A VORTEX STRUCTURE OF A TWO-DIMENSIONAL BACKWARD-FACING STEP BY USING ADVANCED MULTI-POINT LDV

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ABSTRACT

Temporal data of instantaneous velocity profile of a two-dimensional backward-facing step flow between separated shear layer and reattachment region are simultaneously obtained by the multi-point LDV. The details of the large-scale vortex structure at the separated shear layer and large-scale fluctuation by spatial and temporal correlation are discussed. As a result, the large-scale eddy passes frequently at whether around y/h=0.5 or vicinity of the step wall because the different two positive peak in the spatial and temporal correlation can be observed. The instantaneous reattachment point is reduced as the vortex at the separated shear layer grows larger. The trigger for the separated shear vortex to grow larger is the reattachment of the separated shear layer. As concerning with spanwise structure, there is large three-dimensional structure in the separated shear layer at downstream of x/h=2. On the other hand, spanwise velocity profile is similar to two-dimensional structure when the separated shear layer reattaches.

1. INTRODUCTION

Experiments have been performed to study the flow structure around the reattachment region behind a two-dimensional backward-facing step with turbulent shear layer. It is well known that this flow field exhibits a three-dimensional structure with a large-scale vortex of separated shear layer (Troutt et al. 1985) and low-frequency motion of separated shear layer involving a fluctuation of an instantaneous reattachment point (Eaton and Johnston, 1980). It was explained by many investigations that the flow structure caused by the transformation of the shear layer vortex governs the fluid dynamic phenomena near the reattachment region.

Eaton and Johnston (1981) summarized two-dimensional backward-facing step flow and concluded that the experiments were needed around the reattachment region and that work was needed to understand the low-frequency motion of the separated shear layer. LDV measurements were conditionally sampled on the basis of instantaneous flow direction near the reattachment region by Driver et al.(1987). They suggested a scenario about low-frequency motion which it results from momentary disorder of the shear layer that alters the rate of reverse flow. Le et al.(1997) showed by DNS method that the fluctuation in the reattachment location was caused by a large-scale roll-up of the shear layer extending to the reattachment region. They showed that the sudden drop of the pressure fluctuation around reattachment region was caused by the passage of the vortex center. About three-dimensional structure, Hijikata et al.(1991) visualized a instantaneous pressure field of the step wall around reattachment region by the holographic method and showed that there are few large-scale eddy around the reattachment region.

However, the experimental data about the unsteady three-dimensional flow structure so little that the large-scale structure of a two-dimensional backward-facing step flow has not been clarified. This was caused by undevelopement of the measuring method by which a spatial and temporal velocity distribution over an unsteady and three-dimensional flow field is measurable. Especially, the spatial velocity profile crosses the dividing stream line between the separated shear layer and the reattachment region is very important to clarify the process of a vortex concentration, of shedding of large-scale vortex and of vortex deformation near the reattachment region including a low-frequency motion.

We have developed the advanced multi-point LDV using a 1-bit FFT approach reported in he previous paper (Hachiga et al. 1998). Instantaneous velocity profile can be measured as temporal data. By using this LDV system, we accumulated the instantaneous velocity profile around the separated shear layer and reattachment region of a two-dimensional backward-facing step. In previous paper (Furuichi et al. 1998), we reported that a behavior of reattachment flow has two patterns and the dividing stream line reattached fast to the step wall. But we didn't discuss the vortex motion of the separated shear layer and the arge-scale three-dimensional structure.

In this paper, we measured simultaneously velocity profiles of both separated shear layer and reattachment region by using two multi-point LDV systems and to try clarify the correlation between the separated shear layer and reattachment region. In addition, the spanwise velocity profile is measured at the separated shear layer and reattachment region to clarify the three dimensional structure. The spatial structure of a two-dimensional backward-facing step is also discussed.

2. EXPERIMENTAL APPARATUS

2.1 Multi-Point LDV System

The optical system of the advanced multi-point LDV is shown in Fig.1 in detail. The LDV system which was reported in the previous paper (Hachiga et al., 1998), was improved so that this LDV senses the reverse flow by double Brugg cell system to measure the backward-facing step flow. This LDV is made very compact using semiconductor laser with a maximum power of 40mW and a wavelength of 685nm, and optical fiber unit with 96 plastic fibers with a diameter of ϕ 0.25mm. Two Brugg cells are used to introduce the frequency shifts of 80MHz and 79.9MHz. Therefore the Doppler burst signal is shifted to 0.1MHz.

