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THE MECHANISM OF ACTIVE BOUNDARY LAYER CONTROL USING VORTEX GENERATOR JETS

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Abstract

The vortex generator jet method is an 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. Pitched and skewed jets issue into a freestream and the interaction between the jets and the freestream generates longitudinal (streamwise) vortices. The mechanism for suppressing flow separation was studied experimentally by making a comparison between two effects of steady and pulsed jets on generating longitudinal vortices. The suppression of flow separation is accomplished by the secondary flow of longitudinal vortices which transport high momentum fluid of the freestream to the lower wall. However, if the vortex moves away from the lower wall, a counter-rotating vortex of nearly equal strength is induced, and thus an upwash region is produced by the effect of a vortex pair. The upwash makes ineffective the secondary flow toward the lower wall. Consequently, the boundary layer thickness is strongly distorted and is not uniform in the spanwise direction because streamwise velocity decreases near the outer edge of the boundary layer. Pulsed jets enhance the mixing process in comparison with steady jets and indicate effective separation control for the purpose of keeping the vortex near the lower wall.

Nomenclature

D jet hole diameter
f_p pulse frequency
Q_j jet flow rate
U mean velocity in X direction
U_0 local freestream velocity
V mean velocity in Y direction
V_j jet mean speed
VR ratio, V_j/U_0
W mean velocity in Z direction
X streamwise coordinate(measured from jet hole)
Y vertical coordinate(measured from lower wall)
Z spanwise coordinate(measured from the wall on left-hand side viewed from upstream)
α divergence angle of lower wall
ϕ jet pitch angle
θ jet skew angle
ω_x streamwise component of mean vorticity

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1. Introduction

In order to reduce drag and pressure losses it would be necessary to inhibit flow separation by suppressing the boundary layer development. Boundary layer control has been used widely in aerodynamic applications to inhibit flow separation. The boundary layer control techniques are classified as passive and active methods. Passive control technique with solid vortex generators has the advantages such as simplicity, ruggedness, and low cost, and in fact it has practical applications in stall control of airfoils. Shizawa and Eaton [1] indicated the suppression effect and the downstream development of longitudinal vortices produced by solid vortex generators. However, solid vortex generators have a fatal shortcoming. 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).

On the other hand, the vortex generator jet method as an active control technique provides a time-varying control action to optimize performance under a wide range of flow conditions. Furthermore, for flow situations where stall control is not needed, the parasitic drag can be avoided with the jet flow turned off. The vortex generator jet method may accomplish separation control only when necessary and therefore it is available under both design and off-design conditions. Jets issue through small holes in a wall into a freestream and

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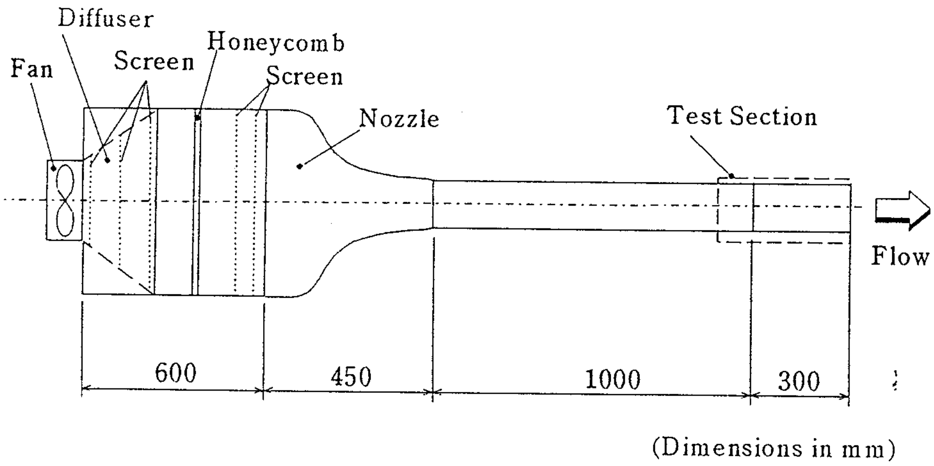


FIGURE 1 - Schematic Diagram of Experimental Facility.

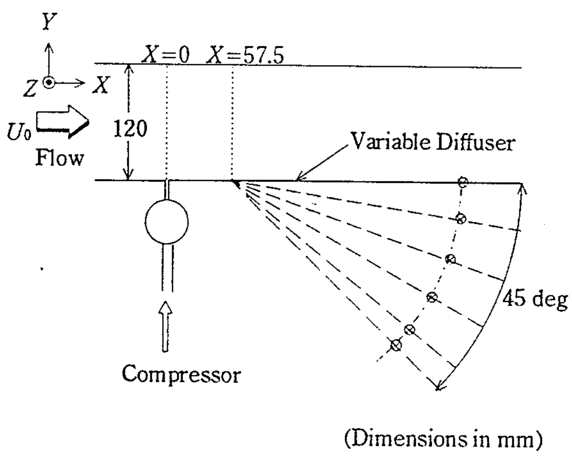


FIGURE 2 - Test Section Geometry.

