Final report

1.1 Project details

Project title	Danish participation in IEA Wind Task 29 Mexnext-III
Project identification (program abbrev. and file)	TILSAGN 14.pdf, EUDP-sekretariatet, d. 16. december 2014, J.nr. 64014-0543, Ref. Hanne Thomassen
Name of the programme which has funded the project	EUDP 14-II
Project managing company/institution (name and address)	DTU Wind Energy, Frederiksborgvej 399, 4000 Roskilde Project leader: Helge Aagaard Madsen
Project partners	DTU Wind Energy
CVR (central business register)	30060948
Date for submission	20-03-2018

1.2 Short description of project objective and results

English
The objective of the project is on basis of participation in the IEA Task 29 MexNext III to utilize the results from a new wind tunnel measurement campaign on a 4.5m rotor (summer 2014) for validation and improvement of aerodynamic and aeroelastic models used by research institutes as well as in industry. Lowering the uncertainty of the design tools will lead to lower safety factors in the design of wind turbines and thus a reduction of CoE.
DTU has contributed with simulations to both of the two major rounds for validation of models using: 1) the aeroelastic code HAWC2; 2) the actuator line code AL and 3) the CFD code EllipSys3D. This has led to improvement of models and simulation procedures as well as identification of areas for future model improvement. See below under 1.5 for more details.

Danish
Formålet med dansk deltagelse i IEA Task 29 Mexnext III er at udnytte resultaterne fra en ny målekampagne på 4.5m (diameter) MEXICO (" Model Experiments in Controlled Conditions") rotoren i sommeren 2014 i den tysk/hollandske vindtunnel DNV-LLF, til validering og forbedring af aerodynamiske og aeroelastiske modeller, benyttet af forskningsinstitutter og industrien. I det lange løb vil nøjagtigere modeller føre til reducerede sikkerhedsfaktorer ved design af vindmøller og derved bidrage til lettere og mere effektive vindmøller og CoE reduktion.
DTU har deltaget med simuleringer til begge modelvalideringsrunder fra modellerne: 1) den aeroelastiske HAWC2 model; 2) aktuatorliniemodellen AL og 3) EllipSys3D CFD modellen. Valideringen har ført til modelforbedring samt identifikation af områder for mulig modelforbedringer. Se nedfor under pkt. 1.5 for detaljerede resultater.

1.3 Executive summary

The objective of the project is Danish participation in IEA Task 29 Mexnext III which is a follow up phase on two previous phases (each of 3 years duration) of Task 29. In the first two phases the main content was aerodynamic and aerodynamic model validation using a data set MEXICO from 2006 (" Model Experiments in Controlled Conditions") which was measurements on a 4.5m rotor tested in the German/Dutch wind tunnel. In this data set from 2006 there were some serious uncertainties on different parts of the data base. A new measurement campaign was therefore conducted in 2014 on the same rotor in the same tunnel and this new data set has been used in the present Task 29.
The work in Task 29 Mexnext III has clearly revealed that some important measured quantities like e.g. the wind tunnel flow speed were not correctly calibrated in the first measurement round in 2006. Also a serious distortion of the measured flow field using the Particle Image Velocimetry (PIV) system from reflection from the painting of the nacelle was solved in the new campaign.
DTU has contributed with simulations to both of the two major rounds for validation of models using: 1) the aeroelastic code HAWC2; 2) the actuator line code AL and 3) the CFD code EllipSys3D. This has led to improvement of models and simulation procedures as well as identification of areas for future model improvement.
Besides delivering simulation results within the two main validation rounds DTU has also been leader of two tasks, Task 4.3 "Angle of Attack" and Task 4.8 "Dynamic inflow", where deeper investigation of the specific subjects have been carried out. See section 4.3 and 4.8 in the final report [1].
It should also be mentioned that it is an important benefit to participate in the Task meetings in order to learn about other partners modelling approach and model performance. DTU has participated in all six Task meetings. As an example of the benefit of performing model validation in a concerted action with other institutes we show in the figure below an example of comparing model results with experimental data.

