

# Flow Field Change before Onset of Flow Separation

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## Abstract

Jets issuing through small holes in a wall into a freestream has proven effective in the control of flow separation. This technique is known as the vortex generator jet (VGJs) method. If a precursor signal of separation is found, the separation control system using VGJs can be operated just before the onset of separation and the flow field with no separation is always attained. In this study, we measured the flow field and the wall static pressure in a two-dimensional diffuser to find a precursor signal of flow separation. The streamwise velocity measurements were carried out in the separated shear layer and spectral analysis was applied to the velocity fluctuations at some angles with respect to the diffuser. The pattern of peaks in the spectral analysis changes as the divergence angle increases over the angle of which the whole separation occurs. This change in the spectral pattern is related to the enhancement of the growth of shear layer vortices and appears just before the onset of separation. Therefore, the growth of shear layer vortices can be regarded as a precursor signal to flow separation.

**Keywords:** Separation, Boundary Layer, Unsteady Flow, Diffuser, Precursor

## 1. Introduction

In order to deal with the gamut of problems that arise when dealing with fluid machinery, a separated and reattached flow must be taken into account. The separated and reattached flow promotes heat and mass transfer, and an efficient mixing effect is achieved for the flame holder and the damp combustion chamber of ramjets and artificial organs. On the other hand, flow separation is mostly an undesirable phenomenon in turbo machinery because it entails large energy losses, aerodynamic noise and extraordinary throb. Boundary layer control has been widely used in aerodynamic applications to inhibit flow separation<sup>[1]</sup>. Boundary layer mixing is an effective method to prevent separation. In mixing, fluid particles that have large freestream energies are supplied to decelerated fluid particles in the boundary layer by the secondary flow of longitudinal vortices<sup>[2]</sup>. In the boundary layer controls using longitudinal vortices, solid vortex generators have practical applications with respect to stall control on airfoils and in diffusers. For example, solid vortex generators installed on airfoils are useful for improving flight performance during aircraft take-off and landing. However, solid vortex generators do not have the ability to adapt to time-varying flow fields. Furthermore, solid vortex generators are always exposed in the flow and increase drag.

On the other hand, vortex generator jets (VGJs) can adjust the strength of longitudinal vortices by varying the jet speed<sup>[3], [4]</sup>. Therefore, they can achieve adaptive control by properly adjusting the jet speed corresponding to flow parameters such as airfoil angle of attack, the diffuser's divergence angle, and freestream velocity. Furthermore, in flow situations where stall suppression is not needed, e.g., an airfoil operating near its design condition, the parasitic drag associated with control devices can be avoided with the jet flow turned off. The vortex generator jet method can perform separation control only when it is necessary. Stall control for aircraft or fluid machinery is not needed for most operations because they are not designed to produce a separation. It is desirable, however, for the control devices to operate when flow separation occurs. In other words, 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 change in design to the airfoil or diffusers. The authors have investigated the effects of jet pitch angle<sup>[5]</sup> and jet orifice shape on suppression<sup>[6]</sup>, and the active separation control system, which has the ability to adjust the jet flow rate in the time-varying flow, was developed in the previous study<sup>[7]</sup>. In the actual use of a separation control system, a high response ability of the jet is required to adaptively suppress flow separation for a time-varying flow.

If the system operates after the separation is detected, the separation itself cannot be prevented. In general, even if separation occurs briefly, fluid machinery will not operate in a favorable manner. Control with no flow separation can always be achieved if

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the system operates just before the onset of flow separation. The experimental results of flow field change with respect to a precursor of separation were already reported<sup>[8]</sup>. However, the results were indicated under laminar flow conditions and, unfortunately, the studies regarding the flow change just before the onset of flow separation under turbulent flow conditions have not been published yet. Turbulent flow has to be taken into account in the actual flow control problem. Moreover, it is important that a common precursor signal of separation is found under both laminar and turbulent flow conditions. This is because, although the boundary layer conditions must generally be known before performing separation control, VGJs can operate to suppress separation with no information regarding boundary layer conditions before the system begins to operate. Additionally, it was reported that energy loss due to separation control can be prevented if the system begins to operate before separation occurs<sup>[9]</sup>. In the present study, in order to apply to the separation control system using VGJs, flow field change, which has no relation to the boundary conditions, was investigated just before the onset of separation.

