The MEXICO project (Model Experiments in Controlled Conditions): The database and first results of data processing and interpretation

H Snel¹, J G Schepers¹ and B Montgomerie²

¹Energy Research Centre of the Netherlands, ECN, Petten, the Netherlands;
²ProgramoGrafik HB, Ekero, Sweden

Corresponding e-mail: snel@ecn.nl

Abstract. The Mexico (Model experiments in Controlled Conditions) was a FP5 project, partly financed by European Commission. The main objective was to create a database of detailed aerodynamic and load measurements on a wind turbine model, in a large and high quality wind tunnel, to be used for model validation and improvement. Here model stands for both the extended BEM modelling used in state-of-the-art design and certification software, and CFD modelling of the rotor and near wake flow. For this purpose a three bladed 4.5 m diameter wind tunnel model was built and instrumented. The wind tunnel experiments were carried out in the open section (9.5*9.5 m²) of the Large Scale Facility of the DNW (German-Netherlands) during a six day campaign in December 2006. The conditions for measurements cover three operational tip speed ratios, many blade pitch angles, three yaw misalignment angles and a small number of unsteady cases in the form of pitch ramps and rotor speed ramps. One of the most important feats of the measurement program was the flow field mapping, with stereo PIV techniques. Overall the measurement campaign was very successful. The paper describes the now existing database and discusses a number of highlights from early data processing and interpretation. It should be stressed that all results are first results, no tunnel correction has been performed so far, nor has the necessary checking of data quality.

1. Introduction.
The MEXICO project consortium is comprised by the following institutions:
- Energy Research Centre of the Netherlands (ECN), coordinator. (NL)
- Delft University of Technology (NL)
- National Aerospace Laboratory, NLR (NL)
- RISOE National Laboratories (DK)
- Technical University of Denmark, DTU (DK)
- Centre for Renewable Energy Sources, CRES (GR)
- National Technical University of Athens, NTUA (GR)
- Swedish Defense Institute FOI/FFA (S)
- Israel Institute of Technology, Technion (IS)
- National Renewable Energy Laboratories NREL (USA, invited participant)
The German-Dutch Wind Tunnel Institute DNW acted as a subcontractor to the project, regarding the wind tunnel facilities.
The consortium embarked on a detailed tunnel interference analysis. Although it is expected that the open test section of the DNW-LSF lowers these effects, at the same time, there is little known about the quantification of the same. Hence some quasi 1-D analysis was performed, together with CFD modeling of the flow.

The total duration of the project (6 years) was much longer than originally proposed. Apart from the unexpected large effort for the tunnel interference study, the major reason for this was the destruction of the first model upon transportation. Additionally some changes in the composition of the consortium caused delays of an administrative type. Nevertheless the final conclusion of the project with the tunnel measurement campaign in December of 2006 was on a very positive note. The complete prepared test matrix could be covered, while some time remained for additional tests. The model withstood the testing without a single problem of material or structural design aspects.

2. Description of the model, the instrumentation and the flow field measurements.

The project consortium was responsible for the aerodynamic and structural design of the model rotor, its support structure and instrumentation. One important consideration was to make the MEXICO database complementary to the NREL NASA Ames database [ref 1.] This was one of the reasons to choose a three bladed turbine and to enable the extensive coverage of the entire operational range, from turbulent wake state to stalled conditions. The standard tip speed of the model was of 100 m/s, in order to maximize the Reynolds number while maintaining the Mach number below 0.3. The model was designed for an optimum tip speed ratio of 6.7, reached at a tunnel velocity of 15 m/s. The model was manufactured at Technion. The blades were numerically milled from aluminum, to ensure (within strict tolerances) identical shapes. Three different aerodynamic profiles (DU91-W2-250, RISOE-A1-21 and NACA 64-418) were used in the design. In order to assure known conditions at each test section, these profiles where strictly maintained over a radial extension of a few chord lengths around the test sections. The remaining length, between constant profile sections was used for transition of one profile to the other. Details of the model geometry can be found in ref 2.

The data acquisition system was designed and manufactured at Delft University and NLR. The rotor instrumentation consists of 148 dynamic pressure sensors (Kulite) divided over 5 span wise sections of the blades (25%, 35%, 60%, 82% and 95% radial position respectively), 2 strain gauge bridges at each of the three blade roots, and a thermometer to monitor the blade temperature, in view of the heating from the data acquisition units. All rotor data were effectively acquired with a sampling frequency of 5515 Hz, after filtering. The data conditioning was actually done on 5 printed circuit boards (one for each instrumented section) which were built into the three blades, where filtering and signal amplification occurred, before sending the data over high quality slip rings to the PC mounted acquisition software.

