Comparison of LES and DNS for the flow past a circular cylinder with fairings

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1 Introduction

The flow past different kinds of cylinders are a key problem in many areas of industry and nature. The simplest configuration is the flow around a smooth, circular cylinder. Even though the problem description is very simple, the flow solution is highly complex and a challenge to calculate numerically. The behaviour of the flow is highly dependent on the Reynolds number $Re = U_\infty D/\nu$ (where U_∞ is the inflow velocity, D is the cylinder diameter and ν is the kinematic viscosity of the fluid), and already for very low Reynolds number, the flow becomes unstable and vortex shedding is observed. For higher Reynolds number, approximately $Re > 200$, the vortex shedding and wake region becomes three-dimensional, and transition to a turbulent wake begins.

One of the main challenges in this flow problem is caused by the separation of the flow. Since the cylinder is smooth, we have no *a priori* knowledge about the point of flow separation. Capturing this point is vital to determine the forces on the cylinder, since the pressure distribution around the cylinder is highly sensitive to the location of this point.

This abstract will focus on a circular cylinder with fairings as shown in figure 1. The purpose of these fairings is to reduce the oscillating forces caused by the vortex shedding process, and hence reduce the VIV (Vortex Induced Vibrations) motions of for example offshore risers. For the present study, we use $Re = 5000$.

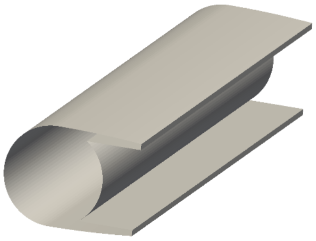

Figure 1: An illustrative sketch of the cylinder with fairings.

Our aim at the current stage of this project is to compare the results from DNS (Direct Numerical Simulations) and LES (Large Eddy Simulations) to enhance our experience with LES in particular. We are able to do fully resolved DNS for this flow configuration and believe that these results are very accurate, however they are costly. We hope that LES can be used as an alternative approach, and that this could be used in conjunction with DNS and experiments to do complementary simulations of cases that we previously could not afford to study.

2 Numerical methods

Different simulation codes have been used to do the DNS and LES. The code *MGLET* [1] has been used to perform the DNS while the LES were performed with *OpenFOAM* [2, 3]. Both tools are finite volume codes, and in both cases linear central differences and linear interpolation have been used for all spatial terms, hence leading to second order accuracy in space. For the DNS, a third order explicit Runge-Kutta time integration scheme have been used, while

Table 1: Grid and simulation setup. The domain size is $70D \times 40D \times 6D$ for all cases. The 'performance' measure is the wall-time per time step divided by the number of grid points per process, i.e. (time per step)/(gridPts/nProcs). Lower number is indicating better performance.

	DNS	10M LES	20M LES	
Grid design	$2048 \times 800 \times 300$	Unstructured	Unstructured	
Number of cells	491×10^6	10.9×10^6	20.3×10^6	
Time step	0.001	0.001	0.001	D/U_∞
Simulation time	300	600	600	D/U_∞
Cost	140.6×10^3	115.2×10^3	207.9×10^3	CPU-hours
Cost per D/U_∞	468.8	192.0	346.6	CPU-hours
Performance	3.43	63.4	61.8	$\times 10^{-6}$

for the LES a second order semi-implicit Crank-Nicolson scheme [4] was used in the temporal dimension.

The major difference between the codes are in the mesh design and handling of solid boundaries. MGLET uses a regular Cartesian mesh, and introduce the solid geometry through an immersed boundary method. This gives an advantage when it comes to the mesh generation which is very simple, while it poses some challenges especially when it comes to the handling of sharp corners on the geometry. This also inherently leads to unnecessary large number of cells. OpenFOAM on the other hand uses a body-fitted unstructured mesh. This is more flexible, because it is possible to do local refinements around the cylinder and in the wake where high resolution is needed, while keeping the resolution coarse in the far-field regions where the flow is of no interest.

