# Final report

## 1.1 Project details

| | |
|---|---|
| **Project title** | Danish participation in IEA Wind Task 29 Mexnext-II - Model validation |
| **Project identification (program abbrev. and file)** | EUDP-sekretariatet, Den 3. juli 2012, J.nr. 64012-0146,Ref. Hanne Thomassen |
| **Name of the programme which has funded the project** | EUDP 12-I |
| **Project managing company/institution (name and address)** | DTU Wind Energy, Frederiksborgvej 399, 4000 Roskilde<br><br>Project leader: Helge Aagaard Madsen |
| **Project partners** | DTU Wind Energy |
| **CVR** (central business register) | 30060948 |
| **Date for submission** | 01-05-2015 |

## 1.2 Short description of project objective and results


**English**

The objective of the project is on basis of participation in the IEA Annex 29 Mexnext II to validate and improve a number of different aerodynamic and aeroelastic numerical models used by research institutions as well as in industry. In this way the project will contribute to a reduction of the safety factors on computation of loads, used in certification of turbines.

During the 3 year project, 20 leading institutes within the field of wind turbine aerodynamics cooperated closely in Mexnext II. Several 'historical' measurements have been assessed as concerns usefulness and missing information and now added to the Mexnext data base.

Two major rounds for validation of models have been arranged during the project; one for uniform inflow to the rotor and one for yawed flow, respectively. DTU has participated in both rounds with a number of different models: HAWC2, EllipSys3D, Actuator Line (AL), BEM which has provided useful insight into the accuracy of the models and thus also can be used to determine which model is best suited for a specific load case. Further DTU has been leader of two tasks: 4.3 "Angle of attack investigations", and of 4.8 "Dynamic Inflow" where a deeper investigation into these fundamental subjects have been carried out.

The work has been reported in a common final report [1] edited by the coordinator ECN: "Final report of IEA Wind Task 29: Mexnext (Phase 2). December 2014, ECN-E--14-060"

Below in section 1.6 selected results are presented.

**Danish**

Projektets formål er gennem deltagelse i IEA Annex 29 Mexnext II at validere og forbedre en række forskellige aerodynamiske og aeroelastiske beregningsmodeller, der benyttes i forskningsinstitutioner såvel som i industrien. Hermed vil projektet bidrage til at reducere de sikkerhedsfaktorer knyttet til beregningsusikkerheden, der indgår ved certificering af vindmøller.

Gennem de 3 års projektarbejde i Mexnext II har 20 førende institutter arbejdet tæt sammen omkring vindmølleaerodynamik. Flere gamle eksperimentelle datasæt er gennemgået og vurderet ud fra egnethed til modelvalidering og evt. manglende information og nu lagt ind i Mexnext databasen.

To større modelvalideringsrunder er gennemført indenfor projektet; én for konstant og uniform indstrømning til vindmøllerotoren og én for skæv indstrømning (yawfejl). DTU har deltaget i begge runder med flere modeller: HAWC2, EllipSys3D, Actuator Line (AL), BEM, hvilket har givet værdifuld indsigt i modellernes nøjagtighed og dermed omkring hvilken model, der kan benyttes i forskellige driftssituationer. Endvidere har DTU været leder af to tasks: 4.3 "Undersøgelse omkring indfaldsvinkel" og 4.8 "Dynamisk Inflow", hvor der er gennemført en grundlæggende undersøgelse af disse størrelser/mekanismer.

Projektarbejdet er rapporteret i en fælles rapport [1] redigeret af koordinatoren ECN: "Final report of IEA Wind Task 29: Mexnext (Phase 2). December 2014, ECN-E--14-060".

Nedenfor i sektion 1.5 præsenteres et lille udsnit af resultaterne.

## 1.3 Executive summary

The overall objective of the IEA Task 29 Mexnext-II was to analyse, in a collaborative way, detailed aerodynamic measurements from a wide variety of sources and use the data for validation of aerodynamic and aeroelastic codes. Several new data sets have been identified and assessed and added to the MEXICO data base as described in WP1 and WP2 of the common final report [1]. DTU has e.g. contributed with an old data set back from the late 1980´s with detailed measurement on the Tellus turbine in yaw operation, section 12.4 in [1].