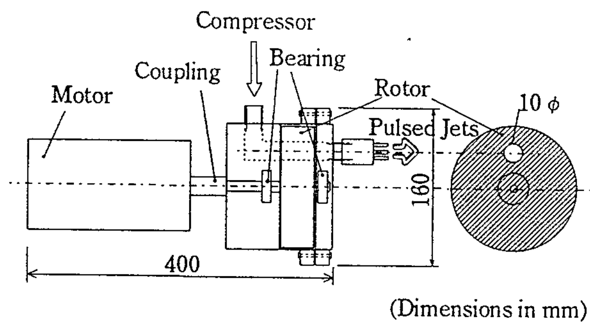


FIGURE 3 – Pulsed Jets Generator.

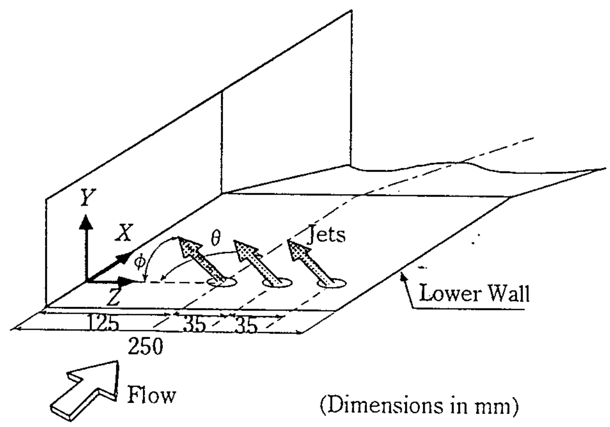


FIGURE 4 - Jets Configuration in Test Section.

the interaction between the jets and the free-stream forms longitudinal vortices. Compton and Johnston[2] showed that the property of longitudinal vortices produced by vortex generator jets is different from that by solid vortex generators. Johnston and Nishi[3] examined five configurations of a spanwise array of skewed and pitched jets issuing from small holes and showed that those discrete jets generate the longitudinal vortices which may delay separation. The suppression effect of flow separation using pulsed vortex generator jets is shown by McManus et al[4]. However, details of the mechanism for suppressing flow separation using vortex generator jets have not been clarified in their studies. The objective of this study is to investigate the mechanism of active boundary layer control using vortex generator jets by making a comparison between two effects of steady and pulsed jets on generating longitudinal vortices.

2. Experimental Apparatus and Method

Experiments were conducted in a low speed wind tunnel. A schematic diagram of the wind tunnel is shown in figure 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 was configured with the lower wall of various divergence angles between 0 deg and 45 deg. A detailed diagram of the test section is shown in figure 2. 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 magnitude of jet flow rate was characterized by the jet-to-freestream velocity ratio (*VR*). The pulsed vortex generator jet device is shown in figure 3. The pulsed flow was produced by passing or shutting off the secondary air from the compressor using a rotor which allowed the pulse rate up to 23 Hz. Figure 4 shows the configuration of jets and the coordinate system used to describe the flowfield. Three jets of 2 mm-diam were placed at the upstream of the divergent lower wall and their holes 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 to the freestream direction and pitched at 45 deg to the lower wall.

Velocity profiles in the test section were obtained using an X-type hot wire probe. The hot wire probe was supported by a three-axis computer-controlled traverse unit. Streamwise velocity profiles were measured at Z=110 mm to avoid the effect of jet holes and at X=40, 70, 110 mm. The velocity measurements in a Y-Z plane are carried out at equal spaces of 5 mm, in the X and Y directions.

3. Results and Discussion

3.1 Waveform of Pulsed jets

Figure 5 shows the waveform of the pulsed jets in this study. Pulsed jet generator has a tendency to broaden a peak region of the waveform for both cases of increasing jet flow rate (correspond to increase jet speed) and lowering a frequency. The feature of lowering-frequency case results from the increased passage time of the secondary air due to the decreased rotor speed.

