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IEA Task 29 Mexnext: Analysis of wind tunnel measurements from the EU project Mexico

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Abstract

This paper presents results from Mexnext, an IEA wind task in which 19 parties from 11 countries cooperate in analysing the measurements which have been taken in the EU project 'Mexico' (Model Rotor Experiments In Controlled Conditions). The project resulted in a database of measurements on a 3 bladed 4.5 m diameter wind turbine model placed in the 9.5x9.5 m² LLF tunnel of the German Dutch Wind tunnel facilities. Pressure and load measurements on the blade have been carried out simultaneously with stereo PIV flow field measurements.

Keywords: wind turbine aerodynamics, wind tunnel measurements

1 Introduction

In the past the accuracy of wind turbine design models has been assessed in several validation projects, see e.g. [1]. They all showed that the modeling of a wind turbine response (i.e. the power or the loads) is subject to large uncertainties. These uncertainties mainly find their origin in the aerodynamic modeling, where several phenomena, like 3D geometric and rotational effects, instationary effects, yaw effects, stall, tower effects etc, contribute to unknown responses in particular at off-design conditions.

The availability of high quality measurements is considered to be the most important pre-requisite to gain insight into these uncertainties and to validate and improve aerodynamic wind turbine models. For this reason the European Union project 'Mexico' (Model Rotor Experiments In Controlled Conditions) has

been carried out. 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 9.5 by 9.5m² open section of the Large Low-speed Facility (LLF) of DNW in the Netherlands. The measurements were performed in December 2006 and resulted in a database of combined blade pressure distributions, loads and Particle Image Velocimetry (PIV) flow field measurements, which can be used for aerodynamic model validation and improvement. Previous measurements (on a 10 m diameter turbine) were performed by NREL in the NASA-Ames wind tunnel [2]. An obvious difference between the two types of experiments lies in the larger size of the latter experiment. On the other hand the NASA-Ames experiment only contained rotor measurements where the Mexico experiment also included flow field measurements of inflow and wake. This is an important feature in understanding discrepancies between calculated and measured blade loads because the calculations of loads basically takes place in 2 steps: First the flow field around the blade (i.e. the induction) is calculated and from that the loads are derived. Each of these steps have their own uncertainty (eg the second step may contain the uncertainty in airfoil characteristics). In conventional experimental programs, only blade loads are measured from which it is not possible to distinguish these two sources of discrepancies. The addition of flow field measurements should open up this possibility.

After completion of the Mexico project, the database was still in a rather rudimentary form and only limited analyses were carried out. Now it should be realised that

the amount of data is very vast by which the time needed to analyse all data is extremely long for a single party. As such it is beneficial to organise the analysis of the Mexico data in a joint project under IEA Wind, since this makes it possible to share tasks. Added value also lies in the fact that the task will serve as a forum for discussion and interpretation of the results. In this way the outcome of the data analysis will be better than the summed result from the individual projects.

In IEA Wind Task 29, MEXNEX(T), the accessibility of data is facilitated and a thorough analysis of the data will take place. This includes an assessment of the measurement uncertainties and a validation of different categories of aerodynamic models. The insights will be compared with the insights which were gained on the NASA-Ames experiment and within other wind tunnel experiments

The present paper gives a global overview of the activities as performed within Mexnext and highlights some of the analyses. It is noted that project results are continuously updated on www.mexnext.org

2 Mexico, experimental set-up and data collected

The setup of the Mexico experiment is given in figure 1. The turbine is placed in the $9.5 \times 9.5 \text{ m}^2$ open jet configuration of the DNW, with a measurement section of 20 meter length. The rotor plane is 7 meter downstream of the nozzle and 13 meter upstream of the collector. The external six component balance is the blue structure in figure 1 which recorded the total rotor loads statically.

Three different aerodynamic profiles (DU91-W2-250, RISØ-A1-21 and NACA 64-418) were used in the blade design. The DU91-W2-250 airfoil was applied from 20 to 45.6% span, the RISØ-A1-21 airfoil from 54.4% to 65.6% span and the NACA 64-418 airfoil outboard of 74.4% span. Hence a constant airfoil is applied over a considerable radial extension around the instrumented sections in order to assure known conditions at each of these sections, where the remaining length is used for the transition from 1 airfoil to another.