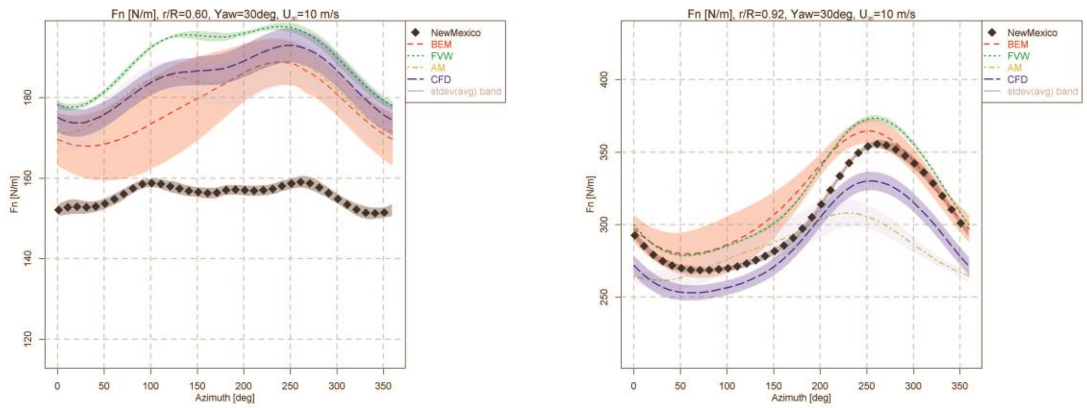

Figure 1 A comparison of measured aerodynamic forces at two radial positions of 60% and 92% radius with simulations with models of different type.

In Figure 1 a comparison of measured aerodynamic forces at two radial positions of 60% and 93%, respectively, is presented. Different types of models are used as indicated with the different colors. The results for the same type of models from the different participants lie within the band of same colors. DTU participated with models of both the BEM and CFD type.
The systematic deviation between all the model results in the figure to the left indicates that here it is probably the measurements that are not correct. If the validation was just carried out by one partner it would be less convincing to claim the experimental results were causing the deviations and not the model itself. In the Figure to the right with the data at 92% radius the correlation between model simulations and measurements is much better.
The achievements by DTU within the project have been communicated through several conference presentations and journal papers. However, a more direct communication of results has been through the close contact DTU has with several industrial partners.

1.4 Project objectives

The objective of the project has been to participate in the IEA Task 29 MexNext III to utilize the results from a new wind tunnel measurement campaign on a 4.5m rotor (summer 2014) for validation and improvement of aerodynamic and aeroelastic models used by re-search institutes as well as in industry.
The project work has developed as planned and conducted within the scheduled three years period. All three milestones were fulfilled satisfactorily.

1.5 Project results and dissemination of results

DTU has contributed with five major parts to the project:

1) Delivering results to round 1 of model validation (Milestone 1) - (Axial Flow), section 4.2 in [1]
2) Delivering results to round 2 of model validation (Milestone 2) - (Yawed flow), section 4.3 in [1]
3) Task 4.3 leader: Angle of Attack – Chapter 6. Task 4.3: Angle of Attack in [1]
4) Task 4.8 leader: Dynamic inflow – Chapter 11. Task 4.8 Dynamic inflow in [1]
5) Contributions to the final report [1] (Milestone 3)

Further DTU has participated in all the six Task meetings:

1) ECN Amsterdam (NL) on March 4, 2015
2) NREL Boulder (USA) on January 11-12, 2016
3) Glasgow June 7, 2016
4) Onera on November 9-10, 2016
5) CENER Pamplona (Spain) on April 6, 2017
6) CWEA in Beijing (China) December 4-6, 2017

Below a few selected results from the four major DTU contributions are presented. For deeper insight into the results the final report [1] should be used.

DTU contributions from different models

DTU contributed with results from 3 different codes but in different versions:

1) HAWC2 and HAWC2-NW
2) Ellipsys3D – with transition model and without, respectively
3) Actuator Line (AL)

The first two codes are widely used at universities as well as in industry and therefore a detailed validation of these codes is of big importance for the users.

