Coherent large scale structures in adverse pressure gradient turbulent boundary layers

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Keywords: PIV, turbulent boundary layer, adverse pressure gradient, large scale structures

ABSTRACT

Over the last several years, the observation of large scale turbulent flow structures in turbulent boundary layer flows has stimulated intense experimental and numerical investigations with the aim of characterizing not only the topological features of the coherent structures but also their dynamics. Due to the large length of the structures (approximately 7-14 times the boundary layer thickness) it is very difficult to analyze them reliably since both a large field of view and a high spatial resolution are simultaneously required to measure all relevant spatial scales. Moreover, a low uncertainty of the experimental techniques is required as the disturbance of the mean velocity field due to the large scale structures can be quite weak. This holds in particular true for investigations at small Reynolds numbers. As a consequence of the recent technological progress, the required measurement uncertainty can be reached with sophisticated image analysis techniques but the resolution of the structures requires a high number of cameras. Therefore, 16 sCMOS cameras in total were provided by different research organizations in order to perform large scale turbulent boundary layer measurements with appropriate spatial resolution. In the case of adverse pressure gradients (APG) the topology and dynamics of the large scale turbulent flow structures is unknown, as is their significance for the statistical properties of the flow. Therefore the fundamental aim of this project was to resolve and characterize these structures in an APG boundary layer flow at the Laboratoire de Mécanique de Lille (LML) wind tunnel. To access the span-wise / wall normal signature of the structures as well, stereoscopic PIV measurements in span-wise/wall-normal planes were performed at specific stream-wise locations in addition. To complement these large field of view measurements, long-range micro-PIV, time resolved near wall velocity profiles and film-based measurements were performed in order to determine the wall-shear stress and its fluctuations at some specific locations along the model, see Soria et al. (2016).
1. Introduction

Over the last several years, the observation of large scale structures in turbulent boundary layer flows has stimulated intense experimental and numerical investigations with the aim of characterizing not only the topological features of the coherent structures but also their dynamics. While the understanding of these structures in zero pressure gradient (ZPG) turbulent boundary layers is fairly well developed by now, our understanding of these structures in decelerating situations is still quite limited. As turbulent boundary layers with streamwise pressure gradient are omnipresent in particular in aerodynamics it is interesting to study the behavior of these structures under pressure gradient. Furthermore, a detailed understanding of these structures may open the door for novel flow control strategies which delay flow separation at take-off and maneuver flight or lower the friction drag at cruise speed conditions of aircrafts. Unfortunately the experimental investigation is quite challenging because of the complex model geometry which strongly raises the aerodynamic load on the model in particular at high Reynolds number. Furthermore, very often, the facilities are too small to reach high Reynolds numbers and to let the boundary layer develop long enough to reach some state of “equilibrium” where theoretical approaches become relevant. Moreover, measurements are generally quite limited leading to a lack of detailed characterization of the flow itself but also of the boundary conditions, which makes the data very difficult to use in practice, both for physical understanding and for models validation.

There are indeed some careful experiments available in the literature on APG wall flows (e.g., Ludwig & Tillman (1950), Perry & Shofield (1973), Skare & Krogstad (1994), Elsbery et al. (2000), Perry et al. (2002), Nagib et al (2003), Maciel et al. (2006)), but most of them provide only single-point turbulence statistics at a few locations, and generally only for one or at best two velocity components. Therefore, no direct information about the large scale structures can be obtained from these investigations. As noted by George (2006, 2007), even the more recent experiments have added little to our understanding, since they either measured the same things or were at a too low Reynolds number or in restricted conditions (e.g. Zhou et al. (2000), Degraaff & Eaton (2000)). As a result, up to now, these data have not been very useful for improving turbulence models or the understanding of large scale flow structures.

However, there have been several important breakthroughs which have dramatically transformed our view of APG boundary layers recently. The first was the confirmation that while the peak in turbulence energy production is maximum around $y^* = 10-20$ in ZPG boundary layers, in APG, the production peak moves away from the wall. Second, this
The movement of the turbulence intensity peak outwards was correlated with the downstream evolution of an inflectional mean velocity profile (George et al. (2010a,b), Fig. 1). The location of this inflection point is not near the wall, but at about 50% of the boundary layer thickness, and near the peak in turbulence intensity. It appears to have been previously noticed only by Elsberry et al. (2000). But it seems to be characteristic of all APG's if allowed to evolve for a large enough distance (which explains why it has not been previously noticed in the typical low Reynolds number short wind tunnel experiments). It is also important to note that it seems to be quite independent of whether the boundary layer ultimately separates. The existence of any inflectional profile in fluid mechanics is a well-known “game changer”, since very different instability dynamics come into play. How this happens exactly in APG boundary layers is not fully understood yet, but a deep understanding it is of major practical importance.