Next another important part of the present IEA Annex work has been the code validation. Two rounds were organized by the project coordinator ECN; 1) one for uniform inflow with experimental data from the NREL UAE Phase VI experiment in the NASA Ames 24.4 m x 36.6 m wind tunnel in year 2000; and 2) yawed inflow. Both exercises are described in details in WP3 in [1].

DTU participated in both rounds with different codes: 1) the aeroelastic code HAWC2 developed at DTU and widely used in industry and at universities; 2) the high fidelity CFD code EllipSys3D from DTU also widely used by industry and universities; 3) the actuator line code (AL) which uses the EllipSys3D code as flow solver; and 4) the BEM test code (only used for test purposes). The overall interpretation of the validation of the 3 first mentioned DTU codes is that they perform quite good compared with similar codes from other institutes. The comparison with the experimental results has led to minor code adjustments. The validation exercise has also indentified the importance of the high fidelity codes that can resolve e.g. the complex 3D flow effects on the inner part of the blades where the lower fidelity codes are less accurate.

DTU has also contributed to the WP4 activities as leader of task 4.3 "Angle of attack" and task 4.8 "Dynamic inflow". WP4 comprises a deeper investigation into some basic aerodynamic flow phenomena. In task 4.8 DTU has investigated inflow measurements on the Siemens 3.2MW wind turbine carried out in the DANAERO project in 2009. The measurements were analyzed for deriving data from which the dynamic inflow time constants could be extracted. A comparison with HAWC2 results shows a good correlation.

Finally, DTU has participated in all 4 plenary meetings which are an important part of the IEA annex work as it is the forum where the results of the validation exercises are discussed.

## 1.4 Project objectives

The objective of the project is on basis of participation in the IEA Annex 29 Mexnext II to validate and improve a number of different aerodynamic and aeroelastic numerical models developed at DTU and used by research institutions as well as in industry. In this way the project will contribute to a reduction of the safety factors on computation of loads, used in certification of turbines.

## 1.5 Project results and dissemination of results

DTU has contributed with four major parts to the project:

1) Participation in round 1 of model validation - (Axial Flow), section 5.2 in [1]
2) Participation in round 2 of model validation - (Yawed flow), section 5.3 in [1]
3) Leader of task 4.3: Angle of Attack
4) Leader of task 4.8: Dynamic inflow

Further DTU has participated in all four plenary meetings:

1) ECN Amsterdam (NL) on December 7 2011
2) NREL Boulder (USA) on November 6 and 7 2012
3) CENER Pamplona (Spain) on September 25 to 27 2013
4) CARDC Mianyang (China), from October 29 to 31 2014

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 contribution 1 - Results from participation in round 1 of model validation**

DTU contributed with results from 4 different codes:

1) HAWC2
2) Ellipsys3D
3) Actuator Line (AL)
4) BEM

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 buy a license to the code. It is a so-called engineering model which means that it is build 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.

**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 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.

**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.

**BEM** is just a sub model for the aerodynamic part of the rotor flow and is a research model for testing different engineering models (low fidelity models).

**Axial flow results – round 1**

A detailed comparison of experimental and model results are presented in section 5.2 in [1]. The experimental results are from the the NREL UAE Phase VI experiment conducted by NREL in US in 2000 and now added to the Mexnext data base. The measurements features a two-bladed turbine with a 10 m rotor in upwind configuration without cone and tilt, placed in the large test section of the Nasa-Ames wind tunnel, Figure 1.
One set of data are selected for illustration of the validation process having the results from many codes (high fidelity to low fidelity) and the experimental results. In Figure 2 the computed loading along the blade for one wind speed is shown. There are two high fidelity codes (CFD code from CENER and DTU, respectively) and then a number of lower fidelity codes that needs the airfoil data as input as mentioned above. The two high fidelity codes are clearly seen to give results closer to the experiment on the inner ½ part of the blade where so-called three dimensional flow effects have influence on the loading and which are not captured when the airfoil data from the two-dimensional wind tunnel experiments are used. Much effort in the project has thus been devoted to develop procedures/methods where a so-called 3D correction of the airfoil data can be introduced to achieve results from the lower fidelity models in better agreement with the blade load distribution from experiments.

