Chapter 4

Simulations on the fine grid

4.1 Description of the test case

4.1.1 2D Mesh

The flow to be simulated here is the same as described in Chapter 3, i.e. the flow past a circular cylinder at Mach number $M_{\infty} = 0.1$ and at a subcritical Reynolds number $Re_D$ of 3900 ($Re_D = \frac{u_{\infty}D}{\nu}$) based on cylinder diameter $D$ and free-steam velocity $u_{\infty}$. The fine grid was definitely more complicated to build than the coarse one. In particular, a grid with at least one million nodes was required. An higher refinement with respect to the coarse grid was required near the body surface, in the recirculation zone behind the cylinder and in the wake down. The first two grid zones are also the most important ones for a correct numerical simulation and for this an ad-hoc refinement was performed. Obviously the shape of the wake was not previously known, so we referred to experiments in Ref. [22]. The averaged distance request of the nearest point to the cylinder boundary is 0.005$D$ which corresponds to $y^+ \approx 1$, where $y^+$ is the distance from cylinder surface in wall units. The domain dimensions have been slightly changed in comparison with the coarse grid, reducing the $y$ dimension, while the $x$ dimension and the spanwise $z$ have remained the same. This modification has been done to try to optimize the
grid, removing the nodes in the zones less interesting on the computational point of view and increasing them around the cylinder.

The computational domain as shown in Figure 4.1 is $-10 \leq x/D \leq 25$, $-15 \leq y/D \leq 15$ and $-\pi/2 \leq z/D \leq \pi/2$ where $x$, $y$ and $z$ denote the streamwise, transverse and spanwise direction respectively. The characteristics of the domain are the following:

$L_i/D = 10$, $L_0/D = 25$, $H_y/D = 15$ and $H_z/D = \pi$

The cylinder of unit diameter is centered on $(x,y) = (0,0)$.

![Figure 4.1. Computational domain](image)

Also the flow domain, as in the case of the coarse grid, is discretized by an all unstructured tetrahedral grid. It is now described how we proceeded.

The grid construction was carried out by *ansys 8.0* software. We started
with the definition of the domain 2D. As we had to build an extremely accurate grid around the cylinder, 30 circumferences have been constructed around the cylinder of which ten $0.005D$ far from the other ones and the others with a constant expansion in the diameter of one percent, following in this way the $D_0 = D_{-1} + D_{-1}/100$ law. The circumferences around the cylinder were divided on 160 parts. The circumferences around the cylinder have been represented in the Figure 4.2.

Figure 4.2. 30 circumferences of construction

A complete view of the lines of the grid construction is represented in Figure 4.3.
As for the coarse grid the fine mesh was performed with the Tetrahedral elements in the volume. We have initially built a 2D mesh show in Figure 4.4 we can note the high refined zone behind the cylinder and relating to the separation of the boundary layer. In Figure 4.5 we have reported the zoom near the cylinder. In Figure 4.6 we have reported the complete 2D mesh which has got 22795 nodes. In Figure 4.7 we can see the progressive expansion of the 30 circumferences of construction.
Figure 4.4. High refined zone behind the cylinder
Figure 4.5. Zoom mesh near the cylinder
Figure 4.6. Complete 2D mesh. Number of nodes: 22795
Figure 4.7. progressive expansion of the 30 circumferences of construction
4.1.2 3D Mesh

After building the 2D mesh we proceeded to construct the 3D mesh. The domain has been extruded of \((\pi D)/4\) and reflected twice. This operation was necessary not to have problems in the machine memory. Using the same procedure we have carried out the lines of construction of the grid in order to give them their relative bonds. Not to have problems of high tetrahedral stretch of the mesh mostly in the zone near the cylinder 32 subdivisions in the \(z\) spanwise direction has been done. We chose this way giving the maximum admissible value of the ratio between the maximum height of the tetrahedra faces and the minimum one could be equal to five:

\[
\frac{h_{\text{Max Tetrahedral}}}{h_{\text{Min Tetrahedral}}} = 5
\]

In our case the minimum height is equal to the distance of the circumferences of construction, that is 0.005\(D\). Knowing that the length in the \(z\) spanwise dimension is \(\pi/4\), we find that:

\[
\frac{\pi/4 \ D}{0.005D} \approx 32
\]

The subdivisions in the spanwise \(z\) will be 128.