The (twisted, tapered) rotor blades were numerically milled from aluminum, to ensure (within strict tolerances) identical shapes. 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. Blade loads were monitored through two strain-gauge bridges at each blade root. Pressures and strains were sampled at 5.5 kHz. It is important to know the definition of the azimuth angle which is defined such that 0 degrees corresponds to the '12 o'clock' position and 270 degrees is at the '9 o'clock' position (the Mexico rotor rotates clock-wise). 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 (or r-coordinate) is oriented outboard along the radial direction at the 9 o'clock position ($y=0$ in the rotor centre).



Figure 1: Set-up of the Mexico model in the LLF tunnel of DNW. The collector is shown in the background and the nozzle in the foreground

The rotational speed was either 424.5 rpm or 324.5 rpm. Note that, unless otherwise stated, the results presented in this paper have been taken at 424.5 rpm.

At 424.5 rpm a chord based Reynolds number of approximately 0.8 M was reached without entering into noticeable compressible conditions; the blades were tripped to avoid possible laminar separation phenomena.

Pressure and load measurements were done at different tunnel speeds (denoted with U_∞) ranging from 10 m/s to 30 m/s, yielding tip speed ratios between 3.3 and 10. Note that the design tip speed ratio is 6.67, which corresponds to $U_\infty = 15 \text{ m/s}$ at 424.5 rpm.

Different yaw angles and pitch angles were covered. The present paper only presents results taken at the design pitch angle of -2.3 degrees.

Extensive flow field mapping of the three velocity components has been done by DNW with stereo PIV measurements. More information on the PIV technique can be found in e.g. [7]. It is anyhow important to realize that all PIV measurements have been done in the symmetry plane of the rotor at the 270 degrees azimuth position (i.e. the 9 o' clock position).

The PIV samples were taken rotor-phase locked with a frequency of 2.4 Hz. Each PIV data point consists of several (30-100) samples. Although all individual samples are stored, the present paper discusses the averaged results only.

The PIV flow field measurements are done in the form of axial and radial traverses. The axial and radial traverses are done at zero yaw and at +/- 30 degrees yaw. The radial traverses are performed at 6 blade azimuth positions with a 20 degrees azimuth interval, where the 3P flow dependency makes it sufficient to cover only 120 degrees azimuth. The axial traverses are done at a blade position of zero degrees.

Moreover tip vortex tracking experiments were carried out. In the tip vortex tracking experiments the position of the tip vortex is searched by 'trial and error' where the position of blade 3 was 270 degrees.

3 Mexnext, project overview

The Mexnext project started in June 2008 and will end in June 2011

3.1 Objective, Work plan, Status

The objective of the IEA Wind Task MEXNEX(T) is a thorough investigation of the measurements which have been carried out in the EU sponsored Mexico project. Special attention will be paid to yawed flow, unsteady aerodynamics, 3D effects, tip effects, non-uniformity of flow between the blades, near wake aerodynamics, turbulent wake, standstill, tunnel effects etc. These effects will be analysed by means of different categories of models (CFD, free wake methods, engineering methods etc.). A comparison of the Mexico findings with the findings of the NASA Ames and other experiments will also be carried out. As such Mexnext

provides insight on the accuracy of different types of models and (descriptions for) improved wind turbine models.

The workplan is divided in 5 work packages (WP's):

WP1: Processing/presentation of data, uncertainties. The aim of this work package is to provide high quality measurement data to facilitate and compare calculations. Thereto the quality of the data is assessed and the data are reprocessed. Several investigations were carried out on the measurement quality. The main conclusion (based on consistency studies between e.g. pressure measurements and balance measurements, pressure measurements and flow field measurements, expectations, visual inspection etc) was that generally speaking the quality is good but some pressure sensors at 25% and in particular 35% span are suspicious. The 25% and 35% span data at parked rotor conditions are considered to be unreliable.

WP2: Analysis of tunnel effects. The 4.5 m diameter wind turbine model was placed in the open jet section of the LLF facility with a size of 9.5 x 9.5 m. This ratio of turbine diameter over tunnel size may make the wind tunnel situation not fully representative to the free stream situation. Section 4.1 presents more information on tunnel effects.