*Figure 1 The NREL UAE Phase VI experiment in the NASA Ames 24.4 m x 36.6 m wind tunnel.*

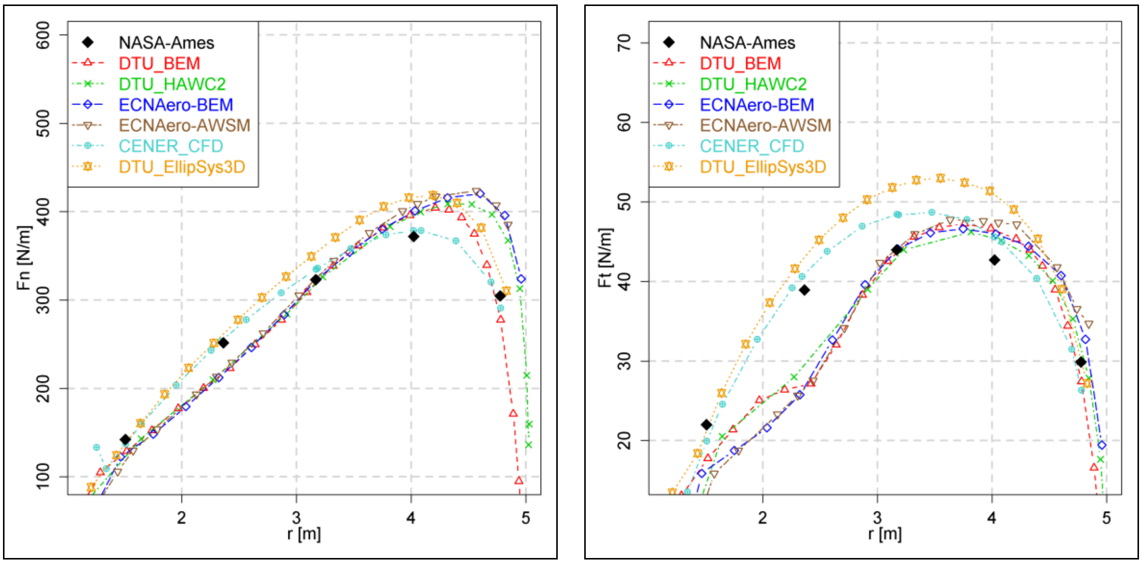


*Figure 2 A comparison of measured loading (load Fn normal to the chord to the left and load Ft tangential to the chord to the right) at 10m/s. Case X10, page 31 [1].*

To illustrate what details in loading the high fidelity codes can provide, the simulated pressure distributions for the same 5 radial positions as shown in Figure 2 are presented below in Figure 3. Overall it can be concluded that in this case the high fidelity EllipSys3D code can provide a very good correlation with experimental results and capture well the complex three-dimensional flow effects on the inner part of the blade.

