Aerodynamic modelling of wind turbine blades exposed to erosion (WP6.1)

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“Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken en Klimaat en het Ministerie van Landbouw, Natuur en Voedselkwaliteit, Nationale regelingen EZK- en LNV-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.”

Contents

1 Introduction

This report summarizes the main results from WP 6.1 of the Airtub project.

The overall goal of Airtub is the development of an automated inspection and repair strategy for wind turbine blades where special emphasis is paid to erosion.

These repairs mitigate the aerodynamic losses from erosion caused by the degradation of aerodynamic optimal design blade shape where in particular the erosion at the leading edge (i.e. the nose of the blade) has a large aerodynamic impact.

A repair from erosion with the strategies developed within Airtub will then obviously increase the AEP, but the costs from the repair need to be balanced against the gain in AEP. This obviously implies that the aerodynamic losses from erosion should be known for which models are developed/improved and validated within WP6.1.

The modelling of AEP losses from erosion in WP6.1 is largely based on the Blade Element Momentum (BEM) Theory. This is a relatively simple theory, see e.g. [5] and it predicts the power curve of a wind turbine (i.e. the power as function of wind speed) which together with a known wind climate determines the AEP.
Some public examples of BEM codes are QBLADE and OpenFast where TNO has also developed several BEM models amongst others the AeroModule

A basic modelling principle of BEM is the division of the blade in a number of blade sections (say 20). These blade sections (of limited length) are assumed to be 2 dimensional and the aerodynamic performance of such section is characterized by airfoil polars which give the lift, drag and moment coefficients as function of angle where for the purpose of power curve modelling the moment coefficient is of less relevance. These airfoil characteristics form input to a BEM code and they are usually given for clean airfoils but in order to predict the power curve of a turbine with eroded blades, the airfoil characteristics need to be determined for eroded conditions.

Hence the challenge in the modelling of AEP losses from erosion lies in the modelling of 2D airfoil characteristics from erosion.
Thereto two categories of models are applied within WP6.1 of Airtub

- Panel methods coupled to integral boundary layer models. Such methods are relatively fast and they are often mentioned to be of medium fidelity due to the fact that several modelling assumptions are made. A well known example of such method is XFOIL but in the present project the RFOIL code is applied [10] RFOIL is originally developed by ECN (now TNO), TUDelft and NLR in the 1990s and further refined by TNO. It is modification of XFOIL but RFOIL is made suitable for wind turbine conditions amongst others by taking into account some rotational effects and by more accurate modelling of thick airfoils. The boundary layer transition point ((i.e. the point where the boundary layer trips from laminar to turbulent) can be fixed or it can be free. In that case the transition point is modelled with the e^N method.
- CFD Computational Fluid Dynamic methods. CFD methods are high fidelity but also time consuming. There are several categories of CFD models but the present project mainly focusses on so-called RANS (Reynolds Averaged Navier Stokes) models implemented in the OpenFoam solver where the boundary layer transition point is calculated with Langtry-Menter's SSTLM model.

Both RFOIL as well as CFD require a characterization of erosion as input. The focus of the present project is on relatively small scale erosion which can be generalized with a roughness height (which is a kind of average measure for the ''deepness" of the erosion) and density (which can be considered as a measure for the number of pits). These roughness heights and density should be translated from the erosion classes on the wind turbine blade as determined in other WP's from Airtub.

The lower aerodynamic performance from erosion is at least partly related to a forward shift of the boundary layer transition point (i.e. the point where the boundary layer trips from laminar to turbulent) from erosion. This can happen at both the pressure and suction side and generally leads to a higher drag and lower lift and so a lower performance. The main challenge in the prediction of airfoil polars with RFOIL or CFD then lies at sub-critical roughness heights for which there is still a region of laminar flow along the airfoil and which requires the determination of the transition point; For above critical roughness heights the transition point is known to be at the nose which implies that the airfoil polars can be predicted with a fully turbulent calculation which is relatively straightforward to do.

The RFOIL and CFD model approaches are validated with measurements on eroded 2D airfoil sections taken in the wind tunnel, or more precisely: airfoil sections with added roughness of known roughness height and density. Part of the validation was supposed to be done with new measurements in the DNW-LST wind tunnel specifically performed in the Airtub project. Despite the fact that a large effort was spent on performing a high quality experiment, the measurements were found to have a non-understood uncertainty see chapter 4.

For this reason the validation of models had to be based on existing data from wind tunnel measurements which were supplied by third parties to the Airtub WP6.1 group
These measurements come from:

- Sandia National Laboratories. Sandia is a US laboratory which performed a the Leading Edge Erosion Study (LEES) project funded by the US Department of Energy https://energy.sandia.gov/programs/renewable-energy/wind-power/wind-plant-data-science-artificial-intelligence/leading-edge-erosion/.
  Part of this research consisted of wind tunnel measurements on 2D airfoils which were exposed to roughness. Sandia made the measurements publicly available but even before they were published Sandia kindly provided them to TNO and Hanze UAS which is very much appreciated.
- LM WindPower. LM WindPower performed wind tunnel measurements on airfoils with different erosion pattern. These measurements were supplied to the AVATAR project group (led by ECN, now TNO) and they may be used with permission from LM in other research as well.
- IRPWIND. Within the EU funded Integrated Research Programme for Wind (IRPWIND), led by ECN (now TNO) an experimental project has been executed under the 2nd Call of Joint Experiments where amongst others wind tunnel measurements have been done on airfoils to which roughness in the form of sandpaper was added. The measurements are made publicly available.

These measurements are described in more detail in chapter 2 where a further analysis of these measurements including a validation of RFOIL and OpenFoam are described in 3.

An additional task within WP6.1 was devoted to the study of the aerodynamic performance at high Reynolds numbers representative for large off-shore wind trubines. The Reynolds number is given by ρ V c/ μ with ρ and μ the density and viscosity of the medium (which is air for wind turbine situations), V the velocity and c the chord. The Reynolds number can be considered as an aerodynamic scaling number which should be comparable in order to have similar aerodynamic phenomena. Hence in order to have wind tunnel measurements which are representative for full scale wind turbines the Reynolds number in the wind tunnel should be the same as the Reynolds number on a wind turbine.

Now it should be realised that the limited size of a wind tunnel generally leads to models witch chords which are much smaller than the chord of blade section on a 10 MW+ off-shore turbine which then leads to a lower Reynolds number as well. As a consequence the above mentioned wind tunnel measurements were often done at Reynolds numbers in the order of 4 Million where the Reynolds number on a 10 MW+ turbine is generally above 10 M.

