INFLUENCE OF PRESSURE GRADIENT ON VORTICAL STRUCTURE GENERATION IN TURBULENT BOUNDARY LAYER

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1 Introduction

It is already known that the 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. In these vortex packets the bursting process occurs and causes high gradients of velocity in time and in space. Kim et al. (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 followed by sweep event. It was shown that the ejection events are important throughout the whole boundary layer, while the sweeps events appeared to be mainly confined to a region close to the wall. The effect of those phenomena is the appearance of many fine-scale structures in the flow.

Study of bursting process in pressure gradient flows and especially APG are much more important from the viewpoint of complexity of the physical phenomenon as well as practical applications. The structure of turbulent boundary layer (TBL) developed on a flat plate, which was 2807 mm long and 250 mm wide. The test section is located in the rear part of the wind tunnel. Its upper wall of test section was shaped according to the assumed distribution of pressure gradient corresponding to the conditions encountered in axial compressor blading (Dróźdż and Elsner, 2013). Test section as well as pressure distribution is shown in Figure 1. It is seen that pressure gradient values varies within the range of $-0.27\text{÷}0.28 \text{ Pa/mm}$.

2 Experimental details

The experiment was performed in an open-circuit low-speed wind tunnel of Institute of Thermal Machinery, Czestochowa University of Technology. Velocity profiles were measured with single hot-wire anemometry probe of a diameter $d = 3\text{mm}$ and length $l = 0.4 \text{ mm}$ (Dantec Dynamics 55P31). Those measurements were supplemented with X-wire probe of wire diameter $d = 5\text{mm}$ and length $l = 1.25 \text{ mm}$ (Dantec Dynamics 55P61). The probes were combined with the DISA 55M hot-wire bridge connected to 14 bit PC card. Acquisition was maintained at frequency 50kHz with 10 seconds sampling records. For the assumed sampling frequency the non-dimensional inner scale representation was $f^+ \approx 1$. During the measurements ambient conditions were carefully measured with single hot-wire anemometry probe of a diameter $d = 3\text{mm}$ and length $l = 0.4 \text{ mm}$ (Dantec Dynamics 55P31). Those measurements were supplemented with X-wire probe of wire diameter $d = 5\text{mm}$ and length $l = 1.25 \text{ mm}$ (Dantec Dynamics 55P61). The probes were combined with the DISA 55M hot-wire bridge connected to 14 bit PC card. Acquisition was maintained at frequency 50kHz with 10 seconds sampling records. For the assumed sampling frequency the non-dimensional inner scale representation was $f^+ \approx 1$. During the measurements ambient conditions were carefully
controlled. The scatter of ambient temperature at the end of the test section did not exceed 0.2°. At the same time the free-stream velocity was monitored by means of a Prandtl tube. The scatter of freestream velocity was found to be around 0.2% of the mean value. The position at the wall closest point of the hotwire probe was determined using the mirrored image.

3 Vortical structures detection 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. The improved method (Dróżdż et al. 2011), allows to identify the vortical structures, rotation and direction of the motion at the measuring point. One of the features that distinguishes this method from the other, known from the literature, is the application of detection algorithm on both u and v components separately. This increases the sensitivity of procedure, especially when the dudy is minor.

Figure 2 presents phase-averaged $u'$ and $v'$ of four VITA detection types.

Figure 2: Distributions of phase-averaged $\langle u \rangle$ and $\langle v \rangle$ of four VITA detection types.

Figure 3: Fluctuations components $u'$, $v'$

The distributions of $u'$ and $v'$ measured by X-wire probe are presented in Figure 3. The $S_g$ is the nondimensional distance from inlet plane, where zero pressure gradient is present. Distributions of $u'$ are not very sensitive to FPG (Fig. 3a), while in APG strong increase of $u'$ in the outer region is observed (Fig. 3b). The similar changes in FPG are visible for $v'$ profiles (Fig. 3c), whereas the reaction on APG is much stronger, but this time in the wall vicinity and not in the outer layer (Fig. 3d).
The new detection method applied for various distances from the wall, in the whole range of variation of pressure gradient, allows to determine the bursting frequency, i.e. so called mean bursting interval (MBI) as well as phase averaged $< u >$ and $< v >$ velocity components of four types of VITA detections. Based on the last set of data the phase-averaged fluctuations $< u' >$ and $< v' >$, are determined. Figure 4 presents $< u' >$ and $< v' >$ distributions for given traverses for FPG (Figure 4a) and APG (Figure 4b). As can be seen, favorable pressure gradient has a very small influence on the shape of the distributions. However, under adverse pressure gradient a substantial reduction of $< v' >$ value in the inner layer (below $y^+=100$), while in the outer region (above $y^+=100$) the strong increase of $< u' >$ value is observed. It can be noticed that those distributions are quite similar to distributions of $u'$ and $v'$ presented in Figure 3, although the changes of the former are much stronger.

