2 mm). The velocity field was measured using an X-type hot wire probe which was supported by a three-axis computer-controlled traverse unit. The velocity measurements in the *Y*-*Z* plane were carried out at equal intervals of 5 mm, in both the *Y* and *Z* directions.

The schematic diagram of this study is shown in Fig. 5. This system mainly consists of a differential pressure transducer, a valve with controller, and a personal computer. The valve was actuated by an electric signal from the personal computer. In this system, a differential pressure was measured initially at two points, the upstream of divergent portion and the measurement station in the diffuser in order to judge the initial flow situation. If a flow separation was detected, the vortex generator jet device operates and controls the jet speed to suppress the flow separation. Furthermore, the suction control system started to reinforce the vortex generator jets when the system judged that the suppression was not achieved with vortex generator jet system alone.

3 Results and Discussion

3.1 Improved System for Control Time

The control time which is necessary to attain separation control is related to the response speed against the change of flow field. In other words, if the system can adapt the flow situations more quickly, the faster separation control can be performed. In this study, the original control system has been improved in order to attain a faster response.

The alteration points from the original system to the improved system are that 1) the jet pitch angle is set at 30 deg (it was set at 45 deg in the original system), 2) the jet flow rate per control step varies adaptively for various flow situations. The jet pitch angle of 30 deg makes effective the pressure recovery and also the separation control at *X*=110 mm [7], where the differential pressure are measured (see Fig. 5). In the original system, the jet flow rate per control step is kept constant for various flow situations. In the improved system, the jet flow rate is variable in the control process for attaining the control target. If flow separation occurs in the jet-off situation, the large increment of the jet flow rate is required. In this case, the system initially controls with the large increment of the jet flow rate. In other words, the jet flow rate per control step makes large to decrease the number of steps until which the system operates in the optimal jet flow rate. Furthermore, the system can decrease the jet flow rate when the system approaches the optimal performance in order to prevent the overshooting of the target value. The alteration point 1) or 2) is useful to reduce the fluctuations in the system by the large pressure recovery because the difference between the differential pressure of the stalled and the unstalled flow fields is large. Therefore, the system attains a faster response.

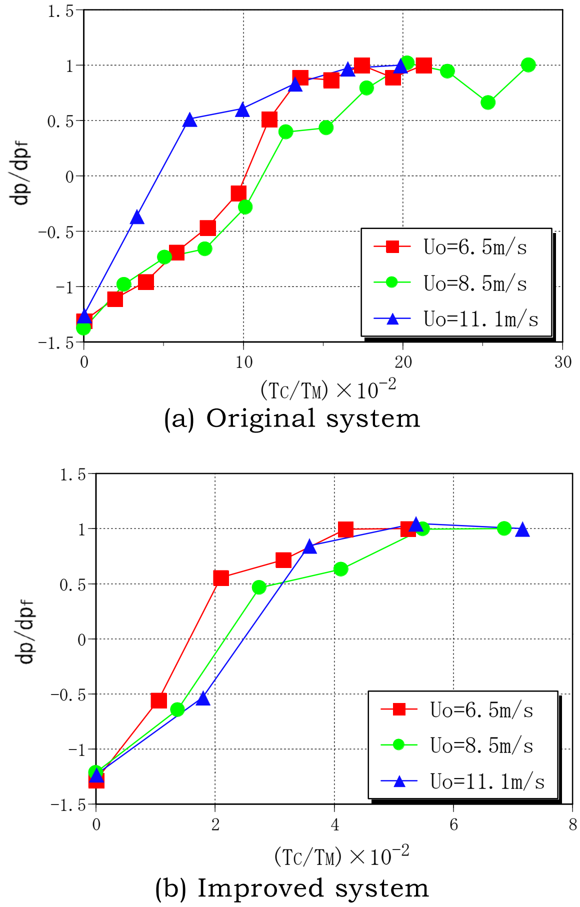
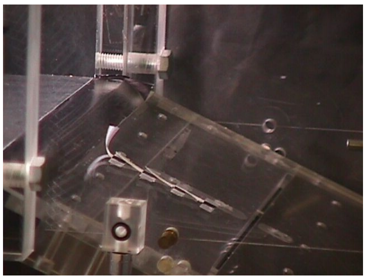
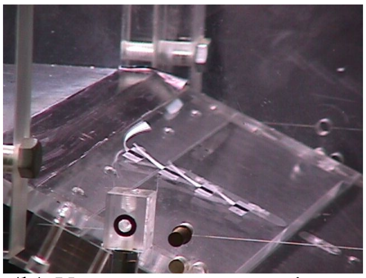


Fig. 6 Variation of differential pressure under control.

