Superstructures in turbulent boundary layers with pressure gradients

M. Bross1,*, F. Eich1, D. Schanz2, M. Novara2, A. Schröder2, and C. J. Kähler1

1 Institute of Fluid Mechanics and Aerodynamics, Universität der Bundeswehr München, 85577 Neubiberg, Germany
2 Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), 37073 Göttingen, Germany

Large-scale coherent structures have been observed in various wall-bounded turbulent flows. In turbulent boundary layers, streamwise elongated regions of high- and low-momentum in the log-law layer that can extent up to several boundary layer thicknesses are often referred to as superstructures. These structures contain a relatively large portion of the layer’s turbulent kinetic energy and have been shown to interact with the near-wall features. In the last few decades extensive research on zero-pressure gradient turbulent boundary layers has been done, however by comparison, the structural characteristics for adverse pressure gradient turbulent boundary layer flows are much less studied. Therefore, the three-dimensional dynamics of turbulent superstructures in a turbulent boundary layer flow is investigated in the Atmospheric Wind Tunnel Munich (AWM) measurement using a novel multi-camera 3D time-resolved Lagrangian particle tracking approach. In this study, the structural properties and dynamics of turbulent superstructures within a zero pressure gradient (ZPG) turbulent boundary layer at Reθ = 5000 or Reθ = 14 000 that then flows over a curved plate subjected to a favorable (FGP) and strong adverse (APG) pressure gradient, which eventually separates, is considered. It was found that while the average superstructure topology is modulated by decelerating flow in the APG when compared to the ZPG region the basic shape and pattern is preserved.

1 Introduction

Large-scale coherent structures present in zero pressure gradient (ZPG) turbulent boundary layers have been studied extensively in the past decades and many statistical and structural properties of the flow are well known, as documented in the extensive review by [1]. High- and low-momentum large-scale coherent motions appearing in the log-law layer called superstructures have been of particular focus in the last two decades [2–6]. An interesting property of the superstructures is their streamwise length, which is on average about $6\delta - 8\delta$. However, instantaneously they can extend up to $10\delta - 20\delta$ in the streamwise direction. In addition, they strongly meander in the spanwise direction [7–9] and it has been shown that they can carry a relatively large portion of the layer’s turbulent kinetic energy, especially at large Reynolds numbers [7]. In effect, these large-scale structures are the main contribution to the formation of the plateau/peak in the streamwise velocity fluctuations in the log-law layer, which appears at high Reynolds numbers [5, 10, 11]. Furthermore, an interaction between superstructures and the near-wall dynamics has been demonstrated [12–14]. Therefore, the investigation of these superstructures is important for understanding the overall dynamics of turbulent boundary layers.

In comparison to the large amount of investigations ZPG turbulent boundary layers the effect of a pressure gradient on statistical quantities and coherent flow motions is by far less examined and understood. As turbulent boundary layer flows with pressure gradients are integral to the aerodynamic performance of many technical components, the physical understanding of these types of flows is of great interest. Experimental measurements of APG turbulent boundary layers in [15–17] study the influence of the pressure gradient on large-scale structures and momentum transport in addition to parametric variation for the development of scaling models. However, strong agreement between various experimental and numerical databases about a scaling framework is absent which is possibly due to history effects [18]. In addition, the details of the transition from the fully attached to the partly and fully separated flow is widely unknown [19]. Recently however, using planar PIV techniques [20] investigated the interaction of incoming turbulent superstructures and a flow separation region/bubble. Using conditional statistics it was found that the superstructures shift the mean separation location either up- or downstream depending on the momentum of the superstructure. One remaining open question is how the 3D superstructure’s topology evolves from a ZPG to a strong APG and eventually separated flow. This is particularly challenging due to the large-spatial scales, in particular in the streamwise direction, involved. With the aim to capture the 3D-flow in a turbulent boundary layer subjected to ZPG, FPG, and APG over many boundary layer thicknesses, a massive experiment involving 13 cameras and 3 overlapping sub-volumes was performed and the results are discussed herein.

