Active Boundary Layer Control System Using Vortex Generating Jets and Operating by the Detection of Precursor of Flow Separation

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Abstract
Longitudinal vortices produced by the interaction between jets and a freestream are useful in enhancing boundary layer mixing and have proven to be effective for controlling flow separation. This technique, known as the vortex generating jet (VGJ) method, serving as an active control provides a time-varying control action to optimize performance under a wide range of flow conditions, because the strength of the longitudinal vortices can be adjusted by varying the speed of the jet. In the present study, an active separation control system using VGJs is proposed and is applied to the practical problem of flow separation control in a two-dimensional diffuser. The proposed system can be operated prior to the onset of separation, and therefore, a separation control is always attained with no flow separation for all the flow fields examined. The experimental results indicate that the growth of shear layer vortices at the corner of the diffuser inlet is a precursor to the large-scale separation over entire surface of the diffuser. If the proposed system starts operating just before the onset of separation, 20 % of the total amount of energy to suppress separation can be reduced in comparison with a standard feedback system, which starts operating after separation occurs.

1. INTRODUCTION

Separation of flow is typically an undesirable phenomenon in engineering practices because it entails large energy losses and produces vibrations in fluid machinery. For this reason, methods have been devised for the artificial prevention of separation. An effective method for the prevention of separation is boundary layer mixing [1]. In this method, the fluid particles in the freestream that have large amounts of energy are supplied to decelerated fluid particles in the boundary layer using longitudinal vortices. This passive control technique with solid vortex generators is advantageous because of its simplicity, ruggedness, and low cost. Boundary layer mixing using longitudinal vortices has been applied to the practical problem of stall control on an airfoil, and in diffusers. For example, solid vortex generators placed on an airfoil are useful for improving flight performance during aircraft take off and landing. However, solid vortex generators cannot provide a time-varying control action, and they add parasitic drag in flow situations where stall suppression is not needed. In other words, solid vortex generators are always exposed in the flow and thereby increase drag.

On the other hand, pitched and skewed jets issued through small holes in a wall into a freestream have proven to be an effective means for controlling boundary layer separation [2, 3]. This technique is known as the vortex generating jet (VGJ) method. In this method, longitudinal vortices are produced by the interaction between jets and a freestream. The VGJ method serving as an active control provides a time-varying control action, because the strength of the longitudinal vortices can be controlled by varying the speed of the jet. Furthermore, the VGJs can be adaptively controlled in time-varying flow fields, making it unnecessary to know in advance whether the boundary layer is laminar or turbulent. For flow situations where separation control is not needed, parasitic drag can be avoided with the jet flow turned off. Separation control with airplanes and fluid machinery is not usually needed because these devices are designed to produce no separation. If the control device operates only when it is necessary and can adaptively suppress flow separation, an ideal flow corresponding to the flow under the device's design condition is always attained without any change in the design of the airfoils or diffusers. Note that fast response capability of the control of the jet is required to actually use such a separation control system to adaptively suppress flow separation in a time-varying flow.

To date, no reports exist in the literature detailing the actual use of VGJs. However, experimental results of a wind tunnel test using an airfoil model with VGJs have been reported [4, 5]. The separation control system in those studies does not have the ability to adaptively suppress flow separation in a time-varying flow. The authors have previously investigated the effects of jet pitch angle [6] and jet orifice shape on suppression [7], and an active separation control system, which had the ability to adjust the jet flow rate in time-varying flow [8]. Although this system had a fast response capability for controlling the jet, separation itself could not be prevented when the system operated after separation was detected. In other words, even if separation occurred briefly, fluid machinery would not operate in a favorable manner. In the previous study, the authors demonstrated flow field change just before the onset of flow separation [9]. Furthermore, a common precursor signal of separation with respect to the flow field change just before separation has been found under both laminar and turbulent flow conditions. In the present study, a separation control system is developed that can operate prior to the onset of separation by detecting the precursor signal of separation. If the system operates before separation occurs, control with no flow separation can always be achieved. The performance of our proposed system is confirmed in a two-dimensional diffuser that can adjust a divergence angle and the freestream velocity.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1 Experimental apparatus

Experiments were conducted using a low speed wind tunnel. Figure 1 shows a schematic of the wind tunnel and the test section in the experimental facility. The freestream velocity U_0 was varied from 0 to 12 m/s. The test section inlet dimensions were 250 × 120 mm (W × H). The test section had a variable diffuser that could adjust the divergence angle between 0 and 30 deg using a step motor controlled by a personal computer. The step motor was operated at a constant angular velocity ω (ω = 1 deg/s or 2 deg/s) and the diffuser's divergence angle was measured by a potentiometer. However, the value of the diffuser's divergence angle was not used for control in our proposed system. Figure 2 shows the configuration of jets and the coordinate system used to describe the flow field. Three jet holes were placed 55 mm upstream of the divergent portion and three holes were placed on the right-hand side of the test section when viewed from upstream. The origins of the coordinates X, Y, and Z are defined as the locations of the jet hole, the lower wall, and the left wall in the test section, respectively. A rectangular jet orifice shape with an aspect ratio of 6.4:1 was installed, and jets were issued through orifices in the lower wall of the test section. The generation of streamwise mixing vortices with vortex generator jets that are pitched at an acute angle relative to the main flow surface and skewed with respect to the local main flow direction is useful for separation control [6, 10]. In the present study, the jets were skewed at 90 deg (θ = 90 deg) with respect to the freestream direction, and were pitched at 30 deg (φ = 30 deg) with respect to the lower wall. The long-side width of the rectangular orifices was 4.5 mm and the short-side width was 0.7 mm. The rectangular orifice with the long side set in the spanwise (z) direction, because it was confirmed in our previous study [11] that these orifice conditions (in terms of shape and direction) produce effective boundary layer separation control. The magnitude of the jet flow rate was characterized by the jet-to-freestream velocity ratio VR written as

