Time-averaged DNS of the asymptotic suction boundary layer

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I. INTRODUCTION

The asymptotic suction boundary layer (ASBL) is an open flow that develops over a flat bottom plate in the presence of suction though that plate. In consequence, the boundary layer thickness remains constant in the streamwise direction, and ASBL shares certain properties with parallel shear flows and spatially developing boundary layers. In direct numerical simulations (DNS), ASBL is emulated by a plane Couette setup using a high simulation domain. That is, we consider a fluid located in a wide gap between two parallel plates. The bottom plate is stationary and the fluid is set in motion through the top plate moving in the x-direction with velocity U_∞. The latter corresponds to the free-stream velocity of the open flow. The flow is assumed to be incompressible and the conditions isothermal such that the density can be regarded as constant.

Expressed in units of the free-stream velocity, the laminar flow is given by

$$\boldsymbol{U} = \begin{pmatrix} 1 - e^{-yVs/\nu} \\ -V_s/U_\infty \\ 0 \end{pmatrix} , \tag{1}$$

where V_s is the suction velocity and ν is the kinematic viscosity. The deviations $\boldsymbol{u}$ of the laminar flow are then described by the dimensionless equations

$$\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + \boldsymbol{U} \nabla \boldsymbol{u} + \boldsymbol{u} \nabla \boldsymbol{U} + \nabla p - \frac{1}{\mathrm{Re}} \Delta \boldsymbol{u} = 0 , \tag{2}$$

$$\nabla \cdot \boldsymbol{u} = 0 , \tag{3}$$

where p is the pressure divided by the constant density ρ and $\mathrm{Re} = U_\infty \delta/\nu$ the Reynolds number based on the free-stream velocity, the laminar displacement thickness $\delta = \nu/V_s$ and the kinematic viscosity of the fluid.

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II. NUMERICAL DETAILS

The DNS data was generated with the open-source code `channelflow2.0` [1]. Equations (2)-(3) are solved numerically in a rectangular domain with periodic boundary conditions in x- and z-directions and no-slip boundary conditions in the y-direction. `Channelflow` uses the standard pseudospectral technique with 2/3rds dealiasing in stream- and spanwise directions, where the spatial discretisation is by Fourier expansions in the homogeneous directions and a Chebychev expansion in the y-direction. Details of the DNS are summarised in table I.

id	Re	Re_τ	$\tau_w/(\rho U_\infty^2)$	δ_b/δ	L_x/δ	L_y/δ	L_z/δ	N_x	N_y	N_z	T/T_0	N
H20-4π	1000	320	0.0003	$\simeq 20$	4π	20	4.6π	64	161	96	35000-39068	4068

TABLE I. Details of the DNS. $\mathrm{Re} = U_\infty \delta/\nu = U_\infty/V_s$, where U_∞ is the free-stream and V_s the suction velocity, $\mathrm{Re}_\tau = u_\tau \delta_b/\nu$ is the friction Reynolds number based on the boundary layer thickness $\delta_b = \delta_{0.99}$, the friction velocity u_τ and the kinematic viscosity ν, τ_w the shear stress at the bottom wall, $\rho = 1$ the density, δ the laminar displacement thickness, L_x, L_y, L_z the box length in streamwise, wall-normal and spanwise directions, N_x, N_y, N_z the number of grid points in the respective directions, T/T_0 the run time in statistically stationary state in units of $T_0 = \delta/U_\infty$ and N the number of samples in statistically stationary state.

III. TIME-AVERAGED 2D FIELDS

All datasets originate from the DNS data described in table I, where velocity fields have been sampled in intervals of T_0. Each snapshot was first averaged in streamwise direction in order to generate two-dimensional (2D) fields. The resulting 2D time series was then averaged over different time intervals I

$$\bar{\boldsymbol{u}}(t_i) = \frac{1}{t_{i+r} - t_i} \int_{t_i}^{t_{i+r}} d\tau \; \boldsymbol{u}(\tau) \; , \tag{4}$$

where r determines the width of the averaging interval $I = t_{i+r} - t_i$. Datasets were created for $r = 10, 60, 120, 250, 500, 1000, 2000$, with details summarised in table II. The time-averaging has been carried out in a comoving frame in order to remove a spanwise drift of large-scale flow structures, as can be observed in a video [2] provided on the SPP webpage. A comparison between an instantaneous and a velocity field averaged over 1000 time units