2 Experimental Setup

The experiments were conducted in the Atmospheric Wind Tunnel Munich (AWM), which is a Eiffel type wind tunnel located at the Universität der Bundeswehr München. The test section is 22 m long and the cross-section area measures 1.85 m × 1.85 m. To achieve a pressure gradient distribution, a turbulent boundary layer model, consisting of two S-shaped flow deflections, was installed in the wind tunnel side wall. The model was designed by [21] by means of RANS simulations. In between

* Corresponding author: matthew.bross@unibw.de, phone +49 089 6004 2566, fax +49 089 6004 3896
the flow deflections, a 4 m long flat plate is installed over which zero pressure gradient conditions are present, see figure 1a. At the downstream flow deflection, the flow is subject to a well-defined adverse pressure gradient (APG). The downstream deflection model section consists of a contour angle of the straight APG section at 18.8° relative to the wind tunnel center line. This results in an APG impact and eventually in flow separation. The boundary layer model ends in a sharp corner at \( x = 0 \) m with the aim to fix the location of the separated flow region in the field of view of the measurements. In figure 1a the boundary-layer model contours with the resulting pressure gradient distributions \( \frac{dp}{dx} \) is plotted for the investigated Reynolds number, \( Re_\tau = 5000 \) or \( Re_\theta = 14 \, 000 \) in the ZPG region.

![Fig. 1](image)

**Fig. 1:** (a) Boundary layer model coordinate system and streamwise pressure gradient distribution. (b) 3D-time-resolved Lagrangian particle tracking experimental setup. Measurements were performed in the Atmospheric Wind Tunnel Munich (AWM).

The flow was measured using a novel multi-camera multi-volume 3D Lagrangian particle tracking (LPT) technique that was able to capture a flow volume 2.9 m by 0.8 m by 0.25 m in the streamwise (\( x \)), spanwise (\( y \)) and wall-normal (\( z \)) directions respectively. This allows for the observation of turbulent superstructures in the ZPG region as they travel through the FPG and APG regions. A sketch of the camera arrangement and field-of-view is shown in figure 1b. The massive effort of planning and performing the measurements were a part of a joint campaign between the UniBw and the DLR. The multi-volume LPT measurements have been calibrated and evaluated by the DLR using their own Shake-the-Box (STB) code [22]. More details about the experimental setup, calibration, and Lagrangian particle tracking can be found in [23].

### 3 Results

In figure 2 an instantaneous snapshot of the Lagrangian particle tracks over the turbulent boundary-layer model is shown. In figure 2a the measurement volume is shown and the trajectories are color coded with the streamwise velocity. The coordinate system origin for the \( x \) and \( z \) direction are not visible in the field of view but correspond to sharp corner at \( x = 0 \) m in figure 1a where the separated flow region is fixed and \( z = 0 \) m is the wind tunnel side wall at that location. In figure 2b the top half of the boundary layer is blanked out in order to see the log-law region more clearly. In this view, the trajectories are color coded with the normalized streamwise velocity fluctuations \( \frac{u'}{\bar{u}} \) which make the low- and high-momentum superstructures visible. From this view, it is evident that both high- and low-momentum superstructures remain connected over the entire measurement FOV. Since the boundary layer thickness (\( \delta_{99} \)) in the ZPG region is approx. 160 mm, instantaneous structures between \( 10^{-15} \delta_{99}(ZPG) \) long in the streamwise direction are visible.

![Fig. 2](image)

**Fig. 2:** (a) Instantaneous particle trajectory field colored with streamwise velocity. (b) Superstructure visualization in log-law layer where trajectories are color coded with \( \frac{u'}{\bar{u}} \).

In order to assess the spatial topological characteristics a two-point correlation method was used to calculate the average large-scale structure pattern. Three streamwise locations were selected for the two-point correlation origin, i.e. one location for the ZPG, FPG, and APG regions. For each streamwise origin location, the two-point correlation was computed over the entire 3D field as a function of wall-normal position. In figure 3 iso-surfaces of the correlation coefficient \( R_{u'u'} \) for correlation calculation located in the ZPG, FPG, and APG regions are shown on the same plot. To be clear, the three different patterns in the streamwise direction shown in figure 3 are not correlated, rather the correlations are independent and just plotted in the
Fig. 3: Iso-surfaces of positive and negative correlation coefficient $R_{u'w'}$ calculated for ZPG, FGP, and APG streamwise locations view from (a) side and (b) isometric view. Correlation shown for wall position $z_0/\delta_y(ZPG)=0.2$.

What is apparent from the iso-surfaces is that the average structure pattern does not change with increasing pressure gradient. In other words, the meandering superstructures do not appear to change in their basic shape and pattern. For each pressure gradient region an elongated positive correlation in the streamwise direction is present flanked by negative correlated regions in the spanwise direction.

