6. GENERATING MECHANISM OF LONGITUDINAL VORTICES USING PULSED JETS

In Chapter 5, the mechanism for suppressing flow separation was investigated by making a comparison between steady and pulsed jets. It was clarified that the shape and the downstream development of vortices for the pulsed jet case were different from those for the steady jet case. However, the reasons why the vortices for the steady jet case behave in a manner different from those for the pulsed jet case are unknown. In this chapter, in order to understand these reasons velocity measurements in a *Y-Z* plane over various phases of pulsed jets are carried out.

6.1 Experimental Method

Figure 3.12 indicates the vortex generator jet device. The pulsed jet flow was produced by passing or shutting off the secondary air from a compressor using a rotor disk of the vortex generator jet device. The revolutions per minute of the rotor were measured by using a non-contact type revolution indicator. A reflector was set on a coupling which connects the rotor with a driving motor of the vortex generator jet device. The revolutions per minute were determined from the time interval for which the signal was detected. The velocity measurements were carried out in response to the signal detection of the revolution indicator in order to know the flow field in a fixed phase of the pulsed jet. Varying the position of the reflector on the coupling, we changed the phase.

6.2 Results and Discussion

6.2.1 Longitudinal Vortices in Various Phases of Pulsed Jets

Figure 6.1 shows various rotor positions relative to the flow pass of the secondary air of the vortex generator jet device. Phase NT is just out of phase to the pass. Phase 3 corresponds to the phase where the hole in the rotor disk coincides with the flow pass. In this phase, the maximum issuing jet rate is attained. Phase 1 corresponds to the phase just before jets are issuing. Phase 5 corresponds to that just after issuing. Phase 2 and phase 4 correspond to the intermediate phase between phase 1 and phase 3, and that between phase 3 and phase 5, respectively. Furthermore, phase 7 indicates a phase delayed by a quarter cycle to phase 3 and phase 6 is in the intermediate between phase 5 and phase 7.

Figure 6.2 shows the contours of streamwise vorticity for the pulsed and steady jet cases. For the pulsed jet case the streamwise vorticity is calculated by averaging data over a whole phase. It is seen from Fig. 6.2 that for the steady jet case the vorticity contours are circular in shape and the negative vortices exist on the upwash side of the positive vortices. The counter-rotating vortex pairs of nearly equal strength are formed. On the other hand, for the pulsed jet case the vorticity contours are not circular but appear to have vertical elongation and the longitudinal vortices exist close to the lower wall.

Figure 6.3 shows longitudinal vortices in various phases of the pulsed jets. In phase NT, longitudinal vortices are not observed in the flow field because the jets are not issued. The longitudinal vortices are generated near the lower wall in phase 1 or 1a corresponding to the instant at which the jets begin to be issued. Phase 1a indicates the intermediate phase between phase 1 and phase 2. In phase 2, the longitudinal vortices grow in the vertical direction. In phase 3, the vorticity contours have the maximum vertical elongation at a pitch angle of 45 degrees. When the phase changes from phase 4 to 6, the longitudinal vortices have no spreading but they move gradually toward the lower wall. Furthermore, after phase 6 the longitudinal vortices are not observed in the flow field. For the reasons mentioned above, the different feature of longitudinal vortices between the steady and pulsed jets can be explained by considering the vortex behavior in each phase of pulsed jets.

6.2.2 Downstream Development of Longitudinal Vortices

Figures 5.9 and 5.12 show the downstream development of longitudinal vortices for the pulsed jet case and the steady jet case, respectively. For the steady jet case longitudinal vortices form counter-rotating vortex pairs and are lifted away from the lower wall in the downstream direction due to the velocity induced by a pair of vortices. On the other hand, for the pulsed jet case longitudinal vortices develop in the downstream direction without forming a vortex pair and exist close to the lower wall. In order to investigate this phenomenon the downstream development of longitudinal vortices was examined in fixed phases of issuing pulsed jets.

Figure 6.4 shows the downstream development of longitudinal vortices in phase 3 which corresponds to the maximum issuing jet rate. At X=5 mm, the vorticity contours are strongly elongated in the vertical direction. The longitudinal vortices have the strong influence of the jet pitch angle and therefore are elongated in the vertical direction in comparison with the steady jet case. At X=20 mm, the positive vorticity contours begin to split out in the vertical direction. In other words, for the pulsed jet case the positive vortex is affected by the adjacent negative vortex in contrast to the steady jet case, and therefore the positive vortex develops downstream in such a way that the vorticity contours are split out in the vertical direction. At X=22 or 26 mm, the split positive vortices exist above the negative vortices because the positive vorticity contours have the vertical elongation. At X=30 mm, the vertical positions of the positive vortices are different from those of the negative ones for three vortex pairs. At X=40 and 44 mm, the negative vortices collapse in shape, since the positive vortices exist above the negative vortices. At X=49 mm, the negative vortices do not keep their circular shape and become weaker. For the reason given above, we see that the negative vorticity decays more rapidly than the positive one. For pulsed jets the interaction between adjacent positive and negative vortices is promoted by the jet pitch angle and as a result any strong counter-rotating vortex pairs are not produced. Therefore, the upward movement of longitudinal vortices is suppressed in the downstream direction.

