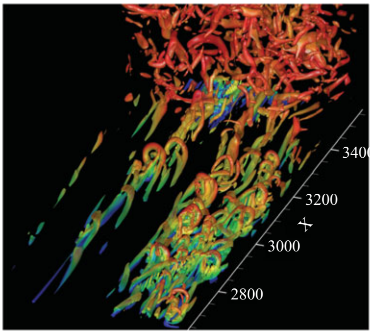
Journal of Fluid Mechanics
Focus on Fluids

Unravelling turbulence near walls



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Turbulent flows near walls have been the focus of intense study since their first description by Ludwig Prandtl over 100 years ago. They are critical in determining the drag and lift of an aircraft wing for example. Key challenges are to understand the physical mechanisms causing the transition from smooth, laminar flow to turbulent flow and how the turbulence is then maintained. Recent direct numerical simulations have contributed significantly towards this understanding.

Keywords. Turbulent boundary layers, Transition

Introduction

The paper by Wu & Moin (2009, this issue, vol. 630, pp. 5–41) presents insightful and intriguing results from one of the largest numerical simulations ever carried out of a spatially evolving boundary layer flow. These flows exist whenever there is fluid flow over a solid surface, or wall, and thus are of significant interest in a great number of fields, with application areas ranging from engineering to meteorology and biology.

Boundary layers are particularly important in engineering applications, where the skin-friction drag and boundary layer transition are critical for aerodynamic and hydrodynamic performance. Predicting where and when ‘transition’ (i.e. the change from a laminar to a turbulent state) occurs can be critical. For example, specification of the entry flight path and the heat shield design for a spacecraft re-entering the Earth’s atmosphere depends on detailed knowledge of hypersonic boundary layer transition, as the heat-transfer and drag on the vehicle are dramatically increased once the boundary layer becomes turbulent.

Transition is a very challenging problem (Schmid & Henningson 2001). Although linear stability analysis is successful in predicting the slow transition process that can occur via streamwise travelling Tollmien–Schlichting waves, in many applications where the free-stream turbulence intensities are of order 1%, the transition process is abrupt, highly non-linear, and generally poorly understood. Such ‘bypass’ transition is the case that Wu & Moin investigate by introducing short regions of high free-stream turbulence intensity that convect through the computational domain.

Turbulent boundary layers are also crucial with regard to energy consumption. For example, on commercial aircraft nominally 50% of the total drag comes from the turbulent skin-friction associated with the boundary layers, and up to 90% in the case of submarines, and so it is obviously desirable to reduce the skin-friction drag. In other applications, such as in combustion chambers, the need is to augment the

J. Fluid Mech. (2009), *vol.* 630, *pp.* 1–4. © 2009 Cambridge University Press
doi:10.1017/S0022112009007708 Printed in the United Kingdom

turbulence. In all these applications the ability to predict and control wall-bounded turbulence is very important, and fundamental to this is understanding the dominant physical mechanisms.

Overview

Direct numerical simulation (DNS) of the incompressible Navier–Stokes and continuity equations, with appropriate boundary conditions, provides the complete time-dependent and spatial information required to study the mechanisms of wall turbulence, albeit at relatively low Reynolds number. However, the majority of previous studies have been for fully developed turbulent channel flows (Hoyas & Jimenez 2006), where the flow does not evolve spatially and therefore, highly efficient, spectral algorithms can be applied in the streamwise and spanwise directions. In the case of a canonical 'external' flow, where a uniform free-stream flows over a flat plate, the boundary layer evolves and grows with streamwise distance. Because of the enormous computational resources required, previous attempts at simulating an evolving boundary layer (Spalart 1988, Khurajadze & Oberlack 2004 and others) have still relied on spectral algorithms. However, this has been controversial as spectral methods invoke unphysical streamwise periodicity which requires specialized treatments of outflow in 'fringe regions'. One of the unique features of the Wu & Moin simulation is that the numerical approach is based on a finite-difference scheme with convective outflow boundary conditions, and thus avoids these problems.

The Wu & Moin simulation is the largest DNS study to date of a spatially evolving boundary layer that avoids the use of spectral methods. The inflow is a laminar Blasius boundary layer that evolves along a flat plate with nominally constant free-stream velocity, undergoes bypass transition, and reaches a fully turbulent state with Reynolds number of $Re_\theta = 940$. The dataset itself is extremely valuable as a validation resource against which other simulations can be compared, and for which experimentalists can compare and access quantities that are challenging to measure (such as vorticity). If differences are observed, then this raises interesting questions about the accuracy of the individual techniques, and/or the importance of the history of the flow evolution, matching initial conditions and the sensitivity to boundary conditions. The small but appreciable differences (in total shear stress for example) between the Wu & Moin results and the famous DNS study of Spalart (1988) at the same Reynolds number are worth noting in this regard. The results reported by Wu & Moin also stand out for the striking preponderance of hairpin-shaped coherent structures that are observed, in both the latter parts of the transition process and in the fully turbulent state, as visualized in figure 1.

