IEA Wind Task 46

Erosion of wind turbine blades

Validation of the Predictive Capabilities of Computational Aerodynamics Codes to Assess Eroded Blade Performance: First Aerodynamic Benchmark

Technical Report

Validation of the Predictive Capabilities of Computational Aerodynamics Codes to Assess Eroded Blade Performance:

First Aerodynamic Benchmark

Prepared for the
International Energy Agency Wind Implementing Agreement

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Purpose

Leading edge erosion (LEE) of wind turbine blades has been identified as a major factor in decreased wind turbine blade lifetimes and energy output over time. Accordingly, the International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) has created the Task 46 to undertake cooperative research in the key topic of blade erosion. Participants in the task are given in Table 1.

The Task 46 under IEA Wind TCP is designed to improve understanding of the drivers of LEE, the geospatial and temporal variability in erosive events, the impact of LEE on the performance of wind plants and the cost/benefit of proposed mitigation strategies. Furthermore Task 46 seeks to increase the knowledge about erosion mechanics and the material properties at different scales, which drive the observable erosion resistance. Finally, the Task aims to identify the laboratory test setups which reproduce faithfully the failure modes observed in the field in the different protective solutions.

This report is a product of Work Package 3 Operation with erosion.

The objective of the work summarized in this report is to:

- Introduce a comparative analysis of the predictive capabilities of diverse computational aerodynamics codes for assessing the aerodynamic performance reductions due to blade erosion

Table 1 IEA Wind Task 46 Participants.

Country	Contracting Party	Active Organizations
Belgium	The Federal Public Service of Economy, SMEs, Self-Employed and Energy	Engie
Canada	Natural Resources Canada	WEICan
Denmark	Danish Energy Agency	DTU (OA), Hempel, Ørsted A/S, PowerCurve, Siemens Gamesa Renewable Energy
Finland	Business Finland	VTT
Germany	Federal Ministry for Economic Affairs and Energy	Fraunhofer IWES, Covestro, Emil Frei (Freilacke), Nordex Energy SE, RWE, DNV, Mankiewicz, Henkel
Ireland	Sustainable Energy Authority of Ireland	South East Technology University, University of Galway, University of Limerick
Japan	New Energy and Industrial Technology Development Organization	AIST, Asahi Rubber Inc., Osaka University, Tokyo Gas Co.
Netherlands	Netherlands Enterprise Agency	TU Delft, TNO
Norway	Norwegian Water Resources and Energy Directorate	Equinor, University of Bergen, Statkraft
Spain	CIEMAT	CENER, Aerox, CEU Cardenal Herrera University, Nordex Energy Spain
United Kingdom	Offshore Renewable Energy Catapult	ORE Catapult, University of Bristol, Lancaster University, Imperial College London, Ilosta, Vestas
United States	U. S. Department of Energy	Cornell University, Sandia National Laboratories, 3M

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Executive Summary

The report presents an initial assessment of the predictive capabilities of computational aerodynamics codes used in industry and academia for predicting the aerodynamic performance impairment of wind turbine blades caused by erosion. Both high-fidelity codes, i.e. Navier-Stokes computational fluid dynamics codes, and lower-fidelity methods, i.e. potential flow codes coupled to integral boundary layer equation and transition model and augmented with empirical correlations, are considered in the exercise. The test cases used for the study consist of wind tunnel aerodynamic experiments carried out in state-of-the-art European and American wind tunnels. The results of this investigation are relevant to predicting the turbine power and energy yield loss caused by erosion.