Figure 6.5 shows the downstream development of longitudinal vortices for issuing a single jet. This case corresponds to phase 3, i.e., the maximum issuing jet rate. It is seen that the downstream development of longitudinal vortices is similar to the three-jet case. It is clear that for the single-jet case the positive vortex is split out vertically into two pieces by the interaction with the opposite sign vortex at X=20 mm. At X=40 mm, the split positive vortex exists above the negative vortex and a counter-rotating vortex pair is produced. The longitudinal vortices disappear at X=60 mm. This phenomenon in which the positive vortex is split out by the interaction with the negative vortex is not affected by the interaction with the adjacent vortex pairs but by the jet pitch angle.

The downstream development of longitudinal vortices in the phase delayed by a quarter cycle to phase 3 (phase 7) is shown in Fig. 6.6. Longitudinal vortices are not observed at X=5 mm. It is seen that the longitudinal vortices are attaching to the lower wall at X=20 mm. However, they do not attach to the lower wall at X= 30 mm and exist apart from the lower wall at X=50 mm. The vorticity becomes stronger in the downstream direction and the trailing edge of longitudinal vortex exists near X=20 mm. Longitudinal vortices produced by issuing jets develop in the downstream in such a way that the trailing edge of vortices attaches to the lower wall.

6.2.3 Upward Development of Longitudinal Vortices

In Fig. 6.4, at X=30 mm three pairs of vortices exist at nearly equal vertical positions. However, at X=49 mm the vortex pair on the left side edge of the figure is placed at the higher vertical position in comparison with the other vertex pairs. The negative vortex which exists at the center or on the right side edge of Fig. 6.4 exists between the positive vortices. The vorticity becomes weaker under the influence of the interaction between the opposite sign vortices on both sides. On the other hand, no negative vortex on the left side edge exists between the positive vortices. The negative vortex on left side edge is maintained further downstream compared with the other negative vortices because a positive vortex exists only on either side. Therefore, the vortex pair at the left side edge has the strong influence of the velocity induced by the vortex pair and thus exists at the higher vertical position than the other vortex pairs. Figure 6.7 shows the upward development of longitudinal vortices for the case of large *VR* due to a single jet in phase 3. The vorticity is strong and therefore persists further downstream because the jet speed is faster. The vorticity contours are strongly elongated in the vertical direction at X=5 mm and are circular at X=110 mm. The pair of vortices have an upward movement at X=130 and 160 mm. The upward movement is brought about by the velocity induced by the vortex pair.

Suppression of flow separation is achieved by the secondary flow of longitudinal vortices which can transport high momentum fluid of the freestream to the boundary layer. In the sense of performing effective separation control it is important that vortices are strong and keep their positions near the lower wall where the secondary flow toward the lower wall is effective (*cf.* Chapter 5). For this reason, the upward movement of longitudinal vortices is not desirable. For the vortex generator jet method it is important to choose properly the jet spacing and also the jet pitch angle which can make the interaction between adjacent vortices. In other words, the suppression of the upward movement of vortices is achieved by the interaction between adjacent vortices under the influence of the jet pitch angle and the effective jet spacing.

6.3 Conclusions

From the study on the generating mechanism of longitudinal vortices due to pulsed jets, the following conclusions were drawn:

1. As the phase of pulsed jets proceeds from the phase of non-issuing jets, longitudinal vortices produced from the lower wall grow in the vertical direction and the vorticity contours have vertical elongation in the phase with the maximum issuing jet rate due to the jet pitch angle. After that time, the longitudinal vortices move toward the lower wall, as the phase changes to the jet-off situation.

2. For pulsed jets longitudinal vortices have the stronger influence of the jet pitch angle in comparison with the steady jet case.

3. For pulsed jets a positive vortex is split out in the vertical direction by the influence of the neighboring negative vortex and the split positive vortex covers the negative vortex. This means that the attenuation of negative vorticity is promoted and therefore the generation of a vortex pair is suppressed. This leads to the suppression of the upward movement of vortices.

4. For the vortex generator jets with multi-jet orifices, it is desirable that the jet spacing which can make the interaction between

adjacent vortices is selected.

