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Amplitude modulation and its relation to streamwise convection velocity

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ABSTRACT

The paper is devoted to show the relation between the amplitude modulation and the convection velocity in a turbulent boundary layer. The analysis has been performed based upon velocity profiles measured with the hot-wire technique in a turbulent boundary layer with pressure gradient corresponding to turbomachinery conditions. The VITA detection method of small-scale structures was used in order to show the impact of the pressure gradient on phase averaged time-traces changes in the aspect of amplitude modulation. The physical significance of the large scales influence on the small scales, formerly known as the amplitude modulation, has been elucidated. It was demonstrated that the measure of amplitude modulation can be used as an indicator of the convection velocity of coherent structures. The convection velocity profile can be described in the inner region using the amplitude modulation term when the proper scale is applied. The convection velocity prediction in favourable and adverse pressure gradients shows that t the strongest impact of the pressure gradient occurs in the buffer layer. The stronger increase occurs in the buffer layer. It was also found that the skewness factor of phase-averaged VITA waveforms, is very similar in shape with the cross-product term of the streamwise skewness factor, which quantifies amplitude modulation. It indicates that the well-known modification of quadrant events in pressure gradient flows is a result of the amplitude modulation phenomenon.

1. Introduction

The physical significance of large-scale motions, in particular their influence on the small-scales turbulence amplitude modulation near the wall still remains unknown. Despite the fact that the large-scale motion itself has no documented impact on the near-wall turbulent energy its footprint is visible on the streamwise skewness factor (Mathis et al., 2011), defined as:

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

where L and S denote the large and the small–scale components related to outer and inner peaks of the streamwise velocity fluctuations, respectively. The cross product term $\overline{3u_L^{+}u_S^{+2}}/\overline{u^{+2}}^{3/2}$ of the skewness factor reveals the strongest changes in comparison with other three terms and is an alternative measure of amplitude modulation (Mathis et al., 2011). The relation between turbulence modulation and the skewness in wall-bounded flows was confirmed for the high Reynolds number zero pressure gradient turbulent boundary layers. As the large-scale motions becomes increasingly energetic at higher Reynolds numbers, their interaction with the inner small-scale motion is also enhanced (Mathis et al., 2009). On the other hand, it was demonstrated that the flow in a favourable pressure gradient (FPG) and an adverse pressure gradient (APG) is also driven by large-scale motions. It was confirmed by the decrease in the skewness factor S_f in the flow subjected to FPG conditions and an adequate increase in the flow subjected to APG conditions, which was shown by Harun et al. (2012) and Dróżdż (2014). Dróżdż (2014) also suggested that due to the lack of high and low speed regions the production of the small-scale turbulence in FPG can be considered rather as a random process. On the other hand in the APG, the large-scale motion enhances production of the small-scale turbulence, but mainly in high-speed regions. Therefore in turn, it should be expected that small-scale structures produced in the high-speed regions gain higher convection velocity in respect to the mean velocity (Dróżdż, 2014). This may explain why with the increasing Reynolds number the boundary layer is more and more resistant to separation.

The recent study of amplitude modulation using wavelet analysis by Baars et al. (2015) showed that not only the amplitude modulation but also the frequency modulation of a small-scale motion

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is present in the boundary layer. Authors (Baars et al., 2015) show that in high-speed large-scale regions near the wall, where the amplitude of small scales increases, the frequency of small-scale structures also increases. The reason of an increased frequency can be twofold. It can be interpreted as the decrease in spatial scale of structures traveling at the same velocity, however it can be equivalently related to the increase in the convection velocity of the structure of the same spatial scale.

The interaction between the inner small-scale motion and the large-scale motion especially the influence on the convection velocity can be elucidated in the study of turbulent quadrant events, especially so-called sweep and ejection events. Quadrant events are defined by the relation of u and v components in streamwise wall-normal plane, 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. In the turbulent boundary layer, Q2, referred to as "ejection" and Q4 referred to as "sweep" are the main contributors of vertical momentum transfer (Adrian, 2007). This especially holds for the zero pressure gradient (ZPG), where the flow is dominated by Q2 and Q4 events, which apart from the inner region are equally important, while Q1 and Q3 events are exceptionally observed (Adrian, 2007). Dróżdż (2014) shows that this explains the equality of the convection velocity of small-scale structures with the mean velocity above $y^+ \approx 15$.

