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Experimental investigation of Surface Roughness effects and Transition on Wind Turbine performance

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Abstract. Aerodynamic experiments have been executed in the wind tunnel and on a wind turbine blade to measure the impact of roughness on the airfoil characteristics and the associated effect on rotor performance and to establish the transition location on a rotating blade. The wind tunnel tests have been performed in the low-speed, low-turbulence wind tunnel of TUDelft. The wind turbine tests were carried out at ECN's Wind Turbine Test Site. Roughness simulation material has been installed on the airfoil leading edge to measure the impact on airfoil performance. Microphones were mounted on the airfoil surface to detect the boundary layer laminar to turbulent transition position both on the wind tunnel model and on the wind turbine blade.

1. Introduction

Wind turbine operation is frequently affected by a decreasing performance over time, which is assumed to be mainly caused by erosion, contamination and roughness occurring on the rotor blade surface [1], especially at the leading edge. This phenomenon has not yet been thoroughly studied. Some qualitative tests on airfoils have been done, where the loss of airfoil aerodynamic performance has been measured [2], but the way to extrapolate the 2D measurements to the airfoil 3D behaviour on blades is not straightforward.

The level of laminar flow over the wind turbine blades can be affected by their surface roughness conditions and turbulent inflow, influencing the aerodynamic performance. The chord-wise position of the laminar to turbulent transition on an airfoil can be easily predicted through 2D computations. But it is not so accurately obtained for the rotating blade where 3D conditions exist [3].

Within the EU funded Integrated Research Programme for Wind (IRPWIND), an experimental project has been executed under the 2nd Call of Joint Experiments where these issues are investigated. The overall goals of the project were on one hand to try a standardized method for simulating and testing surface roughness aerodynamic effects at 2D airfoil and 3D rotor blades levels, and on the other hand to prove a testing methodology for detecting the laminar to turbulent transition position in wind turbine blades at operation.

To reach these goals, 2D wind tunnel tests and wind turbine blade experiments have been performed. The main objectives of the tests were to measure the effect of a roughness simulation material installed on the airfoil leading edge of both the wind tunnel model and wind turbine blades, and to analyse the laminar to turbulent flow transition with surface microphones installed on a wind turbine blade.

This paper focuses in the description of the tests and presents a preliminary analysis of the results.

2. Experimental approach

Both types of experiments, roughness simulation and transition position measurement, have been performed on a 2D airfoil model at wind tunnel and also on rotor blades at an operating wind turbine. The airfoil geometry used at the wind tunnel test is the same as one of the airfoil sections of the tested wind turbine blades, and corresponds to the 18% relative thickness NACA63_3-418 airfoil. The blade section with this geometry is located in the tip region at around 93% radius.

The roughness simulation has been attained by applying sand paper on the leading edge of the airfoil. The sand paper has a normalized size of its grain material designated by its grit number. This allows for an easy repeatability of the tests and for the reproducibility by computational analysis. It is a cheap and very accessible material and can be easily installed with double sided tape on the model or blade surface covering the desired area. On the other hand, the sand paper base sheet and coating have a thickness of their own, which may result in further aerodynamic effects that have to be taken into account.

The boundary layer transition can be derived from the analysis of the PSD spectra of the high frequency surface pressure fluctuations [4]. The use of embedded surface microphones for the analysis of boundary layer transition has been performed since several years ago by DTU in the DANAERO project [3] and has allowed implementing it on wind turbine blades. But they have the inconvenience that the microphones have to be installed during blade manufacturing process. Recently, the use of very thin microphones that can be installed over the blade surface has been tried out. The work performed in this experimental project has been focused on the demonstration of the use of these microphones for transition position detection on existing blades.

The wind tunnel tests have been performed at the Low-Speed Low-Turbulence (LSLT) wind tunnel of the Technical University of Delft (TU-Delft) while the wind turbine tests have been done at ECN's Wind Turbine Test Site (EWTW). A brief description of these facilities is shown below.

2.1. LSLT Wind tunnel

The LSLT is an atmospheric tunnel of the closed-throat single-return type (Figure 1), with contraction ratio of 17.8 and a closed octagonal test section of 1.80 m width, 1,25 m height and 2.6 m long.

