Numerical Methods Applied in Wind Energy Industry

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ABSTRACT

This paper provides an introduction to the application of numerical methods in the field of wind energy and presents some results obtained by the use of these applications. The main objective is to describe the tools that wind turbine designers and wind farm planners can apply to solve the problems they face in their daily work.

The available numerical methods present different degrees of complexity and the selection of the most appropriate one for solving a particular problem is of paramount importance. The use of an excessive level of complexity when solving simple problems wastes time and resources, and in some cases can make reaching a solution to the problem completely impossible. On the contrary, the use of methodologies that do not reproduce the physics of the problem could lead to the necessity of increasing the safety factor in the designs or just lead to a solution with an inacceptable level of accuracy.

The selection of the type of tool to be used for solving a particular problem is one of the most important decisions that has to be made in the design phase of a wind turbine or a wind farm.

Keywords: *Renewable energy, CFD, numerical methods.*

INTRODUCTION

The study of aerodynamics phenomena related to wind turbines is one of the major issues of interest within the wind energy community. In particular, the analysis of unsteady flows have become a priority in the development of new tools. The reason is that wind turbines operate in an environment that changes dramatically with time. In fact, a uniform stream flowing parallel to the axis of the turbine happens to be an ideal assumption that is almost never found in daily practice. Sudden wind gusts, yawing of the rotor disk caused by changes in wind direction, the influence of the ground and of other wind turbines located nearby, all contribute to the complexity of problem modelling in such a way that oversimplified theoretical and quasi-empirical models are not capable to provide fully reliable answers to basic design questions.

Most aeroelastic codes use an aerodynamic model based on the Blade Element Momentum (BEM) theory originally developed by Betz and Glauert [1-2]. The model is complemented with a combination of blade element theory and one dimensional momentum theory. The blade element theory assumes that the blades can be divided into small elements that act independently of the neighbouring elements. In addition, it is assumed that the flow around the airfoils is two-dimensional, and the aerodynamic forces can be calculated from the local flow conditions, i.e. the undisturbed wind speed, the structural vibrations, and the rotor speed. The local angle of attack is assumed to be a function of the direction and magnitude of the local relative wind, which can be obtained as a function of the incoming undisturbed wind speed at the rotor plane and the rotor speed.

Fundamentally, this methodology assumes that the change of axial momentum of the undisturbed flow at the rotor plane is caused by the aerodynamic forces acting on the blades. Moreover, these forces are considered to be constant for each annular blade element, which is based on the assumption of an infinite number of blades. An additional hypothesis is that there is no influence between adjacent annular blade elements.

To correlate the performance of this methodology some semi-empirical corrections have been included to allow the treatment of phenomena that are not compatible with the aforementioned hypothesis. Some of the corrections included in that method are related to the treatment of stall [3-5].

The capability of modern computers have allowed the development of more complex methodologies to treat the problem of unsteady flow around wind turbines. One of the alternatives proposed by the scientific community is the use of panel methods that are capable of simulating the change over time of the velocity field with more accuracy that BEM but with lower level of complexity and use of resources than full CFD. However, when potential methods are not enough to solve the unsteady problem the alternative is the use of CFD.

Concerning wind farms, the AEP estimation is a vital step in the planning phase of new projects. The size of wind farms has increased significantly from landowners with 1-5 WTGs, to massive energy sector developers using wind as an investment base with projects usually consisting of at least 100 WTGs. Taking into account the average price per MW of installed capacity in 2011, wind investments are now in the hundreds of millions Euros, according to the Bloomberg New Energy Finance's Wind Turbine Price Index [6]. Hence, the financial consortiums securing funding for these projects have a very high demand for increased business case certainty. In addition, lowering the levelized cost of energy (LCOE) is a very important factor for wind farm developers to maximize their profit margins.

Since many of the best wind resources available on relatively non-complex terrain sites have already been exploited, many developments are exploring mountainous areas with consistently complex terrain. The obvious advantage is the higher wind speeds due to the speed-up effects, but increases in turbulence and rapid wind direction changes are commonly present as well.

