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Published in:
Scientific Proceedings

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

DAN-AERO MW: Measured airfoil characteristics for a MW rotor in atmospheric conditions

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Abstract

This paper shows examples on pressure and inflow measurements carried out in the DAN-AERO MW project on both a full scale rotor and in a wind tunnel. Wind tunnel tests in the LM Wind Power LSWT on four airfoil sections identical to the blade sections on the LM38.8 blade were carried out. Also, measurements on an NM80 2MW wind turbine were carried out, including pressure measurements in four sections, inflow measured with four Pitot tubes and several other sensors, such as strain gauges, accelerometers and those controlling the turbine. The pressure measurements as well as the integrated normal force and tangential force coefficients, c_n and c_t, revealing the airfoil performance from the full scale rotor in atmospheric conditions and the airfoil performance in the wind tunnel are compared to reflect the differences and compare to models for 3D correction. A general trend is that the negative slope of the c_n curve just above angles of attack corresponding to maximum c_n as measured in wind tunnels is not as pronounced at the rotor. This can be due to 3D effects or the lack of walls around the section on the rotor. Also, delay of separation was observed, especially for the inner section, which caused an increase in c_n for angles of attack above maximum c_n as measured in the wind tunnel. However, 3D correction of wind tunnel data showed for these measurements too abrupt decrease in the forces for angles of attack just above the maximum normal force coefficient as measured in the tunnel.

Keywords: Rotor aerodynamics, Airfoil aerodynamics, Full scale measurements, Wind tunnel measurements

1. INTRODUCTION

Aerodynamic airfoil characteristics used for design of wind turbines are commonly obtained from wind tunnel tests conducted in two-dimensional (2D) steady, flow conditions. However, at an early stage of the development of modern wind turbines it became clear, based on analysis of measurements on different wind turbines, that the actual airfoil characteristics on a rotor operating in the atmospheric flow could be quite different from the airfoil characteristics measured in a wind tunnel. A method to extract so called 3D airfoil data using measured flapwise loads, thrust and rotor power was presented by Rasmussen et al.[1] using data from a 180 kW turbine. The causes for the differences between 2D and 3D airfoil characteristics were discussed by Madsen et al. [2] and ascribed to 1) spanwise pressure gradients; 2) centrifugal forces in the boundary layer and 3) unsteady and turbulent inflow to the rotor.

Later empirical models were proposed to derive 3D data from 2D data. Mechanisms changing the airfoil characteristics driven by the centrifugal forces and Coriolis forces can be taken into account using different empirical correction methods [3], [4], [5], [6], [7]. The changes close to the tip or close to the root are commonly taken into account using methods such as Prandtl's [8] tip correction model

It is now also possible to extract 3D data from full 3D rotor computations using Computational Fluid Dynamics (CFD), but these complex simulations need further validation. One major uncertainty is that these types of simulations so far have been restricted to non-turbulent, steady inflow conditions. Also the transition modelling in particular in 3D CFD is uncertain. Therefore, measured 3D airfoil characteristics on a MW rotor in natural, turbulent flow environment are needed to compare with standard 2D wind tunnel data. This will be a basis for validation of the 2D to 3D conversion of airfoil data and represent a unique verification basis for 3D CFD computations.

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However, insight to the aerodynamic load on wind turbine rotors has been obtained in the past. In the period from around 1985 to 1995 a number of field test measurements on rotors with a diameter in the range from 10-25 m was conducted at the National Renewable Energy Laboratory, NREL (US), Risø Wind Turbine Test Station (DK), Energy research Centre of the Netherlands (ECN), Delft University of Technology (NL) and Imperial College (UK). The Risø experiment comprised measurements of local aerodynamic forces at three stations on one of the blades on a 19 m rotor and correlation with inflow measurements with a five-hole Pitot tube. The derived 3D airfoil characteristics were found to differ considerably from 2D wind tunnel characteristics [9].

A collaborative and coordinated analysis of the different field rotor experiments was carried out within the IEA Annexes XIV and XVIII, which improved the insight into 3D airfoil characteristics on rotors considerably. However, it was also realized that the influence of the natural turbulence in the wind complicated the interpretation of the results. To overcome this, NREL (US) conducted the Unsteady Aerodynamics Experiment (UAE) on a 10 m diameter horizontal axis wind turbine (HAWT) in the NASA Ames 80 feet by 120 feet (24.4 m by 36.6 m) wind tunnel in year 2000 [10]. The experiment was designed to provide accurate and reliable experimental measurements, having high spatial and temporal resolution, for a realistic and rotating blade geometry, under closely matched conditions of dynamic similarity, and in the presence of strictly controlled inflow conditions. Also these data were analyzed and utilized for code development and validation within IEA Annex XX. Later in 2006 a European team conducted a complementary wind tunnel turbine test designated MEXICO (Model Rotor Experiments In Controlled Conditions) [11]. The MEXICO Project was directed toward acquiring high quality experimental data, by testing a well instrumented 4.5m diameter rotor in the DNW 9.5 m x 9.5 m wind tunnel. This experiment comprised comprehensive measurements of the flow field around the rotor using the PIV technique. Also this data set is now utilized in a collaborative work within IEA Task 29 MEXNEXT.

