Final Results from Mexnext-I: Analysis of detailed aerodynamic measurements on a 4.5 m diameter rotor placed in the large German Dutch Wind Tunnel DNW

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Abstract. The paper presents the final results from the first phase of IEA Task 29 ‘Mexnext’. Mexnext was a joint project in which 20 parties from 11 different countries cooperated. The main aim of Mexnext was to analyse the wind tunnel measurements which have been taken in the EU project ‘MEXICO’. In the MEXICO project 10 institutes from 6 countries cooperated in doing experiments on an instrumented, 3 bladed wind turbine of 4.5 m diameter placed in the 9.5 by 9.5 m² open section of the Large Low-speed Facility (LLF) of DNW in the Netherlands.

Pressure distributions on the blades were obtained from 148 Kulite pressure sensors, distributed over 5 sections at 25, 35, 60, 82 and 92 % radial position respectively. Blade loads were monitored through two strain-gauge bridges at each blade root. Most interesting however are the extensive PIV flow field measurements, which have been taken simultaneously with the pressure and load measurements. As a result of the international collaboration within this task a very thorough analysis of the data could be carried out and a large number of codes were validated not only in terms of loads but also in terms of underlying flow field.

The paper will present several results from Mexnext-I, i.e. validation results and conclusion on modelling deficiencies and directions for model improvement. The future plans of the Mexnext consortium are also briefly discussed. Amongst these are Mexnext-II, a project in which also aerodynamic measurements other than MEXICO are included, and ‘New MEXICO’ in which additional measurement on the MEXICO model are performed.

1. Introduction

This report describes the progress of IEA Task 29 ‘Mexnext’. The first phase of Mexnext (Mexnext-I) ran for 3 years from June 1 2008 until the end of 2011 [1]. The main aim of Mexnext-I was to analyze the measurements from the European Union project ‘MEXICO’ (Model Rotor Experiments In Controlled Conditions). In this project 10 institutes from 6 countries cooperated in doing experiments on an instrumented, 3 bladed wind turbine of 4.5 m diameter placed in the open section of the Large Low-speed Facility (LLF) of the German-Dutch Wind Tunnels (DNW) in the Netherlands. The measurements were performed in December 2006 and resulted in a database of combined blade pressure distributions, loads and flow field measurements with PIV, which have been used for aerodynamic model validation and improvement. In Mexnext-I a total of 20 participants from 11 different countries participated.
1.1. Test set-up

The 4.5 meter diameter, three bladed MEXICO rotor features tapered and twisted blades with three different aerodynamic profiles (DU91-W2-250, RISØ-A1-21 and NACA 64-418). The blades were tripped at suction and pressure side to avoid possible laminar separation phenomena. The turbine is placed in the 9.5 × 9.5 m² open jet configuration as illustrated in Figure 1.

Pressure distributions on the blades were obtained from 148 Kulite absolute pressure sensors, distributed over 5 sections at 25%, 35%, 60%, 82% and 92% radial position respectively. An external six component balance (i.e. the blue structure beneath the model in Figure 1(a)) recorded the total rotor loads statically. Blade loads were monitored through two strain-gauge bridges at each blade root. Pressures and strains were sampled at 5.5 kHz. Extensive flow field mapping of the three velocity components has been done by DNW with stereo PIV measurements. The flow field measurements were combined with balance, pressure and blade root strain gauge measurements.

Figure 1. MEXICO wind tunnel setup
The definitions and conventions of the experiment are shown in Figure 2. The rotor azimuth angle is defined such that 0 degrees corresponds to the '12 o clock' position of blade 1 (Note that the MEXICO rotor rotates clock-wise and blade 1 features the pressure sensors at 25%, 35% span, blade 2 the sensors at 60% span and blade 3 the sensors at 82.92% span). A horizontal x-y coordinate system is used, with the x-coordinate along the tunnel velocity direction (x=0 in the rotor plane) and the y-coordinate is oriented outboard in radial direction at the 9 o’clock position (y=0 in the rotor center). For describing radial traverses in yawed conditions also a model based coordinate system is used.

The results presented in this paper have all been taken at a rotational speed of 424.5 rpm. At 424.5 rpm a chord based Reynolds number of approximately $0.8 \times 10^6$ was reached without entering into noticeable compressible conditions. The measurements were performed at different tunnel speeds (denoted with $U_\infty$) ranging from 10 m/s to 30 m/s, yielding tip speed ratios $\lambda$ between 3.3 and 10. Note that the design tip speed ratio is 6.67, which corresponds to $U_\infty = 15$ m/s at 424.5 rpm. Different yaw angles and pitch angles were covered, including the design pitch angle of -2.3 degrees. A more detailed description of the MEXICO experiment can be found in [2].