![Fig. 1 Results of Skare & Krogstad (1994) scaled by George et al. (2010) showing the inflection of the mean velocity profile and the turbulence peak.](image)

The third new phenomenon came from the DNS performed during WALLTURB (Marquillie et al. (2008)), which provides a clue to solve the riddle of its origins. Using this DNS and stability theory, they were able to establish a sudden growth of turbulence intensity arising from inflectional instabilities of the streaks at the imposition of the APG (Marquillie et al. (2010)). It seems quite likely that this phenomenon has some generality. Exploring the relations among these new phenomena is important on the modelling point of view.

Although there has been a great deal of work on boundary layers in the past 50 years, it must be emphasized that it is almost entirely at low to moderate Reynolds numbers. For example, most experiments have been performed at values of \( \text{Re}_\theta < 10,000 \). This limit on the Reynolds number of experiments means there is quite likely a critical gap in our knowledge, since recent theoretical arguments suggest strongly that it is only above this value that the true inertial nature
of the high Reynolds number boundary layer begins to be manifested (George & Castillo (1997), Tutkun et al. (2010)). Measurements beyond this range have only very recently been able to successfully resolve the near wall region in ZPG boundary layers (say $y^+ < 100$, e.g., Osterlund (1999), Carlier & Stanislas (2005)) and even most of these new measurements are under debate. Previously, either the probes were too large, the sublayer too small, or some combination of both. The EU-WALLTURB project extended significantly this range by measurements up to $Re_{\theta} \approx 20,000$ for both flat plate and APG boundary layers. And for the first time, the structural point of view has been linked to a universal scaling of the flow properties (Stanislas et al. (2008)).

Computer simulations (DNS) have also been restricted to quite modest Reynolds numbers, limiting the universality of their findings. Happily, recent simulations in channel flow from Jimenez and co-workers at Madrid, at $Re_{\tau} \approx 2,000$ (and available in WALLTURB) are beginning to remove this limitation.

There has been considerable effort over the past four decades to apply a deterministic approach to near-wall turbulence. For example, coherent structures such as streaks, vortices, sweeps and ejections are agreed upon by many researchers to exist in the near-wall region of ZPG boundary layers and channel flows. The interrelations among all these structures have been the subject of numerous and detailed investigations (Panton (1997)). The mechanics of their formation and of their contribution to the generation and the preservation of the wall turbulence is still the subject of controversy. But at least their general behavior is essentially understood, both from the point of view of how the vortices create the streaks and of how they in turn originate from instabilities of the instantaneous velocity profile (Jeong et al (1997), Jimenez & Pinelli (1999), Schoppa & Hussain (2002), Kawahara (2003)). The hypothesis is a self-sustaining nonlinear cycle which is at the origin of most of the turbulence generation in the viscous and buffer layers (Jimenez & Moin (1991), Hamilton et al. (1995), Jimenez & Simens (2001), Waleffe (2001), Kawahara & Kida (2001) among others). In spite of this, our knowledge of what happens in an adverse pressure gradient boundary layer (especially approaching separation) is far less complete.

Finally, there is much less agreement on how the near-wall region interacts with the outer flow, although it is clear that in attached boundary layers there is a net transport of energy away from the wall (Jimenez & Pinelli (1999)). In addition, the near wall may contribute to the formation of large-scale outer structures in the form of hairpin packets (Adrian (2007)). It is also known that the outer flow modulates the inner layer (Tutkun et al. (2010), Marusic (2010)), forcing some of its characteristics to scale purely in outer units.

In this type of flow, due to the large length of the structures (approximately $7-14\delta$) it is very difficult to analyze them reliably since both a large field of view and a high spatial resolution are simultaneously required to measure all relevant spatial scales. Moreover, a low uncertainty of
the experimental techniques is required as the disturbance of the velocity field can be quite weak. As a consequence of the recent technological progress, the required measurement uncertainty can be reached with sophisticated image analysis techniques but the resolution of the structures requires a number of cameras which is not available at any one research organization alone.