Also, airfoil characteristics have been extracted from measurements carried out by standard instrumentation [12], i.e. with blades instrumented with strain gauges in five radial positions. These characteristics supported the findings from 3D CFD computations and other rotor measurements. However, details about the aerodynamics e.g. inflow turbulence, laminar/turbulent transition and dynamic inflow could not be extracted from these measurements.

The above mentioned data sets have contributed significantly to model development and validation and not the least for validation of CFD rotor computations. On the other hand there are some serious limitations for the wind tunnel models when knowledge should be transferred to full scale MW rotors. The most important is the influence from the unsteady and turbulent inflow, which in the end has to be taken into account although it complicates detailed aerodynamic measurements as well as simulations. Another major drawback of the wind tunnel data sets is that the rotors are not representative for modern MW rotor designs and do not contain the influence of the control system. Finally, there is always the uncertainty from the much lower Reynolds number in the wind tunnel experiments compared with full-scale conditions. Thus, the derivation of airfoil characteristics still introduces uncertainty and conservatism in the rotor design process.

That was the reason for setting up the DANAERO MW tests, where the aerodynamics and loads can be studied in detail on a 2MW NM80 wind turbine [13][14][15][16]. The analyses of the measurements are carried out in the DANAERO MW II project, which will be finalised at the end of 2011. In this paper airfoil characteristics from the four different radial stations at r/R=0.325, 0.475, 0.750 and 0.925 on the 40m-blade are shown as a result of the initial part of the analysis and compared to wind tunnel data from measurements on exact copies of the four airfoil sections. Data in terms of pressure distributions and integral values such as normal and tangential force are shown. Also, the 2D wind tunnel data is converted for use in rotor computations using a 3D correction model [7] for comparison to the full scale measurements.

2. EXPERIMENTAL APPROACH

In this work two different types of measurements were used as a basis:

1. Pressure and inflow measurements on one of the LM 38.8 m blades on the NM80 2 MW turbine at the small Tjæreborg Wind farm in Jutland, Denmark. Such data is needed to know how the aerodynamic characteristics are on a real wind turbine and how 2D wind tunnel data should be transferred to 3D.

2. Measurement on four airfoils with the exact same geometry as the four blade sections on the LM38.8 blade are carried out in 2D in the LM Wind Power wind tunnel. Such data commonly creates the basis for the derivation of airfoil characteristics used for wind turbine design.

2.1 Wind tunnel experiments

The specific objectives with the wind tunnel experiments in the DANAERO MW project were to 1) Investigate the turbulence characteristics in wind tunnels and investigate its correlation with boundary layer transition and surface pressure spectra and 2) Measure 2D airfoil characteristics of the four specific sections on the LM 38.8 m blade for comparison with 3D airfoil characteristics on the NM80 rotor.

Even though the wind tunnel turbulence is an important parameter with influence on the transition characteristics on the airfoils, emphasis is in this work put on how well the pressure measurements in the wind tunnel and on the wind turbine in atmospheric conditions agree. In the wind tunnel the four 2D sections with exactly the same geometry as the four sections on the LM38.8 m blade were tested at corresponding Reynolds numbers. This was done by scanning the blade shape at *r/R*=0.325, 0.475, 0.750 and 0.925 and manufacturing corresponding airfoil models. Each airfoil model had 64 pressure taps around the airfoil with the pressure taps more closely positioned at the leading edge than at the trailing edge. The chord lengths for the airfoil models were 0.900m giving Reynolds numbers between $1.5x10^6$ and $6x10^6$. The airfoil lift was predicted by integrating the pressure distribution around the airfoil and the airfoil drag was predicted by integrating the velocity deficit in the airfoil wake measured by a wake rake. For more details about the measurements in the LM Wind Power Low Speed Wind Tunnel (LSWT) see [17].

