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On the near-wall vortical structures at moderate Reynolds numbers

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Abstract

A recent database from direct numerical simulation (DNS) of a turbulent boundary layer (TBL) up to $Re_\theta = 4300$ [Schlatter & Örlü, J. Fluid Mech. 659, 2010] is analysed to extract the dominant flow structures in the near-wall region. In particular, the question of whether hairpin vortices are significant features of near-wall turbulence is addressed. A number of different methods based on the λ_2 criterion [Jeong & Hussain, J. Fluid Mech. 285, 1995] is used to extract turbulent coherent structures: Three-dimensional flow visualisation with quantitative estimates of hairpin population, conditional averaging and planar hairpin vortex signatures (HVS). First, visualisations show that during the initial phase of laminar-turbulent transition induced via tripping, hairpin vortices evolving from transitional Λ vortices are numerous, and can be considered as the dominant structure of the immediate post-transition stage of the boundary layer. This is in agreement with previous experiments and low-Reynolds-number simulations such as Wu & Moin [J. Fluid Mech. 630, 2009]. When the Reynolds number is increased, the fraction of hairpin vortices decreases to less than 2% for $Re_\theta > 4000$. Secondly, conditional ensemble averages [Jeong *et al.*, J. Fluid Mech. 332, 1997] find hairpins close to the wall at low Reynolds number, while at a sufficient distance downstream from transition, the flow close to the wall is dominated by single quasi-streamwise vortices; even quantitatively, no major differences between boundary layer and channel can be detected. Moreover, three-dimensional visualisations of the neighbourhood of regions of strong swirling motion in planar cuts through the layer (the HVS) do not reveal hairpin vortices, thereby impairing statistical evidences based on HVS. The present results thus clearly confirm that transitional hairpin vortices do not persist in the fully developed turbulent boundary layers, and that their dominant appearance as instantaneous flow structures in the outer boundary-layer region is very unlikely.

Keywords:

1. Introduction

A significant part of the fuel cost of airplanes arises from the frictional drag exerted by turbulent motion within a thin layer adjacent to the surface (near-wall turbulence). The influence of viscosity is mainly contained within this layer. Notable progress in understanding the involved physical processes has been made to unravel the various open questions relating to a turbulent boundary layer (TBL); however, many significant fundamental questions still remain.

Experiments and numerical simulations necessarily study idealised boundary-layer flows, evolving on flat surfaces in simplified geometries. In simulations, due to the ease of prescribing boundary and initial conditions, it has been common to study parallel flows such as plane channel flow. However, "real" open boundary-layer flows have been intensively studied both in wind-tunnel experiments and—more recently—also with computer simulations. Of primary interest, as apparent from recent review articles by Marusic et al. [1], Klewicki [2] and Smits et al. [3], is the description of turbulent statistics, such as the mean flow and the fluctuation intensities. On the other hand, beyond statistics a suitable description of the boundary-layer flow in terms of coherent vortical structures is important, since it has been used to model wall turbulence, *e.g.* by means of the attached eddy hypothesis of Townsend [4]. Knowledge of the dominant structures is paramount, for instance, for designing successful flow-control devices. It is therefore necessary to study the three-dimensional composition of the turbulent boundary layer.