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ECN Airfoils for Large Offshore Wind Turbines Design and Wind Tunnel Testing

Francesco Grasso – grasso@ecn.nl

ECN,
Westerduinweg 3, 1755LE, Petten, the Netherlands

Abstract

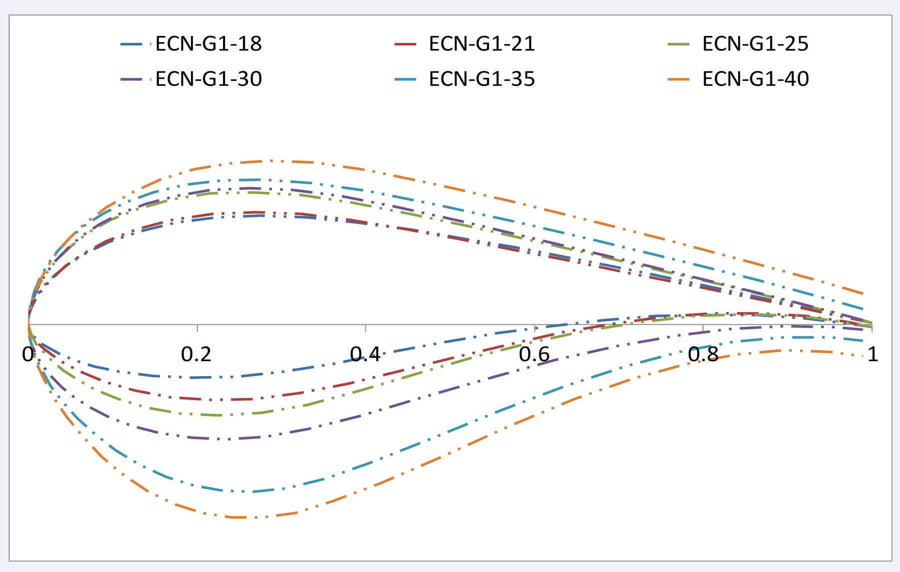
For very large offshore rotors, achieving high performance is mandatory but reduction in loads and mass is also attractive to reduce the costs. The performance of the airfoils installed along the blades have a direct impact on the wind turbine performance. New airfoils tailored on specific requirements can help to obtain outstanding performance, while reducing loads and mass.

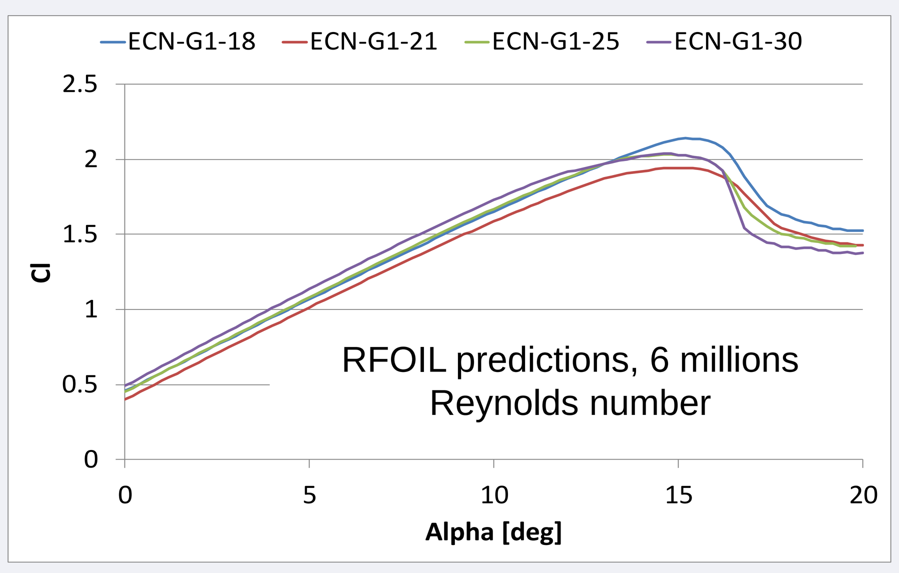
This research has been performed in collaboration with Blade Dynamics Ltd. with multiple goals:

