Final report

1. Project details

Project title	Participation in IEA Task 29: Full Scale Wind Turbine Aero -dynamics, -elasticity and -acoustics
File no.	J.nr. 64018-0084
Name of the funding scheme	EUDP
Project managing company / institution	Technical University of Denmark, Department of Wind Energy
CVR number (central business register)	30060946
Project partners	DTU Wind Energy
Submission date	05 April 2022

2. Summary

The objectives of the project

The objective of the Danish participation is to contribute to an efficient validation of wind turbine simulation models in an international framework by sharing the DanAero data base within IEA Task 29 IV. The DanAero data base contains unique, detailed aerodynamic measurement data from the DanAero project conducted in 2009 in Denmark.. A further specific objective is to validate and further develop the DTU codes HAWC2 and EllipSys3D, each of them in different versions.

Results and conclusions

Besides developing the share point site for sharing the data DTU has contributed to define the test cases that have been used in the different benchmark cases. On basis of the benchmarking and validation DTU has developed further the methods to carry out CFD rotor simulations with turbulent inflow with wind gradient. The benchmarking has also shown that the so-called engineering aerodynamic models still give less accurate results compared with CFD simulations. However, the accuracy of the results can be increased considerably by using airfoil data derived from CFD computations. DTU has further participated in validation of models for wake flow from an upstream turbine. The validation has given basis for possible adjustment of parameters in the engineering DWM model.

Dissemination of results and knowledge

Results have been presented at the conference Torque 2020 and through 5 journal papers. In addition a workshop was held on March 4 2021 with 10 presentations. There were close to 50 attendances and almost half of them were from industry, developers and operators. The presentations can be found on the projects home page (see the link below, contact hama@dtu.dk for permission). Additional dissemination of results is continuously ongoing by the close cooperation DTU has with industry and other partners. Finally, DTU has made a considerable contribution to the final report.

Project home page: Sharepoint site

Formålet med dansk deltagelse i Task'en/Annex'et

Formålet med dansk deltagelse er at bidrage til en effektiv valideringen af simuleringsmodeller i et internationalt forum ved at dele DanAero databasen, der indeholder værdifulde eksperimentelle data fra DanAero projektet i 2009 (Vestas, Siemens, LM, Dong Energy og DTU med støtte fra EFP). Et specifikt formål er at videreudvikle og validere to DTU udviklede beregningsmodeller HAWC2 og CFD koden EllipSys3D, begge i forskellige versioner.

Resultater og konklusioner

Ud over oprettelse af databasen har DTU bidraget til at definere test cases, som blev brugt af internationale partnere for beregninger med 20 forskellige modeller. Metoderne til at gennemføre CFD rotorberegninger med turbulent inflow med vindgradient er videreudviklet. Arbejdet har også tydeliggjort at ingeniørmodellerne for aerodynamik stadig giver mindre nøjagtige resultater end CFD beregninger. Resultaterne kan dog forbedres ved at benytte profildata udledt fra CFD rotorberegninger. Der er lavet detaljerede benchmarks på situationer, hvor den instrumenterede mølle står i kølvandet fra en opstrømsmølle. DTU har benyttet en detaljeret CFD baseret model såvel som wake modellen i HAWC2 (Dynamic Wake Meandering model), som er en hurtig ingeniørmodel. Sammenligninger har givet basis for justering af parametre i DWM modellen.

Formidling af resultater og viden – hvor, til hvem og hvordan

Resultaterne er formidlet ved deltagelse i konferencen Torque 2020 samt gennem 5 tidsskriftartikler. Endvidere er der afholdt en workshop d. 4. marts 2021 med 10 præsentationer og lige omkring 50 deltagere, hvor ca. halvdelen kom fra industrien. Præsentationerne kan findes på projektets hjemmeside (se linket nedenfor, kontakt hama@dtu.dk for adgang). DTU har et tæt samarbejde med industrien, hvorigennem forbedring af modeller og ny grundlæggende viden om simuleringer formidles effektivt. Endelig har DTU bidraget væsentligt til slutrapporten.

Projekt hjemmeside: Sharepoint site

3. Project objectives

The overall objective of IEA task 29 is to facilitate an international collaboration on validation and further development of wind turbine simulation models within aero-dynamics, -elasticity and -acoustics by comparison with experimental results from the DANAERO data base. This data base comprises detailed measurements on the NM80 2MW turbine in 2009 within the DANAERO project, carried out by Vestas, Siemens, LM, Don Energy and DTU and funded through EFP by the Danish Ministry of Energy.