The Smagorinsky eddy viscosity model [5] was used for the LES cases. Both LES and DNS have been performed on the same HPC cluster, hence the CPU hours consumed by the two methods are comparable when it comes to assess the 'cost' of a simulation.

3 Results

Convergence studies have been performed for the DNS with respect to grid resolution. We believe that the simulation presented here is a well resolved simulation which might be considered 'converged' when it comes to mesh resolution. However, for the time-averaged quantities, only 300 D/U_∞ have been simulated after the flow has stabilized, hence there might still be some errors related to the statistical convergence. When it comes to the LES, 600 D/U_∞ have been simulated on each mesh.

The main flow quantities from the simulations are summarized in table 2. An illustration of the instantaneous flow field from the 20M LES is shown in figure 2.

3.1 First and second order statistics

Contours for the time- and spanwise averaged quantities $\langle u \rangle$, $\langle v \rangle$, $\langle u'u' \rangle$ and $\langle u'v' \rangle$ are shown in figure 4. One can observe that some features in the contours from the DNS are not fully symmetric as they should be. This might be due to a too low averaging time. Parnaudeau et al. [6] claimed that over 250 vortex shedding cycles is needed for statistical convergence of the wake behind a circular cylinder at $Re = 3900$. Neither of the simulations presented here are close to that. This can explain some differences, but not all. Please see figure 8 in ref. [6] for an excellent illustration of this issue.

Figure 3 also shows the same significant discrepancies between the LES and DNS in the wake behind the cylinder. LES clearly underpredict both the recirculation length and vortex formation length when compared with DNS. Again this might be due to a too small averaging time for the DNS, however, we do believe that there are other contributions to this deviation as well.

Table 2: Main flow results. C'_L is the RMS of the lift coefficient and C'_D is the RMS of the fluctuating part of the drag coefficient (i.e. after the mean have been subtracted). The overbar indicate a mean quantity. Note that the vortex shedding frequency have been calculated based on a velocity probe in the wake at $x/D = 3$ for the DNS, and based on the time series for lift for the LES.

	DNS	10M LES	20M LES
St	0.227	0.259	0.240
$\overline{C_D}$	0.884	0.813	0.881
C'_L	0.0496	0.0438	0.0503
C'_D	0.0125	0.0140	0.0127
$-\overline{C_{pb}}$	0.767	0.723	0.775

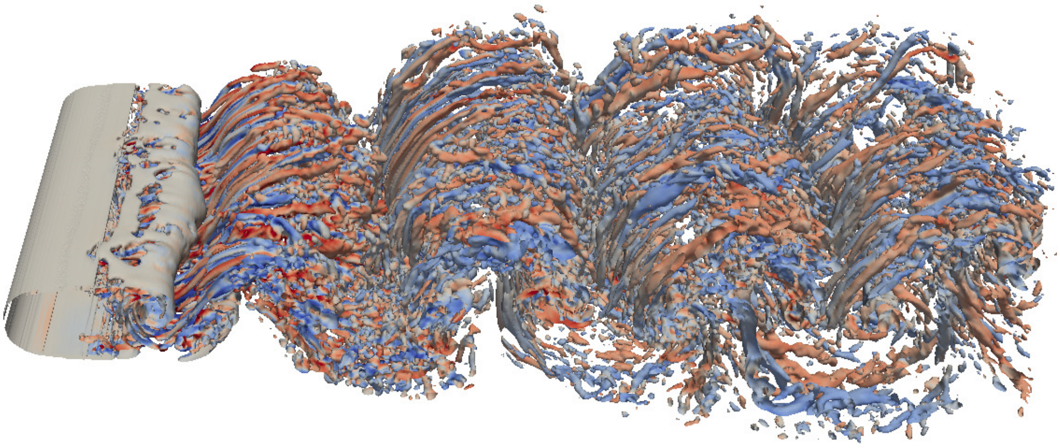

Figure 2: Isosurface of $\lambda_2 = -1$ colored by streamwise vorticity ω_x for the 20M LES case.