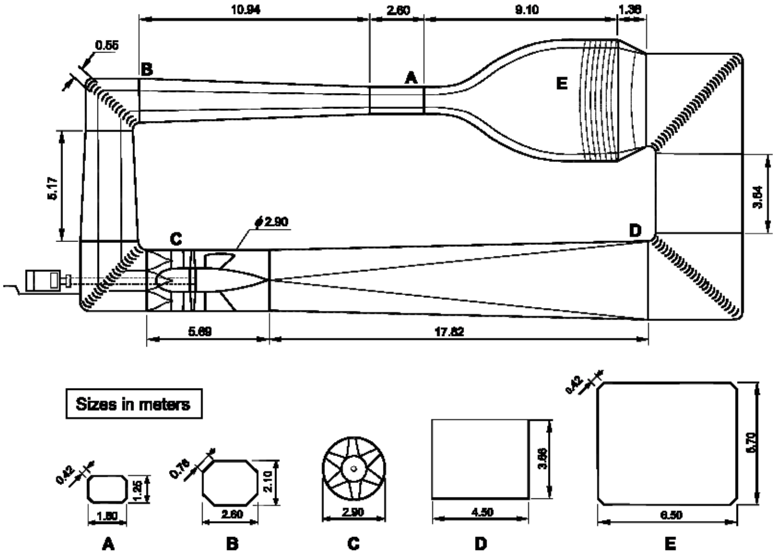

Figure 1. TU-Delft LSLT wind tunnel circuit lay out.

It is powered by a 2.9 meters diameter six-bladed fan driven by a 525 kW DC motor, giving a maximum test section velocity of about 120 m/s.

The free-stream turbulence level in the test section ranges from 0.02 % at a wind speed of 10 m/s to 0.07% at 80 m/s, which correspond to a Reynolds number of $3x10^6$ using a 0.6 m chord model. Electrically actuated turntables flush with the test-section top and bottom wall provide positioning and attachment for a two-dimensional model.

2.2. ECN Wind Turbine Test Site Wieringermeer (EWTW)

The test site, located at Wieringermeer, is a combination of a wind farm and prototype test locations. The wind farm consists of five 2.5 MW turbines with 80 meter diameter rotors. Additionally, six prototype test locations are available for testing, optimising and certifying prototype wind turbines. It has some supporting facilities as five meteorological towers, a 36 MVA grid connection, the measurement infrastructure, data collection equipment and a test site control centre. The site has average wind speed of 8.3 m/s at 100 m height.