The question of whether hairpin vortices exist in turbulent boundary layers has been a topic of great controversy for over 50 years, and goes to the heart of uncovering the main mechanism of wall turbulence. Theodorsen (1952) was the first to propose a hairpin vortex structure as the fundamental building block of wall-bounded flows. A number of studies at Stanford during the 1970s (e.g. Offen & Kline 1975) identified hairpin structures as a likely explanation for transport mechanisms near the wall. However, it was the experimental flow visualization study of Head & Bandyopadhyay (1981) that presented the most compelling evidence of hairpin vortices, although their study was seen by many as inconclusive due to the smoke visualization technique used. Their findings lead Perry & Chong (1982) to propose a reduced-order model for turbulent boundary layer dynamics based on the concept of 'forests' of hairpin vortices distributed, in scale and population density, according to Alan Townsend's

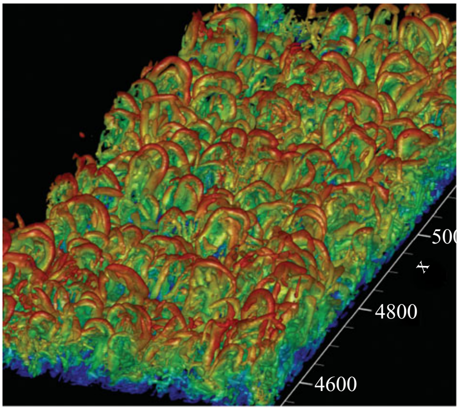

FIGURE 1. Instantaneous view of the coherent structures observed in the simulation of Wu & Moin in the fully turbulent region. The vivid appearance of hairpin-shaped structures is noted.

attached eddy hypothesis (Townsend, 1976). In later refinements of this model, Perry & Marusic (1995) were able to reproduce many of the scaling behaviours and statistics for turbulent boundary layers but this relied on trial-and-error calculations based on guessed shapes of the statistically representative hairpin vortex. The Wu & Moin simulation provides, for the first time, clear evidence of the quantitative shapes of individual hairpin vortices, and surprisingly the shapes are remarkably symmetric. This is in contrast to earlier studies by Robinson (1991), who analysed the dataset of Spalart, and others, who report that hairpin vortices are rarely in complete loops or quasi-symmetric.

More recently, the hairpin vortex paradigm has been extended by Adrian and coworkers (Adrian 2007) to account for spatial organization of the hairpin vortices into streamwise-aligned packets. Wu & Moin's results give tentative support for such organization, and further conclude that the low-speed streaks identified by others in bypass transition are merely a kinematic feature caused by the development of hairpin vortices into packets, and this is the responsible mechanism for the breakdown of the Blasius (laminar) flow.

Nevertheless, there are many studies disputing the existence and relevance of hairpin vortices in wall turbulence. These competing views are highlighted by Panton (2001) who reviewed various studies concerning the self-sustaining mechanism in wall turbulence. Two broad schools are identified, one based on instability and transient growth mechanisms of the viscous near-wall region (for example, Schoppa & Hussain 2002), and the other based on vortex regeneration mechanisms (for example, Adrian 2007). Wu & Moin's paper clearly lends support to the latter, at least in so far as it identifies a prominent role for hairpin-type coherent structures.

Future

Considerable activity is likely to follow in light of the results reported by Wu & Moin. The underlying reasons for the appearance of the hairpin structures are not yet understood, particularly as previous DNS studies with streamwise periodicity do not show comparable results. How, or if, these structures relate to the simulation scheme and the prescription of the inflow and boundary conditions will need to be resolved. This will be of great interest to a number of high-profile DNS simulations of wall turbulence (in Madrid, Stockholm and others) that are presently underway. The data computed by Wu & Moin will also be invaluable for a novel in-depth investigation of the time-dependent dynamics, which should be able to identify the formation mechanisms for the observed hairpin structures.

One other fruitful area of future study will be to investigate the nature of very-large-scale-motions or ‘superstructures’ (Adrian 2007; Hutchins & Marusic 2007), which have been recently identified as key mechanisms for high Reynolds number turbulent boundary layers. The nature of these very long structures remains unclear, although they may be a concatenation of hairpin packets. To study superstructures, the simulations would need to be streamwise extended, with Wu & Moin estimating the need to go beyond $Re_\theta \approx 2000$. Such results are eagerly anticipated.

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