ACTIVE SEPARATION CONTROL WITH LONGITUDINAL VORTICES GENERATED BY THREE TYPES OF JET ORIFICE SHAPE

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Abstract

In order to suppress the separation, the fluid particles which have large energy of the freestream are supplied to decelerated fluid particles in the boundary layer by longitudinal vortices. Jets issuing through small holes in a wall into the freestream have proven effective in the control of boundary layer separation. The vortex generator jets can adjust the strength of longitudinal vortices by varying the jet speed. 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 is active control of flow separation that has the ability to provide a time-varying control action to optimize performance under a wide range of flow conditions. In this study, the suppression effect of the jet orifice shape with non-circular orifices is investigated to make more effective the active separation control system. The vortex generator jets with three types of jet orifice (circular, triangular and square orifices) were used in the separation control of a two dimensional diffuser. The triangular orifice makes strong the vorticity of longitudinal vortices and effective the pressure recovery in the diffuser in comparison with the other orifice shapes.

1 Introduction

Jets issuing through small holes in a wall into a freestream have proven effective in the control of boundary layer separation. Longitudinal (streamwise) vortices are produced by the interaction between the jets and the freestream. This technique for separation or stall control 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 [1, 2, 3]. The principle of boundary layer control by longitudinal vortices trailing over the surface has been used extensively to delay the separation of turbulent boundary layer since the introduction of solid vortex generators by Taylor in 1950. The fluid particles which have large freestream energy are supplied to decelerated fluid particles in the boundary layer by longitudinal vortices. Passive control technique with solid vortex generators has the advantages such as simplicity, ruggedness, and low cost. The technique with solid vortex generators has practical applications in stall control on airfoils and in diffusers. For example, solid vortex generators installed on airfoils are useful to improve flight performance during aircraft take-off and landing. Furthermore, the generators installed in diffusers make the diffuser length shorter. However, solid vortex generators have a fatal shortcoming. They do not have the ability to provide a time-varying control action and they can not be adopted for highly maneuverable aircraft. Furthermore, they add parasitic drag in flow situations where stall control 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 additional drag.

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. They can achieve the adaptive control by properly adjusting the jet speed in response to flow situations 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. Therefore, the vortex generator jet method enables to achieve superior performance under both design and off-design conditions.

In the vortex generator jets, it was concluded that the strength and decay rate in the downstream direction of longitudinal vortices have a relation to the jet skew angle [4]. Furthermore, Hasegawa et al. investigated the effect of the jet pitch angle on separation control and indicated that the vertical positions of longitudinal vortices are affected by the jet pitch angle [5]. However, the circular orifice shape was only used for the separation control using vortex generator jets in the past reports. It is already known that the mixing and diffusion processes for non-circular jets are different from those for circular jets due to the different vortex structure [6]. Furthermore, the characteristics of the flow field depend upon exit geometry of the jet nozzle, the type of exit velocity profile, and the magnitude of the turbulence intensity at the exit plane of the nozzle. Therefore, it is sufficiently presumable that the longitudinal vortices are affected by the jet orifice shape and that the suppression effect of vortex generator jets on separation control can be improved by selecting a proper orifice shape. In this study, the vortex generator jets with non-circular orifices (triangular and square orifices) were practically applied to flow separation control of a two-dimensional diffuser and the suppression effect for non-circular jets was compared to that for the circular jets.