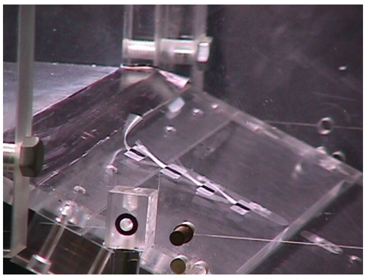
Figure 6 shows the differential pressure variation after the system began to suppress flow separation. The abscissa denotes control time (T_C) normalized by the time (T_M) during which fluid particles move from the position of the jet orifices (X=0) to the controlled point (X=110 mm). The ordinate denotes the differential pressure (dp) normalized by the differential pressure (dp_f) needed for attaining the control target.



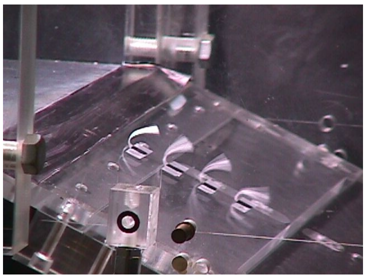
(a) No control



(b) Vortex generator jets



(c) Suction control



(d) Vortex generator jets with suction control

Fig. 7 Surface flow in divergent portion of the test section (U_0=6.5 m/s).

Figure 6(a) shows time variation of differential pressure for the original system and indicates that effective pressure recovery was achieved for each freestream velocity. Figure 6(b) shows the case for the improved system. Comparing Fig. 6(a) with Fig. 6(b), it is seen that the control time of the improved system is shorter than that of the original system for each freestream velocity. In the original system, the U_0=11.1 m/s case indicates the effective pressure recovery and attains faster control compared with the U_0=8.5 and 6.5 m/s cases. On the other hand, in the improved system, the system indicates the same trend of the pressure recovery for each freestream velocity. The jet flow rate per control step is kept constant in the original system and therefore the pressure recovery is affected by the freestream velocity. The strength of longitudinal vortices has relation to the freestream velocity. This is because the effective pressure recovery is accomplished by the strong longitudinal vortices due to faster freestream velocity. Therefore, the effective separation control is achieved for the U_0=11.1 m/s case. The pressure recovery is not affected by the freestream velocity for the improved system because the jet flow rate is variable in the control process.

3.2 Improved System for Suppression Effect

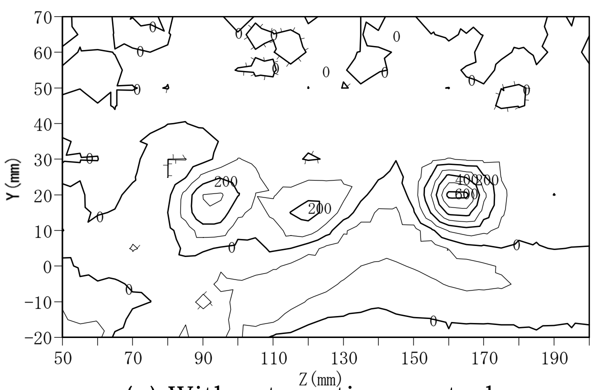
In the original system, the suppression is attained below the diffuser's divergence angle of 20 deg (α=20 deg). The vortex generator jet method with suction control has been developed in the improved system in order to make effective the suppression of flow separation and as a result the suppression is attained for large divergence angle of the two-dimensional diffuser. In other words, the improved system can attain the suppression above the divergence angle of 20 deg. The suction control in this study is used to reinforce the separation control with longitudinal vortices. The suppression of flow separation is accomplished by the secondary flow of longitudinal vortices which transports the high momentum fluids of the freestream to the boundary layer. Longitudinal vortices exist away from the lower wall in large divergence angle and the secondary flow of longitudinal vortices is not useful to transport the high momentum fluids of the freestream toward the lower wall [8]. The suction control in the diffuser enables longitudinal vortices to exist in a region close to the lower wall.

Figure 7 shows the flow visualization in the divergent portion of the test section for U_0=6.5 m/s. The surface tuft method was used as a diagnostic technique to observe the effect of the control system on separated flow. In Fig. 7, the air flows from left to right. Tufts were put on the lower wall of the test section at Z=140 mm and the tuft of the downstream side of this figure is at X=110 mm. The divergence angle of the test section was set at 24 deg (α=24 deg). The separation controls with vortex generator jets and with suction control are shown in Figs 7(b) and 7(c), respectively. In these cases, the suppression effect was not achieved at X=110 mm. It is seen from Fig. 7(d) that the suppression is achieved by using the vortex generator jets with suction control for the divergence angle of 24 deg.

