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Published in:
Proceedings of 10th EAWE PhD Seminar on Wind Energy in Europe

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Frère, A., Chivaee, H. S., Mikkelsen, R. F., Chatelain, P., & Hillewaert, K. (2014). Large-eddy simulations of a S826 airfoil with the Discontinuous Galerkin Method. In Proceedings of 10th EAWE PhD Seminar on Wind Energy in Europe (pp. 55-58). European Academy of Wind Energy.

10th PhD Seminar on Wind Energy in Europe
28-31 October 2014, Orléans, France

LARGE-EDDY SIMULATIONS OF A S826 AIRFOIL WITH THE DISCONTINUOUS GALERKIN METHOD

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ABSTRACT

The aim of the present work is to improve the understanding of low Reynolds flow physics by performing Large-Eddy Simulations (LES) of the NREL S826 airfoil. The paper compares the results obtained with a novel high order code based on the Discontinuous Galerkin Method (ArgoDG) and a recent experiment performed at the Technical University of Denmark. Chordwise pressure evolutions, integrated lift and drag forces are compared at Reynolds number 4.10^4 and angles of attack (AoA) 10 and 12 degrees. Important differences are observed between the simulations and the experiment. These differences are, however, partially explained by the strong sensitivity to the tunnel environment. To overcome this source of error, the ArgoDG LES results are also compared to LES performed with the Finite Volume Method (FVM) code EllipSys3D, a well established wind turbine Computational Fluid Dynamics (CFD) code. The similarity of the results obtained by these two inherently different methodologies provide strong confidence in the validity of the computations.

INTRODUCTION

Accurate prediction of low Reynolds number ($Re < 10^5$) airfoil characteristics is difficult since the transitional flows often feature laminar separation bubbles (LSB), highly three-dimensional stall cells, performance hysteresis as well as a high sensitivity to inlet turbulence. As a result, high uncertainties on the wind tunnel measurements are observed. Therefore, the use of CFD is a very attractive perspective.

The main difficulty of the CFD simulations is the modeling of flow turbulence. Due to the presence of laminar to turbulent transition and the 3D boundary layer development at higher AoA, Reynolds Averaged Navier-Stokes (RANS) is not suited for the prediction of low Reynolds number flows. Instead, scale-resolving approaches such as LES, which compute part of the turbulent structures directly, should be used. The challenge of LES remains its large computational cost for high Reynolds number, although with the present computing capacity, $Re=10^5$ can be modeled fully. For LES computations, high-order discretizations are considered to be more adapted than those typically used in state of the art solvers, as illustrated by the use of high-order finite difference or spectral codes in academia. Due to the lack of geometric flexibility of these methods, novel unstructured high-order discretization techniques as the Discontinuous Galerkin Method (DGM) are currently being developed for industrial applications. The ArgoDG code, based on DGM, has been successfully validated on DNS and Implicit LES (ILES) benchmarks [1][3]. In particular, the validity of the ILES approach, where the subgrid scale stresses are provided by the numerical scheme, has been demonstrated. Argo DGM starts to be used on industrial benchmarks featuring transitional flow and the wind turbine airfoil simulation of this paper is a step forward in the validation of the DG methodology for industrial applications.

In this paper, the ArgoDG code is used for LES of the S826 airfoil at Reynolds number 4.10^4. The S826 airfoil is a 14% thick NREL airfoil which has been used recently in a blind test comparing different wind turbine wake modeling codes. This test demonstrated the importance of capturing correctly the low Reynolds flow physics [4]. This airfoil is hence well representative of the current wind energy challenges.

NUMERICAL SETUP

The discontinuous Galerkin method can be seen as a collection of elementwise defined small finite element problems coupled by “boundary conditions” on the common faces between elements. The high order of convergence is ensured by the polynomial interpolation. In the present study cubic polynomials have been used throughout the domain, formally leading to fourth order grid convergence.

The 3D mesh used for ArgoDG computations is obtained by the extrusion in the spanwise direction of an unstructured O-type mesh composed mainly of triangles in the far-field combined to quadrangles in the boundary layer region, see Figure 1. The span length is equivalent to 20% of the chord and to simulate an infinite span, periodic boundaries are imposed.

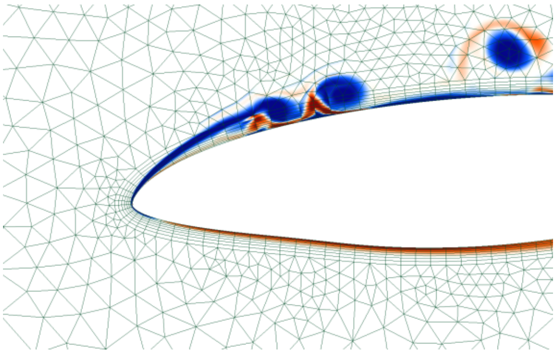

Figure 1: Vorticity and mesh of the Argo run at AoA=12° and Re=4.10^4.