## 2. Experimental Apparatus and Method

### 2.1 Experimental apparatus

Experiments were performed using a low-speed wind tunnel with three jet holes in a lower wall in the test section and no-jet flow conditions. The freestream velocity  $U_0$  was varied from 0 to 12 m/s. Figure 1 shows the schematic diagram of the test section and the coordinate system. The test section inlet dimensions were 250×120 mm (W×H). The test section has a variable diffuser that can adjust the divergence angle between 0 and 30 deg using a stepping motor controlled by a personal computer. In the present study, the stepping motor is operated at a constant angular velocity  $\omega$  ( $\omega=1.7\times10^{-2}$  rad/s) and the diffuser's divergence angle is measured by a potentiometer. Three jet holes of diameter 2 mm were placed 55 mm upstream of the divergent portion and

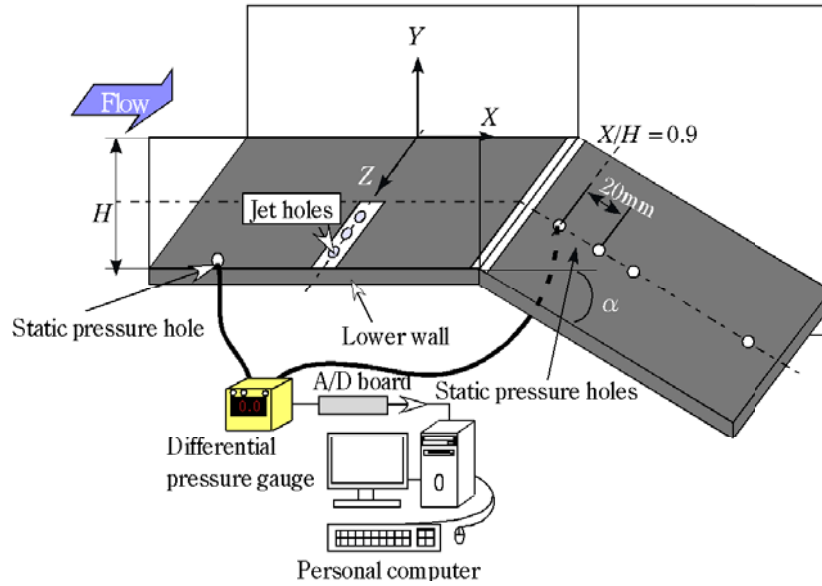


Fig. 1 Schematic of experimental facility.

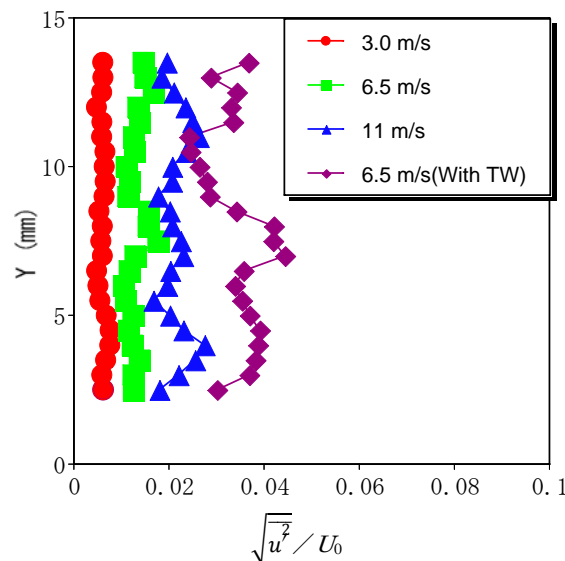


Fig. 2 Turbulent intensity distributions at  $X/H=0.2$ .

three holes were placed on the right-hand side of the test section when viewed from upstream. The origins of 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.