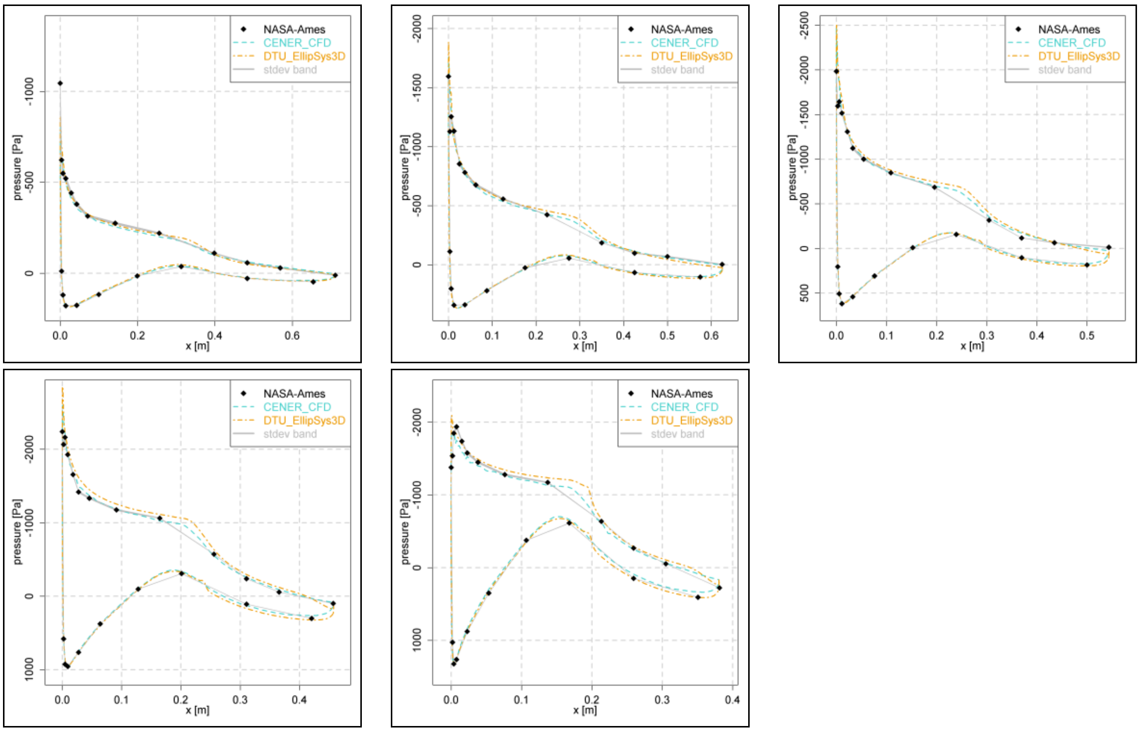


*Figure 3 Simulated pressure distributions for the Case X10 for the NREL rotor by two high fidelity codes. Results from five radial positions: 0.30R, 0.47R, 0.63R, 0.83R, 0.95R.*

## Yawed flow results – round 2

The second round of validation comprises the complex inflow situation yawed flow which means that the inflow direction is not parallel with the rotor shaft. In certification of turbines such cases contribute often with quite high loading and might give loads that are dimension-

ing for certain turbine components. Therefore it is load cases with high focus when validating the flow models.
First we show an example of comparison of the EllipSys3D blade surface pressure computations for a 30 deg. yaw error with experiment, Figure 4. The four graphs are the results for four different blade azimuth positions and overall it can be concluded that the code captures quite well the changes in pressure distributions when the blade turns around in this complex flow field.
Next in Figure 5 is shown an example of the variation of yaw and tilt moments which are the two main moments transmitted into the top of the tower from the rotor for a yaw error of 30 deg. and -30 deg. An overall trend is that the most codes overestimate the variations of both moments. Again the EllipSys3D code provides very good correlation with experiments but also the aeroelastic code HAWC2 shows a quite good correlation with experiments.