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 test section has the function of variable diffuser which can adjust the divergence angle between 0 and 45 deg. The test section was configured with the lower wall of various divergence angles to generate adverse pressure gradient. The gradient gives rise to flow separation. In this study, the freestream velocity U_0 was 6.5 m/s. The boundary layer thickness and the Reynolds number based on the thickness were 6 mm and 2.6×10^3 at the location of jet orifices, respectively. The test section inlet dimensions are 250×120 mm (W×H). The jet orifices were placed at 57.5 mm upstream of the divergent portion. The jet flow was delivered through a metering valve after accumulating the air to a tank by using a compressor. A rotameter was placed downstream of the

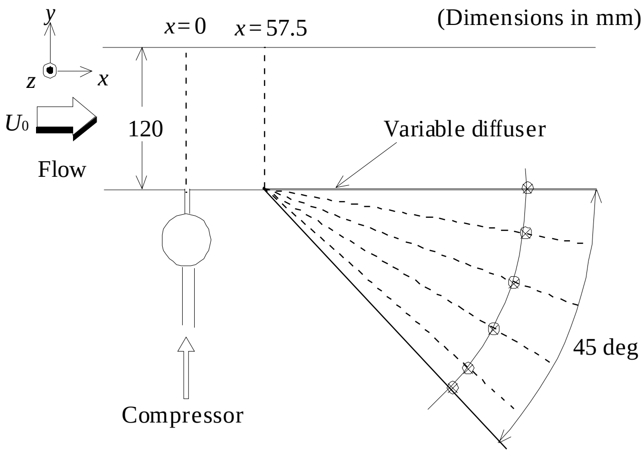


Fig. 1 Test Section Geometry

metering valve. The magnitude of the jet flow rate was characterized by the jet-to-freestream velocity ratio *VR* ($=V_j/U_0$). The divergence angle of the test section α was set at 20 deg. The static pressure holes were set at several stations in the downstream direction on the centerline of the divergent portion in order to measure the pressure recovery of the diffuser. Tufts were put on the lower wall and the surface tuft method was used as a diagnostic to observe the suppression effect of flow separation.

2.2 Experimental Method

Figure 2 shows the configuration of the jets and the coordinate system used to describe the flow field. 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). In this study, the jets were skewed at 90 deg with respect to the freestream direction (0 deg being downstream). The jet pitch angle ϕ was selected as ϕ=30 deg or ϕ=45 deg by changing the jet orifice unit. Three types of jet orifice were circular, triangular and square orifices. For the circular orifice shape, the jet orifice diameter D_j was 2 mm. The cross-sectional areas of the triangular and the square orifices coincide with that of the circular orifice. In other words, the jets had equal cross-section areas but different geometries. Therefore, jets issued in the same flow rate indicate the same value of *VR* for three types of the jet orifice. Figure 3 shows the schematic of the triangular and the square orifices with respect to the freestream direction. The vertex is fixed in the downstream direction for the triangular orifice.

The velocity field was measured using an X-type hot wire probe which was supported by a three-axis computer-controlled traverse unit. Velocity measurements in the *y*-*z* plane were carried out at equal intervals of 5 mm, in both the *y* and *z* (spanwise) directions. The jet velocity distribution in a plane parallel to the lower wall was also measured in order to understand the effect of the jet orifice shape on the strength of longitudinal vortices. The jet velocity distribution was measured in the *x*′-*z*′ plane as shown in Fig. 4. The origins of coordinate *x*′ and *z*′ are defined as the location of modified jet orifice center. In the *x*′-*z*′ plane, the modified jet orifice center is determined by

