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DAN-AERO MW: Detailed aerodynamic measurements on a full scale MW wind turbine

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The paper describes experiments carried out within the collaborative, three year DAN-AERO MW research project between Risø DTU and the industrial partners LM Glasfiber, Siemens Wind Power, Vestas Wind Systems and the utility company DONG Energy. The main objective of the project is to establish an experimental data base which can provide new insight into a number of fundamental aerodynamic and aero-acoustic issues, important for the design and operation of MW turbines. The most important issue is the difference between airfoil characteristics measured under 2D, steady conditions in a wind tunnel and the unsteady 3D flow conditions on a rotor. One hypothesis is that different transition characteristics might explain some of the difference between the 2D wind tunnel airfoil characteristics and 3D airfoil characteristics and the experiments have been set up to provide data on this subject. The overall experimental approach is to carry out a number of coordinated, innovative measurements on full scale MW rotors as well as on airfoils for MW turbines in wind tunnels. Shear and turbulence inflow characteristics are measured on a Siemens 3.6 MW turbine with five hole pitot tubes. Pressure and turbulent inflow characteristics are measured on a 2MW NM80 turbine with an 80 m rotor. One of the LM38.8 m blades on the rotor are replaced with a new LM38.8 m blade where instruments for surface pressure measurements at four radial sections are built into the blade during the blade production process. Additionally, the outmost section on the blade is further instrumented with 56 microphones for high frequency surface pressure measurements. The surface pressure measurements are correlated with inflow measurements from four five hole pitot tubes and a sensor for measuring the high frequency (5-10 kHz) contents of the inflow turbulence. Furthermore, 121 other signals are measured: for instance flap and edgewise blade moment in ten radial sections, accelerometers, wind speeds from a mast in six heights and several other wind turbine parameters such as pitch, rotational speed, power etc. In parallel to the full scale tests, 2D wind tunnel measurements on common airfoils for wind turbine applications have been conducted in three different wind tunnels at Delft University (NL), at LM Glasfiber (DK) and at VELUX (DK). Also, wind tunnel tests on exact copies of the four airfoil sections on the LM38.8 blade are carried out. Initial results from the different measurement set-ups will be presented in order to show the application areas for the total data set.

I. Introduction

Today, the derivation of 3D airfoil data from 2D wind tunnel data still introduces uncertainty and conservatism in the rotor design process although different empirical correction methods have been developed[1,2,3,4,5]. 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 modeling and in particular in 3D 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 improve the 2D to 3D conversion of airfoil data and also represent a unique verification basis for 3D CFD computations.

Experiments have been carried out on wind turbine rotors mounted with pressure taps, Pitot tubes etc. These tests were on rotors between 4.5m and 10m rotor diameter[6,7]. However, this size and the test conditions were far from the size and conditions for modern MW rotors.

A fundamental problem is related to the load variations over MW rotors with a diameter of 100 m or more. These load variations, which are due to wind shear and turbulence causes considerable dynamic variation in induction over the rotor swept area and the modeling of this with the Blade Element Momentum (BEM) method is uncertain. Generally, there is a need for detailed characterization of the inflow characteristics on MW rotors and not the least to get experimental data for the higher frequencies in the inflow, which is thought to be important for the transition from laminar to turbulent boundary layer on the rotating blade.

The new MW rotors are almost exclusively erected in wind farms, which means that operation in wakes from upstream turbines is a major part of total life time. Detailed measurements of flow characteristics in full scale wakes are sparse but on the other hand strongly needed for further improvements of wake modeling.

II. Objectives

The overall objective of the project is to carry out a number of innovative, coordinated experiments in wind tunnels as well as on full scale wind turbine rotors, designed to provide data that can improve our knowledge of some fundamental aerodynamic, aeroelastic and aeroacoustic issues and in general improve the design basis for MW rotors. Specifically the experiments are designed to provide new insight into:

- correlation between 2D and 3D airfoil characteristics
- boundary layer transition characteristics in 2D wind tunnel flow environment compared with full scale 3D rotor flow transition characteristics
- inflow characteristics (shear and turbulence) on MW rotors with particular focus on the high frequency content
- dynamic induction characteristics
- wake flow characteristics
- pressure fluctuations in the boundary layer influencing turbulent inflow noise and trailing edge noise

