Numerical simulation of roughness effects on the flow past a circular cylinder

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Abstract. In the present work large eddy simulations of the flow past a rough cylinder are performed at a Reynolds number of $Re = 4.2 \times 10^5$ and an equivalent sand-grain surface roughness height $k_s = 0.02D$. In order to determine the effects of the surface roughness on the boundary layer transition and as a consequence on the wake topology, results are compared to those of the smooth cylinder. It is shown that surface roughness triggers the transition to turbulence in the boundary layer, thus leading to an early separation caused by the increased drag and momentum deficit. Thus, the drag coefficient increases up to $C_D \approx 1.122$ (if compared to the smooth cylinder it should be about $C_D \approx 0.3 - 0.5$). The wake topology also changes and resembles more the subcritical wake observed for the smooth cylinder at lower Reynolds numbers than the expected critical wake at this Reynolds number.

Keywords: circular cylinder, surface roughness, turbulent flow, critical regime, flow separation, wake topology

1. Introduction

The flow over smooth cylinders has been extensively studied; it is associated with various instabilities that involve the boundary layer, the separated shear layers and the wake. A comprehensive description of the flow phenomena at different Reynolds numbers (Re) can be found in [1]. It is well known that when Reynolds numbers is about $2 \times 10^5$ major changes occur in the flow configuration as the drag coefficient rapidly decreases. This phenomenon is known as the ‘drag crisis’ and considerable experimental work has been carried out measuring the forces acting on the cylinder at these Reynolds numbers; some examples are [2, 3, 4].

On the other hand, the effect of roughness, especially in turbulent boundary layers, has been focus of many research studies (see for instance [5, 6, 7]). Most of the investigations in this area, however, have been performed on fully developed turbulent pipes and channels, and in zero-pressure-gradient turbulent boundary layers. Roughness effects on boundary layers on curved surfaces and in particular on bluff bodies is quite limited. Roughness is known to give rise to an earlier transition to turbulence in the boundary layer [8, 9, 10]. For the surfaces considered by Achenbach [9], for instance, roughness appears to increase the friction drag, without any beneficial effect on the separation characteristics: the onset of the critical transition is shifted to
lower Reynolds numbers [11], but the minimum drag coefficient is larger than that on a smooth cylinder, due to the transition to turbulence occurring at lower Reynolds numbers, and to an earlier separation due to the increased drag (and momentum deficit) caused by the roughness [8, 9, 12].

This paper aims at analysing the effects roughness introduces in the boundary layer of a circular cylinder and as a consequence on the near wake behind it. To do this, the flow past a rough cylinder at a Reynolds number of $Re = 4.2 \times 10^5$ with an equivalent sand-grain surface roughness height of $k_s = 0.02D$ is studied by means of large-eddy simulations (LES). The main interest in this case is that for the specific surface roughness and Reynolds number the flow has entered in the transcritical regime [9] and thus different to the smooth cylinder where the flow is in the critical regime[13, 14]. Thus, changes due to surface roughness in the flow parameters, boundary layer and flow topology behind the cylinder can be analysed by means of the direct comparison with results for the smooth cylinder.

2. Mathematical and numerical models

The spatially filtered incompressible Navier-Stokes equations can be written as

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$  (1)

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} - \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \rho^{-1} \frac{\partial \bar{p}}{\partial x_i} - F_i = -\frac{\partial T_{ij}}{\partial x_j}$$  (2)

where $x_i$ are the spatial coordinates ($x$, $y$ and $z$) in the stream-wise, cross-stream and span-wise directions. $\bar{u}_i$ and $\bar{p}$ stand for the filtered velocity and pressure. $\nu$ is the kinematic viscosity and $\rho$ the density of the fluid. $F_i$ is a body force used to impose the no-slip boundary condition on the rough cylinder surface; it is non-zero in cells with roughness elements [15]. In equation (2) $T_{ij}$ is the subgrid scale (SGS) stress tensor, which must be modeled. Its deviatoric part is given by

$$T_{ij} - \frac{1}{3} T_{kk} \delta_{ij} = -2 \nu_{sgs} \bar{S}_{ij}$$  (3)

where $\bar{S}_{ij} = \frac{1}{2} (g_{ij} + g_{ji})$ is the large-scale rate-of-strain tensor, and $g_{ij} = \partial \bar{u}_i / \partial x_j$. $\delta_{ij}$ is the Kronecker delta. The formulation is closed by an appropriate expression for the subgrid-scale viscosity, $\nu_{sgs}$. In this project the wall-adapting local-eddy viscosity model (WALE) [16], which yielded good results in the previous simulations of the drag crisis (see [13, 14]), is used.