The hardware system was modified so that 32-point scattered light signal could be measured simultaneously. A scattered light signal is converted into an individual Doppler burst signal by Si-APD. This signal is digitized to one bit using a comparator. The sampling frequency of a raw one-bit data is 250KHz, and the sampling interval of the velocity data is 1.024ms according to frequency analysis by FFT of 256 points. Therefore, the data sampling rate is about 976/s.

The data processing is similar to what formed in the previous paper (Hachiga et al., 1998, Furuichi et. al, 1998). In present study, when a value was miss signal, the value was estimated by interpolation using the spatially and temporally adjacent data. The rate of capture for temporal velocity data in all experimental data is over 70%. When there was a lack of data for 3mm or 12msec continuous, the data was not used because the micro scale eddy is undetectable.

Two LDV systems were constructed to measure the velocity distributions of different locations simultaneously ; at the separated shear layer and the reattachment region, as shown in Fig.2. The minimum distance of each location is $3h$. The temporal velocity of 16-point was measured by one LDV system. The spatial resolution of each point set up in the x-z plate is 0.22×1.40mm which was decided by the cross angle of the laser light sheet, and the one in the y direction is ϕ

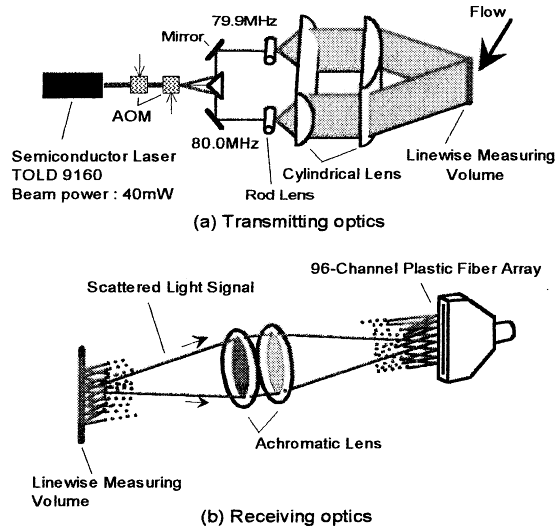


Figure 1. Multi-point LDV system

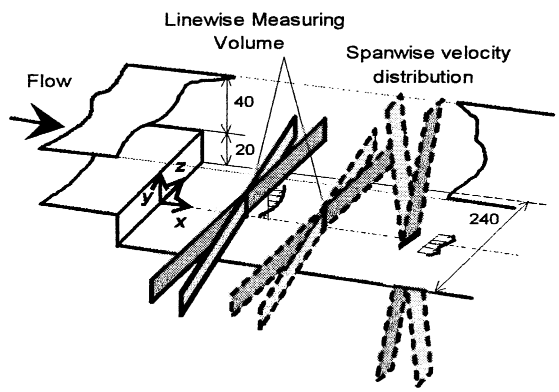


Figure 2. Experimental apparatus

0.24mm, which corresponds to the core diameter of the receiving optical fiber. The distance between adjacent measuring points is 1.25mm. On the other hand, to measure spanwise velocity profile, a laser beam is inserted from the bottom side and the scattered beam is received on the top side. In this case, the spatial resolution of each point set up in the x-z plate is 0.22×0.24mm and in the y direction is 0.8mm. As for seeding, polystyrene particles of 5 μ m in mean diameter were used as the tracer particles for measurement of velocity.

2.2 Backward-Facing Step

The flow field and coordinate system are shown in Fig.2 with LDV set up. The closed-loop water channel used in this experiment has a working section of 240×60mm in cross-sectional area and 2300mm in length. The backward-facing step (with a step height h of 20mm) was formed below the floor plate at a point 250mm downstream from the construction nozzle exit. The expansion ratio is ER=1.5, and the aspect ratio AR=12. The main flow velocity is fixed at

Uc=0.25m/s in all experiments (Re_h=5000). The turbulence intensity of the main flow is Tu=0.6%. The distribution of u-component mean velocity upstream of the step is in agreement with the Blasius theory. The boundary thickness upstream of the step is about 4.6mm. Time-averaged velocity distribution behind a step is in good agreement with the other previous studies (Kasagi and Matsunaga, 1995). The time-averaged reattachment length, determined by the fraction of forward flow at y/h=0.05, is x_R=6.0 in this experimental apparatus.