HAWC2 is an aeroelastic code developed at DTU and now widely used in industry who can acquire a license to the code. It is a so-called engineering model (a low fidelity (LF) model) which means that it is built on many sub-models where only the most important parts of the flow physics are modelled. On the other hand it is a fast code that can simulate a turbine operation almost in real time. **HAWC2-NW** is a new version of the HAWC2 code and it is a kind of hybrid code as it is a combination of a lifting line code and a BEM (Blade element momentum) code. Generally it is expected to perform better for many types of simulations as it models more physics than the standard HAWC2 version. This is illustrated below under the description of the Task 4.8 dynamic inflow simulations.

EllipSys3D is a CFD code also developed at DTU like the HAWC2 code. It is also used in industry on a license basis and widely used by students for research at DTU. It is a so-called high fidelity code (HF) which means that basic flow equations are solved for the flow through a wind turbine rotor or flow around a wind turbine blade. Compared with the HAWC2 code the computational time is several orders of magnitude higher than the time for a HAWC2 simulation. It means that simulation for one wind speed for a wind turbine rotor might take several days of computation time. We supplied results from the EllipSys3D code in two versions, one assuming full turbulent boundary layer on the blade and another one where the transition from laminar to turbulent flow is simulated. This version of the code in the figure is called **EllipSys3D_trans.**

The Actuator Line (AL) model has also been developed at DTU and is a model that uses the EllipSys3D code as the main flow solver. However, it does not resolve the flow field around the turbine blade in details and need the so-called airfoil data as input which is the same for the HAWC2 code. The airfoil data are provided by wind tunnel measurements on the blade sections of the blade but there is an uncertainty in applying these data to a wind turbine rotor.

DTU contribution 1 - Results from participation in round 1 of model validation - axial flow

The test cases for simulation round 1 were defined in the autumn 2015 and comprise simulations at three wind speeds of 10, 15 and 24 m/s. DTU supplied results from the above mentioned codes and the comparisons were presented and discussed at a meeting in January 2016. As an example of the comparisons the results for the 15m/s case are shown below in Figure 2.

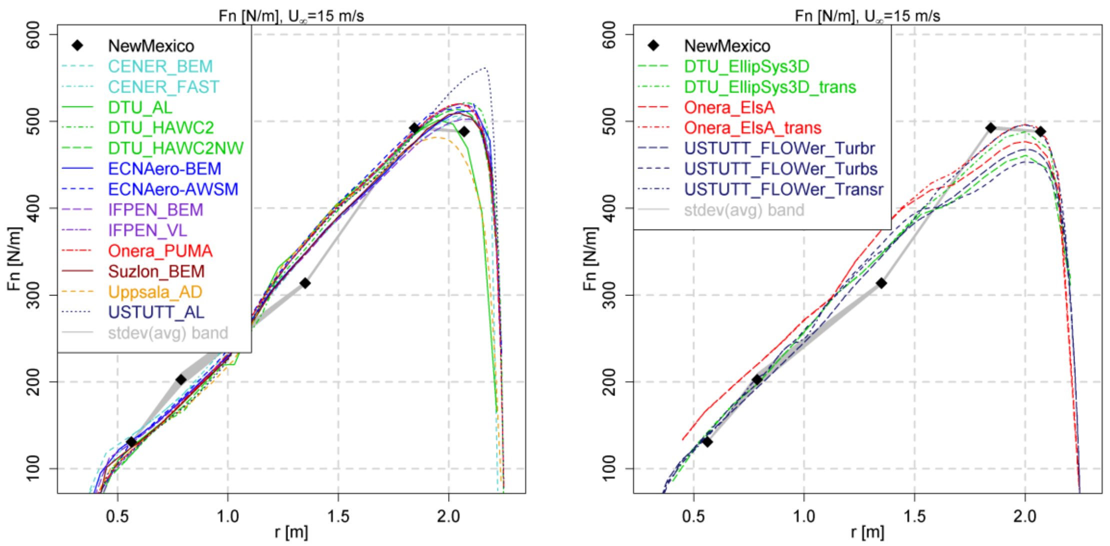

Figure 2 The comparison with two different type of codes are shown here. To the left its results from the lowest fidelity (LF) codes (the fastest computations but also the less accurate codes) in comparison with measured aerodynamic normal forces at five radial positions on the blade. To the right it is model results from the highest fidelity codes which are the CFD codes

