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TNO report

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Wind Turbine Aero-elasticity Uncertainty Quantification, WindTrue

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Summary

This report describes the results from the WindTrue project.

The project is carried out by TNO, CWI, DNV-GL and Suzlon within the framework of TKI Wind op Zee and with subsidy from the Ministry of Economic Affairs and Climate, through RVO.

The main objective of this project is to develop calibrated aerodynamic models *with a quantified level of uncertainty* for optimal design of the next generation of offshore wind turbines. This objective has been met.

Thereto calculations from wind turbine design codes available in the WindTrue consortium have been compared with detailed aerodynamic measurements from the Danish DanAero experiment and with calculational results from other institutes which simulated this experiment in the international project IEA Wind Task 29. These comparisons gave insights into the performance of aerodynamic models in wind turbine design codes.

Moreover, a computationally efficient methodology has been developed with which the most uncertain factors in aerodynamic models (input parameters and model parameters) can be determined including their effect on the model response. The methodology also enabled the calibration of aerodynamic model parameters *with a quantified level of uncertainty* based on detailed aerodynamic measurements.
The main results of WindTrue are a publicly available framework for uncertainty quantification and calibration (which can be linked to wind turbine design codes), insights on the most uncertain parameters in wind turbine aerodynamic modelling and (re-) calibrated aerodynamic model parameters using detailed aerodynamic measurements.

Contents

1 Introduction

Wind turbine design codes are essential for industry to assess the lifetime and the energy production before the investment is made to build a turbine prototype. This obviously requires that the results from those design codes are reliable, i.e. the should have a low or at least a quantified level of uncertainty.
In terms of uncertainty, the aerodynamic modelling part of design codes is extremely challenging because the physics of every aerodynamic process, in its basis, is described by means of the so-called Navier Stokes equations which cannot be solved in an analytical way. A numerical solution of the Navier Stokes equations is also out of reach due to extreme calculational demands. The difficulty of accurate aerodynamic modelling is perhaps most convincingly illustrated by the fact that solving the Navier Stokes equations (as a matter of fact 'only' proving that a smooth solution exists) is one of the seven Millennium Prize Problems as formulated by the Clay Mathematics institute in 2000.

As such every aerodynamic model inherently suffers from simplifications. This is true for general aerodynamic modelling problems but it is even more true for wind turbine aerodynamics where an additional difficulty arises from the fact that the computational effort for design calculations is more extreme than it is for most other applications (e.g. fixed wing aerospace, see [7]). This necessitates the use of very efficient, but also very simplified aerodynamic models, based on the Blade Element Momentum (BEM) method to which engineering models are added to overcome the most crude assumptions in BEM (e.g. the neglect of unsteady and 3D effects and the neglect of yaw).
These engineering models represent the relevant physical phenomena in a simplified way such that the calculational effort remains acceptable. They include several constants or tuning parameters which are often determined from a limited number of measurements.

The representation of the aerodynamic and aeroelastic behaviour in this simplified way, involving many calibration constants, introduces a first source of uncertainty, namely *model uncertainty.*

Apart from this model uncertainty, the input of wind turbine design codes is subject to uncertainties as well. The input is amongst others formed by a description of the wind (which are uncertain due to their stochastic nature) and by a description of the turbine (e.g. aerodynamic and aeroelastic data such as airfoil data and mass/stiffness data). These data are not exactly known however, leading to a significant source of *input uncertainties.*

With this in mind, TNO, CWI, DNV-GL and Suzlon jointly executed the WindTrue project within the framework of TKI Wind op Zee and with subsidy from the Ministry of Economic Affairs and Climate, through RVO. In WindTrue a methodology has been developed with which the most uncertain factors in aerodynamic models (input parameters and model parameters) can be determined including their effect on the model response. The methodology also enabled the calibration of aerodynamic models *with a quantified level of uncertainty* from measurements.
These activities are supported with unique measurements which originate from the DanAero project [8]. This DanAero experiment was carried out at atmospheric field conditions on a 2MW turbine in a Danish project by Danish Technical University DTU and 4 industrial partners (LM Glassfiber, Siemens WindPower, Vestas and Dong Energy) in 2 periods from 2007 until 2010 and from 2010 until 2013. The level of detail from the instrumentation lies far above the level of conventional wind turbine measurements. Amongst others surface pressures and inflow velocities were measured at four sections

along a blade. The pressure distributions are integrated to yield forces in normal and tangential direction with respect to the chord, giving load information on sectional level. The data from the DanAero experiment, including a description of the turbine, were made available to the participants of IEA Wind Task 29 Rotor Aerodynamics [4]. IEA Wind Task 29 is an international cooperation project, coordinated by TNO, carried out under auspices of the International Energy Agency IEA in which more than 20 parties from 8 countries cooperate in analyzing the DanAero measurements. Amongst others, several calculational cases are simulated on the DanAero experiment which are then compared with measurements and with calculations from other Task 29 participants. All WindTrue participants were a member of IEA Task 29 by which they got access to the DanAero measurements and could contribute to the IEA Task 29 calculational rounds.

