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| Abstract | The flow around a rectangular cylinder, having chord-to-depth ratio equal to 5, has been the object of a benchmark (BARC) launched in 2008 (http://www.aniv-iawe.org/barc/). The BARC configuration is of practical interest, e.g. in civil engineering, and, in spite of the simple geometry, the related flow dynamics and topology is complex. Indeed, the high-Reynolds-number flow around such a stationary rectangular cylinder is turbulent with flow separation from the upstream corners and unsteady reattachment on the cylinder side. Furthermore, a vortex shedding also occurs from the rear corners and interferes with the leading-edge vortices, according to the mechanism of impinging shear-layer instability (Nakamura et al, J Fluid Mech, 222:437–447, 1991, [1]). |

# Benchmark on the Aerodynamics of a 5:1 Rectangular Cylinder: Further Experimental and LES Results

**C. Mannini, A. Mariotti, L. Siconolfi and M.V. Salvetti**



## 1 Introduction

The flow around a rectangular cylinder, having chord-to-depth ratio equal to 5, has been the object of a benchmark (BARC) launched in 2008 (http://www.aniv-iawe.org/barc/). The BARC configuration is of practical interest, e.g. in civil engineering, and, in spite of the simple geometry, the related flow dynamics and topology is complex. Indeed, the high-Reynolds-number flow around such a stationary rectangular cylinder is turbulent with flow separation from the upstream corners and unsteady reattachment on the cylinder side. Furthermore, a vortex shedding also occurs from the rear corners and interferes with the leading-edge vortices, according to the mechanism of impinging shear-layer instability [1].

The experimental and numerical results obtained by the benchmark contributors during the first four years of activity were summarized and reviewed in [2]. Good agreement between different results in terms of near-wake flow, base pressure and drag coefficient was found. However, it was observed that some quantities of interest, as the standard deviation of the lift coefficient or the distribution of mean and fluctuating pressure on the cylinder sides, are affected by a significant dispersion, both in experiments and in simulations. Sensitivity analyses carried out by the BARC

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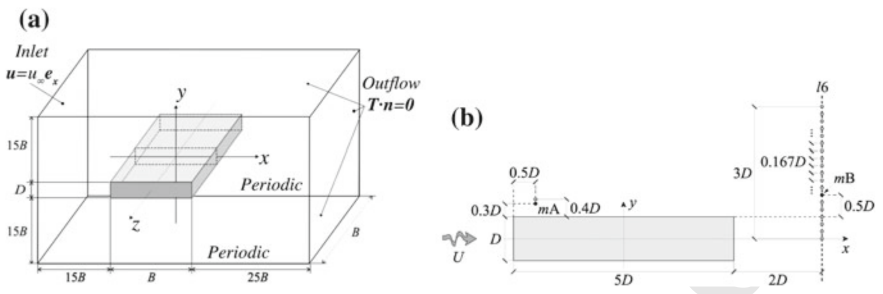



**Fig. 1** **a** Sketch of the computational domain; **b** position of anemometry measurement points in the wake of the cylinder ($l6$, $m$A and $m$B represent respectively a reference transverse line and two reference points of the benchmark study)

contributors were not conclusive to explain the observed dispersion; rather, in some cases, they led to controversial results. In particular, in a single large-eddy simulation (LES) contribution [3] a strong sensitivity to the grid resolution in the spanwise direction was pointed out, but the results obtained for the finest grid significantly deviated from the ensemble average of those of the experimental and numerical contributions [2].

Recently, a set of LES was carried out in the framework of a stochastic analysis of the sensitivity to grid resolution in the spanwise direction and to the amount of subgrid scale (SGS) dissipation [4], and further wind tunnel measurements were obtained for different angles of attack and different oncoming flow turbulence features (intensity and integral length scale) [5], including unsteady surface pressures, forces and wake flow velocities. Experimental data on the flow velocity in the wake were still completely missing among the BARC contributions.

The aim of the present work is to exploit the new sets of LES and experimental results to give a contribution to highlight the reasons of the dispersion of data evidenced in the synopsis in [2].