The model was placed on a six component balance, measuring three forces and three moments at the foot of the tower. These quantities can be used to quantify the axial force, the sideways force, the yawing moment, the tilting moment and the rolling moment. The later is a measure for the shaft torque. Unfortunately, the global rotor forces and moments were not measured directly on the rotor or the shaft. The setup in the tunnel is shown in figure 1.

Figure 1. Setup of the model in the DNW, on the balance, looking into the collector
The tunnel balance data were supplemented with tunnel velocity, temperature, barometric pressure (to give density) and 8 pressures in the collector entrance. These latter pressures measure the speedup in the outer flow (outside the wake) needed for the mass conservation of the tunnel flow. They can be used to quantify the needed tunnel correction.

Perhaps the most important feature of the measurements is the extensive flow field mapping by stereo PIV measurements, executed by the PIV team of DNW. A large number of sheets, of dimensions of approximately 0.337 by 0.393 m² was scanned. The PIV interrogation areas were of 4.3*4.3 mm², resulting in 79 by 92 velocity data points. At each point, x, y and z components of the velocity were determined.

The orientation of the PIV sheets was always in a horizontal plane (x,y) at 270 degrees azimuth, see figure 2.

In x-direction (free tunnel velocity direction) the traversing mechanism was able to cover 10 m of distance, giving the possibility of traverses from approximately 1 diameter upstream, to a little over 1 diameter downstream, for inflow and near wake mapping. In the y (radial) direction) the traversing mechanism could only cover a distance of 120 cm. A choice was made to cover the outer blade part, including the possibility of tracking the tip vortices to a certain extent. This gives the possibility of matching the measured tip vortex strength with the blade loads, utilising pressure distributions and bending moment data.

### 3. Overview of the experimental matrix

#### 3.1 Pressure and load measurements

Every combination of model and tunnel configuration measured, is identified by a unique datapoint number, organized in runs (between tunnel on and tunnel off) and polars. In total approximately 950 datapoints were recorded, which in the limited size of the paper, cannot be described individually.

The first part of the measurements covered a large combination of parameters, for which pressure distributions, blade-bending moments, and all tunnel data were registered. The following table summarizes the different variables and their values. Empty positions in this matrix indicate no further values of the parameter in the measurements.

| Tunnel speed [m/s] | Rotor tip speed [m/s] | Blade tip angle | Yaw angle [deg] |
|-------------------|-----------------------|----------------|-----------------|
| 10                | 100                   | -2.3           | 0               |
| 15                | 76                    | -5.3           | 15              |
| 20                | 4.3                   | 30             | 45              |
| 25                | 2.3                   |                |                 |
| 30                | -1.3                  | -0.3           | 0.7             |
|                   |                       | 1.7            |                 |

Additionally, pitch ramp and rpm ramps were measured, the pitch varying from -2.3° to 5° and back, while in the rpm ramps the tip speed varied from 100 m/s to 76 m/s and back (424.5 rpm and 324.5 rpm respectively. Furthermore for the rotor parked condition (0 rpm), measurements were done at 30 m/s tunnel speed, and tip angles varying from – 2.3° to 90°.
3.2 PIV measurements. The second part of the experimental matrix was reserved for PIV measurements. It is noted that during the PIV measurements, pressures, bending moments and all tunnel quantities were also recorded, resulting in a large number of repeated cases. No interference from the PIV seeding was noticed, in fact a quite good repeatability of the measurements was observed.

The PIV sheet positions are given in some larger detail, since some of the analysis will be concerned with the PIV measurements. The figure below shows the location for the measurements within the rotor plane. Measurements of this type were done for three tunnel speeds, i.e. 10, 15 and 24 m/s, yielding tip speed ratios of 10, 6.7 and 4.2. The PIV sheets directly upstream and downstream of the rotor have a slight overlap, in the rotorplane, so that the repeatability can be checked. This will be further considered in section 4.

Figure 3. PIV measurements in the rotor plane

The measurements in the rotor plane were performed for 7 different azimuth angles, viz.: 0, 20, 40, 60, 80, 100 and 120 degrees, where azimuth 0 is defined when blade 1 is vertically upward. The cases of 0 and 120 degrees are identical and serve for quality control of the data. This feature allows to map the flow between the blades, and verify the effects of non-uniformity of the flow in the tip region, which is usually corrected for by Prandtl’s tip correction model in Blade Element Momentum (BEM) methods. Figure 4 shows the second type of PIV measurements consisting of inflow and wake traverses at two radial positions. The third type of measurements looks into mapping of the intersections of tip vortices with the PIV sheet, at different locations behind the rotor. The principle is shown in figure 5. An attempt was made in all cases to center the vortices in the PIV sheets, to enable the determination of the circulation strength.