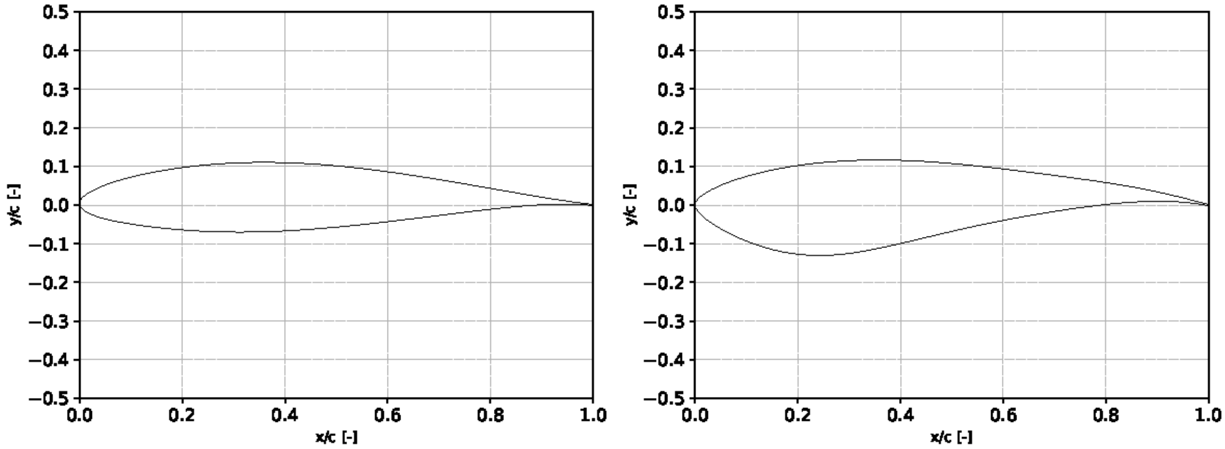
1. Introduction

Predicting wind turbine power reduction and annual energy production (AEP) losses due to blade leading edge erosion (LEE) requires relating the roughness characteristics of LEE to the resulting aerodynamic performance degradation of the blade. This can be done with computational aerodynamics codes that use the geometry of the LEE patch or its metadata (e.g. equivalent sand grain roughness) along with the geometry of the nominal blade section (airfoil) and estimate the aerodynamic performance (e.g. lift and drag coefficient curves of the perturbed blade section. The codes available for this vary greatly for fidelity and computational burden, ranging from 3D Navier-stokes (NS) Computational Fluid Dynamics (CFD) solvers resolving the geometry of the leading edge (LE) perturbations [Campobasso et al., 2022] to lower fidelity approaches, such as 2D potential codes coupled to integral boundary layer equations and laminar-to-turbulent boundary layer transition models [van Rooij 1996]. Aiming to combine the strengths of both approaches, e.g. the high level of fidelity of 3D NS CFD and the low computational requirements of 2D potential flow model-based codes, approaches aiming to model the detrimental impact of LEE roughness in 2D RANS simulations without resolving the LEE geometry are frequently used. One of the most popular approaches of this kind is that based on the equivalent sand grain roughness [Nikuradse 1950], which correlates the actual measured roughness to a more regular pattern that would yield the same viscous stress at the rough surface (the LE). So far, the equivalent sand grain roughness model has not been used in potential flow model-based codes like RFOIL [van Rooij 1996]. Up to a certain roughness level, however, the impact of roughness on the aerodynamic predictions of this type of code can be accounted for indirectly, e.g. by enforcing earlier laminar-to-turbulent boundary layer transition with respect to the case with smooth surface. Above the level of roughness that trips boundary layers at the LE, however, it is still difficult to account for the additional performance loss due to further increase of the wall viscous stress.

The aim of the initial study presented in this report is to assess the scatter of the predictions of the LEE-induced aerodynamic performance degradation of different computational aerodynamic codes or even the same aerodynamic code used by different users. Section 2 defines the considered test cases and Section 3 provides a brief description of the codes used by all IEA Task 46 Work Package 3 (WP3) partners participating in this study. A selection of results is presented in Section 4, with Section 5 providing some preliminary conclusions and an overview of forthcoming analyses.

2. Test cases

Three test cases have been considered for the comparative analyses reported herein. The first two test cases refer to measurements of the aerodynamic performance, the surface static pressure and the position of the boundary layer transition of the 18% thick NACA63$_3$418 and the 18% thick S814 airfoil, the former being representative of the outboard blade sections of medium-size multi-megawatt wind turbines and the latter being representative of root blade section. The geometry of the two airfoils is depicted in Figure 1.



(a)

(b)

Figure 1. (a) NACA63$_3$418 airfoil geometry and (b) S814 airfoil geometry.

The airfoils of the first two test cases were tested at the Oran W. Nicks Low-Speed Wind Tunnel at Texas A&M University. For both airfoils a clean and rough configuration was tested. The equivalent sand grain roughness of the rough LE was estimated to correspond to 101 μm with reference to a 1 m chord. Different values of the Reynolds number were considered, including 3.2M. Full detail of all performed measurements and experimental results can be found in [Ehrman 2014].

The third test case also refers to the NACA63$_3$418 airfoil, but the experiments took place at the low-turbulence low-speed closed-loop wind tunnel of Delft University of Technology. Also in this case, both the smooth and the rough LE airfoils were tested, but the equivalent sand grain roughness, also referred to a 1 m chord, was estimated to be 708 μm. Therefore, the level of erosion severity of the rough airfoil tested at Delft is significantly higher than that tested at the University of Texas A&M. Different values of the Reynolds number were considered, including 3M. Full detail of all performed measurements and experimental results can be found in [Pires et at. 2014].