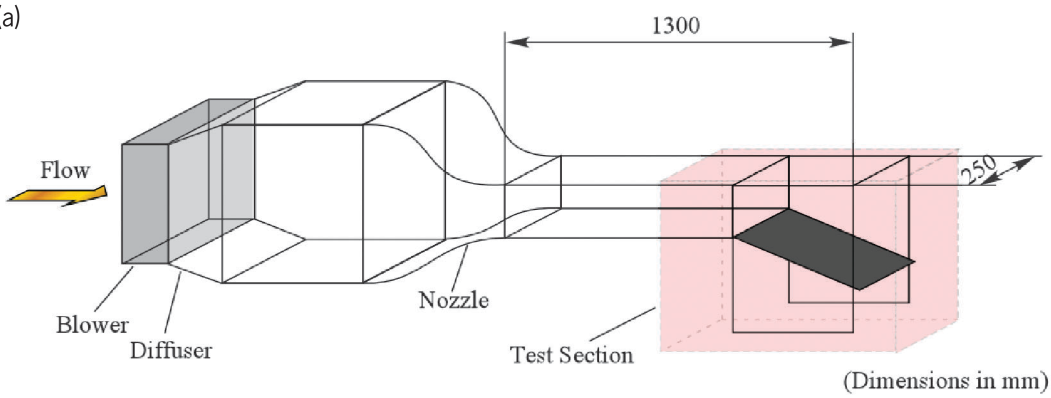
$$VR = V_j / U_0 \tag{1}$$

where V_j is the jet speed.

2.2 Experimental method

In our proposed system, the flow condition was judged by measuring the wall static pressure at two points, upstream of the divergent portion (X = –150 mm, in the unstalled region) and in the divergent portion (X = 110 mm). The hole in the wall for measuring static pressure on the downstream side was set on the center line of the divergent portion. In other words, the information concerning the freestream velocity and the divergence angle of the diffuser is not needed for separation control in our proposed

(a)



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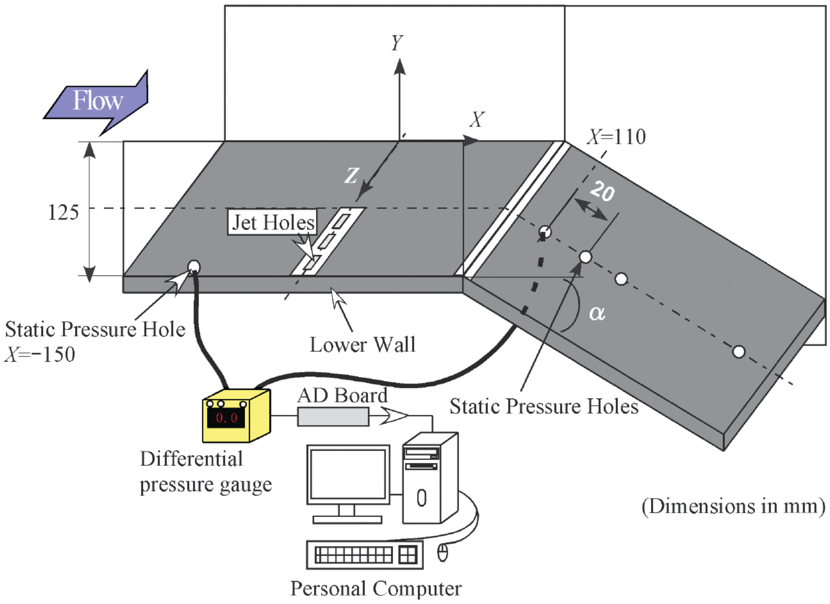

Figure 1. Schematic of test section: (a) experimental facility, (b) enlarged view of test section.

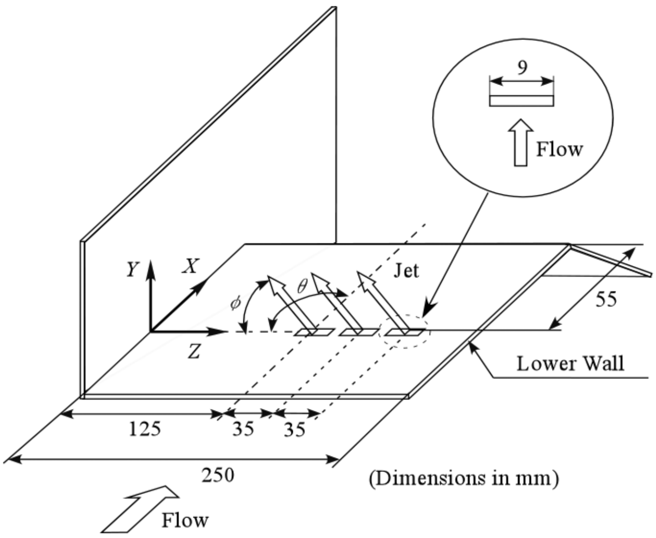

Figure 2. Jet configurations and coordinate system.

system. Separation and a precursor of separation can be found using only the pressure difference between the two points along the wall. Static pressure measurements were conducted using a differential pressure transducer that has the capability to measure very small differential pressures (on the order of 0.001 Pa). Figure 3 shows a schematic of the control system. This system consists of a differential pressure transducer, a valve with a controller, and a personal computer. The valve is actuated by an electric signal from the personal computer. In the present study, the flow conditions were changed by varying the freestream velocity and the divergence angle of the diffuser. The VGJ method could adjust the strength of the longitudinal vortices by varying the speed of the jets. Adaptive control was achieved by adjusting the jet speed corresponding to the degree of separation. Jet flow was delivered after accumulating enough air using a compressor, and the speed of the jets was controlled by adjusting a valve.