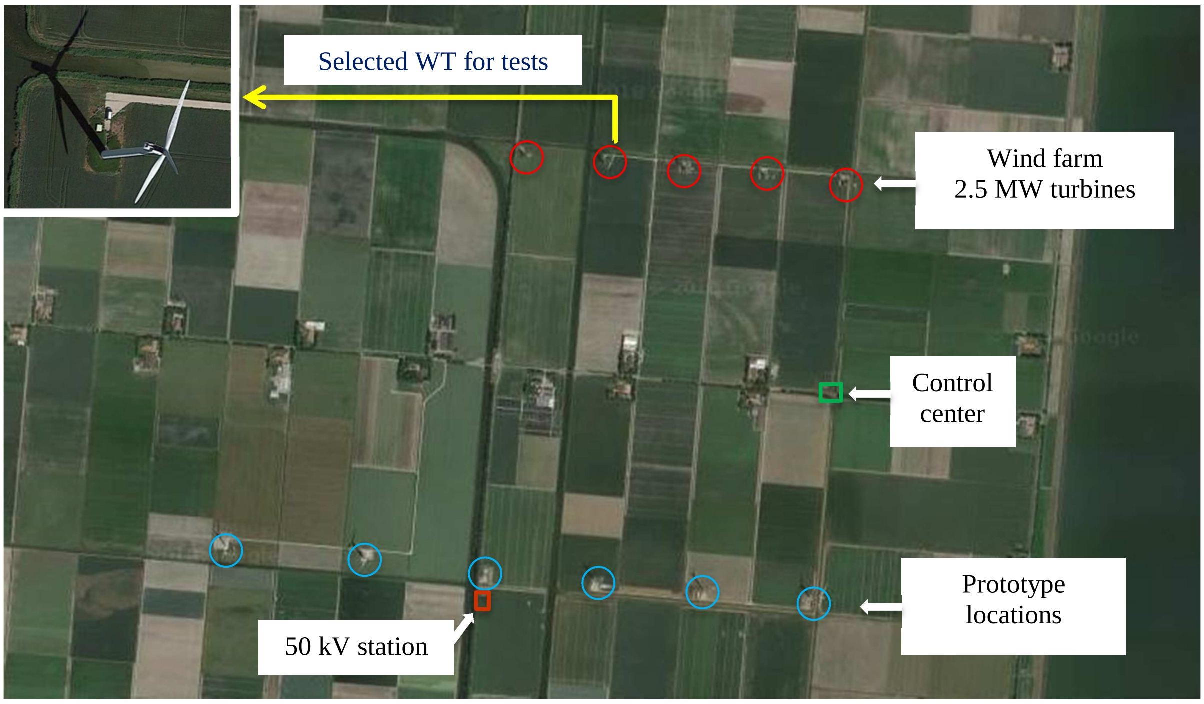

Figure 2. Overview of ECN Wind Turbine Teste Site (EWTW).

The experimental work of this project has been done on one of the 2.5 MW turbine of the wind farm, in particular the second one of the row (as shown in Figure 2). This is a pitch controlled turbine featuring three bladed 80 meter diameter rotor.

3. Wind tunnel test description

The 2D wind tunnel test took place during one week of June 2017. A 0.6 meters chord glass-fibre model was used for the test, representing the geometry of the NACA63_3-418 airfoil, with a trailing edge thickness of 1 mm.

The model, which had previously been used by DTU for testing in the Velux tunnel, was instrumented with 63 pressure taps, staggered in span-wise direction to avoid pressure readings being influenced by the upstream pressure taps. A static and total pressure wake rake was installed around half a chord downstream of the model. The static wake rake consists of 16 static pressures. The total pressure wake rake has 67 pressure tubes with varying spacing ranging from 3 mm over 96 mm in the rake centre to 6, 12 and 24 mm towards both ends of the rake. Figure 3 shows a scheme of the model installation in the test section.

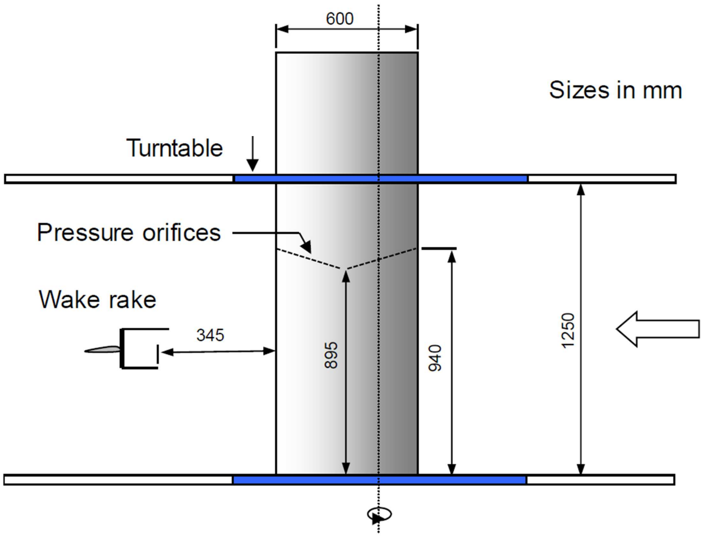

Figure 3. Schematic of model set-up.

The model and the wake rake static and total pressures were fed to the laboratory Initium system, containing 196 high precision pressure ports. The total number of pressures was read with a frequency of 330 Hz and averaged every 200 samples. For those measurements where the wake rake was not performing a traverse this was done during a total averaging time of 20 seconds. The data were on-line reduced to pressure and force coefficients.