3. Computational aerodynamic codes

Eight researchers and industrial participants contributed to this first aerodynamic benchmark, namely AIST (National Institute of Advanced Industrial Science and Technology), CENER (Renewable Energy Centre of Spain), DTU (Technical University of Denmark), IWES (Fraunhofer Institute), LU (Lancaster University), NORDEX (wind turbine manufacturer), TNO (Dutch research centre) and Vestas (wind turbine manufacturer). A brief description of the codes used by all participants is as follows:

OpenFOAM is an unstructured CFD open-source toolbox based on the cell-centered finite volume method. The toolbox also features all functionalities for solving the Reynolds-Averaged NS (RANS) equations, the flow model of choice in all CFD simulations herein. Second order schemes are used for space discretization of all equations. Some participants used the k-ω shear stress transport (SST) turbulence model for the aerodynamic analyses with fully turbulent boundary layers, and the 4-equation correlation-based γ-Re_θ transition model [Langtry et al. 2009] to simulate laminar-to-turbulent transition of the smooth airfoil boundary layers. Modified wall boundary conditions and/or expressions of the eddy viscosity were used for the rough LE analyses. In some cases, the γ-Re_θ transition model was used in conjuction with a fifth transport equation to model transition on rough walls.

The RANS CFD code **EllipSys2D** (Sørensen 1995, Michelsen 1992) uses structured grids and a cell-centered finite volume formulation with a multiblock approach for parallelization. It employs an efficient multigrid algorithm to solve the pressure-correction problem and grid sequencing for faster convergence. The convective terms are discretized with a third order accurate scheme. Transition in the case of smooth airfoils is modeled by coupling the k−ω SST turbulence model to the e^N transition model. Distributed roughness effects at rough walls are captured by using the rough wall model by [Knopp 175 et al. 2009].

ANSYS FLUENT is a commercial unstructured CFD code, which includes the RANS flow model. FLUENT is a cell-centered finite volume code. Second order space discretization was used for the simulations herein. Transition at smooth wall is modeled by means of the 4-equation correlation-based γ-Re_θ transition model. At rough walls, rough wall functions are used, which introduce a downward shift of the logarithmic boundary layer profile depending on the value of the equivalent sand grain roughness [Ortolani et al. 2022].

RFOIL is a 2D panel code solving the 2D potential flow past general airfoils and using an integral boundary layer equation to account for the presence of viscous boundary layers. It also features a transition model that depends on the level of free stream turbulence. RFOIL was derived from XFOIL, the panel code developed at MIT [Drela 1989], developed to improve the predictive capabilities of XFOIL for the thick wind turbine airfoils [van Rooij 1996].

DART (Digital Airfoil Reconstruction Tool) is a software that corrects simulated polar data (e.g. RFOIL simulations) to take into account the impact of roughness and other geometry deviations on aerodynamic performance. DART is based on extensive wind tunnel databases.

Some participants utilized more than one code and some codes were used by more than one participant. The code(s) used by each participant are indicated in Table 1.

	AIST	CENER	DTU	IWES	LU	NORDEX	TNO	VESTAS
OpenFOAM	x	X		X		X	X	
EllipSys2D			X					
FLUENT					X			
RFOIL							X	
DART								X

Table 2 Computational aerodynamics codes used by benchmark 1 participants.

4. Results

The comparison of measurements and predictions of the aerodynamic performance (lift coefficient, drag coefficient and aerodynamic efficiency versus the angle of attack) of the clean NACA63$_3$418 airfoil of the Texas A&M experiment (test case 1) is reported in Figure 2. A reasonably good agreement of all predictions with each other on one hand, and with all predictions and the measured data is observed, particularly from the smallest AoA considered to about 8 degrees. This interval includes the operating conditions of this airfoil (expected to be between about 5 degrees).