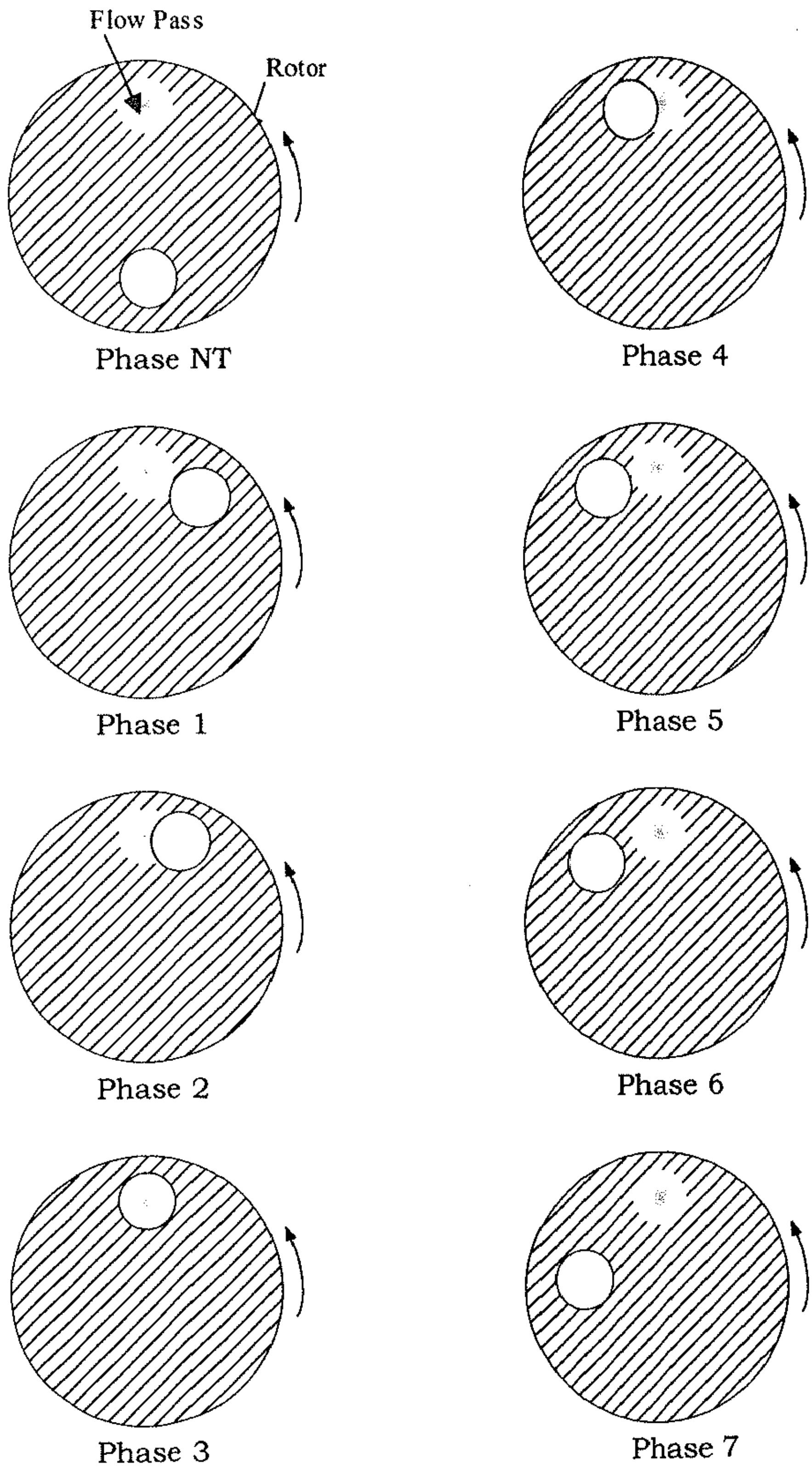
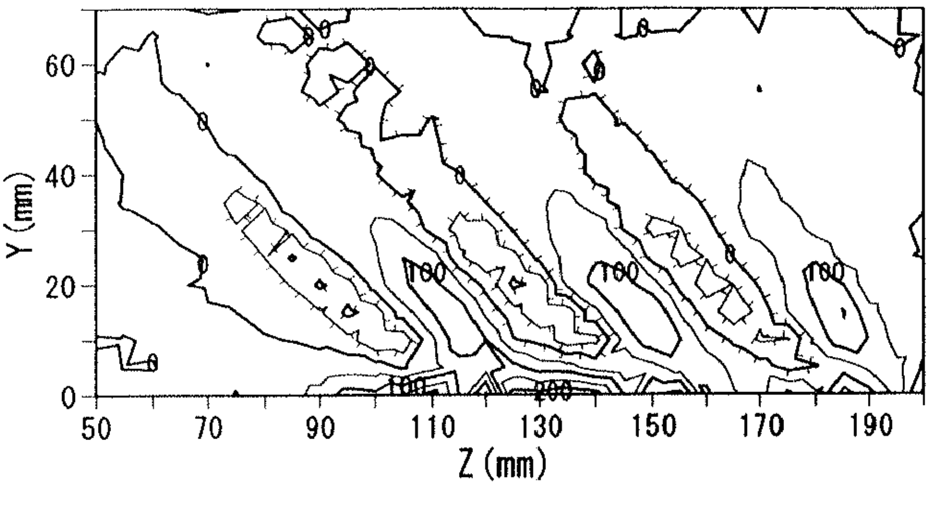
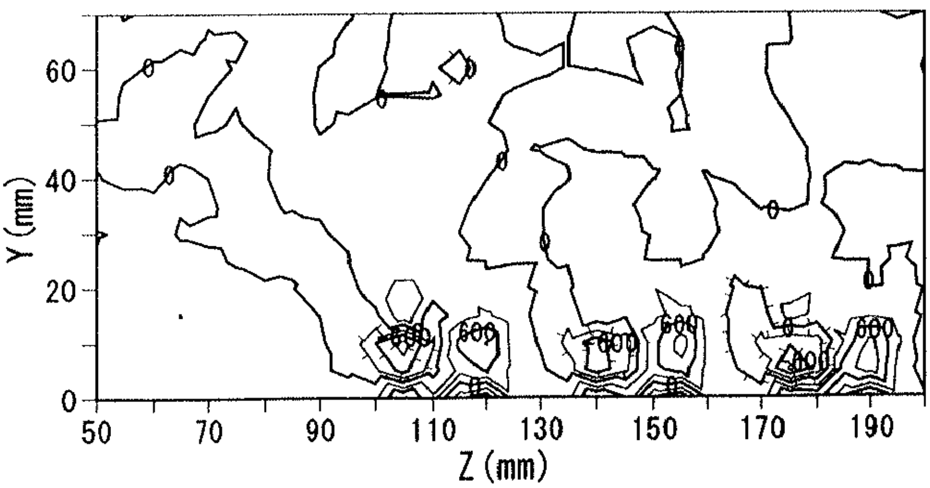


