Investigation of Transitional Flow Structures Downstream of a Backward-Facing-Step by Using 2D-2C- and High Resolution 3D-3C- Tomo- PIV

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Abstract. Transitional flow structures in the shear layer of a laminar separation bubble downstream of a backward facing step (BFS) have been investigated by means of 2D-2C- und highly resolved 3D-3C- tomographic Particle Image Velocimetry (PIV) for Reynolds numbers between $Re_h = 1420$ and 3000 based on free-stream velocity U and step height h. By using an external acoustic excitation of the shear layer it was possible to arrange phase locked measurements of the wavy flow structures which emanate from instabilities according to Kelvin-Helmholtz [1] (KH). Snapshots of fully 3D-3C velocity vector volumes show complex flow topologies of the non-linear part of the laminar-turbulent transition scenario. This part seems to be governed by hairpin-like, streamwise elongated vortices on top of the classical spanwise oriented 2-D waves. These vortices organize a rapid fluid exchange normal to the shear layer leading to turbulent reattachment of the flow and subsequent development of a turbulent boundary layer.

1 Introduction

An experimental investigation of the laminar-turbulent transition of the shear layer along a separation bubble downstream of a BFS leading to reattachment of the flow at relatively low Reynolds numbers is the topic of the present investigation. An analysis of planar and volumetric PIV results shall provide data for a better understanding of many critical flow situations in aerodynamics and technical flows which are mainly governed by the transitional development of laminar

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separation bubbles (see e.g. [2], [3], [4], [5]), e.g. in airfoil aerodynamics. Furthermore numerical simulations need appropriate field data from experiments with generic geometries in order to validate new transition models in RANS methods or advanced codes like LES or DES.

In the past many experimental investigations of the transitional flow along a laminar separation bubble either influenced by a strong adverse-pressure-gradient (APG) or behind a backward-facing-step have been realized by point wise measurement techniques like hot-wire anemometry or LDA. By using forced harmonic excitations (acoustical, mechanical or zero-net-momentum blowing) of the shear layer a more detailed picture of the developing wave structures could be realized. By phase averaging and locking of hot-wire signals it was even possible to measure the development of a wave packet towards vortex loops along a separation bubble (see Watmuff [3]). More recently several approaches using (phase locked) PIV [6] [7] or scanning PIV in water flows [4][8] have been realized for the investigation of the transitional process especially in order to clarify the structure development of its non-linear part. With the scanning PIV method complex 3D-flow structures have been reconstructed for the transition of airfoil separation bubbles. Huppertz [6] used several measurement techniques for the investigation of a manipulated BFS flow including visualisation and phase-locked PIV. Besides a detailed investigation on the excitation frequencies and response of most growing disturbances, he analysed the PIV velocity fields by triple decomposition and POD and compared one case at $Re_h = 3000$ with a spatial DNS [9].

Summarizing the present knowledge on BFS transition briefly: The transitional flow development in laminar separated flows behind a BFS is determined firstly by a formation of 2D- waves emanating from a KH- type instability in the shear layer and secondly by non-linear growing processes of three dimensional vortex structures. The thickness of the boundary layer δ and its ratio to h is a governing measure for the instability frequency and transitional flow development [6]. Topological investigations of these inclined counter-rotating vortex fingers by DNS [9] gave insight into the momentum exchange mechanisms normal to the shear layer. These fluid exchange events lead thirdly to reattachment of the flow and a subsequent development of a turbulent boundary layer. In order to capture the governing physics of this transitional flow scenario it is necessary to resolve various scales within a relatively large measurement volume instantaneously. In the present investigation a tomographic PIV [10] set-up was chosen which fulfils the required scaling requirements within a large range. An additional 2D-2C- PIV system enables the measurement of the average- and rms- fields of the whole separation process including reattachment for a broad range of Re_h.