III. Experimental approach

The overall experimental approach is to carry out a number of coordinated, innovative measurements on full scale MW rotors as well as on airfoils for MW turbines in wind tunnels. Three types of measurements are performed:

1. Measurement on 2D airfoil sections in three wind tunnels at Delft University (NL), LM Glasfiber (DK) and at Velux (DK). Also, four airfoils with the exact same geometry as the four blade sections on the LM38.8 blade are measured in 2D.
2. Measurement of inflow characteristics on the 3.6 MW Siemens wind turbine at the Høvsøre test site (DK)

3. Pressure and inflow measurements (including high frequency kHz data) on one of the blades (LM 38.8 m blade) on the NM80 2 MW turbine at the small Tjæreborg Wind farm in Jutland (DK)

Wind tunnel experiments

The specific objectives with the wind tunnel experiments are the following

1. Verify and investigate the difference in 2D airfoil characteristics measured in three different wind tunnels, which have been used for testing airfoils for wind turbines
2. Investigate the turbulence characteristics in the wind tunnels and investigate the correlation with boundary layer transition and surface pressure spectra
3. Measure the 2D airfoil characteristics on the four specific sections on the LM 38.8 m blade for comparison with 3D airfoil characteristics on the NM80 rotor.

We have found that it was important to get information on how much the airfoil data from different wind tunnels deviates. Therefore we have tested two airfoils, the B1-18 and the NACA 63-418 airfoils, in the three wind tunnels mentioned above, which in the past have been used for a number of measurement campaigns on airfoil sections for wind turbines.

The turbulence characteristics in the tunnels is an important parameter with influence on the transition characteristics on the airfoils and initial measurements with hotwires have been performed to determine the turbulence spectra in two of the tunnels. Furthermore, generation of additional turbulence with grids in the LM tunnel has been performed.

Position of transition has been determined by analyzing the PSD spectra of the high frequency surface pressure fluctuations measured with microphones mounted close to the blade surface, Figure 1

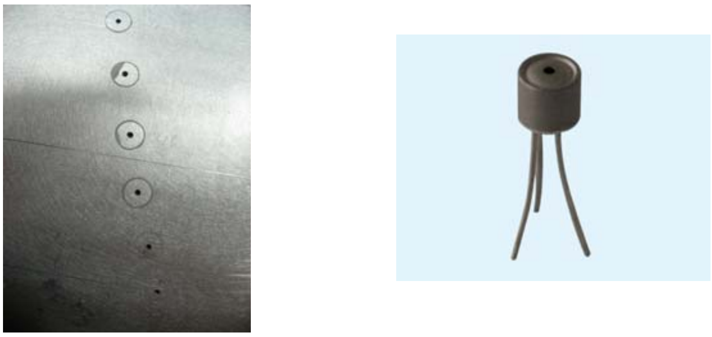


Figure 1 Microphones with a diameter of around 4 mm installed about 1 mm below the surface of the airfoil to measure high frequency surface pressure fluctuations

Finally, 2D sections with exactly the same geometry as the four sections on the LM38.8 m blade will be manufactured and tested in the LM wind tunnel in August 2008.

Inflow measurements on the Siemens 3.6 MW turbine

A five hole pitot tube was installed at radius 36 m on the Siemens 3.6 MW turbine at the Høvsøre test site in Jutland (DK). The Høvsøre test site is the Danish center for testing MW turbine and is situated a few kilometers from the west coast of Jutland.

Figure 2 A five hole pitot tube mounted on a tube from the leading edge of the blade in radius 36 m to measure inflow characteristics (shear and turbulence)

Inflow and surface pressure measurements on the 2MW NM80 turbine

A new LM38.8 m blade has been manufactured for the turbine and during the production process, equipment for measuring surface pressure profiles at four radial stations with 64 pressure taps in each section were placed inside the blade, Figure 3. 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 the same position a high frequency pitot tube is placed adjacent to a normal five hole Pitot tube the 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 aeroelastic response.

The manufacture and the instrumentation of the blade were finished already 2008 and it was installed on the turbine in May 2009. Measurement campaigns have been and will be carried out from June to September 2009.

Apart from the pressure and microphone measurements data is 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.