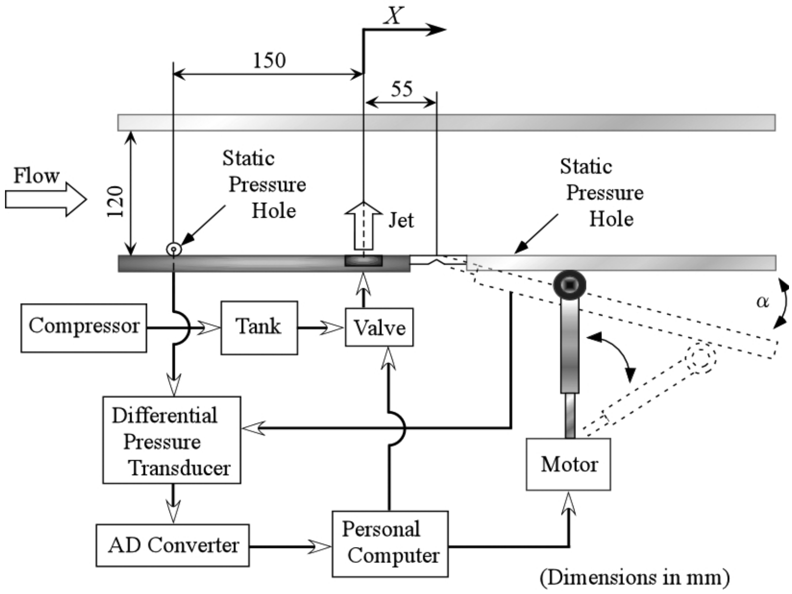

Figure 3. Schematic diagram of control system.

A flowchart of this system is shown in Fig. 4. This system initially samples a differential pressure to judge the flow situation. If flow separation is detected, the VGJ device operates automatically and controls the speed of the jet to suppress the flow separation. The system uses feedback and determines whether the control target is attained or not. If suppression is not achieved, the system recalculates the necessary speed of the jet and adjusts the jet flow rate precisely. When the system achieves sufficient pressure recovery and determines that the control target has been attained, the system maintains the present speed of the jet. The system senses the unstalled flow field and cuts off the jets completely when no flow separation is occurring. When flow separation is caused by a change in the flow situation (e.g., by a change in the freestream velocity or in the divergence angle of the diffuser), the system restarts automatically. In addition, the function of determining a precursor signal of separation is included in the control loop. A separation bubble is formed in separation-reattachment flow when there is a small divergence angle. However, flow perturbations increase on the downstream side of the diffuser as the diffuser's divergence angle is increased. Turbulence phenomena are also promoted by increasing the divergence angle. The separation region expands to the upstream direction, and whole separation occurs as the divergence angle is increased further [12]. If whole separation occurs, pressure recovery in the diffuser cannot be completely achieved. Therefore, it is necessary to perform flow control to avoid whole separation. The system senses the state prior to the occurrence of whole separation and determines a precursor signal of separation. In a previous study, the authors reported that vortex behavior in the separated shear layer developed at the corner of the diffuser is affected by the diffuser's divergence angle [9]. In the present study, this vortex behavior was determined from the wall static pressure, and a precursor signal of separation was detected from the wall static pressure variations.

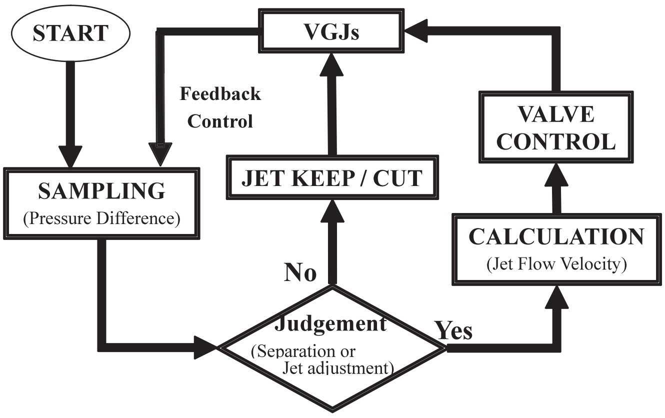

Figure 4. Flowchart.

3. RESULTS AND DISCUSSION

3.1 Control effect of the proposed system

The vortical field generated by the interaction between a freestream and jets was measured using an X-type hot-wire probe that was supported by a three-axis computer-controlled traverse unit. In order to characterize the flow field, the probe was moved in the vertical plane of the freestream direction. The streamwise vorticity Ω is defined as

$$\Omega = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \tag{2}$$

where v and w indicate the velocity components in the Y and Z directions, respectively. The vorticity is calculated by the velocity in the Y-Z plane measured at equal intervals of 5 mm, in both the Y and Z directions, where at each location the flow was sampled for 5 s. Figure 5 shows the contours of the streamwise vortices at X = 110 mm under flow control. Figure 6 shows the secondary flow vectors, corresponding to the vortical field (see Fig. 5) in the Y-Z plane at X = 110 mm. The flow field when the system attains suppression is shown in Figs. 5(a) and 6(a). On the other hand, Figs. 5(b) and 6(b) show the flow field before the system attains suppression. In these cases, a precursor signal is not detected to better understand the difference between two flow fields before and after suppression, and therefore, VGJs operate after separation occurs. When the system does not suppress separation, the speed of the jet (VR = 4.5) is lower than that when suppression is attained (VR = 9.5). In Fig. 5(b), the system does not attain suppression because the longitudinal vortices are weak due to the low speed of the jets. Since three pairs of positive and negative vortices are aligned corresponding to the three jet orifices, the longitudinal vortices and the downwash from the secondary flow in the region close to the lower wall are strong for VR = 9.5, in contrast to those for VR = 4.5. In general, the large energy of the freestream is supplied to decelerated fluid particles in the boundary layer by the longitudinal vortices; thereby separation control is achieved. Therefore, for effective separation control, it is important that the secondary flow toward the lower wall is strong in the region close to the lower wall.