## 2.2 Experimental method

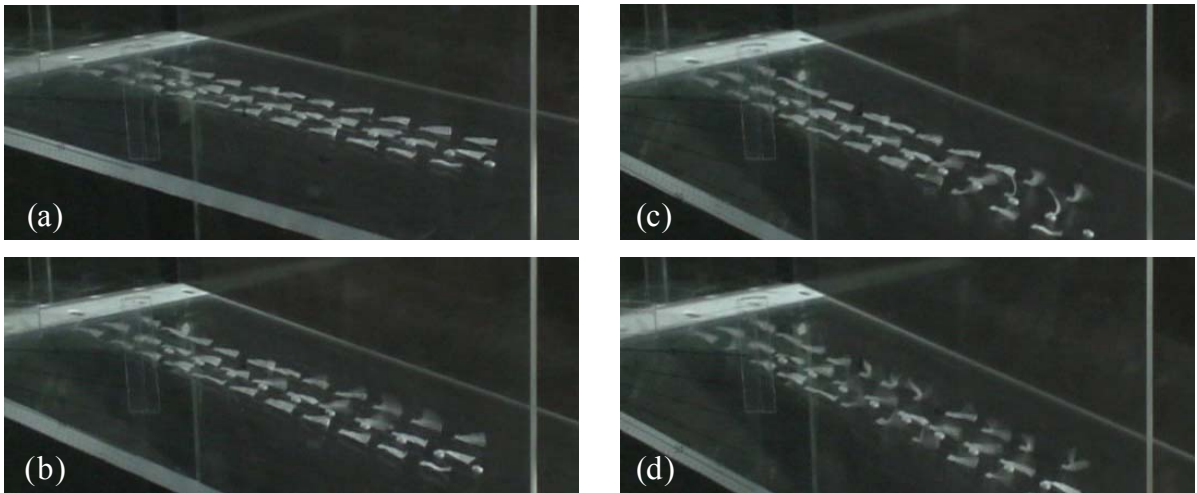
The wall static pressure holes on the downstream side were set on the center line of the divergent portion ( $Z=125$  mm). There are 11 pressure taps mounted on the inclined wall at equal intervals of 20 mm in the downstream direction. The pressure recovery in the diffuser is judged by measurements of wall static pressure at two points, in the upstream of the divergent portion ( $X/H=-1.2$  in the unstalled region) and in the divergent portion. Static pressure measurements were carried out using a differential pressure transducer that has the ability to measure very small differences in pressure (0.001 Pa). Pressure measurements at both constant divergence angle (static conditions) and during movements of the inclined wall (dynamic conditions) were performed by a data acquisition system with a sampling frequency of 20 Hz. In the former case, 480 samples were collected while, in the latter, 8 samples were collected. The measured pressure under the dynamic conditions was calculated by averaging the data from 40 measurements at each divergence angle. For VGJs, the same control device can be used under both laminar and turbulent boundary conditions. VGJs are adaptively controlled in time-varying flow fields, making it unnecessary to know in advance whether the boundary layer is laminar or turbulent. Therefore, in order to operate the control system before the onset of separation, a precursor signal of separation, which has no relation to the laminar/turbulent boundary layer state, must be found.

In the present study, the freestream velocity  $U_0$  was set at 3.0, 6.5 and 11 m/s. The boundary layer becomes laminar for  $U_0=3.0$  and 6.5 m/s and becomes turbulent for  $U_0=11$  m/s. Information regarding the boundary layer state is acquired from the velocity profiles in the boundary layer using a hot-wire anemometer. A probe with a single  $5\text{-}\mu\text{m}$ -diam wire is employed for the streamwise velocity measurements. In order to investigate the effect of turbulence intensity of the flow on a precursor signal, experiments are carried out when the boundary layer condition changes from laminar to turbulent flow by a tripping wire (TW). A tripping wire which was 1.6 mm in diameter was positioned at  $X/H=-0.8$  mm. The turbulence intensity distributions in each case are shown in Fig. 2. It is clear from Fig. 2 that there is a difference in turbulence intensity between the two turbulent boundary layer conditions.