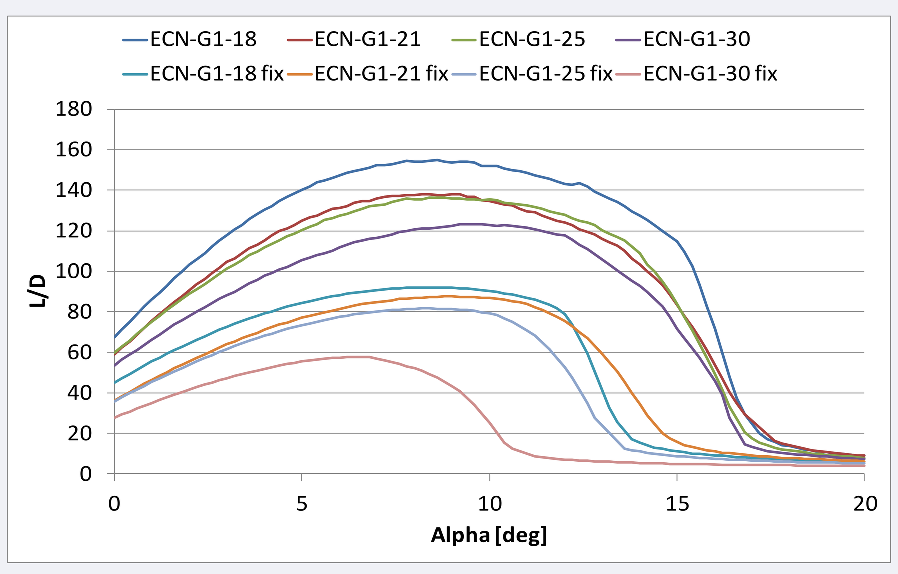
- Design an ECN family of new airfoils (named ECN-G1-XX)
- Assess the accuracy of the predictions by wind tunnel measurements on one of the new airfoils
- Evaluate the impact of the new airfoils on the performance of very large offshore wind turbine rotor

ECN-G1-XX airfoils

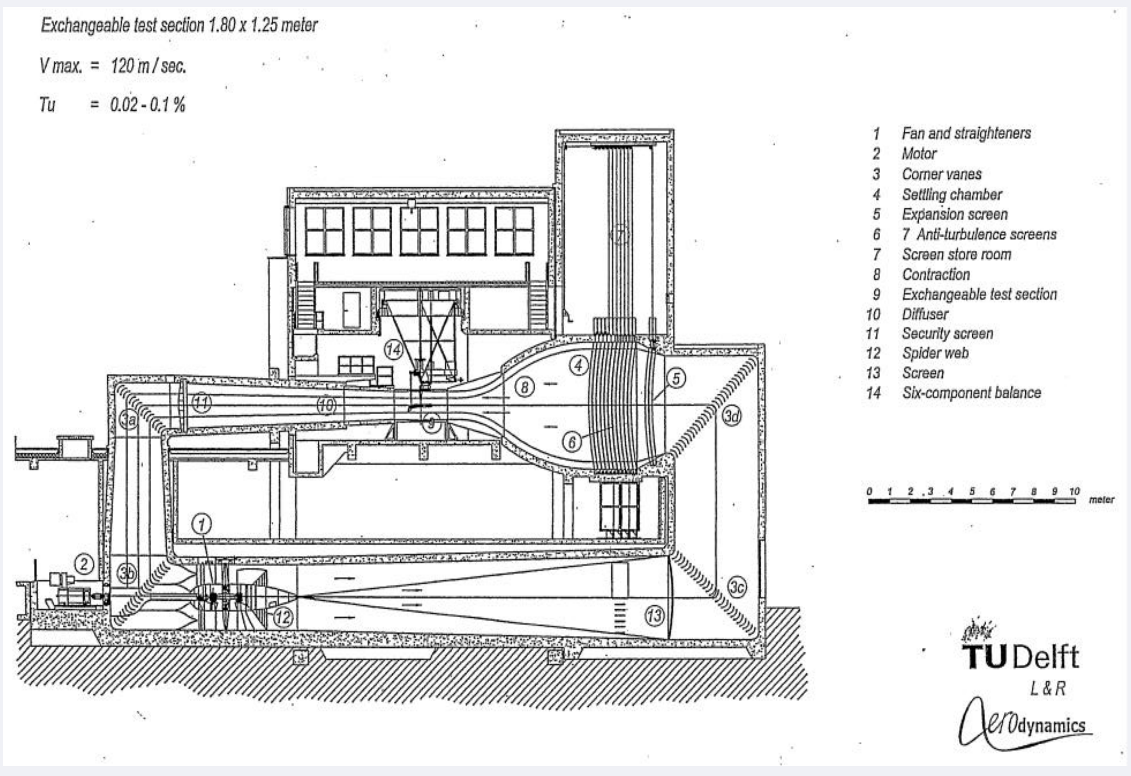
An ECN family of new airfoils has been designed by adopting and advanced design methodology based on numerical optimization scheme coupled with ECN solver RFOIL. The result is a set of airfoils with consistent geometrical and aerodynamic characteristics.

