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Simulations of spatially evolving turbulent boundary layers up to $Re_\theta = 4300$

Philipp Schlatter *, Qiang Li, Geert Brethouwer, Arne V. Johansson, Dan S. Henningson

Linné Flow Centre, KTH Mechanics, Osquars Backe 18, SE-100 44 Stockholm, Sweden

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A B S T R A C T

A well-resolved large-eddy simulation (LES) of a spatially developing turbulent boundary layer under zero-pressure-gradient up to comparably high Reynolds numbers ($Re_\theta = 4300$) is performed. The laminar inflow is located at $Re_{\delta^*} = 450$ ($Re_\theta \approx 180$), a position where natural transition to turbulence can be expected. The simulation is validated and compared extensively to both numerical data sets, i.e. a recent spatial direct numerical simulation (DNS) up to $Re_\theta = 2500$ (Schlatter et al., 2009) and available experimental measurements, e.g. the ones obtained by Österlund (1999). The goal is to provide the research community with reliable numerical data for high Reynolds-number wall-bounded turbulence, which can in turn be employed for further model development and validation, but also to contribute to the characterisation and understanding of various aspects of wall turbulence.

The results obtained via LES show that good agreement with DNS data at lower Reynolds numbers and experimental data can be obtained for both mean and fluctuating quantities. In addition, turbulence spectra characterising large-scale organisation in the flow have been computed and compared to literature results with good agreement. In particular, the near-wall streaks scaling in inner units and the outer layer large-scale structures can clearly be identified in both spanwise and temporal spectra.

1. Introduction

Turbulent flow around bodies with solid walls is a very important research topic today for both technical and industrial as well as environmental applications. Whereas these flows are usually occurring in complex geometries with curved surfaces leading to pressure gradients or even bluff shapes promoting separation, the two-dimensional, spatially developing, zero-pressure-gradient turbulent boundary layer on a flat plate has emerged as an important canonical flow case for theoretical, numerical as well as experimental studies. Of large interest is for example the aspect of universality of the wall-normal profile of the streamwise velocity component in the limit of high Reynolds numbers. Going back to the seminal work conducted by Theodore von Kármán in the first half of the 20th century, the so-called "law of the wall" composed of the linear region close to the wall, followed by a buffer region and logarithmic overlap region up to about 10–15% of the boundary-layer thickness, has been the centre of intense discussions, see e.g. the corresponding section in the book by Pope (2000). In recent years, several careful experiments have been conducted for this canonical flow. For instance, Österlund et al. (2000) performed extensive measurements of mean and fluctuating quantities in the MTL wind tunnel at KTH Stockholm using hot-wire and hot-film anemometry for Reynolds numbers Re_θ based on the momentum thickness θ and the free-stream velocity U_∞ ranging from 2530 to 27300; this data set includes five measurement positions below $Re_\theta = 6000$, which are becoming accessible to numerical simulations nowadays. Partly based on these experimental data, Monkewitz et al. (2007) have recently presented various asymptotic results for high Reynolds numbers, including the mean velocity profile.

Careful analysis (Örlü, 2009) of a large amount of literature data for (experimentally) low Reynolds number turbulent boundary-layer measurements yields that some of these data do not necessarily adhere to accurate zero-pressure-gradient equilibrium conditions and independent determination of the skin friction. Therefore, new experimental measurements in the MTL wind tunnel at KTH Stockholm were performed by Örlü (2009) for a generic, two-dimensional turbulent boundary layer with special focus on equilibrium conditions, for $Re_\theta = 2331–8792$. Sample results have been included in Schlatter et al. (2009). This data will certainly be helpful in the future for detailed comparisons with simulation data obtained at high *Re*.

To get additional insight into the mean-flow properties of turbulent wall-bounded flows, there is increased interest in understanding the dynamics of such flows, both at large and small scales. This is highlighted by the recent article by Marusic (2009). Furthermore, initial studies by Kim and Adrian (1999) who identified very large-scale structures in pipe flows, motivated

* Corresponding author.
E-mail address: pschlatt@mech.kth.se (P. Schlatter).

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the subsequent analysis of large-scale motions in channel, pipe and boundary-layer flows by many authors (see e.g. Hutchins and Marusic, 2007a; Guala et al., 2006; del Álamo and Jiménez, 2003).

However, as opposed to turbulent channel and pipe flow, relatively few numerical results of direct or large-eddy simulations (DNS/LES) pertaining to canonical turbulent boundary layers have been published for medium or high Reynolds numbers. In recent years, the advancement of computer technology has made it possible to perform simulations based on $\mathcal{O}(10^9)$ grid points; in channel geometry this allowed for reaching Reynolds number higher than $Re_\tau = 2000$ (based on friction velocity U_τ and channel half-width h) by means of DNS (Hoyas and Jiménez, 2006). The spatially developing boundary-layer geometry, however, proves more difficult for accurate simulations. In particular, the long streamwise extent of the domain necessary for capturing the downstream growth of the boundary layer, and the resulting longer averaging times due to the loss of one homogeneous direction require a large computational effort even for moderate Re. In addition, the specification of suitable inflow and outflow conditions, and equally important, proper free-stream boundary conditions are essential for a successful simulation setup.

