README: Turbulent boundary layer direct numerical simulations

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Overview

This README describes the DNS dataset of turbulent boundary layers that is part of "A database for reduced-complexity modeling of fluid flows" [3]. Users of these data should cite:

A. Towne, S. Dawson, G. A. Brès, , A. Lozano-Durán, T. Saxton-Fox, A. Parthasarthy, A. R. Jones, H. Biler, C.-A. Yeh, H. Patel, and K. Taira. A database for reduced-complexity modeling of fluid flows. *AIAA Journal*, 61:2867–2892, 2023

Flow conditions

This dataset corresponds to an incompressible zero-pressure-gradient flat-plate turbulent boundary layer. Two simulations are presented and labeled as BL1 and BL2. The dimensionless parameters for BL1 | BL2 are:

- $L_x/\theta_{\text{avg}} = 480 \mid 469$
- $L_y/\theta_{\text{avg}} = 47 \mid 53$
- $L_z/\theta_{\text{avg}} = 70 \mid 79$
- $\text{Re}_{\tau,i}$–$\text{Re}_{\tau,o} = 292$–$729 \mid 481$–1024
- $\text{Re}_{\theta,i}$–$\text{Re}_{\theta,o} = 832$–$1982 \mid 1272$–$2870$
- $\Delta t^+ = 1.5 \mid 4.0$
- $\Delta t^+_{\text{planes}} = 1.5 \mid 0.8$
- $T u_{\tau,\text{avg}}/\delta_{\text{avg}} = 26.1 \mid 7.4$

Here, L_x, L_y, and L_z are the streamwise, wall-normal and spanwise length of the computational domain, θ_{avg} is the streamwise-averaged momentum thickness, Re_τ and Re_θ are the Reynolds number based on friction velocity and the momentum thickness, respectively, $\text{Re}_{\tau,i}$–$\text{Re}_{\tau,o}$ is the range of Re_τ covered from inflow to outflow (similarly for $\text{Re}_{\theta,i}$–$\text{Re}_{\theta,o}$), Δt^+ is the time between provided flow fields (`BLdns*_3D_t#####.h5`) in plus units, $\Delta t^+_{\text{plane}}$ is the time between flow planes in the planar data (BLdns*_planes.h5) $u_{\tau,\text{avg}}$ is the streamwise-averaged friction velocity, δ_{avg} is the streamwise-averaged boundary layer thickness based on 99% of the freestream velocity, and T is the total time simulated after initial transients.

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Data collection

The turbulent boundary layers are computed by direct numerical simulation (DNS) of the incompressible Navier-Stokes equations. The spatial discretization is a staggered second-order central finite difference scheme [2]. Time advancement is achieved by a third-order Runge-Kutta scheme [4] combined with the fractional-step method [1]. The Poisson solver uses the cosine transform to account for the non-periodic boundary conditions in the streamwise direction. The code is parallelized using Message Passing Interface with a global transpose from y-z to x-y planes. All computations were run with constant time step such that CFL<0.5.

The publicly available database includes 3-D space/time-resolved velocity fields for both cases. For both cases, the fields are downsampled by a factor of two in the wall-normal and spanwise spatial directions. For BL2, the fields are also downsampled by a factor of five in time. The database also contains the following precomputed statistics for both BL1 and BL2:

1. C_f, δ, θ, Re_θ, Re_τ, and u_τ as a function of x.
2. Mean velocity and vorticity profiles, mean uv, and root-mean-squared (r.m.s.) velocity and vorticity fluctuations as a function of x and y.
3. Spatial correlations in x-z planes for each velocity component at $y^+ = 15$ and 100 and $y/\delta = 0.1, 0.3, ..., 0.9$, and 1.1, and streamwise locations $\mathrm{Re}_\tau \approx 400, 600, 700$, and 900.
4. Time-space correlations in x-t planes for each velocity component at $y^+ = 15$ and 100 and $y/\delta = 0.1, 0.3, ..., 0.9$, and 1.1, and streamwise locations $\mathrm{Re}_\tau \approx 400, 600, 700$, and 900.
5. Time-resolved velocities in the x–y plane.

Nondimensionalization

The database is nondimensionalized by the streamwise distance of the inlet to the origin of the boundary layer L_o and the freestream velocity U_∞.