In order to increase the Reynolds number in a wind tunnel the tunnel velocity can be increased but this is only possible to a limited extent (due to fact that tunnel speeds above say 100 m/s lead to compressibility effects which forms another source of differences between tunnel and wind turbine conditions). Hence the only feasible option to increase the Reynolds number on small scale wind turbine models is to decrease the viscosity or increase the density.

This was done within the above mentioned AVATAR project, through measurements in the DNW-HDG wind tunnel which is a pressurized tunnel enabling Reynolds numbers up to 15 M even for small wind tunnel models. The measurements were carried out on clean airfoils only but the results are still worthwhile to investigate since they help to understand how a high Reynolds number effects the aerodynamic airfoil performance. This understanding serves as a first step to develop reliable erosion models at high Reynolds numbers. The study on high Reynolds numbers is given in chapter 5.

Conclusions and recommendations from Airtub WP6.1 are given in chapter 6.

2 Wind tunnel measurements on airfoils with erosion from third parties

2.1 Wind tunnel measurements from Leading Edge Erosion Study (LEES) project

Within the LEES (Leading Edge Erosion Study Project) project and led by Sandia National Laboratory in the USA, wind tunnel measurements were performed on two different airfoils, the NACA63418 and the NRELS814 where the NACA63418 airfoil has a thickness of 18% and the NRELS814 has a thickness of 24%

The measurements were done in the Oran W. Nicks Low Speed Wind Tunnel at Texas A&M with a test section of 7 ft x 10 ft, a maximum velocity of 90 m/s and a turbulence intensity of 0.25%

Both airfoils were manufactured specifically for the experiment with detachable leading edges, capable of testing numerous roughness configurations where the roughness was translated from scans carried out on blades which have been in operation and which were affected by erosion. As a reference measurements at clean conditions were done too. The table below displays the Reynolds numbers, angles of attack and roughness configurations for which the experimental data were generated per airfoil.

Airfoil	NACA63418	NRELS814
Chord [m]	0.813 m	0.813 m
Reynolds number (Million)	1.6, 2.4, 3.2, 4.0	2.4, 3.2, 4.0
Roughness configuration (between brackets, roughness in %)	100 μm (3%, 9%, 15%) 140 μm (3%) 200 μm (3%)	95 μm (3%, 9%, 15%) 125 μm (3%) 225 μm (3%)
Roughness length, suction side	2%	2.5%
Roughness length, pressure side	13%	14%
AoA range(1° step)	-5° to 13°	-10° to 5°

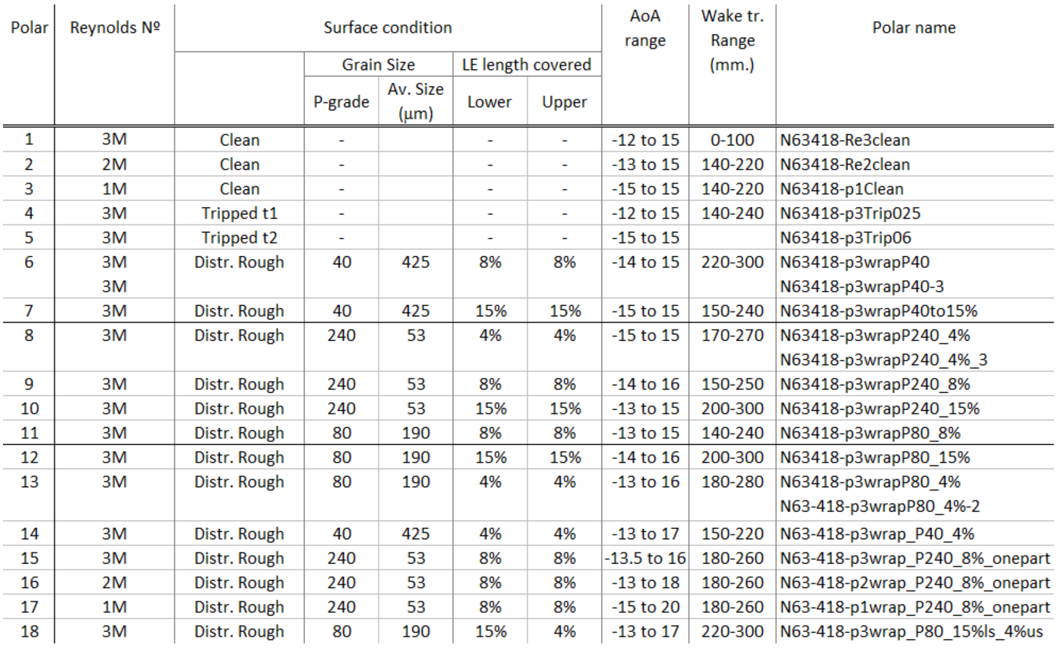
The pressure distributions around the airfoils were measured with 32 static surface pressures from which the lift force has been derived. Drag was measured with a wake rake. The transition point is important additional information from this experiment and has been measured with infrared (IR) thermography

2.2 Wind tunnel measurements from EU project IRPWIND Roughness

Within the IRPWIND roughness project experiments were conducted at Delft University of Technology (TU Delft) LSL (Low Speed Laboratory) with a test section of 1.80m (width) x 1.25m (height) x 2.60m (length). The maximum tunnel speed is 120m/s. The contraction ratio of 17.8 generates very low free-stream turbulence levels in the test section which varies between 0.015% at 20m/s and 0.07% at 75m/s.

The airfoil on which the measurements were performed was a NACA 63-418 with a chord of 0.6 meter to which different sand paper configurations were applied at its nose to simulate distributed roughness effects.

Moreover, zig-zag tapes were studied to compare its influence on the aerodynamics against the distributed roughness cases. As a reference to the distributed roughness and tripped cases a clean section was measured too. In the figure below the test matrix is presented in detail where in addition it can be noted that generally speaking the angle of attack interval was 1 degrees. The zig-zag tape tripped cases were investigated with two different thicknesses (0.25 and 0.6mm), applied at the 8% chord location on both sides of the section. Three sand paper P-grades were investigated: P40, P80 and P240 and they correspond to a grain size of 425, 190 and 53µm respectively, i.e. the larger the P grade the smoother the imitated roughness. The effect of the Reynolds number was studied only for the P240 grade, while the effect of grain sizes were studied at a Reynolds number of 3million. Three distributed roughness cases were studied, which cover both sides of the profile up to 4, 8 and 15% of the chord. Additionally, one study was conducted with the suction side covered up to 4%, while the pressure side was covered up to 15%.



