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Relation of skewness factor and convection velocity in turbulent boundary layer

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Abstract The paper is devoted to prove the relation between skewness factor and convection velocity in turbulent boundary layer. It appears that skewness factor can be used as an indicator of convection velocity of coherent structures, which is not always equal to the average flow velocity. The analysis has been performed based upon velocity profiles measured with hot-wire technique in turbulent boundary layer with pressure gradient corresponding to turbomachinery conditions. The results show that the cross product term of skewness factor decomposed by spectral filtering, which is also alternative measure of amplitude modulation, describes the convection velocity in zero pressure gradient turbulent boundary layer.

INTRODUCTION

Physical significance of large-scale motions and especially they influence on small-scales turbulence amplitude modulation near the wall remains unknown. Despite the fact that the large-scale motion itself has no documented impact on near-wall turbulent energy its footprint is visible looking on the streamwise skewness factor [1], defined as:

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

where: u_L is low-pass and u_S high-pass velocity signals, where L and S denotes large and small–scale component related respectively to outer and inner peak of streamwise velocity fluctuations. The cross product term $3\overline{u_L^{+}u_S^{+2}} / \overline{u^{+2}}^{3/2}$ of the skewness factor reveals strongest changes in comparison with other three terms and is a good alternative to quantify of the amplitude modulation. The relationship between turbulence modulation and the skewness in wall-bounded flow was confirmed for high Reynolds number zero pressure gradient turbulent boundary layers. As the large-scale motion become increasingly energetic at higher Reynolds numbers their interaction with the inner small-scale motion is also enhanced [2]. On the other hand Harun et al. [2] demonstrated that the flow in favorable pressure gradient (FPG) and adverse pressure gradient (APG) conditions is also driven by large-scale motions. Especially, Harun et al.[3] and Dróżdż [4] show that the skewness factor decreases in the flow region subjected to FPG, while it increases in the APG. Moreover, Dróżdż [4] suggested that due to the lack of high- and low-speed regions the production of small-scale turbulence in FPG could be considered as random. In the APG, where the large-scale motion drives the production of small-scale turbulence the production is increased but only in high-speed regions. Therefore, the small-scales should have a higher convection velocity than the mean velocity. This may explain why with the increase of Reynolds number the boundary layer is more resistant to separation in APG.

The study of the interaction between "inner" small-scale motion and the large-scale motion can also be the basis to explain the variation of turbulent quadrant events distribution, especially the so-called sweep and ejection events, in pressure gradient flows. Sweep is an event, which has positive streamwise and negative wall-normal fluctuations, while ejection event has opposite relation. It was observed that, for turbulent boundary layer in zero pressure gradient (ZPG), the sweep and ejection events are equally important for the turbulence production [5]. Dróżdż [4] showed that this is consistent with the equality of convection velocity with the mean velocity, which is valid at least for the small-scale structures. In case of pressure gradient flows however, the turbulence production under FPG is dominated by the ejection events (negative streamwise fluctuations), while in APG by the sweep events (positive streamwise fluctuations). Domination of sweep or ejection events cloud be a result of higher and lower convection velocity of the small-scale vortices respectively. Namely, when convection velocity is higher the sweep event (with $u > 0$) is stronger, while when convection velocity is lower the ejection event (with $u < 0$) is stronger.

The current study is devoted to show the relations between convection velocity and skewness factor in turbulent boundary layer under zero pressure gradient conditions. The analysis has been performed based upon velocity profiles measured with hot-wire technique in turbulent boundary layer with pressure gradient.

RESULTS

The skewness factor data comes from the experiment performed for the pressure gradient conditions representative for practical turbomachinery flows, where sudden changes from FPG and APG pressure gradient occur [6]. The analysis was performed based upon 8 profiles measured with single hot-wire probe of a diameter d = 3μm and length l = 0.4 mm (modified Dantec Dynamics 55P31). The distances of traverses from inlet plane, the corresponding dimensionless distances $Sg=x/L$, where L is the length of the test section (L = 1067mm). Reynolds number were varying from $Re_\theta = 2300 \div 6200$. Velocity profiles were measured with single hot-wire anemometry probe. Acquisition was maintained at frequency 50kHz with 10 seconds sampling records.

The influence of pressure gradient on skewness factor is clearly visible in Fig 1a [4]. For the range of y^+ between 10 and 300 the favourable pressure gradient causes the drop, while the adverse pressure gradient the increase of skewness factor. It is worth to note that when the APG is strong enough, the skewness factor takes the positive values in the whole inner region of boundary layer.