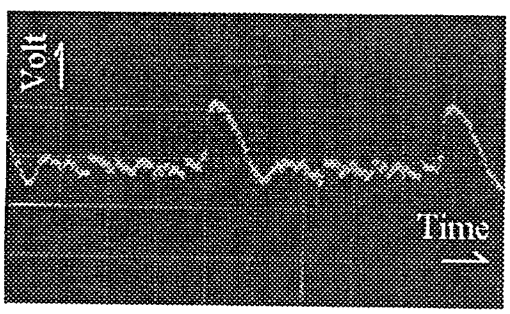


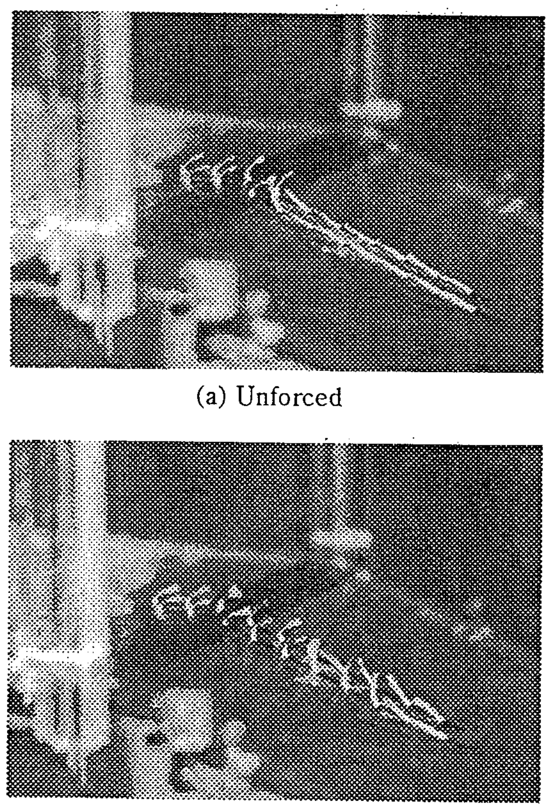
FIGURE 5 - Original Waveform of Pulsed Jets. Time Axis Interval=10 ms (f_p=20 Hz, Q_j=20 l/min).

3.2 Flow Visualization Results

The surface tuft method was used as a diagnostic technique to observe the effect of vortex generator jets on separated flow. Tufts were put on the lower wall of the test section at Z=125, 140 mm. Figure 6 shows the surface flow in divergent portion of the test section. It is seen that the vortex generator jets can delay flow separation in comparison with the unforced case.

3.3 Streamwise Velocity Measurements

Two freestream velocities were investigated corresponding to U_0=6.5 and 11.1 m/s. Figures 7 and 8 show the streamwise velocity profiles in the test section. The data are presented for a lower wall divergence of 20 deg. The profiles for the unforced case in these figures indicate a boundary layer separation in divergent portion of the test section. For the cases of U_0=6.5 and 11.1 m/s, the velocity profile measurements of pulsed jets indicate the velocity increase in the near-wall region at measurement stations of the divergent portion in



(a) Unforced

(b) U_0=6.5 m/s, VR=9.5, f_p=20 Hz

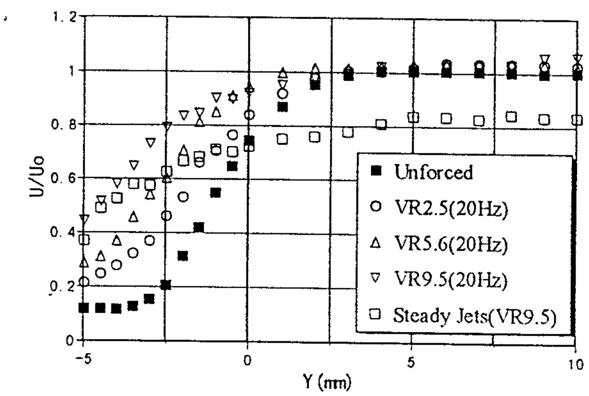
FIGURE 6 - Surface Flow in Divergent Portion of The Test Section.

comparison with the unforced case. Figure 7 shows that the effective near-wall velocity increase is achieved by increasing the jet flow rate. This result coincides with the conclusion by Compton and Johnston [(2)] which states that a strong vortex could be produced by increasing the jet flow rate in the same freestream speed with respect to steady jets.

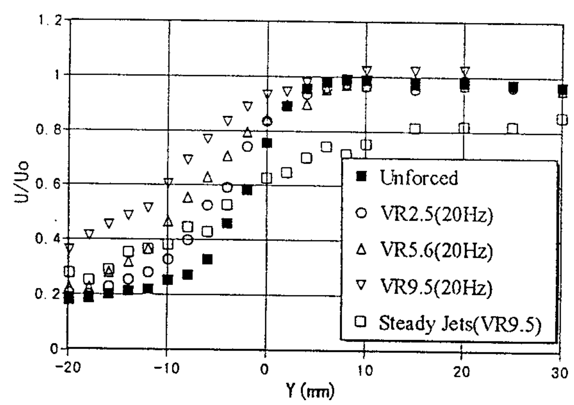
On the other hand, the velocity profiles for the case of U_0=11.1 m/s show similar trends for two different *VR* of the pulsed jet case (see figure 8). In this study, we define the vorticity in a *Y-Z* plane as positive one for clockwise rotating vortices when we view from upstream. Figure 9 shows a comparison between the downstream decay of maximum positive and negative vorticity of longitudinal vortices. The positive vorticity produced by the interaction between the jets and the freestream becomes strong as increasing the freestream velocity at a fixed *VR*. In other words, the case of U_0=11.1 m/s generates longitudinal vortices that are enough strong to achieve the near-wall velocity increase.

Two cases of jet pulse frequency, f_p=10 and 20 Hz, were investigated. The shape of peaks in the original waveform of pulsed jets broadens with respect to the time axis and also the jet flow rate per pulse is increased by lowering a pulse frequency. On the contrary, increasing a pulse frequency leads to the increase of the number of peaks of the original waveform in a time interval. However, the profiles of f_p=20 Hz in figure 10 show that the near-wall velocity is increased in comparison with those of f_p=10 Hz. In the present experiment, it is thus concluded that increasing a pulse frequency is more effective in the control of flow separation in comparison with broadening the shape of peaks by lowering a pulse frequency.

