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Spanwise Structure around a Reattachment Region of a Two-dimensional Backward-Facing Step Flow

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1. INTRODUCTION

Many experiments have been performed to study around a separated shear layer and a reattachment region of a two-dimensional backward-facing step flow. A two-dimensionally flow field to streamwise direction is usually assumed to analyze flow structure, on the other hand, it is well known that this flow field exhibits a three-dimensional vortex structure and low-frequency fluctuation around a reattachment region such as many previous investigation were reported. Kasagi et al.[1] showed a three-dimensional vortex-like structure in the scale of the step height around reattachment region by the smoke-wire visualization method. Neto et al.[2] and Le et al.[3] visualized the three-dimensional vortex that has strong longitudinal vorticity in streamwise direction by numerical experiments. Hijikata et al.[4] visualized a instantaneous pressure field of the step wall by the holographic method and showed that there are some large-scale eddy around the reattachment region. However, the results of visualized vortex structure were only shown in these investigations and it was not clarified enough the three-dimensional structure in quantitative. Especially, it is suggested that the flow structure such as a low-frequency fluctuation around a separated shear layer and a reattachment region is governed by the deformation of the separated shear vortex, however there is less report about this mechanism.

It is difficult to clarify that three-dimensional structure around a reattachment region because there is not a measuring method that can be measured three-dimensional velocity component over a flow field. However, such as Kasagi et al.[5] indicated that the velocity fluctuation of *w*-component becomes greatest of the three-component near the step wall around the reattachment region using PTV method, it is necessary that *w*-component velocity is measured over a reattachment region to clarify the three-dimensional structure. In this investigation, we measure instantaneous velocity profile of spanwise direction by UVP and discussed spanwise structure and large-scale fluctuation around a reattachment region of a two-dimensional backward-facing step flow.

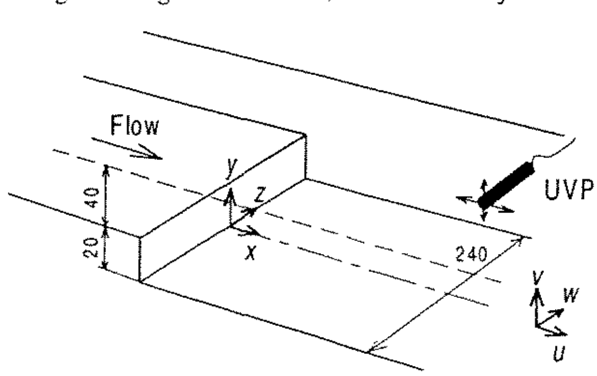

Figure 1. Experimental apparatus and coordinate system

2.EXPERIMENTAL APPARATUS

The flow field and coordinate system are shown in Fig.1. The closed-loop water channel has working section of 240x60mm in cross sectional area

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and 2300mm length. The backward-facing step (with a step height of 20mm) was formed below the floor plate at a point 250mm downstream from the construction nozzle exit. The expansion rate is ER=1.5 and the aspect ratio is AR=12. The mean velocity of main flow is fixed at Uc=0.25m/s in all experiment (Re_h=5000). The turbulence intensity of the main flow is Tu=0.6%. The mean velocity distribution of u-component 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 of u-component behind a step at z=0 is in good agreement with other previous studies (Kasagi et al.[5]). The time averaged reattachment length, determined by the fraction of forward flow at y/h=0.05 is x_R=6.0 in this experiment apparatus. The mean velocity distribution of u-component and reattachment length is almost same over a channel in spanwise direction. These results were obtained by using LDV system[6].

The transducer of UVP was set the outside wall of the test section to measure spanwise w-component velocity profile. The distance of each measuring point is 1.48mm. The measuring interval is 44msec.

3.RESURLTS AND DISCUSSION

The contour map of mean w-component velocity at a time-averaged reattachment point is shown in Fig.2. The solid and dotted line means positive and negative flow direction, respectively. The positive velocity means that the flow direction is right and negative means left in this figure. It can be observed that the flow structure around reattachment region is different with one of y/h>0.4. Especially, vicinity of the step wall, there is a typical flow pattern that a flow of positive and one of negative direction exist alternately in this experiment. On the other hand, it can not be observed typical structure at y/h>0.4. A spanwise structure like this figure has not been clarified so that we can not compare this result with other one directly as mentioned above. However reflecting a reattachment phenomena, it is suggested that there is a strongly three-dimensional structure exists around reattachment region.