The WindTrue project ran from the 1st of January 2019 until 31st of December 2020. This report describes the goals of the project (and resulting Work Packages) in chapter 2, the main activities and results from the project in chapter 3, the conclusions in chapter 4 and the deliverables in chapter 5.

1.1 Goal and Work Packages

The main objective of this project is to develop calibrated aerodynamic models *with a quantified level of uncertainty* for optimal design of the next generation of offshore wind turbines.

Two sub-objectives are formulated to reach this goal:

1. Obtain the main uncertain factors and model parameters in existing aerodynamic models (input parameters, model parameters, etc.) and investigate their effect on the model response (such as fatigue loads). *Work Package 1*

2. Calibrate the uncertain model parameters identified in WP1 by using measurement data. *Work Package 2*

The uncertainty quantification techniques developed in WindTrue make probabilistic risk assessments for financing future offshore wind farms more precise, and consequently lowers the cost of energy.

2 Methods, Results and discussion

2.1 Work Package 1: Quantification of uncertainty related to aerodynamic models

As part of WP1 the WindTrue participants joined the calculational rounds from IEA Task 29 which were defined around the DanAero experiment. The results are compared with measurements and with calculational results obtained from a large variety of models by other IEA Task 29 participants. TNO, DNV-GL and Suzlon supplied results from engineering methods where TNO also supplied results from a more physical free vortex wake method.

A first calculational case was defined for steady axi-symmetric conditions without shear and yaw which could be compared with a measurement case taken with very little shear, turbulence and yaw. The mutual agreement between calculations was generally good but the differences with measurements were larger than expected even for this relatively simple case. This was in particular true for the comparison on mean loads. The prediction of load variations which have been assessed by comparing standard deviation of measured and calculated load agreed slightly better.

Within WindTrue a study was carried out by DNV-GL and TNO which aimed to gain more understanding on these differences see [2]. Thereto results from calculations and measurements are compared in terms of skill-scores which confirmed the large differences in mean loads. Then several dynamic stall models were attempted but none of them improved the agreement in mean loads significantly. At the time of writing the paper, the cause for the differences between calculated and measured mean loads could only be speculated but at a later stage DTU (which had performed the measurements) found that the measured mean loads suffered from a slight off-set. In retrospective this explains the large differences between calculated and measured mean loads.
In contrast to the measurements of mean loads, the measurement of load variations was reliable. Still the differences between calculated and measured standard deviations were relatively large too. The only dynamic stall model which changed the standard deviation in loads and improved the agreement with measurements was found to be the Beddoes Leishman model [9] but the improvement was minor.
This can be explained by the low angle of attack from the IEA Task 29 comparison cases. This low angle of attack makes dynamic stall effects very limited but some unsteady inviscid aerodynamic effects might be expected. The model from Beddoes Leishman is the only one which includes the inviscid unsteady aerodynamic effects.

Two more calculational cases were defined around DanAero measurements at high shear and /or high yaw. The results from engineering models differed significantly from the measured results. This was explained by poor induction modelling and/or poor airfoil modelling. Results from higher fidelity models (including the free vortex wake method from TNO) generally showed a better agreement to measurements.

A detailed description and analysis of Task 29 is presented in the public Task 29 report [4]. The study on dynamic stall effects is described in [2].

Apart from the activities on the IEA Task 29 simulation cases an important deliverable from WindTrue WP1 is a tool (denoted as the framework UQ4WIND) developed by CWI with which a global sensitivity analysis can be performed on aerodynamic model parameters.

The framework is presented in [1]. It is based on the uncertainty quantification toolbox UQLab [6] and a main result was to connect UQLab to TNO's Aero-Module [10]. The Aero-Module is an aerodynamic modelling tool with an easy switch between a BEM based model and a more physical free vortex wake model. The measure for the global sensitivities is formed by so-called Sobol indices.

The strength of the UQ4Wind framework lies in the use of a Polynomial Chaos Expansion (PCE) based approach. Such an approach is computationally much more efficient than alternative approaches based on Monte-Carlo simulations which are commonly used in similar tools.

UQ4Wind has been applied to several cases. In [1] a case study is presented to investigate the sensitivity of input parameters of the DanAero wind turbine model on the loads output. It investigates the sensitivities to chord, twist, lift coefficient, and drag coefficient as functions of the radial distance along the blade. This then leads to a very high-dimensional number of uncertain parameters which is the reason why the geometrical parametrization makes use of Non-Uniform Rational Basis Splines (NURBS). In this way a limited number of control points can approximate a large variety of curves, so that the resulting number of uncertain parameters is relatively small.