In Figure 4.8 we reported the 3D domain and in Figure 4.9 the relative zoom.

Then we built the volume mesh. In Figure 4.10 we reported the volume grid near the cylinder.

In total the 3D mesh has got 1133825 nodes and 6621980 elements.
Figure 4.8. Lines of construction of the 3D domain
Figure 4.9. Lines of construction of the 3D domain. Zoom
Figure 4.10. Mesh 3D: 1133825 nodes
4.1.3 Boundary conditions; CFL number; Numerical viscosity $\gamma$

Boundary conditions are the same as for the coarse grid. At the inflow the flow is assumed to be undisturbed and the Steger-Warming [14] conditions are applied. Boundary conditions based on the Steger-Warming decomposition are used at the outflow as well. On the lateral surfaces ($y = \pm H_y, z = \pm H_z$) slip conditions are imposed. Finally, the flow is assumed to be periodic in the spanwise direction in order to simulate a cylinder of infinite spanwise length.

The numerical parameter $\gamma$, which controls the amount of numerical viscosity introduced in the simulation, has been set equal to 0.3, in order to obtain stable simulations.

The simulations have been implicitly advanced in time, with a maximum CFL number equal to 80.

4.2 Results of the simulations

Following the results of the study on the coarse grid, the simulations on the fine grid have been performed using preconditioning. As usual, for the evaluation of the results we have omitted the initial transient period. We have considered about thirty cycles of vortex shedding to obtain steady statistics. In Figure 4.11(a) the coefficients $C_l$ and $C_d$ are shown as a function of the time.

Time-averaged bulk coefficients for the fine grid are summarized in Table 4.1 in which the results obtained with the coarse grid are also reported for comparison. $\overline{C_d}$ denotes the mean drag coefficient, $C'_d$ and $C'_l$ the root mean square values of the drag and lift respectively, $St$ the Strouhal number, $l_r$ the length of the mean recirculation bubble (measured on the line $y = z = 0$) $\theta_{sep}$ the separation angle and $U_{min}$ the minimum mean streamwise velocity measured on the line $y = z = 0$.

Surprisingly, the table shows that the simulations carried out on the fine
Figure 4.11. Lift (a) and drag (b) coefficients versus time obtained with the WALE model.
<table>
<thead>
<tr>
<th>Data from</th>
<th>St</th>
<th>$C_d$</th>
<th>$C_d'$</th>
<th>$C_l'$</th>
<th>$l_r$</th>
<th>$\theta_{sep}$</th>
<th>$U_{min}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WALE fine grid</td>
<td>0.218</td>
<td>0.95</td>
<td>0.0213</td>
<td>0.0435</td>
<td>1.95</td>
<td>83</td>
<td>-0.25</td>
</tr>
<tr>
<td>Vreman fine grid</td>
<td>0.215</td>
<td>0.94</td>
<td>0.0180</td>
<td>0.0374</td>
<td>2.03</td>
<td>82</td>
<td>-0.27</td>
</tr>
<tr>
<td>Vreman Barth cells fine grid</td>
<td>0.215</td>
<td>0.94</td>
<td>0.0139</td>
<td>0.0415</td>
<td>2.05</td>
<td>82</td>
<td>-0.37</td>
</tr>
<tr>
<td>Smago. coarse grid</td>
<td>0.219</td>
<td>1.18</td>
<td>0.0842</td>
<td>0.497</td>
<td>0.89</td>
<td>95</td>
<td>-0.28</td>
</tr>
<tr>
<td>Vreman coarse grid</td>
<td>0.212</td>
<td>1.17</td>
<td>0.0750</td>
<td>0.483</td>
<td>0.94</td>
<td>93</td>
<td>-0.31</td>
</tr>
<tr>
<td>WALE coarse grid</td>
<td>0.215</td>
<td>1.23</td>
<td>0.0639</td>
<td>0.592</td>
<td>0.92</td>
<td>93</td>
<td>-0.26</td>
</tr>
<tr>
<td>Smago. prec. coarse grid</td>
<td>0.221</td>
<td>0.99</td>
<td>0.0359</td>
<td>0.259</td>
<td>1.11</td>
<td>87</td>
<td>-0.29</td>
</tr>
<tr>
<td>WALE prec. coarse grid</td>
<td>0.220</td>
<td>0.96</td>
<td>0.0274</td>
<td>0.196</td>
<td>1.17</td>
<td>87</td>
<td>-0.27</td>
</tr>
<tr>
<td>Experiments [18], [17], [16] [19], [26]</td>
<td>0.215±0.05</td>
<td>0.99±0.05</td>
<td>1.33±0.02</td>
<td>85±2</td>
<td>-0.24±0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1. Bulk coefficients: results obtained with the fine grid, the coarse grid and from experiments