The governing equations are discretized on a collocated unstructured grid arrangement using second-order spectrum-consistent schemes. Such schemes are conservative, i.e., they preserve the symmetry properties of the continuous differential operators, and ensure both stability and conservation of the kinetic-energy even at high Reynolds numbers and with coarse grids [17, 18]. For the temporal discretization of the momentum equation a self-adaptive two-step linear explicit scheme on a fractional-step method is used for the convective and diffusive terms [19], while for the pressure gradient an implicit first-order scheme is implemented. The analysis of discretization and truncation errors of the present methodology was discussed in detail in [17, 20, 19]. More details about the numerical method can be found in [17, 18]. An immersed boundary method (IBM) is used to recover a smooth no-slip boundary condition on the rough cylinder surface. It is based on the volume-of-fluid approach, i.e. the volume fraction occupied by the fluid of each cell is evaluated in a pre-processing stage and then used in the fractional-step framework to correct the predicted velocity and enforce the no-slip condition on the rough surface [21, 15].

3. Definition of the case

The flow past a rough circular cylinder at critical Reynolds numbers of $Re = 4.2 \times 10^5$ with an equivalent sand-grain surface roughness height of $k_s / D = 0.02$ is considered. Here, the
Reynolds number $Re = \frac{U_{ref} D}{\nu}$ is defined in terms of the cylinder diameter $D$ and the free-stream velocity $U_{ref}$. The main interest in this case is that for this specific surface roughness the flow has already entered in the transcritical regime and thus, the boundary layer should be turbulent before separation [9] in contrast with the smooth cylinder in which the flow should correspond with the critical regime [13].

The case is solved in a computational domain of dimensions $x \equiv [-10D : 20D]$; $y \equiv [-10D : 10D]$ in the stream-wise and cross-stream directions and two different span-wise lengths of $L_z \equiv 0.96D$, 1.92D, with a circular cylinder of diameter $D$ at $(0,0,0)$. The boundary conditions at the inflow consist of a uniform velocity $(u,v,w)= (1,0,0)$. Symmetry conditions are prescribed at the other external boundaries except for the downstream one (outlet) where a pressure-based condition is used. In the span-wise direction periodic boundary conditions are imposed. At the cylinder surface, a virtual sandpaper [21, 15] is used to impose the roughness. The roughness elements are modeled by closely spaced, randomly rotated ellipsoids with semi-axes $k_s/D$, 1.4$k_s/D$ and 2$k_s/D$. A detail of the resulting sand-grain roughness surface is depicted in figure 1(a). In the figure, the visualization of the fraction of volume $\phi = 0.5$ is shown, which is a satisfactory representation of the profile of the rough wall.

A two-dimensional unstructured grid is extruded with a constant step in the spanwise direction for obtaining the three-dimensional mesh. In the two-dimensional mesh, a prism layer is constructed around the cylinder surface, extending up to the edge of the roughness sublayer $\sim 3k_s/D$. Beyond this distance from the wall an unstructured grid is used. The maximum grid spacing required to represent this kind of surface accurately was determined by Yuan and Piomelli [15] in a previous work. On this basis, in the present work, each roughness element is resolved by $n_\theta \times n_z$ cells (see Table 1) of the superficial mesh with 30 − 50 points below the roughness crest in the radial direction. Moreover, as the grid used is unstructured, more control volumes are clustered close to the cylinder and in the near wake, whereas away from the region of interest the mesh requirements are progressively relaxed (see figure 1(b)). Details about the meshes used are given in Table 1.

