C3.4 LES of Periodic Hill Flow

1 Code Description

HiFiLES [2] is an open-source high-order solver written in C++ and CUDA which can be run on CPU and GPU clusters. The code is capable of solving the compressible Euler, Navier-Stokes and RANS equations and is equipped with the SA RANS model and various LES subgrid models. The family of energy-stable Flux Reconstruction (FR) schemes are used to achieve high-order accuracy on structured, unstructured and mixed meshes in 2D and 3D. Up to 6th order accuracy is possible on tetrahedra and up to 8th order on hexahedra. Visualisation of the results is achieved with TecPlot and Paraview.

2 Case Summary

The periodic hill flow was simulated using the Spectral Difference and Discontinuous Galerkin schemes recovered via the FR framework and the 4th-order explicit Runge Kutta timestepping scheme, avoiding the need for global matrix construction and inversion. A fixed timestep was used which depended on the scheme order. Initial conditions were provided by assuming a quartic mean velocity profile satisfying the bulk velocity constraint. The LES was run without any subgrid model (a.k.a. implicit LES) as the low Reynolds numbers would suggest that this is a suitable approach. Pressure gradient forcing was achieved by adding a body force term according to the formula given.

Convergence of the time-averaged solution was assessed in postprocessing by comparing the velocity profiles averaged over different periods. For the results presented below, the time series of viscous force components is presented (Figure 1). The streamwise component (F_x) shows that the flow evolves over the initial 60000 iterations and is in a pseudo-steady state thereafter, completing several cycles of eddy separation and reattachment. Simulations were run on the Stanford Institute of Computational Math and Engineering's (ICME) GPU cluster using 6-12 GPUs. On one CPU of this cluster, a TauBench work unit corresponded to 11.462 seconds of compute time. However, the TauBench code could not be run on GPUs so a direct comparison of TauBench and HiFiLES is not possible. Nevertheless, the submitted results include the time taken normalised by the TauBench CPU work unit.

3 Meshes

Neutral-format meshes of 64x32x32 hexahedral elements with linear surface representation were generated using Gambit. Stretching functions were created to ensure the resulting

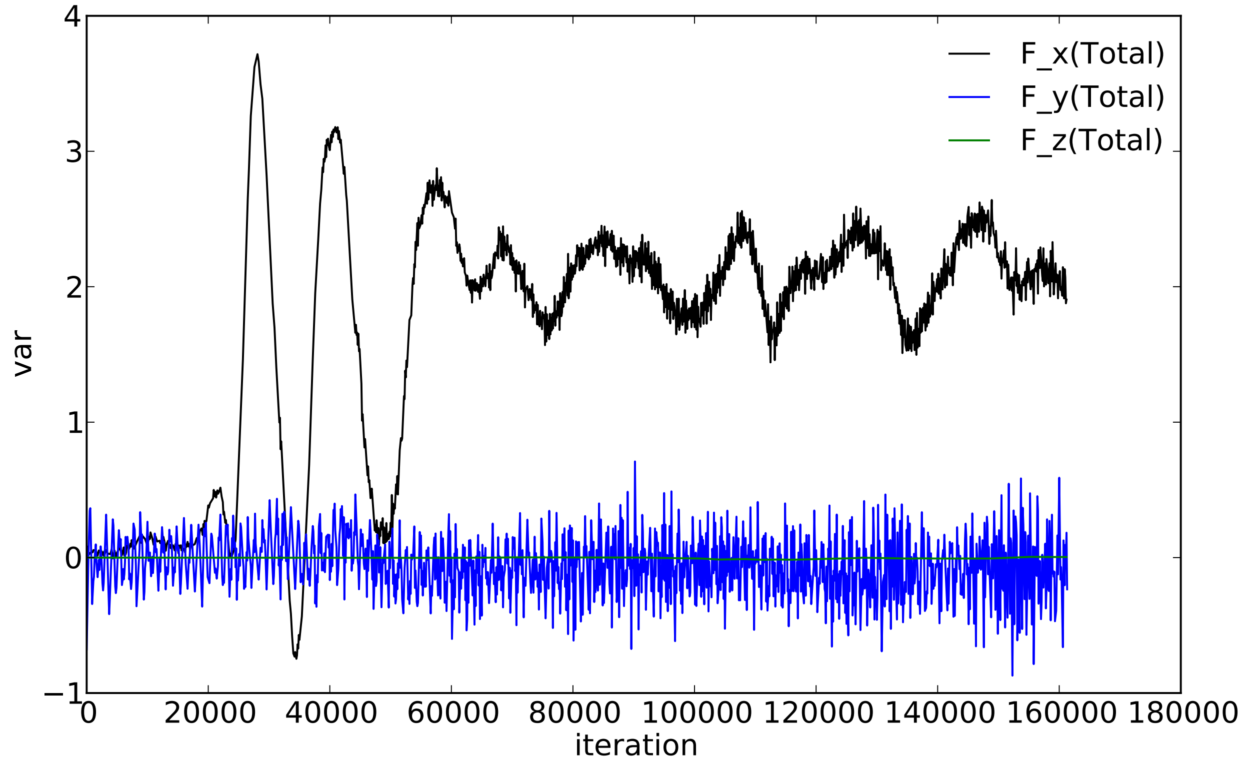

Figure 1: Time series of integrated viscous force components in the case presented below.