WP3: Comparison of calculated results from different types of codes with Mexico measurement data.

In this WP, the calculated results from several codes are compared to the data from the Mexico experiment. It is meant to be a thorough validation of different codes and it provides insights into the phenomena which need further investigation (see WP4). In section 4.4 some first comparisons will be presented.

WP4: Deeper investigation into phenomena. In this WP a deeper investigation of different phenomena will take place. The phenomena will be investigated with isolated submodels, simple analytical tools or by physical rules. This work package is subdivided in several tasks: parked conditions, influence of rotational speed, near wake aerodynamics, non-uniformity of flow in the rotor plane (i.e. tip corrections, 3D

effects, unsteady effects, yawed flow, non-uniformity of the flow between the blades (i.e. tip corrections) the wake flow at different conditions etc.

Within this work package a lot of activities have already been performed, e.g. the measured rotating airfoil characteristics are presented in different ways using different angle of attack methods (or even without angle of attack methods), the airfoil characteristics at different rotational speeds are compared mutually and with the 2D characteristics and with the characteristics on the parked rotor. Furthermore dynamic stall loops have been identified. Moreover a lot of effort is spent on understanding the PIV flow field measurements in the rotor plane and in the near wake also in comparison with calculations from CFD or simple BEM like vortex methods. Some results from this WP are presented in the sections 4.2 and 4.3.

WP5: Comparison with results from other (mainly NASA-Ames) measurements. The results from Work Package 3 and Work Package 4 are expected to provide many insights on the accuracy of different codes and their underlying sub-models. Within WP5 it will be investigated whether these findings are consistent with results from other aerodynamic experiments. In particular, one can think of the data as provided within IEA Wind Task 20 by NREL (i.e. the NASA-Ames experiment). Some results from this WP are presented in [12].

3.2 Mexnext participants

The Operating Agent (i.e. the coordinator) of Mexnext is the Energy Research Center of the Netherlands where the following institutes (and persons) participate.

- Canada (École de technologie supérieure, Montreal (C. Masson, S. Breton, C. Sibuet))
- Denmark(RISO-DTU (H. Madsen and N. Sørensen) and DTU-MEK (W. Z. Shen))
- Germany(University of Stuttgart (T. Lutz), University of Applied Sciences at Kiel (P. Schaffarczyk), ForWind (B. Stoevesandt), Windguard (K Rehfeldt))
- Israel (Technion, A. Rosen)

- Japan (Mie University/National Institute of Advanced Industrial Science. (T. Maeda, J. Murata))
- Korea(Korea Institute of Energy Research, (H. Shin) and KARI, the Korea Aerospace Research Institute (C. Kim))
- Netherlands(Energy Research Center of the Netherlands (G. Schepers, K. Boorsma, H. Snel), Technical University of Delft (N. Timmer, D. Micallef), Suzlon Blade Technology (A. Verhoef), Technical University of Twente (A. van der Weide))
- Norway (Institute for Energy Technology/Norwegian University of Science and Technology (A. Knauer))
- Spain (CENER (X. Munduate))
- Sweden(Royal Institute of Technology/University of Gotland (S. Ivanell))
- USA (National Renewable Energy Laboratory, (S. Schreck))

Note that Israel officially acts as a subcontractor to the Mexnext group.

4 Results

This section presents results on tunnel effects, flow field measurements, rotational airfoil data, and a comparison is made between calculations and measurements. More information on Mexnext results can be found in the references [5] to [15].

4.1 Tunnel effects

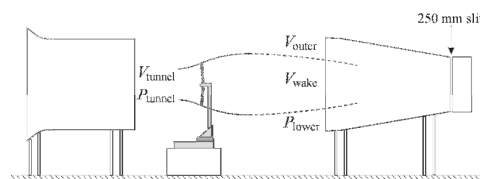


Figure 2: Tunnel configuration

As mentioned before the model is placed in the open test section of DNW. It is well known that tunnel effects in such open configuration will be less severe than those in a closed tunnel section. On the other hand the quantification of the (smaller) corrections is more difficult due to the shear layer between the tunnel flow and the outer flow where the presence of the collector which 'captures' the wind turbine wake, adds to the complexity. As such standard tunnel correction methods cannot be applied and detailed CFD

analysis of the wind turbine and its wake with and without the tunnel geometry is required. The flow situation around the model in the tunnel configuration is shown schematically in figure 2. Within the former Mexico project several investigations on tunnel effects were already performed but all of these investigations assumed a fully closed system between collector and nozzle. The real wind tunnel has slits with a width of 250 mm at the end of the collector contraction.