2.2 Inflow and surface pressure measurements on the 2MW NM80 turbine

A new LM38.8 m blade was manufactured for the 2MW NM80 wind turbine and during the production process, equipment for measuring surface pressure profiles at four radial stations, *r/R*=0.325, 0.475, 0.750 and 0.925, with 64 pressure taps in each section were placed inside the blade, Figure 1. In this way pressure distributions were obtained and integrating the pressure distributions resulted in normal forces and tangential forces normal to and parallel with the chord length, respectively. Additionally, the most outboard blade section was instrumented with 56 microphones to measure high frequency surface pressure spectra for e.g. determination of position of transition. At nearly the same position a high frequency Pitot tube was placed adjacent to a normal five hole Pitot tube for measuring the high frequency (5-10 kHz) turbulence contents in the inflow. Also, strain gauges and accelerometers have been mounted in ten radial sections of the blade to read the structural response. Apart from the pressure and microphone measurements, data was continuously sampled in 10-min series. Within the 10-min period the surface pressure was sampled in 9min and 30sec and for each minute 10sec microphone measurements were carried out. Measurement campaigns were carried out between mid July and mid September 2009 giving around 300 10-min time series of data. The turbine was operating with normal Pitch Regulated Variable Speed (PRVS) and with constant rotational speed and constant pitch to let the turbine operate as a stall regulated turbine.

The surface pressures were sampled using Scanivalve pressure transducers at a sampling rate of 100 samples/sec. It was expected that the length of the tubes from the surface pressure taps to the pressure transducers influenced the response, so that the pressures effectively were sampled at a lower sampling rate. The four 5-hole Pitot tubes were Aeroprobe tubes sampling with 35 samples/sec. From these tubes the total velocity, the angle of attack and the slip angle can be determined. The rotational speed of the rotor, the atmospheric pressure and the temperature were also sampled with 35 samples/sec.

Sensors used

In this investigation the following sensors have been used:

- 4 x 64 surface pressure taps at four different radial sections
- 4 x five hole Pitot tubes at four radial stations: *r/R*=0.363, 0.508,0.775 and 0.900
- Rotational speed of rotor
- Atmospheric pressure and temperature

Figure 1 A photo of the instrumented LM38.8 m blade (top) and the NM80 turbine with the test blade installed (bottom).

Predicting the angle of attack

The results from wind tunnel tests are commonly polars in terms of lift, drag and moment coefficients as a function of angle of attack. These data are used in aeroelastic calculations with corrections of e.g. 3D effects. In this way the rotor performance and the loads on the entire wind turbine can be predicted. However, the angle-of-attack term is an entity, which is not possible to measure directly on or at the blade. The bound circulation on the blade and the downwash are some of the effects influencing the flow around the blade sections. Thus, even though Pitot tubes are measuring the angle of attack, the measured angles are not corresponding to those measured in wind tunnels, because angles of attack in the tunnel are measured as the pitch angle of the airfoil with corrections of blockage, streamline curvature and downwash. The hypothesis in this analysis is that the pressure distributions corresponding to airfoil flow is similar in the wind tunnel and at the rotor. In this way transfer functions from angles of attack measured by the Pitot tubes and angles of attack measured in wind tunnels are established. In situations with attached flow it is expected that good agreement will be seen for all parts of the pressure distribution despite of the rotational effects. This is based on experience from 3D CFD calculations on several rotors. However, with separated flow a delay of the separation is expected based on observations from other experiments and therefore a good agreement is generally expected on the pressure side and close to the trailing edge on the suction side. Therefore, angles of attack are estimated in an optimization process, where pressure distributions measured at the rotor are compared to pressure distributions measured in the wind tunnel, by minimizing the standard deviation of the pressure differences with higher weight from x/c=0.40 to x/c=1.00 at the pressure side and x/c=0.70 to x/c=1.00 at the suction side and lower weight on the rest of the airfoil.

However, in the analysis process it turned out that the inner section, Section 03 at r/R=0.325, needs special treatment. For each measured pressure distribution on the rotor similar distributions from the wind tunnel were searched for, but the agreement was far less pronounced than on the three other sections. Thus, another method for searching for the right pressure distributions was developed for the inner section. Since the dynamic pressure and the angle of attack were determined for the three outer sections, the corresponding inflow velocity can be predicted and good correlations between the inflow velocities for these sections are observed. This was the reason for assuming that the inflow velocity for the inner section, Section 03 at r/R=0.325, can be determined by extrapolating/regression of the inflow velocities from the outer sections.

3 RESULTS

In the following, results from an analysis of a number of selected time series are shown.

