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FLOW AROUND A 5:1 RECTANGULAR CYLINDER WITH UPSTREAM ROUNDED EDGES: SENSITIVITY OF LES RESULTS TO GRID RESOLUTION AND SGS DISSIPATION

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Abstract. A stochastic analysis of the sensitivity to grid resolution and modeling of large-eddy simulation (LES) results is carried out for the flow around a 5:1 rectangular cylinder, having rounded upstream edges. The open-source code Nek5000 is used to carry out all the simulations, in which the subgrid-scale (SGS) dissipation is associated with an explicit quadratic low-pass filter in the modal space. In this work, the grid resolution in the lateral (spanwise) direction of the cylinder and a parameter regulating the introduced dissipation are treated as uncertain parameters. Their effects on the predictability of the LES simulations are studied by employing the generalized Polynomial Chaos (gPC) expansion. The dispersion of the stochastic results is compared with the ensemble average and with the overall dispersion of the BARC predictions and with the same stochastic analysis carried out for the same flow configuration with perfectly sharp upstream edges.

1 Introduction

The high Reynolds number flow around a rectangular cylinder, having chord-to-depth ratio (B/D) equal to 5, is the object of the benchmark BARC [1], collecting several experimental and numerical results. This configuration is characterized by flow separation at the upstream edges and reattachment on the cylinder side. A large dispersion was observed in the numerical predictions of the flow features and of the quantities on the cylinder lateral sides, i.e. the length of the mean recirculation region on the later side. Sensitivity studies carried out by the BARC contributors were not conclusive and, in some cases, controversial. For instance, Mariotti et al. [2] carried out a stochastic sensitivity analysis of the LES results to the amount of SGS dissipation and grid resolution in the spanwise direction. Together with other contributors to the benchmark, they confirm a sort of paradox: the high-fidelity simulations mismatch with the other simulations and, surprisingly, they deviate from experiments. Recently, we tried to explain this counter-intuitive result (see Rocchio et al. [3]) by introducing a small curvature radius of the upstream edges in the BARC simulations, and by adopting the same modeling and setup proposed by Mariotti et al. [2] that predicts a short mean recirculation region on the cylinder side. We showed how even small values of the curvature radius, that are difficult to detect in experimental models, significantly change the flow feature on the cylinder side. Moreover, the agreement with the experiments is considerably improved.

The present work aims at investigating the sensitivity of the LES simulations with rounded edges to SGS dissipation and grid resolution, as in Mariotti et al. [2] for the sharp edges. The analysis is carried out by employing the generalized Polynomial Chaos (gPC) expansion, which allows to obtain continuous response surfaces in the parameter space starting from a few determinist simulations. The question at issue is whether the high sensitivity of the LES results observed in Mariotti et al. [2] is an artifact of the perfectly sharp edges and it is thus reduced in the LES with rounded edges.

2 Methodology

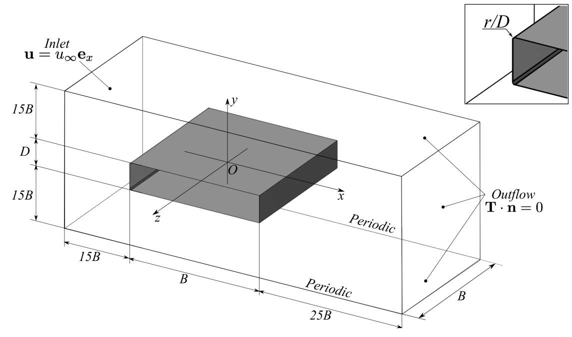

Figure 1: Computational domain with the boundary conditions.

All the simulations are carried out for the incompressible flow around an elongated rectangular cylinder ($B/D = 5$) at zero angle of attack. The cylinder upstream edges are rounded with a curvature radius $r/D = 0.0037$, which is the smallest one analyzed in [3]. The simulations are performed using Nek5000, an open-source code based on a high-order accurate spectral element method [4]. Each spectral element is rectangular or a suitable coordinate mapping of a rectangular. Inside each element, the basis functions are Legendre polynomials of order N for velocity and $N-2$ for pressure; $N = 6$ has been used in this work, as in Mariotti et al. [2]. A third-order backward finite-difference scheme is used for time advancing. At the end of each step of the time integration, a low-pass explicit filter is applied to the velocity field in the modal space. This filter is characterized by a quadratic transfer function, which acts from the unfiltered modes $N-k$ ($k = 3$ herein) up to the highest mode N. The transfer function can be tuned through a weighting parameter ω. Since the filter acts only at the highest resolved modes, it is usually interpreted as a SGS dissipation.