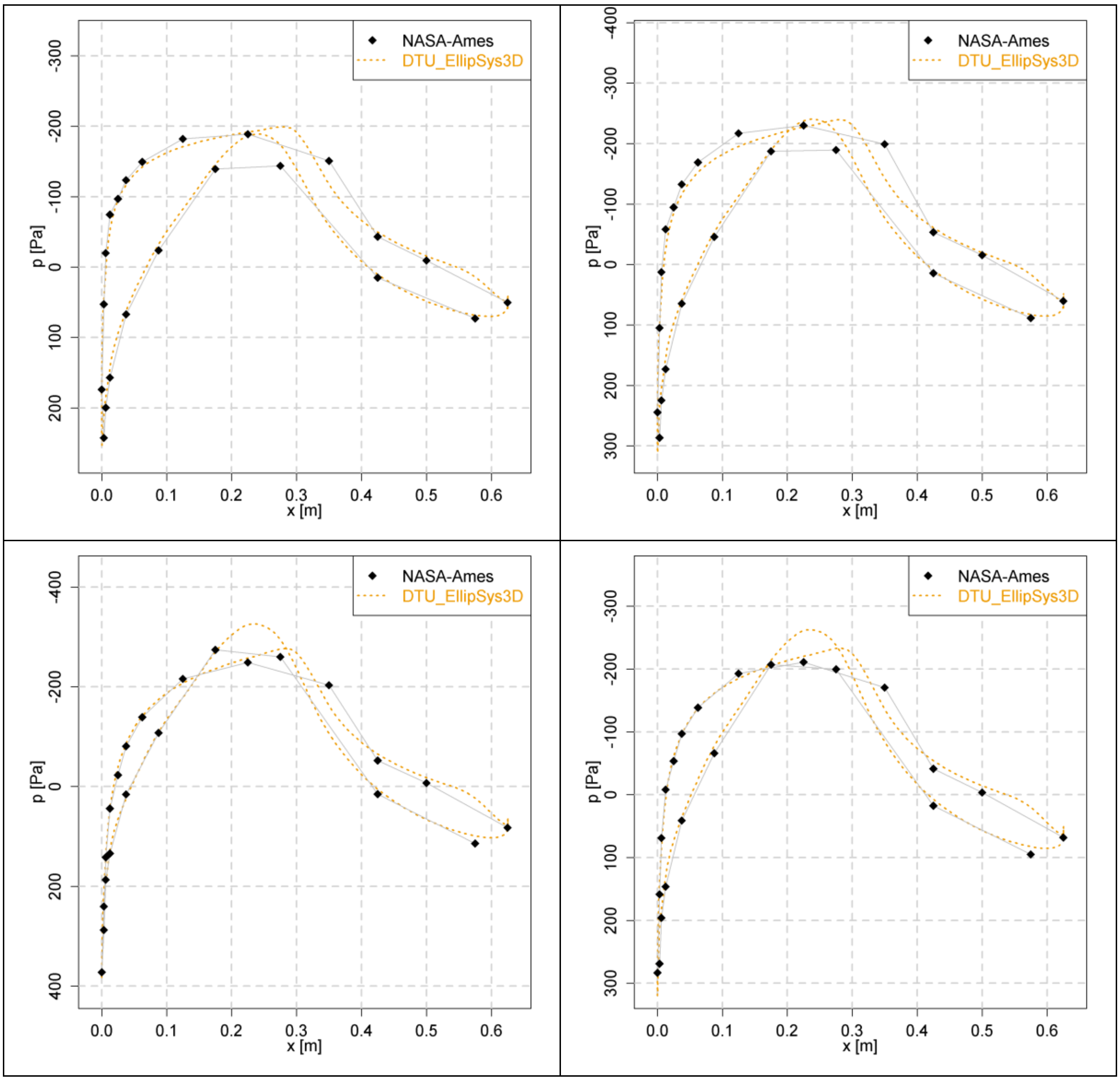


*Figure 4  A comparison of the EllipSys3D results for the 0.47R blade station for a 30 deg. yawed flow with experiment. Case X0500301 from[1] and upper left it is for azimuth 0 deg; upper right 90 deg. azimuth, lower left 180 deg. azimuth and finally lower right 270 deg. azimuth.*