The results from the case study highlight amongst others the importance of the lift coefficient, especially for the axial force prediction.

UQ4Wind has also been used by TNO to carry out a sensitivity study on parameters from the Beddoes Leishman dynamic stall model. The sensitivity study was again applied on the DanAero turbine.
The Beddoes-Leishman model parameters which were chosen for the sensitivity analysis are: time constant connected to the leading-edge pressure gradient, T_p, time constant connected to leading-edge separation of the airfoil, T_f, time constant connected to vortex shedding, T_v, and time constant connected to the vortex advection process, T_{vl}. These constants are typically calibrated by means of wind tunnel tests, and they depend on the specific airfoil under consideration.
The Sobol indices are evaluated by means of Monte Carlo and two types of PCE methods where the latter methods, as explained above, are much more efficient. It is then found that the Tv constant mostly contributes to the overall uncertainty, followed by the T_f constant. More information on this sensitivity study can be found in [2].

The framework was also used to assess the sensitivity of 3D model parameters on the model output for the DanAero turbine. Thereto two 3D models have been assessed, the one from Snel [14] and the one from Chaviaropolous [13]. Also the sensitivity of critical induction factor in the turbulent wake model from Wilson [15] is assessed. The sensitivity studies on 3D modelling and turbulent wake model are reported in [5].

2.2 Work Package 2: Calibration of aeroelastic models using measurement data and surrogate models

WP1 considered a forward modelling approach, i.e. input is fed into a model and from that an output is created which can be compared with measurements.
In WP2 the order is reversed, i.e. a **backward** uncertainty quantification problem is considered, in which the measurement data are employed to **calibrate** the parameters of aerodynamic submodels.
Thereto a so-called Bayesian model calibration is performed for the most sensitive parameters. In Bayesian model calibration, a priori knowledge about the distribution of the selected parameters (e.g. physical bounds, previous calibrations) is used together with (measured) data to calibrate these parameters. However, Bayesian model calibration based on full non-linear aeroelastic models like AeroModule is computationally very time consuming, requiring thousands of model evaluations. For this reason, the AeroModule was replaced by the PCE surrogate model mentioned in section 2.1. The surrogate model is an accurate approximation to the AeroModule which is constructed (trained) by employing a limited number of smartly chosen conditions (‘nodes’), at which the aeroelastic simulations are performed.

The first calibration was carried out on the DanAero case at non-yawed conditions which was discussed in section 2. The lift coefficient (c_l) values were calibrated at the 4 instrumented sections. The c_l values which came out of the calibration differed about 20% from the prescribed c_l values in order to match the experimental data, but in retrospect this may be caused by measurement errors on mean load levels discovered by DTU at the end of IEA Task 29. Although this made the calibration of the c_l values less reliable it anyhow showed the power of a calibration with the developed framework.

Another calibration was carried out on most sensitive parameters from the yaw model of [7]. The yaw model has been developed in 1998 and at that time it could be calibrated with a limited amount of wind tunnel measurements only. In WindTrue it was originally intended to recalibrate this yaw model with DanAero measurements but the amount of data points turned out to be too limited.
A possible solution was then expected from measurements of the so-called EWTW (ECN Wind Turbine Test Site Wieringermeer) database. This database contains measurements which are collected over a period of more than 7 years [12]. However, the measurements in this database consist only of integrated blade and turbine loads. These data hide the radial load distribution which made it difficult to calibrate the radial dependency of the yaw model parameters where this radial dependency is an essential characteristic of these models. The strong radial dependency of yawing phenomena was qualitatively very clearly seen in the DanAero measurements, see [4].

The importance of this radial dependency made the EWTW measurements, even though they are taken over a long period not suitable for a calibration of yaw model parameters.

Eventually the calibration was therefore carried out with data from the New Mexico wind tunnel experiment [11]. In this experiment pressure distributions and resulting local aerodynamic forces were measured on a turbine with a diameter of 4.5 meter placed in the large German Dutch Wind Tunnel DNW. Pressure distributions were measured at 5 locations along the blade which enabled a calibration of the parameters of the yaw model. The amount of yawed measurements in this database was sufficient for a statistical reliable calibration but an obvious drawback is that these measurements are taken in a wind tunnel environment which differs from the full scale field environment. The results of the calibration are reported in [3]. The fact that the model from [7] is extremely non-linear made the development of a surrogate model far from straightforward but eventually good results could be obtained.

In [5] a calibration of 3D model parameters and the critical induction factor in the turbulent wake model from Wilson is reported.

