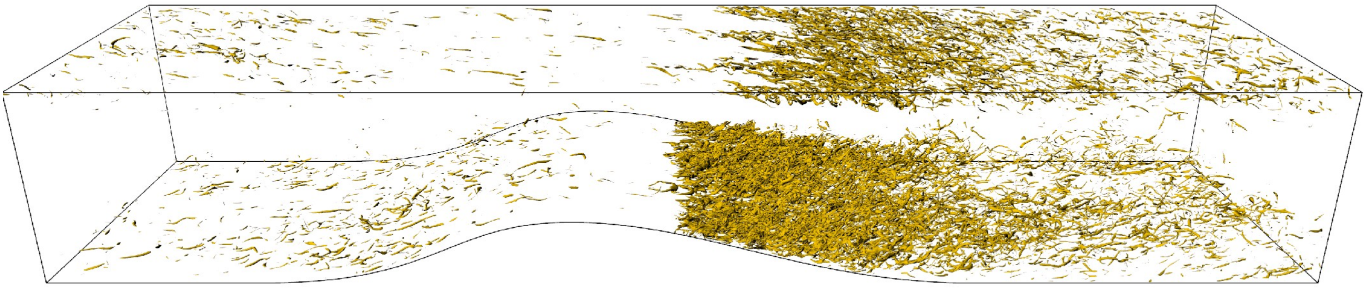
Direct Numerical Simulation
of
converging-diverging channel flow



The database is composed of the data from two direct numerical simulations in the framework of the European project "WALLTURB" (http://wallturb.univ-lille1.fr/). The global aim of the WALLTURB project was to bring in four years a significant progress in the understanding and modelling of near wall turbulence in Boundary Layer. A large amount of both experimental and numerical data on wall turbulence have been gathered within the wallturb project. The present dataset includes data of two direct numerical simulations of converging-diverging channel flow. The two cases have been designed using the same geometry than the one used by the LML (Lille Mechanic Laboratory) in several experiments for the analysis of wall turbulence with pressure gradient and for flow control. Most of the data acquired within the project are available in the « TurBase » database. The current database was generated in order to provide data to test and validate turbulence models.

Presentation of the numerical simulations

The two simulations were conducted using a the numerical code MFLOPS3D developed at LML. The algorithm used for solving the incompressible Navier–Stokes system is described in Marquillie et al. (2008). To take into account the complex geometry of the physical domain (see figure 1), the partial differential operators are transformed using the mapping that has the property of following a profile at the lower wall with a flat surface at the upper wall. Applying this mapping to the momentum and continuity equations, the modified system in the computational coordinates has to be solved in the transformed Cartesian geometry. The three-dimensional Navier–Stokes equations are discretized using fourth- and eighth-order centred finite differences in the streamwise x-direction. A pseudo-spectral Chebyshev collocation method is used in the wall-normal y-direction. The spanwise z- direction is assumed periodic and is discretized using a spectral Fourier expansion, the nonlinear coupling terms being computed using a conventional de-aliasing technique (3/2-rule). The resulting 2D Poisson equations are solved in parallel using MPI library. Implicit second-order backward Euler differencing is used for time integration, the Cartesian part of the diffusion term is taken implicitly whereas the nonlinear and metric terms (due to the mapping) are evaluated using an explicit second- order Adams–Bashforth scheme. In order to ensure a divergence-free velocity field, a fractional-step method has been adapted to the present formulation of the Navier Stokes system with coordinate transformation.

Parameters of the two simulations

The two simulations share the same configuration with a slightly different simulation domain. The geometry is the same but the position of the summit is slightly shifted downstream for the simulation with the highest Reynolds number. A channel flow configuration was chosen instead of two separated boundary layers because channel flow inlet conditions are much easier to generate. The reason is the difficulty in defining a a-priori simulation which leads to two different boundary layers with statistics comparable to the experiment. Therefore, the inlet conditions are generated by precursor DNS (for the highest Reynolds) or highly resolved LES (for the lowest Reynolds) of flat channel flows at the equivalent Reynolds numbers. The simulation domain for the DNS with the bump geometry is 4π in the streamwise x direction, 2 in the normal y direction and π in the spanwise z- direction. The mesh is streched in normal direction following the Chebytchev discretisation. Moreover, the mesh is also refined in the streamwise direction in the region of change of sign of pressure gradient near the summit of the bump (see Figure 1). The main parameters of the two DNS are given in Table 1.