2 Test Set-Up and Procedure

A BFS with a fixed 2D- geometry given in Figure 1 has been placed on a flat glass plate with an elliptical leading-edge with an axis ratio of 3 to 1 in the open test section of the 1-m wind tunnel at DLR in Göttingen, which is closed circuit with a contraction ratio of 4.8 resulting in a turbulence level of Tu ~ 0.5 %. The aspect ratio (AR) of the BFS between spanwise extension and step height was ~160 so that a 2D- flow is guaranteed. The coordinate system with the origin at the upper edge of the step is oriented as follows: x- in flow direction, y- normal to the plate and z- in spanwise direction. The velocity components u, v and w are referenced accordingly. Both PIV techniques have been applied for six different free stream velocities between U = 3.38 m/s and 7.2 m/s corresponding to Re_h between 1420 and 3000. The measurements were performed with and without acoustical excitation of the shear layer by an externally placed loudspeaker, which emitted sound waves at 150 Hz. The corresponding signal generator was used for the triggering of both PIV systems which enables phase locked measurements at 8 different phase positions. The ratio between boundary layer thickness and step height is $\delta/h = 0.88$ for the lowest and $\delta/h = 0.62$ for the highest Reynolds number under investigation. The laminar boundary layer flow can be defined as strongly disturbed by the step according to [13].

In a first step a 2D-2C- PIV system composed of two parallel *PCO sensicam* CCD cameras with 1280 x 1024 pixel resolution, f = 180 mm focal length lenses from *Zeiss* with distance adapters, a pulse laser from *BigSky* with a pulse energy of 35 mJ at 9 ns duration and light sheet optics has been assembled at the wind tunnel test section in order to measure instantaneous velocity vector fields around and downstream of the BFS. The measurement plane was oriented in flow direction and normal to the plate, while the laser light sheet of 1.5 mm thickness was introduced from downstream direction illuminating homogeneously distributed DEHS seeding particles with a diameter ~1µm. This PIV system measured average- and related rms- vector fields of the u- and v- velocity out of up to 4000 samples with a high spatial resolution resulting in a vector spacing of 0.143 mm in each direction at 75 % overlap of 24 x 24 pixel final interrogation windows. By shifting the double camera set-up downstream for an additional measurement a region from x/h = - 1.1 to 20.83 and y/h = -1 to 2.5 could be imaged. With this field of view the whole initial boundary layer, shear layer, separation bubble, and outer flow including reattachment and first steps of the TBL development have been captured. The phase-locking technique enables a triple decomposition of the velocity information on the basis of 500 samples for each phase position. For these cases a distinction between the 2D-waves and the non-periodic effects of the non-linear part of the transition process down to the development of turbulence can be realized.

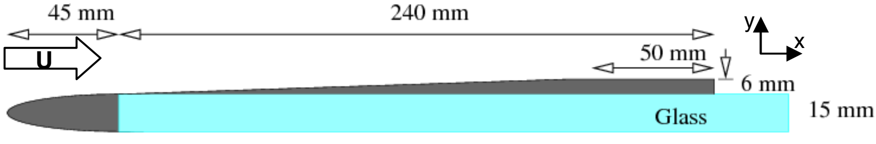

Fig. 1 Geometry of the backward-facing-step with an elliptical leading edge, a long ramp and a 2D- step of h = 6 mm height along 1 m span

Secondly, a tomographic PIV set-up has been constructed using four high-resolution CCD cameras (*Imager pro X* from *LaVision*) with 16.1 Mpix (4904 x 3280 pixel) and 105 mm *Nikon*- lenses at $f_\# = 11$ in a tetrahedral viewing configuration (see Figure 2). Two combined Nd:YAG double oscillator laser from *BigSky* with ~400 mJ pulse energy at 8 ns width served as light sources. An optical set-up expands the laser light beam by two telescopes and two cylindrical lenses to a collimated beam with the shape of an elongated ellipse. A passe-par tout cut out a rectangular plane from this light beam with 70 x 8 mm² extension in x- and y-direction. The collimated rectangular light volume is introduced parallel to the plate by mirrors so that the measurement volume starts 10 mm downstream of the BFS and 0.5 mm above the plate. The light is back-reflected in-itself by a mirror placed on the opposite side of the test section in order to generate simultaneous forward- and backward scattering of the particles for all camera viewings.