Polar	Reynolds Nº	Surface condition					AoA range	Wake tr. Range (mm.)	Polar name
			Grain Size		LE length covered				
			P-grade	Av. Size (µm)	Lower	Upper			
1	3M	Clean	-		-	-	-12 to 15	0-100	N63418-Re3clean
2	2M	Clean	-		-	-	-13 to 15	140-220	N63418-Re2clean
3	1M	Clean	-		-	-	-15 to 15	140-220	N63418-p1Clean
4	3M	Tripped t1	-		-	-	-12 to 15	140-240	N63418-p3Trip025
5	3M	Tripped t2	-		-	-	-15 to 15		N63418-p3Trip06
6	3M 3M	Distr. Rough	40	425	8%	8%	-14 to 15	220-300	N63418-p3wrapP40 N63418-p3wrapP40-3
7	3M	Distr. Rough	40	425	15%	15%	-15 to 15	150-240	N63418-p3wrapP40to15%
8	3M	Distr. Rough	240	53	4%	4%	-15 to 15	170-270	N63418-p3wrapP240_4% N63418-p3wrapP240_4%_3
9	3M	Distr. Rough	240	53	8%	8%	-14 to 16	150-250	N63418-p3wrapP240_8%
10	3M	Distr. Rough	240	53	15%	15%	-13 to 15	200-300	N63418-p3wrapP240_15%
11	3M	Distr. Rough	80	190	8%	8%	-13 to 15	140-240	N63418-p3wrapP80_8%
12	3M	Distr. Rough	80	190	15%	15%	-14 to 16	200-300	N63418-p3wrapP80_15%
13	3M	Distr. Rough	80	190	4%	4%	-13 to 16	180-280	N63418-p3wrapP80_4% N63-418-p3wrapP80_4%-2
14	3M	Distr. Rough	40	425	4%	4%	-13 to 17	150-220	N63-418-p3wrap_P40_4%
15	3M	Distr. Rough	240	53	8%	8%	-13.5 to 16	180-260	N63-418-p3wrap_P240_8%_onepart
16	2M	Distr. Rough	240	53	8%	8%	-13 to 18	180-260	N63-418-p2wrap_P240_8%_onepart
17	1M	Distr. Rough	240	53	8%	8%	-15 to 20	180-260	N63-418-p1wrap_P240_8%_onepart
18	3M	Distr. Rough	80	190	15%	4%	-13 to 17	220-300	N63-418-p3wrap_P80_15%ls_4%us

The pressure distributions around the airfoils were measured with 62 static surface pressures from which the lift force has been derived Moreover the drag was measured with a wake rake. An infrared camera with a hot lamp pointed towards the suction side was used to identify boundary layer transition. Measurement with infrared camera are available for clean conditions only.

2.3 Wind tunnel measurements from LM WindPower

Within the EU project AVATAR LM WindPower performed measurements on a public 21% thick DU-00-W-212 airfoils with chord 900 mm at two Reynolds numbers 3 and 6 Millions. The measurements were done in the LSWT wind tunnel d at LM WindPower in Lunderskov, Denmark. This is a closed return system with a contraction ratio of 10:1 and turbulence intensities (as copied from another experiment described in Pires_high_RE Journal of Physics: Conference Series 749 (2016) 012014) are in the order of 0.05 to 0.1%. The maximum speed is 105 m/s (Mach 0.3), The test section has a width of 1.35 m, a height of 2.70 m and a length of 7 m

The airfoils had a detachable leading edge (DLE) over a length of 2% chord on which three different erosion pattern are applied: light incubation, medium and heavy erosion. Furthermore, a fourth pattern was created, simulating breakthrough and delaminations of the glass lay-up. The erosion patterns were based upon the statistics and characteristics of specimens which resulted from rain erosion testing i.e. tests of an airfoil on a rotating arm exposed to a simulated rain field. Light erosion occurs directly after incubation, where the erosion only penetrates into the coating with maximum depths less than 400 μm. Medium and heavy erosion are located further down the mass loss curve, where erosion would reach the glass-layers with maximum depths higher than 400 μm.

For comparison purposes measurements on airfoil models with clean DLE's were carried out too. The clean DLE's were either of Aluminum or 3D printed, while the eroded DLE's were all 3D Printed. Measurements on an integrated clean DU-00-W-212 airfoil, i.e. without DLE's are described in [8]

The experiment did not include surface pressure measurements except for the clean airfoil. Therefore lift had to be obtained from load cell measurements. Drag was derived from wake rake measurements. The transition point was not measured.

The fact that the present experiment did not include measurements of pressure distributions and transition points and the fact that no detailed information of erosion patterns was known made that priority was given to the analysis of other measurements but some observations from the measurements are still reported in section 3.3

It is noted that [21] also reports measurements in the LSWT wind tunnel on a 18% tip airfoil exposed to different erosion patterns which does not only differentiate between light medium and heavy erosion but also between coverages, see figure 1.

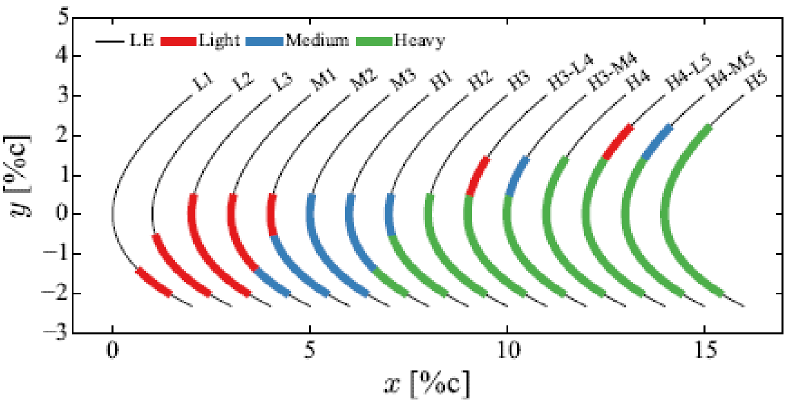


Figure 1: Erosion patterns covered on 18% tip airfoil measured by LM WindPower

Although these measurements cannot be used for validation purposes (because the airfoil geometry as input for airfoil prediction codes is confidential) some interesting qualitative information could still be extracted, helped by the fact that the transition point was measured, see section 3.3

3 Analysis of wind tunnel measurements from third parties

In this section several validations and analyses are described on the wind tunnel measurements from section 2.

3.1 Analysis of Wind tunnel measurements from the LEES project

Section 2.1. describes the wind tunnel measurements from the US leading Edge Erosion project. These measurements have been used to validate both RFOIL and OpenFoam.

