Large Scale Structure in Periodically Perturbed Turbulent Flow over a Backward-facing Step

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The streamwise evolution of large-scale vortical structures in the periodically perturbed turbulent separated flow were experimentally investigated. Backward-facing step flow was chosen for the test case, where the perturbation was applied from its step edge. The phase averaged flow field showed successive shedding of the vortices due to the 'step instability.' Downstream of the reattachment, this vortical motion disappeared and a new dominant frequency emerged. The mechanism of these phenomena is discussed in this paper.

Key Words: *Turbulent Flow, Shear Flow, Separation, Backward-facing Step, Flow Control, PIV*

1. Introduction

To control separated flow, introduction of the periodic perturbation to the shear layer has been attempted. The common results show that the reattachment length is markedly reduced when the frequency of the imposed perturbation falls in a certain range. In this frequency range, organized large-scale vortical structures are successively introduced into the shear layer[1]. This indicates that the mixing in the separated shear layer is promoted by the perturbation.

According to previous reports[2,3], there exists two respective instability in the separated shear layer, i.e., 'shear layer instability' and 'step instability.' The former one exists in the shear layer immediately behind the step edge and the latter one exists in the reattachment region. Although existence of the large-scale vortical motion has been pointed out by many researchers, the relationship between detailed vortical motion and flow instability is still open issue.

The aim of the present study is to reveal how the vortical structures are generated by the instabilities in this flow field. This paper discusses, as a first step, the evolution of large-scale vortical motion introduced into the shear layer by the applied periodic perturbation.

2. Experiments

The experiments were conducted in the periodically perturbed turbulent flow over a backward-facing step located in a closed water system[1]. Periodic perturbation was applied from the spanwise slit, 1mm wide, as alternative injection and suction. Reynolds number Re based on the center velocity at the inlet channel U_c and step height H was set constant to 3700. The normalized perturbation frequency $St_f = f_e H/U_c$ was fixed to St=0.19, where f_e being the perturbation frequency. This frequency was the most effective frequency for the reattachment promotion. An in-house-made two dimensional particle image velocimeter[1] was employed for the flow-field measurement.

3. Results and discussion

Figure 1 shows the phase averaged distribution of the spanwise vorticity synchronized with the perturbation cycle. Two solid lines and a dashed line in each figure

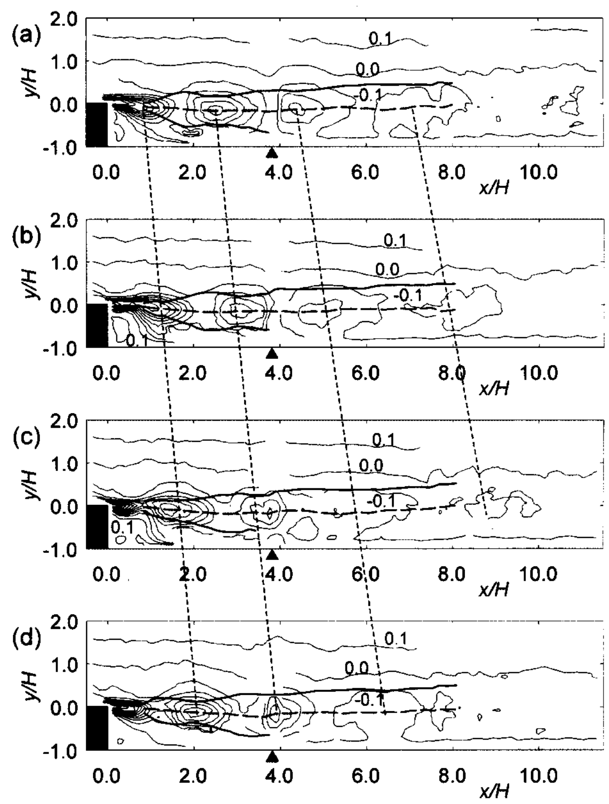

Figure 1. Phase averaged spanwise vorticity, $\langle \omega_z \rangle$.
(a) ϕ=0, (b) $\phi=\pi/2$, maximum injection phase, (c) $\phi=\pi$, (d) $\phi=3\pi/2$, maximum suction phase.

denote the top and bottom edge of the shear layer and locus of the inflection point in the velocity distribution, respectively. It is clearly observed that the large-scale vortical structures are successively shed and move to downstream with the streamwise evolution of separated shear layer, as denoted by dotted lines. This phenomenon is based on the 'step instability' in the shear layer. These vortices seem to decay further beyond the reattachment region, $x/H \geq 6.0$ although the vortical motion is still active in this region. This suggests the vortex passing frequency is changed from the frequency of 'step