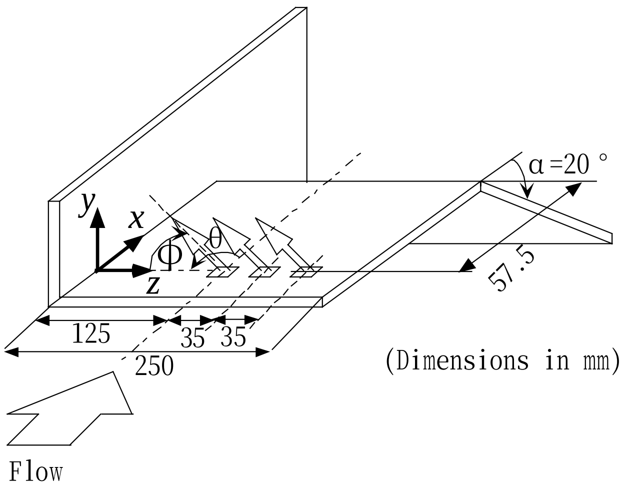


Fig. 2 Jet Configurations in Test Section

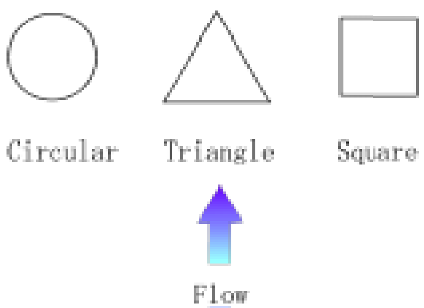


Fig. 3 Schematic of Jet Orifice

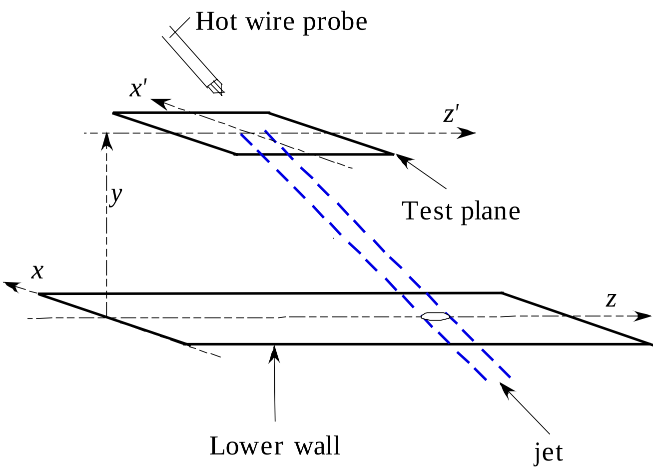


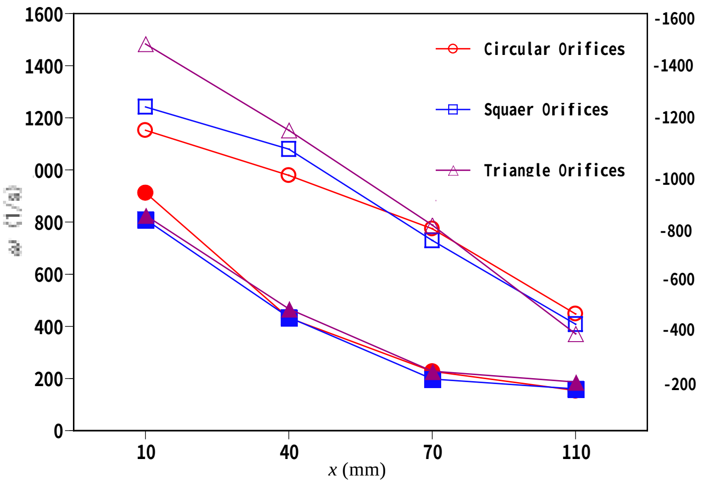
Fig. 4 Schematic of Jet Velocity Measurements

projecting the center of orifice in the direction of the jet pitch angle. The velocity measurements in the x'-z' plane were carried out at equal intervals of 0.4 mm, in both the x' and z' directions.