In a closed system, mass is conserved between collector and nozzle meaning that the lower velocity in the wake should be compensated with a higher velocity in the flow outside the wake. The axial pressure gradient that accompanies this increased velocity also accelerates the wake flow. As a result of these phenomena, the collector inlet pressure is smaller than the nozzle outlet pressure. It furthermore implies that the wind tunnel yields a higher axial force coefficient for similar velocities in the rotor plane (or vice versa, a similar axial force coefficient gives a higher rotor velocity in a wind tunnel situation).

The investigations performed in Mexico were all based on CFD and showed tunnel effects in the form of a higher velocity upstream and in the rotor plane. Nevertheless the disturbance in the rotor plane was limited. Further downstream the tunnel disturbances were much more pronounced due to the acceleration in the wake. These calculations however did not include the slits from figure 2. These slits reduce the tunnel effects since the suction in the collector generates a mass flow from the outer part through this opening into the collector. Within the Mexico project the effect of these slits was assessed in measurements in a scaled down version of the LLF tunnel. This effect turned out to be significant and reduced the tunnel effects considerably [4].

In [3] calculations are performed in which the flow field around the rotor placed in an unbounded situation is compared with the flow field in which the rotor is placed in the tunnel (including slits). These calculations are performed with the Virtual Blade Model (VBM) from the commercial CFD code Fluent (the Virtual Blade Model is comparable to an actuator disc model). These calculations have been made for non-yawed flow and $U_\infty = 15$ m/s.

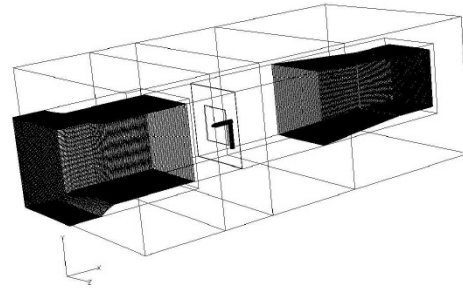


Figure 3: Tunnel geometry as modelled in Fluent VBM

The results for the configuration in the free stream situation are given in figure 4 and compared with experimental data. Results from a more advanced Fluent calculation which takes into account the geometry of all rotor blades, is also shown.

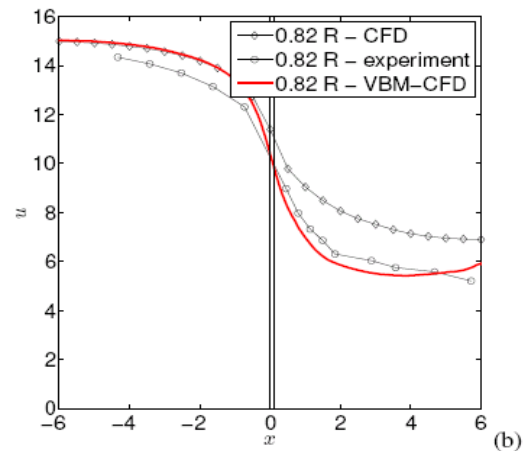


Figure 4: Axial velocity traverse without tunnel effect

In figure 5 the corresponding result is presented for the situation in which the tunnel geometry is included. Although the differences with the experiments (and the full CFD calculation) are obvious (see also section 4.4), there is little difference between the results with and without tunnel geometry.

This indicates the tunnel effects to be small at design conditions. It is acknowledged however that tunnel effects are expected to be more severe at high loading and at yawed flow. For this reason a more thorough study of tunnel effects at all operational conditions is currently carried out within Mexnext.