***Table 1** : Parameters of the DNS of converging-diverging channel flow. The parameters are described in more detail in Marquillie et al (2008) and Laval et al (2012) for the lowest and the highest Reynolds numbers respectively.*

Name	**Inlet conditions**	**Re_τ (1)**	**N_x**	**N_y**	**N_z**	**Δx^+ (2)**	**Δy^+ (2)**	**Δz^+(2)**	**Time (3)**
APG_400	precursor LES	395	1536	257	384	5.1	0.03-4.8	5.1	29
APG_600	precursor DNS	617	2304	385	576	5.7	0.01-3.8	3.8	55

(1) *Reynolds number based on friction velocity at the inlet and half the channel height*
(2) *Resolution in wall units based on friction velocity at the summit of the bump*
(3) *Characteristic integration time (after convergence) based on maximum of mean velocity (U_{max}=1) and half the channel height (h=1)*

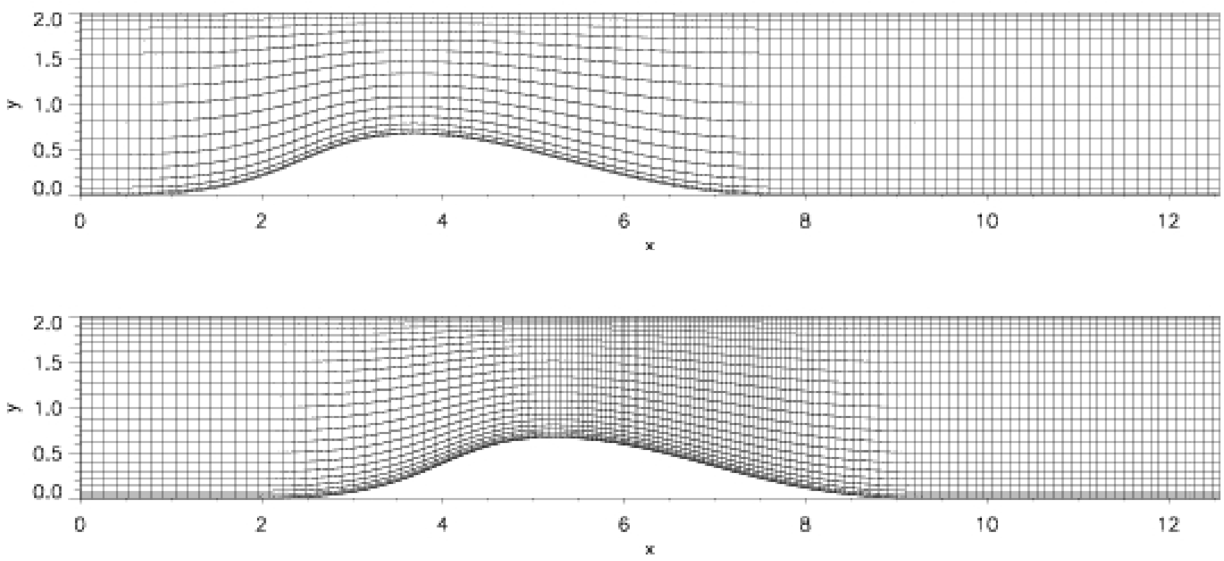


***Figure 1** : Mesh in the streamwise normal plan for the two DNS at Re_τ=395 (top) and Re_τ=617 (bottom)*

Description of the database

The present database is recorded in NetCDF (Network Common Data Form). This format is commonly used and very convenient because it is compact (binary) and self_describing. For more detail one can refer to the NetCDF website (http://www.unidata.ucar.edu/)

3D fields

Table 2 *: Description of the database for the 3D fields. Each file contains the variables for a single time.*