Wind turbine technology is the focus and in particular, verification and validation of the simulation codes used for the design and certification of wind turbines. In the context here it is carried out in an international collaboration between research groups from 9 countries. Most of these simulation codes validated in the present IEA task 29 IV are developed by the participating research institutes. This is e.g. true for the code FAST developed by NREL which is freely available. On the other hand the code HAWC2 developed by DTU Wind Energy is only available on a license basis but still used by several industrial companies.

4. Project implementation

The IEA Task 29, Phase IV proposal was accepted by the IEA executive board on the 15th of November 2017 and planned for a 3 years period with start on the 1st of January 2018. However, the first meeting was fist scheduled to be held in late June 2018 in combination with the conference TORQUE 2018 in Milan from June 20-22 because several participants had to seek funding for their participation. This was also the case for DTU, which send in an application to EUDP in March 2018 on participation and got acceptance

The kick off meeting was held on June 19, 2018. It was kindly hosted by PoliMi in Milan, Italy, and was attended by 26 participants. Different management issues were presented by the coordinator TNO and DTU presented an overview of the experimental data in the DanAero data base. Also the plan for the first benchmark cases was discussed.

The second meeting of IEA Wind Task 29 Phase IV was held on March 14th, 2019 and hosted by NREL at the University of Colorado in Boulder USA. At this meeting the results from the first benchmark round Case IV.1 were discussed and evaluated. Also the work in two sub task with introduced: Task 3.3 Wake inflow and Task 3.6 Transition.

The third (intermediate) meeting of IEA Wind Task 29 Phase IV was held on June 21st, 2019. It was hosted by UCC in Cork Ireland after the Wind Energy Science Conference. A definition of a second calculation round, case IV.2 was detailed by ECN.TNO and DTU. Case IV.2 is subdivided in 2 subcases which are defined in agreement with (time averaged conditions) of experimental cases. Both subcases have a constant wind speed where case IV.2.1 has a large constant shear and case IV.2.2. has a large constant yaw (where it was noted that the large yaw goes together with a shear which is even larger than in case IV.2.1). A shear exponent has been fitted to the measurements at different heights. Hence the results are azimuthally dependent. Further the work in the sub tasks Task 3.1, 3.2 and 3.3 (cases with Turbulence, shear Yaw and Wake Inflow) were presented.

Before the 4th project meeting, an intermediate online meeting was held on October 4th 2019 to follow up on actions.

The fourth meeting of IEA Wind Task 29 Phase IV was held on February 4 and 5, 2020 and hosted by Insean/CNR in Rome Italy. An interesting result was seen in the benchmark case IV.2. The most striking results are a poor agreement between lifting calculations and measurements for the sheared case. For the yawed (+shear) case panel methods, FVW and CFD perform much better than BEM. UStutt extracted airfoil characteristics from the CFD results and these have been supplied to TNO for use in their Lifting line codes. When using these airfoil characteristics a much better agreement is obtained for the shear case.

Shortly after the fourth project meeting the COVID 19 spread and closed down most countries. However the activities in IEA Task 29 IV continued with regular online meetings. They were held with an interval of 2-3 months in between and kept the work going and the interaction between partners.

A considerable task was to collect all the data and results from the benchmarking in a common report. A draft of the final report was ready at the end of the year 2020 where also IEA task 29 IV ended. The final version of the final IEA Task 29 IV report is now available at: https://zenodo.org/record/4817875#.YK-C2Pkzb6c.

During the IEA Task 29 meetings in 2020 it was also time to discuss a continuation of some of the work in a new IEA Annex combined with new activities. It resulted in the proposal: IEA Wind TCP Task 47 "Innovative aerodynamic experiments and simulations on wind turbines in turbulent inflow" which was approved by the IEA ExCo in late 2020.

In spite of the troubles from the COVID19 it was possible to carry out the project almost as planned.

The first two milestones M1 og M2 (M1 - Task 29 website on Danish participation), (M2 - First version of the data base) were fulfilled in August 2018 by opening the first version of DanAero database sharepoint https://share.dtu.dk/sites/IEA-Task-29_293350/SitePages/Home.aspx (access requires permission – mail to hama@dtu.dk).

