Report 2023

Task 47

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TURBulent INflow Innovative Aerodynamics (TURBINIA)

Author *Gerard Schepers, TNO.*

Task 47 began in 2021, aiming to collaborate on high-quality, detailed aerodynamic measurements for MW-scale turbines in atmospheric flow, for a period of four years.

These measurements are extremely difficult, with the Danish DanAero experiment being the only public example, which was also used in the final phase of its predecessor, Task 29: Analysis of Wind Tunnel Measurements and Improvements of Aerodynamic Models (Mexnext III).

Recently, several other countries initiated new experiments for turbines up to a scale of 8 MW, and they are now undergoing a similar learning process with these new measurement techniques. Sharing experiences is a very fruitful way to accelerate the learning curve, therefore, the Task aims to aid this cause.

Moreover, a sound scientific approach requires a cross-fertilisation between measurements and theory, where experiments feed into theoretical insights and vice versa. Therefore, aerodynamic measurements are analysed and simulated by a large group of research institutes as well as industry professionals using a variety of codes, ranging from low-fidelity blade element momentum (BEM) to high-fidelity computational fluid dynamics (CFD).

Simultaneously, simulations are conducted on a 15 MW Reference Wind Turbine designed in Task 37: Wind Energy Systems Engineering.

In 2023, several aerodynamic measurement programmes were completed and collected data, in which, some of them used new measurement techniques. The lessons learned have been documented to ensure that future aerodynamic experimentalists can benefit from these experiences. In terms of modelling, it was found that fatigue loads for sheared conditions are considerably overpredicted by BEM based models which are largely used by industry.

Introduction

To enhance aerodynamic knowledge, the most effective strategy is to conduct experiments specifically focused on measuring the aerodynamic properties of blades. It is important to note that conventional wind turbine measurements, such as power output and blade root bending moments, lack sufficient detail. This creates a demand for highly specialised rotor aerodynamic experiments, often referred to as 'detailed aerodynamic experiments.' In these experiments, pressure distributions at various locations along the rotor blades are measured. Additionally, measurements of local blade inflow and boundary layer properties are extremely valuable.

Such measurements are particularly needed for multi-MW scale turbines due to the increasing aerodynamic modelling challenges as the size of wind turbines continues to grow. At the same time, these measurements are highly specialised and difficult to perform, with the only public example on a MW scale to date, being the Danish DanAero experiment, used in the final phase of Task 29: Analysis of Wind Tunnel Measurements and Improvements of Aerodynamic Models (Mexnext III).

Recently, several other countries have initiated new experiments for turbines up to a scale of 8 MW, and they must undergo a similar learning process for conducting these aerodynamic measurements. For this reason, a new Task has been defined: TURBINIA - TURBulent INflow Innovative Aerodynamics. The first aim of TURBINIA is to share experiences on these measurement techniques to accelerate the learning curves.

Moreover, important knowledge is gained by cross-comparing results from a wide variety of aerodynamic models, ranging from low fidelity BEM to high fidelity CFD, with Free Vortex Wake and panel models in between. In parallel, simulations are being carried out on a 15-MW Reference Wind Turbine as designed in Task 37. From these simulations, aerodynamic knowledge gaps for the design of 15-MW scale turbines are identified. The synergy between experiments and theory will enhance the level of aerodynamic knowledge, ultimately leading to better aerodynamic design models and more competitive designs for 15-MW wind turbines.

Table 1. Countries Participating in Task in 2023.

COUNTRY/SPONSOR	INSTITUTION(S)
Denmark	Technical University of Denmark (DTU); Siemens Gamesa Renewable Energy
France	ECN; ONERA; IFP Energies Nouvelles
Germany	ForWind/Fraunhofer IWES; University of Stuttgart (IAG); Kiel University of Applied Sciences; WINDnovation; German Aerospace Center DLR; Enercon; UAS Emden/Leer
Italy	CNR-INM; PoliMi; University of Rome La Sapienza; University of Rome Roma Tre; University of Florence; Politecnico di Bari
The Netherlands	Netherlands Organisation for Applied Scientific Research (TNO); CWI; Delft University of Technology; Suzlon Blade Technology (SBT); Det Norske Veritas (DNV); LM; University of Twente
Sweden	Uppsala University Campus Gotland
Switzerland	Eastern Switzerland University of Applied Sciences (OST)
The United States	National Renewable Energy Laboratory (NREL)