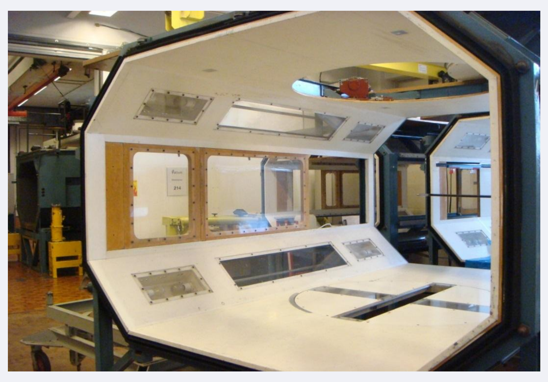




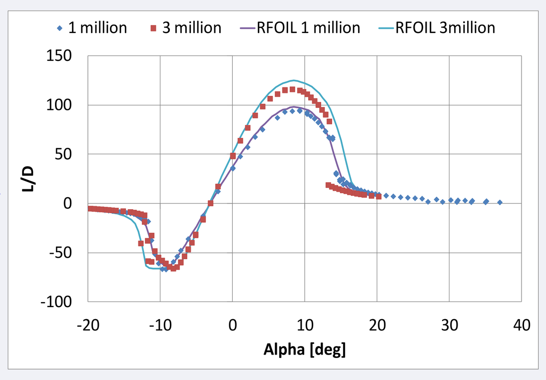


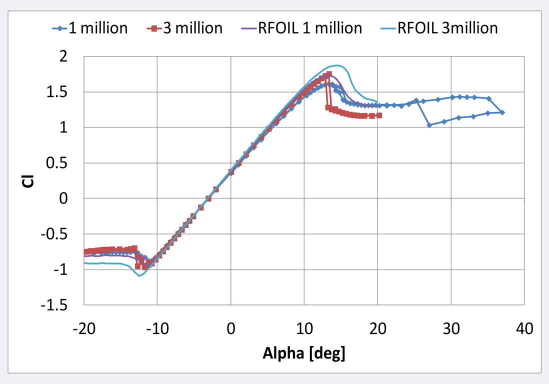
Wind Tunnel Tests at TU Delft LSLTWT on the ECN-G1-21 airfoil