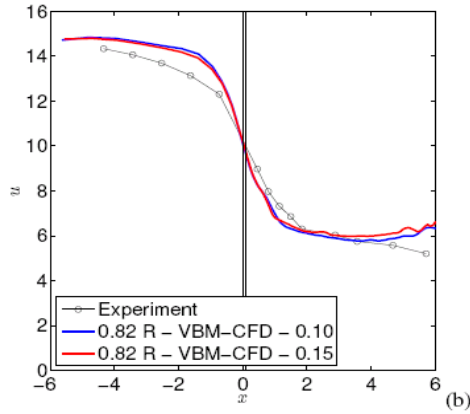


Figure 5: Axial velocity with tunnel geometry

It is worthwhile mentioning that KARI built a scaled down model of the Mexico rotor with a diameter of 2 meter (figure 6) and measured the performance of it in their own wind tunnel. A comparison will be made with some aerodynamic properties on the 'real' Mexico turbine. This comparison might also shed some light on tunnel effects.



Figure 6: KARI wind tunnel with scaled down model of Mexico rotor (compare with figure 1)

4.2 Flow field measurements

Several results from the PIV flow field measurements have already been published, see e.g. [6] and [7] which show the velocities as a function of the axial coordinate for a particular radial position or as a function of the radial coordinate for a particular x-position.

In the figures 7 to 12 the measurements are presented in the form of contour plots. The figures 7, 9 and 11 show the velocities at a blade position of zero degrees for the axial range from $x = -4.50$ m to $x = 5.89$ m where r is from 1.17 m to 2.08 m. It should be noted that gaps in axial direction of the measurement range were filled using

interpolation.

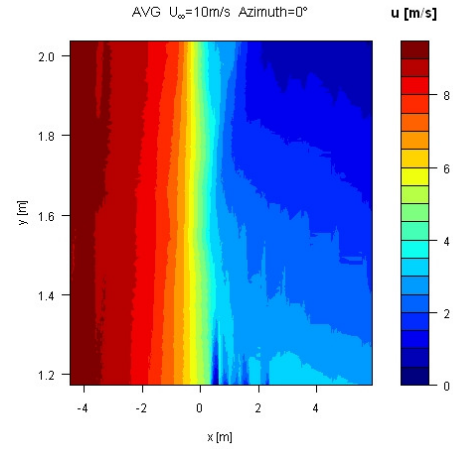


Figure 7: Contour plot of axial velocity at $U_{\infty} = 10$ m/s (axial traverse)

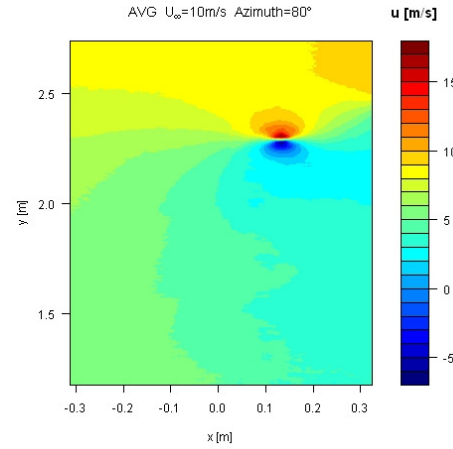


Figure 8: Contour plot of axial velocity at $U_{\infty} = 10$ m/s (radial traverse)

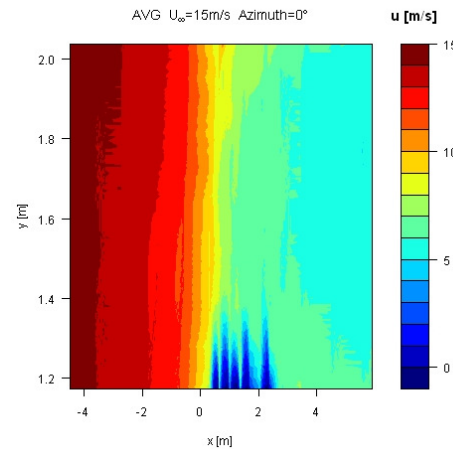


Figure 9: Contour plot of axial velocity at $U_{\infty} = 15$ m/s (axial traverse)

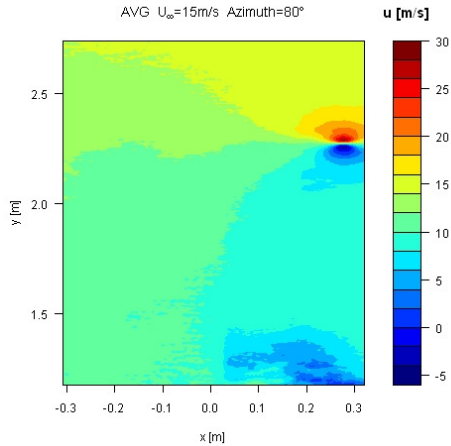


Figure 10: Contour plot of axial velocity at $U_{\infty} = 15$ m/s (radial traverse)