Two infra-red cameras were installed opposite the upper and lower surfaces to detect transition and to make sure the measurements were free of sudden drag increases caused by premature transition.

3.1. Surface roughness test.

The aerodynamic coefficients of the airfoil have been measured at a Reynolds number of 3 million for a clean and for different surface roughness conditions. The surface roughness distribution was simulated by applying sandpaper of three different grits (P240, P80 & P40) covering the upper and lower surface of the leading edge with three different chord length extensions (4%, 8% & 15%).

Also two reference conditions of a tripped model boundary layer have been measured using zig-zag tape of two different thicknesses (0.25 mm. and 0.6 mm.) positioned in both pressure and suction side at a distance of 8% of the chord from the leading edge.

Some additional tests at lower Reynolds numbers of 2 million and 1 million were also performed at clean condition and for the P240 grade roughness covering 8% of the chord.

3.2. Transition test with surface microphones.

For the transition position experiment, six G.R.A.S. 40LS 1/4" CCP Precision Surface Microphones were used. These microphones are 2.5 mm. thick with a diameter of 16.2 mm. They wear a silicone rubber fairing to avoid steps with a diameter of 40 mm. The microphone and fairing are placed on the model surface through a double sided base adhesive pad, and finally fixed with a top adhesive pad which has a total diameter of 50 mm.

The coaxial cables coming from the microphones are routed to the trailing edge of the model. A double sided tape is used to fix the cables over the model surface. Finally all the cables are attached to the trailing edge with aluminum tape and routed out of the test section through the floor. Figure 4 shows some pictures of the microphones installation process.

Figure 4. Sequence of microphones installation on the model.

Each microphone cable is connected outside the test section to a constant current power supply (G.R.A.S. CC Supply 12AL) and the six signals are then acquired by a National Instruments NI cRIO-9033 DAQ System with two NI 9239 Modules. The data were acquired at a sampling frequency of 50 kHz.

The microphones were positioned at two different configurations. In both of them, 3 microphones were placed in the pressure side and the other 3 in the suction side. The microphones were staggered in span-wise direction to avoid upstream microphones altering the flow to downstream microphones. In the 1st configuration the chord-wise positions of the microphones were 10%, 40% and 80% on the suction side and 5%, 30% and 60% on the pressure side. In the second configuration these positions changed to 5%, 30% and 60% on the suction side and 10%, 40% and 80% on the pressure side.

Measurements were taken at three different Reynolds numbers (1, 2 and 3 million). The angle of attack was varied within the range from -8º to 10º. In the second configuration, two stall cases were measured at angles of attack of 15º and 18º at Reynolds number of 2 million.

Pictures with the infra-red cameras were taken at these same conditions to correlate data from the microphones with the actual boundary layer conditions.

4. Wind turbine field test description

The wind turbine tests were performed in two different campaigns. The first one was dedicated to surface microphones testing and the second one to roughness simulation on the blades.

4.1. *Surface microphones test for transition detection*

The transition detection test with microphones took place during one week at mid-October 2017. This week was selected based on weather forecasts and technicians availability. The needed weather conditions had to involve not too high wind (below 10 m/s) and dry weather. The installation of the microphones was performed by rope climbers instead of using a truck-mounted aerial work platform because of budget constraint.

One of the blades of the wind turbine was instrumented with 8 surface microphones (4 in the pressure side and 4 in the suction side). The same six microphones used in the wind tunnel tests were used, plus two additional ones from manufacturer B&K (B&K Surface Microphone Automotive type 4949). Table 1 shows the microphones positions on the blade. The rationale behind the selected position of the microphones has been to be sure on both sides to have measurements in both laminar and turbulent boundary flow which means microphones close to the leading edge as well as microphones much further downstream. This also has the impact that an exact position of the transition position cannot be derived from the measurements which would require at least to mount the 8 microphones on the same side. However, considering the limitation of time availability for this measurement campaign, the main objective was to get an overall insight into the spectra at different conditions and states of the boundary layer

The cabling out of each microphone was taped and routed to the trailing edge of the blade, and then all the cabling was routed and taped through the trailing edge to the hub. In order to allow the blade pitch rotation from idle to run position, the cables were attached to an elastic rope that was anchored to the blade and to the hub in a way that had max tension in those two extreme positions. The anchor point on the blade was fixed with an industrial belt as shown in Figure 5.