grid (fine grid $FG$) are in a worse agreement with the experiments than to the results obtained with the coarse grid (coarse grid $CG$). For instance let us consider the simulations with the WALE and Vreman models. The parameter which results in greatest disagreement with the experiments is $l_r$, the mean recirculation length which is largely overestimated. Conversely, the preconditioned WALE model for the coarse grid (precondition, coarse grid $PCG$) predicts $l_r$ with reasonable accuracy.

The parameters $C_d'$ and $C_l'$ are smaller than those obtained on the coarse grid: the $C_d'$ obtained with the WALE model on the fine grid is about 29% smaller than the one provided by the WALE PCG simulation. The $C_d'$ obtained with the Vreman model results 52% smaller than the one provided by the WALE PCG simulation. Referring to the $C_l'$ and still taking as reference the preconditioned WALE model on the coarse grid, $C_l'$ provided by the WALE model on the fine grid is 4.5 times smaller, while for the Vreman
model is 5.2 times smaller. These wide underestimations of the $C'_d$ and $C'_l$ are in agreement with the overestimation of the recirculation length $l_r$ with the fine grid. Indeed, the longer the recirculation length is, the smaller the parameters $C'_d$ and $C'_l$ become as the alternate vortices develop more downstream and have then less effect on the aerodynamic forces acting on the the circular cylinder.

The separation angle $\theta_{sep}$ for all the simulations is in a good agreement with the experimental data. Instead, concerning $U_{min}$, the WALE FG model and the Vreman FG model are in slightly better agreement with the experimental values than those obtained with the WALE PCG model. The value of $C_d$ does not change significantly from the coarse grid to the fine grid.

The Strouhal number for all the simulations is in a good agreement with the experimental data. Therefore we notice that, the parameter truly far from the experimental data is the recirculation length. In order to investigate the reasons that led to the previously described results, we have then performed another simulation on the fine grid for the Vreman model and using the Barth cells. Indeed, inside the grid there could be some cells with a high aspect ratio affecting the overall accuracy of the simulations. We thus compare the results given by the Vreman FG model with those of the Vreman FG model with the Barth cells. All the values remain essentially the same, except the $U_{min}$. Thus, this test shows that using the Barth cells does not improve the simulation for the fine grid. Further, we have performed simulations reducing the CFL, always using the Vreman model on the fine grid. However, no significant improvement was found.

Subsequently we have reported the typical graphs that summarize all the various tests on the fine grid. As usual the various data of the numerical simulations have been compared to the experimental data. The graphs in Figure 4.12, 4.13, 4.14 have been carried out averaging the data in the 32 planes $x - y$ (so perpendicular to the cylinder axis) equispaced in the $z$ direction between $z_{min}$ and $z_{max}$ ($-\pi/2 ; \pi/2$).