meshes resembled the provided meshes as closely as possible. Figure 2 shows a cross section of the mesh showing the actual number of degrees of freedom when second-order basis polynomials are employed within elements.

4 Results

The results presented here are from the $Re = 10,595$ case using the third-order accurate DG scheme recovered via FR (i.e. second-order polynomial basis functions). Figure 3 shows the mean streamwise velocity at positions from $x/h = 0.05$ to $x/h = 8$ compared to the DNS by Breuer et al. [1]. Time averaging was performed in postprocessing from a series of 60 Paraview output files separated by 1000 timesteps, covering the range of iterations from 60000 to 120000. Spanwise averaging was performed over a set of 30 equally spaced planes across the channel. Figure 5 shows the time-averaged Reynolds stress component $u'u'/U_B^2$ over the same period. To demonstrate convergence of the time averaged results, Figures 4 and 6 present the mean velocity and Reynolds stress profiles averaged over the period 80000-120000 iterations. The results are virtually identical with slight deviations in the Reynolds stresses very close to the bottom surface.

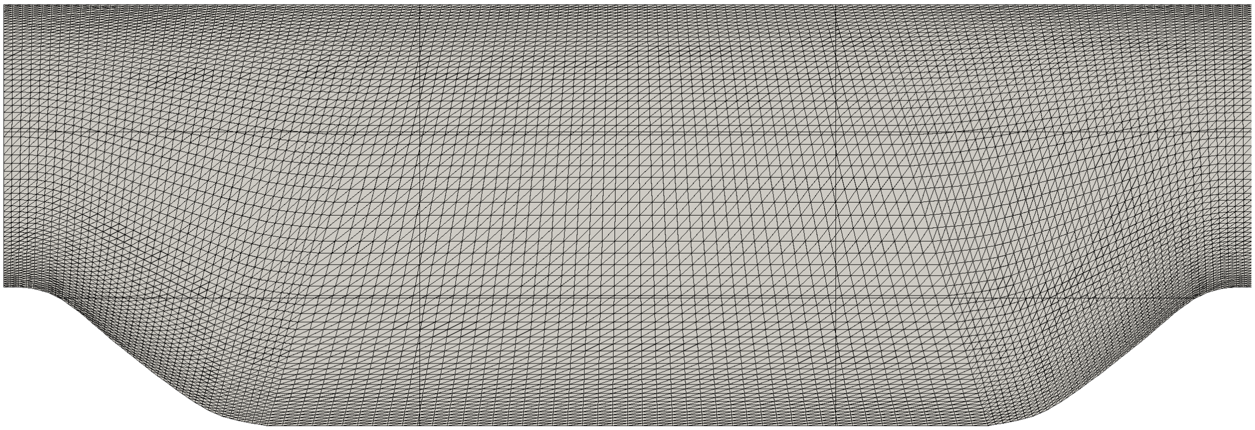

Figure 2: Computational mesh

References

[1] M. Breuer, N. Peller, C. Rapp, and M. Manhart. Flow over periodic hills - numerical and experimental study in a wide range of Reynolds numbers. *Int. J. Comp. Fluids*, 38 (2):433–457, 2009.

[2] M. López, A. Sheshadri, J. Bull, T. Economon, J. Romero, J. Watkins, D. Williams, F. Palacios, A. Jameson, and D. Manosalvas. Verification and validation of HiFiLES: a high-order Navier-Stokes unstructured solver on multi-GPU platforms. *44th AIAA Fluid Dynamics Conference, Atlanta, Georgia, June 16-20, 2014*, 2014.

[3] L. Temmerman and M. Leschziner. large eddy simulation of separated flow in a streamwise periodic channel constriction. *Int. Symposium on Turbulence and Shear Flow Phenomena, Stockholm, June 27-29*, 2001.