2.1. Pressure distributions

Figure 2 shows pressure distributions corresponding to lowest and highest angles of attack extracted from these time series and compared to the wind tunnel data. The pressure distributions are normalized as:

$$C_p = \frac{p_\infty - p}{0.5 \rho W^2}$$

Where C_p is the normalized pressure, p_∞ is the static pressure [Pa] in the far field, p is the pressure [Pa] measured at the blade surface, ρ is the air density [kg/m^3] and W is the relative velocity [m/s]. For the three outboard sections the agreement is very good. For low angles of attack the pressure distributions are very similar and fit well both at the leading edge and trailing edge. However, at high angles of attack Section 05 (r/R=0.475) shows deviations between pressure distributions in the tunnel and on the rotor. The pressure recovery from minimum pressure to the trailing edge is not as abrupt on the rotor as in the tunnel. This could be caused by 3D effects on the rotor, but could also be the influence from the walls in the wind tunnel. This is yet unknown. However, for the inner section, Section 03 at r/R=0.325, the agreement is not so good. The pressure around the leading edge fits well, but the pressure around the trailing edge does not agree as well as for the three outer sections even at fairly low angles of attack. At higher angles of attack, as shown in Figure 2, the pressure distribution measured on the rotor is much bigger than from the wind tunnel and a nearly constant pressure level is reached at a chord position closer to the trailing edge at the rotor (*x/c*=0.44) compared to the wind tunnel data (*x/c*=0.38). This indicates the position of the separation point, which again indicates a delay in stall on the rotor compared to the wind tunnel.

To investigate the precision of this method to derive airfoil characteristics for the rotor the derived angles of attack and dynamic pressures, called "synthetic", are compared to those measured by the Pitot tube in Section 05. There is a distinct trend, however with some scatter of data. This was the reason not to use the Pitot tube measurements directly and it indicates the degree of correlation between angles of attack and pressure distributions.

2.2. Integrated forces

Figure 4 shows the normal force coefficients c_n and Figure 5 shows the tangential force coefficient c_t integrated from the pressure distributions for the rotor and for wind tunnel flows both with clean surface and leading edge roughness (LER). The normal force coefficient, c_n, and the tangential force coefficient, c_t, were computed, respectively, as:

$$c_n = \frac{n}{0.5 \rho W^2 c}$$

$$c_t = \frac{t}{0.5 \rho W^2 c}$$

where *n* and *t* is the normal and tangential force per meter [N/m] , respectively, integrated from the C_p distributions, ρ is the air density [kg/m^3], *W* is the relative velocity [m/s] and *c* is the chord length [m]. For the three outboard sections the agreement is very good for both c_n and c_t. However, it seems that comparing to maximum c_n for the clean wind tunnel model the rotor showed slightly lower c_n. This could be caused by surface roughness or differences in surface quality, i.e. the roughness height on the airfoil surface. More interesting, it seems that the decrease in c_n for angles of attack above maximum c_n observed in the characteristics from the wind tunnel is less pronounced on the rotor at Section 05 at *r/R*=0.475. This might be controlled by centrifugal/Coriolis forces or controlled by the lack of walls around the airfoil section. For the inner section, Section 03 at *r/R*=0.325, the agreement is good, but not as good as the other sections with higher scatter in the values even at low angles of attack. This is due to the method used, where the inflow velocity found by extrapolation/regression of the inflow velocities measured at the outer sections and where angles of attack are not determined by comparison of pressure distributions. At high angles of attack the c_n values in stall are higher than in the wind tunnel which indicates that the separation is delayed like for Section 05. It should be noted that the plot of c_n shows wind tunnel data at two Reynolds numbers, Re=3x10^6 and 5x10^6. The data is different in stall, with low Re c_n higher than the high Re c_n. The increase of c_n in stall supports earlier observations of higher c_n values when separation starts.

Figure 6 shows c_n polars for the two blade sections at the inner part of the rotor, compared to polars derived from wind tunnel tests corrected for 3D effects using the model by Bak et al. [7]. Only the two inner sections are considered because it is only those that are significantly affected by the 3D correction model. However, it seems that the drop in c_n for angles of attack just above maximum c_n still exists despite of the 3D correction. With the given wind tunnel data in Section 03 and 05 it seems that the 3D correction is too small compared to the actual data from the rotor. However, this is mainly due to the drop in c_n just after maximum c_n.