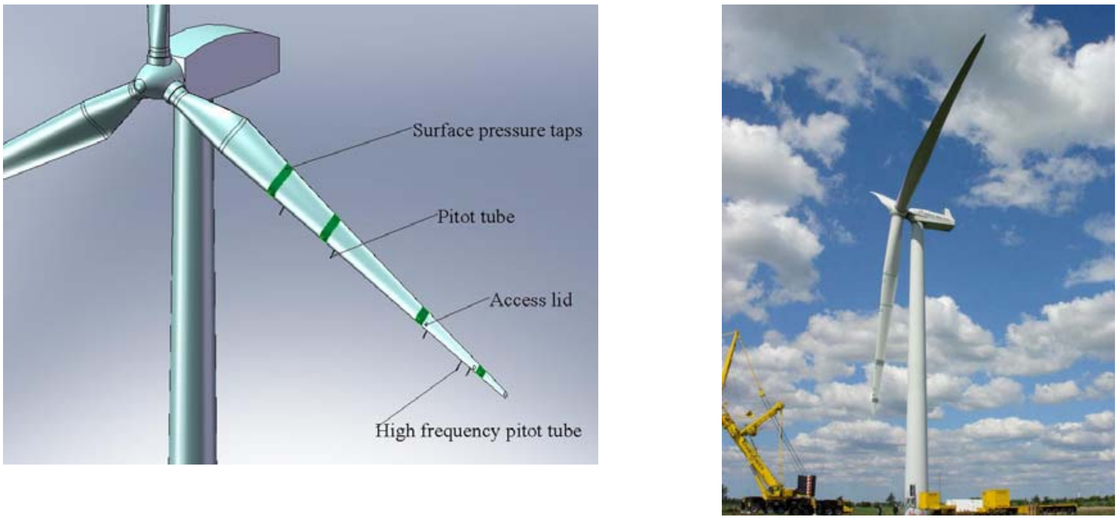


Figure 3 A sketch of the instrumented LM38.8 m blade to the left and to the right the NM80 turbine with the test blade installed on May 13 2009.

IV. Results

A few results will be presented from each of the three main experimental parts in the project to illustrate the future detailed usage of the data for studying the above mentioned fundamental aerodynamic and aeroelastic issues.

Wind tunnel tests

One of the new techniques used in the present project is the high frequency surface pressure measurements with microphones. These data can be used to derive the aerodynamic as well as the aeroacoustic characteristics of the airfoil section. As an example is shown test results for the B1-18 airfoil tested at a Re. no. of 3 mill. in the LM tunnel, Fig. 4. The spectra of the signal for the microphone at a position of 10% chord length from the leading edge is shown in the left figure in Figure 4 at different angle of attack (AOA). Up to an AOA of 7 deg. the spectra show almost no dependency on AOA and are close to a background microphone placed just outside the tunnel. However, at 8 deg. AOA the spectrum changes considerably with a peek around 4 kHz and if the AOA is increased to 9 deg. it becomes almost flat in a considerable frequency interval. Comparing now with similar measurements but with the airfoil flow tripped close to the leading edge, shown in the right graph of Figure 4, all the spectra are almost flat with a slight increase in level as function of AOA. It can thus be concluded, that there is a considerable difference in the spectra above 1 kHz for a laminar and a turbulent boundary layer flow, respectively, and this difference can be used to determine the transition point if the microphones are positioned close to each other in chord-wise direction. The same instrumentation is used at one section on the LM38.8 m blade and will allow detection of transition point on the rotating blade.

In the final paper more results from the different wind tunnel test will be shown.