Table 1. Position of the microphones on the blade.

Distance from tip (m.)	PRESSURE SIDE Chord position	SUCTION SIDE Chord position
3.05	10%	5%
2.8	20%	10%
2.55	40%	20%
2.3	80%	40%

Figure 5. Microphones cabling rooting along the blade

The same data acquisition system as in the wind tunnel was used (National Instruments 8 channels DAQ system), and again the microphones were sampled at 50 kHz. The DAQ system was installed inside the hub in a cabinet. A WiFi antenna was installed in the front part of the hub with magnets to transmit the data to the ground.

The collection of data from the microphones took place during the afternoon of the 19th of October. 2.5 hours of data were collected with the wind turbine in operation and at stand still condition. The measuring time was more reduced than expected. The reason was due to the wind conditions during the 17th of October, which were too high to access the blade by the rope climbers. Additionally the tape used for attaching the cabling on the blade, which was used in former experiments, was not working properly in this type of blade surface and had to be substituted for a different one.

The microphones data were synchronized with the wind turbine SCADA data in order to correlate them with the wind turbine operation. The data files contain measurements obtained during 2 minutes. The time series data are stored as binary single precision floating-point numbers. The file name contains the time stamp (Greenwich + 1 hour) as reference.

4.2. Roughness simulation test

For the roughness simulation, the three blades were covered with sand paper in the leading edge area in the same way that the wind tunnel model was. The objective is to obtain power data of the wind turbine with the simulated roughness installed and compare them to the power obtained at 'clean' conditions so that the roughness effect can be evaluated in terms of power loss. Also the results can be cross-checked with the data obtained at 2D airfoil level in the wind tunnel tests.

In order to stand the outdoor climate conditions of the test, the selected roughness simulation material was the R205 Aluminia Zirconia sanding belt from Sun Abrasives CO, LTD. Long belts of 200mm x 750mm were used to build the roughness strips and double sided 3M tape was used to install them in the blade. The roughness simulation material was installed in the three blades covering 5 meters of the span (between 32m and 37m measured from the blade root) and with a chord-wise extension of 15%. The grit number selected was P60 which has an equivalent mid grain size of 269 microns.

Figure 6. Roughness material installed on the blade

To decide the grit size to be used in the field test the main consideration was to use an equivalent size used in the wind tunnel in order to correlate the data. The wind tunnel tests were performed at Reynolds number of 3 million and with an airfoil chord size of 0.6 m. On the blade, these parameters are not fixed, since in the selected blade covered area the chord varies from around 1 to 1.5 meters. The Reynolds number is also not a fixed value. It changes with the wind conditions and also with the chord dimension. Values of the Reynolds numbers are shown in Table 2.

Table 2. Reynolds number (in million) in the blade area covered with roughness simulation material

Section	6 to 8 m/s	8 to 10 m/s
32	4.5 – 5.8	5.8 - 6
34	4.5 – 5.5	5.5 – 5.8
36	4 - 5	5 – 5.3
37	3.3 – 4.2	4.2 – 4.5

In order to get an equivalent grain size in the blade, since the Reynolds number would be higher at the wind turbine blade, we would need to go for a smaller grain size. But as the blade chords are bigger than the 2D model chord the grain size should then be bigger in the field experiment. Making the equivalent grain size for different wind conditions of the blade showed that it would correspond to values ranging in most of the cases in between the P40 and the P80 grit. Therefore, using an intermediate grit size like 60 would be the best option.

The installation of the material in the three blades was performed in between the 17th and 19th of December 2017. From that date up to beginning of February 2018, when the material was removed, power measurements were recorded in order to compare them with operation of the wind turbine in 'clean' condition.

5. Preliminary results from the tests

A brief resume of preliminary results obtained from the tests are presented below. Further analysis of the data still has to be performed. All data from these tests will be organized and published in open access.