Progress and Achievements

Several aerodynamic measurement programmes have successfully gathered valuable data. While measurement data and underlying models for small turbines can be shared openly, data for large-scale commercial wind turbines (the associated turbine model in particular), still requires permission. Experience from the DanAero turbine model experiments shows that obtaining permission can take 5-10 years. However, efforts will continue to accelerate this process to ensure the entire research community benefits from these new measurements.

An important highlight is found in the application of new aerodynamic measurement techniques, such as the use of wake rakes on wind turbines. While traditional detailed aerodynamic experiments measure pressure distributions (providing information on normal force lift and pressure drag), they do not capture viscous drag, a crucial element for wind turbine performance.

Wind tunnel pressure measurements are often combined with wake rake measurements to gain insights into drag. However, wake rake measurements have not been an accessible method for use on full-scale wind turbines until experiments were carried out within the VIAs project (a collaboration between DTU, Siemens Gamesa Renewable Energy, and Rehau). During this measurement campaign, an inflow measurement device (the so-called flyboard for angle of attack and relative sectional speed) and the wake rake (for total drag measurement) were mounted on a Siemens Gamesa 4.3 MW wind turbine with a rotor diameter of 120m, which had previously been equipped with trailing edge active flaps. A dedicated experimental campaign for the proof of concept of the wake rake was conducted over two consecutive days, during which all operational data of the turbine, the active flap, as well as the measurement data of the flyboard and the wake rake were collected simultaneously. Figure 1 illustrates the experimental set-up with the measured pressure distribution and wake deficit. The pronounced and smooth deficit is a promising result.

Several calculation cases were defined on the DanAero turbine under sheared conditions. The shear was prescribed and a variety of codes simulated this case. A consistent overprediction of fatigue loads was found from the engineering methods based on the Blade Element Momentum (BEM) theory, with a strong sensitivity to the precise implementation of modelling induced velocities. An example is presented below under Highlights. The deficiencies are a result of the fact that shear (and other flow non-uniformities over the rotor plane) inherently violate the assumptions in BEM.

The finding has significant implications as BEM-based models are the industry standard for wind turbine design. The observed discrepancies are expected to become even more pronounced with the ever-increasing rotor size (the DanAero turbine has a diameter of only 80m).

The high sensitivity of calculated loads to specific BEM implementations suggests that there is not a single universally applicable BEM model, although the literature often refers to it as one model. To gain further insight into the most optimal implementation, many comparisons were made between BEM and Free Vortex Wake methods on very specific levels. The results are not conclusive yet; however, efforts will continue with the aim to ultimately formulate recommendations on the best implementation of these models. A joint article from the TURBINIA consortium about the challenging ability to model shear is accepted for oral presentation at the EWEA Science of Making Torque conference [1].

The performance of computational models for even larger turbines was assessed by carrying out calculations on the 15 MW Reference Wind Turbine. A common input for this turbine has been provided with help from Task 37. With this input, many participants supplied results from a large variety of aerodynamic models, first at uniform steady inflow and later at turbulent inflow. Synchronising the model input to make consistent comparisons turned out to be challenging, partly because of differences related to turbine modelling (in particular the aero-elastic modelling), but also because of differences in turbulent wind input between engineering models (prescribed in the rotor plane) and CFD input (which is injected upstream and convected towards the rotor plane). Still, much progress has been made and several insights gained, one of them being a confirmation of the overpredicted fatigue loads from BEM. Moreover, large values of torsion angles at the tip have been calculated (in the order of 2 degrees) even at relatively low wind speeds of 7.5 m/s. Such a large torsion angle obviously has a significant impact on the performance, control, and loads, making the accurate modelling of these angles very important.