Rigorous mesh criteria for LES computations are unfortunately not available. For the classical periodic channel flow, Piomelli and Balaras [5] advise streamwise and spanwise resolution as $\Delta x^+ \leq 100$ and $\Delta z^+ \leq 20$ respectively, while the wall normal direction should satisfy $\Delta y^+ \leq 1$. This rule of thumb is however probably too restrictive for high-order methods, and not appropriate for reattachment zones where one would expect to need a more isotropic mesh parallel to the wall to reflect a highly chaotic flow. The runs were hence made on a slightly coarser mesh providing $\Delta y^+ \leq 1.5$, Δx^+ and $\Delta z^+ \leq 20$ in the turbulent region. The 3D mesh lead to computations of 5.0M degrees of freedom.

LES OF THE S826 AIRFOIL AT REYNOLDS NUMBER 4.10^4

Sarlak [6] demonstrates the presence of hysteresis for Re ≤ 8.10^4 and for angles just above 10°. Re of 4.10^4 and AoA of 10 and 12° were hence considered for ArgoDG simulations with flow conditions such that the freestream Mach number is M = 0.15. Figure 2 presents a global view of the flow at AoA=10° with the instantaneous z-wise vorticity, showing a laminar separation close to the leading-edge followed by a transition close to 40% of the chord.

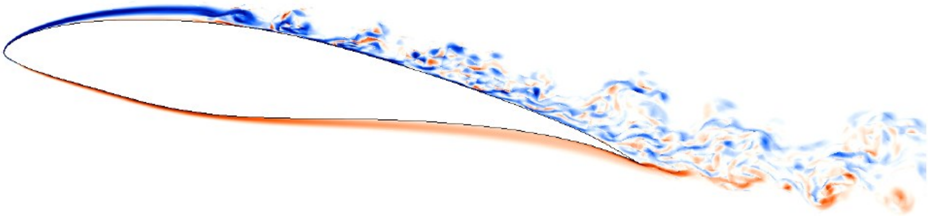

Figure 2: Separation region visualized by z-wise vorticity in the periodic plane for S826 airfoil at Re = 4.10^4 and AoA = 10° with ArgoDG.

Figure 3 provides the experimental lift and drag curves for two different inflow turbulence intensities (TI), respectively 0.1% and 0.8%. A slight increase of the inlet turbulence is hence enough to drastically change the airfoil performance. This figure presents as well computational results obtained with ArgoDG. It is surprising to notice that the CFD results, obtained without imposed inflow turbulence, are much closer to the experimental values obtained at the higher turbulence levels.

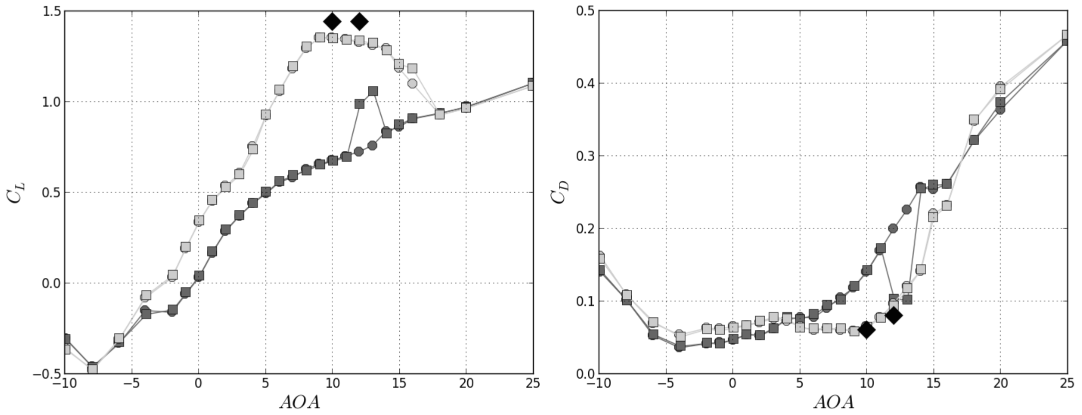

Figure 3: Experimental lift and drag coefficients for increasing (circles) and decreasing (squares) AoA[6]. Dark and light gray markers represent TI= 0.1% and 0.8%. Black diamonds are ArgoDG.

Figure 4 further compares ArgoDG results to the experimental results at different TI by presenting the pressure coefficient evolution along the airfoil chord. This figure shows clearly that the computed flow is very close to the experiment with the highest inflow turbulence. The computational curve and the experimental curve with TI=0.8% are both presenting a pressure plateau, revealing the presence of a LSB. The pressure level and the length of the plateau are not coinciding between the computation and the experiment. Their evolutions between 10 and 12° are however similar: the pressure level increases and the length reduces. The LSB moves hence to the leading-edge and reduces in size when the AoA increases.