4. Results

The cases are simulated for a sufficiently long period of time to guarantee converged statistics. An initial transient period of roughly 60 times units ($TU = tU_{ref}/D=60$) is discarded, after that statistics are collected for about $TU = 120$ (about 25 shedding cycles), which is sufficient integration time to ensure first and second order statistics are well converged.
Table 1. Meshes studied. $N_{CV_{total}}$ is the total number of control volumes; $N_{CV_{plane}}$ is the total number of control volumes in the plane; $N_{planes}$ is the total number of planes in the span-wise direction; $N_\theta$, $N_z$ are the total number of sandgrain elements in the radial and span-wise directions; $n_\theta$, $n_z$ are the average mesh resolution for each roughness element; $L_z$ is the span-wise size of the domain; $n_{y3k_s}$ is the number of grid points in the wall normal direction within a $3k_s/D$ distance.

| Case | $N_{CV_{total}}$ | $N_{CV_{plane}}$ | $N_{planes}$ | $N_\theta \times N_z$ | $n_\theta \times n_z$ | $L_z$ | $n_{y3k_s}$ |
|------|------------------|------------------|---------------|-----------------------|-----------------------|-------|-------------|
| M0   | 41.77 $\times 10^{-6}$ | 217594           | 192           | 78.5 $\times$ 24     | 8 $\times$ 8          | 0.96  | 30          |
| M1   | 219.38           | 285658           | 768           | 78.5 $\times$ 48     | 16 $\times$ 16        | 1.92  | 50          |

4.1. Time-average aerodynamic coefficients

In table 2, the results of the drag coefficient, fluctuating drag and lift coefficients and vortex shedding frequency are given for each of the cases, together with the reported results for the smooth cylinder at comparable Reynolds numbers [13, 14] and experimental results for the rough cylinder at comparable surface roughness reported in the literature [8, 9, 3, 22]. Regarding the experimental results it has to be pointed out that there is some scattering in the experimental measurement. This in part might be due to the reported difficulties for estimating the effective size of the roughness elements. Thus the reported values of $k_s/D$ represent, in most of the measurements, a rough estimate of the actual equivalent surface roughness (e.g. [3, 22, 12]). Other experimental uncertainties reported are the difficulties in the correction for wind tunnel blockage, end conditions issues caused by small gaps that produce some departure from ideal two-dimensional flow conditions, amongst others. Nonetheless, as can be seen in the table, results for the drag coefficient and non-dimensional vortex shedding frequency obtained with both meshes are in fair agreement with the experimental results.

By analysing the results for both meshes (table 2) differences in the fluctuating drag and lift coefficients about 17% can be seen. This might mainly be due to differences in the span-wise length and in the resolution of the surface roughness elements. The former is not only related with the size of spanwise coherent structures that might be being truncated by a smaller length, but also with the number of surface roughness elements considered. Yuan and Piomelli [15] showed that an insufficient sampling might affect the distribution of the total drag on the surface. Thus, considering that both fluctuating lift and drag might be affected by the randomness of the surface distribution, the larger the span-wise size of the domain, the larger the number of roughness samples considered and a better representation of the surface. Moreover, the resolution of the surface roughness element is also important. In fact, at least $16 \times 16$ grid points might be necessary to resolve each surface roughness sample, as was determined in a grid-convergence study (not shown here).

An important effect of the roughened surface observed is the shifting of the transcritical flow regime to a lower Reynolds number. According to Roshko [23], the onset of the transcritical regime for the smooth cylinder is beyond $Re = 2.5 \times 10^6$, and some of the characteristics of this regime are the transition to turbulence in the boundary layer, a wider wake and the increase of the drag coefficient. In fact, if compared to the smooth cylinder (see table 2), the resulting drag coefficient is larger than the expected one, whereas vortex shedding frequency is lower. As aforementioned, at this Reynolds number the flow regime should be critical, with separation about $\phi_s = 142 - 148^\circ$ and the drag coefficient $C_D = 0.481 - 0.3$ (see table 2). However, surface roughness triggers the transition to turbulence in the attached boundary layer (see also figure 2). At the same time, this early transition induces the separation of the boundary layer which occurs before the cylinder apex (at about $75^\circ$). As a consequence, there is an increase in the
Table 2. Flow parameters. Comparison with literature available numerical and experimental results. $C_D$ drag coefficient, $C_{D,rms}$ fluctuating drag, $C_{L,rms}$ fluctuating lift, $St$ non-dimensional vortex shedding frequency. †LES for a smooth cylinder [13, 14], *Experimental results for roughened cylinders with $k_s/D = 4.5 \times 10^{-3} - 3 \times 10^{-2}$ [8, 9, 3, 22]