The aim of this project was to combine the equipment and skills of the teams to perform a detailed characterization of a large scale turbulent boundary layer with the highest spatial resolution possible. The fundamental aim of this project was to resolve and characterize the turbulence structures in an adverse pressure gradient (APG) boundary layer flow. A second aim of the project was to record reliable statistics and boundary conditions in order to use the experiment as a test case for CFD. In addition to two-component two-dimensional PIV measurements in a stream-wise/wall-normal plane with 16 sCMOS cameras, stereoscopic PIV measurements in a span-wise/wall-normal plane were performed at specific locations in order to resolve the span-wise velocity distribution in this APG flow. To complement these large field of view measurements, time resolved near-wall velocity profiles and planar near-wall measurements were performed in order to determine the wall-shear stress and its fluctuations at some specific locations along the model. The aim of the present paper is to present this unique experiment which was a collaboration between five international teams and first results. The detailed analysis of the data will be presented in separate papers as mentioned in the following.

2. Experiments

2.1 Facility

The experiments were performed in the Laboratoire de Mécanique de Lille (LML) boundary layer wind tunnel which has a test section length of 20.6 m in the stream-wise direction (x-direction) and a cross-section 2 m wide and 1 m high. The wind tunnel is made of a metal framework with large exchangeable windows of high quality glass along the whole test section length providing full optical access. The model installed on the floor of the test section was a ramp, built in the frame of the AVERT EC project and modified for the purpose of the present project as shown in Fig. 2. This model allows the generation of boundary layer flows with an extended adverse pressure gradient region (3.5 m long). The APG part of the model was equipped with several windows allowing near wall measurement techniques to be implemented. A PEG smoke generator was used for all measurements to seed the whole flow with particles having a mean size of $d_p \approx 1\mu m$. 
In the sketch of Fig. 2 the flow is coming from left to right. The platform is built up of a 2D-contraction of, 1.25 m in length, which reduces the cross-sectional area, followed by a 2.2 m flat plate in the direction of the flow with a positive angle of +1.5° generating a small favorable pressure gradient and a second flat plate with a length of 3.5 m and a -5° inclination compared to the horizontal wall where the APG BL develops. The free-stream velocities were set to $U_\infty = 5$ m/s and $U_\infty = 9$ m/s at the very beginning of the test section.

![Fig. 2 Top: Side view of the model installed in the wind tunnel with the measurement area of a TBL with adverse pressure gradient marked in green color. Bottom: Top view of the model showing the position of the windows.](image)

![Fig. 3 Wind tunnel with model.](image)

The length of the measurement domain of the multi-camera 2C-PIV measurements is 3.5 m long and 0.25 m high to ensure the possibility of capturing very large scale turbulent structures with lengths of more than 10 boundary layer thicknesses $\delta$. Figure 3 gives an overall view of the model in the wind tunnel.
In complement to the APG experiments, a careful characterization of the boundary conditions was performed. The streamwise pressure distribution was measured on the model and along the upper wall. Mean velocity and Reynolds stresses profiles were determined upstream of the model to serve as inlet boundary conditions. The corner vortices which develop on the side walls of the wind tunnel were characterized using a transverse wall-normal Stereo PIV plane. Only the pressure distribution on the ramp is presented here. The other boundary conditions will be described in a more detailed paper in preparation.

The pressure distribution on the model was measured for two free-stream velocities ($U_\infty = 5 \text{ m/s}$ and $U_\infty = 9 \text{ m/s}$ at the wind tunnel entrance). This was done with the help of scanivalves and a Furness FCO 14, 0 to 10 mmH2O having an uncertainty of ±0.5% of the reading value. The pressure coefficient was computed with P17 (corresponding to the smallest pressure on the model) as reference pressure, $\rho$ the air density and $U_\infty$ the free stream velocity upstream of the ramp. In the following figures, $s$ will refer to the curvilinear abscissa along the ramp with the origin at the leading edge of the ramp.

As can be seen in Fig. 4, the flow accelerates in the converging part, $0 \leq s \leq 1360 \text{ mm}$, of the ramp until the suction peak at $s = 1146 \text{ mm}$ corresponding to pressure tap ‘6’. This suction peak then induces a locally strong adverse pressure gradient as shown in Fig. 5. A region of pressure recovery occurs then, after which the flow begins to accelerate again due to the favorable pressure gradient caused by the 2.14 m long flat plate inclined at 1.5° to the wind tunnel floor. A second suction peak is observed at the articulation of the -5° plate at $s = 3500 \text{ mm}$ close to the reference pressure tap 17. The 3.5 m long plate inclined at -5° to the wind tunnel floor then causes a region of relatively constant adverse pressure gradient with a pressure gradient coefficient of about 0.21 m⁻¹.