Highlight(s)

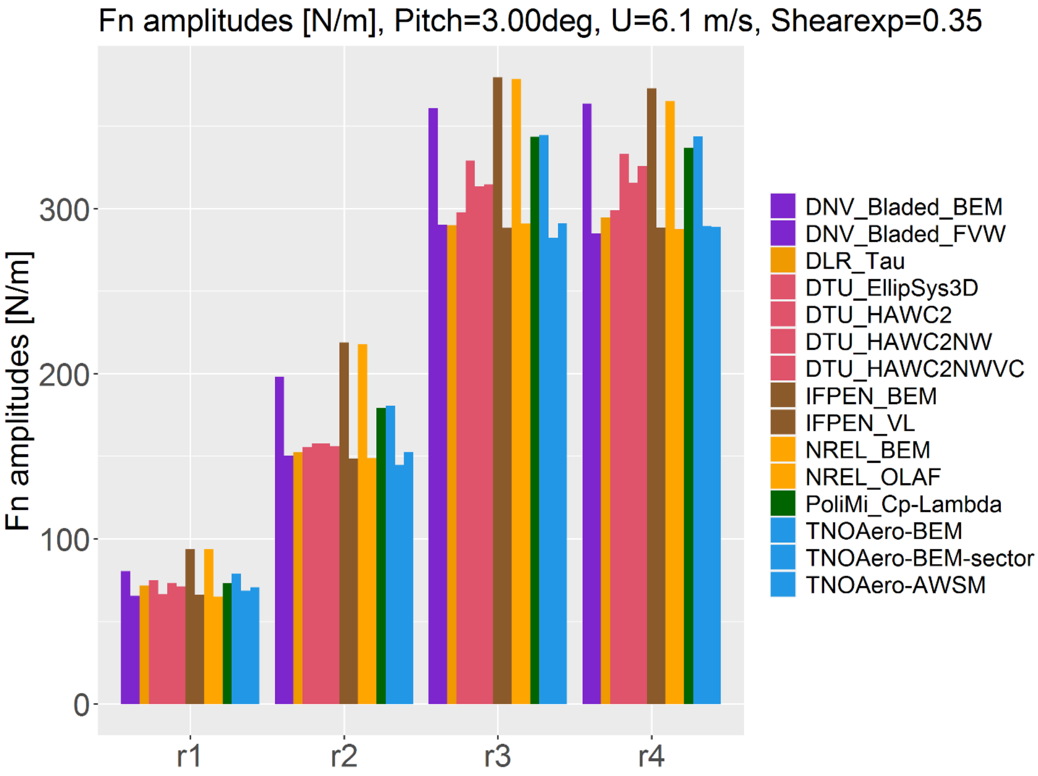

Figure 1: This figure shows the amplitude of the sectional normal force at 4 radial stations for the DanAero turbine. The results are calculated by various participants with BEM based models and higher fidelity models. In all cases the load amplitude from BEM based models is much higher than the amplitude from the corresponding higher fidelity models. This implies a strong overprediction of fatigue loads from the industrial BEM models. Moreover, a strong sensitivity is found in the way the induced velocities are modelled in the BEM models.