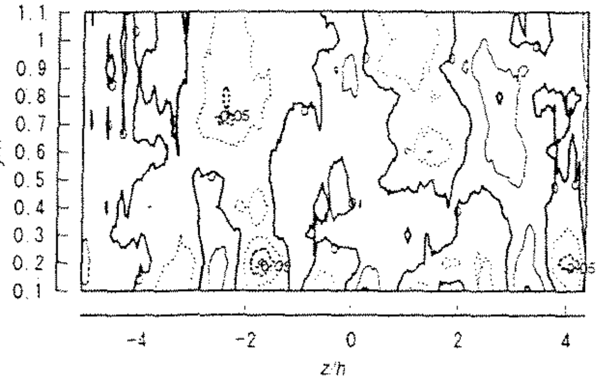

Figure 2. Mean velocity distribution of spanwise component in vertical plate at x/h=6

Typical gradation map of instantaneous velocity which measuring region is at x/h=6, y/h=0.1 is shown in Fig.3. The white color means negative (flow upward in this figure) and black means positive (downward). The horizontal axis means dimensionless time. As shown in this figure, a behavior of instantaneous w-component velocity is very complex such as it can be observed that a flow direction frequently changes in same region and that some longitudinal structure exist around tUc/h=75. It is also seemed that a lump of different flow direction forms like staggered rows. Hijikata et al.[4] showed these structure around the reattachment region in the pressure field and they indicated the these lumps are generated by the roll up of the spanwise voticies. To show this structure in quantitative, a map of two-point correlation is shown in Fig. 4. The vertical axis means a lag time and the fixed point is z/h=1.0. It can be observed a staggered-like structure and especially, a property of these structure is more clear at upward side of the fixed point (z/h>1.0) than downward. In this region, a correlation

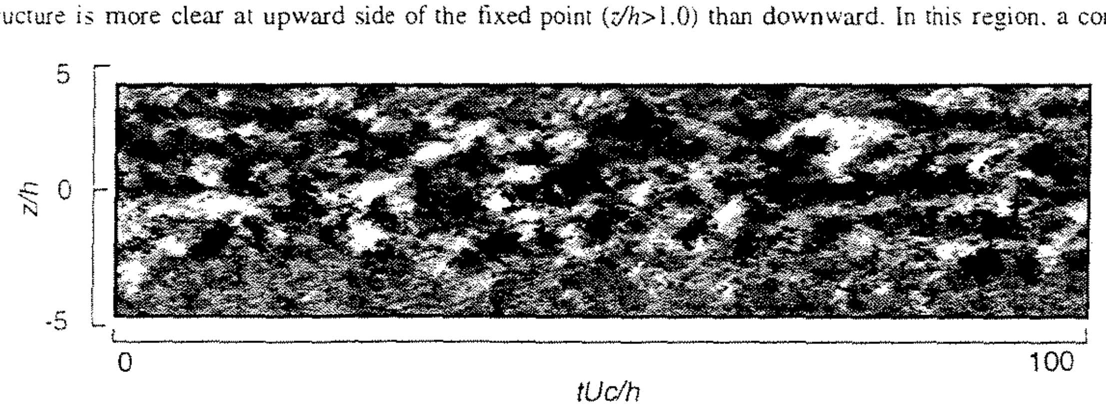

Figure 3. Time series representation of the spanwise component of instantaneous velocity at x/h=6, y/h=0.1

coefficient is negative around z/h=2 or lag-time is zero. It is suggested that the each flow direction of these region is opposite one reflecting a reattachment phenomena. No periodical structure exists at the fixed point because a flow field is unsteady, however it can be observed some islands at about tUc/h=4-5 which corresponds to the frequency of vortex generation at separated shear layer. Thus, it is suggested that the flow direction of spanwise around a reattachment region change alternately like a staggered structure.

