An experimental study of a spanwise structure around a reattachment region of a two-dimensional backward-facing step

N. Furuichi, M. Kumada

Abstract The flow field downstream of a two-dimensional backward-facing step is usually assumed to be independent of the direction along the span of the step. This assumption is made even though it is well known that the flow exhibits a three-dimensional vortex structure. This state of affairs is no doubt due to the lack of detailed information concerning the characteristics of the vortex structure. In this paper, we report our investigations of the flow structure around a reattachment region using an ultrasound velocity profiler to measure the spanwise velocity component as a function of the spanwise coordinate and time. The flow field is found to be very complex both in space and time. The low-frequency component of the spanwise velocity fluctuation becomes dominant in the near-wall region, with peaks in the power spectrum at frequencies $f_h/U_c = 0.05$ and $f_h/U_c = 0.012$. Using multiple ultrasound transducers, we also find that a streamwise vortex exists in the flow.

List of symbols

- $x, y, z$: streamwise, wall-normal and spanwise coordinates
- $x_R$: reattachment length
- $U, W$: mean velocity components in the $x$ and $z$ directions
- $u', w'$: fluctuating velocity components in the $x$ and $z$ directions
- $U_c$: velocity of the main flow
- $h$: step height
- $L_w$: integral length scale
- $T_w$: integral time scale
- $Re_h$: Reynolds number $= Uh/v$
- $R_{uw}$: cross-correlation coefficient

1 Introduction

Because reattachment flows are frequently encountered in a large number of practical engineering configurations, many experiments have been performed to study their structure. In particular, the flow structure downstream of a two-dimensional backward-facing step receives a great deal of attention because it is the simplest configuration of a separated and reattachment flow. However, this flow field is still quite complex due to a low-frequency motion involving the fluctuation of an instantaneous reattachment point and the three-dimensional vortex structure around the reattachment region.

A two-dimensional flow field is usually assumed for the flow behind the backward-facing step and the flow structure in the plane defined by the streamwise and wall-normal coordinates is analyzed. However, it is well known that a three-dimensional vortex structure exists in this flow field. Using the smoke wire visualization method, Kasagi et al. (1977) showed a three-dimensional vortex-like structure in the scale of the step height around the reattachment region. Troutt et al. (1984) and Furuichi et al. (1999) measured the streamwise velocity component along the span as a function of time and showed unsteady flow structure associated with the separated shear vortex. Similar three-dimensional vortex structures have been observed in other types of separated and reattachment flows. For example, Kiya and Sasaki (1983), using conditional sampling, found them in the wake of a bluff body; Rudrich and Fernholz (1986), using flow visualization, found them in the flow behind a fence; In numerical experiments, Neto et al. (1993) visualized an unsteady three-dimensional vortex that had streamwise vortices; Hijikata et al. (1991) visualized an instantaneous pressure field in the streamwise, spanwise plane on the wall with a holographic method and investigated the behavior of lumps around the reattachment region. These results clearly indicate that the flow field behind the two-dimensional backward-facing step has an unsteady three-dimensional vortex structure.

It is usually suggested that the heat and mass transfer around a reattachment region is governed by the separated shear vortex and that the flow structure, such as the low-frequency fluctuation around a reattachment region, is correlated with the deformation of the separated shear vortex. From this viewpoint, it is clearly quite important to obtain information on the unsteady three-dimensional structure of the separated shear vortex around a reattachment region. Although there are many
investigations by visualization experiments of the three-dimensional vortex structure around a reattachment region, they mostly yield qualitative and not quantitative information.

The spanwise fluctuation over the flow field of the separated and reattachment flow is very large, especially around a reattachment region. Kasagi and Matsunaga (1995) indicated that the velocity fluctuation of the spanwise velocity component becomes greatest among the three components near the wall by the PTV method. Concerning a mechanism of the mass transfer around a reattachment region, Tsukamoto et al. (1991) indicated that the spanwise velocity fluctuation is closely related to the heat transfer at the step wall around a reattachment region. Therefore, it is important to clarify the structure of the spanwise velocity component over the reattachment region. By numerical simulations, Friedrich and Arnal (1990), Neto et al. (1993) and Le et al. (1997) showed evidence of the three-dimensional spanwise vortex. It is suggested that this vortex might contribute to the fluctuation of the spanwise velocity. To obtain information on the three-dimensional structure, it is also necessary to study the spanwise structure around the reattachment region.