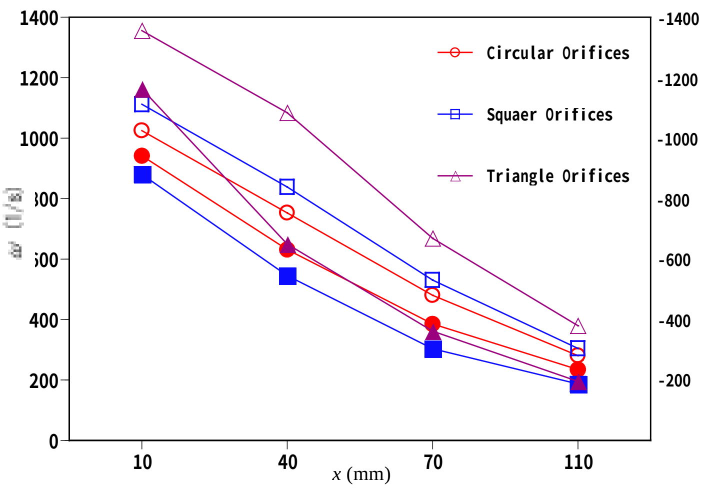
3 Results and Discussion

3.1 Suppression Effect on Separating Flow

Figure 5 shows the downstream decays of the maximum positive and negative vorticities for the cases of the jet pitch angle of 30 deg and 45 deg. In this study, the vorticity is defined as positive one for vortices of clockwise rotation when we view from upstream. The positive vorticity for the 30-deg case is stronger than that for the 45-deg case in all types of the jet orifice. This indicates the conclusion similar to that of the past study that the strong vortex is generated by small jet pitch angle for the circular orifice shape [5]. The triangular jets generate the strongest vortices and the circular jets generate the weakest vortices among the three types of jet orifice shape for each jet pitch

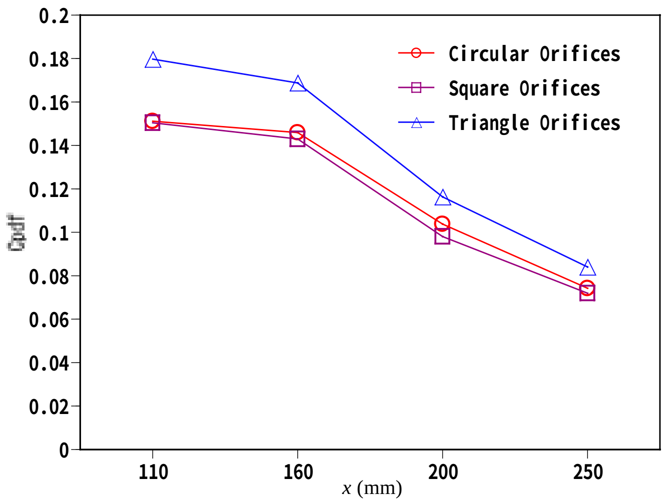


(a) ϕ = 30 deg

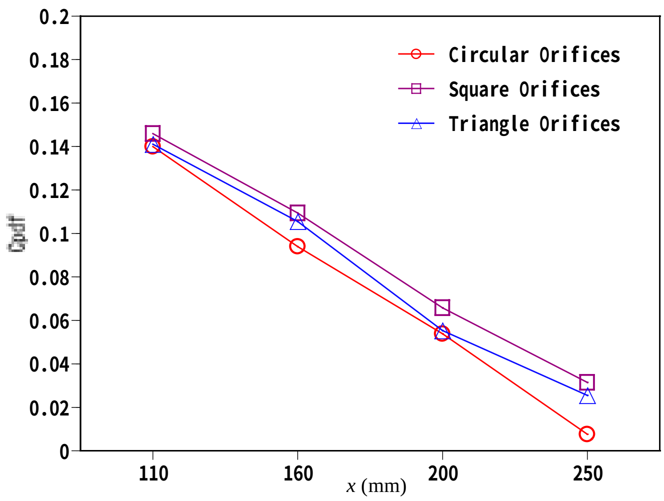


(b) ϕ = 45 deg

Fig. 5 Downstream Decays of The Maximum Positive Vorticity. Open Symbols Denote Positive Vorticity (U_0=6.5 m/s, VR=9.5)



(a) ϕ = 30 deg



(b) ϕ = 45 deg

Fig. 6 Distribution of Pressure Recovery along The Wall Static Pressure Holes of Divergent Portion (U_0=6.5 m/s, VR=9.5) angle. The vorticity for the triangular jets is strong at X=10 mm in comparison with the other measurement stations for the 30-deg and the 45-deg cases. However, the positive vorticity for the triangular orifice shape decays rapidly in the downstream direction and has the strength nearly equal to that for the other orifice shapes at X=110 mm. The negative vorticity profiles indicate similarity in three types of the jet orifice for the 30-deg case. The negative vorticity for the 30-deg case is weaker in comparison with that for the 45-deg case in three orifice shapes. The negative vorticity weakens at a small jet pitch angle.