The traditional tools for siting flow field calculations have been based for many years on linear flow models, such as WAsP [7] developed by the DTU Wind Energy Department. Refinements and improvements of the process behind the WAsP tool have been made through its 25 years of existence in order to improve speed, robustness and precision [8]. Although very efficient in comparison to the non-linear CFD approaches, it is well known that linear flow models cannot resolve flow detachment and recirculation, which become increasingly important in complex terrain analysis and evident in the Bolund blind comparison results [9]. The WAsP tool gives good results in areas with less than 18° terrain slope, or approximately 30%, but can also be used on more complex sites if the limitations of the linear flow model are well known. Considering the above, DTU Wind Energy Department has introduced in 2014 WAsP CFD tool for wind resource assessment in complex terrain based on the EllipSys code [10], their in-house finite volume CFD solver developed since the mid-1990s

The use of more advanced methods to compute the flow field in the wind farm can improve the accuracy of the evaluation of energy production in the wind farm. Additionally the use of these methods can provide a better characterization of the flow in the site, allowing a better assessment of the loads during the lifetime of the turbine.

WIND TURBINE ANALYSIS

When the designer starts analysing the aerodynamics of a wind turbine, he has in front of him a vast number of possible combinations of parameters that affects its performance. It is necessary to define among others the diameter, the chord and twist distribution, types of profiles, and to make the selection ever more complicated there are some constrains that impose limits on noise, maximum chord, etc.

For any of the possible variants of the rotor it would be necessary to evaluate the effect on loads and determine the structure that is capable to withstand these loads. To make the situation even more difficult, mechanical elements are subject to vibration, which changes the velocity field around the blades and consequently the resulting aerodynamic forces.

It is clear that wind turbine designers have to follow an approach that allows them to maintain the maximum physical information in the design loop yet maintaining enough flexibility to explore this universe of possible combinations.

The methodology is quite similar to the one used in aerospace industry where during the design phase numerical methods of different complexity are used to provide an optimum solution to the problem.

The application of methods derived from BEM have demonstrated a very good accuracy in the evaluation of loads and power performance in wind turbines. Therefore, the first step in any design process is the use of these methods to solve the majority of cases. The results have been widely validated and the experimental results have been used to make them even more accurate.

In some cases the complexity of the flow around the wind turbine makes it difficult to apply these methods with enough accuracy, which could lead to the use of extremely high safety margins in the design. To ensure the increase in competitiveness of the wind industry it is essential to optimize the structural design to reduce the weight and cost of components. In this context, the use of more advanced numerical methods could be used to reduce the cost of energy associated to the wind generation.

The first step in the complexity staircase is the use of potential methods that provide an unsteady three-dimensional analysis of the behaviour of a wind turbine. These methods are based on panel methods and are capable of computing the evolution of the wake of the wind turbine and its change with time. Figure 1 shows the results obtained by a panel method for a test turbine [11]:

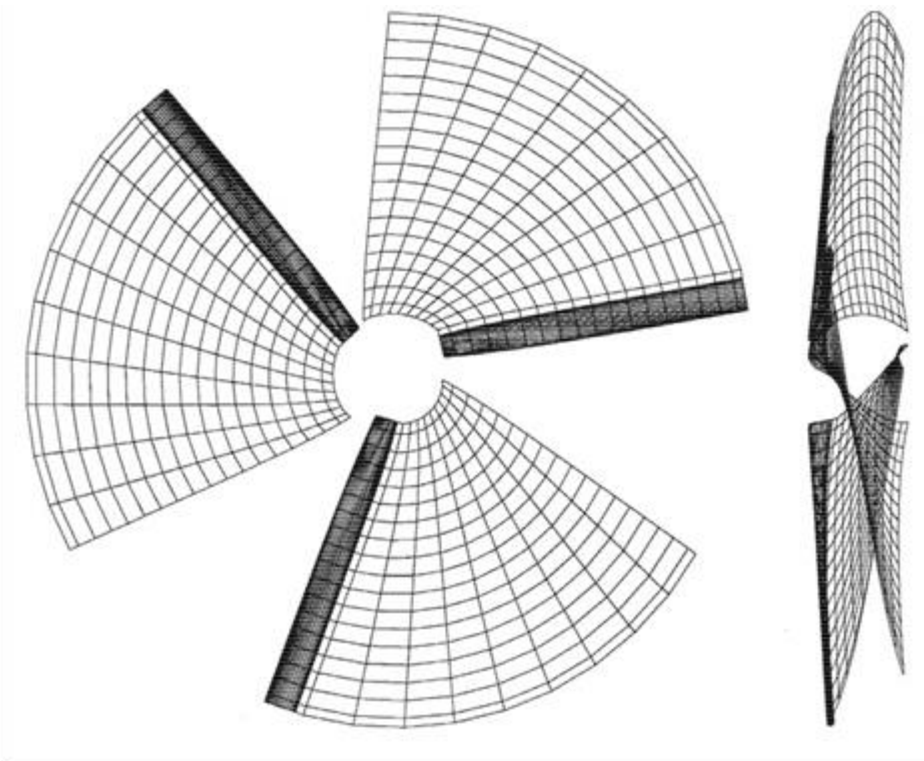

Figure 1 – Wake generation at the NREL horizontal-axis wind turbine .