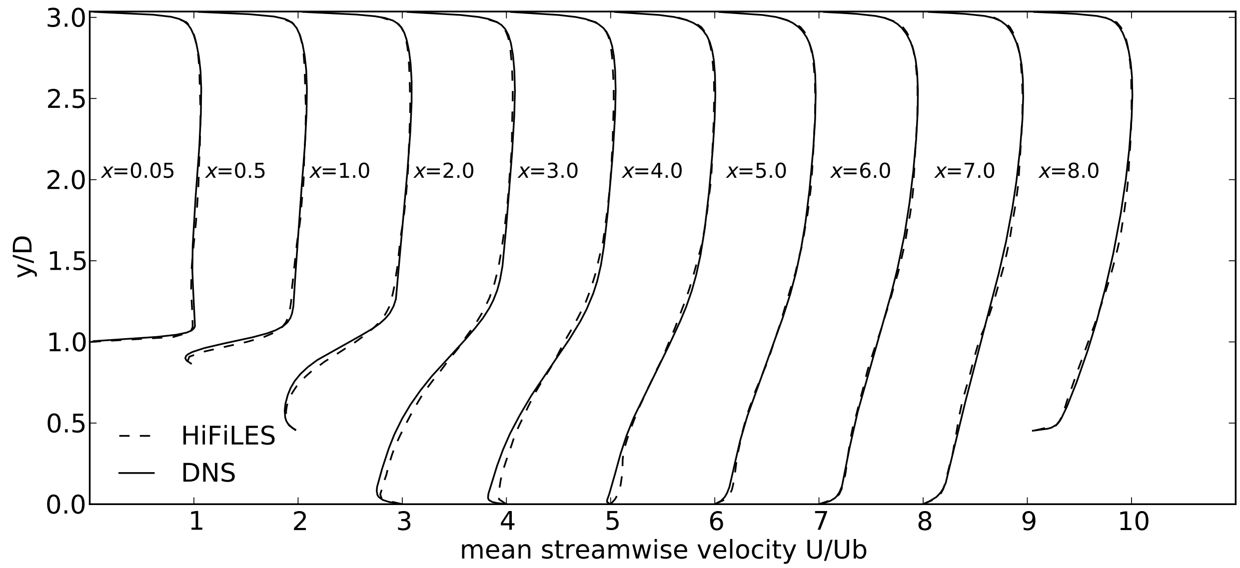

Figure 3: Mean streamwise velocity profiles compared DNS [1]. Time averaging over period 60000-120000 iterations.

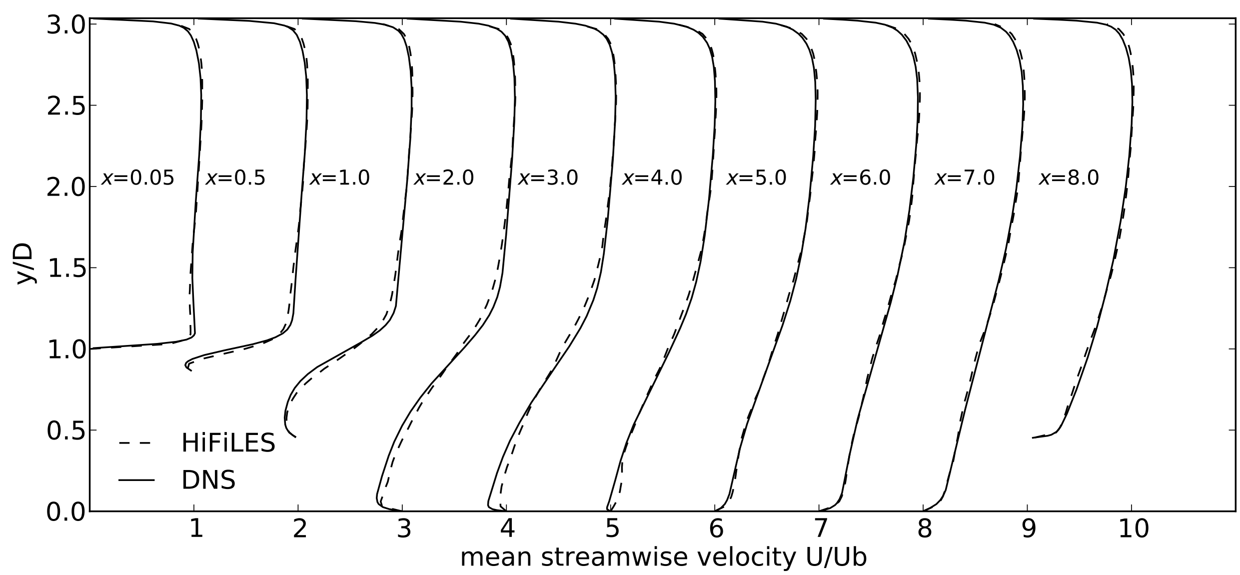

Figure 4: Mean streamwise velocity profiles compared to DNS [1]. Time averaging over period 80000-120000 iterations.