Figure 6 shows the distribution of pressure recovery in the downstream direction for the 30-deg and the 45-deg cases. The pressure recovery coefficient Cp_{df} is defined as the pressure recovery under control against the pressure recovery under no control is given by

$$Cp_{df}=Cp_{VR}-Cp_{uf} \qquad (1)$$

where the subscript VR and uf indicate the situation with control and without control (jet-off situation), respectively. Cp is the pressure recovery, defined by

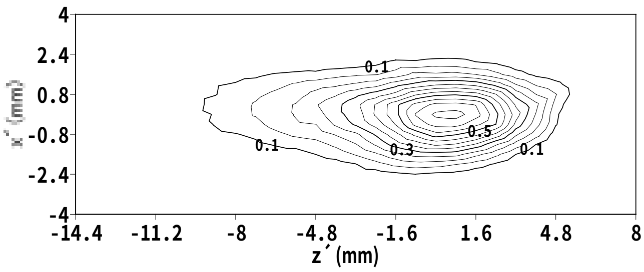
$$Cp=2\Delta p/\rho U_0^2 \qquad (2)$$

where ρ indicates density and Δp the pressure difference between the upstream of the divergent portion (x=-150 mm) and the measurement station in the diffuser (x=110, 160, 200 and 250 mm). The large pressure recovery is attained for the triangular jets in a pitch angle of 30 deg because the vortices generated by the triangular jets are stronger than those for the other cross-section geometry jets (see Fig. 5) and also exist near the lower wall. On the other hand, for the 45-deg case, the pressure recovery profiles show behavior similar to three types of the jet orifice shape. In other words, the pressure recovery becomes larger in the case of the triangular orifice shape for the 30-deg case but the pressure recovery is not affected by the jet orifice shape for the 45-deg case.

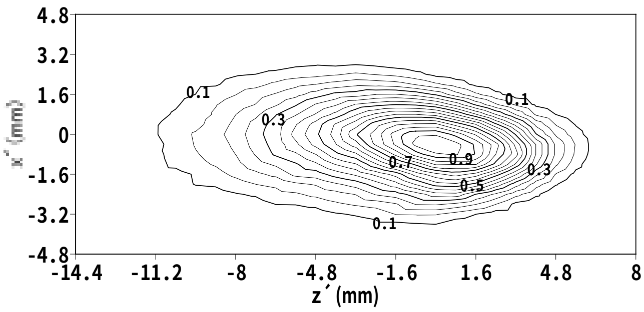
3.2 Jet Velocity Measurement

In order to understand the reason why in the case of triangular orifice shape strong longitudinal vortices are produced and exist near the lower wall, the jet velocity measurements were carried out in the plane parallel to the lower wall. Figures 7 and 8 show the mean-velocity contours in the x'-z' plane without freestream (U_0=0 m/s). The jet velocity is normalized by the velocity measured at the jet orifice center in the x-z plane (y=0mm). The measuring plane and the way of measuring are shown in Fig. 4.