![Figure 2. Definitions and conventions of the MEXICO experiment](image)

2. Summary of main results from Mexnext-I
The final report of Mexnext-I is given in [1]. Moreover a large number of papers and journal articles have been published about the first phase of the Mexnext. A complete list of these references is given in [1] and can be found at www.mexnext.org/resultsstatus. Obviously it is not possible to describe all results of Mexnext-I within this paper. Therefore this section gives a summary of the most important results and section 3 describes the comparison between calculations and measurements. In summary the main results from Mexnext-I are:

- It is the combination of measurements of detailed aerodynamic loads and detailed flow field which makes the MEXICO experiment unique. Moreover the MEXICO experiment was repeated on two smaller scales which led to insights into scaling effects.
- Generally speaking the understanding of the 3D flow field around a wind turbine and the near wake has increased enormously and an assessment could be made of several codes on basis of loads and velocity measurements.
• At first sight the agreement between calculated and measured loads is less than expected from other projects (e.g. the blind comparison from IEA Task 20, [3]). Further analysis shows that the calculational results from IEA Task 20 were generally more randomly distributed in a wide spread around the measured results. In Mexnext the level of disagreement is of the same magnitude but it is striking to see that all loads along the blade are consistently over predicted.

• The experimental uncertainties have been studied together with the tunnel effect. Most studies on tunnel effects indicate little disturbance. Further CFD calculations are still to be performed including more detail. The repeatability of the measurements is very satisfactory. However, some questions on the implementation and calibration of the measurement apparatus are still open.

• Some puzzling results are found on the relation between loads and velocities, see e.g. [4]. This is discussed in more detail in section 3.1.2.

• Despite the fact that some results are not understood it is extremely important to note that many flow details around a wind turbine are predicted extremely well, even in yawed conditions. Examples of that are shown in section 3.2.2 and 3.2.3.

• All engineering codes under predict the loads at stalled conditions. The same was found in the comparisons made with measurements from IEA Task 14/18 and NREL Phase VI (NASA Ames). It was found that CFD predicts these loads better. CFD also predicts the loads under yawed conditions better than most engineering models. Examples are shown in Figures 3 and 6.

• Directions have been given for engineering model improvement: As an example stall delay effects should be enhanced and the tip speed ratio dependency in the Prandtl tip loss factor should be adjusted. Furthermore, in case of non axi-symmetric flow, the velocities at a particular blade should include the velocities induced by the bound vortex of the other blades.

• The MEXICO experiment was repeated on two smaller scales. Information from these experiments led to insights on scaling effects. As an example, [4] points out that there is an effect of the rotational speed on the aerodynamic load coefficients near stall for such small turbines. This could be a result of a Reynolds number effect or a rotor speed dependency on 3D stall effects. For the original MEXICO experiment no rotor speed dependency is found at all. Moreover the scaled down experiments are useful to comprehend several non-understood results from the MEXICO experiments since it can be checked whether similar phenomena occur on a smaller scale.

• The MEXICO data analyzed in Mexnext are stored in a reported database, which, after signing an NDA is made accessible to outside parties.

• Results have been published and presented in at least 30 papers and articles.

3. Comparison between calculations and MEXICO measurements
One of the most important tasks in Mexnext-I was the comparison between calculations and MEXICO measurements. Thereto calculations have been supplied by almost all Mexnext participants with a large variety of codes ranging from simple lifting line models to more advanced CFD codes. These results have been produced for axial flow and yawed flow conditions.

3.1. Axial flow conditions
3.1.1. Loads Measurements have been reproduced for tunnel speeds of 10, 15 and 24 m/s (where the pitch angle is -2.3 degrees and the tip speed is 100 m/s). The tunnel speed of 15 m/s represents design conditions, a tunnel speed of 10 m/s represents turbulent wake conditions and
a tunnel speed of 24 m/s represents stalled conditions. Then Figures 3 shows the results of the normal forces as function of the radial position for $U_\infty=15$ m/s and $U_\infty=24$ m/s.

It is found that the lifting line codes under predict the normal force at the inner part of the blade at stall (24 m/s) where the agreement at 15 m/s (and 10 m/s) is better. This indicates an under prediction of stall delay even though this effect is modelled with a large variety of different 3D corrections. The corresponding results from the CFD codes are generally in better agreement. Similar observations were made in the comparisons from IEA Task 20 for the NREL Phase VI (Nasa-Ames) turbine [5] and [6] and in the comparisons with field measurements as described in [7].