Name of DNS	Variables	Number of 3D fields	Time increment	Name of files	Size of each file
APG_400	Velocity & Pressure	438	0.05 – 0.10	Velocity/BOSS-0000??.??????.nc	2.3 Gb
APG_600	Velocity & Pressure	930	0.06	Velocity/BOSS-0000??.??????.nc	7.7 Gb
	Vorticity	68	0.6	Vorticity/VORT-0000??.??????.nc	5.8 Gb
	$Q=\Omega^2-S^2$	1600	0.03	Q_criterion/QCRI-0000??.??????.nc	2.0 Gb

Statistics

The mean velocity, Reynolds stresses and all the terms involved in the balance of the each Reynolds stress component were computed in both the global coordinate system and a local coordinate system (normal to the geometry of at the lower wall). The definition of each terms are given in the file « **APG_???_statistics_description.pdf** ». All the statistics in the (XY) plane as well as the grid are provided in the NetCDF file « **APG_???_statistics_2d.nc** ». A python script is provided to plot some statistics in the XY plane (**« APG_ ???_statistics_2d_plot.py »**). The mean streamwise velocity and Reynold stresses have been interpolated from the 2D statistics on 48 normal profiles along the streamwise axis at both the lower wall and the upper wall (in « **APG_???_Reynolds_stress_lower.txt »** and « **APG_???_Reynolds_stress_upper.txt »** respectively). The friction velocity, friction coefficient and pressure coefficient are provided (in ASCII) at the lower curved wall and upper flat wall in the file « **APG_ ???_statistics_streamwise.txt »**

Additional materials

Some movies of coherent structures (vortices & streaks) are provided in the directory « Movies » of each DNS :

- **« APG_600_Iso_Q_3D_Full.avi »** & « **APG_400_Iso_Q_3D_Full.avi »**: Iso-value of Q to visualise the vortices
- **« APG_600_streaks_vortices_lower_wall.avi »** : Visualisation low speed streaks (negative fluctuating streamwise velocity) in yellow and vortices in blue (using iso-value of Q) at the lower wall in the APG region.
- **« APG_600_streaks_vortices_upper_wall.avi »** : Visualisation low speed streaks (negative fluctuating streamwise velocity) in yellow and vortices in blue (using iso-value of Q) at the lower wall in the APG region.
- **« APG_400_Streaks_y10+_two_walls.avi »** : 2D contours of fluctuating streamwise velocity interpolated at 10 wall units from each walls.

References

(The full text are available at http://imp-turbulence.ec-lille.fr/Webpage/Laval/Publications/publis-laval.html)

For the DNS « APG_400 » and the numerical code MFLOPS3D

- M. Marquillie, J.-P. Laval and R. Dolganov, 2008, Direct Numerical Simulation of separated channel flows with a smooth profile. J. Turbulence 9, 1-23.

For the DNS « APG_600 »

- J.-P. Laval, M. Marquillie and U. Ehrenstein, 2012, On the relation between kinetic energy production in adverse-pressure gradient wall turbulence and streak instability. J. Turbulence 13 (21) 1-19.

- M. Marquillie, U. Ehrenstein and J.-P. Laval, 2011, Instability of streaks in wall turbulence with adverse pressure gradient, J. Fluid Mech. 681 205-240.

Other references using the data

- L. Kuban, J.-P. Laval, W. Elsner, A. Tyliszczak, M. Marquillie, 2012, LES modeling of converging-diverging turbulent channel flow. J. Turbulence 13 (11) 1-19

- V. J. Shinde, J.-P. Laval, M. Stanislas, 2014, Effect of mean pressure gradient on the turbulent wall pressure-velocity correlations. J. Turbulence 15 (12) 833-856.

Acknowledgements

The DNS APG_600 was performed through two successive DEISA Extreme Computing Initiatives (DEISA is a Distributed European Infrastructure for Supercomputing Applications). The DNS APG_400 and all the post-processing were performed partly with the HPC resources of IDRIS under the allocation 2010-021741 made by GENCI (Grand Equipement National de Calcul Intensif) and partly with the ressources of CRIHAN (Centre de Ressource en Informatique de Haute Normandie, France). The database was made available on Turbase using the support of EUHIT.