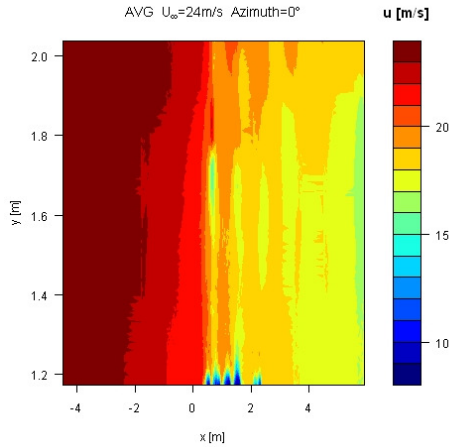


Figure 11: Contour plot of axial velocity at $U_{\infty} = 24$ m/s (axial traverse)

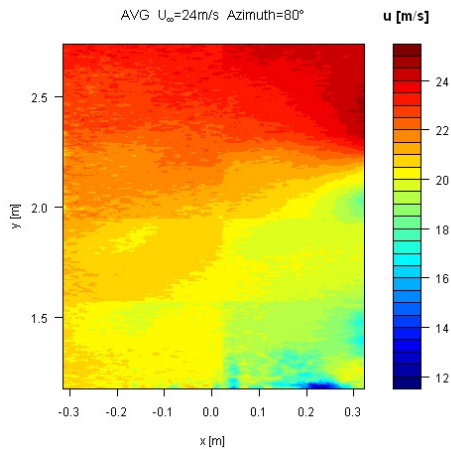


Figure 12: Contour plot of axial velocity at $U_{\infty} = 24$ m/s (radial traverse)

The figures 8, 10 and 12 show the velocity in the rotor plane from $x = -0.3$ m to $x =$

$+0.3$ m where r is from 1.17 m to 2.74 m. The position of blade 1 is 80 degrees, where it is recalled that the PIV sheet is located at 270 degrees. Hence the blade closest to this PIV sheet is positioned at 320 degrees.

In order to understand these figures it should be realized that the axial force coefficient decreases with increasing tunnel speed (this is due to the constant speed operation of the turbine). The figures 7 and 8 are taken at $U_{\infty} = 10$ m/s where the axial force coefficient is high and close to 1, which represents the turbulent wake state. This high value of the axial force coefficients yields a very strong deceleration towards the rotor. The velocity in the rotor plane turns out to be in the order of 5 m/s which corresponds to an axial induction factor of 0.5 in agreement with the axial force coefficient of 1.0. Such induction factor would yield a velocity of zero at the very far wake. The real velocity at the most downstream position is very small (generally < 1 m/s) and still decelerating.

At $U_{\infty} = 15$ m/s (i.e. design conditions, figure 9 and 10) the velocity in the rotor plane is approximately 10 m/s (consistent to an optimal induction factor of 1/3). The velocity in the far wake is approximately 5-6 m/s, i.e. the deceleration is doubled compared to the deceleration in the rotor plane as expected from BEM considerations. At a tunnel speed of 24 m/s (figures 11 and 12) the deceleration is limited due to the smaller axial force coefficient. At this velocity the pressure distributions indicate the entire blade to be stalled. This leads to periodic vortex shedding in the wake, see also the axial traverses presented in [7].

At all axial traverses, but in particular the one at $U_{\infty} = 15$ m/s (figure 9), vortex shedding is visible at the inner part of the measurement range just behind the rotor. This is most likely a result of the transition in airfoils between 46% and 54% span, although until now none of the codes have been able to predict this vortex shedding, see section 4.4. Furthermore the tip vortices, as trailed from the blade at 80 degrees, are clearly discernible at $U_{\infty} = 10$ m/s and 15 m/s. In [6] it was found that the vortex travel speed increases with tunnel speed. This can also be seen in these figures. At $U_{\infty} = 10$ and 15 m/s the vortices are approximately at $x=0.15$ m and $x=0.30$ m respectively, while at $U_{\infty} = 24$ m/s they have already left the measurement range.