The steady jet profile in figure 8(a) shows a velocity defect near the outer edge of the boundary layer of the unforced case, while the pulsed jets have the ability to thin the boundary layer thickness. Figure 11 shows streamwise flow vectors at X=40, 70, 110 mm. For the case of pulsed jets, downward

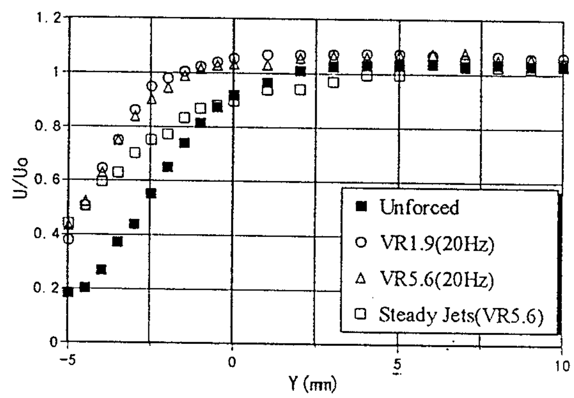


(a) X=70 mm

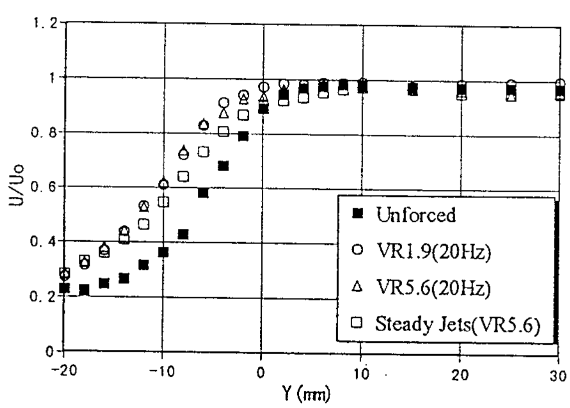


(b) X=110 mm

FIGURE 7 - Streamwise Velocity Profiles (U_0=6.5 m/s, α =20 deg).



(a) X=70 mm



(b) X=110 mm

FIGURE 8 - Streamwise Velocity Profiles (U_0=11.1 m/s, α =20 deg).

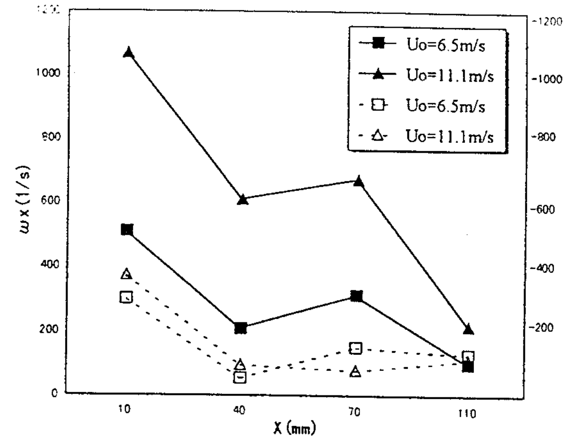
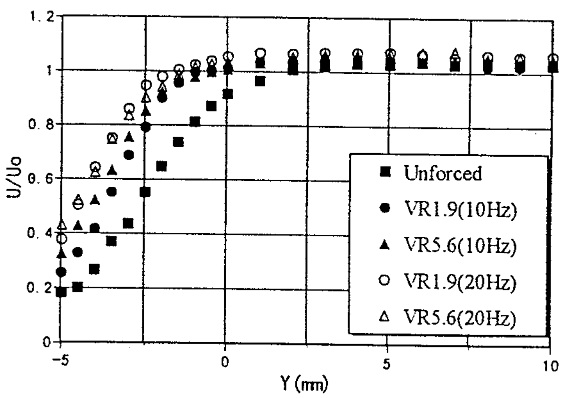
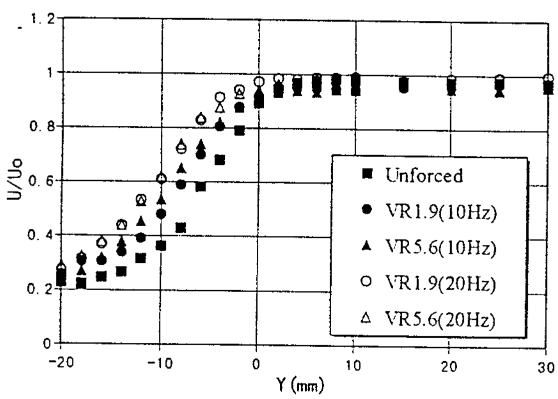


FIGURE 9 - Comparison between the Downstream Decay of Maximum Positive and Negative Vorticity. Dotted Line Denotes Negative Vorticity (VR=5.6, f_p=20 Hz, α =20 deg).