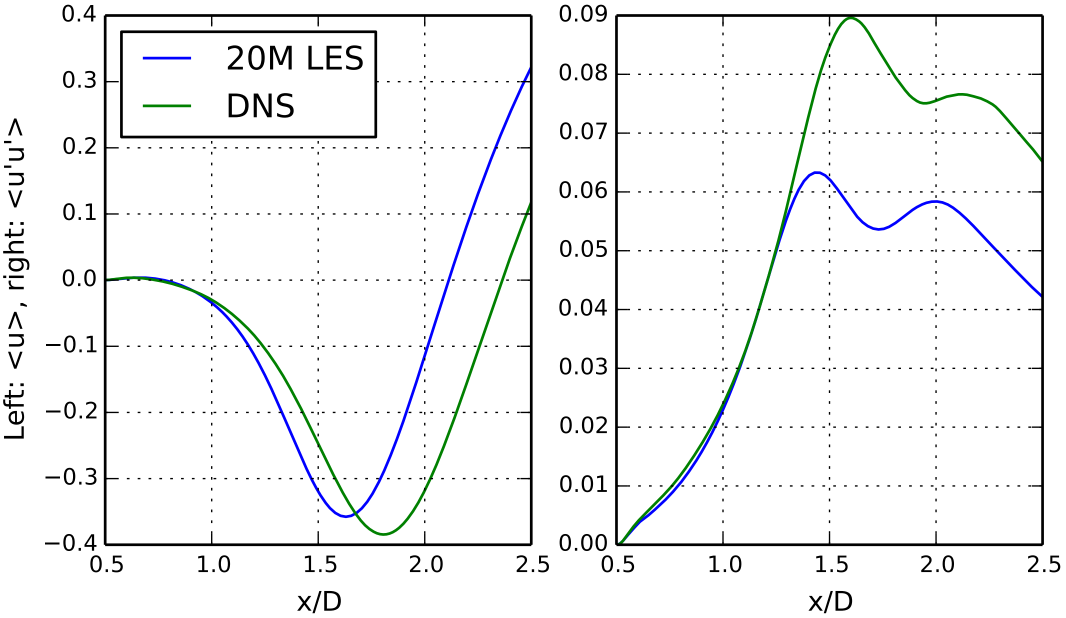

Figure 3: Center-line profiles for $\langle u \rangle$ and $\langle u'u' \rangle$.