5.1. Roughness simulation tests data

The data obtained during wind tunnel tests have been analysed to obtain the effect of roughness grain size and chord-wise extension. Figure 7 compares the 'clean' surface case with different cases of the P40 grit roughness chord-wise extension. Figure 8 shows plots comparing aerodynamic coefficients for different cases of grain sizes.

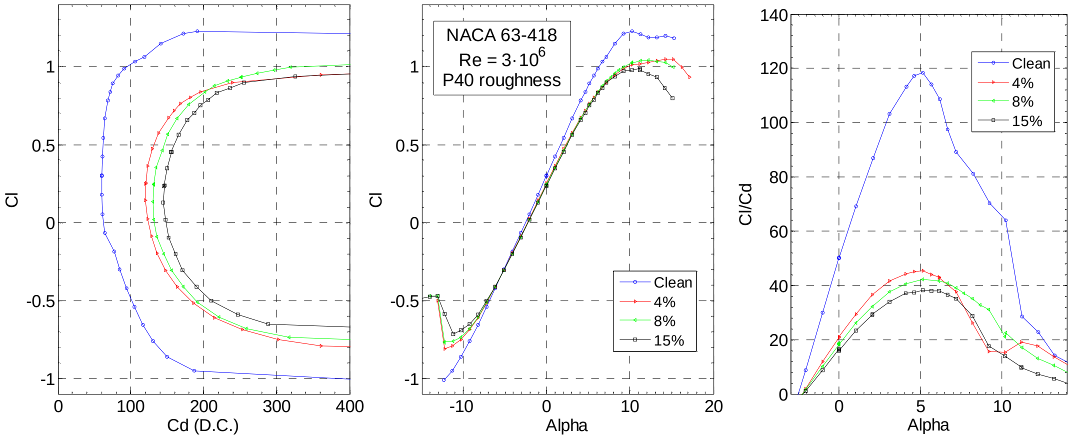

Figure 7. Effect of different roughness extension for same grain size of 425 microns

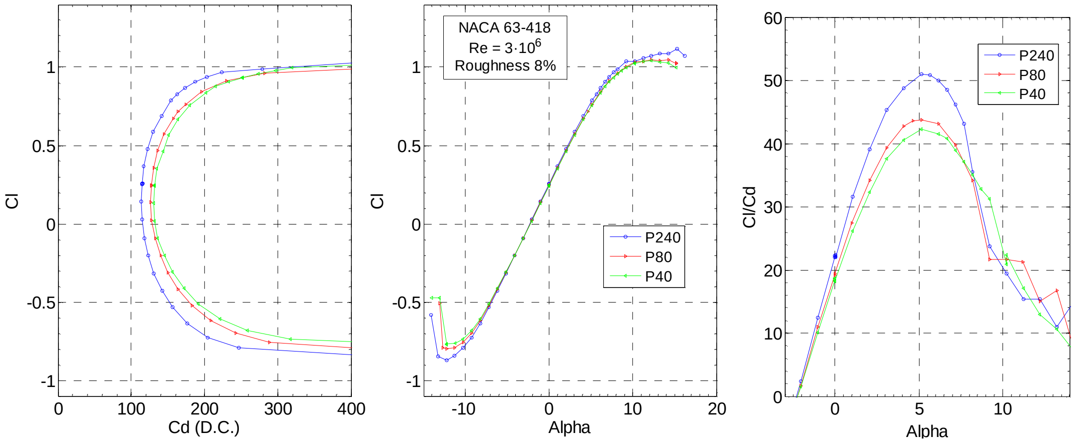

Figure 8. Effect of the different grain sizes for a chord-wise extension of 8%

As it is expected, the roughness produces an increase of drag and decrease of lift slope resulting on a significant reduction of lift to drag ratio. And it is more severe with higher extension and grain size.

Figure 9 shows the trends of the minimum drag and maximum lift-to-drag ratio for the different configurations tested at wind tunnel. As it can be seen at the plots the effects are almost linear with the extension of the roughness, but not with the grain size.