3. RESULT AND DISCUSSION

3.1 Simultaneous Measurement

A typical gradation maps of velocity distributions of separated shear layer and reattachment region, being measured simultaneously are shown in Fig.4. The measuring locations are x/h=3 and x/h=6 respectively. The measuring point at the bottom in both figures is obtained at y/h=0.05 and the top at y/h=0.94. The measuring width is 18.75mm. The time progresses from left to right. It can be observed that the concentration of a separated shear vortex occurs at x/h=3 and that reattachment of shear layer and shear vortex occurs in the reattachment region as reported in a previous paper. A typical correlation between separated shear layer and reattachment phenomena is not observed only by these instantaneous velocity profile.

To clarify the mechanism of reattachment, time and spatial correlation between separated shear layer and reattachment region are calculated. The contour maps of the value R_{uu} of correlation are shown in Fig.5. The figures (a) and (b) represent the contour map between x/h=3 and x/h=6 , x/h=3 and x/h=6.5 respectively. The step of contour sets 0.02. The fix region for calculation the correlation value R_{uu} is y/h=0.7-1.0 at x/h=3. The moving region is whole region at x/h=6. The horizontal axis means the dimensionless lag time and the vertical axis means the center position at x/h=6.

It can be observed that there are high correlation areas where the dimensionless lag time is tUc/h=5-6 in figure (a) and tUc/h=7.5 in (b). Therefore, the traveling velocity of the large-scale eddy is about 0.125m/s which is a half velocity of the main flow. This result is in good agreement with the result of Hijikata et al.(1991).

If one looks at the figure more in detail, there are different two positive peaks which indicate high correlation value at tUc/h=5-8 (about 0.4-0.64sec). This correlation map means that the large-scale eddy of the separated shear layer passes frequently around y/h=0.5 or vicinity of the step wall. Each peaks exists separately. It means that the position where the eddy passes moves fast between two regions. The behavior of the eddy corresponds to the dividing stream line as reported in the previous paper. The peak at the vicinity of the step wall indicates that the separated shear layer reattaches there.

On the other hand, there is no typical peak in the contour map of correlation between x/h=3 and x/h=6.5. Especially, the lower side peak detected in (a) disappears in spite of only a few downstream of x/h=6. It is suggested that the eddy is largely deformed caused by reattachment. It may be estimated that the reattachment phenomena will not occur at downstream of the time-averaged reattachment point.

There is always a possibility that the property of the instantaneous structure of reattachment phenomena is hiden in he long time correlation. Because as mentioned the above paragraph, the eddy passes through two regions, it is necessary to observe the condition where the eddy passes in order to clarify the instantaneous structure.

The temporal position of the maximum correlation R_{uu} is shown in Fig.6 that corresponds to Fig.4. To clarify the instantaneous structure, the reference time of separated shear layer is set at tUc/h=3; is the period of the vortex shedding. If the position of the maximum correlation si defined as the region where the eddy passes thorough, its position moves fast. There is a tendency that the time when the maximum correlation exists in lower side is when the separated shear layer reattaches as that can observe in Fig.4. Therefore the eddy passes at the vicinity of the step wall when it reattaches. It passes away over around y/h=0.5 at other time.