Figure 7 shows instantaneous photographs in the divergent portion of the test section for U_0 = 6.5 m/s and α = 21 deg. Figure 8 (a) shows a schematic view of tufts set-up in the divergent portion and the tufts are agitated when the surface flow in the downstream direction occurs in this arrangement. The freestream is always from left to right, and tufts are placed on the lower wall on the centerline of the diffuser (Z = 125 mm). The tuft on the downstream side in this photograph is set at X = 210 mm. The tufts on the downstream side do not agitate before the system attains suppression, and separation is not suppressed in Fig. 7(a). On the other hand, the flow visualizations show that surface flow in the divergent portion is observed, and flow separation can be suppressed by operating the system (see Fig. 7(b)). Furthermore, the flow visualization diagnostic was used extensively to interrogate the effect of our proposed system on separated flow in the test section, and to study modifications in the turbulence structure associated with the action of the VGJs.

In order to make the flow pattern visible in the diffuser, flow visualization was also performed using a smoke method as follows. A schematic view of flow visualization set-up by smoke method is given in Fig. 8(b). Smoke was used to observe surface flow in the diffuser. Titanium tetrachloride is dropped

(a)

(b)

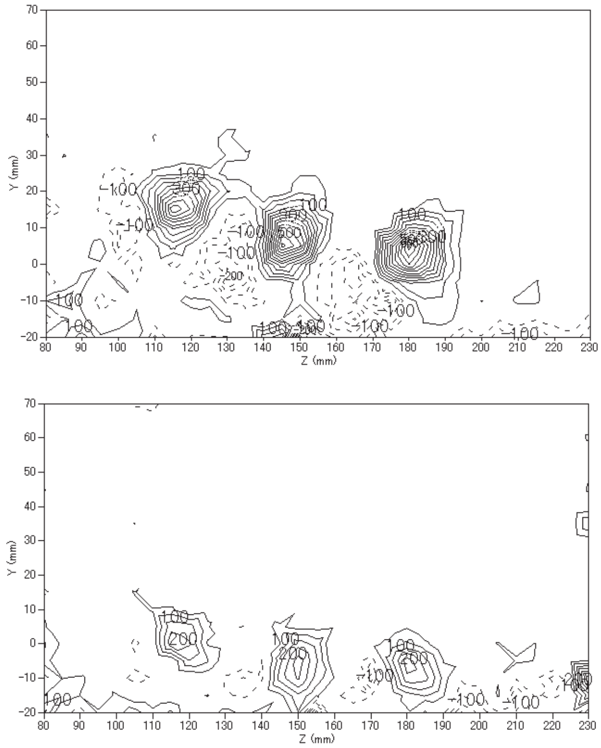

Figure 5. Contours of streamwise vorticity at x=110mm (U_0=6.5 m/s, α=21 deg, Contour intervals=50 1/s). Dotted lines denote negative vorticity: (a) Flow situation when the system attains suppression (*VR*=9.5), (b) Flow situation before the system attains suppression (*VR*=4.5).

(a)

(b)

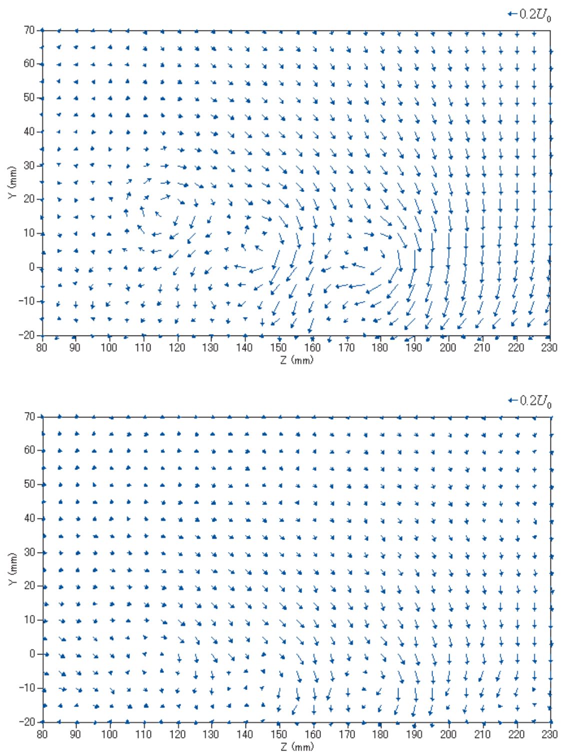

Figure 6. Secondary flow vectors at X=110mm (U_0=6.5 m/s, α=21 deg): (a) Flow situation when the system attains suppression (*VR*=9.5), (b) Flow situation before the system attains suppression (*VR*=4.5).

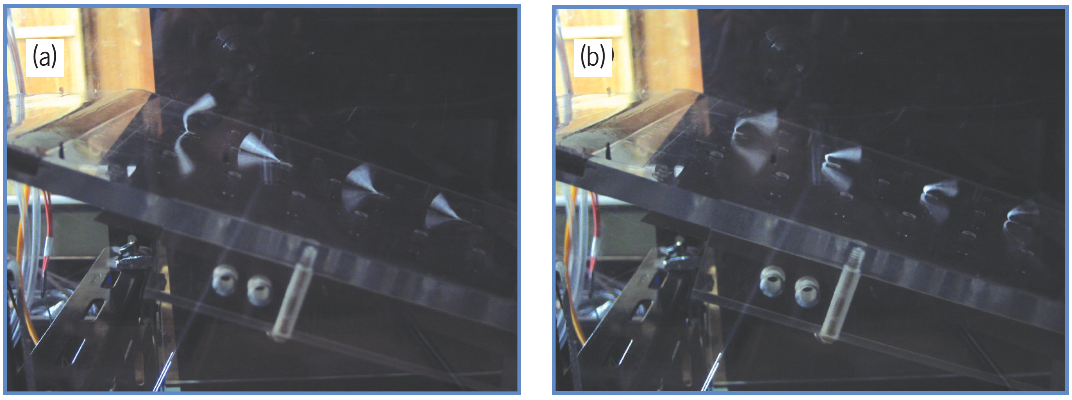

Figure 7. Surface flow in divergent portion of the test section (U_0=6.5 m/s, α=21 deg): (a) Flow situation before the system attains suppression (*VR*=4.5), (b) Flow situation when the system attains suppression (*VR*=9.5).