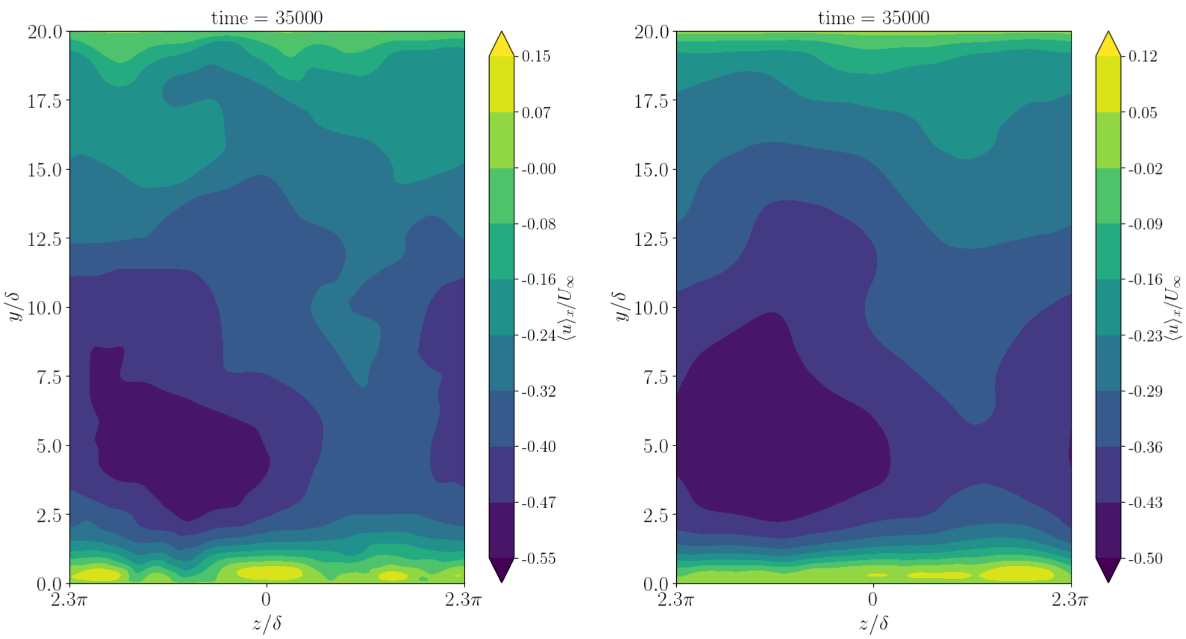

FIG. 1. Instantaneous (left) and time-averaged (right, $r = 1000$) streamwise component of the streamwise-averaged velocity field. Both cases show the deviation from the laminar flow.

id	dT/T_0	I/T_0	T/T_0	N
av-10	10	10	35000-39060	406
av-60	10	60	35000-39000	400
av-120	10	120	35000-38940	394
av-250	10	250	35000-38810	381
av-500	10	500	35000-38560	356
av-1000	10	1000	35000-38060	306
av-2000	10	2000	35000-37060	206

TABLE II. Summary of time-averaged datasets, where dT is the sampling interval, I the averaging interval, T the total timespan and N the number of time-averaged fields in the respective datasets.

is shown in fig. 1. A large-scale flow structure is present in both images. In contrast, the small-scale near-wall structures visible in the instantaneous velocity field are smoothed out by time-averaging and give rise to a boundary layer, which is nearly homogeneous in spanwise direction.

IV. DATA STRUCTURE AND POST-PROCESSING

The snapshots are saved in configuration space in NetCDF format. The data structure is

$$u[z,y,x] \qquad \text{streamwise component,}$$
$$v[z,y,x] \qquad \text{wall-normal component,}$$
$$w[z,y,x] \qquad \text{spanwise component,}$$

where x, y, z are the streamwise, wall-normal and spanwise directions, respectively. Note that one point is present in streamwise direction. The data can be read with the python script `read-netcdf.py` that is available for download with the data. Matlab provides the function `ncread` to access NetCDF data. The key entries `Velocity_X`, `Velocity_Y` and `Velocity_Z` correspond to the data arrays for u, v and w, respectively, while x, y and z-vectors can be read via the key entries `X`, `Y` and `Z`.

[1] J. F. Gibson, F. Reetz, S. Azimi, A. Ferraro, T. Kreilos, H. Schrobsdorff, M. Farano, A. F. Yesil, S. S. Schtz, M. Culpo & T. M. Schneider, "Channelflow 2.0", manuscript in preparation (2019), see `channelflow.ch`

[2] `https://www.tu-ilmenau.de/fileadmin/media/turbspp/Benchmark_cases/suctionBL_Re1000-dT10-orig-frate6.mp4`.