The integral length scale sampled conditionally is shown in

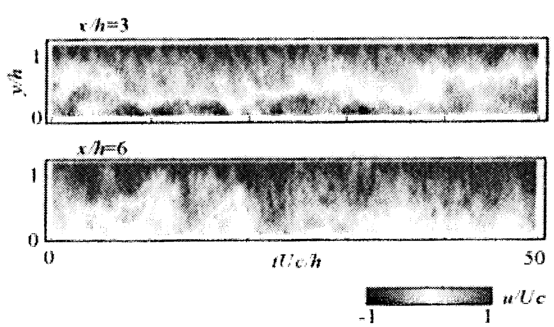


Figure 4. Contour maps which measured simultaneous at x/h=3 and x/h=6

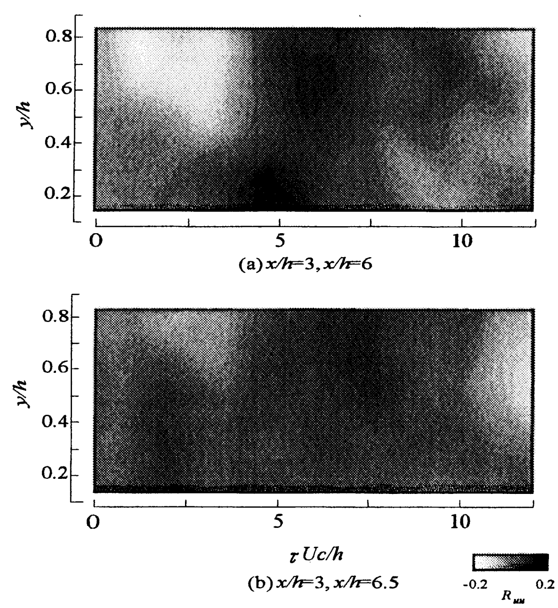


Figure 5. Time and spatial correlation map of two line measurement

Fig.7. Black dot shows that the maximum correlation exists in y/h<0.4, and white dot y/h>0.4. This value 0.4 correspond to the saddle of two peaks which shown in a long time correlation map in Fig5. The dotted line shows the integral length scale unconditionally calculated at each stereamwise location.

It can be seen that the when the maximum point appear at the vicinity of the step wall, the integral scale of separated shear layer is longer. When it appears upper side and unconditional sampled, the integral scale is shorter. It is suggested that the growth rate of the separated shear layer vortex is closely related to reattachment. Therefore the separated shear vortex which grows larger makes the reattachment length reduced. This result is in good agreement with Roos and Kegelman (1985) that the greater mixing and entrainment of the excited shear layer by oscillating flap at the separation point result reduced the time-averaged reattachment length.

Mean velocity distribution and turbulent intensity conditionally sampled are shown in Fig.8. The turbulent intensity obtained when the maximum correlation appears at vicinity of the step wall is larger than the obtained when it appears at around the y/h=0.5. In this result, it is also suggested that the separated vortex grows larger when reattaches. Mean velocity is almost similar in both cases in separated shear layer. In recirculation zone, however, the reverse flow of the case of vicinity is smaller than the case of around y/h=0.5. This means that the entrainment increases caused by vortex generation and reverse flow decreases in the recirculation zone which was indicated by Eaton and Johnston(1980).

As summarized mentioned above, the separated shear layer reattaches upstream of the time-averaged reattachment point because of the lager growing vortex of separated shear layer. So the instantaneous reattachment point moves toward upstream fast and eventually the recirculation bubble contracts, in appearance.

It is well known that a turbulent intensity in the recirculation zone of a separated shear flow is larger than plane-mixing layer. Castro and Bradshaw(1976) suggested that the turbulence does a "positive feedback" into a recirculation zone. The result of cross-correlation which is estimated between reattachment region x/h=6 and separated shear layer x/h=3 is shown in Fig.9(a). The fix point is chosen near the step wall at x/h=6 and moving point is in recirculation zone at x/h=3. The typical 3 points is shown in the figure are obtained at y/h=0.03,0.46,0.78. The horizontal axis is the lag time.

As a whole, there is a typical peak at tUc/h=17. This means that the fluctuation caused by reattachment moves toward upstream because of the reverse flow in the recirculation zone. Especially, the lower side at the separated shear layer (y/h=0.78) has higher correlation than other location, it is suggested that a fluctuation by reattachment gives an influence on the separated shear layer. As mentioned above, it has been found that, when a separated shear vortex grows large, a velocity of reverse flow is slower. Therefore, this fluctuation by reattachment of a separated shear layer is the very trigger of the growth of the separated shear vortex.

The result of cross-correlation estimated between reattachment region x/h=6,6.5 and separated shear layer

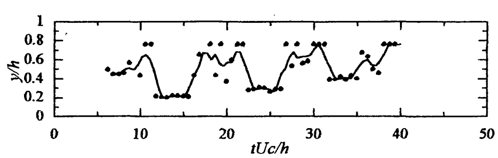


Figure 6. Position of maximum correlation R_{uu}

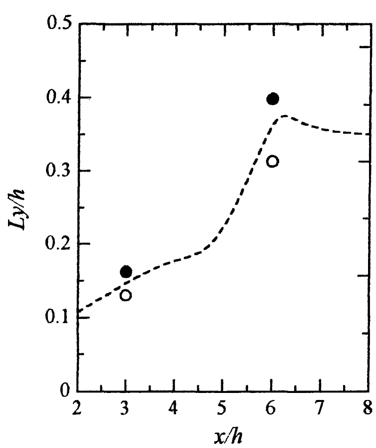
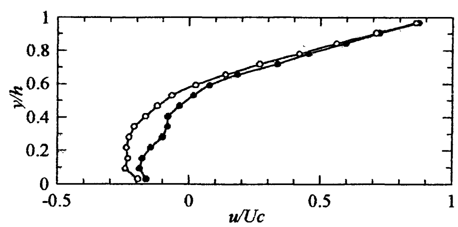


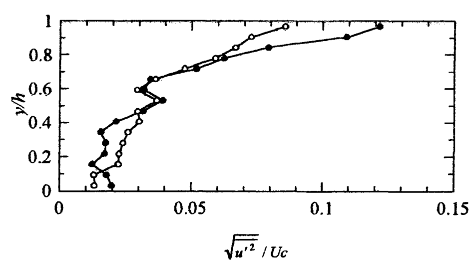
Figure 7. Integral length scale

The position of maximum location R_{uu} is ●:y/h<4,○:y/h>4.