Figure 6.1 Various rotor positions relative to flow pass of secondary air.

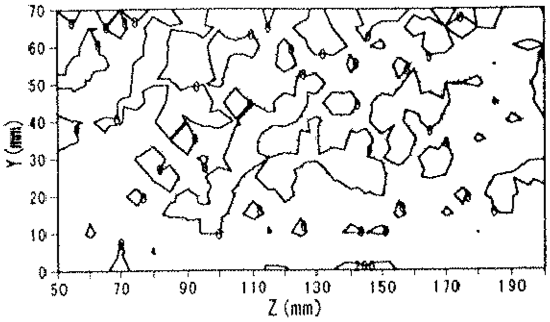


(a) Pulsed jets (VR=5.6, f_p=10 Hz, Contour interval =50 1/s)

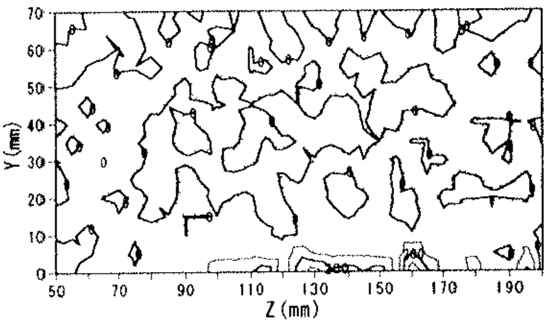


(b) Steady jets (VR=9.5, Contour interval =300 1/s)

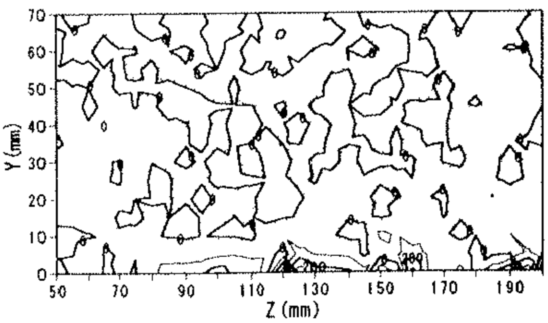
Figure 6.2 Contours of streamwise vorticity at X=10 mm. Decorated lines denote negative vorticity (U_0=6.5 m/s).