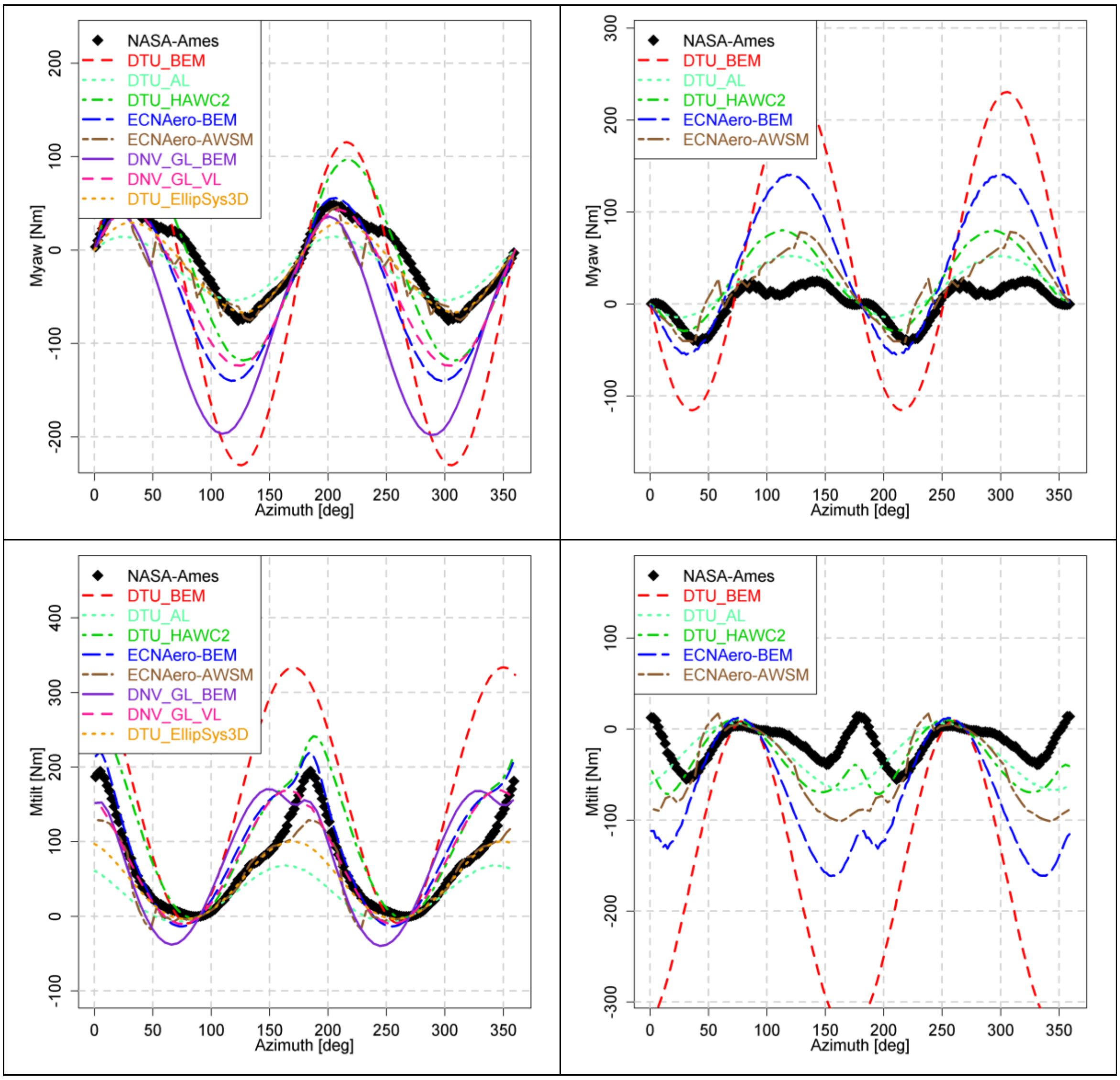


*Figure 5  Results from the validation of two yawed flow cases: left 30 deg. yaw error and right -30 deg. yaw error. In the upper row the yaw moments are shown as function of rotor azimuth position and in the lower row it is the rotor tilt moment as function of rotor azimuth position.*

**DTU contribution as leader of task 4.3: Angle of Attack**

In aerodynamic prediction codes using airfoil data, such as the Blade Element Momentum (BEM) methods or Actuator Disc/Line/Surface Navier-Stokes techniques, angle of attack (AoA) is an important quantity which is required to know at each cross-section on rotor blades. When the AoA is known, the loading on each cross-section can be calculated by using the blade element theory and tabulated airfoil data obtained from 2D wind tunnel measurements with correction to rotational effects. A wrong estimation of the AoA on a rotor blade can influence subsequent predictions of the rotor performance. However the definition, determination and measurement of the AoA on a rotating wind turbine blade is far from straightforward.
As an example of the work carried out within this task is shown the computed AoA with the DTU AL model Figure 6. In this case no measurements of the AoA were available but the computed AoA is used to determine the blade forces and the right graph of Figure 6 shows the computed normal force as function of azimuth for five radial positions. The good correlation of the forces indicates that also the AoA computations have been close to the experimental AoA.