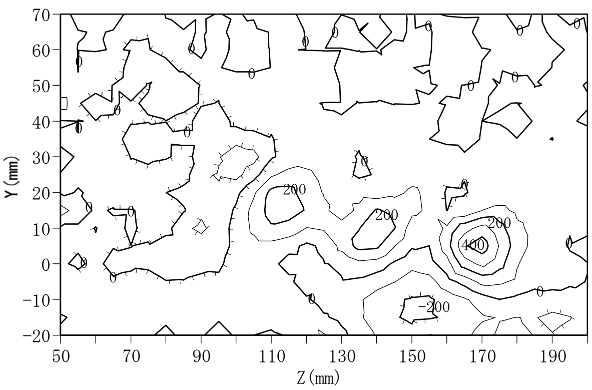
Figure 8 indicates the longitudinal vortices generated by the interaction between the jets and the freestream. Figures 8(a) and 8(b) show the case without and with suction control, respectively. In this study, the vorticity is defined as positive one for vortices of clockwise rotation when we view from upstream. The longitudinal vortices exist apart from the lower wall because the divergence angle is set at 24 deg. The longitudinal vortices exist close to the lower wall in operating the suction control. Therefore, the secondary flow produced by the longitudinal vortices become large in the region close to the lower wall and the fluid particles of the freestream are supplied to the boundary layer.

Figure 9 shows the flow chart of the improved system. This system initially samples a differential pressure to judge the flow situation. If the system senses flow separation, the jet flow rate per control step is calculated to operate the vortex generator jet device. The vortex generator jet device is operated to suppress flow separation. If the system achieves the pressure recovery sufficiently, the system judges the attainment of the control and keeps the jet speed constant. The system senses the unstalled flow field and cuts off the jets

completely for the situation in which no flow separation occurs. When flow separation is caused by change in the flow situation (e.g., freestream velocity and divergence angle of the test section) the system restarts automatically. If the system can not make effective the suppression of flow separation under control using vortex generator jets alone, the system judges the large divergence angle (greater than 20 deg). In this control system with vortex generator jets alone, the suppression is attained below the



(a) Without suction control



(b) With suction control

Fig. 8 Contours of streamwise vorticity at X=110 mm (U_0=6.5 m/s). Decorated lines denote negative vorticity.

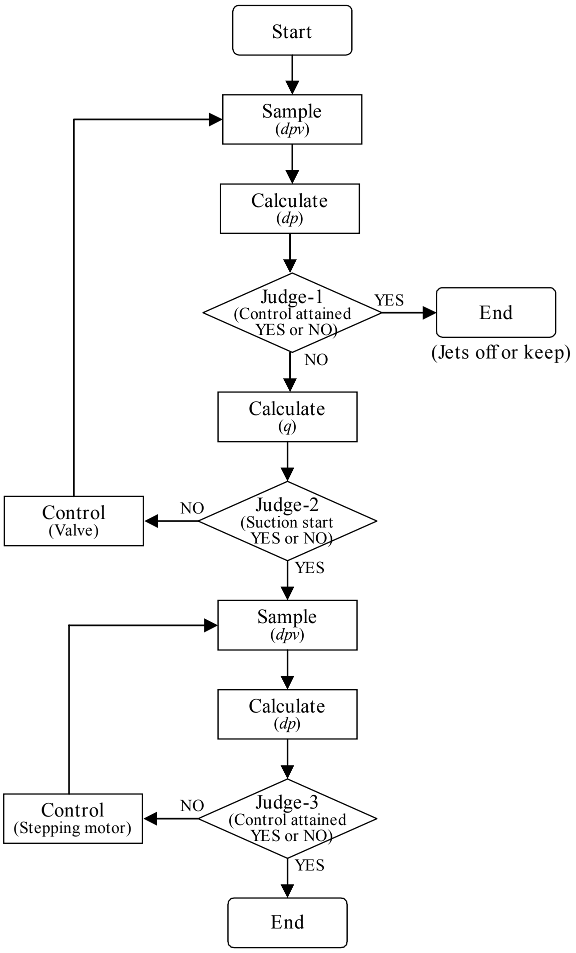


Fig. 9 Flow chart of improved system.

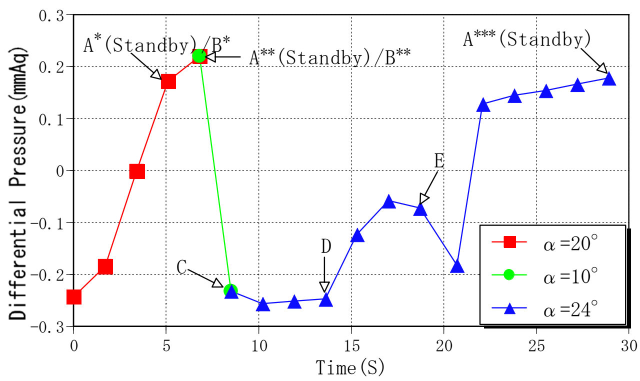


Fig. 10 Variation of differential pressure under control (U_0=8.5 m/s).

divergence angle of 20 deg. The system starts suction control when the system judges the large divergence angle. The system initially increases the jet speed in order to enhance the secondary flow. However, the longitudinal vortices move apart from the lower wall under the influence of the induced velocity as the vorticity becomes large. For this reason, the system adjusts the jet speed before the system starts suction control.