In the left graph in Figure 2 the results from the LF codes are shown and to the right it is results from all the high fidelity (HF) codes like the CFD code EllipSys3D.
We should thus expect a better correlation between the HF models and measurements in the graph to the right than for the LF models to the left. For the two most inboard stations between a radius of 0.5 and 1.0m this is also the case. However, in the tip region we can see that the there is a tendency that the LF results are above the measurements and the HF models below. For the LF models it is the so-called tip correction model that is important for the load level. Considerable work on improvement of the tip correction model which is found in many versions has been carried out within task 29 and we can expect that we will see an improved correlation in the near future.

The same results as presented in the two graphs in Figure 2 are now summarized in the left graph of Figure 3 in the way that all the results from the models of the same type are shown by the mean value. One clear result is that the HF models correlate better the measurements inboard between radius 0.5-1.0m. It´s where stall can be present and it is expected that the HF codes can model this flow phenomena better than LF codes.

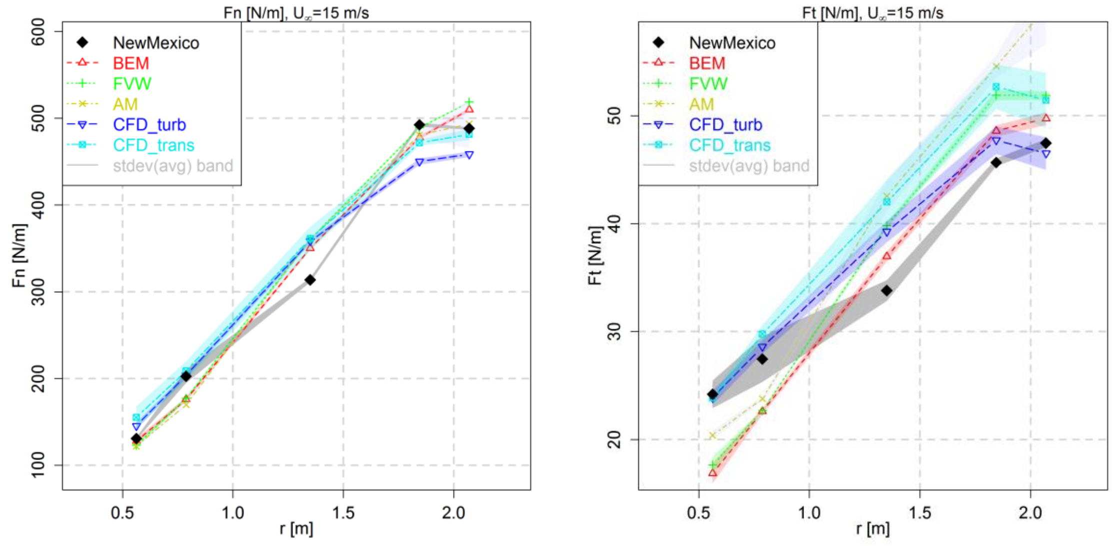

Figure 3 In the left figure is shown a comparison of the same data as shown above in Figure 2 but the model results have now been grouped according to model type, indicated by color bands for the different type of codes. To the right the same type of results but now for the tangential force.

DTU contribution 2 - Results from participation in round 2 of model validation – yawed flow

This round comprises validation for yawed inflow which is a complex inflow and a challenging case. As an example the results for a test case of 30 deg yaw at 15m/s is shown in Figure 4.