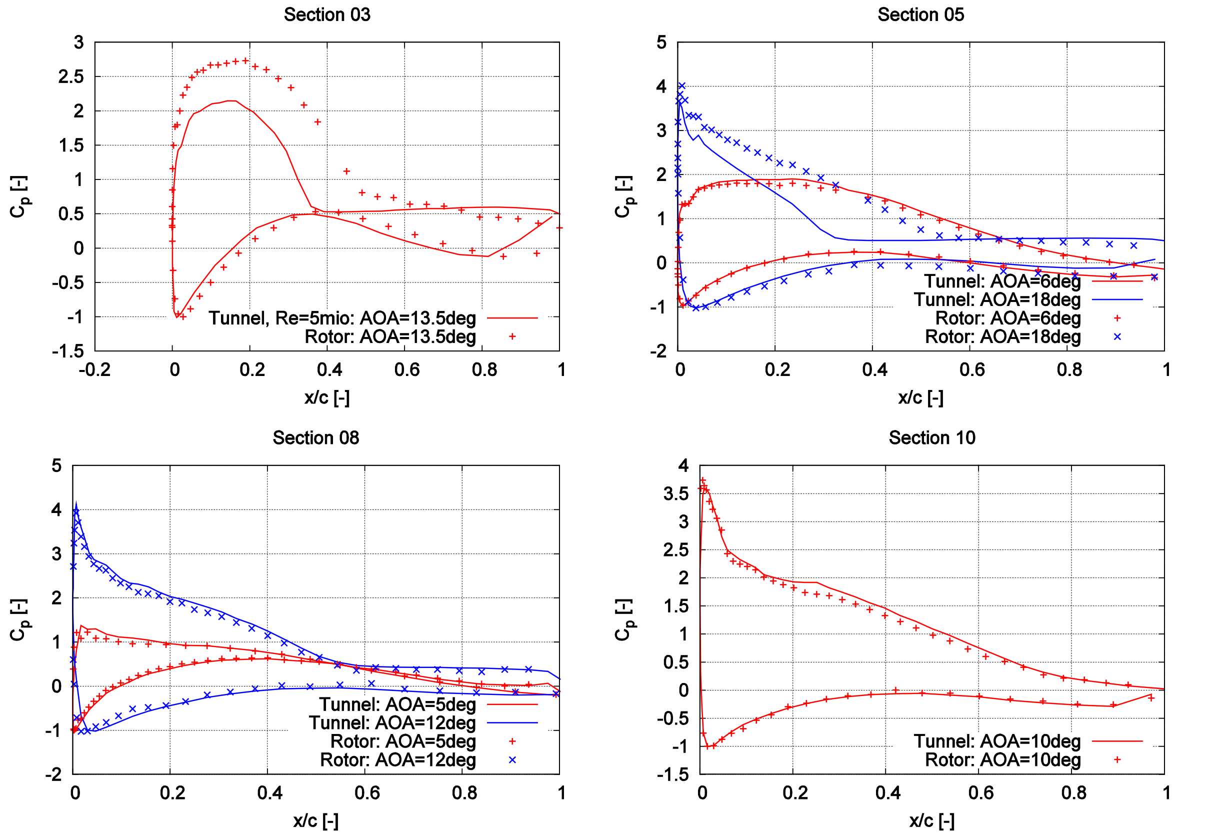

Figure 2 Pressure measurements for four different blade sections. Upper left: Section 03 (r/R=0.325). Upper right: Section 05 (r/R=0.475). Lower right: Section 08 (r/R=0.750). Lower left: Section 10 (r/R=0.925).

