Detection of coherent structures in a turbulent boundary layer with zero, favourable and adverse pressure gradients

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Abstract. The paper presents the analysis of turbulent coherent structures found in a turbulent boundary layer subjected to zero, favourable and adverse pressure gradient. The analysis of the shape of conditionally averaged traces of $u$ and $v$ velocity components obtained by VITA (Variable Interval Time Averaging) technique based on signals recorded by X-wire probe allows to detect four types of coherent structures. The paper documents a presence of coherent vortical structures of positive or negative vorticity moving upward and downward. It is shown also that the acceleration and deceleration of the mean streamwise velocity, due to the pressure gradient, modifies the vortex convection velocity magnitude and the angle. This effect is clearly seen especially for the adverse pressure gradient flow, where $Q$ events in first and fourth quadrants are enhanced near the wall.

1. Introduction

During last years significant progress has been made towards understanding of turbulent boundary layers (TBLs). The investigations were directed not only towards the better description of the mean flow and the analysis of global characteristics, including scaling problems (George & Castillo, 1997), but also to the understanding of discovered organized motions and the interpretation of bursting phenomena (Kim, Kline & Reynolds, 1971). Recent experimental and computational studies suggest that significant part of wall turbulence could be described in terms of deterministic structures. The near wall region is characterized by the presence of low-speed streaks and hairpin vortices that used to be assembled into large-scale coherent groups termed vortex packets. These structures are qualitatively consistent with the horseshoe vortex model proposed by Theodorsen (1952). The oscillation and then the breakup of these structures, termed as bursting phenomena, cause high gradients of velocity in time and in space. Kim, Kline & Reynolds (1971) revealed that the bursting process, which produces roughly 70% of total turbulence, is a result of brake-up of shear layer caused mainly by ejection event in a buffer layer. Subsequently, Corino & Brodkey (1969) proved that this event was closely related to a sweep event that is a large-scale motion towards the wall.

One of the most widely used method to detect bursting phenomena is a VITA technique, developed by Blackwelder & Kaplan (1976). Although, the large-scale motions i.e. ejection and sweep could not be identified directly with this technique, it allows to observe the brake up
of large-scale structures into smaller scales characterized by high gradients of a velocity signal. Application of VITA method together with quadrant analysis simultaneously to streamwise and normal velocity components allows to explain the origin of the bursting process. Quadrant analysis is commonly used to describe a relation of \( u \) and \( v \) velocity components in \( xy \) plane. The \( xy \) plane can be divided into four quadrants, where four events commonly named as Q1 (\( u > 0, v > 0 \)), Q2 (\( u < 0, v > 0 \)), Q3 (\( u < 0, v < 0 \)) and Q4 (\( u > 0, v < 0 \)) exist. It means that quadrant analysis allows to identify bursting process i.e. sweep (Q4) event and ejection (Q2) event (Adrian, Meinhart & Tomkins, 2000). For zero pressure gradient (ZPG) TBL the flow is dominated by Q2 and Q4 events, which apart from inner region, are equally important. Q1 and Q3 events in the whole boundary layer are exceptionally observed.

From the viewpoint of complexity of the physical phenomenon as well as practical applications the most important is the knowledge of transport processes in the TBL subjected to the impact of pressure gradient and especially adverse pressure gradient (APG). As it is clear from many studies (see Krogstad & Skare, 1974; Drozdz, Elsner & Drobniaik, 2011; McEligot, Brodkey & Eckelmann, 2009) the energy production of the Q events is different under the pressure gradient. The research on bursting phenomena in the TBL subjected to the APG were carried out, among the others, by Krogstad & Skare (1974) and by Drozdz, Elsner & Drobniaik (2011). Their analysis allowed to conclude that, APG flows, especially close to the wall, are strongly dominated by high speed fluid toward the wall (Q4 event) and high speed fluid outward the wall (Q1 event) on the other hand Q2 and Q3 events barely disappear. According to Drozdz, Elsner & Drobniaik (2011) the enhancement of Q4 and Q1 events of ascending and descending structures respectively, especially near the wall is an effect of the delayed reaction of vortical structures on the mean velocity deceleration. McEligot, Brodkey & Eckelmann (2009) show, in turn, that for the favourable pressure gradient (FPG) flow the energy balance of Q2 and Q4 events is achieved close to the near wall peak of fluctuations. In near wall region Q4 event dominates, but in the outer layer the Q2 event plays the key role in turbulence energy production.