Figure 2 show the comparison between measured and calculated pressure distributions for three different blade sections at a specific time [12]. The numerical results show a good agreement with the measured ones. These potential methods do not include viscous effects and are not capable of computing flow separations which reduces the number of cases where they can be applied. To increase their capabilities it is possible to couple this inviscid method with a treatment of boundary layer that could reproduce part of the viscous effects and can detect separation.[13]

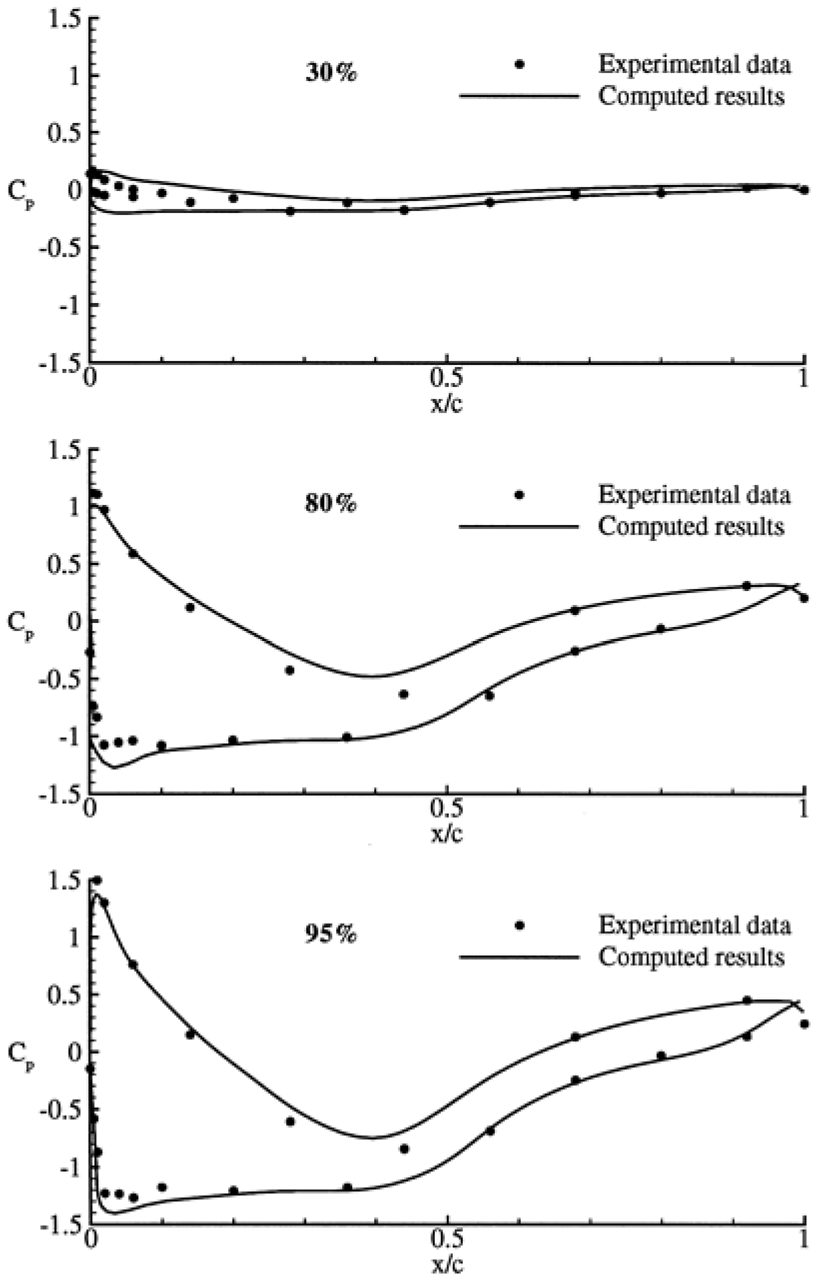

Figure 2 – Comparison of Cp distributions on three different blade locations .