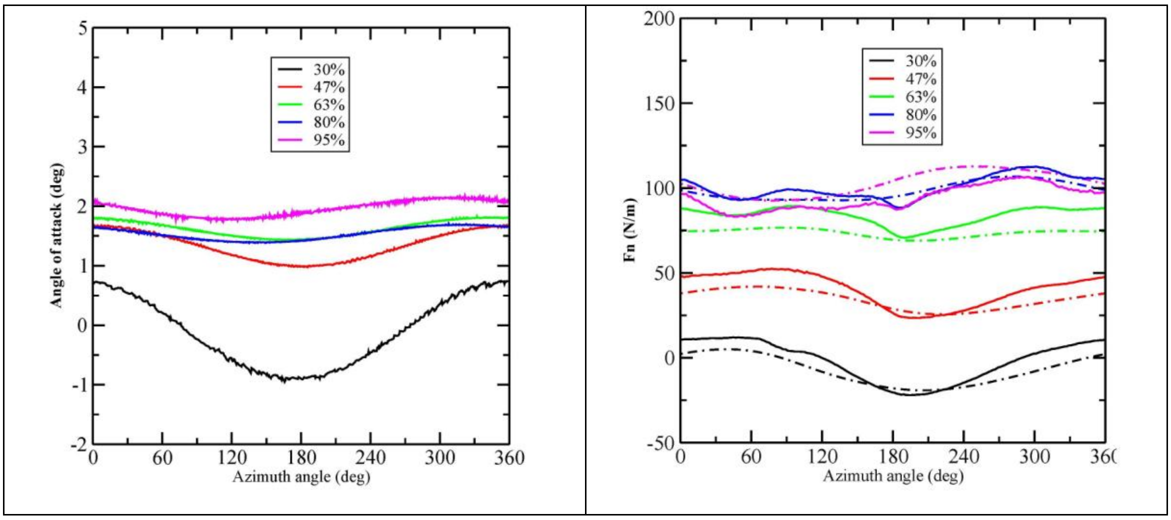


*Figure 6 To the left is shown the computation with the AL code of the AoA at 5 different radial stations for a yaw error at 30 deg for the NREL UAE Phase VI rotor at a rotational speed of 90 rpm and a wind speed of 5m/s. To the right is shown the corresponding normal force computed at the same 5 rotor positions.*

**DTU contribution as leader of task 4.8: Dynamic inflow**

Dynamic inflow is a fundamental flow mechanism related to wind turbine rotor aerodynamics. It covers the unsteady induction flow characteristics related to the response of a change in rotor loading and could therefore also be called “dynamic induction”. Because the Blade Element Momentum model normally used for computation of induction in aeroelastic time simulation models is a steady model, it is necessary to include a sub-model for modeling the dynamic induction. Different engineering models were developed in the 90´s and validated against flapwise blade root moments.

The present task 4.8 work had the following main objectives:

- Identify possible new data sets for studying dynamic induction effects
- characterize dynamic inflow parameters such as time constants
- show the impact on e.g. loading of varying the dynamic inflow time constants
- potential improvement of dynamic inflow models

Besides organizing the work in Task 4.8 DTU has contributed with dynamic inflow measurements from the Siemens 3.6MW turbine from the DANAERO experiment conducted from 2007 to 2010 in Denmark. During the 2 month measurement campaign in the DANAERO experiment the turbine changed its pitch one degree each one minute and this provided a very good data base for studying dynamic inflow events on a full scale turbine. As an example is shown in Figure 7 the power response (blue curve) to a pitch change of 1 deg. It is seen that almost instantaneously (the pitch change takes about one second) the power drops from about 755 kW to 680 kW but then within about 20 sec. recovers to about 730 kW. This time lag is what is important to model correctly in dynamic inflow.
As an example on how simulations compare with measurements a simulation with the BEM model (Blade Element Momentum) in HAWC2 is compared with measurements in Figure 8. The blue curve is simulated using the default time constant in HAWC2 whereas the green curve is simulated with the double constant and the red curve is the result of a simulation with a time constant that is half of the default. It seems that the best correlation is found with the default value in HAWC2.

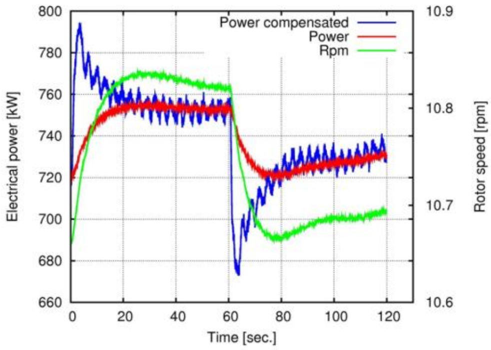


*Figure 7  To the left a photo of the Siemens 3.6MW turbine which was used in the DANAERO project (2007-2010) for inflow measurements that in the present study were used for dynamic inflow investigations. To the right is shown a graph where the blue curve shows the response of aerodynamic shaft power to a pitch change of 1 deg. based on about 600 realizations.*

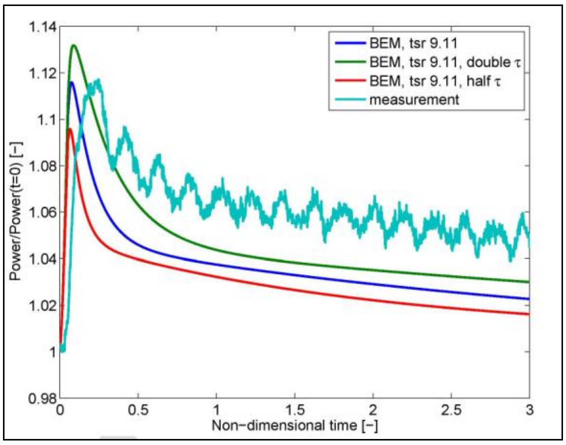


*Figure 8  Comparison of simulated power variations using different time constants with experimental data from Figure 7.*

## 1.6 Utilization of project results

As mentioned above three of the codes, HAWC2, EllipSys3D and AL used for the validation exercises in the present work are used in the industry, certification institutes and at universities. It means that changes in the codes will be present in the new code versions released and thus the project results have a direct link to the end users of the code.