The 3D- particle intensity distributions have been reconstructed from each of four simultaneous camera images by means of a tomographic SMART [11] algorithm in a volume of 70 x 93 x 8 mm³ corresponding to 2502 x 3324 x 286 voxels and stored digitally (11.5 GB per volume). Before final reconstruction of the particle image volumes a volume-self-calibration according to [12] has been performed. Then the particle image volumes were analyzed by 3D cross-correlation with an iterative multi-grid volume deformation scheme reaching a final 36³ voxels interrogation box size by *DaVis7.3*. With a given magnification of 27.5 µm/voxel the final 36³ voxel correspond to an interrogation box volume of ~ 0.99 x 0.99 x 0.99 mm³. With 75 % overlap a series of instantaneous three-dimensional velocity vector volumes over a grid of 286 x 444 x 29 (3,682,536) measurement points located every 0.248 mm in all directions in space have been achieved. The number of spurious vectors was always less than 1.5 %. For Reynolds numbers 2350, 2690 and 3000 the shear layer has been acoustically excited by 150 Hz sound waves and at each of 8 phase position 100 locked tomo PIV samples have been captured. In the present work data are presented which delivers the complete instantaneous velocity gradient tensor with a high spatial resolution.

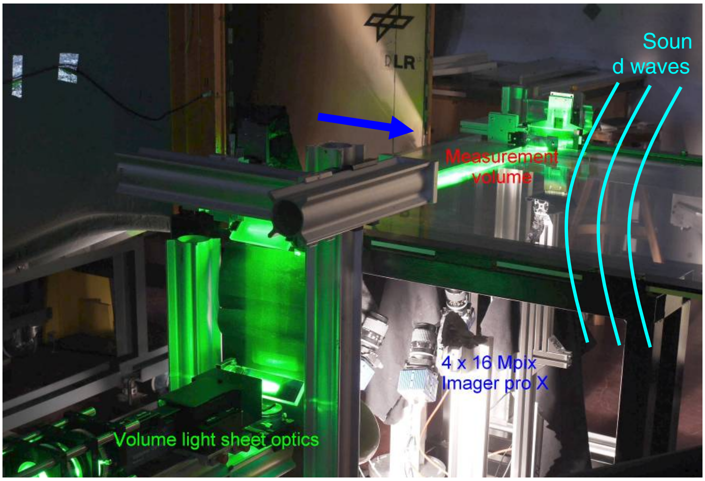

Fig. 2 Four CCD cameras with 16 Mpix each in a tomographic PIV set-up with tetrahedral viewing directions and a laser light volume behind a BFS at 1m - wind tunnel of DLR Göttingen. The measurement volume of 70 x 8 x 93 mm³ begins x =10 mm downstream of the BFS with h = 6 mm height.

3 Results

3.1 Averaged 2D-2C Velocity Vector Fields

Average laminar separation bubble sizes downstream of the BFS at increasing Reynolds numbers are given in Figure 3. With increasing U the thickness of the separating boundary layer δ decreases. The pronounced inflectional profile accelerates the growing process of fitting disturbance frequencies in the shear layer, resulting in a decrease of the separation bubble extension at higher Re_h. The maximum average reverse flow velocity of ~ 15 % U is found close to the wall upstream of the reattachment line.

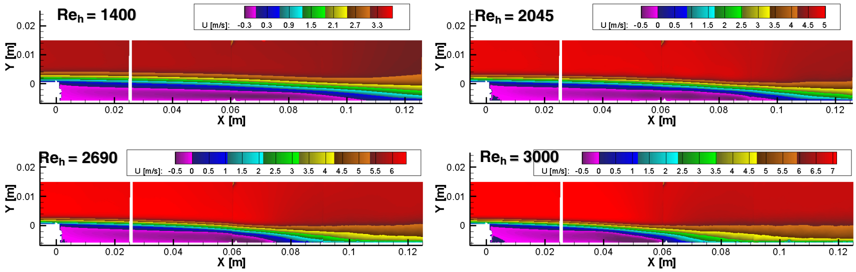

Fig. 3 Average u- velocity distributions behind a BFS for four different free stream velocities at Re_h = [1420, 2045, 2690, 3000] (in reading order) without shear layer excitation including separation bubble and reattachment position (negative u- velocity coloured in purple).