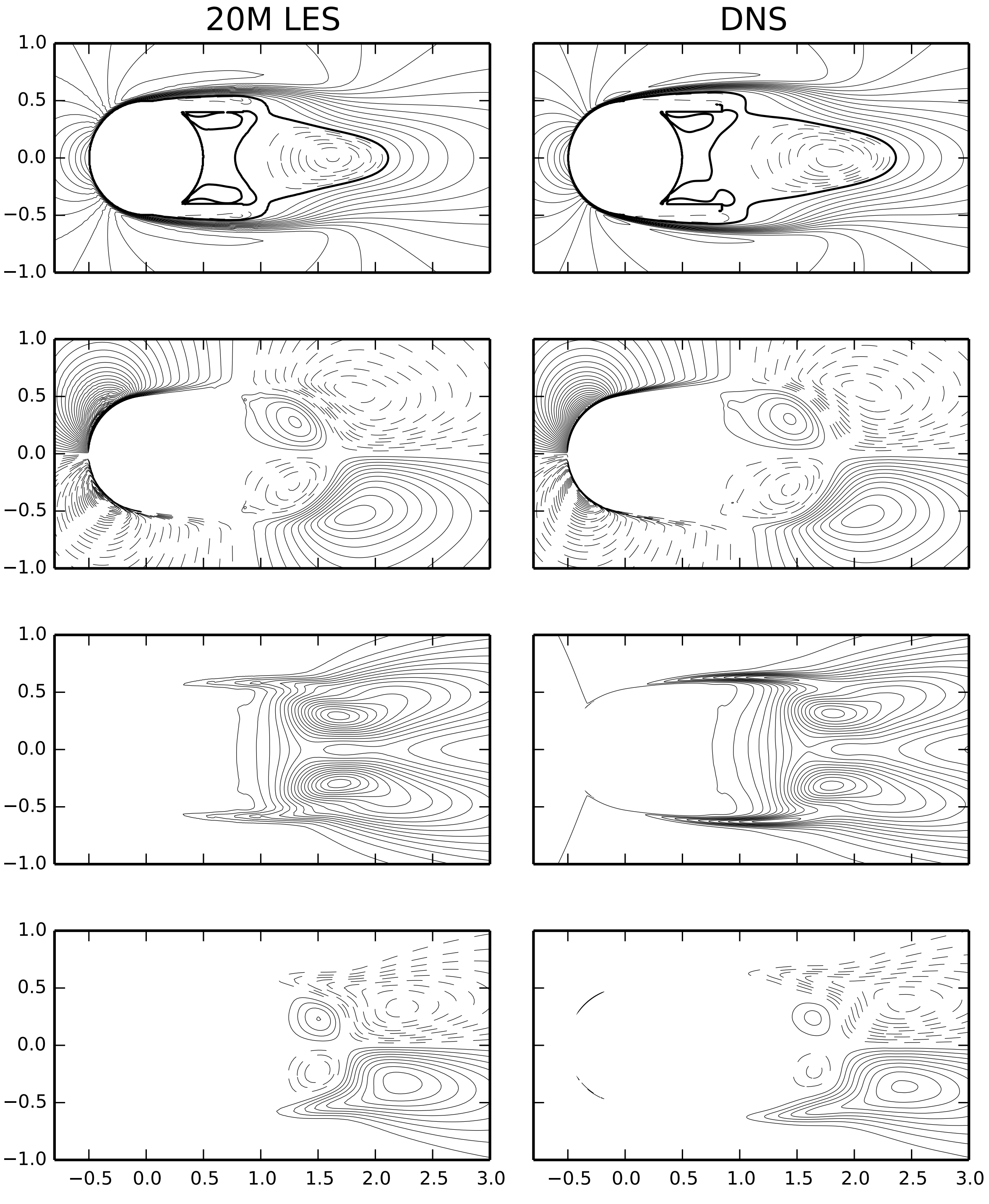

Figure 4: Isocontours of $\langle u \rangle$, $\langle v \rangle$, $\langle u'u' \rangle$ $\langle u'v' \rangle$ (in order from top to bottom) for the 20M LES and DNS respectively. Dashed lines are negative, and a thick line indicate a zero contour (not shown in all plots).

4 Concluding remarks

The DNS and LES presented here do not agree on important statistical flow parameters. Even tough lift and drag forces are captured by the LES simulation, the flow in the wake is not sufficiently accurate to be of any use. *You simply cannot create a mesh, turn on LES and expect the results to be good!*

The difference in computational cost between LES and DNS is not as huge as one might intuitively guess based on the cell counts alone. However, MGLET is a very specialized code and the Cartesian grid facilitates much higher performance than the unstructured grids of OpenFOAM. The internal data structures are very different, and if MGLET can utilize the vector operations available on modern CPUs, while avoid excessive cache misses, that explain much of the higher performance.

In addition to the internal numerics, it is also important to remember that the general concept behind LES is to filter away *isotropic* turbulent scales, while leaving the non-isotropic scales to be resolved. At $Re = 5000$ it is possible that the amount of work saved saved by filtering away these scales are small, because there is little isotropic turbulence present.

5 Further work

This is obviously work in progress. We need to work on the LES and figure out how to get better agreement between LES and DNS. One possible parameter to change is the eddy viscosity model. We believe that a dynamic model in which the Smagorinsky constant C_s is no longer uniform over the domain could be a candidate for a next step in these studies.

We have also access to databases with results from PIV (Particle Image Velocimetry) experiments for the same flow configuration. Comparison of the numerical results with these experiments will be conducted, but problems with statistical convergence will still be an issue in these data.

Additional LES, both with higher and lower mesh resolutions and higher Reynolds numbers are also planned. Due to the computational efficiency of MGLET, it is possible that we will try to do LES with this code as well.

References

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