The paper aims to propose the interpretation of vortical structures behavior in the TBL under zero, favorable and adverse pressure gradient. The research is based on examination of velocity signals recorded with hot-wire probe across boundary layer thickness. Application of VITA technique combined with quadrant analysis allow to demonstrate such properties of vortices motion as: swirling direction, ascending or descending direction and angle of the motion, as well as the relative speed of vortex propagation. Analysis of those features helps in understanding of bursting phenomena in TBL subjected to varying gradient conditions.

2. Test section and measuring technique

To investigate the effect of the pressure gradient on the coherent motion in the TBL an experimental study has been undertaken. The measurements of the velocity field with the X-wire probe were performed in an open-circuit wind tunnel, where the TBL developed along the flat plate, which was 2807 mm long and 250 mm wide. The upper wall of test section was shaped according to the assumed distribution of pressure gradient corresponding to the conditions encountered in axial compressor blading (Figure 1a). The velocity at the inlet plane outside the boundary layer was 15 m/s, while the turbulence intensity equals \( Tu = 0.4 \% \). Tripping of boundary layer after the leading edge of a flat plate, allowed to obtain value of Reynolds number \( Re_\theta = 3000 \). For the purpose of current investigations three cross-sections from zero, favorable and adverse gradient regions were selected. The location of those cross-sections was shown in Figure 1b) by dashed lines, while corresponding parameters are given in Table 1. The static pressure distribution (Figure 1b) was measured at the flat plate with DATA INSTRUMENTS DCXL01DN pressure transducer connected to KULITE D486 amplifier. Two velocity components signal from X-wire probe with diameter \( d = 5 \mu \text{m} \) and length \( l = 1.25 \text{ mm} \).
Figure 1. The view of test section a), corresponding static pressure distribution along the plate b).

(Dantec Dynamics 55P52) where analyzed. The X-wire probe was combined with the DISA 55M hot-wire anemometer connected to 14 bit PC card. Acquisition was maintained at frequency 50kHz with 10 seconds sampling records.

Table 1. Location and characteristic parameters of measuring cross-sections.

| No. | $x_s$ [mm] | $Sg$ [-] | $u_r$ [m/s] | $dP_x/dx$ [Pa/mm] | $U_{\infty}$ [m/s] | $PG$ | $H$ [-] |
|-----|-------------|-----------|-------------|------------------|------------------|------|--------|
| 1   | 197         | 0.185     | 0.62        | −0.08            | 15.14            | ZPG  | 1.39   |
| 2   | 367         | 0.344     | 0.74        | −0.26            | 16.97            | FPG  | 1.31   |
| 3   | 667         | 0.625     | 0.47        | 0.19             | 14.47            | APG  | 1.57   |

3. Vortical structures detection based on VITA method

As it was said in the first section the commonly applied VITA method allows to detect events characterizing ejection and sweep process in the TBL. This method was improved by Drozdz, Elsner & Drobnia (2011), who proposed to extend detection process by detection of four possible combination of instantaneous gradients of $u$ and $v$ velocity traces. Application of those improved VITA technique supplemented by quadrant decomposition allows to identify not only the very vortex but also its rotation and direction of the motion at the measuring point. The VITA detection scheme is based on the analysis of a running variance $\text{var}(t, T)$ of a detection parameter.
Figure 2. Changes of $< u >$ and $< v >$ of four VITA structures types along TBL thickness under ZPG: retrograde in left column, prograde in right column, ascending in upper row, descending in lower row ($N$—number of detection for particular structures).

$$a(t) \text{ given by equation:}$$

$$var(t, T) = \frac{1}{T} \int_{t-T/2}^{t+T/2} a(t')^2 dt' + \frac{1}{T} \int_{t-T/2}^{t+T/2} a(t') dt'^2$$

