Convection Velocity Variation as a Result of Amplitude Modulation Phenomena

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Abstract The paper discusses the method of convection velocity estimation in turbulent boundary layer using its relationship with amplitude modulation mechanism. To verify this method the two-point correlation measurements using hot-wire technique was applied in strong adverse pressure gradient flow for two Reynolds numbers. Additionally, streamwise velocity profiles were measured in the same locations. It was shown that the changes in the convection velocity due to Reynolds number and pressure gradient results from amplitude modulation mechanism. The convection velocity in the strong adverse pressure gradient region can be two times higher than the mean velocity in the buffer layer.

1 Introduction

For the understanding physics of the turbulent boundary layer (TBL) the study of the convection velocity U_C of vortical structures is extremely important. It is known that the transport velocity depends on the size of the individual structure, the stage of their development and their location in the boundary layer [1]. The most common published research focuses on the study of small scale motion in zero pressure gradient (ZPG) TBL [1–3]. Recent studies of Dróżdż and Elsner [4] indicate that the U_C in ZPG flow can be estimated using cross product term $\overline{3u_L^+u_S^{+2}}/\overline{u^{+2}}^{3/2}$ of decomposed skewness factor (S_f) calculated according to Mathis et al. [5], where subscripts L and S denote the large and the small-scale components of the streamwise velocity fluctuations u, respectively. This term is also alternative measure of amplitude modulation [5] resulting from the large-scale motion (LSM). As the LSM becomes increasingly energetic at higher Reynolds numbers or with pressure gradient, their interaction with the inner small-scale motion is also enhanced [6–8]. This

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Table 1 Parameters of analyzed TBL profiles

Symbol	PG case	Re	H	u_τ [m/s]	Δx^+	Δx^+_{max}
◁	ZPG	6400	1.35	0.72	–	–
○	ZPG	10,200	1.32	0.37	–	–
△	APG	10,900	1.81	0.22	10	60
□	APG	18,100	1.62	0.43	40	240

was confirmed by the decrease of S_f in the flow subjected to favourable pressure gradient (FPG) conditions and an adequate rise in the flow subjected to adverse pressure gradient (APG) conditions, which was shown by Harun et al. [7]. Dróżdż [8] suggests that because of hardly observed high and low speed regions the production of small-scale turbulence in FPG can be considered rather as a random process. On the other hand in the APG, the LSM enhances the production of the small-scale turbulence, although only in high-speed regions. Therefore, it can be expected that small-scale structures in APG flow have higher U_C than the mean velocity [8].

In order to estimate the convection velocity U_S the following relation, based on amplitude modulation skewness factor term, was proposed [4]:

$$U_S^+ = U^+ + \frac{\overline{3u_L^+ u_S^{+2}}}{\overline{u^{+2}}^{3/2}} C^+ \tag{1}$$

where U^+ is the non-dimensional mean velocity and C^+ is the non-dimensional scale. The formula of convection velocity estimation using the proposed relation was introduced and verified in the TBL under ZPG conditions. It was concluded that the change of small-scale structures U_C can be the result of the amplitude modulation mechanism.

In the paper the verification of the proposed formula (1) using two point correlation method in strong APG flows was presented. This was done by employing two hot-wire probes separated by a given distance in the near wall region (see Table 1).

2 Test Section and Methodology

2.1 Test Section

The data comes from the experiment performed in the open circuit wind tunnel shown in Fig. 1, where the TBL was developed along the flat plate, which was 6870 mm long. The inlet rectangular channel with a length of 5.035 m located upstream the proper test section has the triangular corner inserts to control corner vortices and two pairs of suction gaps aimed to reduce boundary layers on the side walls. A slight inclination of the upper wall helped to keep zero pressure gradient (ZPG) conditions