We have measured the spatio-temporal velocity field using a multi-point LDV and reported the structure of the flapping mode (Furuichi et al. 1999). In this investigation, we measured the spatio-temporal flow field of the spanwise velocity component using a UVP (ultrasound velocity profiler) at a fixed Reynolds number and will discuss the spanwise structure around a reattachment region using the correlation and frequency analysis. In particular, attention is paid to the large-scale fluctuation and behavior of the streamwise vortex.

2 Experimental methods

2.1 Backward-facing step

The flow field and coordinate system are illustrated in Fig. 1. The closed-loop water channel has a working section with a cross-sectional area of 240 × 60 mm and a length of 2300 mm. The backward-facing step (with a step height of 20 mm) was formed beneath the bottom plate at a point 250 mm downstream from the flow conditioner. The expansion ratio is ER = 1.5 and the aspect ratio is AR = 12. The mean velocity of the main flow was fixed at $U_c = 0.25$ m/s in all experiments ($Re_h = 5000$). The turbulence intensity of the main flow was $Tu = 0.6\%$. The mean velocity distribution of the streamwise component upstream of the step was in agreement with Blasius theory. The spanwise velocity component was almost zero upstream of the step, so that the condition at the inlet was a fully two-dimensional flow. The boundary layer thickness upstream of the step was about 4.6 mm. The time-averaged velocity distribution of the streamwise velocity component behind the step at $z = 0$ was in good agreement with other previous studies. The time-averaged reattachment length, determined by the fraction of forward flow in the vicinity of the wall, was $x_h/h = 6.0$ in this experimental apparatus. These results were obtained by laser Doppler velocimetry and are described in more detail in Furuichi et al. (2000).

2.2 Experimental techniques

In this study, we used the UVP to measure velocity field. The UVP measurement technique is based on pulsed ultrasonic echography and is described in detail by Takeda (1991). An ultrasound pulse is emitted from the transducer along the measuring line and the same transducer receives the echo reflected from the surface of microparticles suspended in the liquid. The position information is derived from the time of flight and the velocity information is derived from the Doppler shift frequency. The UVP monitor used in this experiment was a Met-Flow model X3-P5. This instrument measures the velocity component along the ultrasonic beam direction at 128 points simultaneously, so that an instantaneous velocity profile can be obtained as a function of time. The spatial resolution of this method is $\leq 1$ mm and the threshold velocity is $\approx 1$ mm/s (Takeda 1991). The accuracy of this method is better than 5% for velocity and 1% for spatial information (Teufel et al. 1992). The parameters of the present experiment are as follows: pulse repetition frequency $\approx 2800$ Hz, number of repetitions for Doppler shift frequency computation equals 64, number of cycles in an ultrasound pulse equals 4, basic frequency of the ultrasound equals 4 MHz. The transducer (TDX in Fig. 1) was set on the outside wall of the test section to measure the spanwise velocity profile. The measuring region is $z/h = -0.45 \sim 0.45$ and the distance between each measuring point is 0.074 $h$. The measuring region in the wall-normal direction was $y/h = 0.1 \sim 1.1$. The measuring interval in this experiment was 44 ms and the measuring time length is about 90 s (2048 profiles). Nylon powder (mean diameter 50 μm, density 1.02 g/cm³) was used for the reflecting particles.

A schematic of a multi-line measurement to obtain a relation between the separated shear layer and reattachment region is also illustrated in Fig. 1. Two transducers are positioned to measure the velocity profile in the separated shear layer and the near-wall region. The transducers emitted the ultrasound beam alternately, switched by a multiplexer. Thus, velocity profiles in these regions were measured alternately. As mentioned above, the measuring interval for one profile was 44 ms,