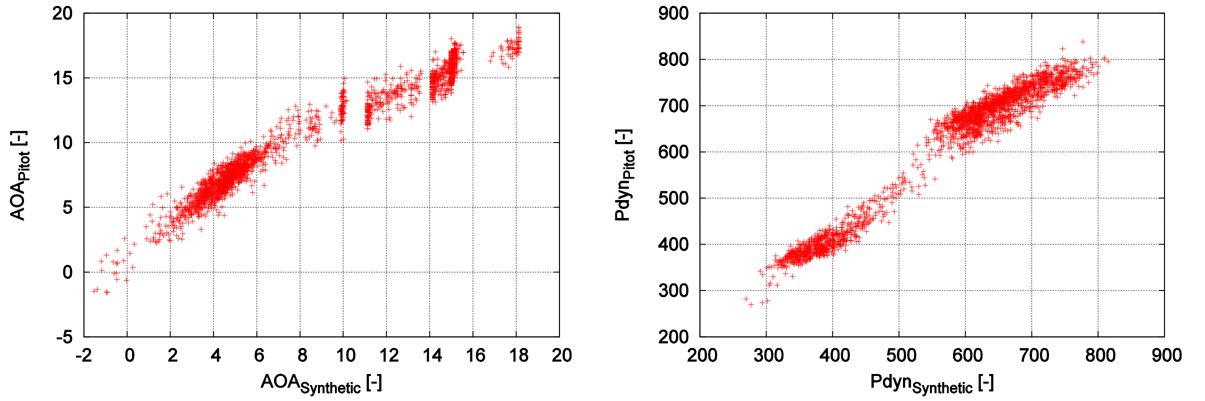

Figure 3 Angles of attack (left) and dynamic pressures (right) predicted by comparing pressure distributions from the rotor with pressure distributions from the wind tunnel ("synthetic") plotted against the angles of attack and dynamic pressures as measured by the Pitot tube in Section 05 ("Pitot"), respectively.

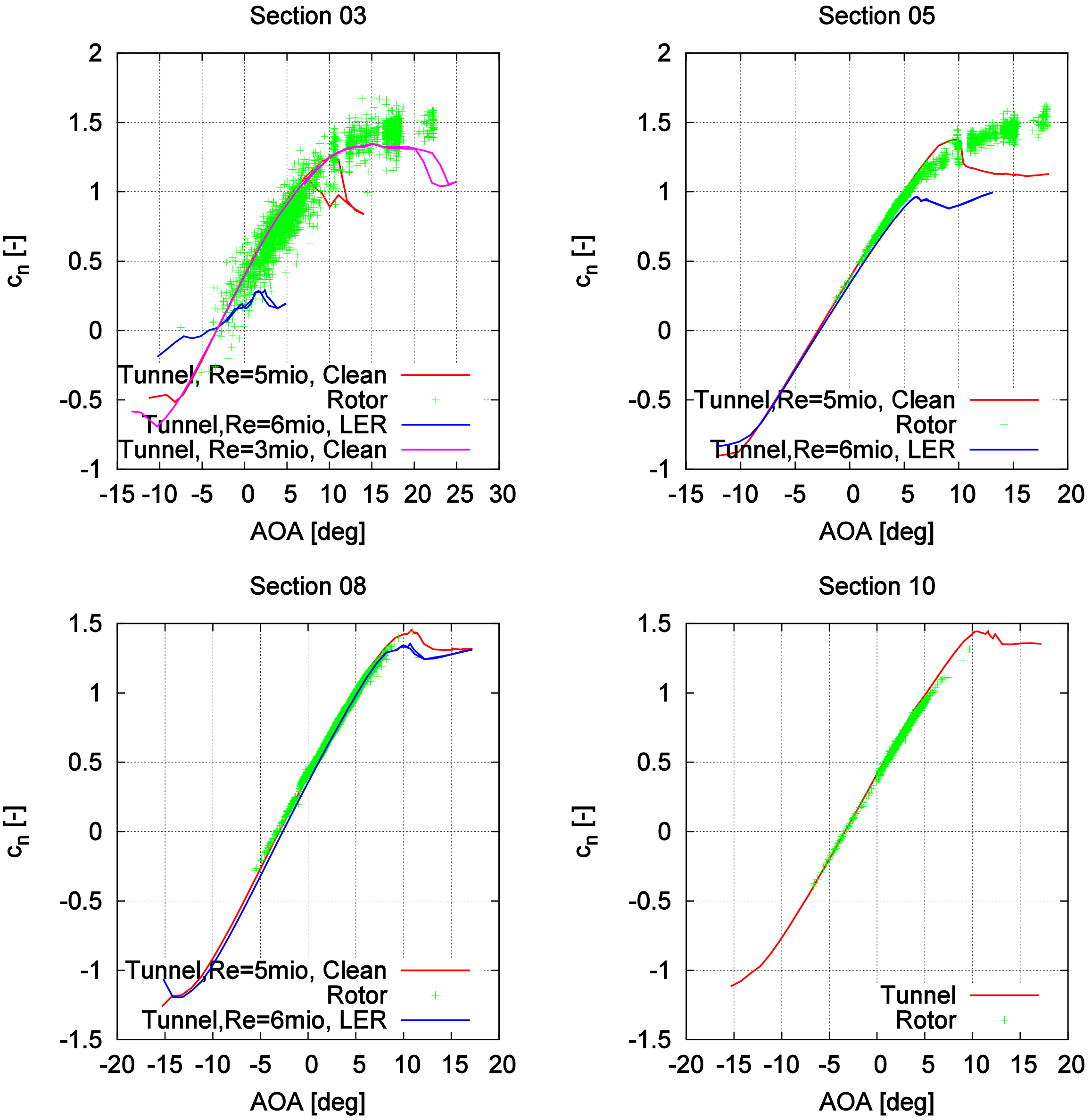

Figure 4 Measured c_n polars for four different blade sections. Upper left: Section 03 (r/R=0.325). Upper right: Section 05 (r/R=0.475). Lower left: Section 08 (r/R=0.750). Lower right: Section 10 (r/R=0.925).