The streamwise variation of an integral length scale is shown in Fig.5. Upstream of a reattachment region, the showing point is on the dividing stream line and downstream is the vicinity of the step wall. The integral scale increases forward to a reattachment region at a separated shear layer and it slightly increases downstream of reattachment region. Especially, it is noted that integral scale does not change drastically near the step wall at reattachment region. To pay an attention to the spanwise structure of a reattachment region, spanwise variation of integral scale at x/h=6 is shown in the Fig.6. The distribution of correlation coefficient around a fixed point is different between positive and negative side in spanwise direction so that each side integral scale is shown separately. The solid line means positive side and the dotted line negative side integral scale. An integral scale is not uniform in spanwise location and one of each direction shows a peak alternately. As suggested in the Fig.4, there is some lumps around a reattachment region.

There is a possibility that the operation of the long time correlation eliminates the property of the instantaneous structure. In Fig.7, the temporal variation of the correlation coefficient is shown to consider the instantaneous structure around reattachment region. The time period for the reference is 1.8sec (fh/Uc=0.045) that means the frequency of the large-scale structure of the separated shear layer such as flapping[7]. The reference point is at z/h=-1.2 and calculating point is z/h=-1.8 (the solid line) and z/h=0.3 and -0.5 (the dotted line). These points are the peaks in Fig.6. The horizontal axis means the lag-time and vertical axis means the correlation coefficient. It can be observed the large-scale fluctuation periodically that frequency is about fh/Uc=0.01 in dimensionless time and more small fluctuation that considered a flapping is fh/Uc=0.1. A frequency of large-scale fluctuation is larger than that of flapping. This fluctuation of correlation coefficient means that the instantaneous flow direction change alternately same or opposite between reference point and calculating one. As shown in figure, the solid line and the dotted are 180 out-of-phase so that this fluctuation exists over a reattachment region. To more clear this mechanism, we calculated the power spectrum of the velocity fluctuation. Reflecting many scale fluctuations, it can be observed many peaks of the power spectrum over the flow field, however we paid attention to the low frequency around