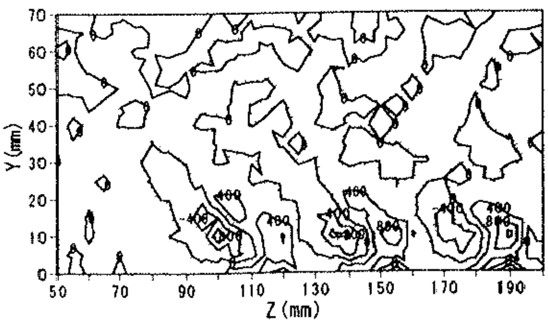
(a) Phase NT



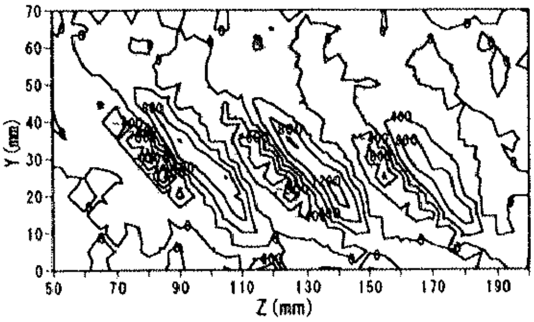
(b) Phase 1



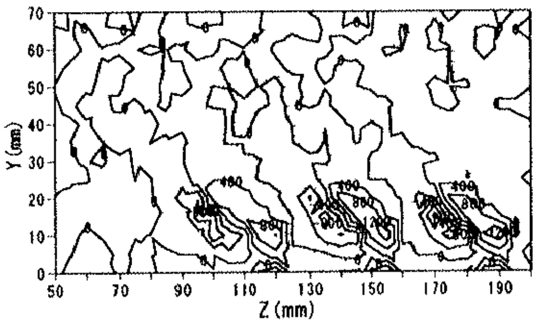
(c) Phase 1a



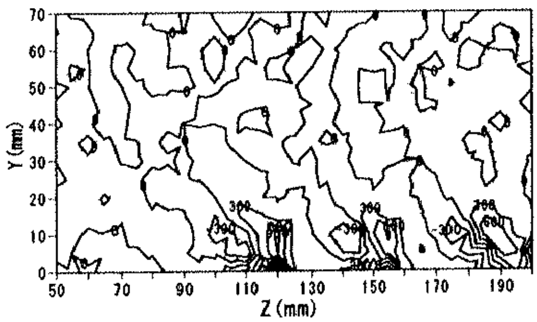
(d) Phase 2



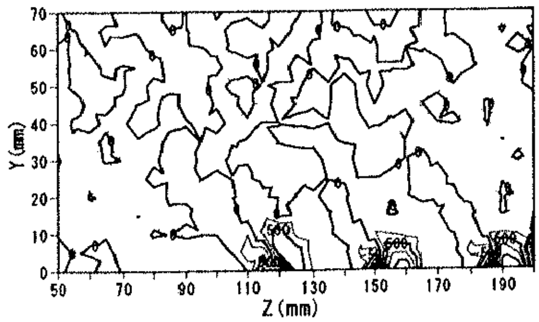
(e) Phase 3



(f) Phase 4



(g) Phase 5



(h) Phase 6

Figure 6.3 Situation of longitudinal vortices in various phases (X=5 mm, U_0=6.5 m/s, VR≒5.6, f_p=10 Hz).