The dotted line means unconditional sampled.



(a) Mean velocity profiles



$\sqrt{u'^2}\,/\,Uc$

(b) Turbulent intensity profiles

Figure 8. Mean velocity profile and turbulent intensity of conditioning sampled

The position of maximum location R_{uu} is ●:y/h<4,○:y/h>4.

x/h=2,3 are shown in Fig.9(b). Between x/h=3 and x/h=6 there is a typical peak at the vicinity of the wall. Although it is suggested that there is a high correlation between x/h=2 and x/h=6, there is no typical peak. This means that a turbulence caused by reattachment influences on the separated shear layer only at around x/h=3. On the other hand, between x/h=3 and x/h=6.5, there is typical peak around tUc/h=15. The lag time is shorter than x/h=6. It is suggested that there is high correlation between the fluctuation after reattachment and separated shear layer because the traveling time from x/h=6 to x/h=6.5 is 2 in dimensionless time.

The time when the separated shear vortex moves from x/h=3 to x/h=6 is 5 in dimensionless time. The fluctuation of reattachment move to separated shear layer is 17 in dimensionless time. Furthermore, the time from x/h=3 to x/h=6.5 is 7 and the time from x/h=3 to x/h=6 is 15. The summation is tUc/h=22 (1.76msec) between the separated shear layer and the reattachment region. This large-scale fluctuation is fh/Uc=0.045 (0.57Hz) which is related to the frequency of reattachment of the separated shear layer. This frequency are less similar to the previous study (eg. Eaton and Jofnston, 1980), that the large-scale fluctuation is caused by a series of fluid motion mentioned above.

3.2 Three-dimensional Structure

Instantaneous velocity profiles of typical locations from separated shear layer and reattachment region are shown in Fig.10. The horizontal axis shows spanwise location.

After separation, there is a periodical structure as like as a stripe of vortex concentration. This frequency is about 4Hz which is detected upstream x/h=2. The stripe structure looks inclined at x/h=2. This is caused by the rolling with concentration. The measuring width is relatively narrow in this experiment. Therefore, it can not be clarified whether this structure is uniform to spanwise direction. The intervals of stripes become irregular downstream of x/h=3. This indicates that the periodical motion disappear as the vortex concentration progresses. More downstream, a two-dimensional structure like structure is observed. This is reflected by the fact that there is a two-dimensional structure in the main flow because the separated shear layer approaches to the step wall in these region that has reported in previous paper.