When the coupling between inviscid and viscous terms is stronger, the aforementioned method cannot be applied. In this case, a full CFD approach should be used. There is a wide range of complexity in the methods that can be used to solve the flow field around the wind turbine. The variety among these methods is mainly originated by the treatment of turbulence. According to this treatment, the possible methods are:

- RANS with Algebraic closure
- RANS with 1 of 2 closure equations for turbulence (k-ε, k-ω, etc)
- Reynold Stress Model
- Detached Eddy Simulation
- Large Eddy Simulation

More information about the applicability of these methods for wind turbine analysis can be found in [14]

WIND FARM ANALYSIS

CFD is integral part of the micro-siting activities performed in Vestas. A large amount of sites have been analyzed in the last year, providing us with a very wide range of experience in the application of this technology to evaluate wind farms. The objectives of these micro siting activities are the increment of accuracy in the determination on annual energy production and in obtaining engineering quantities of interest, including turbulence intensity, wind shear, wind veer and flow inclination.

The results obtained by our models have been widely validated with internal data and with the publicly available datasets of Bolund [9], and Askervein [15] field measurement campaigns. The results of the validation campaign have confirmed the accuracy of the methodology and have provide an increased confidence in the model performance.

The first step in the analysis of the wind farm is to establish its degree of complexity to decide on the fidelity level of best suited method to solve it. Figure 3 shows the different methods that could be applied to the wind farm analysis. The complexity of the method and the resources in terms of man-hours and CPU times increases from bottom to top. Typical analysis times for different levels are provided in Table 1.

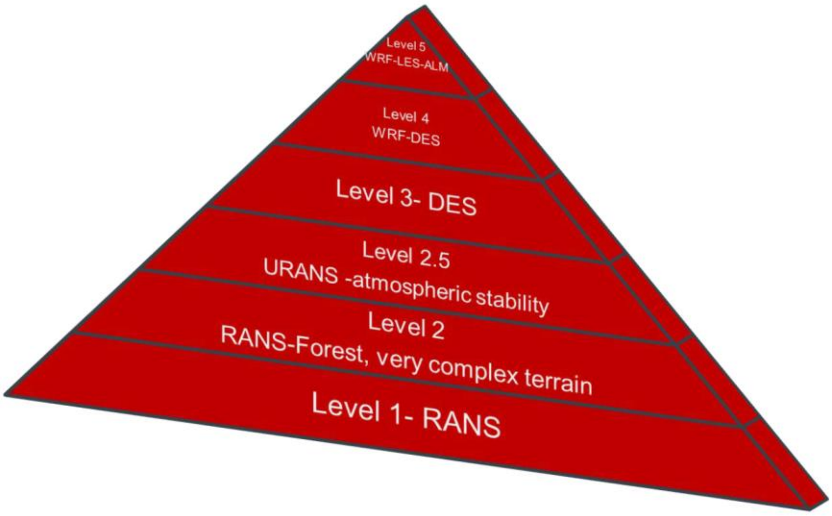

Figure 3 – Possible levels of wind farm analysis

Table 1 Typical times per Level

Level	Time
1	10-20 hours
2	1-3 days
2.5	1 week
3	1 week
4	weeks
5	months

CFD in Vestas can also be used for wind resource AEP predictions [16]. A benchmarking project was undertaken, in which a statistically significant number of sites of varying complexity was analyzed comparing actual production values with the *a priori* CFD and WAsP (No ΔRIX correction applied) AEP calculations. Figure 4 demonstrates the AEP percentage improvement in the CFD vs. WAsP predictions across the 50 sites analyzed. Overall, it was determined that by using a neutral CFD model of the atmospheric surface layer (ASL), roughly 8% improvements in the mean error can be expected.