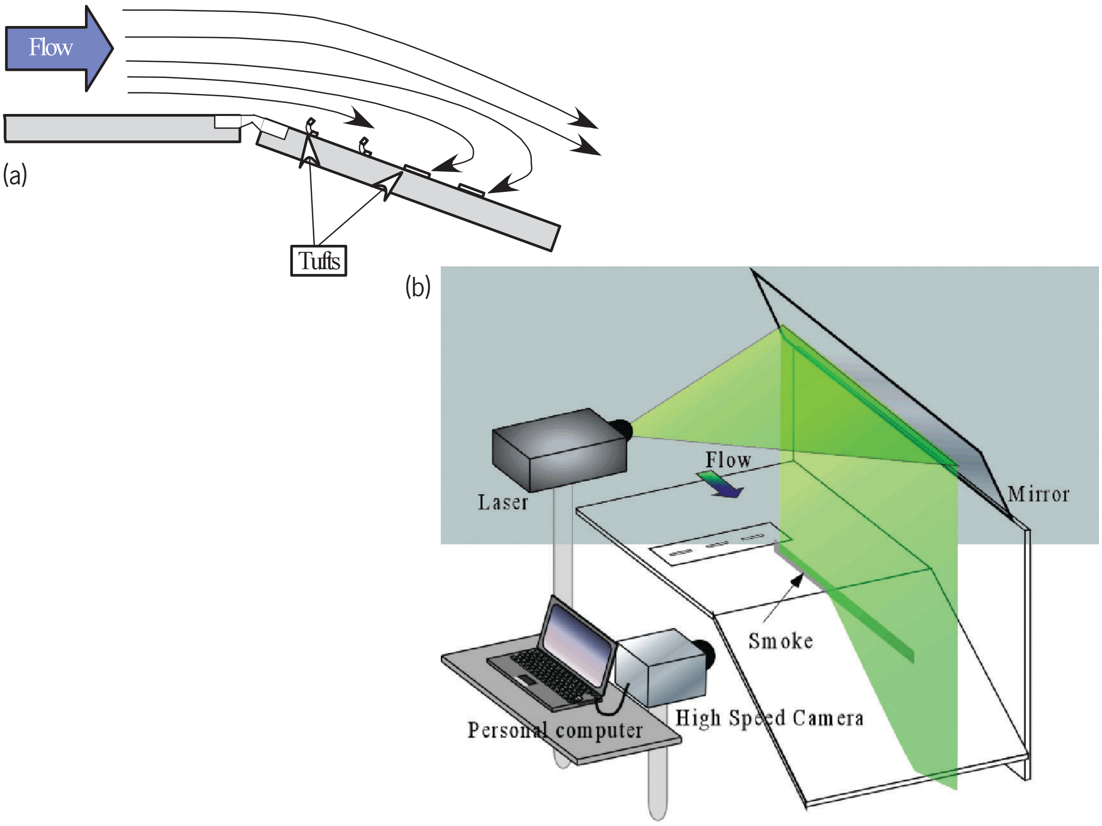

Figure 8. Schematic diagram of experimental setup for flow visualization by (a) tuft method, (b) smoke method.

at the lower wall of the diffuser inlet, and a high-speed camera (FASTCAM-1024PCI; Photron Ltd.) was used to capture the smoke pattern produced by the separated shear layer at the corner of the diffuser inlet. Figure 9 shows an example of instantaneous images of the smoke distribution in the test section for comparing between the cases with and without control. The dotted lines in Fig. 9 indicate the profile of the lower wall in the divergent portion. Figure 9(a) clearly shows that the flow in the absence of jets separates at the leading edge of the lower wall. In contrast, in Fig. 9 (b), with VGJs acting for control, the flow has less of a tendency to separate. That is, Fig. 9 (b) shows a reduction in the tendency toward separation when compared with the no jet (no control) case. This image set clearly shows that a vortex structure is formed as a result of the jets and that the surface flow in the divergent portion is observed

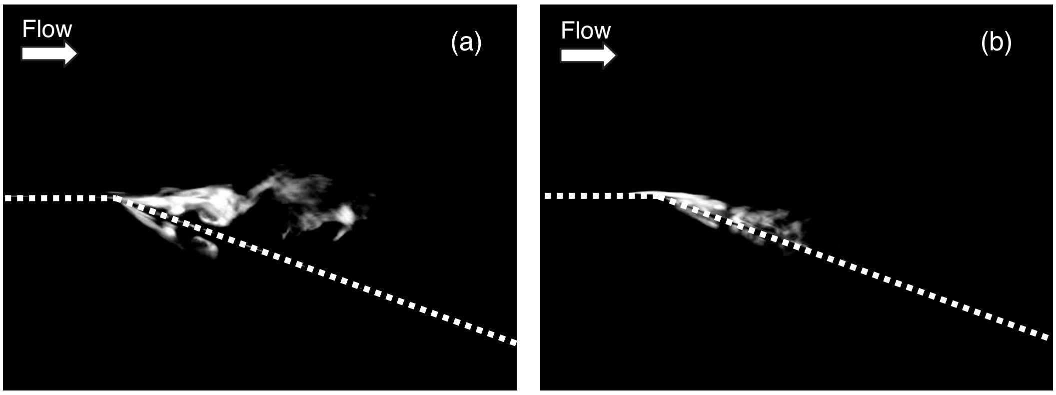

Figure 9. Side view of the separated shear layer at the inlet of the diffuser visualized by smoke-seeding the freestream boundary layer (U_0=6.5 m/s, α=21 deg): (a) Surface flow under no control (no- jet situation), (b) Surface flow after the attainment under control (*VR*=9.5)

in the downstream direction. These results suggest that vortex formation and evolution is responsible for enhanced cross-stream mixing in the boundary layer.