DNS relies on resolving all relevant temporal and spatial scales on the underlying numerical grid. In LES, however, the resolution requirements can be relaxed to some extent (Sagaut, 2005). The large, energy-carrying scales of the flow are discretised on the grid and accurately simulated in both space and time, whereas the influence of the smaller scales, which are presumably more homogeneous, is modelled. For this purpose, a so-called subgrid-scale (SGS) model is then added to the equations of motion to compensate for the truncated resolution. Depending on flow case, accuracy requirements and employed SGS model, typically a reduction of the number of grid points by a factor of $\mathcal{O}(10)$ can be obtained for wall-resolved simulations compared to a DNS of the same case.

For boundary-layer flows, the DNS by Spalart (1988) using an innovative spatio-temporal approach provided valuable data at $Re_\theta = 300,\ 670,\ 1410$; this data set has been extensively used as reference for model development, and validation of experimental techniques for the last decades. As a next step, a simulation taking into account the true growth of the boundary layer in the downstream direction has been performed by Komminaho and Skote (2002) up to $Re_\theta = 700$. This technique to include proper inflow and outflow conditions in a spatially developing setting is usually termed "spatial simulation" as opposed to flow cases with parallel mean flows such as channel or pipe flows. Very recently, Wu and Moin (2009) performed a spatial DNS of a boundary layer undergoing transition due to a periodically passing box of turbulence; the turbulent state just after transition was located $Re_\theta = 900$ close to the outlet. A similar Re_θ was also simulated spatially by Li et al. (2009); this simulation also includes the advection of passive scalars with various Prandtl numbers.

Focusing on DNS of higher Reynolds numbers, Khujadze and Oberlack (2004) were using a spectral method with laminar inflow similar to the present simulation setup, however in a much shorter domain. Nevertheless, $Re_\theta = 2240$ was reached in these simulations. An even higher Reynolds number of $Re_\theta = 2900$ was reached by Ferrante and Elghobashi (2005). Their spatial simulation was not started from laminar flow, but rather from turbulent inflow conditions located at $Re_\theta = 2340$. A long domain stretching from about $Re_\theta = 1000$ to 2000 was considered in the recent simulations briefly summarised in Simens et al. (2009). Also in this case, laminar-turbulent transition is not part of the setup, and the flow is started directly from turbulent inflow conditions. Nevertheless, a comparably long adjustment and settling region at the beginning of the domain was necessary until equilibrium conditions could be assured.

A DNS using a spectral method similar to the one used by Komminaho and Skote (2002), but in a much larger computational box was recently presented by Schlatter et al. (2009), reaching $Re_\theta = 2500$ in a fully spatial setup with the (laminar) inlet located at $Re_\theta \approx 200$. A comparison with new experiments performed at the same Reynolds number revealed excellent agreement between DNS and measurements. This dataset will be used in the present work extensively to validate the chosen simulation approach.

For turbulent boundary layers, the Reynolds number $Re_\theta \approx 4300$ has to be considered at present high from a simulation point of view. Due to the difficulty of performing simulations and experiments at Reynolds numbers Re_θ on the order of a few thousand, there is a comparably large spread of the existing data in the literature for integral, mean and fluctuating turbulent quantities, see e.g. Honkan and Andreopoulos (1997). There is thus a need for accurate and reliable simulation data of spatially developing turbulent boundary layers with Re_θ to be compared to high-quality experimental results. To this end, the inflow in the numerical simulation should be positioned far enough upstream, i.e. comparable to where natural transition occurs, to ensure that the flow reaches a fully developed, undisturbed equilibrium state further downstream. However, as pointed out by Österlund et al. (2000), a clear overlap region can only be detected above $Re_\theta \approx 6000$, which might be just about to become accessible for adequately resolved transient numerical simulations.

The aim of the present study is to perform and validate well-resolved spatial large-eddy simulations (LES) in an effort to obtain accurate and reliable data at higher Reynolds numbers exceeding $Re_\theta = 2000$. A snapshot of such a simulation is presented in Fig. 1, with several relevant downstream positions indicated. The inflow is positioned at a low streamwise Reynolds number, $Re_{\delta^*} = 450$ based on the displacement thickness δ^* at the inlet. An exhaustive amount of statistics, e.g. one and two-point statistics, Reynolds-stress budgets and time series pertaining to turbulent quantities, are collected and evaluated. In the present contribution, a selection of these statistics is presented, and discussed in relation to previous numerical and experimental data.

The paper is organised as follows: In Section 2 the numerical method and the simulation parameters are introduced. Then, Section 3 discusses statistical quantities such as mean profiles, fluctuations and budgets. Spectral information about turbulent structures are introduced in Section 4. Finally, conclusions are given in Section 5.

2. Numerical methodology

The simulations are performed using a fully spectral method to solve the three-dimensional, time-dependent, incompressible Navier–Stokes equations (Chevalier et al., 2007). In the wall-parallel directions, Fourier series with dealiasing are used, whereas the wall-normal direction is discretised with Chebyshev polynomials.

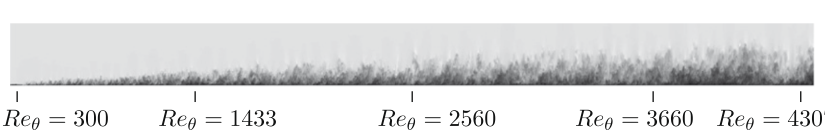

Fig. 1. Instantaneous side view with grey-scale contours of the streamwise velocity component. The domain shown corresponds to the computational box for the present LES, reaching up to approximately $Re_\theta = 4350$. Note that only half of the domain extent in the wall-normal direction is shown, and the fringe region connecting outflow and inflow is not included. The representation of the box is enlarged by a factor of four in the wall-normal direction.