## 2 Simulation and Experiment Set Up

LES simulations are carried out for the incompressible flow around a fixed sharp-edged rectangular cylinder with a chord-to-depth ratio, $B/D$, equal to 5. The angle of attack is zero. The computational domain is sketched in Fig. 1a. A uniform velocity profile is imposed at the inflow (no turbulence), while no-slip conditions are applied at the solid walls. Periodic conditions are imposed in the spanwise direction, and traction-free boundary conditions are used at the outflow, on the remaining lateral sides of the computational domain. Finally, the Reynolds number based on the free-stream velocity and on the cylinder depth, $Re$, is equal to 40,000. The sensitivity to the value of $Re$ was observed to be low [2], although not null [5].

The simulations are performed through an open-source code, Nek5000, based on a high-order accurate spectral-element method (http://nek5000.mcs.anl.gov). The order of the Legendre polynomials used as basis functions inside each element is kept herein constant $N = 6$. The grid resolution in the streamwise and lateral directions is $\Delta x = \Delta y = 0.125D$. As for the LES formulation, a simple approach based on the application of a low-pass explicit filter in the modal space, which is characterized by a cut-off $k_c$, here equal to $N - 3$, and by a weight $w$, is adopted (see [4] for more details). This modal filter provides a dissipation in the resolved modes that are higher than the cut-off value, and can be interpreted as a SGS dissipation.

The parameters chosen for the sensitivity analysis are the grid resolution in the spanwise direction, defined in terms of the average element size, $\Delta z$ (in the range $[0.321D, 0.674D]$), and the weight of the explicit filter, $w$ (in the range $[0.01, 0.131]$). The latter has been chosen because it directly controls the amount of SGS dissipation, while the grid resolution in the spanwise direction is investigated because of the high impact of this parameter shown in the LES simulations in [3]. A total of 16 LES simulations were carried out (see [4] for more details).

The wind tunnel tests were conducted in the CRIACIV laboratory at the University of Florence on an aluminum sectional model with a cross section $300 \times 60$ mm and a spanwise length of 2.38 m. The model presented very sharp edges, smooth surfaces and high degree of symmetry. For a null angle of attack, the blockage ratio was 3.75%. Unsteady pressure measurements were performed through 61 taps distributed along the midspan section. A single-component hot-wire anemometer allowed the measurement of the fluctuating flow velocities in the wake downstream of the model and in the shear-layer region. The experiments were carried out for Reynolds numbers in the range 12,000 to 110,000, for various angles of attack (up to 10°), in smooth and various grid-induced free-stream turbulent flows (for further details, see [5]).

## 3 Results and Discussion

Figure 2 shows the distribution over the cylinder side of the pressure coefficient averaged in time, in the spanwise direction and between the upper and lower half perimeters of the cylinder, denoted as $t\text{-}avg(C_p)$, obtained in the 16 LES simulations. As in [2], the local abscissa $s/D$ denotes the distance from the cylinder stagnation point measured along the cylinder side. The considered values of the spanwise spacing of the grid nodes are denoted in the following as $\Delta z_1$ to $\Delta z_4$ (from the coarsest to the finest), whereas the values of the weight of the explicit filter are indicated as $w_1$ to $w_4$ (from the lowest to the highest level of SGS dissipation). It can be seen that most of the calculated $C_p$ distribution are characterized by a recovery occurring upstream compared to the experimental data. As explained in [2], the mean pressure distribution on the body surface is directly related to the curvature of the time-averaged flow streamlines and, in particular, to the shape and length of the main recirculation region on the cylinder sides. Therefore, most parameter combinations lead to a main recirculation region that is significantly shorter than those obtained in most of the BARC contributions. This is consistent with the findings of the most refined LES in

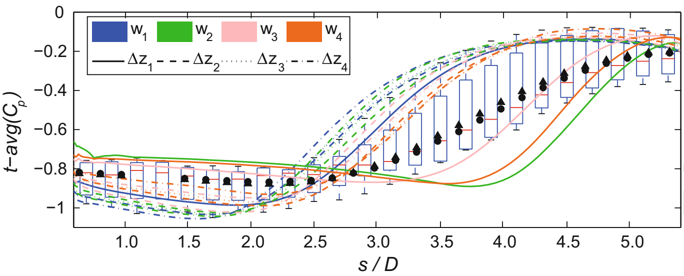



**Fig. 2** Mean pressure coefficient on the lateral sides of the prism cross section obtained in the LES analysis. A comparison is provided with the ensemble statistics of the BARC experiments [2] and the experimental data in [5] (circles and triangles refer respectively to $Re = 56{,}700$ and 112,200