Another use of the project results is for the part of the industry that has developed their own codes. For them it is of big importance to have some data sets that are well assessed and analyzed and that have been used for validation of codes similar to their own type of codes. The considerable interest to get access to the Mexico data base also indicates that many institutes and industries want to use the data in this way.

## 1.7 Project conclusion and perspective

It is the overall experience from the project that experimental data base assessment and code validation in a common international framework and corporation is of considerable value. Assessment of the quality of an experimental data base cannot be done properly only by one or two partners but when up to twenty partners are involved it turns out that it is possible in some cases to identify shortcomings or inaccuracy in the measurements when a majority of the code results show different trends. This was the case with some of the data from the first MEXICO model rotor results from 2006 which were analysed in both the Mexnext and Mexnext II IEA Annex 29 work. A new measurement round on the MEXICO rotor was conducted in the summer 2014 where one of the objectives were to clarify these uncertainties identified in the Mexnext and Mexnext II IEA work. The new data sets from the 2014 campaign will now be analysed in Mexnext III (2015-2017) where Denmark will participate.

**Annex**

**References**


1. J.G. Schepers, K. Boorsma (ECN), S. Gomez-Iradi (CENER), P. Schaffarczyk (Fachhochschule Kiel), H.A. Madsen, N.N. Sørensen, W.Z. Shen (DTU), T. Lutz, C. Schulz (University of Stuttgart), I. Herraez (ForWind), S. Schreck (NREL). "Final report of IEA Wind Task 29: Mexnext (Phase 2)". December 2014, ECN-E--14-060
2. K Nilsson, WZ Shen, JN Sørensen, SP Breton, S Ivanell, "Validation of the actuator line method using near wake measurements of the MEXICO rotor", Wind Energy 2015, vol. 18: 45,5-514 DOI: 10.1002/we.1714.
3. NR Garcia, JN Sørensen, WZ Shen, "Simulation of the yawed MEXICO rotor using a viscous-inviscid panel method", Journal of Physics: Conference Series (Online) (ISSN: 1742-6596) (DOI: http://dx.doi.org/10.1088/1742-6596/524/1/012026), vol: 524, 2014.
4. WZ Shen, WJ Zhu, H Yang, "Validation of the actuator line model for simulating flows past yawed wind turbine rotors", accepted for the 5th Conference on New Energy and Sustainable Development (NESD 2015), Shanghai, and will be published in Journal of Power and Energy Engineering, 2015.
5. Sørensen, N. N., Bechmann, A., Réthoré, P-E., & Zahle, F. (2014). Near wake Reynolds-averaged Navier–Stokes predictions of the wake behind the MEXICO rotor in axial and yawed flow conditions. Wind Energy, 17(1), 75-86. 10.1002/we.1559
6. Guntur, S., & Sørensen, N. N. (2014). A study on rotational augmentation using CFD analysis of flow in the inboard region of the MEXICO rotor blades. Wind Energy, 18(4), 745–756. 10.1002/we.1726
7. Guntur, S., & Sørensen, N. N. (2014). An evaluation of several methods of determining the local angle of attack on wind turbine blades. Journal of Physics: Conference Series (Online), 555, [012045]. 10.1088/1742-6596/555/1/012045.
8. Sørensen, N. N., & Schreck, S. (2014). Transitional DDES computations of the NREL Phase-VI rotor in axial flow conditions. Journal of Physics: Conference Series (Online), 555, [012096]. 10.1088/1742-6596/555/1/012096.

9. Guntur, S., Sørensen, N. N., & Schreck, S. (2013). Dynamic Stall on Rotating Airfoils: A Look at the N-Sequence Data from the NREL Phase VI Experiment . Key Engineering Materials, 569-570, 611-619. 10.4028/www.scientific.net/KEM.569-570.611