DYNAMIC WALL MODELLING FOR LARGE-EDDY SIMULATION OF WIND TURBINE DEDICATED AIRFOILS.

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Abstract This work aims at modelling the flow behaviour past airfoils used for wind turbine blades at high Reynolds number and large angles of attack (AoA). A previous work has been carried out on the airfoil profiles of DU-93-W-210, DU-91-W2-250 and FX-77-W-500 with a parallel unstructured symmetry preserving formulation together with wall-adapting Local-eddy viscosity model within a variational multi-scale framework (VMS-WALE) as a subgrid-scale model. However for the FX-77-W-500 profile, a mismatch between experimental results and numerical ones has been observed for the drag coefficient. To overcome this disagreement, a dynamic wall model has been implemented in order to compute accurately the wall shear stress without increasing prohibitively the computational costs.

INTRODUCTION

The flow around aerodynamic profiles in pre- or full-stall at high Reynolds numbers is a problem of increasing interest since it is a normal operation state for wind turbine blades. This work aims at modelling the flow behavior past airfoils used for wind turbine blades at high Reynolds number and large AoA by means large-eddy simulations (LES) techniques together with a dynamic wall model. LES calculations are still prohibitively expensive at high Reynolds and this approach can help to solve accurately the boundary layer without increasing excessively the computational cost. In the present work, two profiles have been selected, DU-91-W2-250 and FX77-W-500.

To do this, a parallel unstructured symmetry preserving formulation has been used. The wall-adapting local-eddy viscosity model within a variational multi-scale framework (VMS-WALE) has been used to model subgrid scales (SGS) in the present study. This model has been proved to perform well on unstructured grids [1]. To model the boundary layer, a dynamic wall formulation based on the boundary layer equations hypotesis has been implemented. The simulations are being carried out for Reynolds numbers up to 3×10^6 and AoA up to $16°$. Numerical results will be compared with experimental ones.

MATHEMATICAL AND NUMERICAL MODEL

The turbulent flow is described by means of LES using symmetry-preserving discretizations. The spatial filtered and discretized Navier-Stokes equations can be written as,

$$\mathsf{M}\boldsymbol{u} = 0 \tag{1}$$

$$\Omega \frac{\partial \overline{\boldsymbol{u}}}{\partial t} + \mathsf{C}(\overline{\boldsymbol{u}})\,\overline{\boldsymbol{u}} + \nu \mathsf{D}\overline{\boldsymbol{u}} + \rho^{-1}\Omega\mathsf{G}\overline{\boldsymbol{p}} \;=\; \mathsf{C}(\overline{\boldsymbol{u}})\,\overline{\boldsymbol{u}} - \overline{\mathsf{C}(\boldsymbol{u})\,\boldsymbol{u}} \;\approx\; -\mathcal{M}\mathcal{T}_m \tag{2}$$

where M, C, D and G are the divergence, convective, diffusive and gradient operators, respectively, Ω is a diagonal matrix with the sizes of control volumes, ρ is the fluid density, ν the viscosity, $\overline{\boldsymbol{p}}$ represents the filtered pressure, $\overline{\boldsymbol{u}}$ is the filtered velocity, $\mathcal{M}$ represents the divergence operator of a tensor, and $\mathcal{T}_m$ is the SGS stress tensor. The LES model used in the present work is the WALE model [2] within a variational multiscale framework [3] (VMS-WALE).

The governing equations have been discretized on a collocated unstructured grid arrangement by means of second-order spectro-consistent schemes [4]. 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 balance even at high Reynolds numbers and with coarse grids. These conservation properties are held if, and only if the discrete convective operator is skew-symmetric ($\mathsf{C}(\boldsymbol{u}) = -\mathsf{C}^*(\boldsymbol{u})$), the negative conjugate transpose of the discrete gradient operator is exactly equal to the divergence operator ($-(\Omega\mathsf{G})^* = \mathsf{M}$) and the diffusive operator D, is symmetric and positive-definite. For the temporal discretisation of the momentum equation a two-step linear explicit scheme on a fractional-step method has been used for the convective and diffusive terms, while for the pressure gradient term an implicit first-order scheme has been used. This methodology has been previously used with accurate results for solving the flow over bluff bodies with massive separation [5, 6].