Later in 2018 (M3 Simulation results delivered to first round) were fulfilled by delivering data to the benchmark from the codes HAWC2 and EllipSys3D. Then followed fulfillment of M4 (Simulation results delivered to second round) in July 2020. Finally, DTU delivered all material to the final report during the end of 2020 and fulfilled thus M5 (Input to the Task 29 final report by ECN delivered). Also M6 (Final version of of the data base) was fulfilled with updates of the data base.

However, it can be mentioned that the COVID19 had some negative impact on dissemination of the results as it was the plan to held and annual workshop presenting the results for industry and research community in Denmark. We succeeded to held one online workshop in March 2021 which had good attendance from industry with about 25 attendees and almost the same number of people from the research community

5. Project results

A corner stone in the IEA task 29 IV is validation of wind turbine simulation models with experimental results from the DANAERO data base.

This data base is quite unique as it comprises detailed measurements on the NM80, 2MW turbine in 2009 within the DANAERO project, carried out by Vestas, Siemens, LM, Don Energy and DTU and funded through EFP by the Danish Ministry of Energy. From 2009 to 2017 the data base was only accessible for the participants in the DanAero project. However, the international research community was very interested to get access to the data base as nothing similar exists at the moment. This led in 2017 to the proposal of sharing the data within IEA Task 29 IV so that the data base came accessible to research institutes and companies from countries participating in Task 29 IV

The DANAERO data base contains experimental data that can give guidance to improve the engineering modelling of complex inflow. The DANAERO experiment comprised measurements of blade surface pressure at four radial positions on a LM38.8m blade on the 2MW NM80 turbine. The measurements were conducted in short campaigns from June to September in 2009. At each radial position the inflow was measured with a five hole pitot tube. In parallel detailed atmospheric flow measurements with anemometers and sonics were carried out at several heights in a nearby meteorological mast. Besides the measurements on the rotor a 2D blade section model was manufactured based on the measured contour at each of the four radial positions on the blade. Wind tunnel measurements were conducted on these four sections and form an excellent basis for comparison of 2D airfoil section aerodynamics with 3D rotor airfoil characteristics.

Transition is a flow phenomenon in the boundary layer of the wind turbine blades where the boundary layer flow undergoes a dramatic change from laminar to turbulent flow. Close to the leading edge the flow is laminar but dependent on the angle of attack, blade surface roughness and turbulence in the inflow the flow will become turbulent. The DANAERO data base contains information on the position of the transition as 60 flush mounted surface microphones were mounted at a radial position about 3m from the tip of the blade. By performing a spectral analysis of the microphone signals it is possible to determine if the flow is laminar or turbulent. The same microphone instrumentation was used on the 2D airfoil section model for the wind tunnel tests. We have thus a solid basis for studying differences in transition characteristics from wind tunnel to rotor flow and this is part of the Task 29 activities.

A considerable work by DTU has thus been in WP1: “Establishing and maintenance of web data base - DANAERO data”. A first version of the data base and share point was already opened for IEA Task 29 IV participants in August 2018 shortly after the start of the project. Since the first version the data base has continuously been further developed and updated. At the moment 116 researchers have got access to the data base and it is foreseen that the data will be used in many articles in the future.

See the reporting on development of the data base from page 17 to 38 in the final report.

WP2 - Comparison of calculated results from different codes with DANAERO experimental data

DTU has contributed to the design of the test cases as well as supplied simulated data from different codes. DTU has searched for relevant data files that could fulfil the desired characteristics and together with the coordinator TNO made the final definition and description of the cases.

First round benchmarking (pages 40-45 in final report)

The results from the first benchmarking of codes are presented in section 4.2 of the final report. DTU contributed with results from two codes, the aeroelastic code HAWC2 (described on page 164-165) and the CFD code EllipSys3D (described on page 184-186). In particular the pressure distributions from the CFD codes showed good correlation with the measurements, Figure D9 on page 220.

Second round benchmarking (pages 48-51)

This benchmarking comprises two complicated flow cases. The Case IV.2.1 with considerable shear in the inflow and Cas IV.2.2 with the turbine operating in yaw. Again DTU delivered results from the HAWC2 and the EillipSys3D CFD codes. In particular the shear case showed that the CFD type codes outperform the aeroelastic codes like HAWC2 as they rely on input of airfoil data from wind tunnel tests which might not be representative for complex flow cases. At least a big improvement was seen with HAWC2 simulations using airfoil data derived from CFD computations.