File inventory

The database contains the following files and variables for BL1 (similarly for BL2):

- `BLdns_example.zip`: zip archive containing a representative subset of the following data and scripts as an entry point for users
- `BLdns_read.m`: Matlab script showing how the data can be read and manipulated.
- `BLdns1_parameters.h5`: hdf5 file containing flow and data parameters
  - `Lx`: streamwise length of the domain
  - `Ly`: wall-normal length of the domain
  - `Lz`: spanwise length of the domain
  - `Lo`: distance of the inlet to the boundary layer leading-edge
  - `time`: time
  - `dt`: time step between snapshots provided in `BLdns1_3D_t#####.zip`
  - `dt_plane`: time step between planes provided in `BLdns1_planes.h5`
  - `Uinf`: freestream velocity
  - `nu`: kinematic viscosity
  - `Retheta_inlet`: Re_θ at the inlet

- Retheta_outlet: Re_θ at the outlet
- theta_inlet: θ at the inlet
- theta_outlet: θ at the outlet
- Retau_inlet: Re_τ at the inlet
- Retau_outlet: Re_τ at the outlet
- delta99_inlet: δ at the inlet
- delta99_outlet: δ at the outlet.

■ BLdns1_grid.h5: hdf5 file containing grid information

- x: streamwise grid
- y: wall-normal grid
- z: spanwise grid
- yd: x2 downsampled wall-normal grid
- zd: x2 downsampled spanwise grid

■ BLdns1_3D_t#####.h5: hdf5 file containing a snapshot of the three-dimensional flow field at time index ##### $\in [00000, 10000]$ (only for BL1). The original full-resolution fields for BL1 and BL2 are available upon request to the authors.

- u: streamwise velocity at each (x, yd, zd) grid point
- v: streamwise velocity at each (x, yd, zd) grid point
- w: streamwise velocity at each (x, yd, zd) grid point

■ BLdns1_3D_t#####.zip: zip archive of BLdns1_3D_t#####.h5 files, each containing 1000 snapshots

■ BLdns1_means.h5: hdf5 file containing mean flow fields

- Umean: mean streamwise velocity at each (x, y) grid point
- Vmean: mean wall-normal velocity at each (x, y) grid point
- Wmean: mean spanmwise velocity at each (x, y) grid point
- UVmean: mean uv at each (x, y) grid point
- urms: root-mean-squared streamwise velocity fluctuations at each (x, y) grid point
- vrms: root-mean-squared wall-normal velocity fluctuations at each (x, y) grid point
- wrms: root-mean-squared spanwise velocity fluctuations at each (x, y) grid point
- oxrms: root-mean-squared streamwise vorticity fluctuations at each (x, y) grid point
- oyrms: root-mean-squared wall-normal vorticity fluctuations at each (x, y) grid point
- ozrms: root-mean-squared spanwise vorticity fluctuations at each (x, y) grid point
- Cf: mean C_f at each x grid point
- Retheta: mean Re_θ at each x grid point
- Retau: mean Re_τ at each x grid point
- utau: mean u_τ at each x grid point
- delta99: mean δ at each x grid point
- theta: mean θ at each x grid point

■ BLdns1_correlations.h5: hdf5 file containing the mean flow fields

- Deltax: streamwise length of the correlation

- Deltaz: spanwise length of the correlation
- Deltat: time span of the correlation
- Retau_corr: Re_τ at Deltax=0
- y_corr: wall-normal location of the correlation
- delta99_corr: δ at Deltax=0
- Cuu_xz: x–z streamwise velocity correlations as a function of (Retau_corr, Deltax, y_corr, Deltaz) point
- Cvv_xz: x–z wall-normal velocity correlations as a function of (Retau_corr, Deltax, y_corr, Deltaz) point
- Cww_xz: x–z spanwise velocity correlations as a function of (Retau_corr, Deltax, y_corr, Deltaz) point
- Cuu_tx: t–x streamwise velocity correlations as a function of (Retau_corr, Deltat, Deltax, y_corr) point
- Cvv_tx: t–x wall-normal velocity correlations as a function of (Retau_corr, Deltat, Deltax, y_corr) point
- Cww_tx: t–x spanwise velocity correlations as a function of (Retau_corr, Deltat, Deltax, y_corr) point

■ BLdns1_planes.h5: hdf5 file containing x–y time-resolved velocity planes

- Uplane: streamwise velocity at each (t, x, y) time and grid point
- Vplane: wall-normal velocity at each (t, x, y) time and grid point
- Wplane: spanwise velocity at each (t, x, y) time and grid point

References

[1] J. Kim and P. Moin. Application of a fractional-step method to incompressible Navier-Stokes equations. *J. Comp. Phys.*, 59:308–323, 1985.

[2] P. Orlandi. *Fluid Flow Phenomena: A Numerical Toolkit*. Number 1 in Fluid Flow Phenomena: A Numerical Toolkit. Springer, 2000.

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[4] A. A. Wray. Minimal-storage time advancement schemes for spectral methods. Technical report, NASA Ames Research Center, 1990.