The Figure 4.12 represents the mean streamwise velocity $\overline{U}$ along the
Simulations on the fine grid using different subgrid scale models in the fine grid. The difference between the experimental data and the various curves is considerable. As reported in the Table 4.1 the recirculation length is much larger for all the various models on the fine grid than to the experimental one. The WALE model is slightly better than the other ones. Using the Barth cells does not improve the simulation, on the contrary it deteriorates the of $U_{min}$. Far from the cylinder the various curves show the same trend.

In figure 4.13 the curves of $\overline{Cp}$ are shown. The curves related to the fine grid are in a better agreement respect the experimental data than those ones related to the coarse grid. In particular, the trend of the 60 and 90 degrees is in a better agreement for the simulations on the fine grid than for those ones on the coarse grid and in fact the values of cdm are better (they are closer to the experimental data) than those ones on the coarse grid.

Figure 4.14 shows the components $\overline{u'v'}$ and $\overline{u'u'}$ of the SGS tensor. For Figure 4.14(a) it is possible to notice the similar v-shape between the curves simulated and the curve in the experimental data. In Figure 4.14(b) the simulated curves have a completely different trend. To understand these incongruities we have to analyse the field of SGS viscosity.
Figure 4.12. Mean streamwise velocity along the centerline using different subgrid scale model
Figure 4.13. \( \overline{C_p} - \theta \) curve and relative zooms
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Figure 4.14. Total resolved Reynolds stresses $u'u'$ (a) and $v'v'$ (b) at $x/D = 1.54$
4.3 Analysis of the flow fields

The average fields relating to $\overline{Cp}$ are examined, first. In Figure 4.15 and in Figure 4.16 we have reported the $\overline{Cp}$ obtained with the WALE FG, Vreman FG, Vreman FG Barth cells, compared with the Smagorinsky PCG model taken as a reference. We immediately can see that the region of negative $\overline{Cp}$ behind the cylinder is much wider in the streamwise direction for the Smagorinsky model, that is the recirculation length is much more evident in comparison with the coarse grid. In the Smagorinsky PCG model the $\overline{Cp}$ are much larger in absolute value (that is they are more negative), since an eddy originates just behind the cylinder and so we have strongly negative $\overline{Cp}$. There are no considerable differences among the various models as shown comparing Figure 4.15(b), Figure 4.16(a) and Figure 4.16(b). Using Barth cells, as we see from Figure 4.16, does not improve the results.

In Figure 4.17 we have reported the vorticity field $\omega_z$ relating to the WALE FG model in the plane $z = 0$. In Figure 4.17(b) we have also shown the grid. You can notice how the vorticity structures which are detaching from the cylinder are visible. These structures remain delimited inside the refined grid region behind the cylinder. In Figures 4.17(a) we can see the vorticity that separates from the cylinder and that forms eddies more downstream. In Figure 4.19 we can see a zoom view of the field in Figure 4.17(a). The Figure 4.18 shows that the recirculation zones and the separation of the boundary layer is inside the most refined zone behind the cylinder as it was requested in advance. Figures 4.19 show the main differences between the recirculation length for coarse grid and fine grid. We can notice that, as for Figure 4.19(a) the boundary layer separates from the cylinder and forms an eddy immediately after it. For the figure 4.19(b), on the contrary, the boundary layer separates from the cylinder but forms the eddies definitely more downstream.