For the results at Re_h = 2690, shown in Figure 4, harmonic sound waves at 150 Hz have been introduced for excitation of the shear layer. The averaged u- and v- velocity distributions at four phase locked positions of the acoustic excitation with $\pi/2-$ steps are shown indicating a periodical reverse flow with amplitudes up to ~22 % of U around the time averaged reattachment line. The excitation decreases the average size of the separation bubble compared to results at the same Re_h of the non-excited flow shown in Figure 3. The convection velocity of the associated 2D- waves best visible at the v- velocity distributions is approx. 36 % of U. The spanwise oriented waves are organising clearly at about x = 0.024 m or x/h = 4 and transport high-momentum fluid towards and low momentum fluid away from the wall in large coherent rollers. The high-momentum fluid interacts with the near wall fluid in a region of an APG. This precondition leads to rapidly growing three-dimensional vortex structures (see Figure 6) resulting in a disintegration of the near-wall wave part of the positive v- velocity around the oscillating reattachment area due to high local non-periodic fluctuation velocities (see Figure 5). This non-periodic high rms- region of the u- velocity evolves while moving in phase with the waves. It is located at the downstream ends of the positive v- velocity area and can be connected to the jittering position of the inclined vortex- fingers visible in Figure 6.

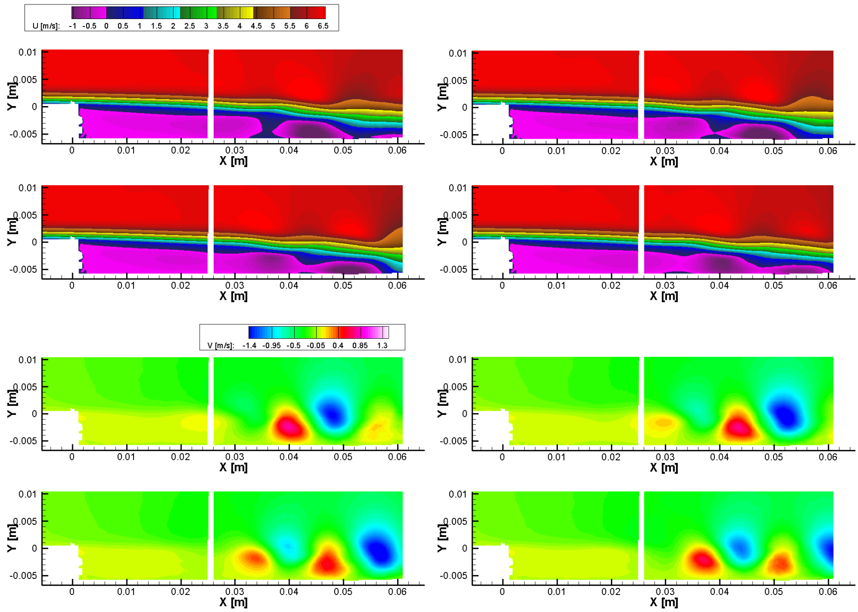

Fig. 4 Averaged u- (top-four) and v- (bottom-four) velocity distributions at four phase locked positions of the acoustic excitation with π/2– steps behind a BFS at Re_h = 2690 (negative u in purple, negative v in blue)

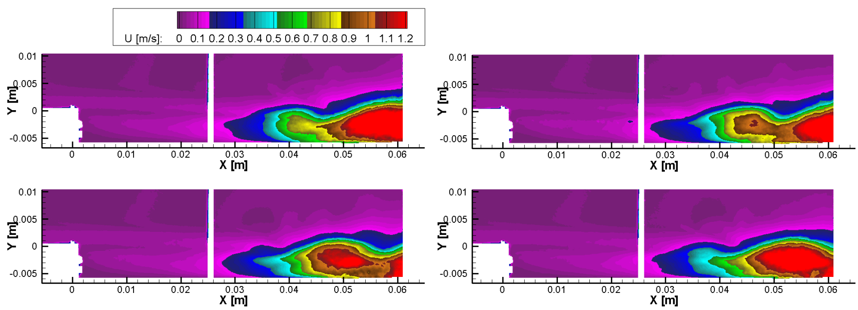

Fig. 5 Non-periodic rms of the u- velocity distributions at the same four phase locked positions of the acoustic excitation as in Figure 4 with π/2– steps behind a BFS at Re_h = 2690 (similar for the corresp. v- velocity part)