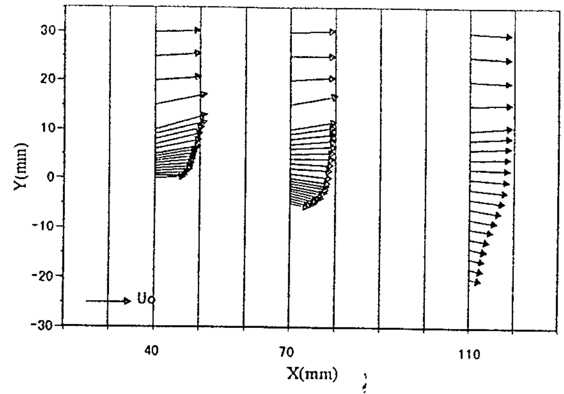


(a) X=70 mm

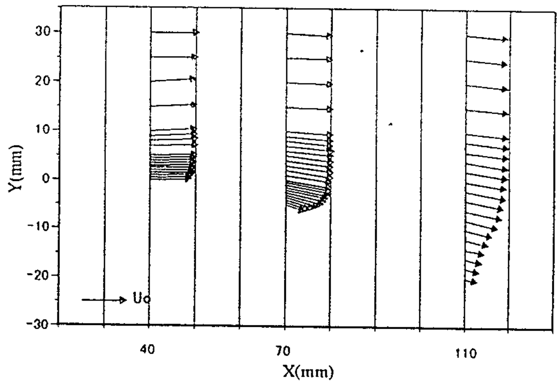


(b) X=110 mm

FIGURE10- Streamwise Velocity Profiles (U_0=11.1 m/s, α =20 deg).



(a) Steady Jets (VR=5.6)



(b) Pulsed Jets (VR=5.6, f_p=20 Hz)

FIGURE 11 - Streamwise Flow Vectors (U_0=11.1 m/s, α =20 deg).

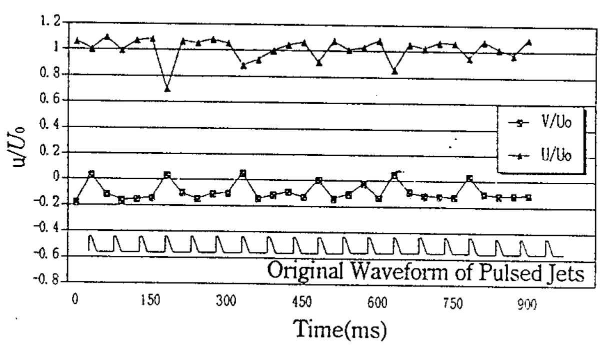
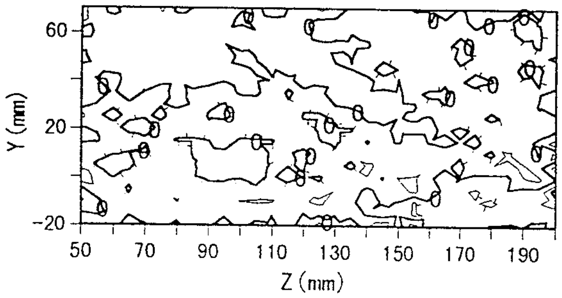


FIGURE 12 - Sampling Interval of Streamwise Velocity, Compared to Original Waveform of Pulsed Jets at X=70 mm, Y=6 mm (U_0=11.1 m/s, VR=1.9, f_p=20 Hz, α =20 deg).

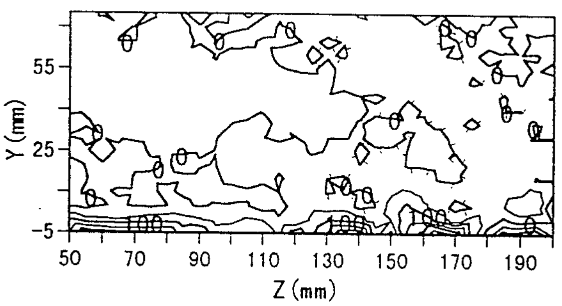
flow vectors exist in the measurement region. On the other hand, for the case of steady jets, upward flow vectors exist near the outer edge of the boundary layer. In the steady jet case there is a velocity defect because downward flow does not exit near the outer edge of the boundary layer in contrast with the pulsed jet case (see figure 11).

The correlation of U and V with respect to the period of pulsed jets and the velocity measurements for the case of pulsed jets are shown in figure 12. For the case of f_p=20 Hz and the sampling time of the streamwise velocity set at 30 ms, the period of issuing jets coincides with the period of sampling data at every interval of 150 ms. The streamwise velocity decrease is observed at that time. In other words, if the velocity is measured at the instant that the jets are blown, the streamwise velocity decrease is observed. It is hence supposed that steady jets have a tendency to increase the velocity in Y direction near the outer edge of the boundary layer and also to decrease the streamwise velocity there.

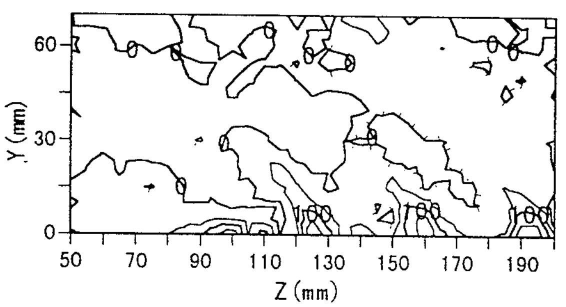
For the vortex generator jet method, an increase of the jet flow rate causes the near-wall velocity increase and makes effective the control of the separated flow for the same freestream speed. The increase of the jet flow rate corresponds to broadening the shape of peaks of the pulsed jets. In order to avoid the velocity defect near the outer edge of the boundary layer, the pulsed jet method therefore is of important use.