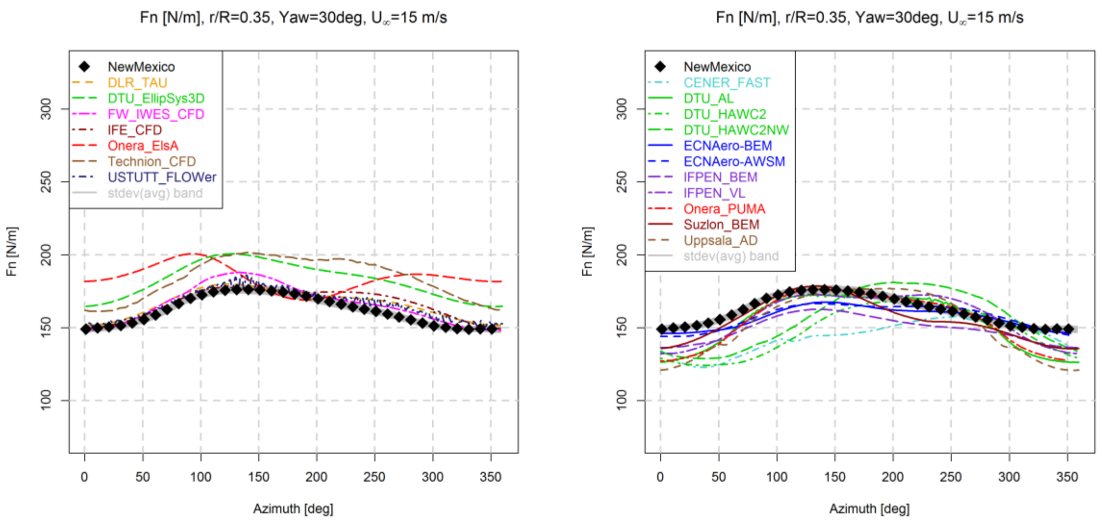

Figure 4 Comparison of simulated and measured normal force at radius 35% and at 15m/s. To the left results from HF codes and to the right results from LF codes.

The normal force at 35% radius is compared with measurements in that figure. In the left graph it is results from HF codes and to the right the LF codes results. In the right graph we can see that the DTU HAWC2 results do not correlate so well with the measurements on this inboard part (35% radius) of the blade and this has initiated an improvement of the yaw sub model in HAWC2 and this work is ongoing. In Figure 5 all the model data for the same cases as shown in Figure 4 are grouped together in the left graph. There is a slightly better correlation with measurements for the HF codes which should be expected. In particular this is true for the tangential force component shown in the right figure.

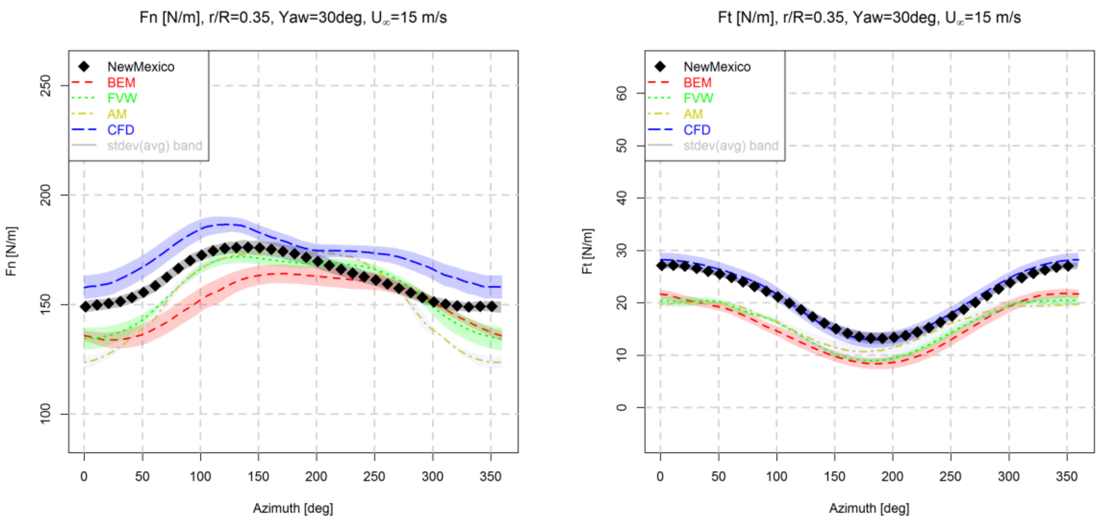

Figure 5 Comparison of simulated and measured normal force (left graph) and tangential force (right graph) at radius 35% and at 15m/s. Model results groups of same type of model.