Figure 4. PIV traverses upwind and downwind of the rotor.

Finally, the same type of measurements was performed at yaw misalignment angles of 30 and –30 degrees. An example of PIV sheet locations for these measurements is shown in figure 6.
4. First data processing and interpretation

Data processing of the large amount of measurements (100 GB) has only just started. First results are shown, concerning:

- Pressure measurements and some interesting PIV results in yaw.
- Wake traverse and vortex tracking for a tip speed ratio of 6.7
- Wake traverses and vortex tracking including details of the flow in the rotor plane, for a tip speed ratio of 10
- Determination of circulation and comparison with loading

4.1. Pressure measurements and PIV information in yaw. Figure 7 shows the processed pressure measurements at the 60% radial location, for a case of 45 degrees yaw. The pressures are averaged over 60° sectors. Note that the raw data have the pressures at every 0.5 degrees approximately. It can clearly be observed that dynamic yaw is taking place over the section. Around the zero degree position, the blades move in the same direction as the in-plane component of the wind, so that the relative in-plane component is smaller, and the resulting angle of attack is larger, estimated at approximately 19 deg. A pressure distribution with trailing edge separation starting at 30% chord is observed. Passing to the next sectors, the angle attack decreases, to attain an estimated value of about 9 degrees at the 180 azimuth position. The pressure distribution for this sector is clearly one of attached flow. Further increases of the azimuth cause flow separation again. This material is very well suited for the validation and improvement of dynamic stall modelling in rotating flows.
To demonstrate the extent of PIV velocity information in figure 8 a sheet is shown for the 30 degrees yaw case. The velocity field is shown 10 degrees after blade passage. The average velocity components in the sheet have been subtracted. The green coloured line shows up-flow, following the blade. This is the viscous wake behind the blade. Although this figure shows only qualitative data, the quantitative velocity data form part of the result. Later work will investigate to what extent viscous profile drag values can be estimated from these data.

Figure 7. Sectorial pressure distributions at 60% radial position, for 45° yaw, showing dynamic stall (the x = 60% caption above each figure refers to radial position)

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Figure 8. PIV sheet 10 deg. after blade passing in yawed flow
4.2. Wake traverse and tip vortex tracking for tip speed ratio of 6.7. For the design tip speed ratio of 6.7 (15 m/s wind speed) the inflow and wake traverses, together with the rotor plane measurements, have been analysed to study the induction field of the rotor and compare with BEM and other methods. Figure 9 shows the measured velocity as a function of x-position. Values are obtained by averaging over the 39 cm y-extent of the PIV sheets around the 82% and 61% sections. The 61% position shows some anomalies, which can also be seen in figure 10 and its discussion. The 82% position shows completely expected behaviour.

Figure 9. Rotor induction field from 1 D upstream to 1.25 D downstream for a tip speed ratio of 6.7

To analyse the distribution of the speed in the rotor plane, use is made of PIV sheets around the rotor plane, as shown in figure 3. For the upwind sheets, the section at \( x = 0.0022 \) was selected, for the downwind sheets the section at \( x = 0.0038 \), 1.6 mm apart. The choice of these stations is based on their availability, so that no interpolation is needed. The distance is well within the PIV resolution of 4.3 mm. The resulting velocity distribution, between blades, is shown in figure 10. Apart for the innermost section, the results almost overlap. The reason for the deviation around \( y = 1.37 \) is not known, but as was indicated in the wake velocity survey, the recorded flow conditions at that section are definitely strange. Also, at these conditions of the design tip speed ratio, BEM theory would give an induction factor of approximately 1/3, i.e. a velocity of about 10 m/s in the rotor plane, while the measurements show approximately 11 m/s, equivalent to an induction factor of 0.27. Although the difference is not surprisingly large, it should be investigated if this can be due to tunnel effects: the pressure gradient that causes the acceleration of outside air, will also affect the airflow through the turbine and in the wake. This has not been investigated yet.

Finally, the tip vortex position was examined from the vortex tracking PIV sheets. A total number of 8 vortex intersections could be clearly traced, over a total downstream distance of approximately 1
rotor diameter. This is equivalent to 3 intersections for two of the blades and 2 intersections for the third blade. The results are shown in figure 11. From the tip vortex locations, an approximate convection speed can be deduced of 11.8 m/s. This value does not seem to change with distance, as is sometimes assumed in fixed geometry vortex wake models.