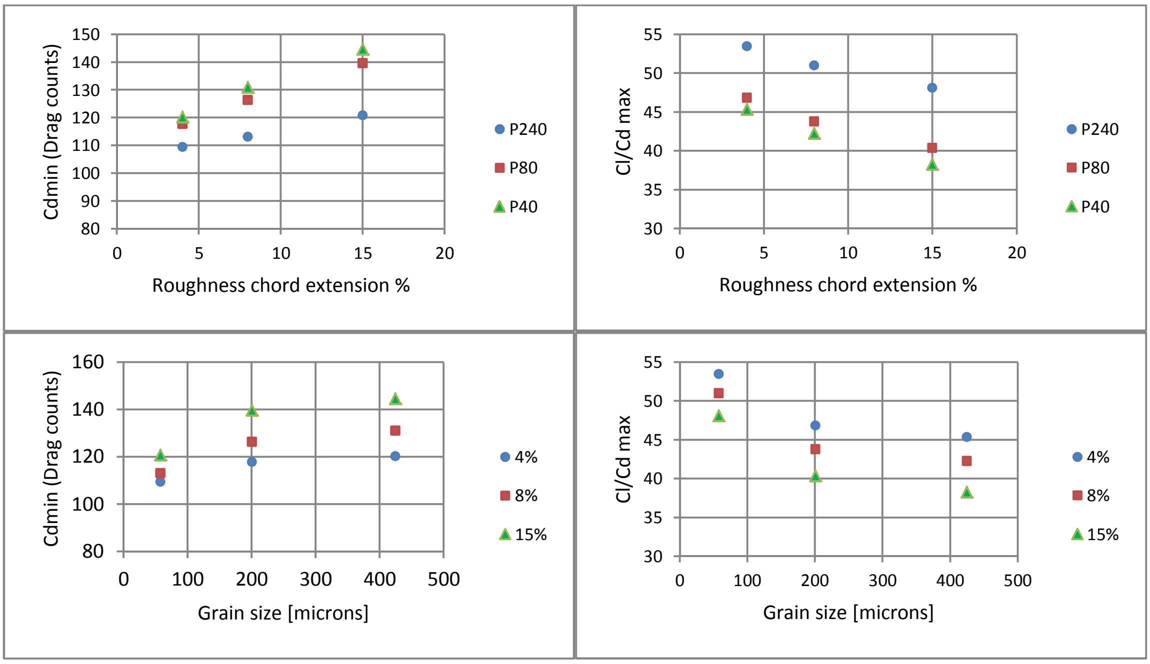

Figure 9. Overview effect of roughness extension and grain size on drag and efficiency

A preliminary analysis of the data obtained from the wind turbine campaign shows that the mean power obtained with the roughness simulation material installed on the blades is around 5% lower than without it. This is compatible with some computations that have been performed using ECN's Blade Optimization Tool (BOT) to estimate the power loss.

5.2. *Results from the transition measurements with surface microphones*

Data obtained from the microphones have been preliminary analysed to check their quality and potential use. The power spectral density of the surface pressure measured by each microphone are obtained and plotted.

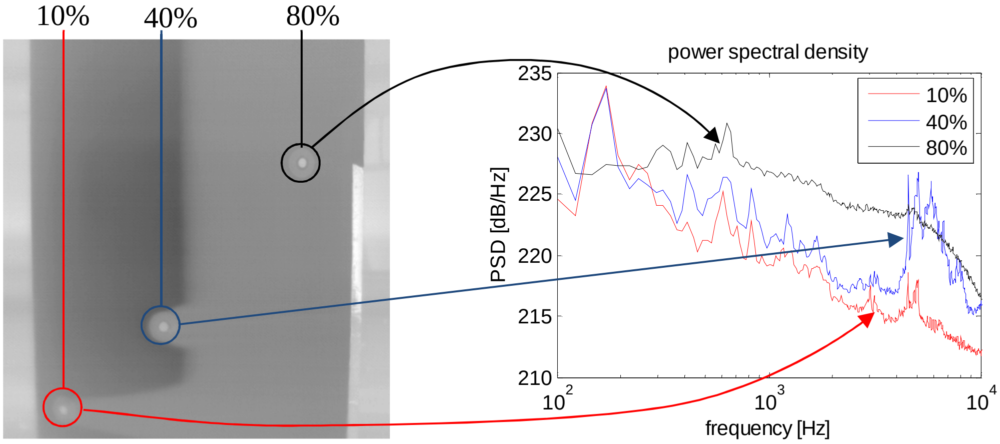

Figure 10. Model suction side. Wind comes from the left. Reynolds 3 million, AoA=3º