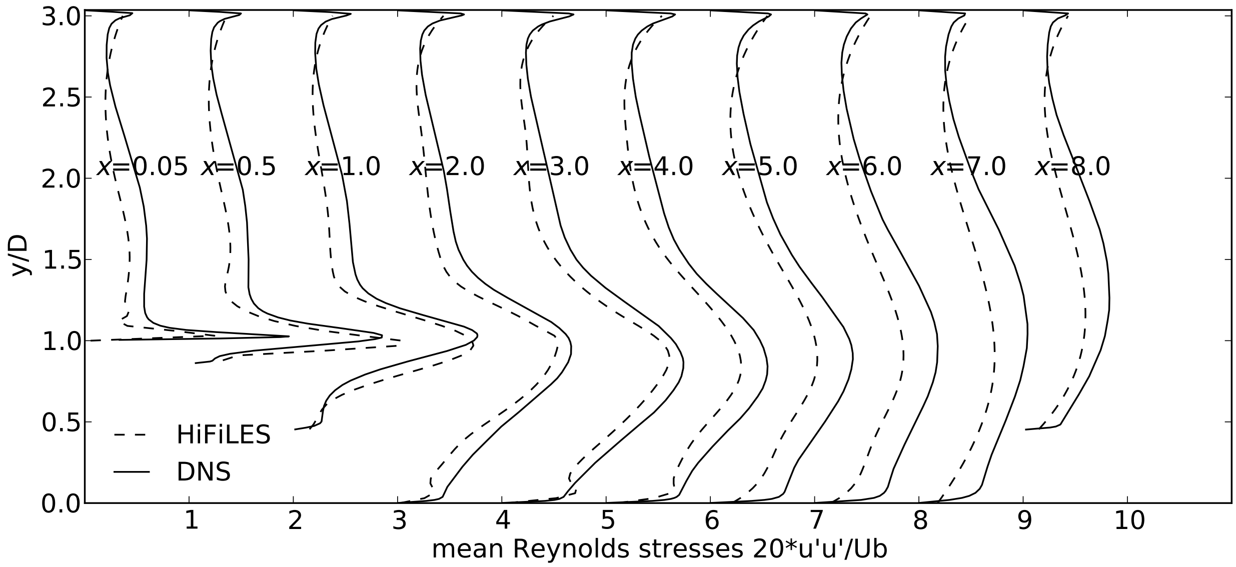

Figure 5: Mean Reynolds stress component $u'u'/U_B^2$ compared to DNS [1]. Time averaging over period 60000-120000 iterations.

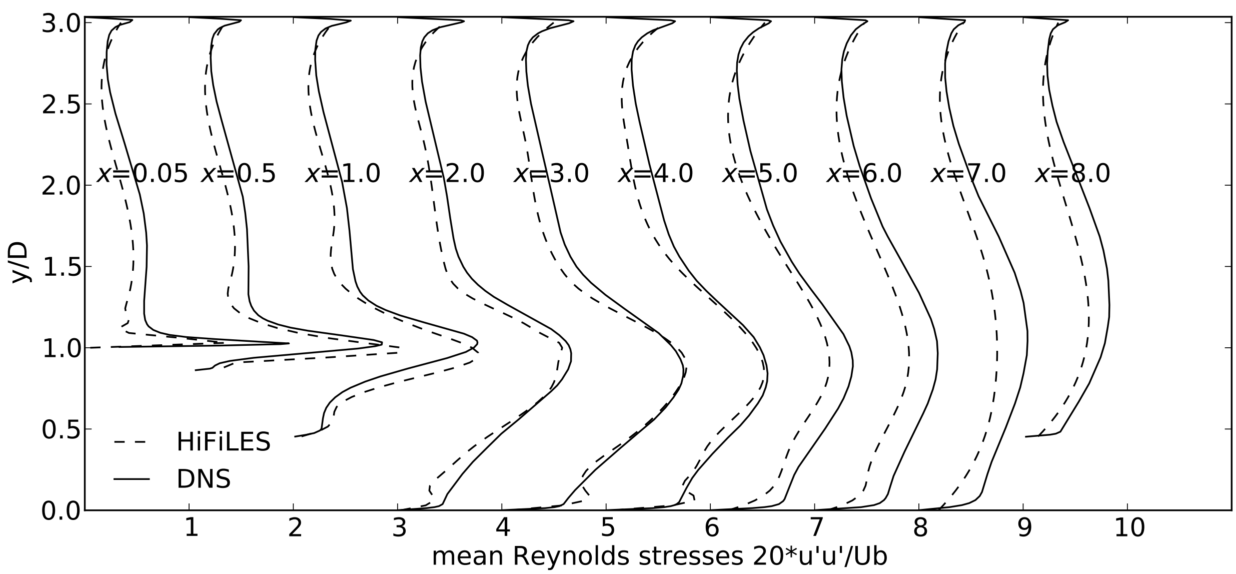

Figure 6: Mean Reynolds stress component $u'u'/U_B^2$ compared to DNS [1]. Time averaging over period 80000-120000 iterations.