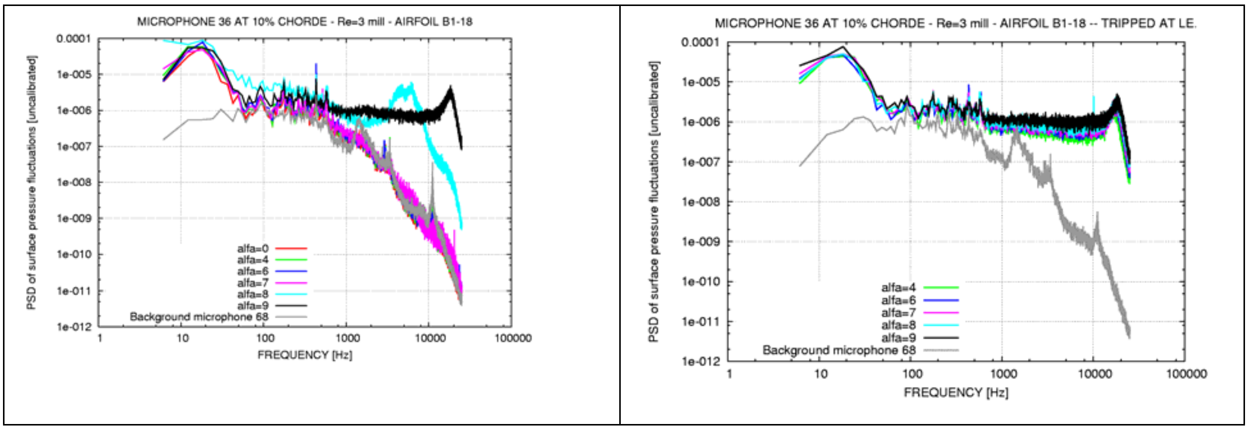
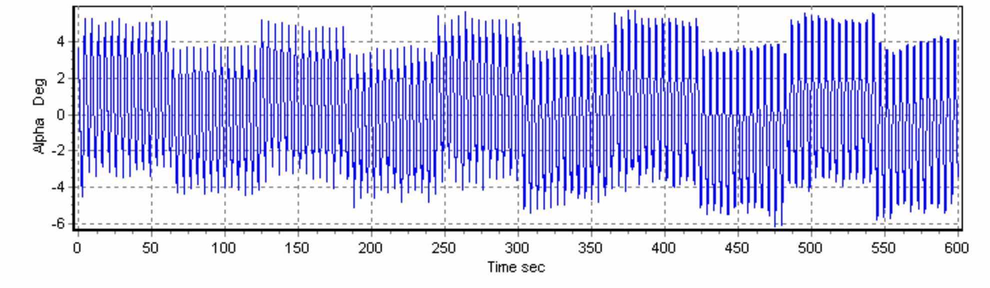


Figure 4 To the left is PSD spectra of surface pressure fluctuations at different angle of attack for a non-tripped airfoil in the LM wind tunnel and to the right the same for tripped flow.

Inflow measurements on the Siemens 3.6 MW turbine

The inflow measurements with one five hole pitot mounted at a radius of 36 m on one of the blades was initiated in March 2007 and a considerable data base on different inflow situations including wakes from other turbines has been established from this measurement period. As an example of one type of inflow is shown data from a period in the spring 2007 where a very stable boundary layer flow developed during the night resulting in strong shear and low turbulence, upper graph in Figure 5. Then during the following morning the heating of the flow by the sun caused mixing so that the strong shear gradually disappeared but also with an increase in turbulence, lower graph in Figure 5.

During night – low turbulence and strong wind shear



During day – turbulence and moderate wind shear

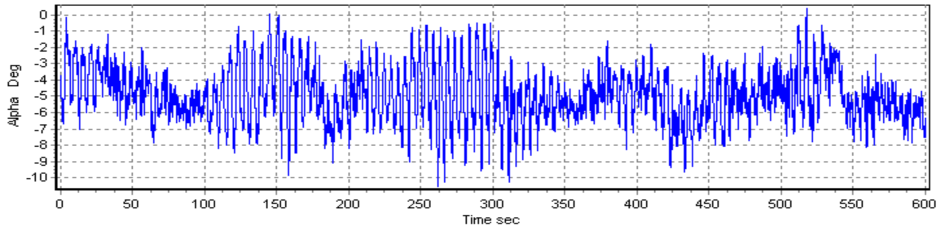


Figure 5 To the left is PSD spectra of surface pressure fluctuations at different angle of attack for a nontripped airfoil in the LM wind tunnel and to the right the same for tripped flow. In the upper figure the pitch is changed in a step for each 1 min. period.