As a boundary layer model, fully 3D Reynolds Averaged Navier-Stokes (RANS) equations have been solved in an embedded mesh generated by extrusion of the superficial mesh of the solid face until the first off wall velocity nodes. The prescribed boundary conditions at the outer surface are the velocities from LES while at the solid face, no-slip conditions are applied [7]. Finally, Neumann conditions are considered on the side boundaries. The turbulent eddy viscosity is modeled by a mixing-lenght RANS type model with wall damping. RANS type eddy viscosity is used because only the unresolved part of Reynolds stress must be taken into account when wall-layer equations with nonlinear convective terms are used [8]. According to the boundary layer theory, the variation of the pressure along the wall normal direction is negligible. This assumption allows the use of the LES pressure field as an input data for the RANS equations, turning the pressure gradient term into a known source term and therefore, the RANS equations into convection-diffusion ones. In order to enforce the divergence-free constraint, the discrete continuity equation has been substracted from the resulting discrete RANS equations. Finally, the wall shear stress components τ_{wi} and τ_{wj} (in local tangential coordinates) are evaluated from the wall model results to supply LES as solid wall boundary conditions.

PRELIMINARY RESULTS AND CONCLUSIONS

LES calculations not including the dynamic wall model have been carried out on DU-93-W-250 and FX77-W-500 airfoils. The results concerning drag and lift coefficients have been compared with experimental data provided by Risø National Laboratory (Denmark) [9] and the Institut für Aerodynamik und Gasdynamik (Germany) [10]. Additional parameters have been also computed in order to gain further insight in the flow dynamics and also to evaluate the mathematical and numerical formulation performance such as turbulent kinetic energy (TKE), skin friction (C_f) and pressure (C_p) coefficients or iso-surface plots of the velocity gradient tensor second invariant (Q). Some illustrative results are shown in figure 1. In order to enhance the LES results without dynamic wall model, calculations taking into account the whole model are currently being carried out. Improvements specially in the wall shear stress values (i.e. C_d and C_f coefficients) as well as an overall improvement of the LES results are expected. Special attention will be paid to the evaluation of the dynamic wall model contribution to the global perfomance by comparing LES results with and without wall model.

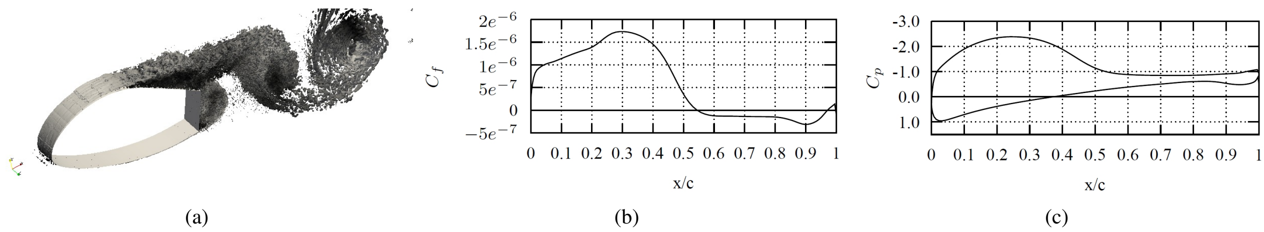

Figure 1. Q iso-surfaces (a) C_f (b) and C_p (c) coefficients for FX77-W-500 at AoA of 16°.

Airfoil	AoA	C_l LES	C_l Exp	C_d LES	C_d Exp
DU-91-W2-250	6°	1.04	1.07	0.015	0.011
DU-91-W2-250	9°	1.27	1.37	0.030	0.013
DU-91-W2-250	15°	1.19	1.18	0.134	0.105
FX77-W-500	0°	0.29	0.33	0.174	0.082
FX77-W-500	11°	1.54	1.58	0.185	0.085
FX77-W-500	16°	1.26	1.06	0.376	0.078

Table 1. Aerodynamic coefficients. Comparison between LES results and experimental ones at different AoA.

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