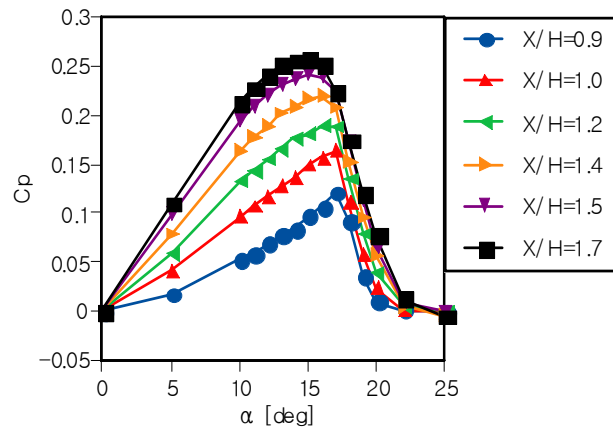
## 3. Results and Discussion

### 3.1 Separated flow in divergent portion

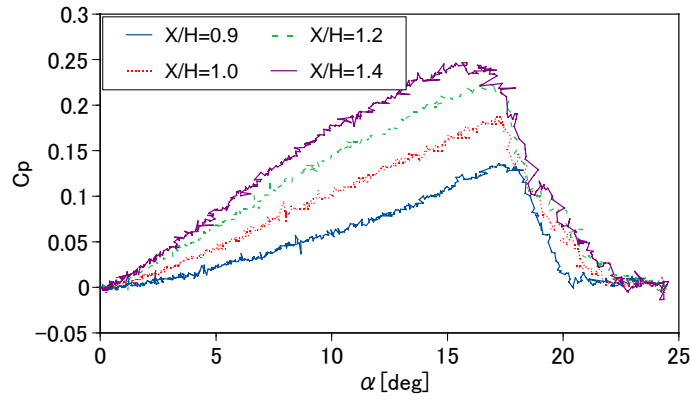
In order to find a precursor of separation, the comparison of flow fields before and after a separation is the most practical



**Fig. 3** Surface flow of divergent portion in the test section ( $U_0 = 11\text{ m/s}$ ). (a)  $\alpha=10\text{ deg}$ , (b)  $\alpha=16\text{ deg}$ , (c)  $\alpha=18\text{ deg}$ , (d)  $\alpha=20\text{ deg}$ .



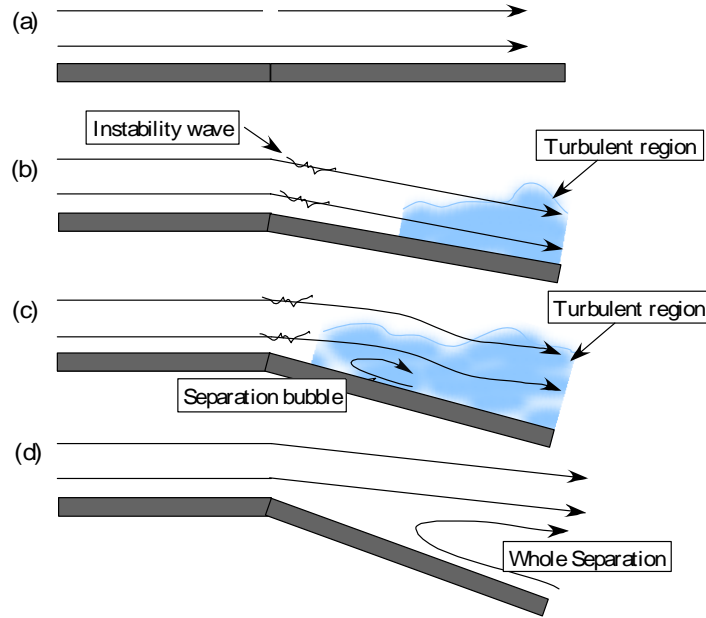
**Fig. 4** Distribution of pressure recovery against  $\alpha$  for different  $X/H$  ( $U_0=11$  m/s).