3.2 Tomographic PIV Results

Figure 6 shows a 3D- 3C- velocity vector volume result of a tomographic PIV measurement in the volume described in section 2 at Re_h = 2690 and U = 6.4 m/s. For the visualization of the instantaneous flow structures iso-contour surfaces of the 3D- vorticity have been plotted (blue) together with a horizontal vector plane at y = –h/2 colour coded by the v- velocity component. Counter-rotating vortex pairs are visible, stretched in flow direction and inclined towards the wall. Some of them can be identified as hairpin-type vortices with arches, evolving sometimes in packages along flow direction (see Figure 6 left-structure). Vortex-loops are also found in a transition scenario of a wave-packet developing in the shear layer of a separation bubble [3]. In the present data they are located at many spanwise positions with a wave-length smaller than the 2D- wave and start to evolve downstream of the positive v- velocity part of the average waves. In between such a pair of counter rotating vortex legs low momentum fluid is transported in positive wall normal direction, while at the lateral sides high momentum fluid is guided towards the wall. These structures are well known as organiser for turbulence producing negative instantaneous Reynolds stresses u'v' s.c. Q2- and Q4- events in late transitional- [14][15] and turbulent boundary layers [16]. The turbulent mixing of the late transition in the investigated BFS case is clearly connected to lambda-vortices turning into hairpin- vortex fingers.

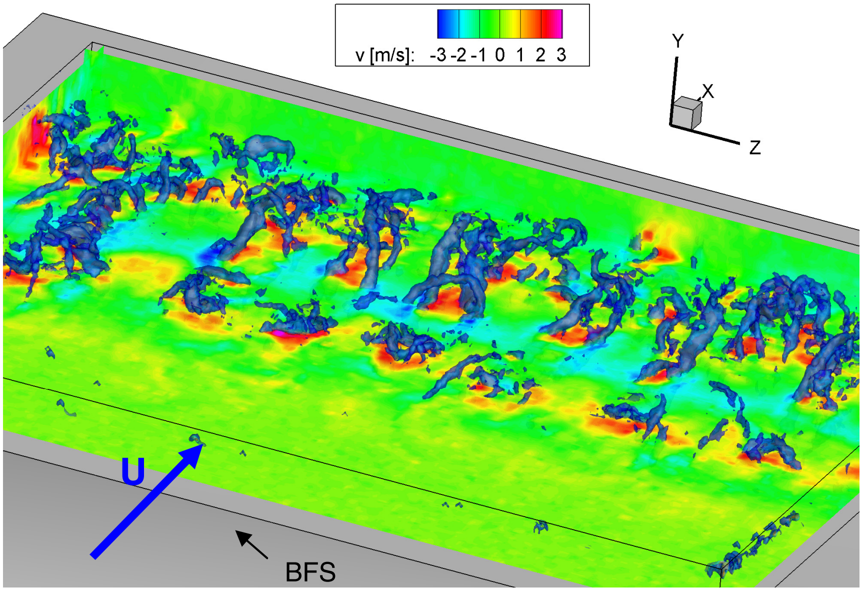

Fig. 6 An instantaneous 3D- velocity volume depicting flow structures of the shear layer transition behind a BFS by iso-surfaces of 3D- vorticity and selected velocity planes (horizontal plane at y ~ -h/2, v colour coded, U = 6.4 m/s)

4 Conclusions and Outlook

Highly resolved tomographic and standard PIV techniques have been applied for an investigation of the transitional flow structures downstream of a BFS at Re_h between 1420 and 3000. Four 16.1 Mpix CCD cameras imaged tracer particles which are illuminated by a pulse laser in a rectangular volume. Instantaneous 3D-3C velocity vector volumes include the complete velocity gradient tensor enabling a topological investigation of the vertical flow structures in the non-linear stage of the shear layer transition down to reattachment of the flow. Besides the known 2D-waves emanating from KH- instability arch- and hairpin-like vortices are identified developing in a spanwise array. The connection of the streamwise elongated counter-rotating vortex fingers and turbulence producing Q2- and Q4-events has been made responsible for the turbulent breakdown of the shear layer and reattachment process.

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