| Re          | $C_D$  | $C_{D,rms}$ | $C_{L,rms}$ | $St$         |
|-------------|--------|-------------|-------------|--------------|
| $4.2 \times 10^5$ (M0) | 1.141  | 0.094       | 0.523       | 0.211        |
| $4.2 \times 10^5$ (M1) | 1.122  | 0.080       | 0.445       | 0.204        |
| $3.8 \times 10^5$ (smooth)† | 0.481  | 0.0.061     | 0.217       | 0.238/0.358  |
| $5.3 \times 10^5$ (smooth)† | 0.296  | 0.011       | 0.071       | 0.368        |
| (exp)*       | 0.9-1.3| -           | -           | 0.21-0.24    |

Figure 2. Instantaneous spanwise vortical structures. $\omega_z = \pm 15$. (a) $Re = 4.2 \times 10^5$; (b) $Re = 3.8 \times 10^5$ (smooth cylinder) and (b) $Re = 5.3 \times 10^5$ (smooth cylinder)

momentum deficit and in the drag coefficient. Moreover, as turbulent shear layers are more separated each other (if compared with the smooth cylinder), a larger fluctuation of both lift and drag coefficients is produced by the interaction of both shear layers. As a consequence, a decrease in the vortex shedding frequency also occurs. In fact, the flow parameters obtained for the rough cylinder resemble those of the smooth cylinder in the subcritical regime (see for instance [24, 25]), as their value depend on the separation location rather than if separation is laminar or turbulent.

4.2. Overview of the flow and wake topology

Instantaneous vortical structures near the cylinder surface are shown in figure 2 by means of spanwise vorticity isocontours ($\omega_z = \pm 15$). For the rough cylinder, boundary layer instabilities can be observed as earlier as at angular position of 45°. These instabilities rapidly grow-up and are amplified, thus triggering the transition to turbulence. At the cylinder apex, the flow is already detached and a turbulent shear-layer can be observed departing from that location. This is in contrast with the flow regime observed for the smooth cylinder, where boundary layer instabilities are triggered near the cylinder apex, but transition to turbulence occurs just after separation (see figure 2b) [13]. The fact that surface roughness triggers these early instabilities forces the rapid separation of the flow, thus changing the topology of the near wake as it is shown hereafter.

A direct comparison of the wake statistics between both the rough cylinder and the smooth cylinder is plotted in figure 3. In the figure, the data of the rough cylinder at $Re = 4.2 \times 10^5$, which is supossed to be in the transcritical regime [9] is compared to those of the smooth cylinder at a Reynolds numbers of $Re = 5.3 \times 10^5$, which is at the end of the critical regime [13] and
to the smooth cylinder in the subcritical regime at $Re = 3900$ [26]. Direct comparison of the wake statistics with the smooth cylinder at $Re = 3.8 \times 10^5$ are not included as at this Reynolds number the wake configuration is asymmetric due to the changes occurring in the critical regime, (see [13] for more details). As the length of the recirculation region behind the cylinder (the distance from the cylinder center to the streamwise location in the wake centreline where the streamwise velocity is zero) changes depending on the Reynolds number, to make comparable the flow statistics in the near wake they are plotted at streamwise locations normalized by the length of the recirculation zone. In the figure statistics are plotted at $x/L_r = 0.5$, $x/L_r = 1$ and $x/L_r = 2$. The length of the recirculation region is of $L_r/D = 1.395$ at $Re = 4.3 \times 10^5$, $L_r/D = 1.225$ at $Re = 5.3 \times 10^5$ [14] and $L_r/D = 1.86$ at $Re = 3900$ [26].