3.1.1 Modelling of erosion with RFOIL

As explained before RFOIL is a medium fidelity solver based on a panel method coupled to a viscous integral boundary layer model capable of modelling 2D airfoil characteristics (strictly speaking quasi 2D characteristics because some 3D effects on the boundary layer equations are included but the method is still applied in a 2D way). RFOIL is extensively validated for the prediction of airfoil characteristics at clean conditions but not for the prediction of characteristics at eroded conditions as is done in the present project. Strictly speaking the prediction of airfoil characteristics with RFOIL is not done with one straightforward calculation but it can best be described as a calculational procedure in which two RFOIL calculations are involved where information from the first calculation together with an empirical formula which depends on the roughness characteristics gives the forward shift of boundary layer transition point from erosion. It is then assumed that this forward shift of transition point is the dominant effect for the change in aerodynamic performance and so the airfoil characteristics at erosion are found from a 2nd RFOIL calculation with fixed transition using this forward shift of transition point.

The relevant input values for this RFOIL procedure (apart from input data which are standard for every RFOIL calculation. e.g. airfoil shape, angle of attack, chord Reynolds number etc) is the non dimensional integrated roughness parameter I_K. This integrated roughness parameter I_k has a slightly complicated expression, see [15] but it is an integral over the airfoil surface from the stagnation point to the edge of the roughness of a function in which the dimensionless height parameter appear which in turn depends on a representative height of the roughness elements and their density.

This makes the heights of the roughness elements and their density the main input parameters for the RFOIL modelling erosion. They have to be assessed from the actual erosion pattern.

More specifically the modelling procedure starts with this assessment of erosion and translation to I_k. Within the present study based on the LEES wind tunnel measurements this was relatively straightforward to do due the structured erosion patterns.

Then this value of I_k is fed into an empirical function $f(I_k)$ which is a function calibrated on wind tunnel measurements and which gives the ratio between the momentum thickness Reynolds number ($Re_{,\theta}$) at transition (indicated with index *t*) for the airfoil at eroded conditions (indicated with *rough*) and the momentum thickness Reynolds number at transition for the clean airfoil (indicated with *clean*) in other words:

$f(I_k) = Re_{\theta,t,rough}/Re_{\theta,t,clean}$ [1]

The value of $Re_{\theta,t,clean}$ is found from an RFOIL calculation on a clean airfoil which provides the position of the transition point and the corresponding momentum thickness $\theta_{t,clean}$ (normalized to the chord length) so that $Re_{\theta,t,clean}$ can be calculated with the known chord Reynolds number.

Next the value of $Re_{\theta t,rough}$ can be determined from expression 1 with the value of $Re_{\theta,t,clean}$ and the calibration function $f(I_k)$. Then the transition point at rough conditions is found by comparing $Re_{\theta t,rough}$ to $Re_{\theta,clean}$ along the surface, i.e. the RFOIL calculated values of Re_θ at clean conditions. Then the position where $Re_{\theta t,rough}$ matches the values of $Re_{\theta,clean}$ is assumed to be the transition point. With this forward shifted transition point another RFOIL calculation is done to give the airfoil characteristics at erosion.

A main uncertainty in this modelling approach lies, apart from the uncertainty in choosing the input parameter I_K from the representative height and density of the roughness elements, in the calibration function $f(I_k)$. Figure 1 shows the qualitative behavior of this function where it can be seen that $f = 1$ for $I_K < I_{k,crit}$ which implies that there is no shift in transition for relatively low values of I_k, i.e. relatively smooth surfaces. For larger I_k ,i.e. larger roughness there is a linear decrease of f to values lower than 1 which makes $f < 1$ and which corresponds to a forward shift in boundary layer transition point.

This linear decrease is modelled with parameters C_{l1} and C_{l2} by which the calibration function f can be written as 1 for $I_K < I_{k,crit}$ and as $C_{l1}I_k + C_{l2}$ for $I_K > I_{k,crit}$ The values of $I_{k,crit}$ and C_{l1} and C_{l2} are calibrated with wind tunnel measurements of the transition point. Originally Sandia Lab performed this calibration with their LEES wind tunnel measurements for one airfoil and one Reynolds number.

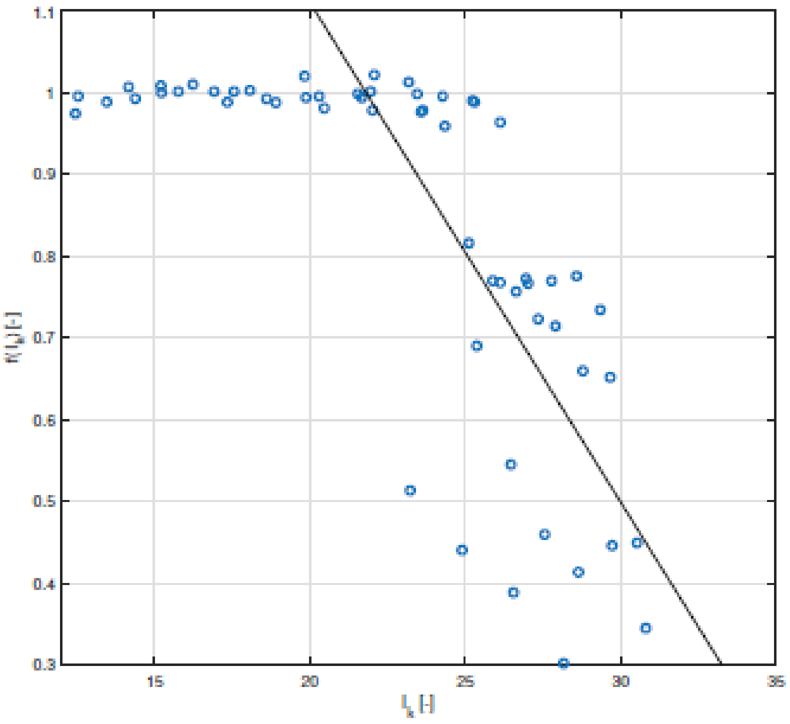


Figure 2: Qualitative behavior of f(Ik)

In the present study [15] the calibration curves is determined for more Reynolds numbers and both airfoils and the results of aerodynamic load predictions and transitions points are assessed for different calibrations. It is then concluded that if f is calibrated on experimental data relevant to the Reynolds number and roughness, the method can be used with confidence.

3.1.2 *Modelling of erosion with CFD*

In addition to the RFOIL modelling as described in the previous section TNO also performed CFD simulations with the OpenFoam code using the steady-state, incompressible simpleFOAM solver with the k-omega SST RANS turbulence model. Laminar-turbulent transition has been accounted for by the Langtry-Menter's SSTLM model (Langtry, 2006; Langtry and Menter, 2009).

For the purpose of erosion modelling a roughness amplification model (denoted as SSTLMkvAr) was added to the SSTLM transition model.