(1)

Parameters of the detection process were properly tuned in order to obtain the best possible efficiency of the procedure. The most important are a time averaging window $T$, which should be related to the scale of dominant structure and a threshold value $k(u')^2$ of detection function $D(t, T)$ used to detect structures in both distributions of $var(t, T)$ calculated separately for $u$ and $v$ velocity signals. To determine the signs of the gradients of $u$ and $v$ velocity components a slope detection function $D(t)$ was used which takes following values $\{-2, -1, 1, 2\}$. Sign in the detection function describes the slope of gradients of $u$ velocity component during detection, values 1 and 2 correspond to ascending and descending vortices respectively. Finally, for each type of the four possible structures the phase-averaging procedure of $u$ and $v$ distributions was applied. Further details of modified VITA detection scheme can be found in Drozdz, Elsner & Drobiński (2011).

Figure 2 presents phase-averaged $u$ and $v$ velocity components of four types of VITA structures. Three specific locations along $y$ direction has been chosen i.e. at $y^+ = 22.6$, in the log region $y^+ = 173$ and in the wake region at $y^+ = 834$. The structure characterized by the positive gradient $+$ of $u$ and the negative gradient $-$ of $v$ velocity components, which is marked as $(+,-)$, can be interpreted as the so-called retrograde (positive vorticity) vortex passing through the sensor in the direction from third to first quadrant. The VITA method also detects the negative gradients $-$ of $u$ and the positive gradient $+$ of $v$ velocity components, marked as $(-,+)$, which are the effect of prograde vortex (negative vorticity) passes through the sensor.
This approach allows to recognize prograde vortex (left column of Figure 2) and retrograde vortex (right column of Figure 2). For both vortical structures two convection directions exist: ascending (moving away from the wall - upper row of Figure 2) and descending (moving towards the wall - lower row of Figure 2). Rotation direction in the schemes indicates type of vortex, while the black arrow shows the vortex passage direction through the sensor location. Zero level corresponds to the mean values of $U$ and $V$ velocity components. Ascending or descending character of vortex movement can be confirmed also from the analysis of mean values of the phase-averaged distributions of velocity components. One can observe (Figure 2) that for ascending vortices the distributions of $<u>$ velocity component is slightly shifted towards negative values, while $<v>$ distribution is shifted towards positive values. This confirms that ascending structure arrives from a lower momentum zone thus have a lower convection velocity than mean velocity $U$ at the measuring point. The opposite situation is visible for descending structures. One can observe in Figure 2 that for the ascending vortices their velocity components are in opposite phase and give negative Reynolds stresses $-uv$ (i.e. Q2 and Q4 events). While the retrograde ascending vortex passing the measuring point then it gives Q2 event before and Q4 event after the vortex centre while for the prograde ascending vortex these events change their order. Because most of the vortices are moving upward the wall, the negative Reynolds stresses dominates in the TBLs. While descending vortices passing through the measuring point the velocity components are in phase and give, less common, positive Reynolds stresses $uv$ (i.e. Q1 and Q3 events). Figure 2 also contains information about number, marked as $N$ in the legend, of detected particular structures.

4. Impact of pressure gradient on the vortex movement in TBL

The phase-averaged velocity components presented in Figure 2 are composed for ZPG conditions. It is the cross-section marked as 1 in Figure 1b. Based on those data one can determine the relative movement angle of detected vortical structures. The literature data from two point correlations (Osterlund, Lindgren & Johansson, 2003) indicates that the coherent structures in the boundary layer are more inclined in the log region than in the vicinity of the wall. One can also deduce based on Figure 2 that near the wall the vortices movement is less inclined with respect to the wall, which leads to high value of $v$ component. In the log region due to the steppe angle of vortex motion the transfer of energy from $v$ to $u$ component occur. All Q-type events loose their energy with the increase distance from the wall, apart from Q2 event in the weak region, which strength results from smaller vortex velocity in comparison with mean local velocity.