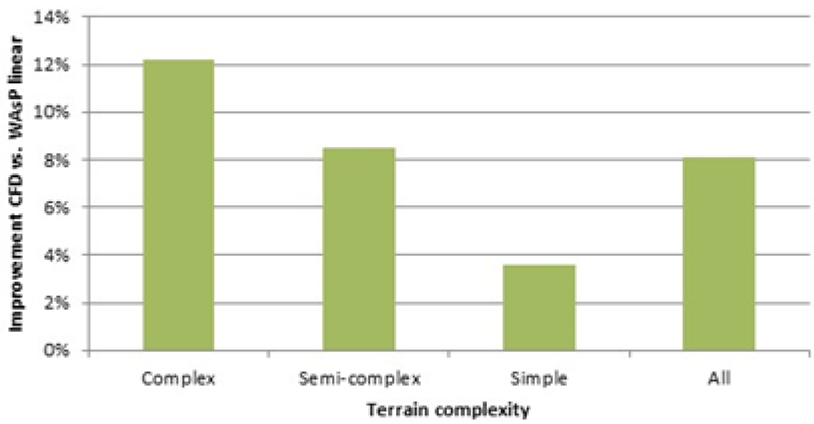

Figure 4 – AEP percentage improvement CFD vs WAsP linear

One of the biggest difficulties when analyzing a wind farm is to determine the validity of wind variables across the wind farm. In some cases, the distance between turbine position and met mast is too big to consider these results as accurate enough to determine the loads in the wind turbine. In other cases, CFD allows the analysis of what is happening in the vicinity of the met mast where measurements are not available. This is especially important to know the flow structure in the upper part of the rotor where usually there are not measurements.

Figure 5 shows the results obtained in the analysis of stratification in a wind turbine location. The left side of the figure provides the stability rose (expressed as vertical gradient of potential temperature) while the diurnal surface temperature cycle for a typical day is presented in the right.

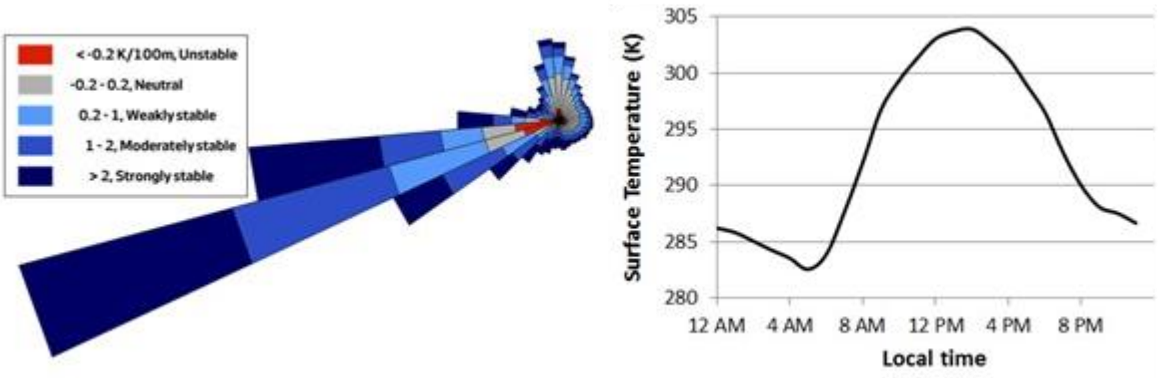

Figure 5 – Mesoscale simulation results

More information can be found in [17].

CONCLUSIONS

The constantly increasing capacity of the computers has permitted the Wind Industry to make huge advance in the flow modelling, either to design new turbines models or to assess the wind conditions in complexes sites.

The big question is to define the complexity level of the study and the necessity of precise results. As aforementioned, the use of an excessive level of complexity when solving simple problems wastes time and resources, and on the contrary, the use of methodologies that do not reproduce the physics of the problem could lead to the necessity of increasing the safety factor in the designs.

Finally, having a benchmark for the different models capacities could help to enhance the choice of the proper method for the right situation. Moreover, if the associated uncertainties can be well defined, the necessity of using complex studies can be reduced, in exchange of performing a risk assessment.

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BIOGRAPHIES

Rafael De Vecchi – was born in Ourinhos, São Paulo-Brazil on May 9th 1984. He has graduated in Electrical Engineering in 2008 from the Technological Federal University of Paraná in Curitiba, Brazil and holds a M.Sc. Degree in Renewable Energy from the University of Oldenburg, Germany, 2011.

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He has been heavily involved in the Wind Industry and participated in several international Renewable Energy Conferences. From 2003 until 2008 he worked in Gamesa and since 2008 he is working in Vestas.

Renato Loureiro Goncalves – was born in Rio de Janeiro, Brazil. He has a Brachelor´s degree in Mechanical Engeneering from the Universidade Federal do Rio de Janeiro.

He has been heavily involved in the Wind Industry and has worked directly in the development of several wind farms in Brazil and around the world. He has worked for developments and consultancy companies, and since 2016 is working at Vestas, and is responsible for Wind and Site studies.