# Study of Turbulent Boundary Layer Approaching Sepration

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## Introduction

Among various types of near wall flows the turbulent boundary layers (TBLs) subjected to an adverse pressure gradient (APG) are in the spotlight. If a turbulent boundary layer flow encounters a strong APG, the flow becomes unstable and, if the APG is sufficiently large, it separates from the surface. The existence of separation involves an increase of energy losses connected sometimes with pressure and velocity fluctuations. The evidence of the latter phenomenon was given by Cherry et al. (1984) [1], who investigated the unsteady structure of a separated and reattaching flow. Unstable location of turbulent separation results among the other from the impact of vortex structures that fall into the area of separation, causing a temporary increase in momentum.

It has recently been shown that large scale motion influences the convection velocity of the near-wall small-scale structures and that the convection velocity varies near the wall depending on the pressure gradient [2]. Dróżdż and Elsner (2017) showed using a two point correlation for the flows with strong APG ($\beta = 17$) that convection velocity surpasses the mean velocity two times on average in the buffer layer. It follows that the increased convection velocity can play an important role in wall-normal momentum transport for the strong pressure gradient near detachment and especially for high Reynolds number flows.

The experiment was performed in an open-circuit wind tunnel, where the turbulent boundary layer was developed along the flat plate, which was 6870 mm long. The wind tunnel was designed with large dimension settling chamber and three contraction sections in order to achieve free stream turbulence intensity of below 0.7% at the inlet plane ($x$ = 0 mm). The velocity measurements were performed with hot-wire anemometry CCC developed by the Polish Academy of Science in Krakow. A single hot-wire probe of a diameter $d$ = 3 μm and length $l$ = 0.4 mm was used. The fringe skin friction (FSF) technique was used) to verify reference friction velocity $u_\tau$ along the flow. The inlet Reynolds number based on friction velocity and boundary layer thickness $\delta$ was 1900 and 3300. On the test stand, the adverse pressure gradient can be controlled by the shape and position of the upper wall and by the suction of the given amount of air flux.

## Results

The experiment was performed for a relatively narrow range of the Reynolds number (Re increases only twice). However, even for this range some conclusions on near separated flow dependence on Reynolds number can be already drawn.

The iso-contours of the wavelet energy spectra $E$ (equivalent to premultiplied energy spectra), scaled by the friction velocity $u_\tau$ versus streamwise length scale $\lambda^+$ and wall distance $y^+$ for the suction case, 10 m/s (solid iso-contours) and 20 m/s (gray-scale iso-contours) are presented in Fig. 1. Mean local velocity was used to transform between time and spatial scale. Close to the separation there is a rise of small scale energy with the increasing Reynolds number. It was only observed close to detachment. The small scale energy ($\lambda^+ \leq 3000$; $y^+ \leq 150$) is almost twice higher for 20 m/s compared to 10m/s. Meanwhile, the large-scale energy maximum increases only by 15%.. The increased momentum near the wall is balanced by the decrease of momentum in the outer zone of TBL and induced by a stronger rise of boundary layer thickness with the Reynolds number. This is illustrated in Figure 1b, where the outer spectral peak is moving clearly towards the outer edge of the boundary layer (compare Figs. 1a and b). At the same time, there is an increase in energy and in the scale of the dominant structures. The effect is related to the large-small scales interaction and the resulting increased convection velocity with the Reynolds number for such flow. The result of this interaction is the increase of momentum near the wall, where the increased turbulence production is also observed.

a) b)

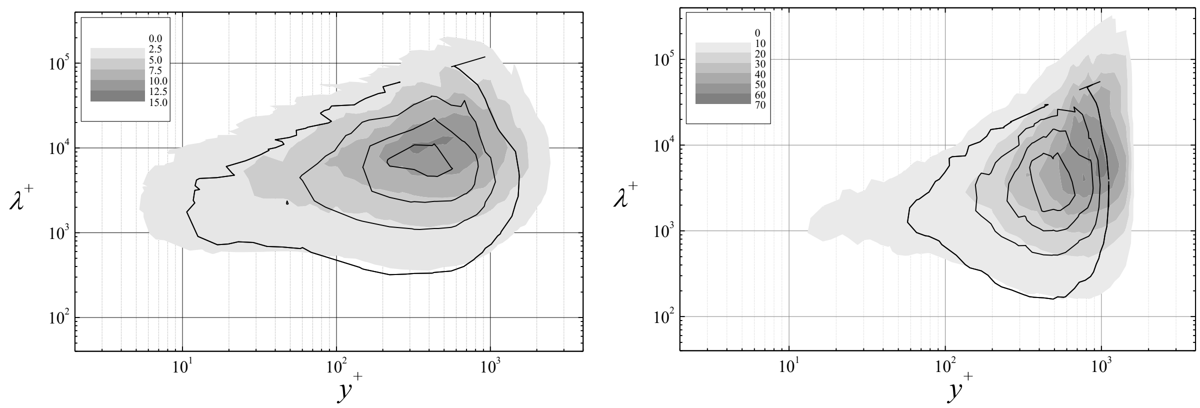


Figure 1: Friction velocity scaled pre-multiplied energy spectra for (900 mm) (a) and ITD (1100 mm) (b). Black iso-contours for 10 m/s and gray scale for 20 m/s. Contours from 2.5 to 12.5 with step 2.5 for (a) while contours from 10 to 70 with step 10 for (b).

## References

[1] N. J. Cherry, R. Hillier, and M. E. M. P. Latour, *Unsteady measurements in a separated and reattaching flow*, *J. Fluid Mech.*, vol. 144, no. 1, pp. 13–46, Jul. 1984.

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