4.3 Airfoil characteristics at rotation

Figure 13 shows the normal force coefficient as function of angle of attack as derived by NREL, using the angle of attack as derived by TUDelft [8] with an inverse free wake method.

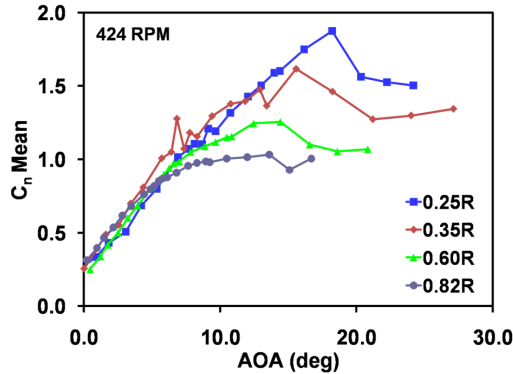


Figure 13: Normal force coefficients as function of angle of attack (results derived by NREL)

This is an iterative method which generates a lift and bound circulation along the blade from the normal and tangential forces and an assumed angle of attack distribution. The resulting vortex wake should then produce an angle of attack distribution which converges with the angle of attack from the previous iteration. The results clearly show stall delay effects at the inner part of the blade, similar to the results from previous experiments, see e.g. [2].

4.4 Comparison between calculations and measurements

In the figures 14 to 17 some representative examples are presented of a comparison between calculated and measured results. All of the results have been obtained at a design wind speed of 15 m/s. The results are still preliminary, which is the reason why the codes have not been identified yet. Note that most of the codes do not take into account the tunnel geometry.

Figure 14 shows the axial velocity as function of x coordinate at 80% span. It is recalled that these measurements are done at a blade position of 0 degrees where a few codes are based on actuator disc models which obviously cannot account for rotor azimuth.

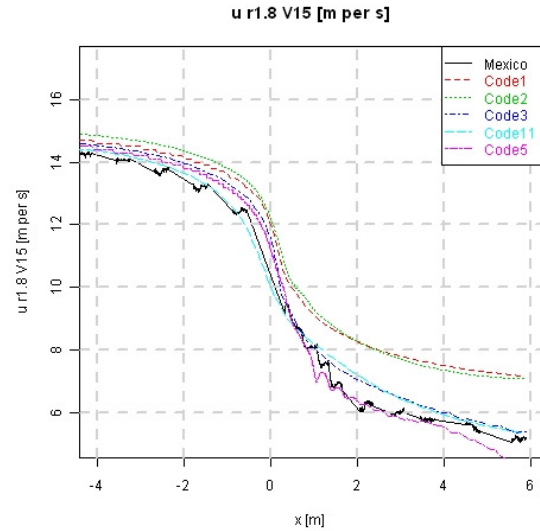


Figure 14: Axial velocity as function of axial coordinate at 80% span; $U_\infty = 15$ m/s, blade position = 0 degrees

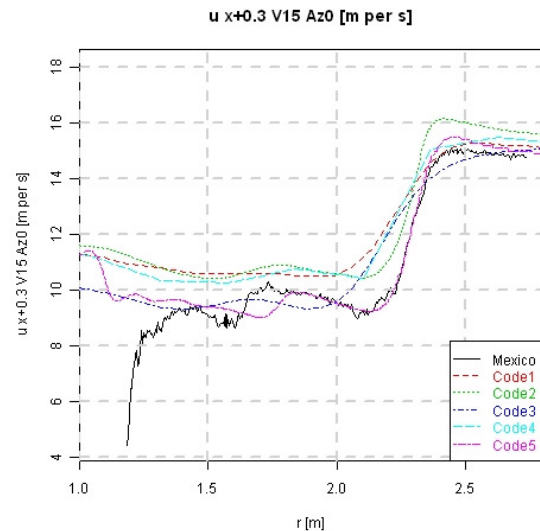


Figure 15: Axial velocity as function of radial coordinate at $x=0.3$ m; $U_\infty = 15$ m/s, blade position = 0 degrees