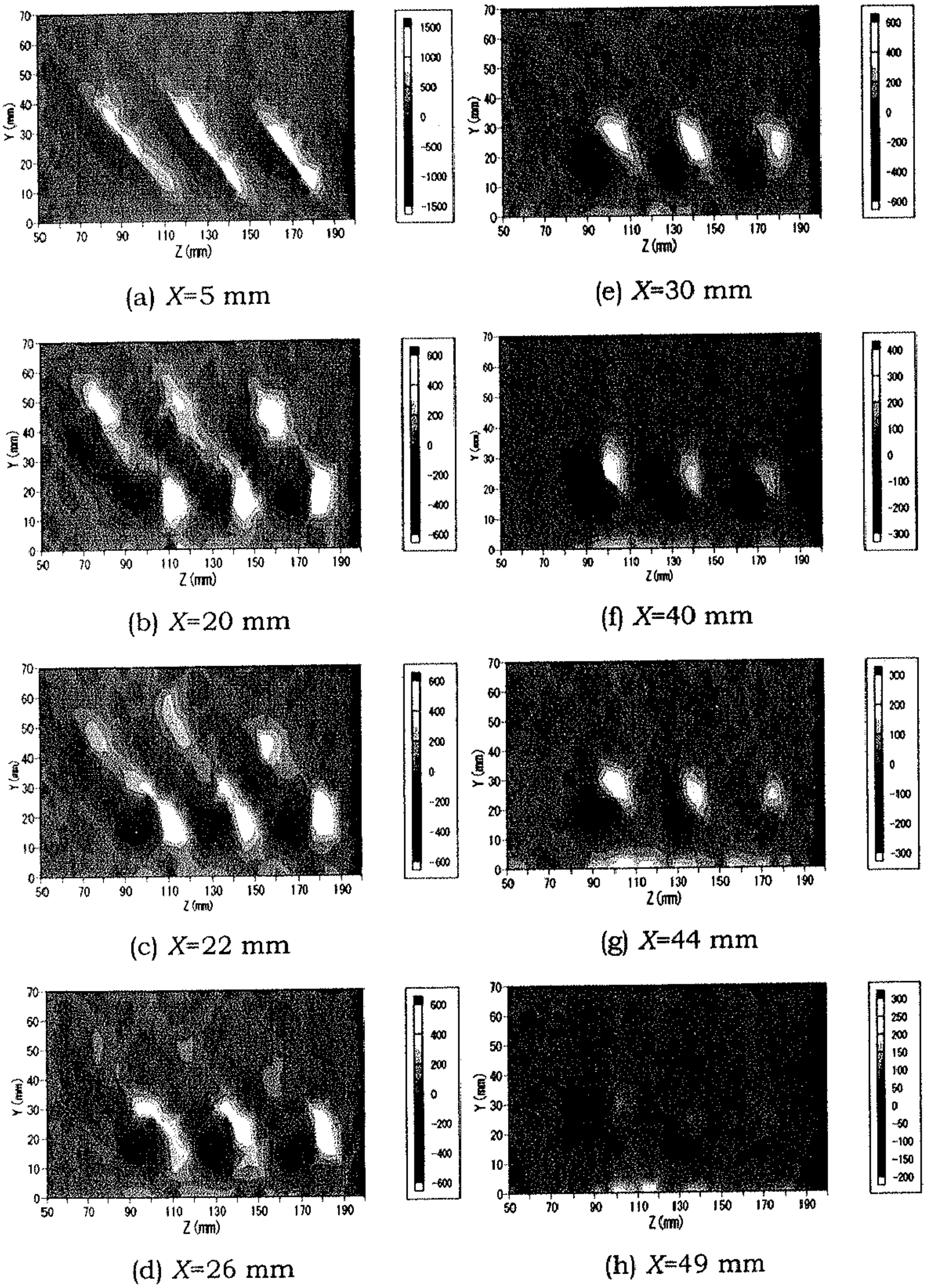
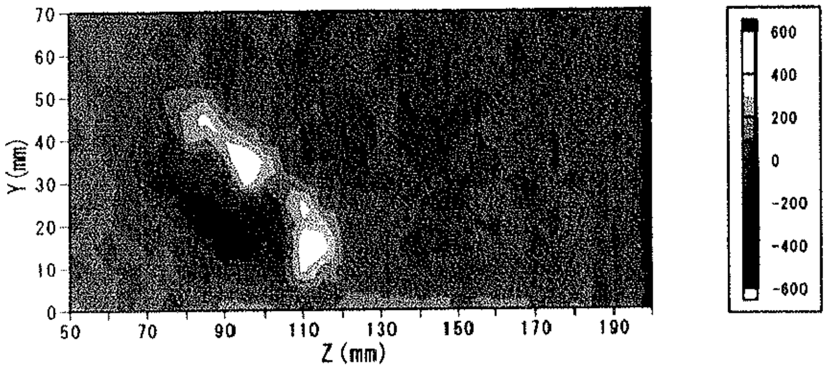
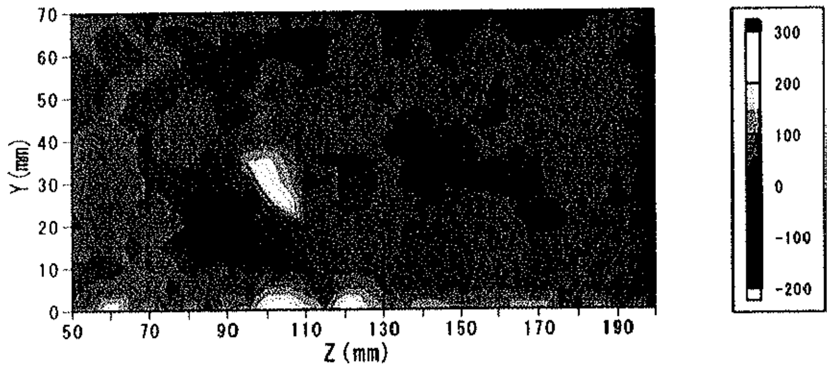


