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# Mesh generation, sizing and convergence for onshore and offshore wind farm Atmospheric Boundary Layer flow simulation with actuator discs

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ABSTRACT

A new mesh generation process for wind farm modeling is presented together with a mesh convergence and sizing analysis for wind farm flow simulations. The generated meshes are tailored to simulate Atmospheric Boundary Layer (ABL) flows on complex terrains modeling the wind turbines as actuator discs. The wind farm mesher is fully automatic and, given the topography and the turbine characteristics (location, diameter and hub height), it generates a hybrid mesh conformal with the actuator discs and refined upwind and downstream. Moreover, it presents smooth element size transitions across scales and avoids extending high-resolution areas to all the domain. We take advantage of our automatic and robust mesher to study the mesh convergence of our RANS solver with linear elements, obtaining quadratic mesh convergence for a quantity of interest in all the tested cases. In addition, we quantify the mesh resolution at the terrain surface and at the actuator discs required to achieve a given numerical error in simulations in onshore and offshore frameworks. Finally, we present the generated meshes and the simulation results for an offshore and an onshore wind farm. We analyze in detail one particular wind direction for both cases, and for the onshore wind farm we use our automatic framework to estimate the yearly production of energy and measuring the error against the actual produced one.
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## 1. Introduction

Advances in Computational Fluid Dynamics (CFD) techniques during the last two decades have widened the spectrum of engineering and industrial applications involving numerical analysis. In wind energy, numerical modeling has become a key tool for industry at several stages, from early wind resource assessment and wind farm design to final management and exploitation. During a wind farm design stage, numerical modeling allows improving the emplacement of wind turbines by optimizing relevant parameters such as expected wind power production, turbulence intensity or wind loads. During a production stage, operational power forecasts based on local-scale wind flow simulations is emerging as an alternative to current methodologies based on time series of observations and statistical downscaling. In parallel with the advances in

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CFD techniques, the exponential growth on computing power has allowed to increase the number of computational cells and therefore to increase the extent and/or the resolution of the simulations. This aspect is relevant when modeling wind farms because, typically, the computational domains involved are large (scale of kilometers) and, at the same time, the local wind dynamics have to be captured around turbines (scale of meters). Such a combination of large domains and small spatial scales can result in space discretizations leading to a large number of elements/nodes and, consequently, on large computational solver requirements, particularly if structured meshes are considered.

There are several aspects that hamper and slow the transferring of numerical improvements from research to industry. One aspect regards the complexity of modeling wake effects combined with the simulation of Atmospheric Boundary Layer (ABL) flows in complex terrains. Wind resource assessment at on-shore wind farms requires to solve wind flow over a complex terrain, typically considering computational domains extending over tens of kilometers and containing from tens to few hundreds of wind turbines. In this context, existing modeling strategies span from Large Eddy Simulation (LES) to Reynolds Averaged Navier–Stokes (RANS) models. LES models for rotor wakes in complex terrains have been introduced recently with promising results [1,2], but they are still costly at wind farm scales and difficult to converge to a statistical steady state solution, particularly when accounting for Coriolis effects. In contrast, RANS-based approaches [3–5] involving actuator discs [6] provide a steady-state solution and are widely used in research and industry given its compromise between accuracy and computational cost. The actuator disc model [7–13] treats wind turbines as a sink of momentum by imposing a uniform force that depends on the thrust coefficient and disc-averaged inflow velocity [7,8]. Several studies have shown that, at distances exceeding two rotor diameters downwind from the disc, the actuator disc approach gives accurate velocity and turbulence kinetic energy results for both single rotor and large wind farms [3–5,14,15,9,16]. A second bottleneck in wind farm simulations is the complexity to discretize in an automatic and robust manner the multi-scale computational domains involved. Ideally, target meshes should preserve topographic features, resolve the terrain ABL and, simultaneously, be fine enough downstream and around turbines to capture the relevant wake scales.

This paper focuses on the second aspect, *i.e.* on the generation of computational meshes for ABL flow simulations in wind farms modeling the turbines using the actuator disc theory. Each of these aspects has geometrical requirements that must be transcribed into the computational mesh. First, it is necessary to discretize the underlying topography. Second, the need to capture ABL flow gradients poses mesh resolution and stretching requirements to the CFD solvers and, therefore, a boundary layer mesh is required close to the ground. Third, the actuator discs that emulate the effects of wind turbines on the flow must be discretized during the mesh generation procedure and embedded in the mesh. Finally, the computational mesh requires of a higher resolution upstream and downstream of a turbine in order to capture the wake effects that cause wind speed deficits and interactions among different turbines within a farm. All these meshing features impact on the simulation accuracy and computational requirements of the solver since they affect the mesh quality and increase the element count of the mesh.

In this work, we propose a new mesh generation approach for onshore and offshore wind farms. The method is devoted for the case in which the turbines are modeled using the actuator disc theory. We first generate a semi-structured mesh without turbines that dicretizes the topography. This mesh resolves the ABL and is generated using a sweeping (extruding) approach combined with a quality optimization procedure to deliver high-quality meshes. Next, the mesh around the turbines is removed and the actuator disc are discretized using hexahedra. The mesh around the turbines is generated with the desired mesh sizing upstream, downstream and radially from the turbines. Finally, the ABL and disc meshes are coupled taking advantage of the flexibility of tetrahedra and using different tetrahedral/pyramid templates to generate a conformal hex-dominant hybrid mesh. The resulting meshes are used to solve the Reynolds Averaged Navier–Stokes (RANS) equations with a k-$\varepsilon$ turbulence model adapted to the Atmospheric Boundary Layer [17]. The model was developed by Avila et al. [18,19] and implemented in the finite-element multi-physics parallel solver Alya [20,21]. However, the meshing code has been implemented as an external model-independent pre-process program. As a result, meshes generated with this utility can be used to simulate both with steady-state RANS or Large-Eddy Simulation (LES) turbulence models and, in addition, are also valid for solvers based on other numerical methods such as Finite Volumes. In addition to presenting the mesh generation method, several convergence analyses of the solver with respect to different meshing parameters are performed. These analyses are used to determine the different mesh sizing parameters to perform the simulations with an error below the desired tolerance.

The rest of the paper is organized as follows. Section 2 details the existent works related to topography and wind farm meshing, highlighting the main differences and contributions of the current work. Section 3 states the problem, defines the relevant input data, and describes the main steps of the meshing approach. Section 4 describes our optimization-based approach to generate semi-structured hexahedral meshes conformal with the topography to perform ABL flow simulations. Following, Section 5 proposes a new methodology to embed the wind turbines as actuator discs and adapt the mesh to add the required resolution around them, leading to an hybrid mesh conformal with the discs. Section 6 presents a mesh convergence study of the Alya solver, which is used to determine an optimal topography and disc element size. Finally, Section 7 shows simulation results for real onshore and offshore wind farms in order to illustrate the applicability of the methodology.

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