4.3 The case of turbulent wake state, tip speed ratio of 10. The case of turbulent wake state has not often been examined in detail. The MEXICO measurement for a tunnel speed of 10 m/s and a tip speed of 100 m/s give interesting insight into these conditions. In the first place, the velocity distribution in the rotor plane is compared with calculations based on Anderson’s [ref.3] turbulent wake state model, in figure 12.

The turbulent wake state is apparent from the fact that the velocity in the rotor plane is less than half of
the free stream velocity, i.e. the induction factor is larger than 0.5. The two PIV sheets used for the rotorplane now give almost equal results, also for the 60% location, in contrast with the $\lambda = 6.7$ case. As stated before, the exact reason for the deviation in the $\lambda = 6.7$ case is not known, and even more mysterious in view of the good agreement in the present case. The reliability of these measurements should also be investigated.

It can be seen that, whereas the agreement between measurements and Anderson’s model is reasonable in the inner part of the rotor, towards the tip it becomes much more deficient, to the effect that the modeled velocity is only 60% of the measured velocity. The comparison is based on the calculated induction factor, without including the tip correction factor. However, in this case with the closely spaced tip vortices, Prandtl’s tip correction formula would give a factor of 0.95 at the outermost station, and 0.99 to 1 at the rest of the calculated stations. Hence the results would not be affected much by including the tip correction. Regarding the measurements, these were taken at a phase locked azimuth of 0 degrees, i.e. blade 1 would be vertical, 90 deg away from the PIV sheet, and blade 2 would be 30 degrees below the PIV sheet.

The next item addressed is the induction field of the rotor, shown in figure 13. The velocities are averaged over the $y$ values of a PIV sheet of 39 cm y-extension, the mean radial position being $y = 1.845$ m, close to 80%.

Figure 13. Induction field for $\lambda = 10$

The analysis of the wake PIV sheets around the 1.845 m radial position, at different positions, shows the velocity in the wake to be sheared, while the sign of the shear can change sign between x station, as is seen in figure 14. This interesting redistribution of velocities can be part of the rapid expansion of the vortex wake. This is something to be studied in more detail in the future.

Figure 14. Velocity distributions in wake at $x = 1.0$ and $x = 1.7$ m (behind the rotor)

Finally, also for this case, the tip vortex location was traced. Only 5 intersections could be found,
due to the stronger expansion that caused the vortices to move outside of the y traversing possibilities of the PIV instalation. Figure 15 shows the results:

Although the expansion is much stronger than in the $\lambda = 6.7$ case, it should be noted that the vortices, in both cases, are well inside the stream boundary defined by the rotor mass flow, if the velocity measured over the different PIV sheets is indicative of the average flow in the sections. Note that the inner part of the rotor could not be measured, which adds a measure of uncertainty.

Figure 15. Tip vortex location for the case of $\lambda = 10$.

4.4. Comparing vortex circulation strength and blade loading. For the case of $\lambda = 10$, the circulation strength of the vortices was calculated and compared to blade loading by the third author. The determination of the circulation was done with the aid of the integrals on circular sections about the observed vortex centre in the PIV sheet shown in figure 16. In this figure, the average values of the velocity have been removed, aiding in the determination of the precise location of the vortex. The vortex shown is in fact the second vortex from figure 15, of a blade that passed 1/3 of a revolution ago. The result of the integration gives a total circulation value of approximately 2.5 m$^2$/s. At the same time, the bound circulation is estimated on the base of the measured pressure distribution for the 82% instrumented section, which results in a $c_l$ of 0.553 and a circulation of 2.56 m$^2$, hence a very good comparison.

Figure 16. Tip vortex details and location, $\lambda = 10$
Conclusions.
The MEXICO project has reached a positive ending. A large amount of detailed pressure data, blade and total loads and quantitative flow field information is now available. First results of data processing and interpretation have been described. The data are found to be very interesting for validation and improvement of wind turbine rotor aerodynamics. Very much additional work will have to be performed to make optimal use of the database.

Future work.
Apart from the considerable effort needed for processing and interpretation of the existing data, it would be important to complement the data with PIV data for the inner 40% of the rotor plane, including details of the root vorticity. Due to the limited traversing possibilities of the PIV setup, this part of the rotor could not be covered. Hopefully, future measurements on the same model can be arranged to fill this gap.

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