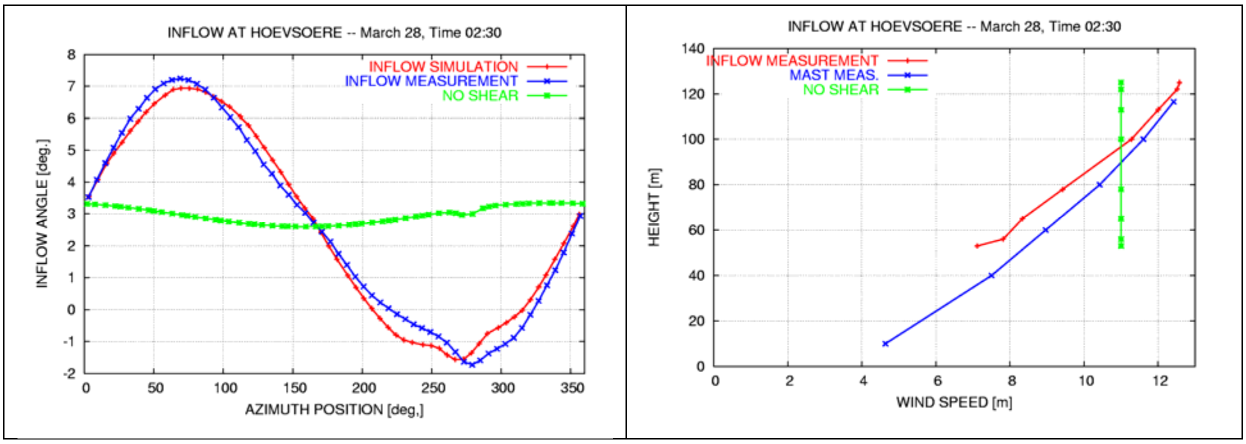


Figure 6 A procedure has been developed so that the measured inflow angle as function of rotor azimuth (blue curve) can be converted to an estimate of the wind shear for the axial flow component as well as the cross component, red curve.

The inflow measurements describe directly the variation in inflow to the rotating blade. However, for some applications it is desirable to be able to estimate the shear in a fixed reference frame and corrected for the induction and from the local upwash. Such a procedure has been developed and one example is shown in Figure 6, where the shear has been derived as an average over the rotor disc from a height interval corresponding to the pitot tube in bottom and top position, red curve in right figure in Figure 6. A comparison is made with measurements from a nearby met. mast (blue curve).

More results on inflow will be included in the final paper

Pressure and inflow measurements on the NM80 turbine

The measurements on the NM80 2MW wind turbine have been carried out from June and will end mid September 2009. The measurements are carried out for the turbine operating with normal Pitch Regulated Variable Speed (PRVS) and with constant rotational speed and pitch to let it operate as a stall regulated turbine. Until now more than 100 time series have been measured. Because the data acquisition is divided into three synchronized parts, results will be presented in three sub sections: 1) 10min measurements of strain gauges, accelerometers, Pitot tubes, wind, general wind turbine setting etc at 35Hz, 2) 9min and 30sec measurements of blade surface pressure at four sections at 100Hz and 3) 10sec measurements of pressure fluctuations using microphones at 50kHz. Only one time series is shown to give the impression of the data set. This series is from 21. July 2009, 11:20AM to 11:30AM, with the wind turbine in PRVS configuration. However, more data will be shown in the final paper.

Wind turbine data

Figure 7 shows wind turbine data in terms of wind speeds and wind direction.