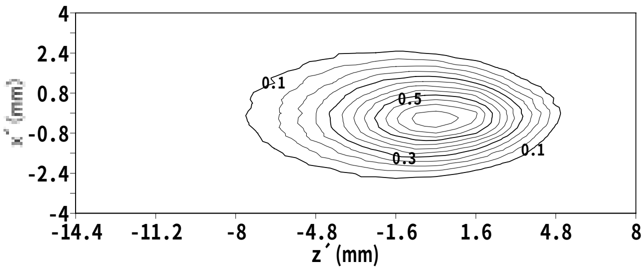
It is seen from Figs. 7 and 8 that all types of the jet orifice indicate the elongation of the jet velocity contours in the -z' direction for the



(a) Circular Orifice

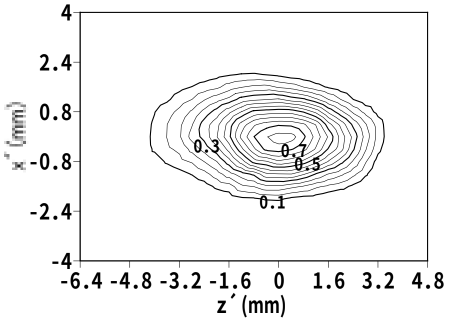


(b) Triangular Orifice

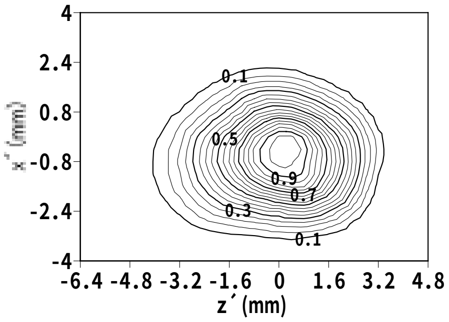


(c) Square Orifice

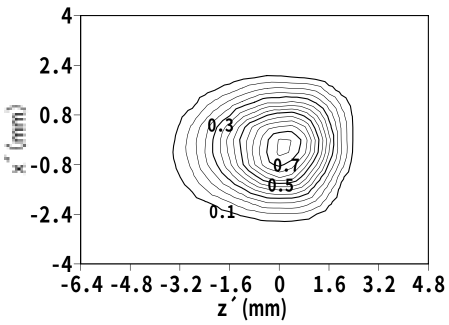
Fig. 7 Contours of Jet Mean-velocity at y=5 mm (ϕ=30 deg, V_j=26m/s)



(a) Circular Orifice



(b) Triangular Orifice



(c) Square Orifice

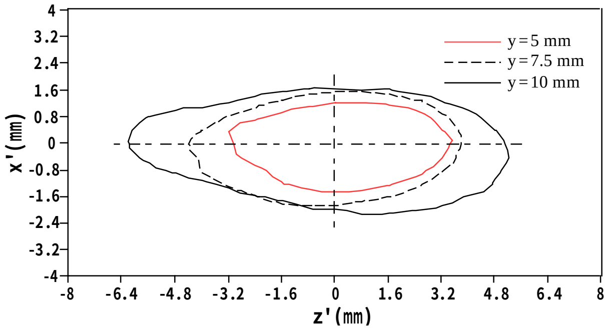
Fig. 8 Contours of Jet Mean-velocity at y=5 mm (ϕ=45 deg, V_j=26m/s)

jet pitch angle of 30 deg case in contrast to the 45 deg case. Furthermore, the square orifice suppresses the elongation in the -z' direction in comparison with the other orifice shapes in each jet pitch angle. Since the cross-sectional area of the jet orifice is equalized in three jet orifice shapes, for the square orifice, the side set in the x' direction is shortest among the three types of jet orifice. The square jets suppress the elongation of the jet velocity contours in the -z' direction because the side set in the x' direction is short.