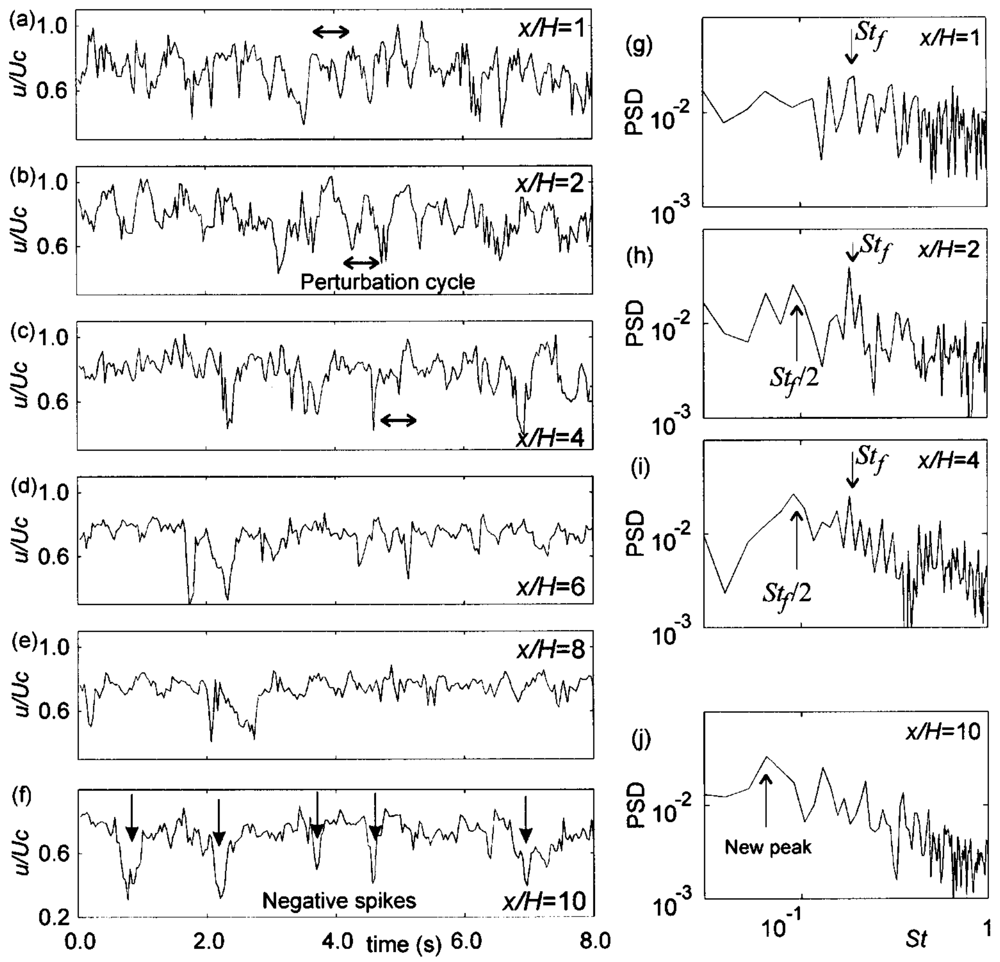

Figure 3. Velocity signals at various streamwise locations. (a)-(f), Time domain, (g)-(j), frequency domain.

instability' to another frequency. To confirm this, the velocity data in time series are investigated next.

Figure 3 shows the streamwise velocity signal at the upper edge of the shear layer at various streamwise locations. In the region upstream of the reattachment region, $x/H \leq 4$, the wavy pattern that cycle corresponds to the applied perturbation is observed as shown in Figs. 3(a)-(c). The subharmonics ($St_f/2$) appeared in the power spectra indicate the vortex merging occurs in this region, see Figs. 3(g)-(i). In further downstream region, the frequency of the applied perturbation almost disappears (Fig. 3(e)) and another new dominant frequency motion emerges (Figs. 3(f) and (j)). Because this new frequency, St=0.07, differs from that concerns with the applied frequency, it is inferred that this new dominant motion is attributed to another instability based on the shear flow beyond the reattachment zone.

The disappearance of the vortical structure in the reattachment region may be due to the existence of the streamwise rib vorticies that are generated between the organized spanwise vortical structures in the shear layer[4,5]. The re-generation of new dominant frequency can be explained as follows: After the flow reattaches, the rib vortices weakened and two dimensionality comes back. Then, new dominant spanwise vortical motions are emerged due to the instability of the shear layer itself, which has nothing to do with the 'step instability' of upstream region.

4. Concluding remarks

The flow structure of periodically perturbed turbulent separated flow over a backward-facing step has been experimentally investigated. The phase averaged flow field shows the successive shedding of the large scale vortces into the shear layer due to the 'step instability.' The investigation of velocity signals in time series reveals the disappearance of the organized motion introduced by the perturbation at the reattachment region and new dominant vortical motion is generated further downstream. It can be said that this new motion is generated by another flow instability downstream of the reattachment zone, although further investigation on this point is still needed.

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