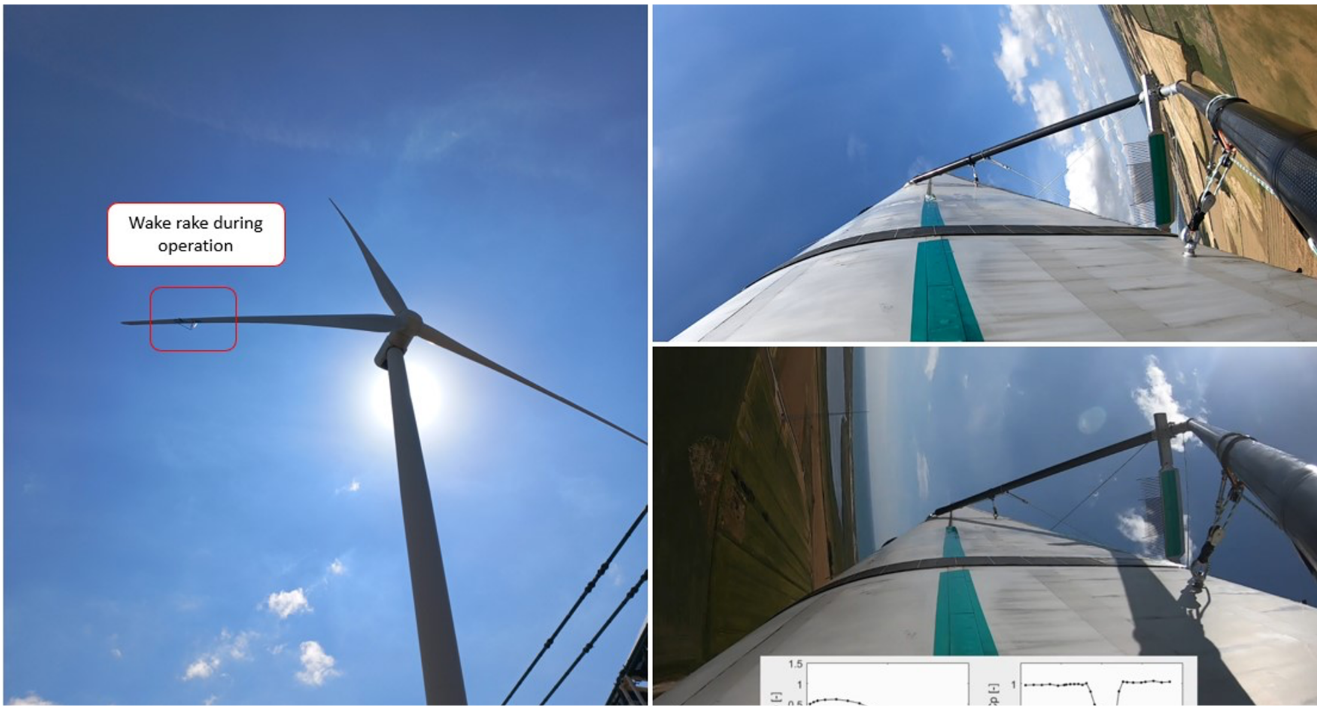

Figure 2: This figure shows the wake rake and the resulting wake deficit on the ViA experiment (see above). This is the first experiment on a wind turbine where such wake rake is applied.

Outcomes and Significance

The most important outcomes include (some of which are still under preparation):

- Innovative aerodynamic measurement technologies applied to large-scale wind turbines.
- Documentation of best practices on how to conduct detailed aerodynamic measurements.
- Documented databases of detailed aerodynamic measurements on various wind turbines.
- Improved and validated aerodynamic (and related aero-elastic) models to design large-scale wind turbines (up to 15 MW).
- Dissemination of the generated wind turbine aerodynamic knowledge through publications, presentations and other activities where the Wind Energy Human Capital Agenda is supported by employing many students and PhD's in TURBINIA. These students will find positions in the wind industry after graduation. In this way, they spread the TURBINIA knowledge in industry.

Next Steps

Next steps will be to perform more detailed aerodynamic measurements and/or analysis of measurements. Lessons learned will be documented so that future experiments will benefit from it. Moreover, Task will attempt to formulate recommendations for the best BEM implementation of induced velocities at shear. In parallel, calculations on the 15 MW Reference Wind Turbine at turbulent conditions will provide insights into the modelling capabilities of very large turbines. The current phase will end in December 2024. In the coming period brainstorms will be held to generate ideas on the continuation of the project.

References

[1] Boorsma K., Schepers J. G., Pirrung G. R., Madsen H. A., Sorensen N. N., Grinderslev C., Bangga G., Imiela M., Croce A., Cacciola S., Blondel F., Branlard E. and Jonkman J. (2024) *Challenges in Rotor Aerodynamic Modeling for Non-Uniform Inflow Conditions.* Accepted for Science of Making Torque, May 2024.

Task Contact

Gerard Schepers,
TNO,
The Netherlands.
Koen Boorsma,
TNO,
The Netherlands.
Helge Madsen,
Danish Techinical University (DTU),
Denmark.

Email:
gerard.schepers@tno.nl
koen.boorsma@tno.nl
hama@dtu.dk

Website:
https://iea-wind.org/task47/