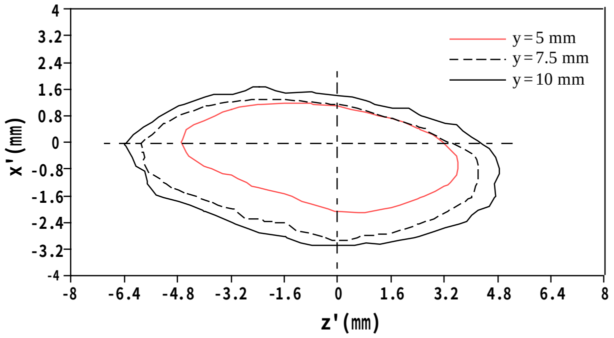
It is confirmed that the orifice shape for the jet pitch angle of 45 deg affects the shape of jet velocity contour. The shapes of the jet velocity contours for the circular, square and triangular orifices indicate ellipse, square and triangle, respectively. However, the differences are small because the jet velocity contours are elongated in the -z' direction due to the jet pitch angle. Therefore, the difference of the shape of the jet velocity contours is not confirmed for a pitch angle of 30 deg. The jet velocity contours are elongated in the -z' direction due to the jet pitch angle because the jet velocity distribution was measured in the plane parallel to the lower wall. The jet velocity contours for the jet pitch angle of 30 deg case are strongly elongated in the -z' direction in comparison with those for the 45 deg case and therefore the difference of the shape of jet velocity contours is not confirmed in three types of the jet orifice. For the vortex generator jets, the jet pitch angle is dominant compared to the jet orifice shape. The elongation in the z' direction of the jet velocity contours has a relation to the strength of longitudinal vortices. The jet velocity contours are elongated in the z' direction as decreasing the jet pitch angle.

The jet core where the jet velocity is of maximum magnitude in the x'-z' plane coincides with the geometric center of the jet velocity contours for the jet pitch angle of 90 deg case. For a pitch angle of 90 deg, the positive and negative vortices are symmetrically generated and the strength of the positive vortices equals the negative ones. On the other hand, for the inclined (pitched) jets, the jet velocity contours indicate the asymmetric elongation in the z' direction and the jet core does not coincide with the geometric center of the jet velocity contours. If the jet velocity contours are not symmetrically elongated in the z' direction, the resulting positive and negative vortices are not symmetric and their strengths are different.

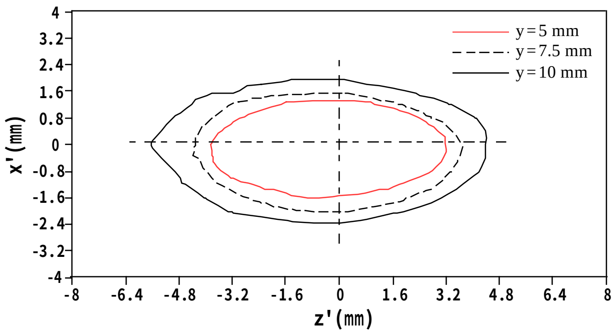
The jet velocity contours indicate the



(a) Circular Orifice

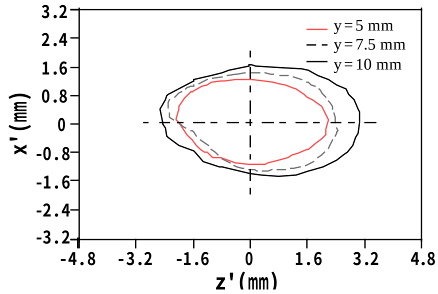


(b) Triangular Orifice

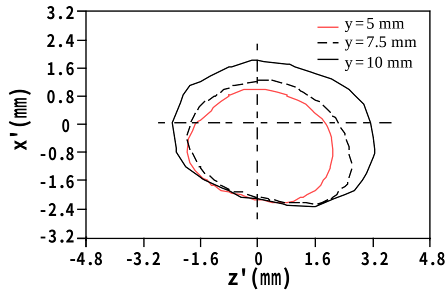


(c) Square Orifice

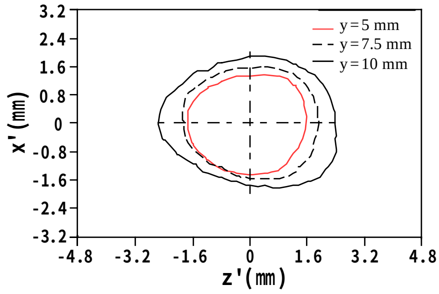
Fig. 9 Comparison of V_y/V_j Contours at y=5, 7.5 and 10 mm (V_y/V_j =0.5, ϕ=30 deg)