DTU contribution as leader of task 4.3: Angle of Attack

The LF models use airfoil sectional data (lift, drag and moment coefficient) as input. Such data can be obtained from 2D wind tunnel measurements on a blade section but often it is more accurate to derive the coefficients from CFD rotor simulations. However, in this case the problematic part of the procedure is how the angle of attack (AoA) shall be determined. This is the main subject of this task. Several methods have been investigated by a number of different institutes participating in this task work.

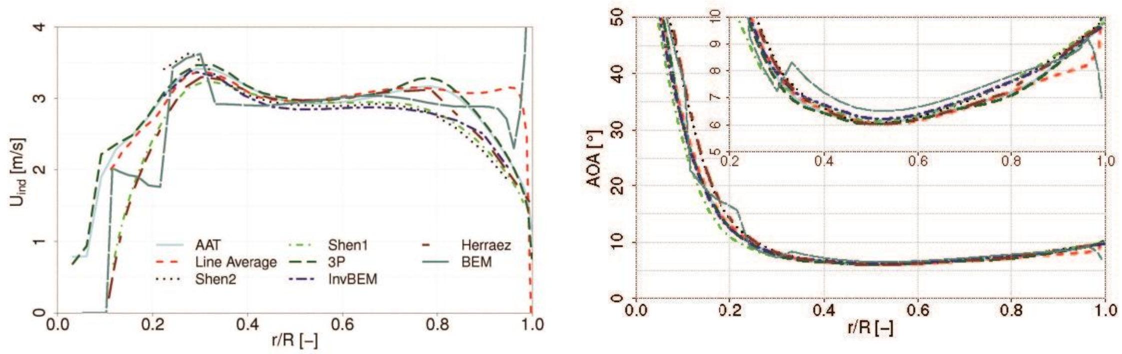

Figure 6 In the left graph is shown the induced velocity along the blade span derived from CFD simulations on the Innwind rotor at a wind speed at 9m/s, using different models. In the right graph the AoA along the blade span derived by the same models.

In Figure 6 in the graph to the right is shown an example of derived AoA for the Innwind 10MW rotor at 9m/s based on the 8 different models applied in the present study. Two of the models named Shen1 and Shen2 have been developed at DTU. The AoA derivation requires that the induced velocities are calculated first and the results for the different models are shown in the graph to the left. It is seen that the deviation between the models in particular is found in the root and tip region. The final result of using the models is the airfoil coefficients cl and cd shown in Figure 7. For the cl coefficient shown in the left graph there is a good correlation between the different models while the spread for the drag coefficient cd is larger.

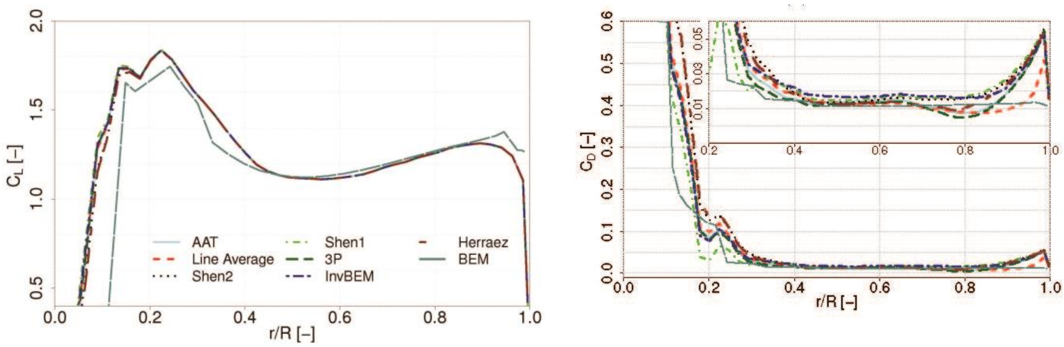

Figure 7 In the left graph is shown the lift coefficient cl along the blade span derived from CFD simulations on the Innwind rotor at a wind speed at 9m/s, using different models. In the right graph the cd coefficient along the blade span derived by the same models.