Spanwise pressure measurements were also carried out at four locations to check the spanwise homogeneity and the two dimensionality of the flow. The first two stations were located on the +1.5° plate at $s = 1727 \text{ mm}$ and $s = 3010 \text{ mm}$ while the last two stations were located on the -5° plate at $s = 4301 \text{ mm}$ and $s = 6176 \text{ mm}$. The pressure distribution was found to be almost constant at the 4 stations for both velocities except slight variations close to $z = -800 \text{ mm}$ and $+800 \text{ mm}$. This confirms the two dimensionality of the flow for $-600 \leq z \leq 600 \text{ mm}$. 
Fig. 4 Streamwise pressure coefficient distribution along the ramp for $U_\infty = 5$ m/s and 9 m/s.

Fig. 5 Streamwise pressure coefficient gradient distribution along the ramp for $U_\infty = 5$ m/s and 9 m/s.

2.2 2D2C PIV setup with 16 sCMOS cameras

In order to obtain an overview over the boundary layer development in the region of the adverse pressure gradient with high spatial resolution, an experimental setup consisting of 16 sCMOS cameras was built. A photograph of the setup is given in Fig. 6.
8 cameras (number 1-8 from left) were provided by UniBw operated by 4 PIV systems from LaVision, each consisting of a computer with PTU (programmable timing unit) and 2 cameras. 6 additional cameras (number 9-14) were operated by DLR Göttingen, and 2 cameras (number 15 and 16) by LML. The LML system was a LaVision system, similar to the UniBw systems. Most of the cameras were equipped with 100 mm Zeiss lenses. Camera 6 and 14 were equipped with 85 mm Zeiss lenses and a 50 mm Zeiss lens was connected to camera 13. The different lenses were used in order to avoid problems due to the struts of the wind tunnel. The field of view for all cameras was of the same order: approximately 230 mm in the streamwise direction and 255 mm in the wall normal direction. A Nd:YAG laser provided by LML with $2 \times 200 \text{ mJ} \times 532 \text{ nm}$ was used for generating the light-sheet with a height of approximately 260 mm and a thickness of approximately 1 mm over a length of about 3 m. This constant thickness over 3 m length was obtained by using a spherical lens with a focal length of 7500 mm and placing the laser outlet approximately 10 m from the middle of the ramp (field of view). The cylindrical lens had a focal length of -250 mm. In order to allow for detailed statistical analysis and structure analysis, 30,000 double pair images were recorded for each of the free-stream velocities, resulting in a total number of 16 cameras x 2 free-stream velocities x 30,000 double images per camera and velocity = 960,000 double-pair images (in total approx. 21 TB raw data).

All of these fields have been used for the fluid mechanical analysis. However, the question arises how many vector fields are required in order to achieve converged statistics. Figure 7 shows a convergence plot for $U_\infty = 9 \text{ m/s}$ at location $x = 2,000 \text{ mm}; y = 80 \text{ mm}$. While a good convergence for the mean velocity $u$ is obtained after a few hundred samples, the Reynolds shear stress
requires much more measurements for a sufficient convergence. It can be concluded that 10,000 – 20,000 samples are sufficient for the analysis of statistical values like mean and RMS values.

An investigation of the convergence of the two-point correlation is given in Fig. 8. The black line in this figure corresponds to a correlation coefficient $C = 0.15$. Obviously 1000 or 2000 samples are not sufficient in this turbulent boundary layer in order to obtain a proper two-point correlation. The correlation distributions are quite noisy. Using 10,000 instantaneous flow fields results in a relatively smooth two-point correlation field. However, the result using 30,000 fields is even smoother and allows for a reliable estimation of the characteristics of the two-point correlation. This indicates that 30000 statistical independent velocity fields are essential to obtain statistical converged information. The large number of samples required for valid statistical measurements is consistent with the observations by Kähler et al. (2016) in a turbulent channel flow.