3.2 Determining a precursor to separation

In our proposed system, it is important that a precursor of separation can be detected as a control signal. If the control system operates well before separation occurs, the system is ineffective because a large total jet flow rate is required to suppress separation, and therefore, jet flow loss is unavoidable. Furthermore, drag increases and the effectiveness of fluid machinery is decreased by issuing jets when separation control is not needed. Therefore, it is better for a separation control device to only operate just before the onset of flow separation.

Vortex growth in the separated shear layer is affected by the progression of flow separation in the diffuser. A large-scale vortex exists further upstream in the diffuser as separation progresses [9]. A large-scale vortex has the tendency to entrain surrounding fluid, and it is presumed that the vortex scale can be determined by measuring the wall static pressure. In other words, the existence of a large-scale vortex causes fluctuation in the wall static pressure in the divergent portion of the flow, and therefore, the generation of a large-scale vortex can be captured by this static pressure fluctuation in our proposed system.

Figure 10 shows the variations in pressure difference between the upstream and downstream portions in the diffuser with and without control, when the divergence angle is varied from 10 to 21 deg for the various freestream velocities. In this diffuser, flow separation does not occur at _ = 10 deg for all freestream velocities. The wall static pressure on the downstream side increases with increasing divergence angle of the diffuser. However, the wall static pressure does not increase over a large angle without control due to the generation of separation in the definite region. Furthermore, if the divergence angle increases, separation progresses, and thereafter whole separation occurs. The pressure difference between the upstream and downstream positions of the diffuser shows a negative value consequent to whole separation. Therefore, the pressure does not recover in the diffuser and the wall static pressure in the downstream position becomes lower than that at the upstream position. The angle at which the abovementioned whole separation occurs is not discussed in this paper, because we have described whole separation for various freestream cases in our previous study [9].

On the other hand, for the case with control in Fig. 10, the system starts issuing the jets at the time in the middle of increasing the divergence angle. In this figure, point S indicates that the system senses the precursor of separation and starts the operation. In our proposed system, information about the divergence angle and the freestream velocity is not used to operate the system. The flow conditions are only judged from the control variable corresponding to the differential pressure. Whole separation is not observed yet when the system starts the operation. The wall static pressure at the upstream location is larger than that at the downstream location, and effective pressure recovery is accomplished in the diffuser. The system starts the operation just before separation occurs, and the wall static pressure can always be recovered in the downstream direction. Point A indicates the point at which separation control is attained by operating the system and adjusting the speed of the jets. Separation does not occur entirely as the divergence angle increases up to 21 deg. However, more time is needed for the system to recognize attainment of control as the freestream velocity increases. This is because the system operates with minute adjustments due to pressure fluctuation with increasing divergence angle. In general, for the same jet flow rate, effective pressure recovery is accomplished by the strong longitudinal vortices due to high freestream velocity. Therefore, as the freestream velocity increases, adjustments to the jet flow rate corresponding to the changes in the flow field become sensitive. In general, if flow field change largely depends upon the jet speed, then the jet flow rate of the system can be adjusted easily. However, when the freestream velocity is faster, only a slight adjustment of the jet flow rate corresponding to changes in the flow field is needed, and the time during which the system determines the suppression of separation increases. This is because the change in the jet flow rate reduces to avoid jet flow loss for a small change in the flow field in our proposed system. However, the system controls the flow field with no separation because the system is operated by sensing the precursor signal of separation, and therefore, the increment of the control time until the suppression is not very significant. Furthermore, the results confirm that the system can also attain a control target with no separation with a time-varying flow caused by changing the divergence angle of the diffuser at a constant rate of 2 deg/s (see Fig. 10(d)).

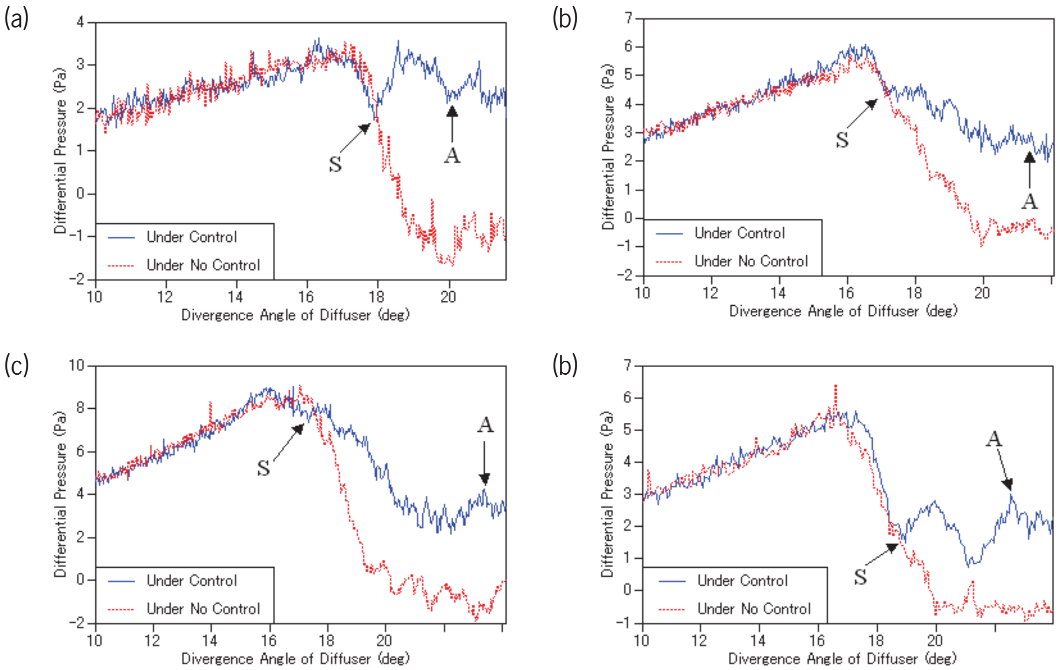

Figure 10. Variation of differential pressure for (a) U_0=6.5 m/s, ω_d = 1 deg/s, (b) U_0=8.0 m/s, ω_d = 1 deg/s, (c) U_0=10.0 m/s, ω_d = 1 deg/s, (d) U_0=8.0 m/s, ω_d = 2 deg/s.