At 60, 82 and 92% span and tunnel speeds of 15 m/s (and 10 m/s) almost all codes over predict the normal force. At 92% span an over prediction from the lifting line codes is consistent with the over prediction of tip loads in [6] and [7]. These discrepancies were explained by the use of 2D airfoil data near the tip. However this does not explain the over prediction at 60 and 82% span. It also does not explain the over prediction from the CFD codes at 92% span since these codes do not apply airfoil characteristics. Generally speaking the over prediction from the CFD codes is less than the over prediction from the lifting line codes.

The lifting line results for $U_\infty=15$ m/s show a shift in normal force roughly between $r=1.3$ and $r=1.7$ m. This is attributed to the discontinuity in airfoil distribution, since the RISØ profile, which is applied mid-span has a different zero lift angle of attack compared to the surrounding DU and NACA profiles. In addition to that the validity on the 2D airfoil data of the RISØ profile has been questioned, since this data was obtained in a wind tunnel which features rather high turbulence levels. The fact that this jump is most pronounced for $U_\infty=15$ m/s can be attributed to the difference in lift coefficients being larger for the angle of attack corresponding to this operating condition. It is interesting to note that the measured near wake velocities by PIV show an unexpected axial velocity decrease aft of this transition.

### 3.1.2. Velocities traverses

The comparison between the CFD calculated and measured velocity decay at 80% span is shown for two tunnel speeds in Figure 4. Most of the codes over predict the velocities (i.e. they under predict the axial induced velocity). For those codes which do not over predict the velocities it is found that they over predict the loads to a larger extent. Hence the prediction of loads and velocities of the MEXICO experiment seems to act as communicating vessels: A better prediction of velocities goes together with a larger over prediction of the loads and vice versa. Despite this puzzling observation it is encouraging to see a good qualitative prediction of the velocity decay even at $U_\infty=24$ m/s where the velocity fluctuations due to stall are predicted very well.

As such it is found that none of the calculations from the Mexnext group can predict both the velocities AND loads in a correct way. Moreover an odd velocity behaviour was found near 55% span, possible due to the discontinuity in airfoil distribution which is not predicted by any of the codes, [1]. This can be related to the observations from [4] which showed that the velocity behavior agrees very well with the expected velocity behavior from the momentum theory as long as the axial force coefficient is the design value of 0.89. Measurements however seemed to indicate the axial force coefficient to be much lower (in the order of 0.75). Thereto actuator disc theory was applied with an axial force from either the balance measurements or from integration of the pressure forces along the blade. In Figure 5 this problem is assessed from a different perspective. It shows the measured axial induction factor $a$ and the axial force coefficient $C_{d_{ax}}$ on local blade element level for all three tunnel speeds and three radial positions $r=1.35$ m, $r=1.85$ m and $r=2.07$ m. These induction values are determined by averaging the measured velocities in the rotor plane over azimuth angles of $0^\circ$, $20^\circ$, $40^\circ$, $60^\circ$, $80^\circ$ and $100^\circ$. The values of $C_{d_{ax}}$ are determined by decomposing the integrated normal and tangential forces from the measured pressure distributions at the 60%, 82% and 92% stations perpendicular to
The rotorplane. A line representing axial momentum theory \( (C\text{d}_{ax} = 4a(1 - a)) \) is plotted as well. A good agreement with momentum theory is observed for \( U_\infty = 10 \text{ m/s} \) and \( U_\infty = 24 \text{ m/s} \). However, the higher theoretical loads at design conditions are also apparent in this analysis since the \( C\text{d}_{ax} \) from momentum theory is higher than the measured values at all three radial positions. For values \( a > 0.38 \) the turbulent wake state (TWS) is entered and the quadratic formula is replaced by the linear tangent to momentum theory at \( a = 0.38 \), [8]. In the turbulent wake state the induction is far from uniform in radial direction. At more inboard stations, the wake can be expected to mix less vigorously with the air outside of the streamtube. This could explain why the measured combination of force and induction at \( r=1.35 \text{ m} \) is far off from turbulent wake state theory (solid line), but comes closer to the original quadratic curve (dashed line).