![Fig. 7 Convergence of the mean velocity $u$ and the Reynolds shear stress $u'v'$ depending on the number of samples for $U_\infty = 9$ m/s at location $x = 2000$ mm; $y = 80$ mm.](image-url)
Fig. 8 Convergence of the two-point correlation of the velocity fluctuation $u'$ for $U_\infty = 9$ m/s at location $x = 2000$ mm; $y = 80$ mm. The black line indicates the iso-contour of the correlation coefficient $C = 0.15$.

2.3 Stereoscopic PIV setup with 2 x 2 sCMOS cameras

Since the spanwise organization and average distance of the superstructures as well as their role for the overall dynamics of wall bounded turbulent flow under the influence of a mild adverse pressure gradients are not fully understood, it was essential to also install a three-component stereo PIV (3C-PIV) systems for investigating the flow in a plane normal to the wall and mean flow direction. During the campaign at LML such measurements have been performed at two different streamwise locations in the adverse pressure gradient region.
The combined field-of-view (FOV) of both SPIV systems has a spanwise extension of $z = [-175; +160]$ mm around the wind tunnel mid-line at $z = 0$ mm and up to $y = 130$ mm in wall normal direction for both streamwise positions. Figure 9 shows the estimated pinhole positions of both Stereo PIV camera pairs referring to the mid-line position ($z = 0$ mm) and the wall ($y' = 0$) at both measurement planes. For both SPIV measurement positions four sCMOS cameras from PCO with $2560 \times 2160$ px sensor size at 16 bit greyscale dynamics equipped with Zeiss lenses at a focal length of $f = 100$ mm and an aperture number of $f/ = 11$ were used in forward particle scattering mode for the laser light. All cameras were connected via double-camlink to a separate computer with RAID 0 storage blocks for direct-to-disk data acquisition at 5 Hz rate. The low image frame rate warrants statistical independence of the snapshots. The used laser system was a Nd:YAG double-PIV laser system from BigSky with four laser cavities in total. This laser system enables the possibility to combine two oscillators each and generate laser pulses of 400 mJ with a pulse length of 9 nsec and a repetition rate of 10 Hz. Proper light sheet optics combining a telescope and a cylindrical lens were used to form a light sheet plane of almost constant thickness of $\sim 2$ mm in the combined FOV. Synchronization of lasers and camera acquisition has been gained by TTL-trigger signals generated by the programmable Sequencer V5.1 from Hardsoft. Figure 10 shows a picture of the laser light sheet and stereo camera set-up at the second (downstream) position at the LML wind tunnel.
The first measurement plane position was located at $x = 594.5$ mm downstream the edge where the inclined flat plate section begins. The second measurement plane position was located further downstream at $x = 2,192$ mm from the articulation. Both planes were oriented in a wall-normal-spanwise ($y$-$z$) plane.

![Fig. 10 Stereo PIV set-up at second downstream position at $x = 2192$ mm with two pairs of sCMOS cameras in Scheimpflug mounts and laser sheet normal to the wall and mean flow direction.](image)

For both SPIV setups and respective streamwise positions, again two free-stream velocities were adjusted at $U_\infty = 5$ m/s and 9 m/s. The other variables chosen for the first and second measurement planes (a and b) are listed in Table 1, whereas the temperature remains at 20 °C for all cases. All in all four collections of data have been recorded (each in 6 blocks of 5,040 images) with a total number of slightly more than 30,000 valid snapshots for each Reynolds number and position of the combined SPIV camera set-up. Calibration and mapping of the two FOV have been realized using a glass target with a squared regular grid of 10 mm x 10 mm.

<table>
<thead>
<tr>
<th>Velocity $U_\infty$ [m/s]</th>
<th>Position $x$ [mm]</th>
<th>Pressure $p$ [hPa]</th>
<th>Air humidity [%]</th>
<th>$\Delta t$ [$\mu$s]</th>
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<td>594.5</td>
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<td><strong>Measurement b</strong></td>
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<td>9</td>
<td>2192.0</td>
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<td>5</td>
<td>2192.0</td>
<td>1004.1</td>
<td>56</td>
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Table 1 Different recording parameters for the camera positions for both Reynolds numbers.
3. Results

3.1 2D2C PIV with 16 sCMOS cameras

The acquired particle images were analyzed using LaVision DaVis 8 software employing iterative multi-grid interrogation with image deformation. The following settings are used in the analysis: A final window size of 24 x 24 px at a step-size of 12 px corresponding to 50% window overlap has been employed. The 16 vector fields were mapped onto a common grid by means of a bi-cubic interpolation.