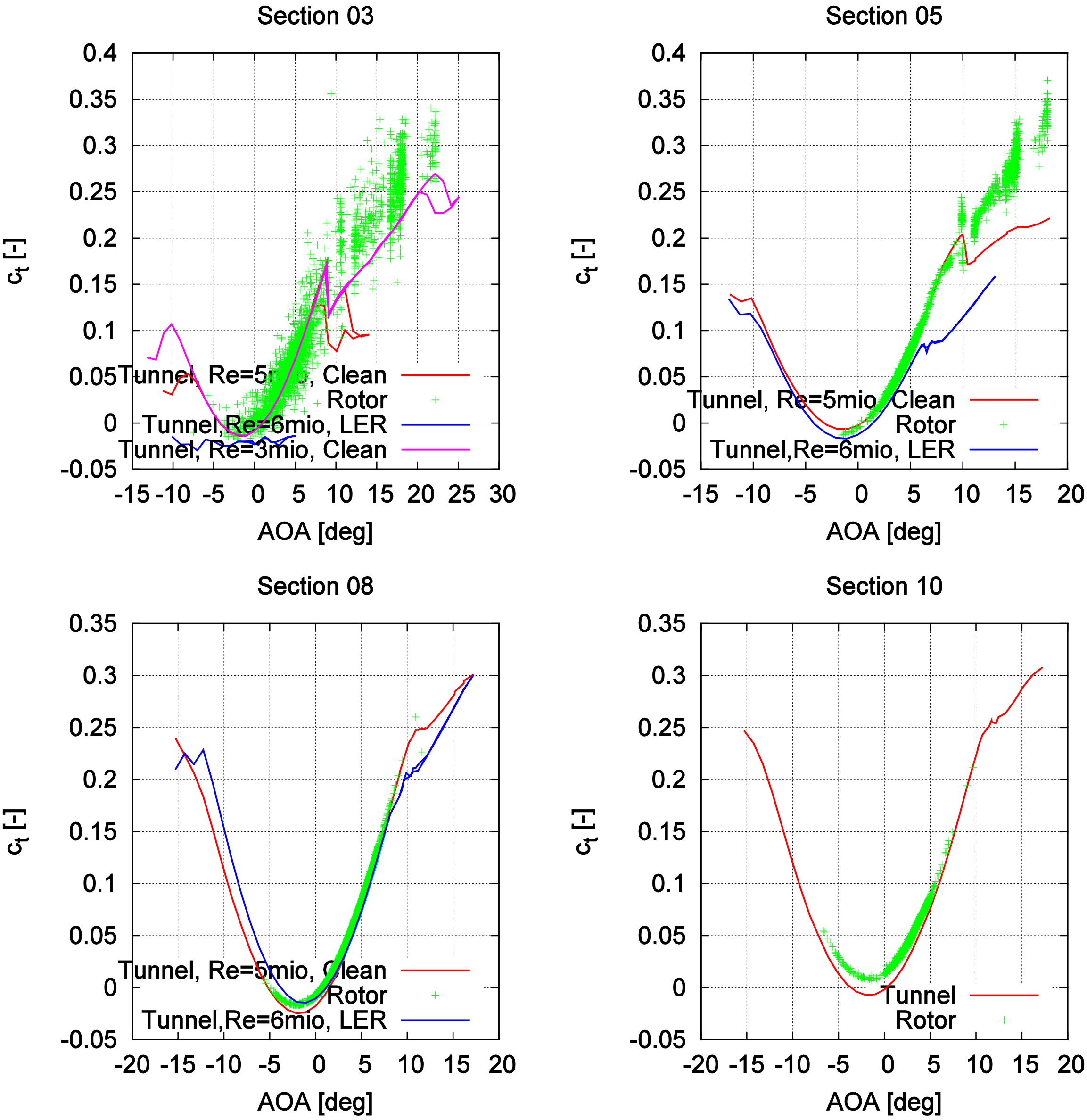

Figure 5 Measured c_t polars for four different blade sections. Upper left: Section 03 (r/R=0.325). Upper right: Section 05 (r/R=0.475). Lower left: Section 08 (r/R=0.750). Lower right: Section 10 (r/R=0.925).