3.3 Comparing the proposed system with and without detecting a precursor of separation

For separation control, it is preferable that the total jet energy applied be minimized in order to avoid jet flow loss. It has already been shown that control effectiveness can be improved by operating the system just before separation occurs [13]. Therefore, in this section, the total jet flow rate when using the proposed method for detecting a precursor of separation is compared to the jet flow rate without detecting a precursor of separation.

Differential pressure variations under control with and without detection of a precursor of separation are shown in Fig. 11. The results were obtained for divergence angle changes from 10 to 20 deg with a constant rate of change of 1 deg/s. The divergence angle is maintained constant after the angle reaches 20 deg. In Fig. 11, point S indicates that the system senses the separation or the precursor of separation and starts the operation. Point A indicates the point at which separation control is attained. The divergence angle was measured using a potential meter. For the system without detection of a precursor (the original system), separation is determined and the jets start to issue when the divergence angle reaches 20 deg, at which time whole separation occurs. Therefore, differential pressure shows the negative value during the divergence angle changes. Subsequent to that, the differential pressure increases at the instant the jets are issuing, and the system determines the suppression when the pressure in the diffuser recovers. On the other hand, for the system that can detect a precursor of separation (the improved system), the onset of separation can be detected at an angle less than 20 deg, and then the jets are issued. After that time, if the divergence angle increases until α = 20 deg, a decrease in the differential pressure can be prevented by adjusting the jet flow rate. That is, for the improved system, the divergence angle can be increased with effective pressure recovery in the diffuser by avoiding the generation of separation.

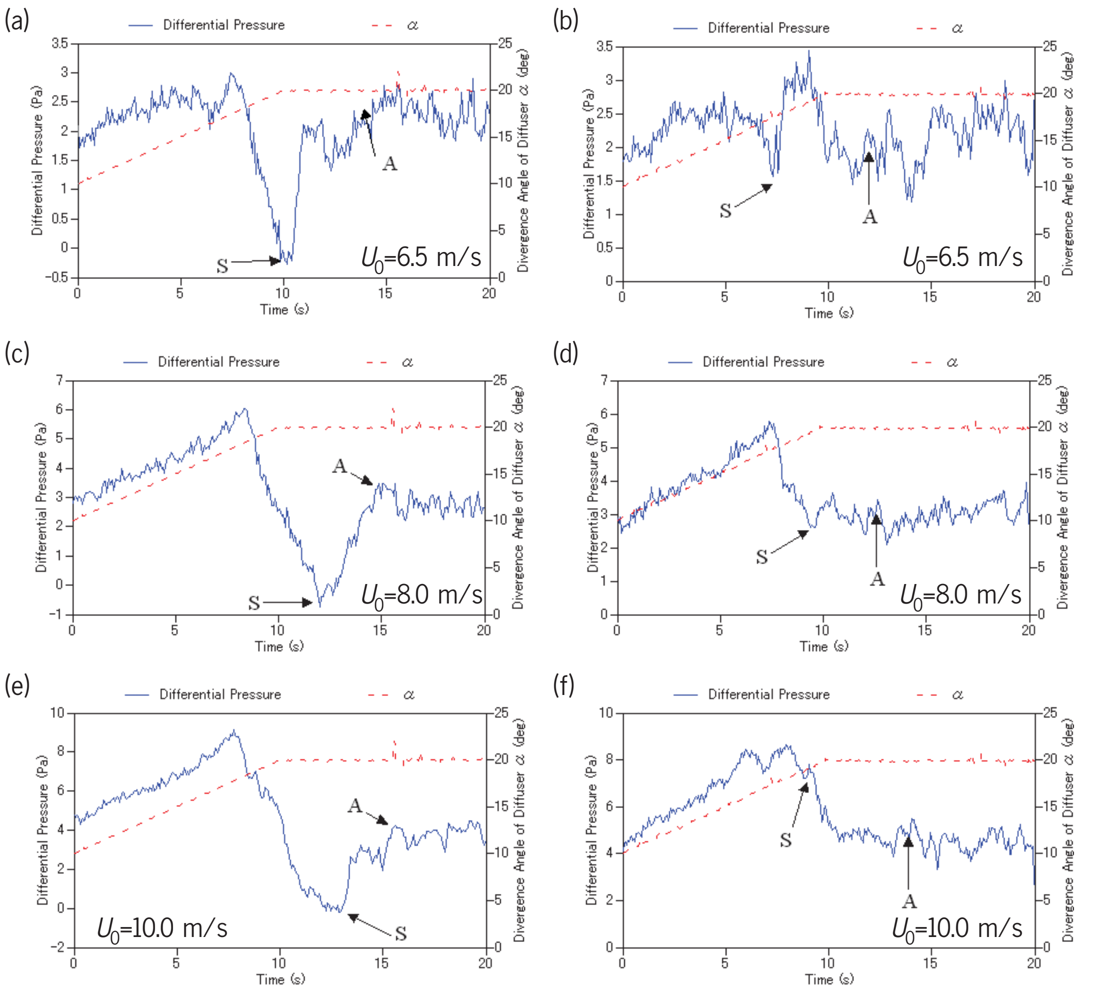

Figure 11. Comparison of variation of differential pressure between two systems for ω_d = 1 deg/s: (a) Without detecting a precursor of separation, (b) With detecting a precursor of separation.