Details of the boundary layer characteristics for the inflow velocity of $U_\infty = 5$ m/s are given in Figs. 11 and 13. The corresponding results for $U_\infty = 9$ m/s are given in Figs. 12 and 14. For both inflow velocities a slight influence of the change of the pressure gradient due to the end of the inclined flat plate is observed for $x > 3,000$ mm. However, the influence is small and the results up to $x = 3,000$ mm are undisturbed. The boundary layer thickness increases from approx. 100 mm at $x = 0$ mm to approx. 240 mm at $x = 3,000$ mm for both inflow velocities investigated. Also the development of the displacement thickness as well as the momentum thickness is quite similar for the different cases, see Figs. 11 and 12. Larger differences are seen in the skin friction velocities $u_\tau$ as well as in Re$_\tau$ and Re$_\theta$. For $U_\infty = 5$ m/s Re$_\tau$ is in the order of 2,500, for $U_\infty = 9$ m/s it is in the order of 4,200. The skin friction velocity was determined by means of the Clauser chart method, which is well applicable with the adverse pressure gradient present in this experiment.

In order to determine the size of the structures in the turbulent boundary layer under adverse pressure gradient, two-point correlations of the fluctuation velocity $u'$ were performed. The length $l_1$, which is the total length in $x$-direction of a bounding box at a correlation coefficient of $C = 0.15$ was used as a measure of the structure length, see Fig. 15 for explanation.

Plots of the length $l_1$ normalized with the local edge velocity $U_e$ are shown in Fig. 16 for $U_\infty = 5$ m/s and $U_\infty = 9$ m/s, respectively. The normalization with the local edge velocity compensates the effect of stretching / shrinking of the structures due to a changing free-stream / edge velocity. For static structures, whose lengths only change due to continuity reasons, the curves would coincide. As can be observed in the given plots, only small differences between the curves at different locations occur. This holds for the low as well as high Reynolds number case. This means that the length of the structures in fact does not change – the structures are only shrunked due to a decreasing edge velocity. However, with increasing $x$-location the maximum normalized length $l_1$ moves to smaller $y/\delta$-locations - in a relative view they move nearer to the wall.
Fig. 11 Boundary layer parameters for $U_\infty = 5 \text{ m/s}$.

Fig. 12 Boundary layer parameters for $U_\infty = 9 \text{ m/s}$.
Figure 17 shows the intermittent factor, $\gamma$, which is defined as the ratio of the number of turbulent events to the number of total events at a certain location. Thus, $\gamma = 1$ means that only turbulent boundary layer occurs. It is observed that the laminar-turbulent interface width decreases with increasing $x$-location and moves to higher $y/\delta$-locations. Nearly no differences for both of the flow velocities investigated can be noticed.
Fig. 15 Explanation of the length $l_1$ and the length $l_2$ of the two-point correlation.

Fig. 16 Normalized two-point correlation length $l_1$ over normalized wall-normal location. Left: $U_\infty = 5$ m/s. Right: $U_\infty = 9$ m/s.

Fig. 17 Intermittent factor for $U_\infty = 5$ m/s (left) and $U_\infty = 9$ m/s (right).
3.2 Stereoscopic PIV with 2 x 2 sCMOS cameras

The acquired particle images were analyzed using PIVview 3.60 software employing iterative multi-grid interrogation with image deformation. The following settings are used in the analysis: A final window size of 24 x 24 px at a step-size of 6 px corresponding to 75% window overlap has been employed leading to 975 x 373 grid points. Thus, a spatial resolution of 1.33 mm in both in-plane directions is reached in the final datasets at a vector spacing of 0.33 mm. The regions below the wall surface are masked and a random dot pattern is applied during cross-correlation in order to achieve unbiased (although still low-pass filtered) results in the near wall region. This results in approximately 360,000 instantaneous three-component velocity vectors per snapshot in the given combined FOV of the two SPIV systems. The layout of the final FOV is represented as two instantaneous contour plots of the streamwise velocities in Fig. 18 for the two free stream velocities at \( x = 2,192 \) mm downstream of the articulation of the negatively inclined flat plate. In the figure one can clearly see the increase of turbulent scales (especially towards smaller scales), changes of the near-wall velocity profile towards higher wall-normal velocity gradients and higher maximum velocities in the outer boundary layer region with the increase of the free stream velocity from \( U_\infty = 5 \) m/s (left) to \( U_\infty = 9 \) m/s (right) and Reynolds number, respectively. The spanwise alteration of large scale regions of high and low \( u' \)-velocities is clearly visible around medium wall-normal heights of the given FOV for both examples of instantaneous velocity vector fields indicating a typical cross-flow-plane cut through the instantaneous large scale- and super-structures.