The fluid motion at the vicinity of the step wall is not

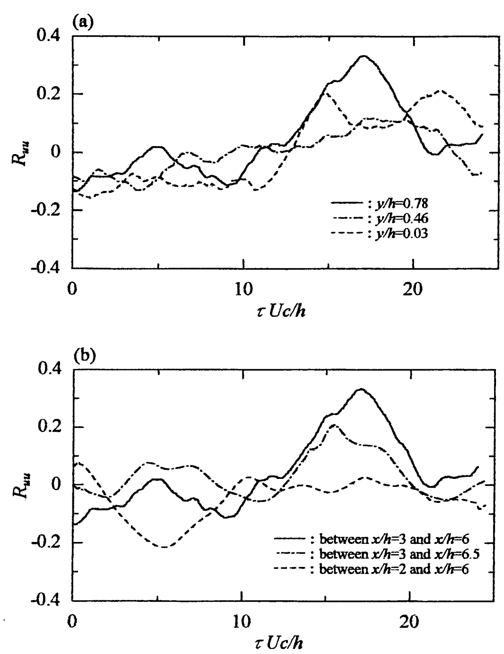


Figure 9. Cross-correlation between reattachment region and recirculation zone

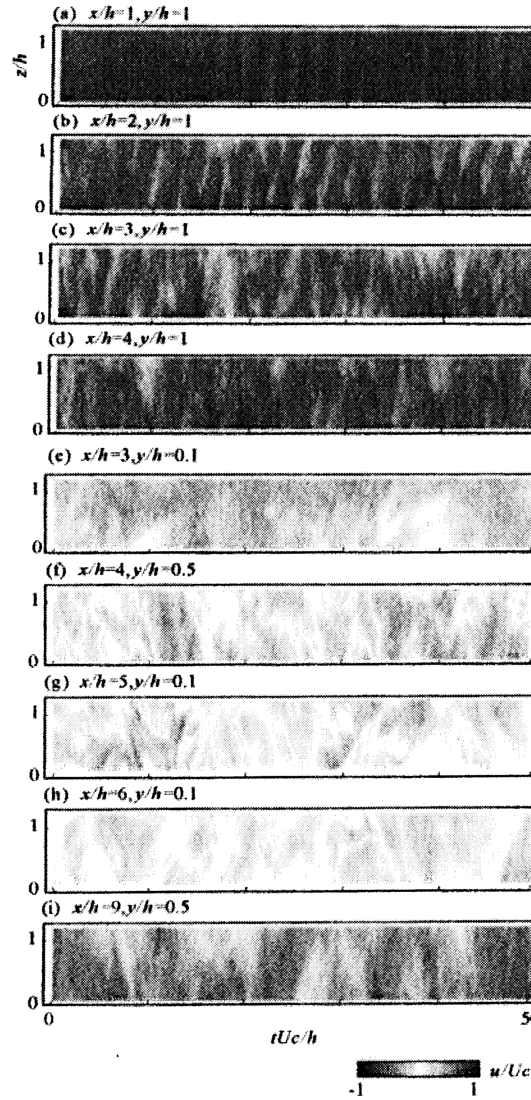


Figure 10. Contour maps of spanwise instantaneous velocity at each streamwise location

uniform to spanwise direction because of the three-dimensional structure of the separated shear vortex. If it is defined the boundary region between forward and reverse flow as the instantaneous reattachment point (however measuring point is a little far from the step wall), it is not uniform to spanwise direction. The angle of inclined is not uniform, which is different from the feature seen in the separated shear layer. It turns over irregularly. This fluid motion is not observed at x/h=6. As the flow proceeds downstream of a reattachment region, still three-dimensional structure, but stripe structure is detected over measuring line, almost become two-dimensional structure.

Two type velocity profiles measured simultaneous at x/h=6 are shown in Fig.11. The upper side figure is u-component velocity as similar Fig.3. The lower side graph is spanwise profile of u-component velocity. The arrow means each measuring point. A velocity at the vicinity of the step wall increases when a separated shear reattaches. It can be seen tUc/h=10 and 40 in this figure. At that time, spanwise velocity profile is like to a two-dimensional structure relatively. Other time, a boundary region between a forward flow and reverse flow is complex and velocity is very slow or stagnated. Therefore it is suggested that the reattachment phenomena is large-scale structure.

4.CONCLUSION

Temporal data of instantaneous velocity profile of a two-dimensional backward-facing step flow between separated shear layer and reattachment region are simultaneously obtained by the multi-point LDV. The details of the large-scale vortex structure at the separated shear layer and large-scale fluctuation by spatial and temporal correlation are discussed.

As a result, the large-scale eddy passes frequently at whether around y/h=0.5 or vicinity of the step wall because the different two positive peak in the spatial and temporal correlation can be observed. By using two peak position, conditional average of the separated shear layer is calculated. The instantaneous reattachment point is reduced as the vortex at the separated shear layer grows larger. The trigger for the separated shear vortex to grow larger is the reattachment of the separated shear layer.

As concerning with spanwise structure, there is large three-dimensional structure in the separated shear layer at downstream of x/h=2. On the other hand, spanwise velocity profile is similar to two-dimensional structure when the separated shear layer reattaches.

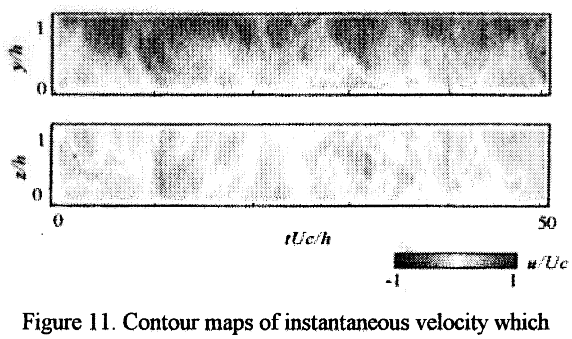


Figure 11. Contour maps of instantaneous velocity which measured simultaneous at x/h=6

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