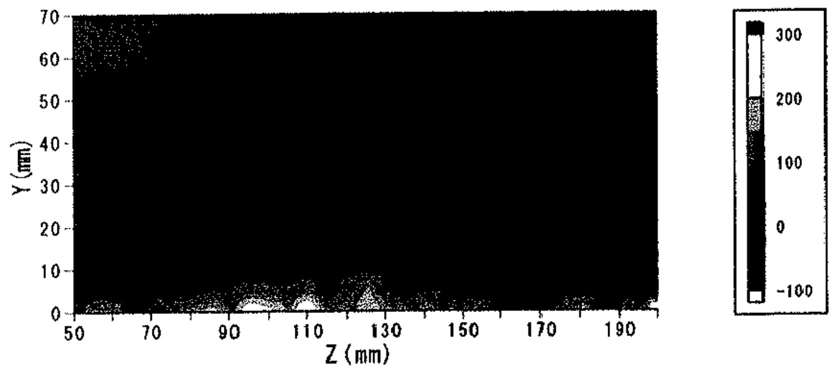
Figure 6.4 Downstream development of longitudinal vortices in phase 3 (U_0=6.5 m/s, VR=5.6, f_p=20 Hz).



(a) X=20 mm



(b) X=40 mm



(c) X=60 mm

Figure 6.5 Downstream development of longitudinal vortices (U_0=6.5 m/s, VR=7, f_p=20 Hz).

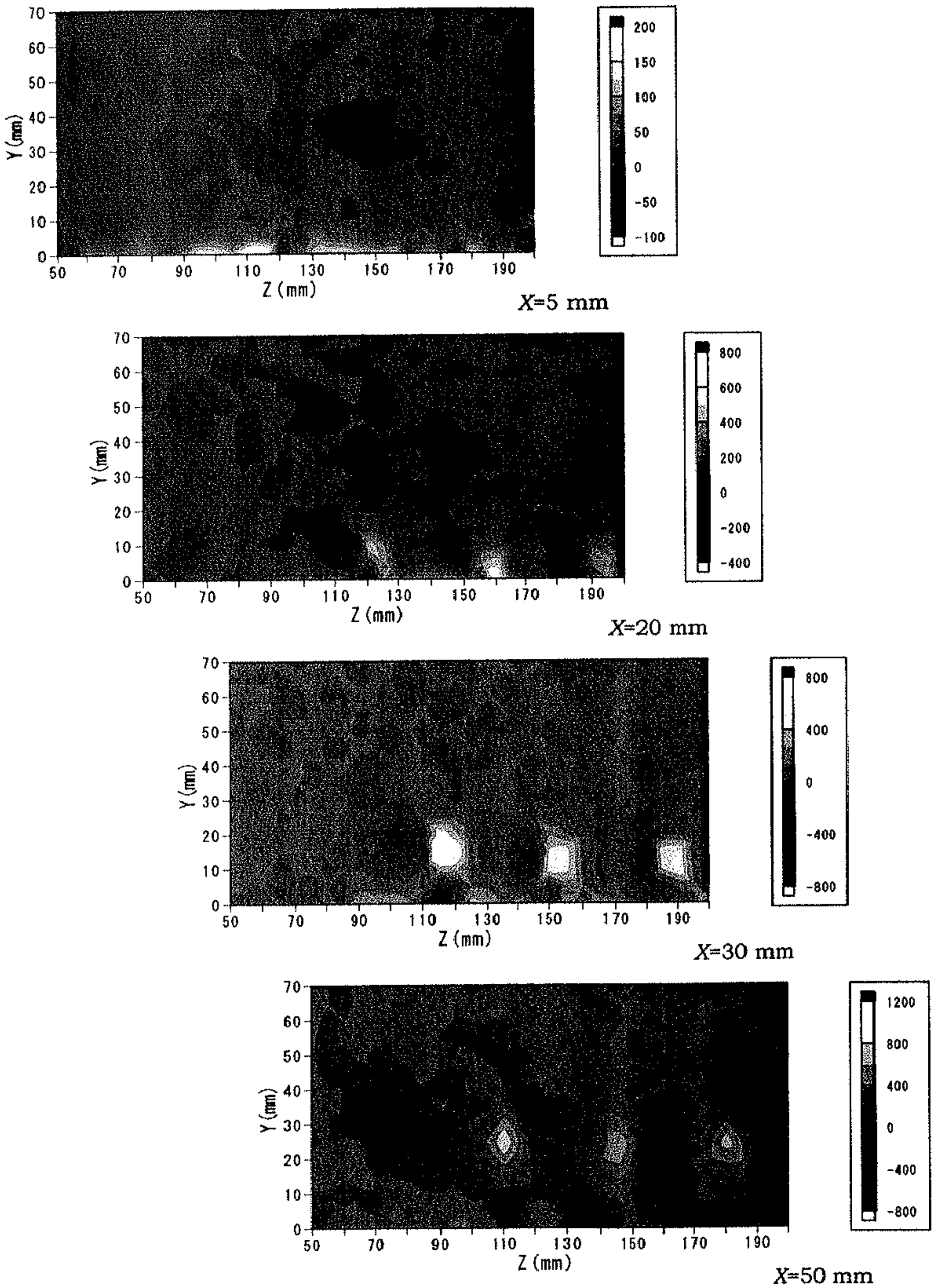


Figure 6.6 Downstream development of longitudinal vortices in phase 7 (U_0=6.5 m/s, VR=5.6, f_p=20 Hz).