This SSTLMkvAr model was originally developed by Dassler, Kozulovic and Fiala (see Dassler et al, 2010, 2012). More recently Langel from Sandia National Laboratory published a thesis on this model which was implemented in their flow solver OVERFLOW-2 (Langel et al., 2017)

More specifically the model adds a transport equation for a parameter AR to the SSTLM transition model where the parameter AR depends on the roughness characteristics through an equivalent sand grain roughness k_s which in turn depends on the roughness height R_h and the roughness density R_d . As such the parameter AR has some similarity to the I_k parameter from section 3.1.1

The parameter k_s is calibrated as function of R_h and R_d with the measurements of the transition point from the LEES experiment

The calibration was done for three different roughness heights: 100, 140 and 200μm, at a constant roughness density of 3%. Furthermore, the calibration of three different roughness densities (3, 9 and 15%) was performed for the roughness height of 100 μm.

Generally speaking OPENFOAM with the newly calibrated SSTLMkvAr model gave good results in comparison to the measured transition location and to the measured drag and lift coefficients for roughness heights in the order of 140-200 μm. For smaller roughness heights in the order of 100 μm the agreement in transition location is still good but the prediction of the forces, i.e. drag and lift is poorer. It must be noted however that the modelling results (partly) rely on a calibration of k_s which is carried out on the same airfoil as used in the validation which led to the recommendation to perform a validation study on another independent experiment.

It is also noted see chapter 5 that the SSTLM model, in its standard form, does not accurately predict the transition point for Reynolds numbers which are representative for off-shore wind turbines (> 10 Million). This implies that the prediction of roughness effects with the SSTLMkvAr model will also give poor results for large wind turbines since this model is based on the SSTLM model.

3.2 Analysis of the wind tunnel measurements from EU project IRPWIND roughness

Section 2.2. describes the wind tunnel experiment from the EU project IRPWIND roughness experiment. It is mentioned that direct measurements of the transition point with an Infra-Red camera have only been done for clean conditions and not for rough conditions.

For this reason the transition point has been determined in an indirect way i.e. from the pressure distributions where the transition point is apparent through a kink in the pressure distribution. This kink can be determined by visual inspection but within Airtub an algorithm is developed which determines the kink in an automated way, see [18]. A check between the transition point determined in this way with the transition point from the Infrared camera at clean conditions gave a very good agreement. Moreover the algorithm was tested on XFOIL pressure distribution and the resulting transition point was compared with the transition point from the XFOIL boundary layer model which again showed a very good agreement. In a next step the algorithm was applied to the IRPWIND

roughness project measurements at rough conditions. As mentioned in section 2.2 these measurements were done with sand paper of P40, P80 and P240 covering 4% 8% and 15% of the chord.
A clear forward shift in transition point was found for the measurements with 4% coverage in particular at low angles of attack. For larger coverages no transition point could be detected possibly because the transition point has moved to the nose already so there is no region of laminar flow. Another explanation could be insufficient resolution of pressure sensors around the transition point to detect a kink. The observation that the number of pressure sensors should be as large as possible in order to detect the transition point from the pressure distributions was considered a lesson learned in the definition of the Airtub experiment, see chapter 4.
Another recommendation which followed from the IRPWIND roughness measurements and which is included in the Airtub experiment is related to the use of sandpaper which has a backing paper with a thickness in the order of 0.2 mm. This is roughly similar to the grain size of the P80 sandpaper and much larger than the grain size of P240 sandpaper. Although the influence of backing can be tested by performing an experiment on an airfoil with backing paper only, i.e. without grains, a better solution is believed to be the spraying of grain particles directly to the surface, see chapter 4.

3.3 Analysis from the wind tunnel measurements from LM WindPower

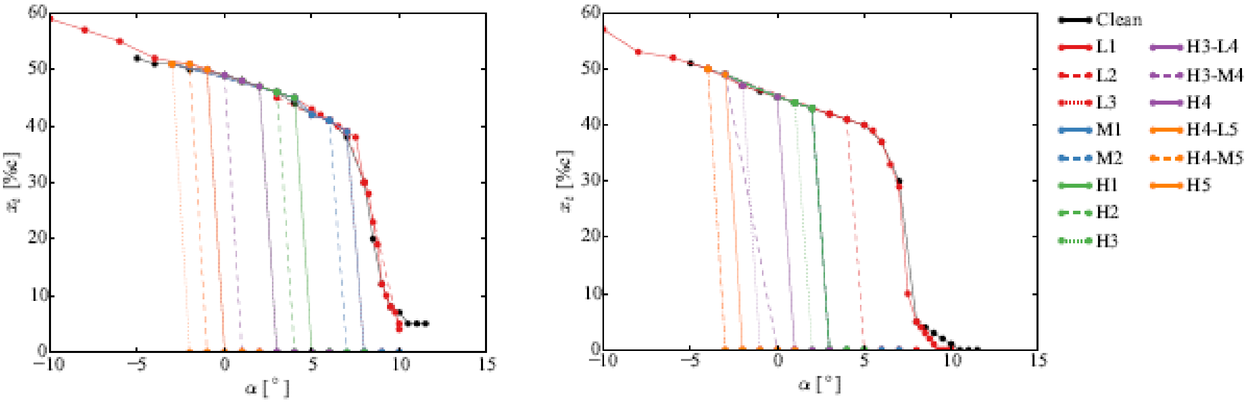
Section 2.3 describes measurements from LM Wind Power in their LSWT wind tunnel on the DU-00-W-212 airfoil to which detachable leading edges (DLE's) with erosion patterns were inserted. It is mentioned that the experiments with DLE's did not include measurements of pressure distributions and transition points. This, with the fact that no detailed information of erosion patterns was known made that priority was given to the analysis of other measurements.

Nevertheless some observations can be made. Amongst others, in LSWT *Campaign Report on DU-00-W-212 DLE*, LM Wind Power report, October 2017 a comparison is made between the aerodynamic performance of the DU-00-W-212 airfoils with clean inserts and the measurements taken on an integrated clean *DU-00-W-212* which are presented in [8]. Some differences are found which are partly explained by lines from the printing process but also by the gaps from the inserts. The possible distortion from a gap was considered a lesson learned to avoid these inserts in the definition of the Airtub experiment, see section 4.

Another observation is the decrease in c_l/c_d from roughness where above certain erosion levels the measured aerodynamic performance becomes almost insensitive to the considered erosion. This confirms that above a critical roughness there will not be much additional aerodynamic disturbance.

Moreover LM also provided measurements in the LSWT wind tunnel on a 18% tip airfoil exposed to a large variety of erosion patterns which does not only differentiate between light medium and heave erosion but also between coverages, see figure 1 from section 2.3.