Under the pressure gradient the production of quadrant events is different. The analysis of quadrant events in TBL subjected to the APG were carried out, among the others, by Krogstad and Skare (1995) and by Dróżdż et al. (2011). They concluded that APG flows, especially near the wall, are strongly dominated by high speed fluid toward the wall (Q4 event) and the high speed fluid outward the wall (Q1 event), where on the other hand Q2 and Q3 events barely disappear. McEligot et al. (2009) showed, in turn, that for FPG flows the energy balance of Q2 and Q4 events is achieved close to the near-wall peak of fluctuations. In the outer layer however, the Q2 event plays the key role in turbulence energy production. Dróżdż (2014) suggested that such effect is a result of the difference between convection and mean velocities. Namely, when convection velocity is higher then Q4 and Q1 events (with $u > 0$) are stronger, whereas when the convection velocity is lower, then Q2 and Q3 events (with $u < 0$) are stronger. Dróżdż (2014) quantified small-scale quadrant events under the pressure gradient by estimation of the velocity u_C defined as $u_C = (< u_{positive} > + < u_{negative} >)/2$, where $<\_>$ means the phase-averaging of small-scale events local extrema. It was obtained based on conditionally averaged velocity signals of detected small-scale structures using the VITA (Variable Interval Time Averaging) method introduced by Blackwelder and Kaplan (1976). Further on, Dróżdż (2014) demonstrated that the shape of u_C distribution across the boundary layer thickness is similar to the distribution of the skewness factor. Therefore, the change of the small-scale structures convection velocity can be a result of the amplitude modulation mechanism. Based on that observation, he proposed a model of quadrant events strength variation due to convection velocity, which explains the physical significance of amplitude modulation.

The current study is devoted to show the direct relation between convection velocity and the cross product term of skewness factor, which quantifies amplitude modulation. The formula to determine the convection velocity using the proposed relation was introduced and verified in the turbulent boundary layer under zero pressure gradient conditions. The application of the method in favorable and adverse pressure gradient flows is then presented. The analysis is performed based upon velocity profiles measured with the hot-wire technique in the turbulent boundary layer with a pressure gradient.

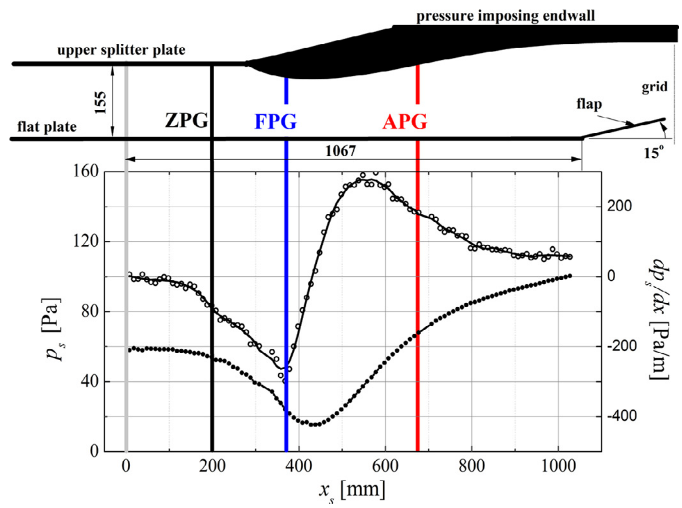

Fig. 1. The channel shape with corresponding static pressure and pressure gradient distributions.

2. Experimental setup

The skewness factor data comes from the experiment performed in the open-circuit wind tunnel shown in Fig. 1, where the sudden change from FPG to APG occurs (Dróżdż et al., 2015). 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 50 kHz with 10 s sampling records. In order to obtain a turbulent boundary layer the tripping device, after the leading edge of a flat plate, was used. Application of 2 mm cylindrical wire fastened to the plate at 210 mm from the leading edge allowed to obtain the value of Reynolds number, based on the momentum loss thickness θ, equal to $Re_\theta \approx 2400$. The turbulence intensity at the inlet plane, located in the zero pressure gradient area was equal to $Tu = 0.4\%$. Profiles from ZPG, FPG and APG region (see Fig. 1) were taken under consideration. The length of the test section was $L = 1067$ mm.

Static pressure measurements were performed using 70 pressure holes and results of measurements are shown in Fig. 1. The pressure distribution is typical for turbomachinery case, where after short region of the zero pressure gradient flow accelerates (from $x_s = 197$ mm) and then (from $x_s = 427$ mm) it decelerates. It can be seen that pressure gradient values are within the range of $-270 \div 280$ Pa/m. To have the reference friction velocity $u_\tau = \sqrt{\tau_w/\rho}$ along the flow ($\tau_w = \mu \frac{dU}{dy}$ is the wall shear stress, μ is the dynamic viscosity while ρ is the flow density), the fringe skin friction (FSF) technique was applied (Dróżdż et al., 2008). The wall shear stress distribution was compared with the ones obtained by the Clauser plot method (Clauser, 1956). Further experimental details are given in Dróżdż et al. (2015). The analyzed ZPG profile is in fact at the beginning of the FPG region because the pressure gradient parameter β defined as:

$$\beta = \frac{\delta^*}{\tau_w}\frac{dP}{dx} \tag{2}$$

is equal to -0.69. The effect of the strong favorable pressure gradient is, however, minor for that location because constant channel height extends 80 mm farther downstream. For the second profile (FPG) the minimum of the pressure gradient occurs and $\beta = -1.24$. The last profile (APG) comes from location slightly downstream of maximum of the pressure gradient and $\beta = 5.03$. The most important flow parameters are presented in Table 1, where x_s is the test