Fig. 4: Streamwise length scales (a) $L_1$ and (b) $L_2$ based on $R_{u'w'}$. (c) Relative inclination angle $\phi$ of positive $R_{u'w'}$ contour at a given threshold. (d) Spanwise spacing $S_2$ between $R_{u'w'}$ minima.

To investigate in more detail the effect of the pressure gradient on the average structure topology, the relevant length scales calculated from the two-point correlation analysis have been plotted as a function of wall-normal location in figure 4. The streamwise length scales $L_1$ and $L_2$ correspond to the streamwise length of $R_{u'w'}$ at a given threshold value through the wall-normal correlation origin point $z_0$. $L_1$ is calculated from a line starting at the most upstream and ending at the most downstream threshold value of $R_{u'w'}$ that passes through the $z_0$. In contrast, $L_2$ is calculated from a line starting at the most upstream and ending at the most downstream threshold value of $R_{u'w'}$ but passes through $z_0$ parallel to the wall, which is why $L_2$ is always shorter than $L_1$. The spacing length scale $S_2$ is the distance between the $R_{u'w'}$ minima in the spanwise direction. Finally, the relative inclination angle $\phi$ is calculated by fitting the contour of positive $R_{u'w'}$ at a given threshold with an ellipse and calculating the inclination angle with respect to the wall. This means that for the curved parts of the model, the
relative inclination angle is with respect to the wall angle at the origin location in the streamwise direction where the two-point correlation is calculated.

The streamwise length scales $L_1$ and $L_2$ are normalized with the boundary layer thickness in the ZPG section, $\delta_{99(ZPG)}$, in order to compare the structures in the FPG and APG with the ZPG despite the changing $\delta_{99(loc.)}$ for each pressure gradient region. For both $L_1$ and $L_2$, see figures 4a and b, there is almost no different for the ZPG and FPG regions where the maximum values appearing around a wall position $z_{0}/\delta_{99(loc.)}=0.25$ are 5.55$\delta_{99(ZPG)}$ and 4.25$\delta_{99(ZPG)}$ for $L_1$ and $L_2$ respectively. In contrast, $L_1$ and $L_2$ are significantly shorter in the APG location when scaled with $\delta_{99(ZPG)}$. The shortening of the superstructures is due to the resistance imposed by the APG because of the strong flow deceleration in the streamwise direction. This behavior is also visible in the relative inclination angle plot shown in figure 4c. For the ZPG and FPG regions the maximum relative inclination angle approaches 10° while for the APG $\phi$ is roughly 2 times larger for each $z_{0}/\delta_{99(loc.)}$ location. Interestingly, the structure spacing $S_2$ shown in figure 4d is relatively collapsed for all pressure gradient cases, especially for the wall positions $z_{0}/\delta_{99(loc.)} < 0.5$. Therefore, it can be said that the basic spanwise superstructure pattern is not physically modified under the impact of a APG when compared to the pattern in the ZPG and FPG regions.

4 Conclusions

In this work, the 3D-dimensional flow structure of an evolving turbulent boundary layer from ZPG to FPG to APG and eventually flow separation, was studied using a novel large-FOV Lagrangian particle tracking technique. The large-volume allowed for the simultaneous tracking of large-scale turbulent superstructures in the streamwise, spanwise, and wall-normal directions. In order to investigate the average superstructure topology, two-point correlations were used on the entire 3D field. It was found that the average length and inclination angle of superstructures in the log-law layer are modified by the APG eventually flow separation, was studied using a novel large-FOV Lagrangian particle tracking technique. The large-volume allowed for the simultaneous tracking of large-scale turbulent superstructures in the streamwise, spanwise, and wall-normal directions. In order to investigate the average superstructure topology, two-point correlations were used on the entire 3D field. It was found that the average length and inclination angle of superstructures in the log-law layer are modified by the APG comparison to the FPG and ZPG regions. In contrast, the average structure spacing in the spanwise direction does not physically change under the impact of the APG.

In addition to the average structure properties, this data set can be used to investigated the temporal evolution of superstructures. Furthermore, the availability of Lagrangian trajectories allows for the investigation of how individual trajectories behave and their relationship with the turbulent superstructures. The analysis of the Lagrangian properties of the flow is ongoing.

Acknowledgements  This work is supported by the Priority Programme SPP 1881 Turbulent Superstructures funded by the Deutsche Forschungsgemeinschaft project numbers KA1808/211, KA1808/212, and SCHR1165/51. In addition, this work was partially funded by the DFG project number KA1808/14.

Open access funding enabled and organized by Projekt DEAL.

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