**Fig. 5** Wall static pressure signals during the increment of  $\alpha$  for different  $X/H$  ( $U_0=11$  m/s).

**Table 1** Whole separation angle

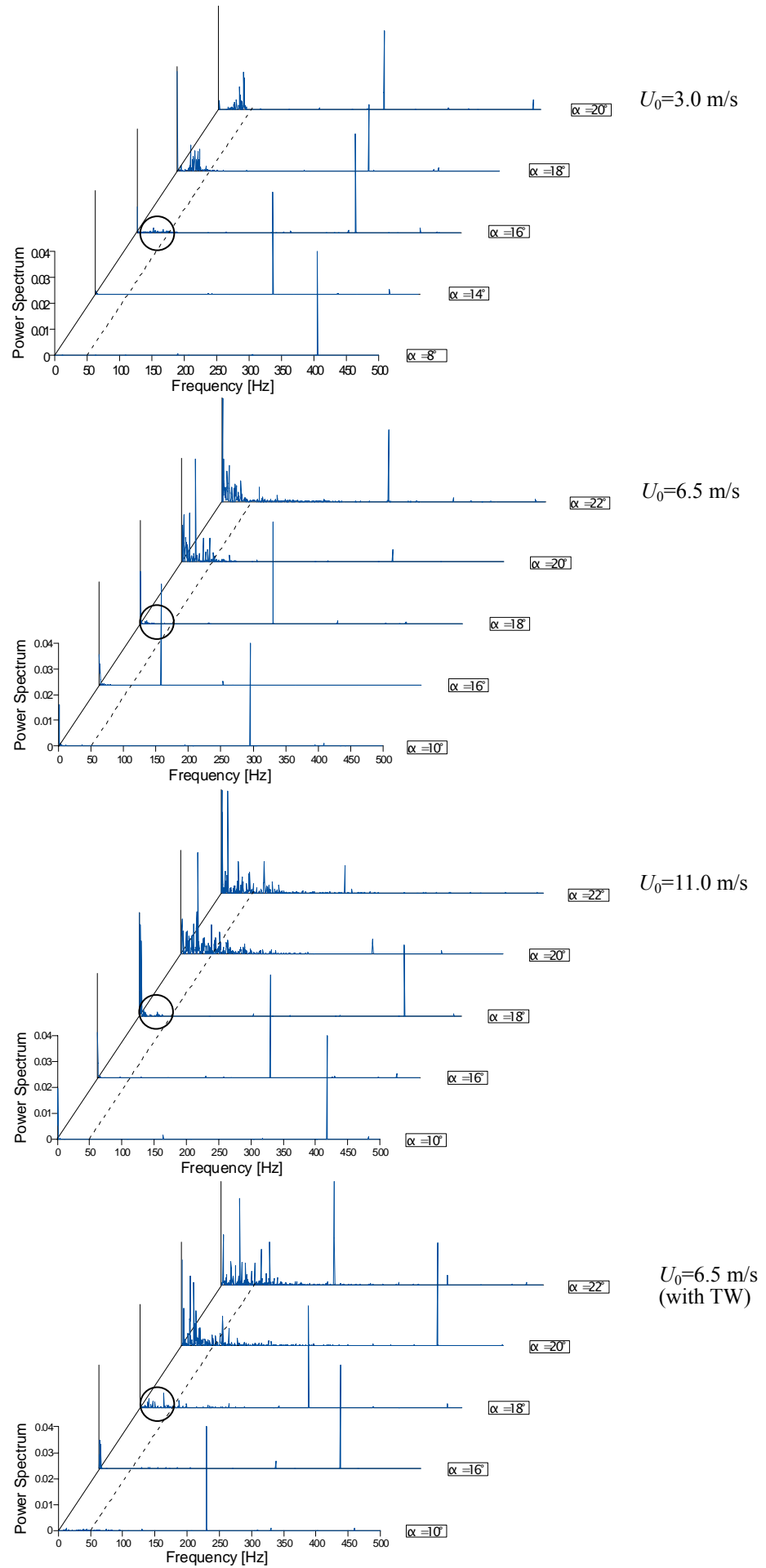
$U_0$ [m/s]	3.0	6.5	6.5 (With TW)	11
$\alpha$ [deg]	19	21	21	21



**Fig. 6** Cartoon depiction of flow field change in the divergent portion due to upstream propagation of disturbances. (a) No separating flow, (b) Occurrence of turbulence at the downstream position, (c) Disturbances propagating upstream, (d) Whole separation.

method, provided the separation angle is known in advance. Therefore, the angle at which separation occurs in the diffuser is investigated by using flow visualization techniques as well as wall static pressure measurements under several freestream conditions. For  $U_0=11.1$  m/s, the instantaneous photographs of the surface flow in the divergent portion with increasing divergence angle are shown in Fig.3. The freestream is always from left to right, and tufts are placed on the lower wall with three rows including the centerline of the diffuser ( $Z=125$  mm). In this arrangement, the tufts are agitated when the reverse flow occurs in the divergent portion. The flow visualizations show that the surface flow in the divergent portion is observed with no reverse flow at  $\alpha=10$  deg. At  $\alpha=16$  deg, the tufts on the downstream side begin to be partially agitated. At  $\alpha=18$  deg, most of the tufts on the downstream side are agitated, the tufts on the upstream side are also agitated at  $\alpha=20$  deg, and all tufts are agitated over  $\alpha=20$  deg. That is, the extension of the reverse flow region is observed and large scale separation occurs. Figure 4 shows the pressure recovery of the diffuser along the flow direction against  $\alpha$  for  $U_0=11.1$  m/s. It is confirmed that the pressure recovery is not attained over  $\alpha=20$  deg at all downstream positions. In other words, there is no difference of wall static pressures between the outside (upstream) and the inside of the diffuser, and the diffuser makes the pressure recovery ineffective due to flow separation.