(a) Circular Orifice



(b) Triangular Orifice



(c) Square Orifice

Fig. 10 Comparison of V_y/V_j Contours at y=5, 7.5 and 10 mm (V_y/V_j =0.5, ϕ=45 deg)

strongest elongation in the x' direction for the triangular orifice among the three types of jet orifice and the triangular jets significantly increase the jet diffusion. For the triangular jets issued from sharp-edged orifice, the local jet speed decreases at the corner of the jet orifice and increases at the center of the jet orifice. Therefore, the jet velocity contours are broadened in the plane parallel to the lower wall in comparison with those for the circular and square jets. For the circular and square jets, the jet velocity contours have the symmetric elongation in the x' direction. For the triangular jets, the jet velocity contours are not symmetrically elongated in the x' direction due to the asymmetric jet orifice shape. Figures 9 and 10 show the development of jet velocity contour in the various x'-z' planes (y=5, 7.5 and 10 mm) for the cases of the jet pitch angle of 30 and 45 deg, respectively. The jet velocity contour indicates the jet core speed in each x'-z' plane / the jet speed of V_y/V_j = 0.5. The elongation of the jet velocity contour in the x'

and z' directions becomes larger as increasing y for three types of jet orifice. Also, the elongation for the jet pitch angle of 30 deg is stronger than that for the jet pitch angle of 45 deg.

4 Conclusions

The separation control of three different cross-section geometry jets have been studied in a two-dimensional diffuser and compared with that of a circular cross-section jet for the vortex generator jets. The jets had equal cross-section areas but different geometries. Furthermore, the jet velocity distribution was measured in the plane parallel to the lower wall in order to understand the effect of the jet orifice shape on the strength of longitudinal vortices. The present study is summarized as follows:

1. For the vortex generator jets, the triangular jets make strong the vorticity of longitudinal vortices.
2. For the triangular jets, the effective separation control is achieved because the vortices become stronger.
3. The elongation of the jet velocity contours in the spanwise direction affects the strength of positive and negative vortices. If the jet velocity contours are not symmetrically elongated in the spanwise direction, the resulting positive and negative vortices are not symmetric and their strengths are different.
4. The effect of the jet pitch angle is dominant in comparison with that of the jet orifice shape on the elongation of the jet velocity contours.

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] Selby, G. V., Lin, J. C. and Howard, F. G. Control of Low-speed Turbulent Separated Flow Using Jet Vortex Generators. *Experiments in Fluids*, 12, pp 394 -400, 1992.Smith J, Jones B and Brown J. The title of the conference paper. *Proc Conference title*, where it took place, Vol. 1, paper number, pp 1-11, 2001.

[3] Hasegawa, H., Matsuuchi, K. and Yamakami, J. The Mechanism of Active Boundary Layer Control Using Vortex Generator Jets. *Proc 21st Congress of the International Council of the Aeronautical Sciences*, Melbourne, Australia, ICAS98-31545, 1998. Smith J, Jones B and Brown J. The title of the journal paper. *Journal Name*, Vol. 1, No. 1, pp 1-11, 2001.

[4] Compton, D. A. and Johnston, J. P. Streamwise Vortex Production by Pitched and Skewed Jets in a Turbulent Boundary Layer. *AIAA Journal*, Vol. 30, No. 3, pp 640-647, 1992.

[5] Hasegawa, H. and Matsuuchi, K. Effect of Jet Pitch Angle of Vortex Generator Jets on Separation Control. *Proc Third International Conference on Fluid Mechanics*, Beijing, China, pp 526-531, 1998.

[6] Toyoda, K. Shirahama, Y. and Kotani, K. Manipulation of Vortical Structures in Noncircular Jets. *Tans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol. 58, No.545, B, pp 7-13, 1992.