The experimental curve at lower TI does not present a pressure plateau. The flow seems to separate close to the leading-edge, without reattachment. The inflow turbulence has hence a very strong impact on the flow characteristics. As mentioned by Genç [2], Schubauer and Skramstad [7] demonstrated that the transition over a flat plate is already affected by a turbulence level of 0.1%. The step from TI = 0.1 to 0.8% realized in the experiment has hence a strong impact on the LSB stability. This , however, does not explain why the computation is closer to the case with inflow turbulence.

A potential explanation lies in the numerical dissipation of the code. In order to verify this effect, the results obtained with ArgoDG for an AoA of 12° are compared to those obtained with EllipSys3D, code based on a very different discretization scheme and therefore featuring a distinct dissipation behavior. Figure 4 shows that the two computations provide very similar results, increasing the confidence in their validity. Both computations, performed without inflow turbulence, are very close to the experiment performed with TI=0.8% and they both present a lower and longer pressure plateau.

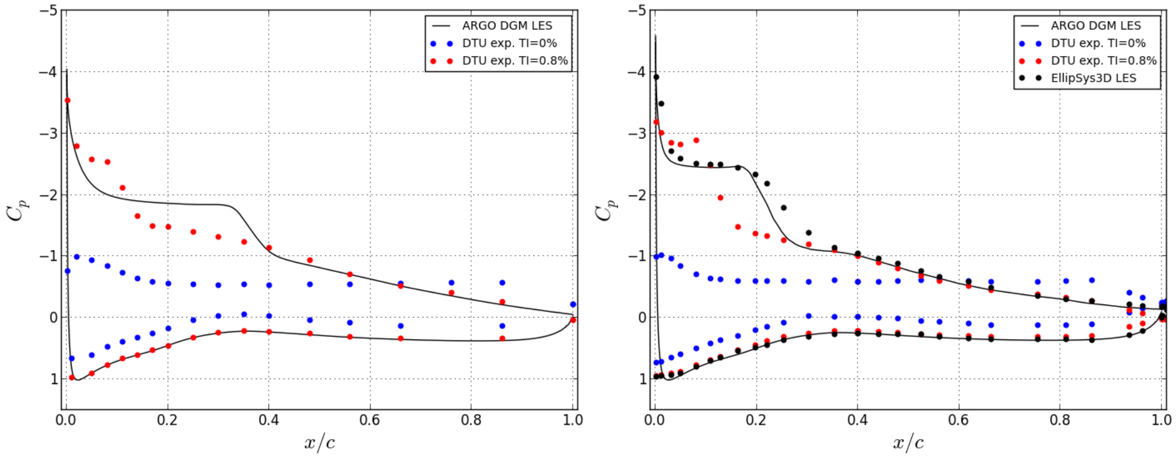

Figure 4: Pressure coefficient at Re=4.10^4, for AoA=10°(left) and AoA=12° (right)

Other reasons for the discrepancy between the LES and the experiments are, on the computation side, unadapted grid refinement or insufficient span width to allow the development of long wavelength structures and stall cells. On the experimental side, one can mention the impact of pressure taps on the transition and separation of the boundary layer as well as the interaction of the flow with the wind tunnel leading to secondary flow near the walls, or interaction with large stall cells. To verify and understand these discrepancies, further mesh and span analyses will be performed on the computational side, and more detailed experiments will be undertaken, including oil visualization.

CONCLUSION

ILES of the S826 airfoil were performed at a Reynolds number of 4.10^4 and at angles of attacks of 10 and 12 degrees with a novel high order code based on the Discontinuous Galerkin Method, ArgoDG. The pressure distribution over the airfoil as well as the lift and drag coefficients obtained with ArgoDG were compared with experiments and LES performed at DTU Wind Energy. The results obtained by ArgoDG are very similar to those predicted by EllypSys3D, providing a good confidence in ArgoDG ILES accuracy.

Some differences are however observed with the experimentation. Although the computations are both realized without inflow turbulence, the results match better the experimentation performed with the highest inflow turbulence. Multiple authors showed however that at low Reynolds, the inflow turbulence plays a crucial role in the establishment of the flow, leading to cases with or without turbulent reattachment. In view of the extreme sensitivity to the tunnel environment and considering the similarity with Ellipsys3D simulations, the ArgoDG results obtained in this paper are considered as a good step forward in the use of DG Method for solving low Reynolds number flows around airfoils.

Further studies, based on oil flow visualization, Reynolds number and inflow turbulence sensitivity analyses are expected to shed some light on the details of separation behavior and contribute to reconcile the simulations and observations at various TI and Re.

AKNOWLEDGMENT

A. Frère gratefully acknowledges her funding by the Walloon Region in the frame of the FirstDocA framework and thanks Torben J. Larsen and Jens N. Sørensen for the fruitful discussions and precious inputs.

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