Task3.1: Effects of Turbulence (pages 56-69)

InTask3.1 the impact of inflow turbulence on the aerodynamic characteristics of a rotating rotor is studied at various conditions.

The overall conclusions from these comparisons were that the engineering models like the HAWC2 model from DTU performed quite well for the turbulent inflow as a good correlation to measurements from the DanAero data base was seen. This is an important result as all simulations for turbine certification are carried out with turbulent inflow.

Task 3.3: Wake effects (pages 73-79)

Wake effects are very important as most turbines from time to time operate in the wake of one or several other turbines. The Task 3.3 has fully concentrated on a benchmark on specific inflow cases from the DanAero data base. The ambition has been to compare different numerical approaches to assess how well today's state-of-the-art modelling possesses capabilities to reproduce the flow interaction of turbines.

DTU participated with the EllipSys3D code in an actuator line version and with the Dynamic Wake Meandering (DWM) model integrated in HAWC2. The first model can be characterized as a high fidelity model and is expected to provide more accurate results than the engineering DWM model. However, there is also a huge difference in simulation time where simulations with the DWM model almost runs in real time whereas the EllipSys3D code requires hours of simulation time on a computer cluster.

Overall the results showed that the mean deficits behind turbines in a row of 4 machines are predicted reasonably well even with the engineering type models like the DWM model. However, the profiles of turbulence differ more and typically the engineering models under predict the turbulence intensity in the wake.

Task 3.6: Boundary layer transition (pages 106-117)

Boundary layer transition is an important mechanism relating to the flow close to the blade surface. Close to the leading edge the flow in the boundary layer is laminar, which is associated with low airfoil drag. However, further downstream, maybe 10-30% from the leading edge the flow in the boundary layer changes from laminar to turbulent flow where the latter results in an increased airfoil drag. We are thus interested in having as much laminar flow as possible.

However, the atmospheric flow that the turbine operates in has a tendency to give less laminar flow than e.g. if the similar airfoil is tested in a wind tunnel where the flow is very uniform. The DanAero data base gives a unique possibility to get insight into this difference as transition is measured both on one section on the rotor and on a similar airfoil section in the LM wind tunnel.

Analysis of the measurements have proven that the atmospheric flow that a wind turbine is operating in gives less laminar flow and to some degree it has also been quantified. Simulating transition with a CFD code is very time consuming but the participant from Kiel University was able to carry out such simulations at different turbulence levels and it confirmed the tendencies seen in the measurements. However, it is also concluded that much more work has to be done for a clearer picture of laminar to turbulent transition on a wind turbine blade.

Rest of material in the final report

Above the activities where DTU has been most involved have been summarized but the final report should be studied for more insight into the activities and the contributions from DTU

As mentioned previously the main objective of Task 29 IV has been to facilitate international collaboration on validation of codes using the DanAero data base, As several of the codes are used by industry it has an important effect on the further technology development in the industry as we have provided an improved insight into the accuracy of the simulation results. In what type of simulations can we expect good results and what complicated cases should we be causes about?

It should also be mentioned that the validation of fluid structure interaction simulations in turbulent inflow now benefits industry through the IFD project PRESTIGE.

The following dissemination activities took place during the project:

- Workshop by DTU on 4th of march from 10:00-16:15 with attendees from DNV GL, Ørsted, Vestas, Envision and Goldwind Denmark and Siemens Gamesa
- Final report available on Zenodo https://zenodo.org/record/4817875
- Direct dissemination to industry through licenced tools HAWC2 and EllipSys3D
- Wind Energy Science Journal
  - Grinderslev, C., Sørensen, N. N., Horcas, S. G., Troldborg, N., and Zahle, F.: Wind turbines in atmospheric flow: fluid–structure interaction simulations with hybrid turbulence modeling, Wind Energ. Sci., 6, 627–643, https://doi.org/10.5194/wes-6-627-2021, 2021.
  - Özçakmak, Ö. S., Madsen, H. A., Sørensen, N. N., and Sørensen, J. N.: Laminar-turbulent transition characteristics of a 3-D wind turbine rotor blade based on experiments and computations, Wind Energ. Sci., 5, 1487–1505, https://doi.org/10.5194/wes-5-1487-2020, 2020.
- Wind Energy Journal
  - Grinderslev, C, González Horcas, S, Sørensen, NN. Fluid–structure interaction simulations of a wind turbine rotor in complex flows, validated through field experiments. *Wind Energy*. 2021; 1– 17. https://doi.org/10.1002/we.2639
- Torque 2020 conference
  - Grinderslev, C., Vijayakumar, G., Ananthan, S., Sørensen, N., Zahle, F., and Sprague, M.: Validation of blade-resolved computational fluid dynamics for a MW-scale turbine rotor in atmospheric flow, J. Phys.: Conf. Ser., 1618, 052049, https://doi.org/10.1088/1742-6596/1618/5/052049, 2020