Although these measurements cannot be used for validation purposes (because the airfoil geometry as input for airfoil prediction codes is confidential) some interesting qualitative information can be extracted which is very well summarized in [21]There it is shown that higher values of erosion lead to a forward shift of transition but regions of laminar flow at design angles of attack remain for not too heavy erosion. Light 1 erosion (figure 1), with erosion located at the design angle of attack stagnation point, even gives almost no change in compared to the transition point of the clean airfoil. This is nicely illustrated in Figure 2 which shows the transition location for the various levels of erosion.



a $Re = 3 \cdot 10^6$ **b** $Re = 6 \cdot 10^6$

Figure 3: Transition location for Re = 3M and 6M for different angles of attack and different erosion patterns as measured in the LSWT wind tunnel on an 18% thick tip airfoil

4 Wind tunnel measurements on airfoil with erosion in DNW-LST carried out within Airtub

The present chapter describes the wind tunnel measurements which were carried out within the Airtub project. The experiment is described in detail in [19].
The measurements were done by NLR in the DNW-LST wind tunnel with a test section of 2.25x3.00 m2, a maximum velocity of 80 m/s and turbulence levels of 0.02% and 0.03% in tunnel and perpendicular directions respectively.
The selected airfoil was a DU 00-W-212. This airfoil was also measured in the LSWT tunnel, see section 3.3 and it is used in the high Reynolds number experiment which is described in chapter 5.
The model was constructed from a metal core and a Polyurethane body and it was coated to achieve a surface roughness of 0.07μm for the clean configuration.
The model was instrumented with pressure taps to measure the pressure distribution and the resulting lift where the pressure distributions were also expected to give an indication of the boundary layer transition point through a kink in pressure distribution (see section 3.2). Moreover a wake rake was used to measure the drag.

The project team spent a large effort on a good preparation of the experiment and included several lessons from the previous experiments described in section 3.

Amongst others it was decided to apply an integral airfoil model to avoid the drawbacks of DLE's which are mentioned in section 2.3

Moreover a large number of pressure sensors (90) was chosen since this was found to be a pre-requisite to achieve a good detection of the transition point from the kink in pressure distribution. This large number of sensors is in particular needed near the expected transition locations. In order to find the expected transitions location XFOIL calculations have been performed at clean conditions (ie. calculations with free transition) and various angles of attack. The transition points from these locations are considered to be the extreme values since the transition point will move forward from erosion.

Moreover the importance of the transition point at the pressure side was assessed because this is often mentioned to be less relevant than the transition point at the suction side which would make it unnecessary to spend effort on the determination of a transition point at the pressure side. Therefore XFOIL calculations have been performed with fixed positions of transition at both the suction and pressure side and the impact on the aerodynamic loads was determined. A shift of transition points at the suction side was found to have more impact on the airfoil performance than a shift at the pressure side indeed but the drop in airfoil performance from the latter was still considered significant enough, to aim for a good detection of transition at the pressure side as well [17]

Three different carborundum grain sizes where applied directly to the model to simulate roughness instead of sandpaper which was used in the IRPWIND roughness project. This avoids the drawback of a relatively thick backing of sandpaper as mentioned in section 2.2.

The grains where applied by a water soluble transparent glue, which could be washed off between the different data points. The applied grain sizes where 50, 150 and 250 μm. Sizes of 50 and 150 μm are expected to be sub critical because this corresponds to a roughness Reynolds number $Re_k = \rho U_k k/\mu$, (with k the roughness height and U_k the velocity at roughness height) between 120 and 400 which according to literature is the subcritical range. Note that the determination of Re_k requires U_k which was calculated with CFD (Marco Caboni, Personal communication).

The additional roughness of $250\mu m$ was chosen to show the effect of severe roughness The resulting test matrix is summarized in the table below

Run	Erosion	Reynolds number	Angle of attack
5	Clean model	[2.3 : 3.6]	[0 , 5 , 10]
6	Clean model	3.27	[-25 : 25]
8	50 μm	[2.3 : 3.6]	[0 , 5 , 10]
9	50 μm	3.18	[-25 : 25]
10	150 μm	[2.3 : 3.6]	[0 , 5 , 10]
11	150 μm	3.24	[-25 : 25]
12	250 μm	[2.3 : 3.6]	[0 , 5 , 10]
13	250 μm	3.17	[-25 : 25]
14-17	Clean model	3.2	[0:12]

Figure 4 Model in DNW wind tunnel, picture NLR.

The measurements were done in December 2020 and figure 7shows the c_l/c_d as function of angle of attack for a Reynolds number of 3.6 M.

As expected the c_l/c_d at rough conditions is lower than the values at clean conditions where the performance decreases with increasing roughness although the difference in performance between 150 and 250 μm roughness is very small. This might be an indication that at 150 μm roughness the transition point has moved to the nose already

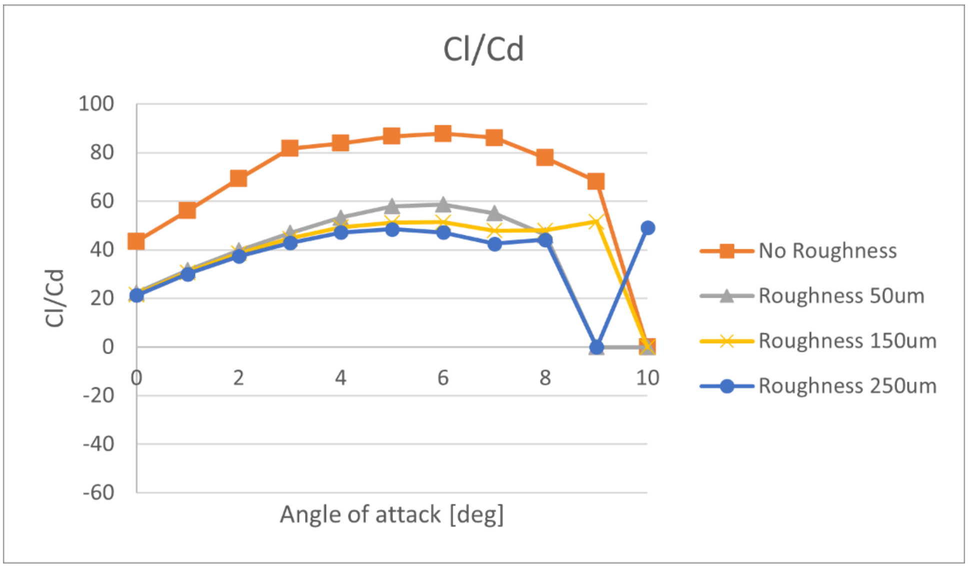


Figure 5: C_l/C_d as function of angle of attack for Airtub measurements in DNW-LST

However the maximum c_l/c_d in figure X for clean conditions is only 87 where within the AVATAR project a much higher value in the order of 125 has been measured independently in two different tunnels (the LSWT and the DNW-HDG tunnel) at almost the same conditions [8. The fact that the measurements in the LSWT and DNW-HDG tunnel compared extremely well is believed to be an indicator of good measurement quality. This then suggests that the c_l/c_d at clean conditions from the DNW-LST measurements is 30% too low.