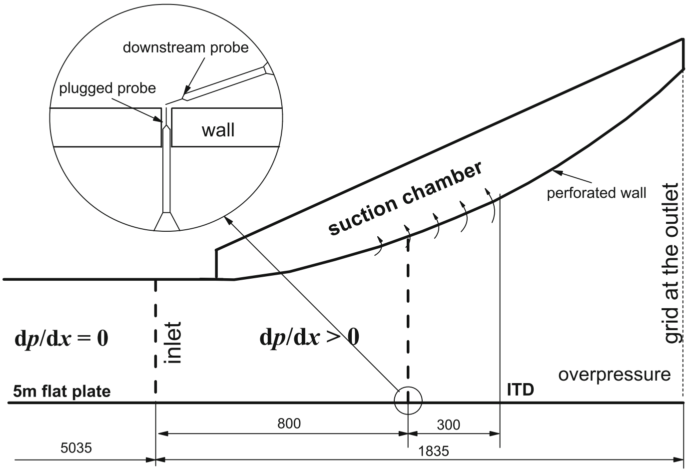

Fig. 1 Test section geometry with correlation probes setup

at the inlet. The specially designed test section located at the end of the wind-tunnel (see Fig. 1) is equipped with perforated wall. By playing with the suction flux it is possible to generate strong pressure gradient conditions leading to separation on the lower flat plate. The static pressure in the test section is increased by the throttling on the outlet of the test section.

The velocity measurements were performed with hot-wire anemometry CCC developed by Polish Academy of Science in Krakow. The analysis was conducted based on measurements of a single hot-wire probe with diameter $d = 3\ \mu$m and length $l = 0.4$ mm (modified Dantec Dynamics 55P31). The acquisition was maintained at frequency 25 kHz with minimum 30 s sampling records. For two point correlation the pair of the same probes was used.

To have the verified the reference friction velocity u_τ along the flow the fringe skin friction (FSF) technique was also applied. The facility is equipped with the computer-controlled traversing system (in streamwise x and wall-normal y direction). The traverse carriage was driven over the maximum wall displacement of 180 mm by a servo motor with the step equals 0.01 mm and uncertainty of the drive step equals 0.001 mm. In the streamwise direction the drive step was equal 0.375 mm with the uncertainty of the drive step equals 0.0375 mm.

2.2 Convection Velocity Estimation

The two-point correlation method employing two single hot-wire probes was used in the present work. During the measurements the first probe was plugged in the wall. The other probe was situated above the first one and shifted downstream the flow (see Fig. 1). The averaged value of U_C was calculated from six streamwise probes distances Δx on to the maximum probe distance Δx_{max} shown in Table 1. The output voltage from two hot-wires were sampled simultaneously and the time shift was obtained from conditionally averaged velocity signals processed using Wavelet Transform Analysis (WTA). Detection of the most dominant structure in the velocity signal (setting properly time scale of the wavelet) gives the good representation of the mean convection velocity. The analysis of velocity signal measured by downstream traversing probe using first derivative of Gaussian function was performed. In order to detect the accelerations and decelerations events in the signal the threshold level was applied on the transformated signal. Local extrema of the transform was used as detection time, while the maximum or minimum of wavelet transform was the criterion splitting the rapid acceleration or the rapid deceleration detections. The scale of the wavelet a was related to the scale of the dominant structure for which the maximum number of detected events N occurs. The criterion of detection threshold value applied on the wavelet transform was varied in order to obtain the high number of detections ($N > 4000$). The high number of detections ensured the smooth phase-averaged waveforms captured by the traversing probe which was the final result of the procedure. It was averaged on the time detection of the acceleration (+) and deceleration (−) events detected in velocity signal from downstream probe using the following formula:

$$\langle u(\tau)\rangle^{\pm} = \frac{1}{N^{\pm}} \sum_{i=1}^{N^{\pm}} u(t_i^{\pm} + \tau) \tag{2}$$

where t is the detection time for ith detection, while τ is the phase time.

The $\Delta\tau$ shifts of phase-averaged events on stationary probe for consecutive Δx shifts of traversing probe was used to calculate U_C. The advantage of the method is the undisturbed measurements on both probes since the traversing probe was always downstream the plugged probe, which was also very close to the wall. Because the number of accelerations and deceleration detections was different the weighted averaging, depending on the number of positive and negative events, was introduce in order to calculate mean convection velocity value.