[3]. In particular, increasing the spanwise resolution and decreasing the SGS dissipation, very small vortical structures, which originate from the instability of the shear layers detaching from the upstream corners, are observed in LES (see [4]), and this behavior corresponds to short main recirculation regions. A similar result was also obtained through detached-eddy simulation (DES) in [6] when reducing the artificial viscosity introduced to stabilize the central-difference scheme for the discretization of the convective term in the governing equations. It is worth noting that a grid with a fine spanwise resolution ($\Delta z = 0.078D$) was employed in that case.

The still open question is whether these perturbations have a physical or a numerical origin. Indeed, the mean $C_p$ distribution obtained in the experiments, reported in Fig. 2, shows that, for low turbulence in the oncoming flow, the length of the plateau, and thus that of the main recirculation region, is significantly longer than that obtained in most of the LES computations, which are yet carried out for smooth oncoming flow. Indeed, the level of flow perturbation upstream of the leading edge separation is negligible in all the LES simulations.

In order to investigate how the differences between experiments and simulations are related to the features and dynamics of the separated shear layers and of the downstream wake, a comparison with the flow velocity measurements reported in [5] is carried out.

Figure 3a shows the mean streamwise velocity profile in the shear-layer region at the point $m$A of Fig. 1b ($x/D = -2$). The mean velocity profile in the calculations exhibits low uncertainty and a very good agreement with the experiments. In contrast, the standard deviation in time of the velocity fluctuations is very different from one simulation to another, and the experimental data fall inside the uncertainty band (Fig. 3b. Nevertheless, a low level of fluctuations at this streamwise position is not necessarily associated with a long recirculation bubble. Indeed, there are solutions characterized by fluctuations in the shear layer significantly lower than or of the same order as in the experiments that correspond to much shorter mean recirculation regions, as demonstrated by the streamlines in Fig. 4b, d. For example, the simulation with $w_1$, $\Delta z_1$, in spite of the very good agreement with the experimental data in terms of flow velocity fluctuations, is characterized by a short bubble. The simula-

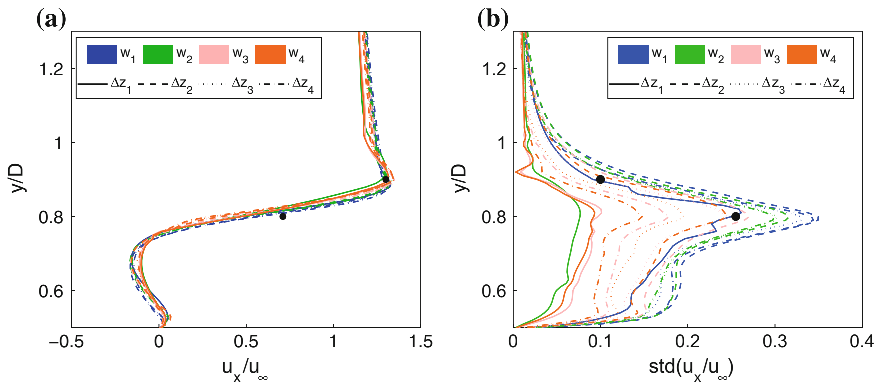
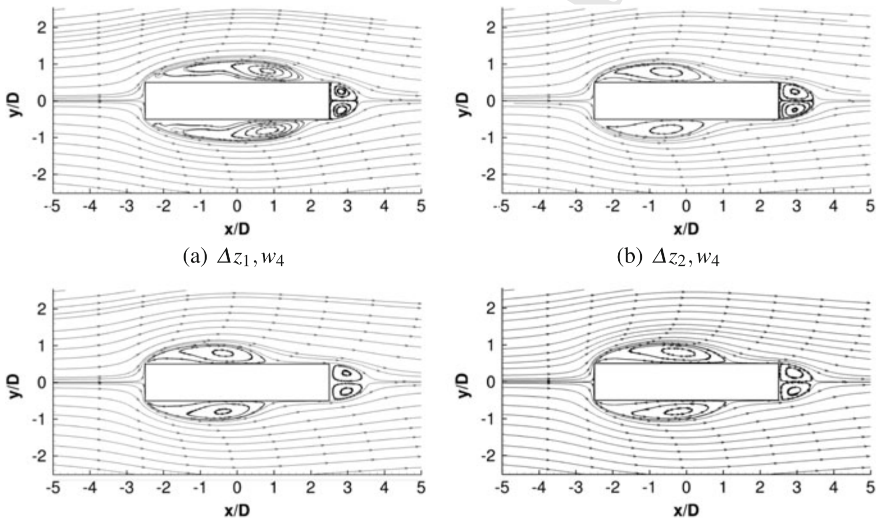