**Figure 3.** IEA Task 29 Mernext: Comparison between measured and calculated normal force distribution on the MEXICO rotor blade (left: CFD, right: Lifting line codes)
Figure 4. IEA Task 29 Mexnext: Axial velocity decay at 80% span, measured and calculated with CFD codes, Azimuth = 0°

\[ U_\infty = 15 \text{ m/s} \]

\[ U_\infty = 24 \text{ m/s} \]

Figure 5. Local $C_{dax}$ versus axial induction factor $a$: Measured and calculated with momentum theory

Unfortunately no PIV data has been taken further inboard from this section, which prevents a comparison for the 25% and 35% stations.

3.2. Yawed flow conditions

3.2.1. Loads

In Figure 6 the load variation is presented as a function of azimuth angle for the normal forces at 35% and 82% span. The standard error of the processed data points is displayed using a grey band. The grey band was generally found to be very small although the
standard error at the 35% span station is slightly higher due to an intermittently malfunctioning pressure sensor. The measurements are compared with calculations from lifting line codes and CFD codes.

A phase shift is visible in the azimuthal load variation between the inner and outer part of the blade: At 82% span the maximum normal force is found at the upwind part of the rotor plane. This maximum shifts towards the downwind side at 35% section. It leads to a stabilizing yawing moment contribution at the outer part and a destabilizing yawing moment at the inner part. For the lifting line codes, the qualitative agreement is generally speaking better for the outboard sections compared to the inboard sections. This can be explained by the fact that the advancing and retreating blade effect is more dominant there and more straightforward to predict. For the inboard sections the aerodynamics becomes more complicated and the combination of a varying induction together with separated flow proves difficult to model. The inboard agreement for the CFD codes is better than for the lifting line codes.

3.2.2. Axial velocity traverses In Figure 7(a) to 7(d) the calculated and measured axial velocity traverses are presented for 30° yaw. Generally speaking the velocities are predicted in good agreement with the measurements, except the upwind part (y<0) of the near wake (x≈1 m). For the downwind side (y>0), the wake deflection causes the traverse to move outside the wake for x>4 m (y=1.4 m) and x>3 m (y=1.8 m). This is predicted by most codes.

In Figure 7(c) (y=1.4 m) the traverse slices through the nacelle near x = 2 m. However, few codes included the nacelle and hence most codes predict a finite velocity there. The sinusoidal fluctuations in the near wake for y=1.8 m are caused by slicing through the tip vortices, which is often reproduced in good agreement.

3.2.3. Radial velocity traverses In Figure 7(e) to 7(f) the calculated and measured radial velocity traverses are presented just downstream of the rotor plane. The results for negative yaw angle are mirrored and interpreted as positive yaw with negative radial positions. It is noted that the radial direction is parallel to the rotor blade.

The radial traverses are predicted surprisingly good for the downwind traverse. Although not shown here, the same holds for the traverse just upwind of the rotor plane. Dependent on the azimuth angle the downwind traverse slices through the tip vortex, of which most codes are able to predict both position and strength accurately.

4. Recommendations from Mexnext-I and follow-up projects

The main recommendations as formulated by the Mexnext-I project group are:

- Aerodynamic validation material is far too limited: Much more detailed aerodynamic measurements are needed, both in the field (full scale) as well as in the wind tunnel of the pressure distributions and loads, the flow field, the boundary layer and the noise sources. With regard to the latter it should be realized that the acoustics of a wind turbine is ‘driven’ by the aerodynamics. As such a good understanding of the acoustics requires detailed acoustic measurements in combination with detailed aerodynamic data.

- ‘New MEXICO’ measurements are needed including flow field measurements of the inner part in order to clarify
  - the unexpected near wake axial velocity pattern aft of the profile transition.
  - the relation between loads and induction (section 3.1.2).

- A limited number of (sometimes almost forgotten) aerodynamic experiments exist, which are not fully explored yet. Such measurements could potentially deliver new insights and they might also offer explanations for non understood phenomena. Therefore it is recommended to further analyze these measurements.
Figure 6. IEA Task 29 Mexnext: Azimuthal variation of normal force as calculated by CFD and lifting line codes, $U_\infty=15$ m/s, Yaw = 30°, Pitch = -2.3°

Within Mexnext-II New MEXICO measurements will be carried out funded from the EU Aerospace program ESWIRP and the FP7-Energy project Innwind. The measurements will be performed on the MEXICO model in the DNW-LLF in mid-2013.

Mexnext-II will also include an analysis of historical aerodynamic wind turbine measurements (including the MEXICO experiment).
Figure 7. IEA Task 29 Mexnext: Axial velocity as function of streamwise coordinate and radial position, $U_\infty=15 \text{ m/s}$, Yaw=30°, Pitch = -2.3°.
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