The computational domain is sketched in Figure 1, where x/D, y/D and z/D denotes the streamwise, vertical and spanwise directions respectively. The boundary conditions are also reported in Figure 1. The cylinder center is located at $x/D = y/D = 0$. The

Reynolds number based on the free-stream velocity and on the cylinder height, Re, is $4 \cdot 10^4$.

The gPC expansion is employed to study the sensitivity of the LES simulations to the following free parameters: the grid resolution along the spanwise direction ($\Delta z/D$) and the weight of the explicit filter (ω). The values of these two parameters are treated as uncertain in the following variational intervals: $\Delta z/D \in (0.31, 0.67)$ and $\omega \in (0.01, 0.131)$. For both parameters a uniform PDF was chosen, which implies the use of the Legendre polynomial as basis in the gPC expansion. By means of this approach a generic quantity of interest can be expressed as a truncated projection over an orthogonal basis (the Legendre polynomials in our case), where the truncation index depends on the number of parameters and on the maximum order of the polynomial basis for each parameter. The third order is chosen for the basis, thus only 4 quadrature points for each parameter are needed to compute the projection coefficients of the gPC expansion. Each couple of quadrature points corresponds to a determinist simulation to perform, thus we need to carry out 16 LES simulations for building the response surface of each quantity of interest.

3 Results and discussion

The results of the stochastic sensitivity analysis are presented and compared to the ensemble average of the BARC experiments. We show here the pressure coefficient, which has been averaged in time, along the homogenous direction, i.e. $z-$ direction, and between the upper and lower half perimeters of the cylinder. Figure 2 shows the PDF of the mean pressure coefficient $\langle C_p \rangle$ for the LES simulations with the upstream rounded edges as a function of the local abscissa, s/D, that is the distance between the stagnation point on the front face of the cylinder (located at $x = -B/2$, $y = 0$ and $z = 0$) and a generic point along the upper half perimeter of the body. The numerical results are compared to the BARC ensemble statistics. The largest variability of the $\langle C_p \rangle$ falls inside $2.9 \leq s/D \leq 4.3$. This is the region where the recovery of the pressure coefficient occurs, which roughly corresponds to the change of curvature of the streamlines bounding the mean recirculation region and, thus, it is related with the mean reattachment point location. However, the variability of the $\langle C_p \rangle$ falls inside the overall dispersion of the BARC experiments everywhere. Thus, we can speculate that the introduction of a curvature radius of upstream edges always leads to results in good agreement with the experiments, regardless the chosen set-up of the LES simulation.

Figure 3 shows the PDF of the $\langle C_p \rangle$ for the same analysis carried out for the sharp edges case. By looking at the two probability distributions, we can observe that the introduction of a small curvature radius reduces the overall variability of the mean pressure coefficient along the entire cylinder side. Furthermore, for the case of rounded edges, the most probable values of the $\langle C_p \rangle$ recovery position are shifted downstream, where the tail of the PDF for the sharp edge case are found.

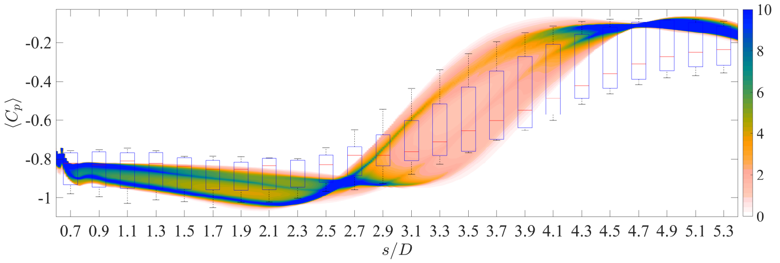

Figure 2: PDF of the averaged pressure coefficient.

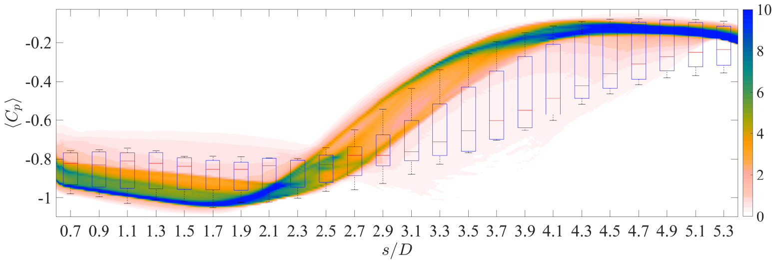

Figure 3: PDF of the averaged pressure coefficient.

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