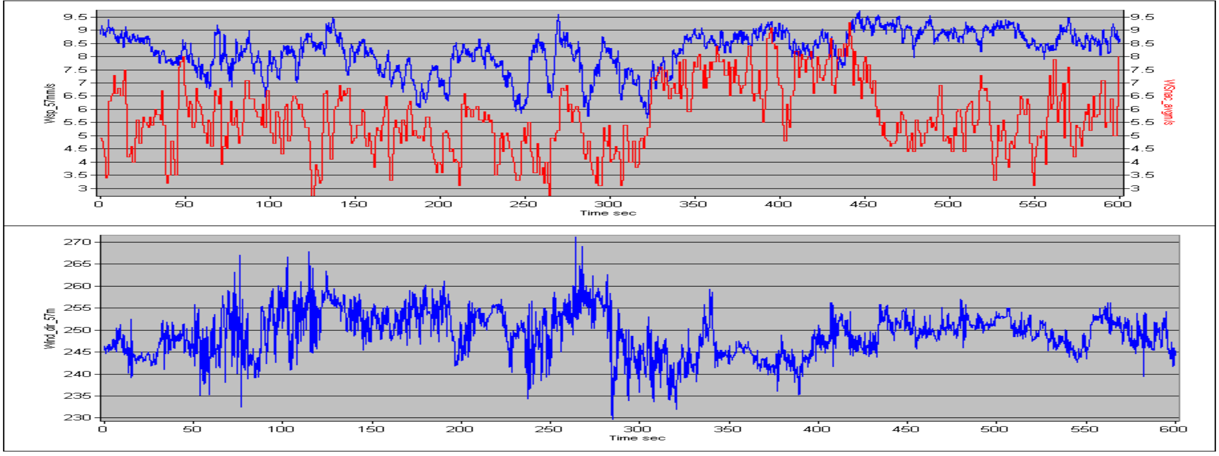


Figure 7 Wind turbine data for the NM80. Top plot: Wind speed from mast (57m height) with blue and from nacelle (57m height) with red. Bottom: Wind direction from mast (57m height).

Pressure measurements

Figure 8 shows mean pressure distributions from the 9min and 30sec measurement series. Section 03 to Section 10 is from the inner most section at r/R=0.325 to the outer most section at r/R=0.925. With a further analysis out-of-plane and in-plane force coefficients can be shown as a function of inflow angle of attack. Also, with a further analysis these polars can be compared to 2D wind tunnel measurements carried out on the exact same geometry.