A large effort was spent on finding the explanation for these too low c_l/c_d values (e.g. tunnel effects, small differences in Reynolds number, tunnel turbulence etc) but none of them were satisfactory. Eventually an analysis of pressure distributions at zero degrees angle of attack show that the LSWT and DNW-HDG pressure distributions have clear kinks, at roughly 45 and 55 % chord for respectively the pressure and suction sides indicating transition at these locations. These kinks are not visible in the DNW-LST measurements which suggests that these measurements suffer from premature transition possibly due to some irregularities in airfoil shape.

For this reason the geometry of the airfoil model used in the DNW-LST measurements has been scanned by NLR [MarkJan Vermeulen Personal communication] and some seemingly small differences were found between the actual shape at the pressure sensors and the design shape, see figure 8.

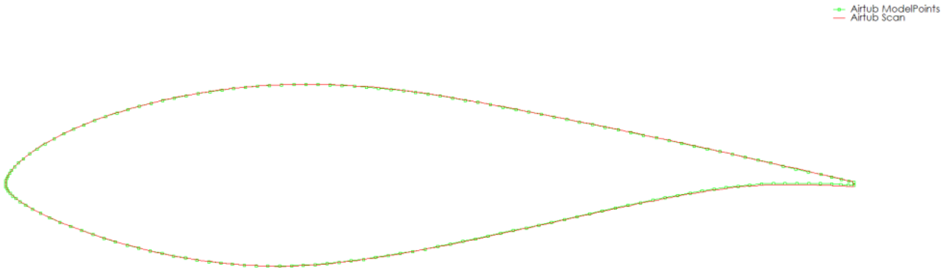


Figure 6 Difference between scanned model geometry for DNW-LST experiment and design geometry of DU00-W-212 airfoil

Then the 2D airfoil performance of the scanned geometry was calculated with XFOIL and compared with the calculated performance of the design shape where the scanned geometry leads to a reduction in c_l/c_d in the order of 7% so this does not explain the difference of 30% as mentioned above, completely [Niels Adema personal communication] In a next step [Niels Adema Personal communication] the 3D shape of the wind tunnel model was assessed from which a variation in spanwise direction was found where the model was supposed to be 2D. This is shown in the figure below.

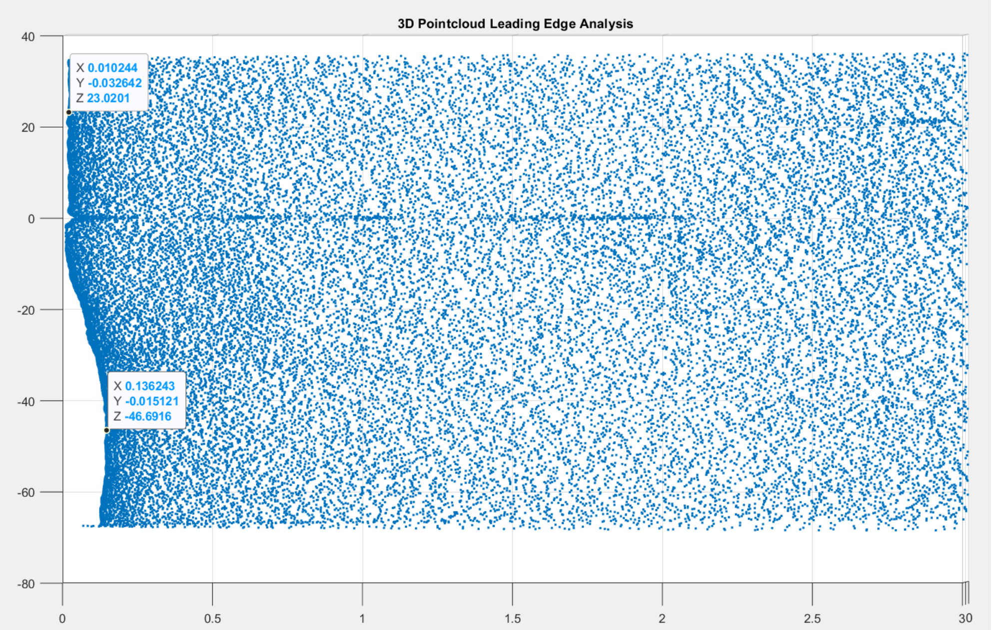


Figure 7 Scanned geometry of wind tunnel model in DNW-LST experiment. Horizontal direction is chordwise, vertical direction is spanwise.

In chordwise direction the differences are in the order of 125 μm. Although this may seem small it remains unknown whether these differences can explain the above mentioned drop in c_l/c_d This can be investigated with 3D CFD modelling but this task was not foreseen and it is outside the scope of the project which is the reason why it could not be done.

Unfortunately this implies that the explanation for the lower c_l/c_d in the present experiment at clean conditions remains unknown and until the source of differences has been found the data cannot be used with confidence. This implies that the measurements at rough conditions should be considered with care too.

5 High Reynolds numbers

Off-shore wind turbines often operate at Reynolds numbers above 10 Million where most erosion studies, also the ones described in the previous chapters are carried out at much lower Reynolds numbers, 3-4 Million. The measurements at the LSWT are done at 6 Million but even this Reynolds number is much lower than the Reynolds number on large off-shore turbines. As explained before the forward shift of transition is one of the most important drivers for the aerodynamic effects from erosion and this transition location is largely determined by the Reynolds number.
Moreover a higher Reynolds numbers decreases the boundary layer thickness (at least relatively to the chord, upscaling could have an opposite effect) which then implies that the relative size of erosion/roughness particles/pits in relation to the boundary layer thickness changes and this change in relatively size of roughness is expected to impact the aerodynamic performance too.
This makes the aerodynamic effects from erosion on off-shore turbines undoubtedly different from the aerodynamic effects which were measured in the sections 3 and 4.

For this reason the modelling capabilities of airfoil performance at high Reynolds numbers were assessed.