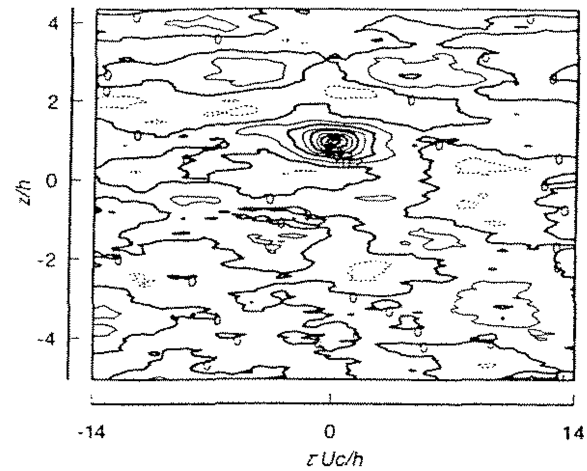

Figure 4. Contour map of two-point correlation at x/h=6, y/h=0.1

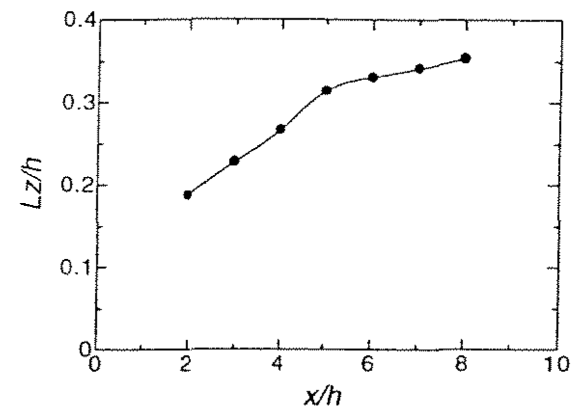

Figure 5. Streamwise variation of integral scale

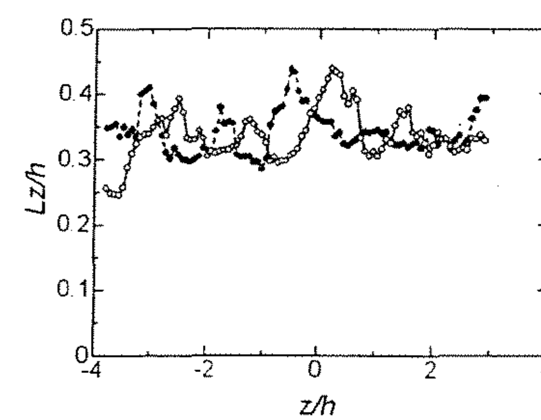

Figure 6. Spanwise variation of integral scale at x/h=6, y/h=0.1

the 0.18Hz. In Fig.6. the spanwise distribution of the power spectrum is shown around 0.18Hz (fh/Uc= 0.01) at x/h=6,7. At x/h=6, several typical peaks can be observed such as indicate by arrows. The position of these peaks is good agreement with the one of the cross point of integral scale in Fig.6. On the other hand. more downstream at x/h=7, typical peak can not be observed. Therefore, it is considered a typical spanwise fluctuation over the flow field at a time-averaged reattachment region.

Around a reattachment region, it is well known that low frequency fluctuation becomes larger than at the separated shear layer. Kondo et al.[8] showed the fluctuation of pressure field around reattachment region and they indicated that there was a large scale fluctuation which frequency is about fh/Uc=0.01. Eaton and Johnston[9] also indicated that 30% energy of the u-component velocity exists fh/Uc<0.1. It has not been clarified that a large scale fluctuation of spanwise velocity component in quantitative in previous study. however in our experiment, low frequency fluctuation around a reattachment region becomes larger than that at the separated shear layer same as one of u-component velocity. Especially the component of fh/Uc=0.015 shows a typical behavior. These phenomena can be observed clearly only the vicinity of the step wall around a time-averaged reattachment point. It is suggested that this large scale fluctuation is concerned to the one of instantaneous reattachment point over a channel and it might contribute largely to w-component fluctuation.

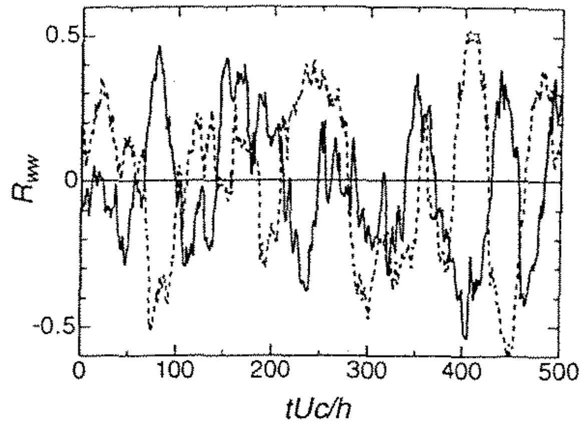

Figure 7. Temporal variation of the two-point correlation coefficient between z/h=-1.2 and z/h=-1.8 (solid line), z/h=0.3 and z/h=-0.5 (dotted line)

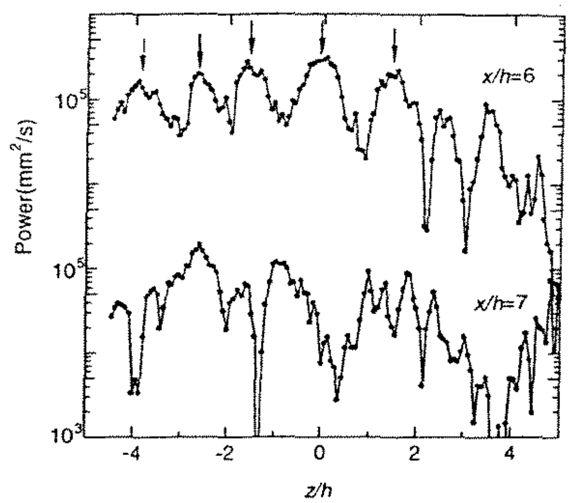

Figure 8. Spanwise variation of power spectrum of the fh/Uc=0.015.

4.CONCLUSION

A spanwise structure of a two-dimensional backward-facing step flow around a reattachment region is clarified by using UVP. As a result, around reattachment region, it is found that the spanwise structure is not uniform to spanwise direction and there is some lump that is staggered-like structure vicinity of the step wall. A fluctuation of the w-component velocity around reattachment region is larger in a low-frequency than that of the separated shear layer. Especially the component of fh/Uc=0.015 in dimensionless time shows a typical behavior which fluctuate to spanwise direction over a channel.

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