In Figure 4.20 and in Figure 4.21 we have reported the field of the $\overline{U}$ variable on the $z = 0$ plane for Smagorinsky, Vreman and WALE models.
Figure 4.15. $\bar{C_p}$ time average isocontours. Smagorinsky PCG $[\text{min max}]_{\text{value}} = [-1.78 1.28]$; WALE FG model $[\text{min max}]_{\text{value}} = [-1.10 1.05]$
Figure 4.16. $\overline{C_p}$ time average isocontours. Vreman FG (a) with the median cells $[\text{min max}]_{value} = [-1.10 1.05]$; Vreman FG with Barth cells (b) $[\text{min max}]_{value} = [-1.17 1.06]$
The minimum values for the Smagorinsky PCG model and for WALE FG model are approximately the same, while for the maximum values, the $\overline{U}$ of the Smagorinsky model appears a little higher. In Figure 4.21 we can see that for the model Vreman FG with the Barth cells and for Vreman FG with the median cells the maximum values are the same, while the minimum values (in absolute value) are higher for the model with the Barth cells. Figure 4.22 and Figure 4.23 shown a zoom of Figure 4.20 and Figure 4.21. From these figures the significant differences between the coarse grid (Figure 4.22(a)) and the fine grid (Figures 4.22(b) can again be seen.

In Figure 4.24 a section (plane $x - z$, $y = 0$) of the instantaneous velocity field $U$ is reported for the models Vreman FG with the median cells and Vreman FG with the Barth cells. In the figures only the negative velocity field is shown so that the recirculation zone could be put qualitatively in evidence. We can see that the recirculation length is approximately the same.

In Figure 4.25 and in Figure 4.26 we have reported the turbulent kinetic energy field and in Figure 4.27 and Figure 4.28 the corresponding zooms for the models Smagorinsky PCG, WALE FG, Vreman with median cells and Vreman with the Barth cells. The wake in the coarse grid appears shorter and more energetic than the other ones on the fine grid.
Figure 4.17. 2D WALE FG model vorticity $\omega_z$ in the plane $z = 0$ without (a) and with (b) grid plotted together. Range $[-1 1]$
Figure 4.18. 2D WALE FG model zoom vorticity $\omega_z$ in the plane $z = 0$ without (a) and with (b) grid plotted together. Range $[-1 1]$
Figure 4.19. 2D precondition WALE model vorticity zoom coarse grid (a) and fine grid (b). Plane $z = 0$. Range $[-1, 1]$
Figure 4.20. $\bar{U}$ time average isocontours. Smagorinsky PCG (a) $[\text{min max}]_{\text{value}} = [-0.24 \ 1.53]$; WALE FG model (b) $[\text{min max}]_{\text{value}} = [-0.25 \ 1.37]$
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Figure 4.21. $U$ time average isocontours. Vreman model with the median cells (a) $[min\ max]_{value} = [-0.27 1.37]$; Vreman model with Barth cells (b) $[min\ max]_{value} = [-0.37 1.37]$
Figure 4.22. $\bar{U}$ time average isocontours, Smagorinsky PCG (a) and WALE FG (b), zoom
Figure 4.23. $\bar{U}$ time average isocontours, Vreman FG and Barth cells without (a) and Vreman FG and Barth cells with (b), zoom
Figure 4.24. Instantaneous isocontour velocity U, x-y plane on the fine grid: Vreman model (a) with Barth cells and WALE model (b) with the median cells.
Figure 4.25. Turbulent kinetic energy in the wake compared. Smagorinsky PCG (a) $[\min \ max]_{value} = [0 \ 0.713]$; WALE FG (b) $[\min \ max]_{value} = [0 \ 0.55]$
Figure 4.26. Turbulent kinetic energy in the wake compared. Vreman FG with the median cells (a) $[\min \ max]_{value} = [0 \ 0.538]$; Vreman FG model with Barth cells $[\min \ max]_{value} = [0 \ 0.518]$
Figure 4.27. Turbulent kinetic energy in the wake compared, zoom. Smagorinsky PCG (a) and WALE FG (b)
Figure 4.28. Turbulent kinetic energy in the wake compared, zoom. Vreman FG with the median cells (a) and Vreman FG with Barth cells (b)