**Fig. 3** **a** Mean streamwise velocity profile, and **b** standard deviation of the velocity fluctuations in the $x$-direction at $x/D = -2$ (see Fig. 1b). The experimental data (black circles) correspond to $Re = 11,800$ [5]




(a) $\Delta z_1, w_4$ (b) $\Delta z_2, w_4$

(c) $\Delta z_3, w_4$ (d) $\Delta z_4, w_4$

**Fig. 4** Mean flow streamlines obtained with LES simulations for four values of the grid spanwise resolution and the same SGS-like dissipation

tions with $w_4$, $\Delta z_1$ and $w_4$, $\Delta z_4$ have a similar level of fluctuations in the shear layer being, nonetheless, characterized by significantly different lengths of the recirculation regions (compare Fig. 4a, d). It is also noteworthy that the behavior of velocity fluctuations in the bubble and shear layer with the mesh resolution is not monotonous (see for instance the results for $w_4$ in Fig. 3b). In conclusion, the comparison with the available wake measurement data is not yet conclusive, and further analyses are required in the shear layers at more upstream and downstream locations.



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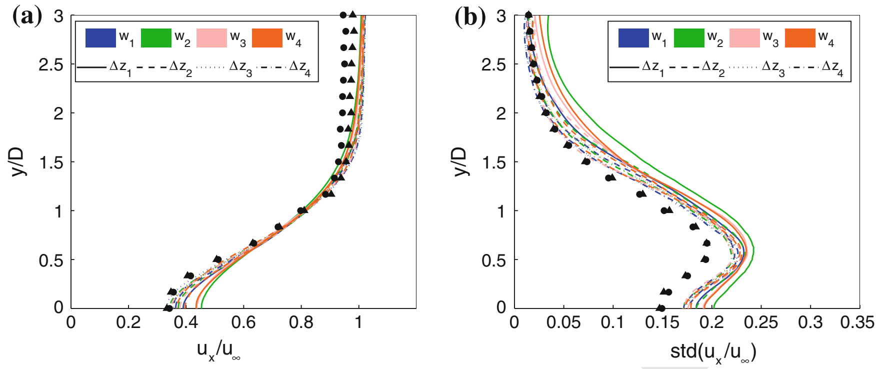


**Fig. 5** **a** Mean and **b** standard deviation of the velocity fluctuations in the streamwise $x$-direction at $x/D = 4.5$ (along line $l6$ in Fig. 1b). Circles and triangles denote the experimental data [5] and refer respectively to $Re = 44{,}900$ and 112,600

Focusing now on the near wake, Fig. 5 shows the mean velocity profile and the standard deviation of the velocity fluctuations in the streamwise direction along the line $l6$ of Fig. 1b. It is clear that, in spite of the large differences observed in the flow on the cylinder lateral surface, the dispersion of the results in the wake is small and the agreement with the hot-wire anemometry measurements is good, especially for the mean velocity profile. Such a result suggests that the interaction between the wake behind the cylinder and the upstream dynamics near the body is rather weak, and that the mesh resolution and artificial dissipation have a minor influence on the former.

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