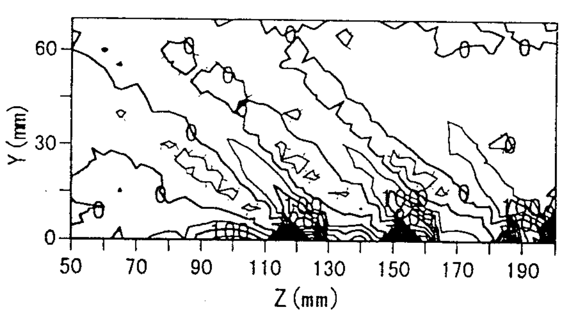
(a) X=110 mm



(b) X=70 mm



(c) X=40 mm



(d) X=10 mm

FIGURE 13-Contours of Streamwise Vorticity. Contour Interval =50 1/s., Decorated Line Denotes Negative Vorticity (U_0=6.5 m/s, VR=5.6, f_p=20 Hz, α =20 deg).

3.4 Velocity Measurements in a Y-Z Plane

Figure 13 shows the downstream development of longitudinal vortices for the case of pulsed jets. Secondary flow vectors at X=70 mm are shown in figure 14. Figure 13 indicates that the longitudinal vortices persist near the lower wall in the downstream direction. The vortices exist in the near-wall region and strong vortices do not exist apart from the lower wall. From figure 14 it is seen that the secondary flow toward the lower wall is induced by the effect of the longitudinal vortices in the near-wall region. The secondary flow of longitudinal vortices may transport high momentum fluid of the freestream to the lower wall. The suppression of flow separation in a separated flowfied is accomplished by transporting high momentum fluid of the freestream to the lower wall.

Figure 15 shows the downstream development of longitudinal vortices for the case of steady jets. A comparison between figures 13 and 15 makes clear that the downstream development of longitudinal vortices for the case of pulsed jets is quite

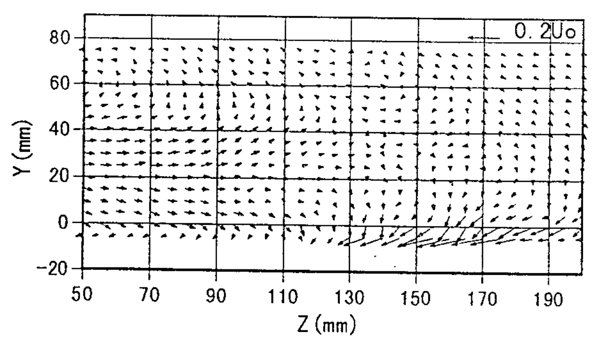
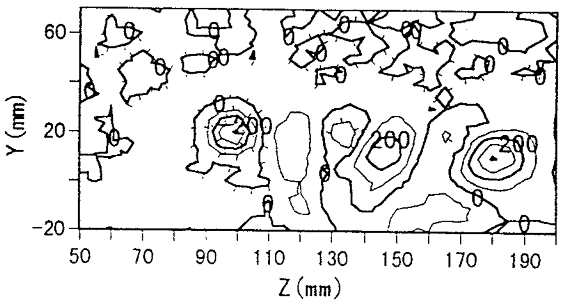


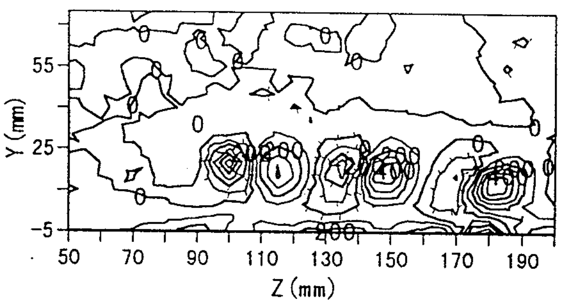
FIGURE 14 - Secondary Flow Vectors at X=70 mm (U_0=6.5 m/s, VR=5.6, f_p=20 Hz, α = 20 deg).

different from that for the case of steady jets. Pulsed vortex generator jets keep the vortices near the lower wall. Because pulsed jets further enhance the mixing process between the jets and the freestream than steady jets, the upward movement of longitudinal vortices is suppressed.

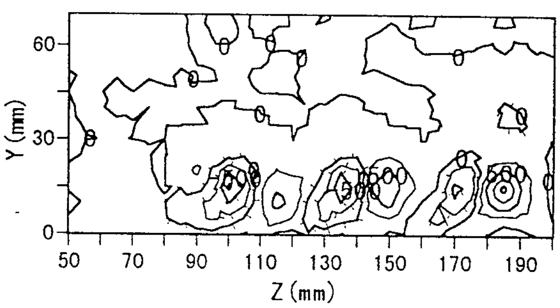
Counter-rotating vortices (negative vorticity) produced on the upwash side of the longitudinal vortices at $X=10$ mm are seen in figure 15. It is supposed that the counter-rotating vortices are induced by the longitudinal vortices moving away from the lower wall. Vortex pairs are then formed. Three pairs of positive and negative vortices align on the right-hand side of figure 15 corresponding to the three jets. The formation of vortex pairs is due to the steady jets which make ineffective the mixing process between the jets and the freestream. The suppression of mixing brings about the upward movement of vortices. The pairs of vortices continue to be lifted away from the lower wall in the downstream direction due to the effect of induced