Figure 19 shows the corresponding two-point correlation result \( R_{u'u'} \) of the \( u' \)-component with a reference point height at \( y = 50 \) mm for the same measurement plane at \( x = 2,192 \) mm and \( U_\infty = 9 \) m/s. This wall-normal position exhibits the largest negative correlation maxima in both spanwise directions at about \( \Delta z = \pm 65 \) mm (\( \sim 0.35 \delta \)) with up to \( R_{u'u'} = -0.2 \) indicating roughly the position of the second peak in the spatial velocity spectrum. The first peak close to the wall has not been resolved with the given spatial resolution.

In Fig. 20 the amplitude weighted distribution of the negative Reynolds stress events \( u'v' \), namely Q2 and Q4, which can be regarded as the instantaneous turbulence production terms are plotted in the wall-normal \( y \)-direction (averaged over the spanwise direction). Within the limits of the resolution of the given SPIV measurement a clear shift and widening of the turbulence producing region away from the wall from the upstream to the downstream position is remarkable, while the Q4- or sweep events are located in a slightly narrower region closer to the wall compared to the Q2- or ejection events. According to the streaky large scale structure topologies of the respective wall-normal region larger amplitudes are visible for the Q2-events...
compared to Q4-events. But the latter one are organized in spanwisely more extended regions according to the respective two-point correlation functions (not shown here) and the continuity equation.

**Fig. 18** Two instantaneous 3-component velocity vector fields measured in the APG region at a wall-normal- spanwise plane at $x = 2,192$ mm downstream of the articulation ($x$-origin) of the flat plate by Stereo PIV at $U_\infty = 5$ m/s (left) and $U_\infty = 9$ m/s (right) (contours color coded by streamwise (wall-parallel) velocity).

**Fig. 19** Two-point correlation function $R_{u'u'}$ in the APG region at reference point with $y = 50$ mm height in a wall-normal- spanwise plane at $x = 2,192$ mm at $U_\infty = 9$ m/s (contours color coded by normalized correlation coefficient).
Fig. 20 Amplitude weighted PDF with arbitrary units of the two negative Reynolds stress events Q2 (ejections, blue) and Q4 (sweeps, green) averaged over spanwise directions plotted in wall-normal $y$-direction for $U_\infty = 9$ m/s free stream velocity at $x = 594.5$ mm (top) and $x = 2,192$ mm (bottom) in the APG region.

4. Conclusion

An extensive data base has been captured for an adverse pressure gradient turbulent boundary layer flow. In order to achieve very high spatial resolution and spatial dynamic, 16 sCMOS cameras have been used for capturing the flow in the streamwise / wall-normal direction. Two stereo PIV systems were used for observing streamwise / wall-normal planes. To ensure statistically converged results of mean flow fields, Reynolds stresses and two-point correlations, 30,000 instantaneous flow fields were captured.

Large scale structures with an extension of several boundary layer thicknesses in streamwise direction are observed. Due to the decreasing flow velocity caused by the divergent wall, these structures grow in wall-normal direction and shrink in streamwise direction as expected from continuity. However, after compensating this effect by normalizing with the velocity at the
boundary layer edge all spatial correlation results collapse well and agree with the flat plate boundary layer results. This implies that the pressure gradient considered here does not have a significant effect on the average size and shape of the large scale superstructures. The results are consistent for the two Reynolds-numbers investigated here.

5. Acknowledgement

The authors would like to acknowledge the financial support of the EuHIT project in the frame of its Transnational Access activity. EuHIT: "European High performance Infrastructures in Turbulence" is a project coordinated by Max Plank Institute Göttingen and funded by the European Commission under Grant agreement no: 312778, in the frame of the Research Infrastructures Integrating Activity framework of FP7.
The data obtained from the measurements performed within this project will be available soon at https://turbase.cineca.it (data sets “Adverse Pressure Gradient Turbulent Boundary Layer: streamwise plane” and “Adverse Pressure Gradient Turbulent Boundary Layer: Near wall parallel planes”).

References


adverse pressure gradient turbulent boundary layer. 18th International Symposium on Applications of Laser and Imaging Techniques to Fluid Mechanics. Lisbon, July 4-7.
