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Low- and high-speed structures in the outer region of an adverse-pressure-gradient turbulent boundary layer

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A B S T R A C T

Large- and very large-scale structures in the form of elongated regions of low and high streamwise momentum have been studied in the outer region of a turbulent boundary layer subjected to a strong adverse pressure gradient. Large sets of streamwise–spanwise instantaneous velocity fields are acquired by particle image velocimetry at three wall-normal positions (0.2δ, 0.5δ, 0.8δ) at three different streamwise locations and at 0.1δ at the last streamwise location which allows us to study the wall-normal and streamwise variations of the structures. Subsequently, a pattern-recognition method and a classification scheme are employed in order to detect, classify and characterize the structures in an efficient and rigorous manner. Like in the case of zero-pressure-gradient turbulent boundary layers, long meandering streaky regions of low and high momentum are observed in the outer region of the present flow but they appear less frequently; especially in the lower part (at 0.1δ and 0.2δ) of the large-velocity-defect zone, i.e. near detachment. The dimensions of these large structures scale on boundary-layer thickness (δ) and are generally comparable to those previously reported for such structures in the overlap region of zero-pressure-gradient turbulent boundary layers. Interestingly, the adverse pressure gradient does not significantly affect the dimensions and arrangement of the large-scale structures in the upper part (at 0.5δ and 0.8δ) a segment of the outer region where the scaled Reynolds stresses also remain fairly self-similar.

1. Introduction

Over the past several decades a vast number of studies on turbulent flows support the existence of certain recurrent, organized and dynamically important features, collectively termed coherent structures. Although there exist several important types of coherent structures in turbulent wall-bounded flows, we focus the discussion here on the structures consisting of low and high streamwise momentum regions. The detection of the near-wall streaky structures with high- and low-speed regions aligned in the streamwise direction was one of the first clues to the existence of coherent structures within a turbulent boundary layer [1–3]. Kline et al. [4] by using hydrogen-bubble wire confirmed the existence of low-speed streaks in the buffer layer of turbulent boundary layers subjected to different pressure gradients. Kim et al. [5] showed the importance of low-speed streaks in generating the turbulent energy through a sequence of bursting events taking place especially in the buffer region. Because of this important relationship between low-speed streaks and turbulent energy production, the physical characteristics of these streaks, e.g. width, spanwise distance and length, have been studied extensively.

The pattern-recognition method of Lin et al. [6] applied on the instantaneous velocity fields obtained from stereoscopic PIV (particle image velocimetry) not only confirmed the results of previous studies but also permitted to investigate additional statistical characteristics of both low- and high-speed streaks, such as spanwise angle of the streaks, in the inner layer of a zero-pressure-gradient turbulent boundary layer (ZPG TBL). Moreover, several authors have shown that the low-speed streaks near the wall are associated with quasi-streamwise vortices which pump low-speed fluid from the wall [7,8]. The hairpin-type vortex, first proposed by Theodorsen [9] is a paradigm which has gained support over the years to explain many observations in wall turbulence. Based on this paradigm, some researchers propose that the quasi-streamwise vortex, the hairpin, horseshoe or omega-shape vortex, and the one-sided cane-type vortex are all part of the same entity at various stages of its evolution [10].

Away from the wall in the outer region of the boundary layer, different types of dynamically important coherent large-scale structures have been observed by both numerical and experimental works. PIV measurements of Adrian et al. [10] in agreement with the flow visualization of Head and Bandyopadhyay [11] and the model of Smith [12] reveal the frequent occurrence of structures consisting of streamwise organized hairpin-type vortices, termed hairpin packets, in the outer region of the ZPG TBL. These packets of vortices were interpreted to induce large regions of

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