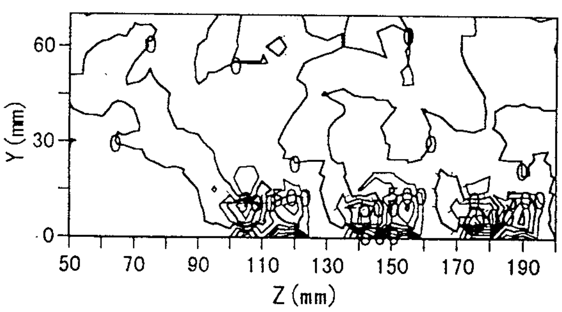
(a) $X=110$ mm



(b) $X=70$ mm



(c) $X=40$ mm



(d) $X=10$ mm

FIGURE 15-Contours of Streamwise Vorticity. Contour Interval =250 1/s at $X=10,40$ mm, 100 1/s at $X=70,110$ mm. Decorated Line Denotes Negative Vorticity ($U_0=6.5$ m/s, $VR=9.5$, $\alpha=20$ deg).

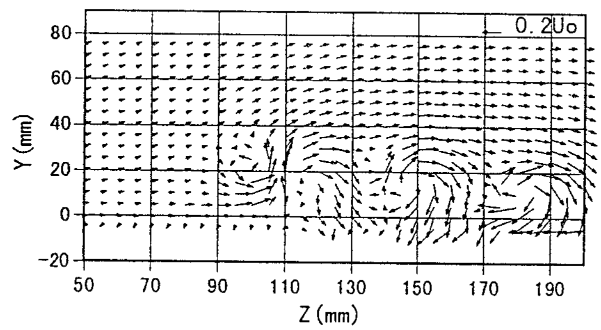
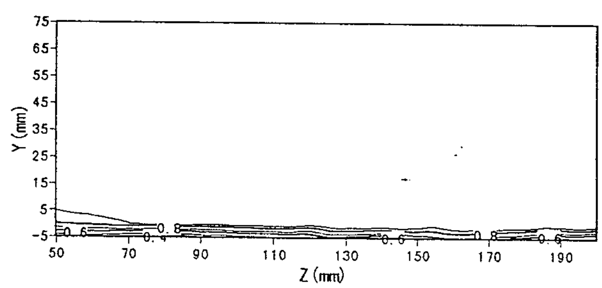
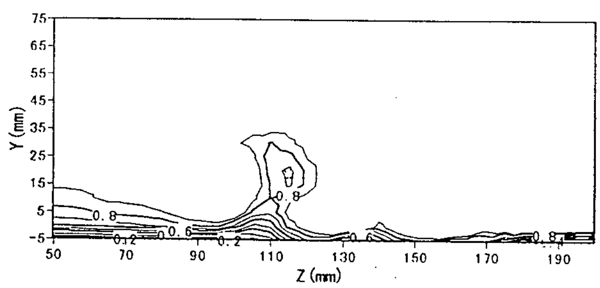


FIGURE 16- Secondary Flow Vectors at $X=70$ mm ($U_0=6.5$ m/s, $VR=9.5$, $\alpha=20$deg)



(a) Pulsed Jets ($VR=5.6$, $f_p=20$ Hz)



(b) Steady Jets ($VR=9.5$)

FIGURE 17 - U/U_0 Contours at $X=70$ mm. Contour Interval=0.1($U_0=6.5$ m/s, $\alpha=20$deg).

velocity by each vortex pair itself. The vortices except for the edge vortices on both sides of this array become weaker and disappear in the downstream direction. The secondary flow vectors at X=70 mm are shown in figure 16. An upward secondary flow is produced near Z=110 mm. It is supposed that the upwash is induced by a vortex pair which is formed by the production of a counter-rotating vortex of nearly equal strength (see figure 15).

For the case of steady jets, maximum negative vorticity has the strength nearly equal to maximum positive vorticity. On the other hand, for the case of pulsed jets, the maximum strength of positive vorticity increases as increasing freestream velocity, while that of negative vorticity is almost unchanged for various freestream velocities (see also figure 9). The suppression effect against upward flow is achieved by keeping the longitudinal vortices near the lower wall. These vortices can transport effectively high momentum fluid of the freestream to the lower wall.

Figure 17 shows the contours of streamwise velocity. For the case of steady jets, the contours exhibit the strong distortion near the outer edge of the boundary layer near Z=110 mm and as a result the boundary layer thickness increases. This is due to the upwash induced by a pair of vortices of nearly equal strength at the spanwise location (see figure 16). Even if the case of steady jets, the suppression effect against separation is achieved, but the upwash makes ineffective the secondary flow toward the lower wall in a narrow spanwise region. Moreover, the velocity defect near the outer edge of the boundary layer is brought about by the effect of upwash and thereby the boundary layer thickness varies largely in the spanwise direction. This characteristic is also confirmed in figure 7 where the mean velocity for the steady jet case is much lower than that for the unforced case. The streamwise velocity measurements are carried out just at Z=110 mm where the upwash occurs (see figure 17(b)).