Table 1 shows the total jet flow rate to perform the control for the two systems. In this table, the diffuser effectiveness is also indicated when the system attains the control target, and the value in brackets shows the diffuser effectiveness at α = 20 deg under no control. If the rate of pressure recovery of the diffuser is defined near the center axis of the wind tunnel, then pressure losses may be neglected. The local pressure recovery coefficient Cp_L is then given by

$$Cp_L = \Delta P \Big/ \frac{1}{2}\rho U_i^2 \tag{3}$$

where,

$$\Delta P \approx \frac{1}{2}\rho\left(U_i^2 - U_e^2\right) \tag{4}$$

and where subscripts i and e indicate the inlet and outlet of the diffuser, respectively. In the present study, U_i is measured at $X = -10$ mm and U_e at $X = 250$ mm. The diffuser effectiveness η is defined by $\eta = Cp_L/Cp_{th}$, where Cp_{th} is the ideal pressure recovery coefficient ($Cp_{th} = 0.6$ at $\alpha = 21$ deg). For the two systems, the diffuser effectiveness is nearly identical when the system attains the control target. The speed of the jet at the instant the control target is attained for the improved system is lower than that for the original system. Furthermore, the total jet flow rate during the control operation for the improved system is smaller than that for the original system. That is, the improved system provides effective suppression and superior performance for separation control.

Table 1. Comparison of jet flow rate between two systems.

System	Total jet flow rate QT (L)	Jet flow rate QA (L/min)	Final jet speed V_j (m/s)	Diffuser efficiency η (0.20)
Original system	1.56	30.5	54.0	0.52
Improved system	0.56	25.2	44.6	0.51

3.4 Applications to time-varying flow

In order to adaptively suppress flow separation, the proposed system was applied to time-varying flow fields caused by changes in the freestream velocity and in the divergence angle of the test section. Figure 12 shows a time history of differential pressure under control. In this example, the initial flow condition is $U_0 = 10$ m/s and $\alpha = 10$ deg. In this figure, the symbol ● indicates the point at which the system starts to accomplish separation control, and the symbol ■ indicates the point at which the control target is attained by operating the system. The flow conditions are changed at points A, B, and C. The dotted line indicates variation in the diffuser's divergence angle. In this example, the divergence angle is changed with a constant rate of 1 deg/s.

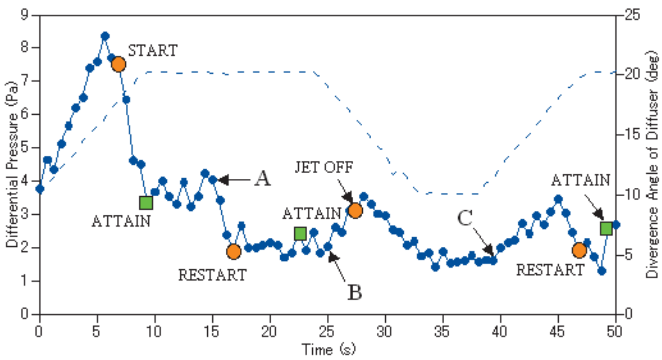

Figure 12. Variation of differential pressure under control for time-varying flow ($\omega_d = 1$ deg/s)

The jet is not issued when the system starts because separation does not occur initially. Then, as the divergence angle increases, the system operates and starts to jets at $\alpha = 18$ deg. The system senses a precursor of separation at this point. Subsequent to that, the system can control the jet speed until the divergence angle increases to $\alpha = 20$ deg, and it attains the control target (the first "ATTAIN"). The freestream is changed from $U_0 = 10$ m/s to 6.5 m/s at point A. In the case of a decrease in the freestream velocity, the strength of the longitudinal vortices weakens if the jet speed is maintained constant. In addition, the differential pressure decreases. In this situation, the system senses the lack of the jet speed because the system cannot suppress the separation with the present jet speed, and therefore, the system increases the jet flow rate just before the onset of separation. The system starts to increase the jet flow rate, and the differential pressure is recovered. The decrease in the differential pressure is suppressed and the system attains the control target when the differential pressure increases slightly (the second "ATTAIN").

Further, the divergence angle is changed from 20 deg to 10 deg at point B. The system cuts off the jets completely after the divergence angle reaches an angle of 10 deg and attains the control target, because flow separation does not occur at $\alpha = 10$ deg for all freestream velocities in this diffuser. At point C, the divergence angle is changed again until it reaches 20 deg. The system senses a precursor of separation at $\alpha = 18$ deg and starts to reissue jets. Then, the system adjusts the speed of the jets and attains suppression (the third "ATTAIN"). Later, the system maintains a constant speed of the jets.

Thus, the results of these tests confirm that our proposed system can sense a precursor of separation and can completely suppress separation under various time-varying flow conditions with separated flow by adjusting the speed of the VGJ.

4. CONCLUSIONS

In the present study, an active separation control system with the ability to sense a precursor of separation has been developed and is practically applied to the flow separation control of a two-dimensional diffuser. The results confirm that the proposed active separation control system can adaptively achieve suppression of the separation for a time-varying flow field by changing the speed of the jets for all the flow fields examined in the present study. Furthermore, our proposed separation control system can be operated prior to the onset of flow separation by sensing a precursor of separation, and therefore, a flow condition with no separation can always be attained for time-varying separated flow fields. The jet flow loss is improved for our proposed system in contrast to our previously proposed control system that lacked detection of a precursor to separation. In future work, the suppression effect will be investigated for several freestream conditions faster than those of the present study, and the system will be installed in an airfoil type model to devise a control system for use in practical applications.

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