To this end within the AVATAR project, measurements were carried out on a DU00-W-212 airfoil (i.e. the same airfoil as used in section 2.3 and 4) in the DNW-HDG pressurized wind tunnel. The DNW-HDG wind tunnel is a closed circuit wind tunnel with a test section of 60cmx60cm. The tunnel can be pressurized from 1 to 100 bar where the tunnel temperature is changing from ambient to 45 degrees. The pressurization made it possible to reach Reynolds numbers of 15 Million, i.e. values which are considered representative for larger off-shore wind turbines despite the small size of the wind tunnel model (150 mm chord length) and despite the fact that the tunnel speeds are relatively low (less than 30 m/s, i.e. below the values where compressibility effects appear). The DU00-W-212 airfoil model was equipped with 90 pressure taps from which the lift was determined. Drag is measured with a wake rake

The experiment only measured the airfoil performance at clean conditions so there are no measurements on rough/eroded airfoils. Still it is considered worthwhile to validate the TNO CFD tools with these measurements in order to understand how a high Reynolds number effects the aerodynamic airfoil prediction. This understanding serves as a first step to develop reliable erosion models at high Reynolds numbers. For this reason the experiment at a Reynolds number of 15 Million was simulated with the OpenFOAM solver with the Langter Menters Transition model (SSTLM) as described in section 3.1.2.

This model requires, as input, an empirical relation for the transition momentum thickness Reynolds number, $Re_{\theta,t}$ as function of turbulence intensity. This relation is derived for flat plate conditions and gives a value of 703 for $Re_{\theta,t}$ at an angle of attack of zero degrees and a turbulence intensity of 0.55% for the involved experiment as reported in [8]. Unfortunately with this value of $Re_{q,t}$ OpenFOAM gave poor results and a far too early transition

A possible explanation could be a wrong value of turbulence intensity in the experiment because [8] reports some uncertainty on that value. Therefore an additional verification of the turbulence intensity was done in [12]. Thereto the Ncrit at this turbulence intensity was determined with the Mack’s formula and found to be 4. This value was then used as input to XFOIL and it gave polars, pressure distributions and transition points which agreed very well with the measured data. This is then considered an indirect but very strong indication of the correctness of the experiment’s turbulence intensity of 0.55% and implies that there should be another explanation for the poor CFD results. For this reason the Langtry-Menter's empirical correlations for $Re_{q,t}$ itself was assessed by determining the value of $Re_{q,t}$ with XFOIL where it is noted that that XFOIL makes use of the e^N method for boundary layer transition which is known to be accurate also for high Reynolds numbers

The value of $Re_{\theta,t}$ from XFOIL tuned out to be 2600 i.e. much higher than the value from the Langtry-Menter's empirical correlation.

Using this value of $Re_{q,t}$ as input to the SSTLM model, a very good agreement was achieved between the experiment and simulations in terms of pressure distributions c_l/c_d and transitions point.

Hence, for accurate modelling of aerodynamic performance at representative Reynolds numbers for off-shore wind turbines It is recommended to investigate alternative RANS-based transition models, or alternative formulations of the SSTLM model, like the one presented by Khayatzadeh and Nadarajah. In this publication the authors showed that a much better agreement with experiments can be achieved by simply tuning a constant in the SSTLM model.

6 Conclusion and recommendations

In WP6.1 of the Airtub project modelling approaches have been developed, improved and validated to calculate the AEP of turbines with eroded blades.
The modelling approach focussed on the prediction of 2D airfoil characteristics which include the effect of erosion and which can be fed into standard BEM codes to calculate the power curve of the turbine with eroded blade. This power curve in combination with the known wind climate gives the AEP.
Two model approaches are considered: the first relies on the fast engineering approach RFOIL, i.e. a panel method coupled to a viscous integral boundary layer mode and the e^N transition model where the second approach is based on OpenFoam RANS with the SSTLM transition model. Both model approaches require a generalised erosion height and density as input.

The main challenge in these modelling approaches lies in the prediction of boundary transition for subcritical roughness since the modelling of erosion for roughness heights above critical can be covered with a fully turbulent calculation which is relatively easy to do, at least for erosion levels which are not very extreme.

Within the present Work Package the model approaches were validated with 2D wind tunnel measurements. The conclusion is that the approaches predict the aerodynamic effects of erosion in a reliable way. This is anyhow true for not too large turbines with moderate Reynolds numbers up to 4 Million until which the validations have been carried out. Indications have been found that the Langter Mantry transition models as used in OpenFoam requires adaptation for the high Reynolds numbers (> 10 Million) of large off-shore turbines. The transition model used in RFOIL is expected to be reliable for high Reynolds numbers.
It is also noted that the model approaches include empirical relations which were derived from the same measurements as those used in the validation. For this reason an independent set of wind tunnel measurements specifically designed for Airtub was planned as additional validation. The measurements were carried out by NLR in the DNW-LST tunnel and despite a very good preparation which took into account several lessons learned from other experiments the resulting data were found to be uncertain for reasons which are not fully understood. The most likely cause are shape deviation of the wind tunnel model.

Therefore in order to reduce model uncertainties further the following recommendations are formulated.

- An independent set of new wind tunnel measurements is needed for a more general validation. These measurements should take into account the lessons learned from previous experiments as this was done in the design of the Airtub measurements in the DNW-LST:
  - This holds amongst others for the recommendation to grain particles directly on the surface instead of applying sand paper
  - Another recommendation is to use solid models instead of DLE inserts.
  - A direct measurement of the transition location e.g. through IR is recommended. This needs to be done at both the pressure and suction side. Alternatively the transition point can be derived indirectly from the pressure distribution for which an algorithm is developed within Airtub This however requires a high number of pressure sensors in particular around the expected transitions point.
  - The measurements need to be performed at representative Reynolds numbers, above 10 Million. These are difficult to achieve in conventional wind tunnels but they can be achieved in a pressurized tunnel e.g. the one from DNW-HDG.
  - The cause for the uncertainty the NRL Aitrub measurements need to be understood so that this uncertainty will not affect the results of a future experiment. The most likely cause are 3D shape deviations of the tunnel model. The impact of these deviations can be assessed 3D CFD

simulation of the actual wind tunnel model shape. If the relatively minor shape deviations have such significant aerodynamic impact this is an important point of attention in the design of a future wind tunnel model.

- The present modelling approach is based on BEM with 2D polars which take into account erosion through small scale roughness. Thereto the actual erosion patterns are translated to global measures for erosion depth and density of erosion. This translation brings in some arbitrariness where moreover the 2D model approach is a simplification in view of the fact that erosion patterns on blades are 3D. These drawbacks can be overcome by a 3D CFD modelling of the actual eroded blade as is done in [Kisorthman Vimalakanthan, 2022] where very promising results were obtained (at the obvious expense of a much higher calculational time). This approach can also cover very deep erosion, i.e. erosion which exceeds the small scale roughness levels considered in the present study.

Acknowledgement

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