For the strong FPG, where the pressure gradient reaches minimum (see cross-section 2 in Figure 1b), different picture of vortices motion is observed. Figure 3 presents phase-averaged distributions of velocity components at $y^+ = 27$, 183 and 813. Under FPG condition the higher contribution of $v$ component is observed, what means much more vortices are moving parallel to $x$ direction. In comparison with ZPG case the contribution of Q4 events for ascending vortices is lower. It is however compensated by the enhancement of Q2 events. On the other hand descending vortices produce stronger Q3 events and weaker Q1 events. The further distance from the wall the lower difference between $<v>$ and $<u>$ peak to peak values, what is not observed for ZPG. The domination of Q2 and Q3 events, respectively for ascending and descending structures is caused by the lower velocity of vortices propagation in comparison with mean local velocity. It is observed as a negative shift of $<u>$ distribution noticed for all structures.

The last cross-section is located slightly downstream the maximum of APG (see cross-section 3 in Figure 1b), where, as is clear from the previous studies (Drozdz, Elsner & Drobnia, 2011), the strongest influence of APG is observed. Authors (Drozdz, Elsner & Drobnia, 2011)
demonstrated the activation of Q4 and Q1 events and the suppression of Q2 and Q3 events under APG. Current results (see Figure 4) confirm this phenomenon, indicating further that the enhancement of Q4 and Q1 events results mainly from \( \langle u \rangle \) contribution. It should be added, that this dominant contribution is observed as far as in the log region and is a reason for appearance of the outer peak of the turbulence production. However, activity of the Q4 and Q1 events vanish with the increased distance from the wall and already for \( y^+ = 180 \) almost the same strength of events as for ZPG flow is observed. Enhancement and suppression of particular Q-type events is mainly caused by delayed reaction of vortices on the drop of the streamwise mean velocity.

The detailed analysis of the APG flow can be found also in Materny, Drozdz, Drobnick & Elsner (2008). Authors conclude that the near-wall region grow much more slowly than the outer part of the boundary layer, what in turn implies that most contribution to APG boundary layer growth originates from areas located far from the wall. The bursting process governs the production of turbulence not only near the wall, but also as high as to the end of logarithmic zone, especially in APG region. Appearance of the second peak of TBL confirms that the outer region drives the downstream development of TBL. It is accompanied by strong increase of the boundary layer thickness (\( \delta \)), what is not observed for ZPG and FPG flows. This fast build-up of \( \delta \) is combined with high positive value of mean \( V \) velocity component. High positive \( V \) velocity together with the enhancement of \( u \) fluctuations indicate that vortices move at higher angle with respect to the wall. One can speculate that the near wall structures are thrown incidentally in the log region and have no time to evolve in to classical horseshoe or hairpin vortices. It is the reason why in APG TBL the longitudinal structures are hardly observed.

Figure 3. Changes of \( \langle u \rangle \) and \( \langle v \rangle \) of four VITA structures types along TBL thickness under FPG: see description of Figure 2.
Figure 4. Changes of $< u >$ and $< v >$ of four VITA structures types along TBL thickness under APG: see description of figure 2. Arrows indicate changes in $y$ direction.

5. Conclusions

Presented interpretation of detected coherent structures with the use of VITA method supplemented by the quadrant decomposition gives a consistent explanation of turbulent motion. The acceleration and deceleration of mean streamwise velocity due to pressure gradient, modifies vortices convection velocities and angles of motion. This modification is clearly seen for APG region where Q4 and Q1 events are enhanced, and the increased angle of vortices motions occur. This phenomenon is a reason of a second maximum appearance of the turbulent production in the log region. Enhancement and suppression of particular Q-type events is mainly caused by the delayed reaction of vortices on the change of streamwise mean velocity. Delayed reaction is probably caused by resistance of the vortical structure against pressure forces. Highly energetic vortical structures have some kind of inertia caused by its rotation so they are nearly independent of the change of pressure forces. Changes of the amplitudes relation of the velocity components is caused by changes of the angle of motion of the vortices. When the angle of motion increasing, with respect to the wall, then $u$ component of velocity fluctuations is amplified while $v$ component is damped. Under FPG condition the higher contribution of $v$ component near the wall is observed. The further distance from the wall the flow pattern is similar to that that observed for ZPG case.

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