The data from the wind tunnel can be cross-checked with the infrared camera pictures that show the areas where flow is laminar and turbulent on the model (Figure 10). The setup is well suited to detect transition. The measured surface pressure spectra are in agreement with the infrared pictures.

The surface pressure spectra of the two microphones in the laminar flow region show a growing narrowband peak at frequencies higher than 5 kHz. These peaks indicate a Tollmien-Schlichting instability that leads to transition. The PSD at 80% shows a broad-band energy distribution which is typical for a turbulent flow.

Figure 11 shows the spectra of suction (left plot) and pressure side (right plot) microphones installed on the blade in an operation condition. On the pressure side plot, the spectrum for 40% and 80% position are quite similar and rather flat indicating a turbulent boundary layer, and the ones for 20% and 10% position correspond to a laminar boundary layer. The suction side plot shows turbulent spectra for 40% and 20% position whereas at 10% and 5% it's difficult to make a clear characterization.

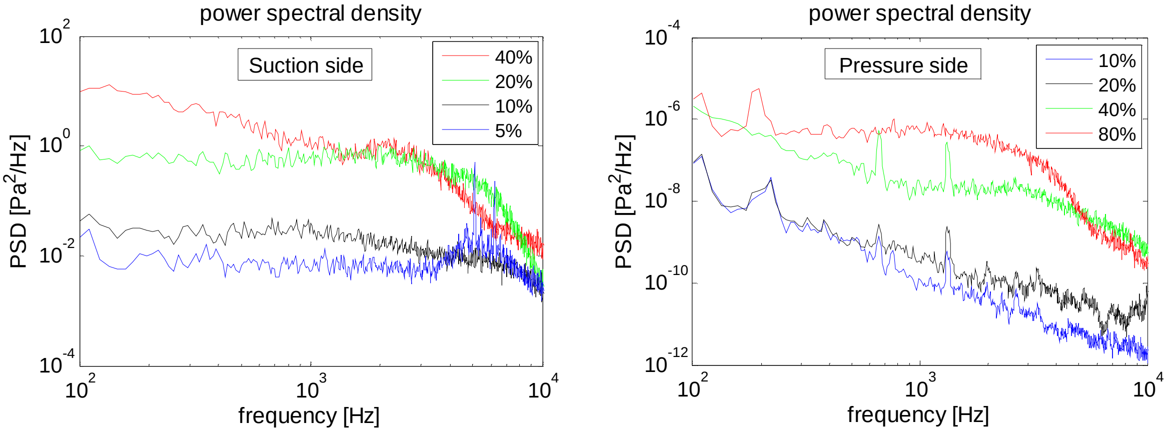

Figure 11. Suction (left) and pressure side (right) spectra of microphone signals on blade

6. Conclusions

Roughness experiments have been performed on an airfoil both in a 2D wind tunnel model and in wind turbine blade. The airfoil aerodynamic performance has been measured in the wind tunnel at different roughness conditions and the effect of one roughness case on the wind turbine power output has been evaluated.

The effect of different chord-wise extension and grid sizes of roughness on airfoil performance has been evaluated at the wind tunnel test. A chord-wise roughness extension increase between 4% and 15% has shown to produce a close to linear degradation effect on the airfoil minimum drag and maximum lift-to-drag ratio. The grain size variation doesn't show the same trend, and the airfoil performance degradation has a lower proportional variation between the higher size grains.

Surface microphones have been installed on a wind turbine blade. The data preliminary analysis has demonstrated that it is possible to detect laminar and turbulent boundary layer on the blade. The acquired data also contains valuable information on the high frequency characteristics of the atmospheric inflow to the blade on a full scale turbine.

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