3 Conclusions, recommendations and follow-up

3.1 Results and Conclusions

A comparison has been made between calculations from wind turbine design codes in the WindTrue and detailed aerodynamic measurements from the Danish DanAero experiment. The results were brought into IEA Task29 which enabled a comparison with calculational results from other IEA Task 29 participants as well. Generally speaking the mutual agreement between calculational results is good but the comparison between calculations and measurements showed differences. It was found that part of these differences were measurement related: although the measurement of load variations turned out to be reliable, the measurements of mean loads suffered from a slight off-set. This shows the difficulty of doing detailed aerodynamic measurements in the field.
Differences between calculations and measurements were also caused by fundamental modelling deficiencies and they mainly appeared at challenging conditions with large shear and yaw. Higher fidelity codes (e.g. Free vortex wake methods or CFD methods) generally showed a better agreement with measurements than lower fidelity BEM models.

A framework, known as UQ4Wind, for uncertainty quantification in wind turbine design has been developed by CWI. It was very encouraging to find that that this framework could be interfaced very easily to the TNO design tool AeroModule. Since the framework is generic and publicly available it may be expected that the framework can be interfaced easily to other wind turbine design code as well.
With the framework several sensitivity studies were carried out on the DanAero wind turbine. The sensitivity of both input parameters (e.g. geometrical parameters and airfoil polars) and model parameters (e.g. parameters in dynamic stall, yaw and 3D models) has been investigated.
These studies gave insights into the most important parameters for wind turbine design modelling which then need to have the highest priority in improvement.

The framework was also used successfully to calibrate input and model parameters. The calibration of c_l polars and 3D correction model polars however was complicated by a slight off-set in DanAero measurements. A further complication from the DanAero experiment lied in the fact that many datapoints are needed for a statistically valid calibration. Therefore an alternative for the DanAero measurements, i.e. data from the wind tunnel experiment New Mexico were used for calibration of yaw model parameters and 3D model parameters. With these measurements the calibrations could be performed successfully but an obvious drawback of wind tunnel measurements lies in the small scale which limits the validity.

3.2 Recommendations

The framework UQ4Wind which is developed in WindTrue enables sensitivity studies and calibration of virtually all BEM model parameters with which uncertainties in wind turbine design and so cost of energy can be reduced.

The limiting factor in doing so is then formed by lack of good and sufficient measurement data. Measurements are needed on representative MW scale in the field but conventional measurements of e.g. blade root bending moments lack detail. As such aerodynamic measurements of sectional loads are required. Many data points are needed for a statistical valid calibration. This then leads to the main recommendation from WindTrue which is that many good data of local aerodynamic loads should be measured in the field.

It is also found that detailed aerodynamic measurement on MW scale wind turbines are far from routine and difficult to do. It is then extremely useful to share practical experiences between the few parties which carry out aerodynamic experiments. In this way problems can be prevented and successes can be copied so that the learning curve for future experiments is steepened.

3.3 Follow-up

The recommendations from WindTrue, i.e. the need for much more reliable detailed aerodynamic measurements on full scale wind turbines are aligned with the recommendations from IEA Task 29 and they formed input for a new IEA Task "Innovative aerodynamic experiments and simulations on wind turbines in turbulent inflow".
This IEA Task (with number 47) has recently been approved and it will run from January 1st 2021 until December 31st 2024. In Task 47 several parties cooperate which recently initiated aerodynamic field experiments on wind turbines. The practical experiences on these experiments are shared which then helps all partners in improving the quality of their measurements.

In the Netherlands aerodynamic measurements on a 3.8 MW turbine will be carried out in the project TIADE (Turbine Improvements for Additional Energy) funded by RvO. This project already makes use from experiences gained in WindTrue since the test matrix of the TIADE experiment includes the insight on the necessary amount of data points for a successful calibration.

After the measurements from TIADE (and public measurements from Task 47) have been generated the final step will be the actual improvement of aerodynamic models. WindTrue has now provided the framework to do this in an automatic way.

4 Deliverables and references

Much of the text from the present report is almost literally copied from the deliverables in report form:
References 1 to 2 describe the results from WP1 in detail where reference 3 describes the results from WP2 in detail. These deliverables culminated in journal papers which are publicly available. WindTrue also contributed with chapter 6 to [4] on yaw (and associated dynamic stall) modelling. This report will be public and available at IEA Wind TCP.

Other deliverables are the BEM models of the DanAero turbine with which the Task 29 calculations have been performed. These models are implemented in the design tools of the WindTrue participants. Results from them are shown in [4].
Also the uncertainty quantification framework UQ4Wind from CWI with the surrogate model of the DanAero turbine is a deliverable. This framework is made publicly available on GitHub.

Another public deliverable is the student report [5] which describes several applications with UQ4WIND.

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