The wall static pressure distributions between divergence angle values 0 deg to 25 deg were shown in Fig. 5.  $C_p$  approaches 0 as the divergence angle of the diffuser increases in all downstream directions. For diffuser separation, the separation region becomes wider in the downstream direction, and separation occurs. Figure 6 shows a cartoon depiction of flow field change as the



**Fig. 7** Spectrum of streamwise velocity fluctuation for different  $\alpha$  at  $X/H=0.9$ .

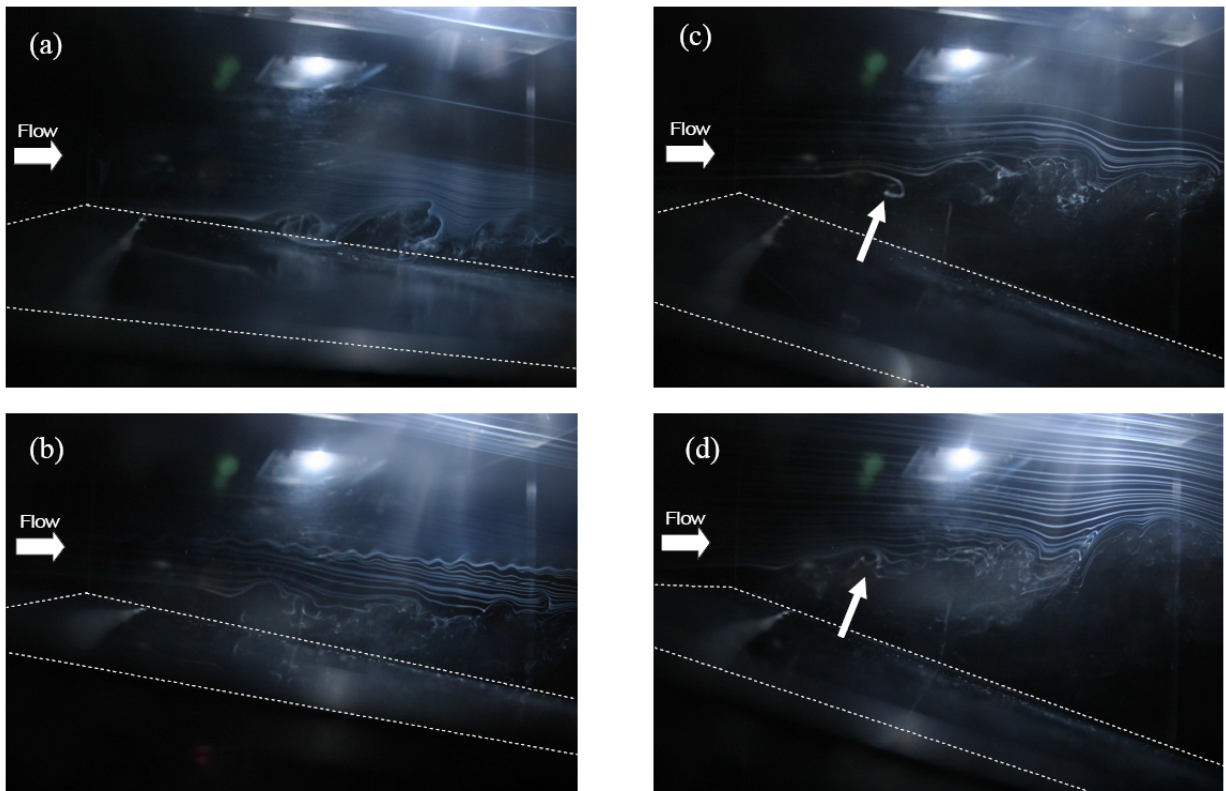
divergence angle of the diffuser increases. The turbulent region due to separation widens between the downstream and upstream sides, and disturbances begin to propagate upstream. The features of flow field change which were mentioned earlier coincide with the results reported by Mochizuki<sup>[8]</sup>. In the present study, the angle where the value of  $C_p$  becomes zero at the first tap ( $X/H=0.9$ ) of the divergent portion is defined as the whole separation angle of the diffuser. In other words, it was concluded that the separation occurs in the wide area of the diffuser at  $\alpha=21$  deg because the angle indicated by  $C_p=0$  at  $X/H=0.9$  coincides with  $\alpha=21$  deg. In Table 1, the separation angles for several freestream conditions are shown. The angle immediately before whole separation begins to occur is defined as the angle of the onset of separation, and the flow field change is examined to investigate any precursors to separation.