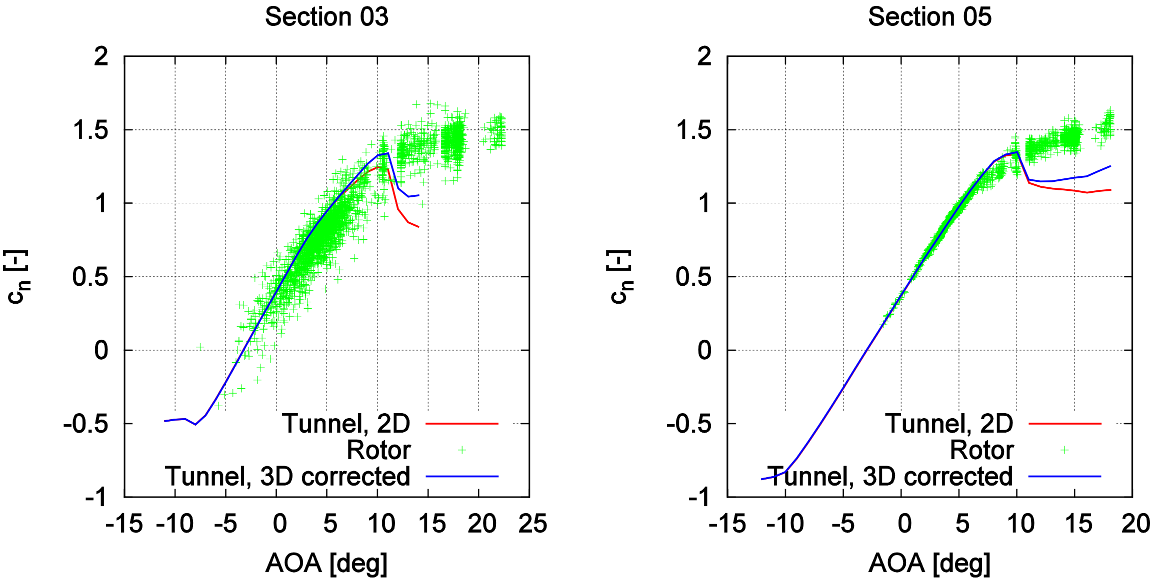

Figure 6 Measured c_n polars for two different blade sections compared to 3D corrected wind tunnel data using the method by Bak et al [7]. Left: Section 03 (r/R=0.325). Right: Section 05 (r/R=0.475).

4 CONCLUSION

This paper showed examples on pressure and inflow measurements carried out in the DAN-AERO MW project on both a full scale rotor and in a wind tunnel. Wind tunnel tests in the LM Wind Power LSWT on four airfoil sections identical to the blade sections on the LM38.8 blade were carried out. Also, measurements on an NM80 2MW wind turbine were carried out, including pressure measurements in four sections, inflow measured with four Pitot tubes and several other sensors, such as strain gauges, accelerometers and those controlling the turbine. The pressure measurements as well as the integrated normal force and tangential force coefficients, c_n and c_t, revealing the airfoil performance from the full scale rotor in atmospheric conditions and the airfoil performance in the wind tunnel are compared to reflect the differences and compare to models for 3D correction. A general trend is that the negative slope of the c_n curve just above angles of attack corresponding to maximum c_n as measured in wind tunnels is not as pronounced at the rotor. Whether this is due to 3D effects or the lack of walls around the section on the rotor is not known. Also, delay of separation was observed, especially for the inner section, which caused an increase in c_n for angles of attack above maximum c_n as measured in the wind tunnel. However, 3D correction of wind tunnel data showed for these measurements too abrupt decrease in the forces for angles of attack just above the maximum normal force coefficient as measured in the tunnel.

Since the airfoil characteristics are in the phase of being analyzed to reveal the challenges, further work is planned. More time series are needed to expand the angles-of-attack range, but this requires re-calibration of some of the sensors that broke down during the test period in the sense that they changed characteristics. Also, other ways of deriving the airfoil characteristics will be considered.

5 ACKNOWLEDGEMENTS

This project was funded partly by the Danish Energy Authorities, EFP2007 and EUDP2009-II and partly by eigenfunding from the project partners. Also, this project was only possible because of skilled people at the different partners. Thanks to Vestas Wind Systems, Siemens Wind Power, LM Wind Power and DONG Energy for their invaluable support. Special thanks to the research technicians Per Hansen, Michael Rasmussen and Kasper Clemmensen (Risø DTU), the technicians at LM Wind Power, who made the building of the blade and the entire measurement system a success and the technicians at Vestas Wind Systems who made the test on the NM80 possible.

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