This mainly effects the results near the rotor plane (say within $0.25D$ of the rotor) where the flow field will be strongly non-uniform due to the finite number of blades. The results far upstream and downstream are much more uniform. The qualitative agreement between calculations and measurements is very good but almost all codes overpredict the axial velocity or in other words they underpredict the axial induction. It is striking to see this deviation to appear already far upstream of the rotor. In this respect it is noted that DNV has guaranteed a very accurate velocity at

the nozzle exit for empty tunnel conditions. Taking into account tunnel effects would even further increase the predicted upstream axial velocity (see also section 4.1). Hence tunnel effects are not expected to be the explanation for the overprediction of axial velocity. In this respect it is worthwhile to mention that a simple, BEM compatible, cylindrical vortex sheet model with a prescribed axial force coefficient yields only a very limited overprediction in velocity upstream of the rotor [7].

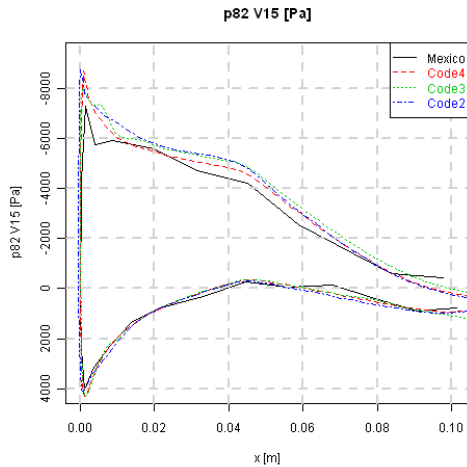


Figure 16: Pressure distribution at 82% span; $U_\infty = 15$ m/s

Another striking result is the fact that almost all codes overpredict the normal forces, in particular at the 60%, 82% and 92% span positions, although for some codes the overprediction is relatively small. Also the comparison between calculated and measured pressure distribution at 82% span, figure 16, indicates an overprediction of the normal force at that position.

This overprediction is not consistent with the underpredicted induction since momentum theory relation says that an increase in induction goes together with an increase in axial force coefficient.

It must be noted that tunnel effects are not believed to be the cause for this overprediction in normal force since these effects would increase the axial force. A measurement quality problem of the normal force (as derived from the pressure distributions) has also been considered but several studies indicate these forces to be reliable. As a matter of fact the normal forces are very consistent with the axial force as measured with the external balance [7]. This means that a comparison

with the axial force from the balance would yield the same overprediction.

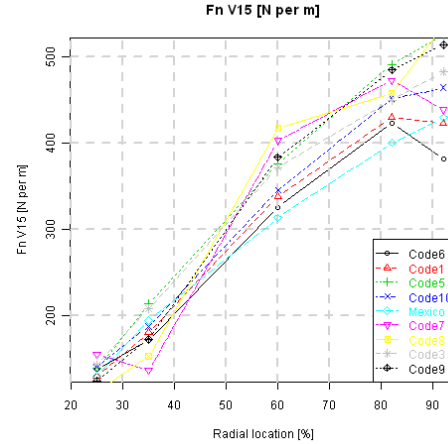


Figure 17: Normal force as function of radial position: $U_\infty = 15$ m/s

The radial traverse, figure 15, shows a lower velocity in the wake (for $r < 2.25$ m) and an increase towards the free stream velocity near $r = 2.25$ m. Apart from the, already observed, overpredicted velocities this behavior is qualitatively speaking reproduced very well. The lower measured velocities at say $r < 1.2$ m are most likely a result of the transition in airfoils, see section 4.2. They are predicted by none of the models even though they do take into account this change in airfoil shape.

5 Conclusions

The paper presents an overview of the tasks which are currently performed within IEA Task 29 Mexnext, a joint project in which 19 institutes cooperate in analyzing wind tunnel measurements. One of the main tasks is a comparison of calculated results from different types of codes with Mexico measurements. This comparison is not only made on basis of blade loads (i.e. pressure measurements) but also on basis of PIV measurements by which the accuracy of the underlying flow field prediction can be assessed. It is then found that most codes underpredict the axial induction where they overpredict the axial force. This is inconsistent to the BEM relation between axial force and induction. Until now the reason for this inconsistency is unknown. Many investigations within Mexnext are currently carried out which may shed light on this and other phenomena.

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