DTU contribution to Task 4.8: Dynamic inflow

In this task the flow mechanism caused by a pitch step on a wind turbine rotor is investigated. This is in particular important for an emergency shut down of a turbine because in such situation the pitch of the turbine is changed at a maximum rate, e.g. 10 deg per second.

The data used for the investigation comprise both experimental data from the MEXICO rotor and one test case using results fromEllipSys3D simulation on the AVATAR rotor.

In order to simulate the dynamic inflow effect a sub model in the LF codes is needed because they are derived from a steady model theory. The overall goal with the task 4.8 work is thus a validation of the dynamic inflow sub models.

One example of comparing model simulations for a step change in aerodynamic loading due to a fast pitch change is shown in Figure 8. Both the measured and simulated results in the left graph for the 35% radial position show the general trend of the so-called overshoot effect of dynamic inflow. This means that the instantaneous change in load is bigger than when comparing the difference in loads for the steady two positions of the pitch. This effect is less in the right graph for the radial position of 92% and predicted well by most of the models.

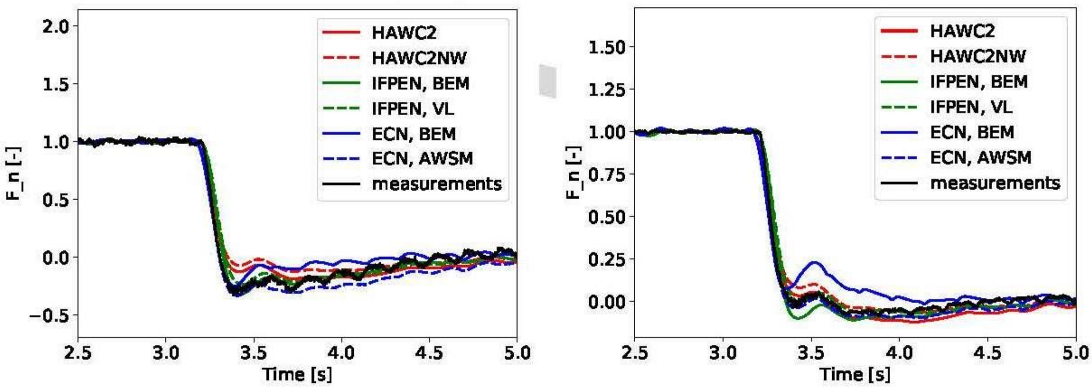

Figure 8 Normal force at 35% (left) and 92% (right) radius measured in the New Mexico experiment at 7.68 m/s tunnel speed for a pitch step and compared with different models.

Finally we show the thrust variation due to a series of pitch steps on the 10MW Avatar rotor in Figure 9. The diameter of the Avatar rotor is around 204m and thus many times bigger than the MEXICO rotor presented above. This gives a stronger dynamic inflow effect seen in the way that the force overshoot is bigger than what we saw above for the MEXICO rotor. In this case the validation exercise led to an improvement of the NW version of the HAWC2 code. In the right graph in Figure 9 we can see a characteristic stair case form of the results from the two HF codes, EllipSys3D and the vortex code AWSM. However, this is not seen in the HAWC2 results. The stair case characteristics are due to the blade passing the tip vortex originating from the previous blade. Although the NW version of HAWC2 is a LF code it was possible to change the model so it includes the effect of the blade passing the tip vortex from the previous blade.