3.3 Applications of Improved System to the Separated Flow

Figure 10 shows the time variation of differential pressure under control for the flow field which causes flow separation. In order to suppress flow separation adaptively, the improved system was applied to the time-varying flow fields caused by change of the divergence angle. In Fig. 10, point “A” is just when the separation control is attained by operating the system. Point “B” indicates the point at which the flow condition is changed and point “C” is when the system senses change in the flow conditions and restarts suppressing the flow separation. At point “D”, the system senses the divergence angle greater than 20 deg and requires the additional operation of suction. At point “E”, the system starts suction control.

In this example, the flow is initially separated. The system tries to suppress flow separation and attains the suppression at point “A*”. When the divergence angle is changed at point “B*”, the flow condition indicates the unstalled flow field. The system senses the unstalled flow field and cuts off jets completely at point “A**”. Furthermore, the divergence angle is set at 24 deg at point “B**” and the flow condition indicates the stalled flow field. The system senses flow separation and restarts the suppression of separation at point “C”. The system adjusts the jet speed to attain the suppression. However, the differential pressure does not recover and the system senses the divergence angle greater than 20 deg at point “D”. The system requires the additional operation of suction because it judges to make ineffective separation control using vortex generator jets alone. At point “D”, the system adjusts the jet speed before the system starts suction control. The vortex generator jets with suction control are performed at point “E” and as a result the suppression is attained at point "A***" for the flow situation in the divergence angle of 24 deg. After that time, the system keeps the jet and the suction speed constant.

4 Conclusions

An active separation control system using vortex generator jets with the ability to adapt various flow conditions has been improved in order to attain a faster response and make separation control more effective. It was confirmed that the improved system could perform the faster separation control and could suppress flow separation in larger divergence angle of the test section in comparison with the original system. In addition, we conclude that the improved system could adaptively achieve the suppression for flow fields caused by some changes in freestream velocity and the divergence angle.

Acknowledgements

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References

[1] Johnston, J. P., and Nishi, M., "Vortex Generator Jets-Means for Flow Separation Control," *AIAA Journal*, Vol. 28, No. 6, pp. 989–994, 1990.

[2] McManus, K. R., Lenger, H. H. and Davis, S. J., "Pulsed Vortex Generator Jets for Active Control of Flow Separation," *25th AIAA Fluid Dynamics Conference*, Colorado Springs, CO, AIAA Paper 94–2218, 1994.

[3] McManus, K. R. and Magill, J., "Airfoil Performance Enhancement Using Pulsed Jets for Active Control of Flow Separation," *4th AIAA Shear Flow Control Conference*, Snowmass Village, CO, AIAA Paper 97-1971, 1997.

[4] Goldstein, R. J. and Eckert, E. R. G., "Effect of Hole Geometry and Density on Three-Dimensional Film Cooling," *J. Heat Mass Transfer*, Vol. 17, pp595-607, 1974.

[5] Magill, J. C. and McManus, K. R., "Control of Dynamic Stall Using Pulsed Vortex Generator Jets," *36th Aerospace Sciences Meeting & Exhibit, Reno*, NV, AIAA Paper 98-0675, 1998.

[6] Hasegawa H., Matsuuchi K. and Tanaka J., "Development of Active Separation Control System Using Vortex Generator Jets," *3rd ASME/JSME Joint Fluid Engineering Conference*, San Francisco, CA, FEDSM 99-6944, 1999.

[7] Hasegawa H. and Matsuuchi K., "Effect of Jet Pitch Angle of Vortex Generator Jets on Separation Control," *3rd International Conference on Fluid Mechanics*, pp. 526-531, 1998.

[8] Hasegawa H. and Matsuuchi K., "The Mechanism of Active Boundary Layer Control Using Vortex Generator Jets," *21st Conference of the International Council of the Aeronautical Sciences*, ICAS-98-3,4,3, 1998.

Nomenclature

D_j jet orifice diameter
dp differential pressure
dp_f differential pressure needed for attaining control target
dp_v output voltage of pressure transducer
Tc control time
T_m time during which fluid particles move from X=10 to 110 mm
q control variable (jet flow rate per control step)
U_0 local freestream velocity
W_s width of suction slot
X streamwise coordinate(measured from jet hole)
Y vertical coordinate(measured from lower wall)
Z spanwise coordinate(measured from left-hand side wall viewed from upstream)
α divergence angle of lower wall
ϕ jet pitch angle, θ jet skew angle
ω_x streamwise component of mean vorticity