6. Utilisation of project results

The project was focused on validation and improvement of design tools for the wind turbine industry. Today turbine design and certification relies almost fully on the numerical results from these tools and a reduction of the uncertainty of these codes will lead to less conservatism in the turbine design and thus contribute to a LCOE reduction of wind energy.

As mentioned previously several of the validated codes are used by the wind turbine manufactures, developers and operators, either for free use as the FAST code from NREL and the OpenFoam CFD code or on a license basis as HAWC2 or EllipSys3D from DTU. It means that the improvements in the codes will be incorporated in new updates or versions and thus quickly have impact.

The experiences of fluid structure interaction in turbulent inflow are used to evaluate the risk of vortex induced vibrations of modern turbines together with major Danish players in the IFD project PRESTIGE.

Another way of having impact is that the validation cases can be used by companies that want to internally validate their codes and not in a public research project. In this way they have state-of-the-art results from a suit of different codes and can evaluate how their own codes perform relative to this.

Finally, it can be mentioned that the PhD study of Christian Grinderslev benefited the benchmarking and validation cases in Task 29 IV. Link to PhD report:

https://orbit.dtu.dk/en/publications/fluid-structure-interaction-for-wind-turbines-in-atmospheric-flow

7. Project conclusion and perspective

The project was overall carried out as planned although a major part of the project period coincided with the COVID19 shut down periods.

A sharepoint site with experimental data from the DanAero experiment was established soon after the project start. There was from the beginning a big interest in getting access to the site and data and at the end of the project there are 116 registered users. This also indicates how important the DanAero experiment conducted back in the period from 2007-2010 is.

DTU has contributed to several of the benchmark exercises carried out and we have got a good insight into how our codes performs relative to the experimental data but also relative to results from other codes. The importance of accurate airfoil data as input to the engineering models was fully exemplified for the complex case with strong shear in the inflow. Using the airfoil data extracted from 3D CFD rotor simulations improved the simulation results considerably and it could be the method to use in the future for more accurate simulations.

Then benchmarking results on the wake flow cases showed that the turbulence from the engineering models should be improved and the results can be used for guidance on this.

Finally the work on transition together with Kiel University has improved our insight into the important but also complex mechanisms. The impact of the external turbulence in the atmospheric flow was seen both in CFD simulations and in the analysis of the experimental data.

Some of the research areas will be continued in the new IEA task 47 "Innovative aerodynamic experiments and simulations on wind turbines in turbulent inflow". This new task will have high focus on impact of turbulent inflow, both on load response but also transition.

Improved understanding of e.g. transition mechanisms in turbulent flow and improved modelling of transition can lead to design of more efficient airfoils that are designed to operate in such turbulent flow.

8. Appendices

- Final report 'IEA Wind TCP Task 29, Phase IV: Detailed Aerodynamics of Wind Turbines'
- https://share.dtu.dk/sites/IEA-Task-29_293350/SitePages/Home.aspx (requires login permission from hama@dtu.dk)
- Publications
  - Wind turbines in atmospheric flow: fluid–structure interaction simulations with hybrid turbulence modeling
  - Fluid–structure interaction simulations of a wind turbine rotor in complex flows, validated through field experiments
  - Validation of blade-resolved computational fluid dynamics for a MW-scale turbine rotor in atmospheric flow
  - Laminar-turbulent transition characteristics of a 3-D wind turbine rotor blade based on experiments and computations
  - M Zhou, M Sessarego, H Yang, WZ Shen, "Development of an advanced fluid-structure-acoustics framework for predicting and controlling the noise emission from a wind turbine under wind shear and yaw", Applied Sciences 2020, 10, 7610. https://doi.org/10.3390/app10217610.

- Codes that were used and modified in the project
  - HAWC2
  - EllipSys3D
- Follow up project IEA Wind TCP Task 47 'Innovative Aerodynamic Experiments and Simulations on Wind Turbines in Turbulent Inflow'
  - Danish participation