One of the reasons for this could be the expected increase of vortex trajectory inclination in the APG conditions, what explains the schematic sketch in Figure 5. When the center of the vortex passes through the measuring point the probe senses the velocity fluctuations in the direction perpendicular to the trajectory of the vortex. With the increase of trajectory inclination the $u$ velocity component increases while $v$ component decreases. It seems therefore that the increase of the trajectory inclination present in the APG can be partly responsible for the enhancement of fluctuations in the outer region of boundary layer and be partly responsible for the appearance of the outer peak.

Valuable information about the bursting process is provided by the mean bursting interval (MBI) parameter. MBI is a measure of the average time between detections. It means that if the MBI decreases the level of burst energy contribution increases. If the process is influenced by generation of phenomena that occur in the inner or outer layer zone, the appropriate time scale selection should normalize MBI values in such a way, that the result is independent of other conditions. For the analysis used in the paper the inner viscous scale was adopted and the resulting parameter is marked as $MBI^+$.

Figure 6 presents $MBI^+$ as a function of $y^+$ for FPG and APG conditions. It is seen that along the flow the viscous scaled $MBI^+$ is almost constant in the inner region of turbulent boundary layer, while in outer zone the increase of this parameter for FPG and the decrease for APG is noticed. It suggest that in the outer region of pressure gradient flows the bursting process is driven by the additional mechanism than in the zero pressure gradient case.

The next part concerns the analysis of the change of the bursting frequency separately for four types of vortical structures detected for APG. X-wire measurements make it possible to detect four types of vortices i.e. retrograde ascending (N(+−)), prograde ascending (N(−+)), retrograde descending (N(−−)) and prograde descending (N(++) vortices number. The results presented in Figure 7 are reduced by total number of detected vortices N from X-wire probe. It is seen that number of detections is different for each type of structures. The dominant type of the structure is retrograde ascending one, which fraction is almost...
two times higher the fraction of detections observed for prograde ascending. Significantly smaller fraction is of prograde descending structures. It can be noticed that the percentage share of detections for each type of vortices varies as a function of y+. The percentage share of the dominant N(+)−=N structures strongly decrease toward the edge of the boundary layer, whereas the trend is reversed for the outer structures. However, the increase in the wake region is observed for both prograde vortices. It is worth to note that at the edge of boundary layer the ascending and descending structures are more or less equally frequent. It could support observation of Adrian (2007) that at the edge of boundary layer the direction of prograde vortices trajectory is changing from ascending to descending due to bulge structures related to the large-scale motions. In turn, the impact of the pressure gradient is not too pronounced. Some changes are observed mainly close to the wall, where share of ascending structures decrease while descending structures increase along the flow. It means that under the influence of APG the change of the vortex motion from ascending to descending appears. The drop of the inner scaled bursting process in the near wall region (see MBI+ distribution in Figure 6) could be due to the increased percentage share of descending vortices coming from outer zone. The increased energy of small scales not only in the outer, but also in the near wall region was also observed by Harun et al. (2013) for higher Reynolds number with APG conditions.

5 Conclusions

The analysis of coherent structures within the turbulent boundary layer with the use of modified VITA technique was performed. It allows to extract subtle information, i.e. convection velocity or trajectory direction, and provides consistent explanation of turbulent flow using single point measurement technique. It gives an evidence of four types of vortical structures present in the TBL which are responsible for the production of Q-type events.

It was shown that the mean time interval between detections, inversely proportional to the number of structures, has an impact on the level of $\langle u' \rangle$ and $\langle v' \rangle$ fluctuations. The presented analysis confirmed, that the turbulent kinetic energy production is closely related to the presence of coherent structures and that pressure gradient conditions have a distinct impact upon the intensity of bursting process. In particular one may conclude that the bursting process for APG is damped near the wall (where the first maximum of fluctuations occurs) and enhanced in the outer region of boundary layer where the second maximum of fluctuations is located. The influence of FPG gradient is much less visible.

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References