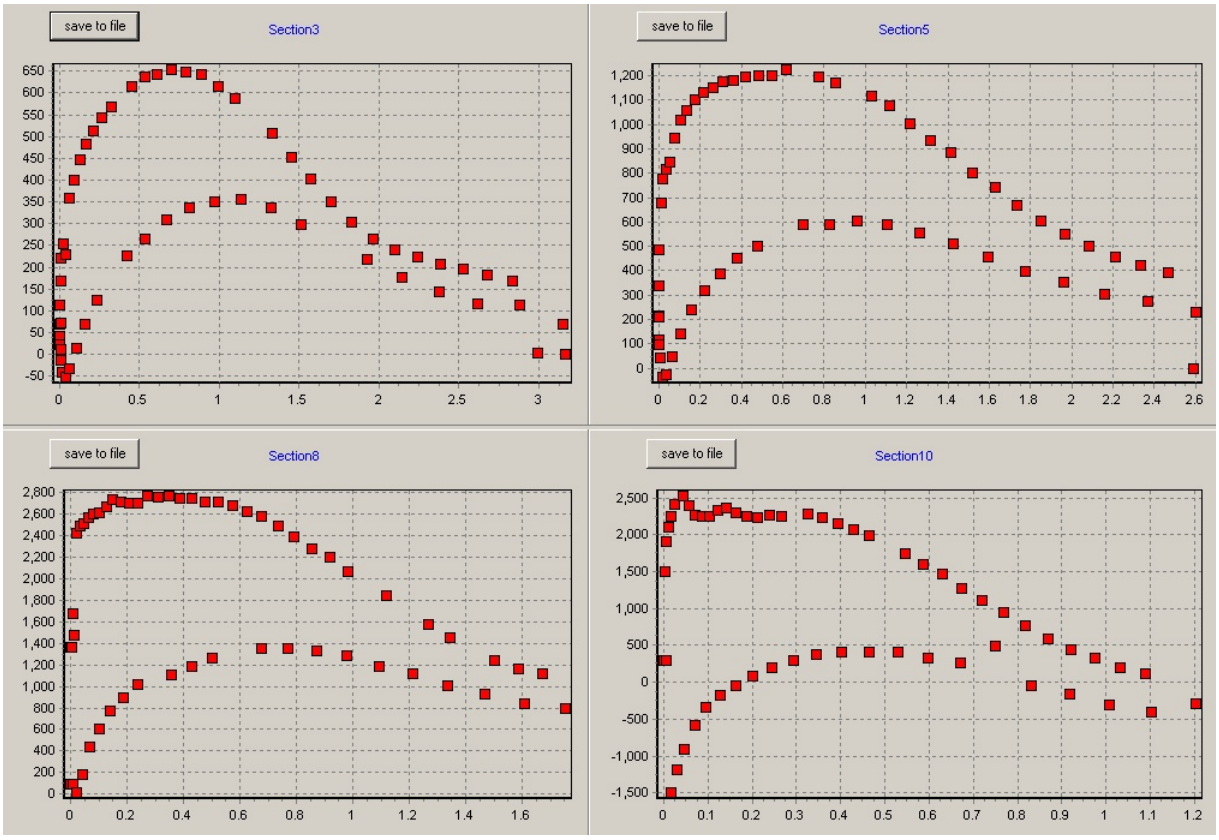
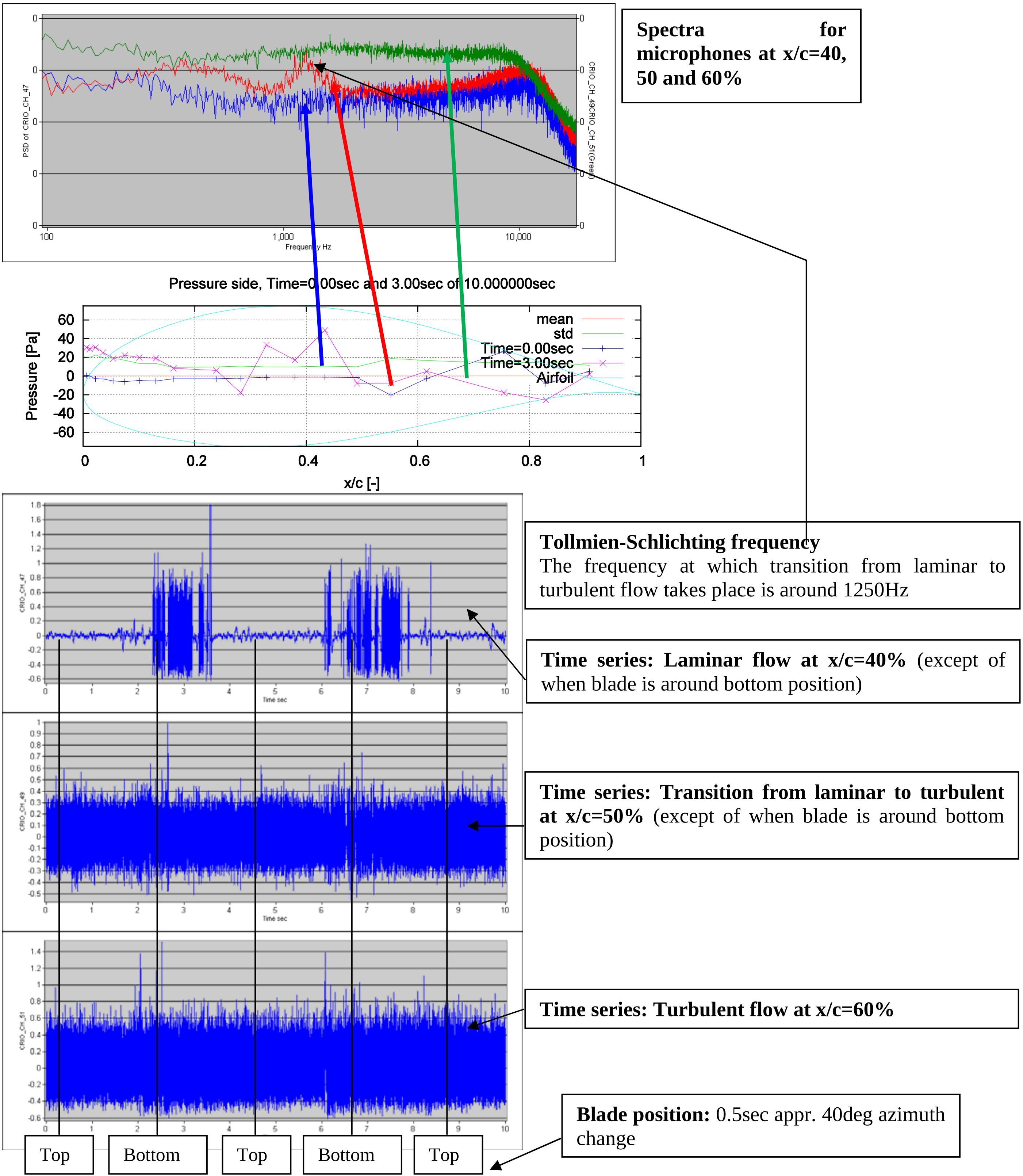


Figure 8 Pressure measurements for four different blade sections: Section 03 (r/R=0.325), Section 05 (r/R=0.475) , Section 08 (r/R=0.750) and Section 10 (r/R=0.925). From measurements 21. July 2009 11:20 to 11:30AM. The pressure is shown in psi.