As can be seen, roughness not only affects the location where the boundary layer separates from the cylinder and the transition to turbulence, but also it changes the topology of the wake behind the cylinder. On the one hand, the early separation of the boundary layer produces a wider wake than the expected one for the smooth cylinder. On the other hand, first order statistics in the recirculation bubble ($x/L_r \leq 1$) matches quite well the statistics for the smooth cylinder in the subcritical regime ($Re = 3900$). In fact, for the circular cylinder, the topology of the near wake inside the recirculation zone depends on the position of the shear layers and on the location where the recirculation bubble closes. At the same time, the average location of the shear layers only depends on the separation point from the cylinder surface. This is the reason why the topology of the recirculation zone for the rough cylinder resembles quite well that of the smooth cylinder in the subcritical regime. Notice that for $x/L_r = 0.5$ and $x/L_r = 1$ streamwise velocity profiles at $Re = 4.2 \times 10^4$ and $Re = 3900$ are nearly the same. In both cases, flow separation occurs just before the cylinder apex; for the rough cylinder ($Re = 4.3 \times 10^5$) it is located about 75° whereas for the subcritical cylinder ($Re = 3900$) it is reported to be at 88° [26]. Beyond the recirculation region, i.e. $x/L_r > 1$, the way the wake recovers changes. With downstream distance and due to the entrainment of the flow from both sides of the wake, it becomes wider. However, for the rough cylinder this flow entrainment is the largest of the three at a distance of $x/L_r = 2$ being the velocity at the wake centreline the lower one.

Regarding the second order statistics, streamwise normal stresses for the roughened cylinder are larger than those obtained for the smooth cylinder. Notice that stresses for the critical regime are the lower of the three and are confined in a reduced zone close to the cylinder centreline. It has to be borne in mind that a large part of the contribution to the Reynolds stresses in the wake of a cylinder comes from the coherent component due to the vortex shedding. Thus, the wider the wake the larger the contribution of the coherent component to the Reynolds stresses. On the other hand, part of the random fluctuations for the rough cylinder comes from the production of turbulent kinetic energy in the roughness sublayer, which is convected downstream to feed the wake. This is the reason why peaks in the normal and shear stresses for the rough cylinder are about 20% larger than those for the smooth cylinder in the subcritical regime.

5. Concluding remarks

In order to analyse the effects of surface roughness on the boundary layer and the wake behind a circular cylinder, large-eddy simulations of the flow past a rough cylinder at a Reynolds number of $Re = 4.2 \times 10^5$ and an equivalent sandgrain roughness height of $k_r = 0.02D$ are performed. An immerse boundary method is also used for enforcing the no-slip condition on the rough surface.

Significant changes in the boundary layer and the flow topology behind the cylinder are observed as a consequence of the roughness elements. Roughness introduces instabilities in the boundary layer which are observed along the whole span of the cylinder at about 45° from the cylinder stagnation point. These instabilities trigger an early transition to turbulence and the detachment of the turbulent boundary layer before the cylinder apex at about 75°. As a consequence there is an increase in the drag coefficient up to $C_D = 1.122$, if compared with the
Figure 3. First and second order statistics in the wake of the cylinder. (a,c,e) Streamwise velocity and (b,d,f) streamwise normal Reynolds stresses at $x/L_r = 0.5$, $x/L_r = 1$ and $x/L_r = 2$

smooth cylinder. Other flow parameters are also affected such as the fluctuating lift and drag coefficient and the vortex shedding frequency.

The early separation of the boundary layer changes the characteristics of the wake behind the cylinder, with a wider near wake and a flow topology that resembles that of the subcritical regime, but with turbulent shear-layers from the separation point and larger normal and shear stresses. In fact, part of the turbulent kinetic energy is produced at the roughness sublayer and transported downstream into the wake. Further research is needed in order to study the changes occurring in the attached boundary layer and the role of the surface roughness in triggering the early transition to turbulence.

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