### 3.2 Flow field variations just before whole separation

The measurements of the velocity distribution and the power spectrum were carried out by using an I type single hot-wire probe. For the velocity measurements, the sampling frequency of 1 kHz and 2048 samples were fixed. The streamwise velocity fluctuation spectrum is shown in Fig. 7. The spectral and velocity measurements were carried out by hot-wire anemometry at  $Z=125$  mm, and the measurement position in the  $Y$  direction was determined as the place that indicates the maximum fluctuations in the  $u$  component in order to evaluate the velocity perturbations along the separated shear layer. For the velocity measurements, the divergence angle is a constant during data acquisition. It can be seen from Fig. 7 that the spectrum peak is only observed in the high frequency region at the divergence angle with no separation, and there is no peak in the low frequency region. With a few differences in the peak value, the peak of the power spectrum is over 100 Hz in all freestream velocities. On the other hand, the peak of the power spectrum is observed in the low frequency region when the divergence angle increases to the point where separation in the diffuser begins. The spectrum peak in the low frequency region appears just before the onset of the whole separation, and the peaks are marked by the circle in Fig. 7. The spectrum peak with frequencies below 50 Hz is related to flow separation. These results show the same tendency for all freestream velocities in the present study, and therefore it is presumed that the existence of the low frequency peak of the power spectrum can be taken into account as the signal of precursor to separation.

### 3.3 Vortex behavior in the separated shear layer

The flow visualization technique was used to aid in the understanding of the flow field change arising from the existence of the low frequency peak. It is presumable that the spectrum peak of streamwise velocity fluctuations in the low frequency region is related to flow separation. Flow visualization along the separated shear layer via the smoke-wire method is employed to capture the unsteady vortical structures. Smoke-wire flow visualization reveals vortex flow structures in the separated shear layer. Smoke is produced from a thin stainless steel wire 0.1 mm in diameter coated with oil which is positioned vertically at  $X/H=0.1$  and  $Z/H=1.0$ . It was confirmed by comparing the velocity profiles both with and without wire that the wire does not disturb the flow. The separated shear layer develops at the corner of the diffuser inlet because there is a sharp edge at the corner. Vortices roll up in the separated shear layer due to the Kelvin-Helmholtz instability. It is already known that a large-scale vortex is produced in the



**Fig. 8** Structure of the separated shear-layer visualized by smoke streaklines entrained into the inlet of the diffuser ( $U_0=3.0$  m/s). (a)  $\alpha=8$  deg, (b)  $\alpha=14$  deg, (c)  $\alpha=18$  deg, (d)  $\alpha=20$  deg.



separated shear layer<sup>[10]</sup> due to the increment of vortex deformation in the downstream direction whenever vortex coalescence is repeated. The three-dimensional large-scale vortex forms as a result of the “rolling up” of the separated shear layer.

The flow visualization results from the smoke-wire method are shown in Fig. 8. The dotted lines in Fig. 8 indicate the lower wall of the diffuser and easily identify the relationship between the vortices in the separated shear layer and position of the diffuser’s lower wall. The development of the separated shear layer is suppressed in the case of the small divergence angle. Smoke in the presence of small disturbances is observed at the inlet of the diffuser, and the large-scale vortices do not appear. Large-scale vortices only exist in the downstream region of the diffuser. Vortices in the separated shear layer exist near the region of the diffuser’s lower wall (see Figs. 8 (a) and (b)). If the divergence angle is small, the boundary layer separated at the corner of the diffuser forms separated-reattaching flows. The vortex size varies by coalescing in the downstream direction, and large-scale vortices impinge on the lower wall of the diffuser in the reattachment region. The large-scale vortices can be observed further upstream in the separated shear layer as the divergence angle of the diffuser increases.