3.5 Application for Divergence Angle of 30 Deg

Figure 18 shows the streamwise velocity profiles at X=110 mm in a lower wall divergence of 30 deg for the pulsed jet case. The profiles indicate that the near-wall velocity hardly increase. Figure 19 shows the downstream development of the longitudinal vortices produced by the interaction between the jets and the freestream. The longitudinal vortices begin to lift away from the lower wall at X=70 mm and exist far from the lower wall at X=110 mm. A counter-rotating vortex of nearly equal strength is produced below the longitudinal vortex because the longitudinal vortex moves away from the lower wall. Accordingly, the secondary flow toward the lower wall cannot be produced, as seen in figure 20. The high momentum fluid of the freestream is not carried effectively toward the

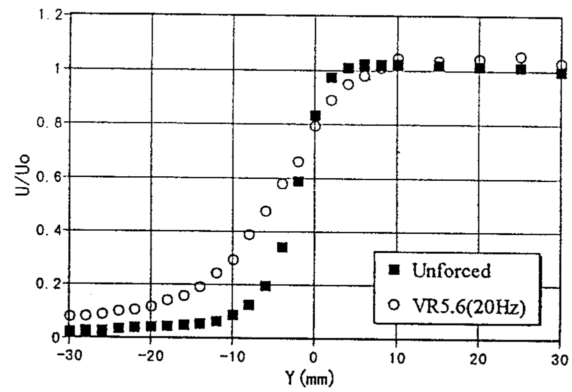
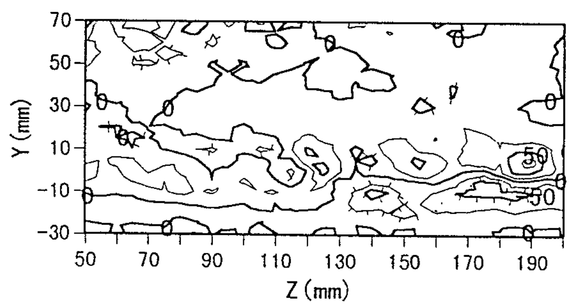
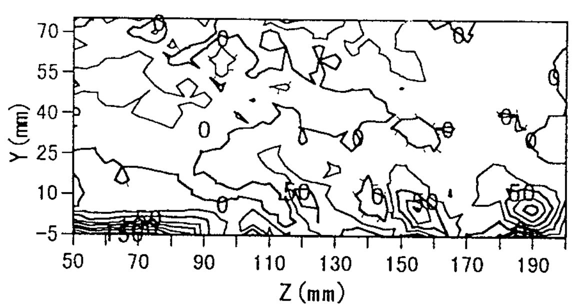


FIGURE 18-Streamwise Velocity Profiles at X=110 mm (U_0=6.5 m/s, VR=5.6, f_p=20Hz, α =30 deg).



(a) X=110 mm



(b) X=70 mm

FIGURE 19-Contours of Streamwise Vorticity. Contour Interval=25 1/s. Decorated Line Denotes Negative Vorticity (U_0=6.5 m/s, VR=5.6, f_p=20 Hz, α =30 deg).

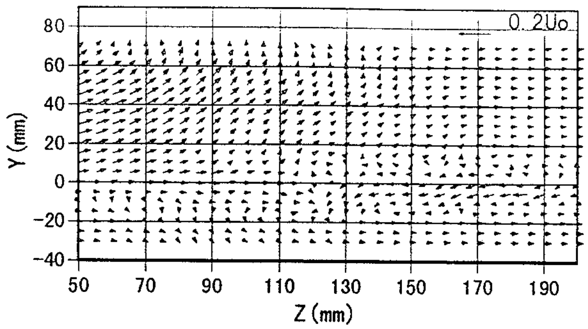


FIGURE 20-Secondary Flow Vectors at X=110 mm (U_0=6.5 m/s, VR=5.6, f_p=20 Hz, α = 30 deg).

lower wall and as a result the near-wall velocity in divergent portion of the test section does not increase.

4. Conclusions

From the present experimental study for the mechanism of active boundary layer control using longitudinal vortices, the following conclusions are drawn:

1) The suppression of flow separation is achieved by the secondary flow of longitudinal vortices, produced by the interaction between the jets and the freestream, which transports high momentum fluid of the freestream toward the lower wall.

2) If a counter-rotating vortex is induced by the vortex which moves away from the lower wall, a pair of vortices are formed. An upwash is induced by a pair of vortices and as a result the boundary layer thickness is strongly distorted. The thickness becomes inhomogeneous in the spanwise direction because the streamwise velocity decreases in the upwash region.

3) The increase of near-wall velocity in divergent portion of the test section is achieved by adjusting the strength of longitudinal vortices which depends on the jet flow rate. Pulsed jets further enhance the mixing process between the jets and the freestream in comparison with steady jets. It keeps longitudinal vortices close to the lower wall and never produces any upwashes.

Acknowledgements

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