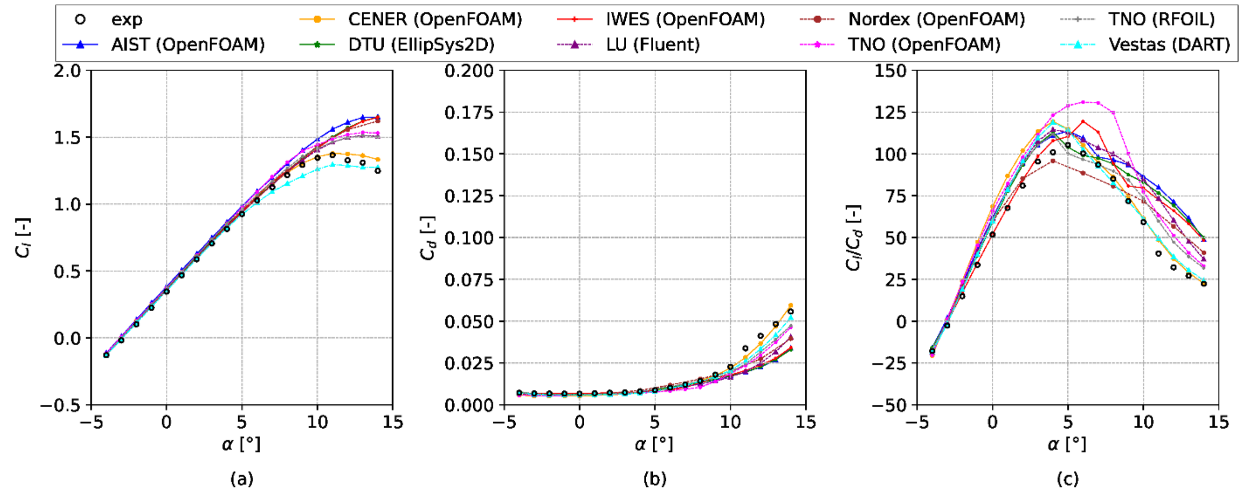
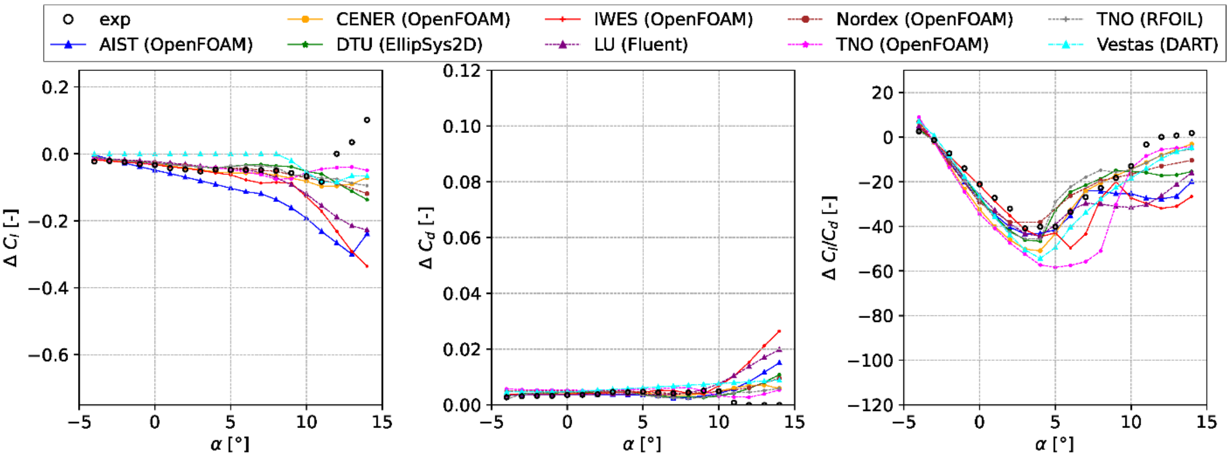


Figure 2 Comparison of measured data and computed results of the clean NACA63$_3$418 airfoil of the Texas A&M experiment: (a) lift coefficient c_l against AoA α; (b) drag coefficient c_d against α; (c) ratio c_l/c_d against α.

Figure 3 considers measured and computed performance differences between the NACA63$_3$418 airfoil with rough LE and that with a smooth surface of the three aerodynamic coefficients. The agreement of all computed performance differences with each other and the measured differences is reasonably good between the minimum AoA considered and an AoA of about 5 degrees. Above this value a more significant scatter of the computed and measured performance variations is noted.



(a) (b) (c)

Figure 3 Comparison of differences of measured and computed force coefficients of clean and rough NACA 63_3418 airfoils of the Texas A&M experiment: (a) c_l difference against AoA α; (b) c_d difference against α; (c) difference of c_l/c_d against α.

Turbine energy yield analyses being conducted in this study show that the AEP loss predictions of a multi-megawatt turbine featuring the NACA 63_3418 airfoil with the considered level of roughness in its outboard region are closer to each other than the performance curves shown in Figures 2 and 3. This is because the AoA of the outboard blade sections is relatively small, at levels for which the agreement of measurements and predictions is relatively good. More detailed results of the benchmark cases and the impact of AEP loss predictions are planned for an upcoming publication.

5. Key Conclusions/Recommendations

The predictions of significantly different computational aerodynamics codes have been compared to measured data for the case of a smooth wind turbine airfoil and that of the same airfoil featuring roughness of levels comparable to those of the early stages of LEE. Despite the significant differences of these codes, used in industry and academia, the agreement of their predictions with measured data is reasonable. More importantly, the agreement is fairly good in the range of AoA at which this airfoil operates when featured by the outboard sections of medium sized multi-megawatt turbines. This leads to the fact that the AEP losses predicted by wind turbine codes using the computed airfoil performance data discussed herein are quite close to each other, and also to the AEP loss estimated using measured airfoil performance data of the smooth and rough airfoils.

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