In general, the vortices in the separated shear layer increase the vortex size and the distance between adjacent vortices as the downstream distance increases. This is due to the fact the coalescence of vortices is promoted. Therefore, the number of vortices that pass through one local point (position) in the downstream direction per unit time decreases as the distance in the downstream direction increases. In other words, the frequency of vortex generation becomes higher when the separated shear layer does not develop. On the other hand, the smoke flow is disturbed at short distances downstream as the divergence angle increases. When the divergence angle becomes large and the flow separation occurs over a wide area in the diffuser, the large velocity gradient in the separated shear layer is measured and the rolling-up of the separated shear layer becomes more prominent. This is due to the fact that the development of the separated shear layer is promoted at short distances downstream in the divergent portion for large divergence angles, and large-scale vortices exist at short distances downstream. The disturbance produced by a large-scale vortex impinging on the surface propagates upstream. The turbulent area extends from the downstream side to the upstream side of the diffuser with increasing divergence angle, and the whole separation occurs after undergoing the separated-reattaching flows. These results that the separation area extends from downstream to upstream of the diffuser due to the increment of the divergence angle coincide with the flow visualization results.

In order to interpret the frequency of vortex generation, the interval of vortex generation is measured by using instantaneous photographs of flow visualization results. The moving velocity of the vortex in the separated shear layer  $U_c$  is estimated to be  $U_c=0.5U_0$ <sup>[11]</sup>. That is, the interval of vortex generation is calculated from the moving velocity of the vortex which is interpreted by the distance between two vortices from the flow visualization results. It is essential that the interval of the vortex generation be determined by delayed time at which the correlation of the streamwise velocity disturbance is taken into account between two points in the streamwise direction. However, in the present study, it is considered that the interval of the vortex generation can be determined by using instantaneous photographs of flow visualization. The frequencies of vortex generation marked by the arrow in Figs. 8(c) and 8(d) indicate 30 and 24 Hz, respectively. If the whole separation occurs, the frequency of spectrum peaks below about 50 Hz remarkably appears (see Fig.7). These frequencies of vortex generation are similar to those of spectrum peaks observed after the whole separation occurs. There is a separated shear layer at the corner of the diffuser inlet and the vortices in this layer coalesce in the downstream direction thereby producing three-dimensional isolated large-scale vortices. The large-scale vortices exist in the upstream region of the diffuser as the separation progresses and, therefore, the large-scale vortices are formed at the same downstream position. If the generation of this large-scale vortex is captured, the precursor of separation can be interpreted. This precursor signal is useful for the actual separation control using vortex generator jets, which can be adaptively controlled for a time-varying flow with no information regarding initial flow conditions because the precursor signal is not affected by the flow conditions. Furthermore, a large-scale vortex makes effective the ambient fluid entrainment into a vortex in contrast to a small-scale vortex. It is presumable that large-scale vortex generation can be interpreted by the wall static pressure.

In the actual separation control system, it is important that the precursor signal of separation is found by using wall static pressure, because these measurements are easily performed in contrast to velocity fluctuation measurements. In the previous study, the active separation feedback system was developed, and the proposed system could judge the various flow situations by using wall static pressure alone<sup>[7], [12]</sup>. In future work, the active separation control system will be improved by adding the ability to judge the precursor signal of separation. As a result, the separation control system can be operated just before the onset of separation, and the flow field with no separation is always attained.

## 4. Conclusions

In the present study, the divergence angle at which separation occurs is investigated by flow field change for various divergence angles in a two-dimensional diffuser. The velocity fluctuations before and after separation occurs have been measured to find a precursor signal of separation. The findings of the present study are summarized as follows:

- (1) When the whole separation occurs, the spectrum peak with frequencies below 50 Hz in the streamwise velocity fluctuations is observed. Furthermore, this spectrum peak appears just before the whole separation occurs.
- (2) The low-frequency spectrum peak can be observed independently for all freestream velocities and every boundary layer condition in the present study.
- (3) The smoke-wire flow visualization results indicate that the frequency of the spectrum peak is comparable to the frequency of the generation of large-scale shear layer vortices.
- (4) The shear layer vortices grow at positions further upstream of the diffuser and the large-scale vortices promote the growth of the separated shear layer as separation progresses. If the generation of the large-scale vortex is captured, a precursor signal of separation can be found.

## Nomenclature

$C_p$	Wall pressure recovery coefficient= $2\Delta p/\rho U_0^2$	$Z$	Spanwise coordinate
$\Delta p$	Differential pressure between inlet and outlet of diffuser	$\alpha$	Divergence angle of lower wall
$U_0$	Local freestream velocity	$\rho$	Fluid Density
$X$	Streamwise coordinate	$\omega$	Angular velocity = $1.7 \times 10^{-2}$ rad/s
$Y$	Vertical coordinate		

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