3 Results

The convection velocity obtained from two-point correlation measurements was used to verify the U_S calculated using cross-product term of the skewness factor, $(\overline{3u_L^{+}u_S^{+2}}/\overline{u^{+2}}^{3/2})$, where the cut-off timescale separating large- and small-scale signals was set on 200 viscous units. In order to verify the universality of the constant $C^{+} = 16.34$ two Reynolds number in ZPG and in strong APG conditions were considered (Table 1). The pressure gradient parameter $\beta = -\frac{\delta^* U_\infty}{u_\tau^2}\frac{dU_\infty}{dx} = 17$, where δ^* is displacement thickness, and U_∞ is free stream velocity.

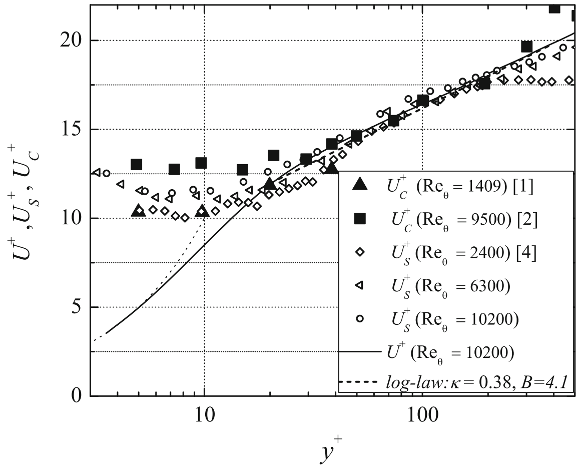

Fig. 2 Estimated convection velocities U_S and literature data values of U_C for ZPG conditions for analyzed cases (Table 1)

Figure 2 presents the estimated profiles of U_C (open points) using (1) in ZPG flow. The profiles were compared to mean velocity profile (thin black line) and to the data of Krogstad et al. [1] and Österlund [2]. It can be noticed that estimated U_C profiles are in satisfactory agreement with the literature data. The dependence of U_C^+ with Reynolds number is also observed as the amplitude modulation increases with Reynolds number.

The estimated convection velocity for APG were compared with the measured convection velocity using two-point correlation method and shown in Fig. 3. The last data are shown with the error bars related to the uncertainty of the streamwise traversing system. Additionally, the mean velocity profiles (black line) and log-law profile (dotted line) were shown. As can be seen results agree well with the profiles

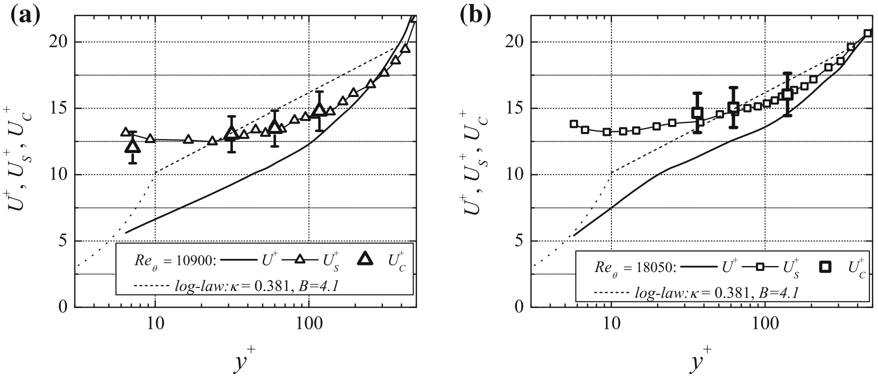

Fig. 3 Estimated convection velocities U_S and measured U_C for APG: $Re_\tau \approx 10{,}900$ (**a**), $Re_\tau \approx 18{,}100$ (**b**)

obtained according to (1). The convection velocity in the strong APG region can be two times higher than the mean velocity in the buffer layer. It can be also noticed that with the increase of Reynolds number the U_C distribution is similar to the one from ZPG conditions.

4 Conclusions

The convection velocity estimation based on the measure of amplitude modulation was verified with the convection velocity obtained from two-point correlation in the APG conditions. It was shown that the changes in the convection velocity due to Reynolds number or pressure gradient result from amplitude modulation mechanism. Distributions of the convection velocity based on the measure of amplitude modulation for both Reynolds numbers are in satisfactory agreement with the convection velocity based on two-point correlation, which confirms the correctness of C^+ value estimated for ZPG conditions. The convection velocity in the strong APG region can be two times higher than the mean velocity in the buffer layer.

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