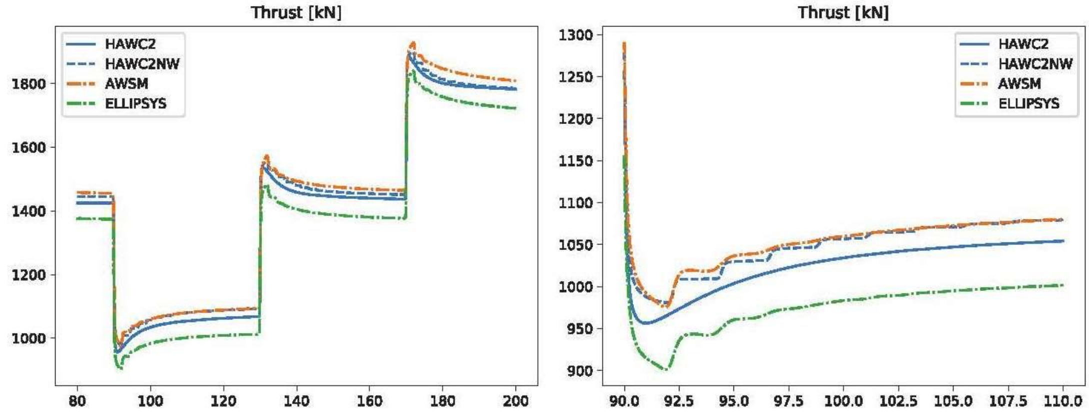

Figure 9 In the left graph is shown the thrust variation from simulated pitch step on the 10MW Avatar rotor with different models. In the right graph is shown a zoom of the left graph. The characteristic stair case is seen in the results of the two HF codes, EllipSys3D and AWSM and in the near wake version of HAWC2, after model improvement based on the present validation exercise.

1.6 Utilization of project results

The direct utilization of the project results are through the improved and validated codes HAWC2, HAWC2-NW and EllipSys3D, that are licensed to the industry and other research institutes. This comprises e.g. the updated dynamic inflow model in the HAWC2-NW code and an improvement in the near future of the yaw model on the inner part of the blade for the HAWC2 and HAWC2-NW codes. An improved insight into transition modelling with the EllipSys3D has also been obtained which will be valuable in future rotor simulations with this code.
Finally, the results from the work have been communicated through the publications from the project. See reference list below [1],[2],[3],[4],[5],[6],[7],[8],[9],[10]

1.7 Project conclusion and perspective

The project has clearly shown the big synergy in validating codes in an international framework under IEA. In the preceding phase of IEA Task 29, Mexnext II, the majority of the codes showed for some measured quantities systematic deviations that pointed to uncertainties in the measurements rather than model issues. This was the major motivation for the new measurement campaign in 2014, followed by the present Task 29, Mexnext III, for analysis of the data set. The work in the present Task has clearly confirmed that there were systematic measurement uncertainties on some of the experimental quantities in the previous data set from 2006 which are not present in the new data set from 2014. One can mention an improved calibration of the tunnel speed and the improved flow visualization data (Particle Image Velocimetry data) that in the 2006 data were distorted by reflections from the painting on the nacelle.
The Task has thus resulted in a very good experimental data set that will be used in future model validations. The participation by DTU in the task has led to model improvements like the HAWC2-NW model and pointed to areas of further model development not yet implemented (improved yaw model in HAWC2). However, by participation in the task work and the meetings there is also a highly valuable build-up of knowledge by the interaction with the other partners.
The perspectives of the Task 29 is a new proposal for a phase 4 of Task 29 where Denmark will make access to the DANAERO data base that contains detailed measurements on a 2MW NM80 rotor. The DANAERO experiments were carried out in an EFP funded project from 2007-2009 (LM, Siemens, Vestas, DONG Energy and DTU) and the DANAERO data base es-

tablished in a follow up project from 2011-2013. With the new data set there will be a major shift in the type of validation of the codes. Most important is that the new data are measured in a realistic inflow with shear and turbulence. The model capabilities for such flow are very important to document as it is flow conditions that the models are used for in their daily use in the industry.

Annex

Relevant links

http://www.mexnext.org/

References

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