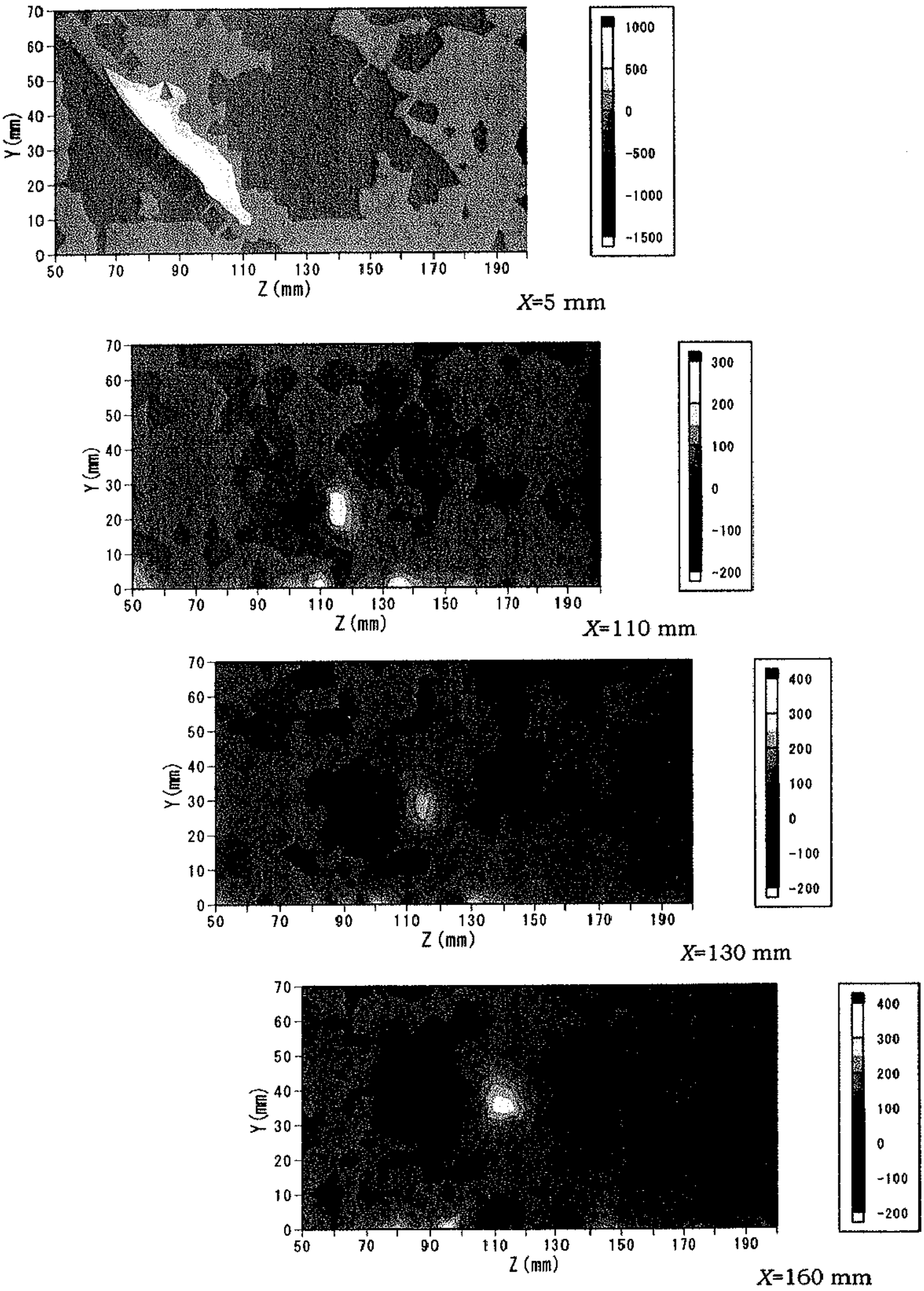


Figure 6.7 Downstream development of longitudinal vortices in phase 3 (U_0=5 m/s, VR=14, f_p=20 Hz).