Microphone measurements

Figure 9 shows results from a 10sec time series from the microphones mounted at the pressure side at r/R=0.925 (r=37m). The data shows clearly the transition from laminar to turbulent flow, which takes place from x/c=0.4 to x/c=0.6. Also, it shows how the transition point is dependent on the blade azimuth position, where the transition point moves towards the leading edge when the blade is the bottom position. Whether this is due to the tower shadow or differences in the inflow characteristics requires more analysis. Also, the Tollmien-Schlichting frequency, where the transition from laminar to turbulent appears is clearly seen around 1250Hz.



Spectra for microphones at x/c=40, 50 and 60%

Tollmien-Schlichting frequency
The frequency at which transition from laminar to turbulent flow takes place is around 1250Hz

Time series: Laminar flow at x/c=40% (except of when blade is around bottom position)

Time series: Transition from laminar to turbulent at x/c=50% (except of when blade is around bottom position)

Time series: Turbulent flow at x/c=60%

Blade position: 0.5sec appr. 40deg azimuth change

Figure 9 Microphone measurements on r=37.0m (r/R=0.925) on the pressure side.

V. Conclusions

This paper showed examples on some of the measurements carried out in the DAN-AERO MW project. Wind tunnel tests in different tunnels have been carried out and also wind tunnel tests on four airfoil section identical to the blade sections on the LM38.8 blade were carried out. Inflow measurements were carried out on the Siemens 3.6MW turbine which shows interesting results on shear and how the shear develops during the day. Finally, measurements on an NM80 2MW wind turbine were carried out including pressure measurements in four sections, surface-microphones in one section, inflow measured with four Pitot tubes and one Pitot tube with high frequency and several other sensors, such as strain gauges, accelerometers and turbine settings. All, measurements were carried out successfully and especially the measurements on the NM80 wind turbine requires detailed analysis to compare to existing and new models.

VI. Acknowledgements

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VII. References

[1] Snel, H.; Houwink, R.; van Bussel, G.J.W.; Bruining, A., ‘Sectional Prediction of 3D Effects for Stalled Flow on Rotating Blades and Comparison with Measurements’, Proc. European Community Wind Energy Conference, Lübeck-Travemünde, Germany, 8-12 March, 1993, pp. 395-399, H.S. Stephens & Associates

[2] Du, Z.; Selig, M.S., ‘A 3-D Stall-Delay Model for Horizontal Axis Wind Turbine Performance Prediction’, AIAA-98-0021, 36th AIAA Aerospace Sciences Meeting and Exhibit, 1998 ASME Wind Energy Symposium, Reno, NV, USA, January 12-15, 1998

[3] Chaviaropoulos, P.K.; Hansen, M.O.L., ‘Investigating Three-Dimensional and Rotational Effects on Wind Turbine Blades by Means of a Quasi-3D Navier Stokes Solver’, J. Fluids Engineering, vol. 122, June 2000, pp. 330-336.

[4] Lindenburg, C., ”Modelling of Rotational Augmentation Based on Engineering Considerations and Measurements”, European Wind Energy Conference, London, 22-25 November 2004

[5] Christian Bak, Jeppe Johansen, Peter B. Andersen, Three-Dimensional Corrections of Airfoil Characteristics Based on Pressure Distributions, Presented at the European Wind Energy Conference & Exhibition (EWEC), 27. Feb. – 2. Mar. 2006, Athens, Greece

[6] Herman Snel, Gerard Schepers, THE MEXICO PROJECT: ANALYSIS OF YAW MEASUREMENT AND COMPARISON WITH EXISTING MODELS, Presented on EWEC 2008

[7] Hand, M., Simms, D., Fingersh, L., Jager, D., Cotrell, J., Schreck, S., and Larwood, S., “Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns,” NREL/TP-500-29955, December 2001. Available electronically at http://www.nrel.gov/docs/fy02osti/29955.pdf