Dróżdż [4] quantified small-scale ejection and sweep changes under the pressure gradient by estimation of the velocity u_C defined as $u_C = \left(< u_{sweep} > + < u_{ejection} > \right) / 2$ based on conditionally averaged velocity signals during sweep and ejection events. Further on he claimed that u_C distribution across the boundary layer thickness is similar to the distribution of the skewness factor. Therefore, the change of convection velocity of sweep and ejection events could be the result of amplitude modulation mechanism. Finally, he proposed a model of quadrant events modification due to convection velocity (Figure 5 in [4]).

This paper is devoted to show the relation between convection velocity and amplitude modulation. For this purpose the cross product term $3\overline{u_L^+ u_S^{+2}} / \overline{u^{+2}}^{3/2}$ was calculated from time-traces decomposed by spectral filtering in similar way as it was done by Harun et al. [3]. This term was used in order to describe the convection velocity U_C using velocity obtained from skewness factor u_{Sf} calculated by following relation:

$$U_C^+ = U^+ + u_{Sf}^+ = U^+ + \frac{3\overline{u_L^+ u_S^{+2}}}{\overline{u^{+2}}^{3/2}} w^+ \tag{2}$$

where U is mean velocity and w is the unspecified scale. The results obtained for one chosen profile (i.e. Sg = 0.185) where compared with the convection velocity profile determined based on two-point correlation at Reynolds number Re_θ = 1409 taken from Krogstad et al. [7]. The results on Fig. 1b show that convection velocity estimated by eq. 2 is very close to convection velocity obtained by Krogstad et al. [7]. Its mean that using cross product term, which is a measure of amplitude modulation could be used to calculate convection velocity. The convection velocity is higher than mean velocity below $y^+ \approx 15$ and lower above $y^+ \approx 15$. The position $y^+ \approx 15$ is also the upper border of sweep events domination for analyzed profile.

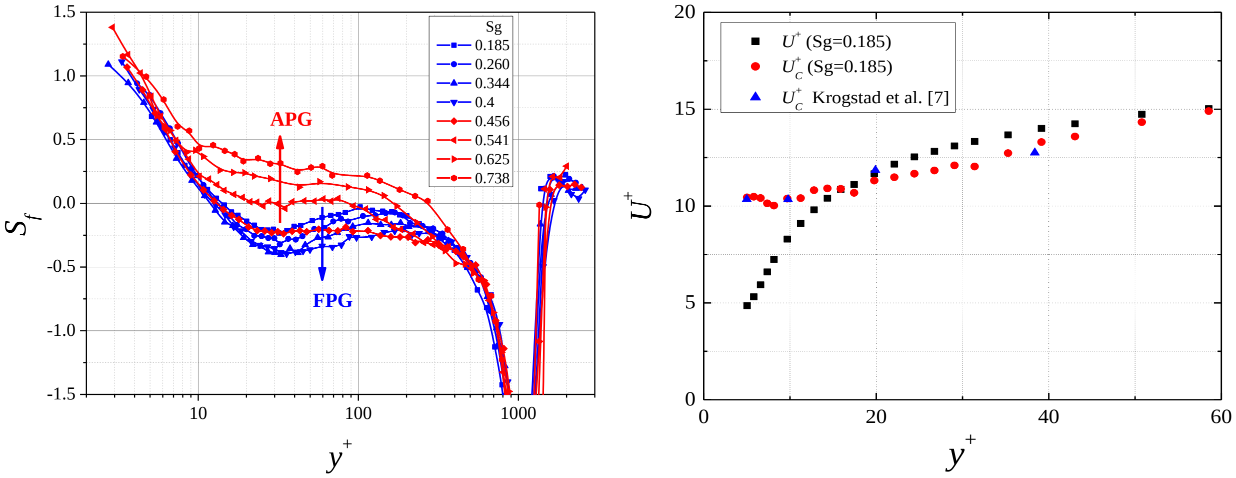

Figure 1. Skewness factor distributions in pressure gradient [4] a), mean and convection velocity U_C profiles b)

The result shows that skewness factor is strongly correlated with convection velocity for given scale w. Keeping in mind the substantial variation of the skewness factor under the pressure gradient, it can be suspected that convection velocity will also follow the trend. In order verify the statement the measurement of convection velocity should be performed for non-zero pressure gradient flow.

Acknowledgments

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