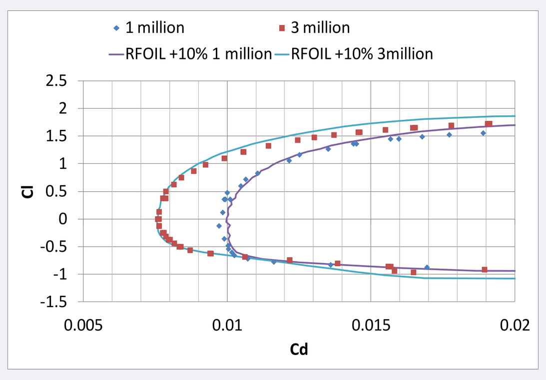




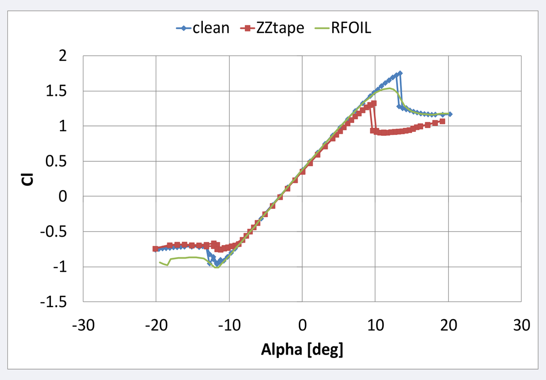
Free transition

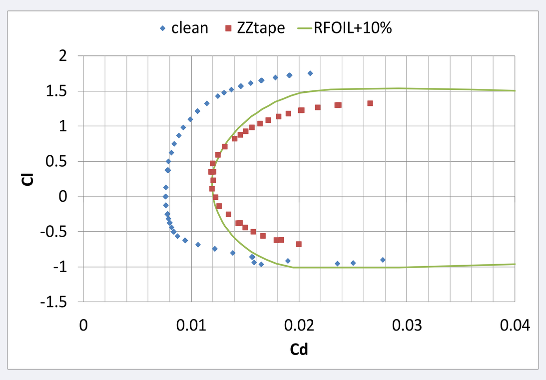






Fixed transition

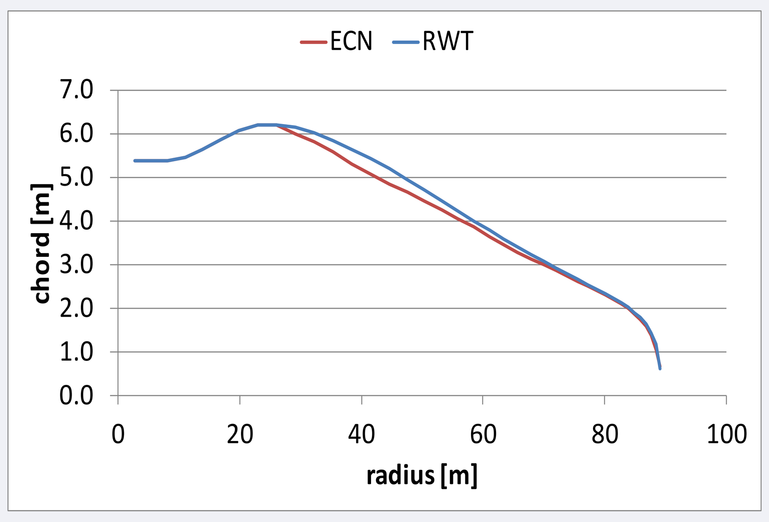


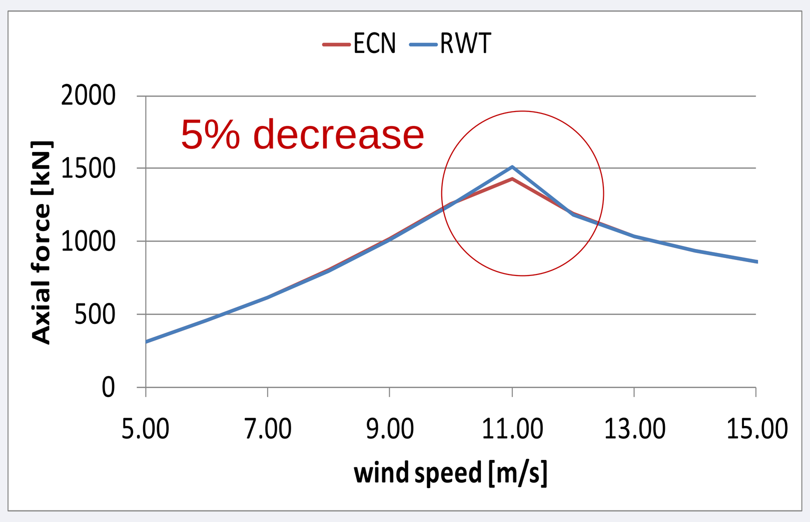


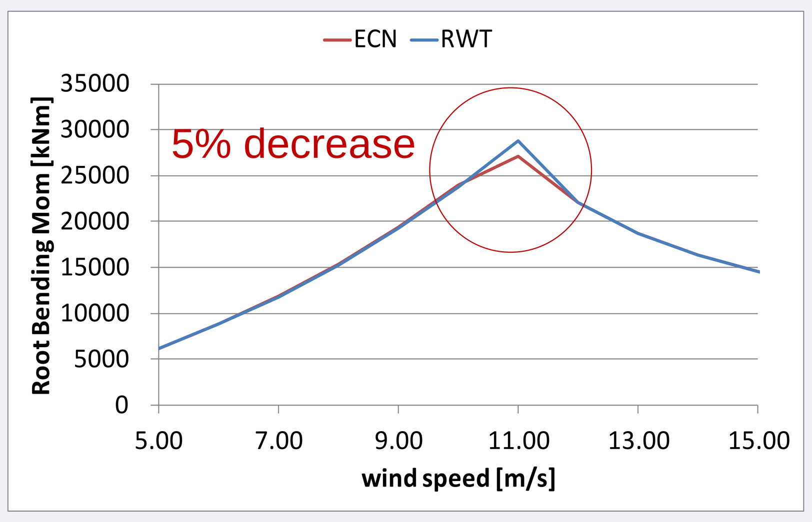
Impact of ECN Airfoils on Wind Turbine Performance

In order to evaluate the impact of the new airfoils on the rotor performance a new blade has been designed with the ECN airfoils. The 10MW reference wind turbine of the European project INNWIND.EU has been used for comparisons.

		RWT	ECN
Yield:	GWh/yr	53.41	53.41
P_{rated}:	kW	10000	10000
U_{rated}:	m/s	12.00	12.00
C_{Pmax}:	(mech)	0.4980	0.4987
I_0:	-	7.500	7.500
Q_{start}:	kNm	89.113	93.141







Conclusions

A collaboration with Blade Dynamics Ltd. has been set, aiming to evaluate the impact of new airfoils on the performance of very large wind turbines and to assess the reliability of advanced design methodology.

- The results show that ECN airfoils contribute visibly to decrease the loads along the blade, while the annual energy production is kept.
- Wind tunnel tests show that the stall behavior is still a crucial area where further improvements are needed.

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* The complete list of references can be found in the full paper

Acknowledgement

This work is the result of a research project in collaboration with Blade Dynamics Ltd.

BLADE DYNAMICS

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Francesco Grasso

ECN, Westerduinweg 3, 1755LE, Petten, the Netherlands

grasso@ecn.nl

Abstract

For very large offshore rotors, achieving high performance is mandatory but reduction in loads and mass is also attractive to reduce the costs. The performance of the airfoils installed along the blades have a direct impact on the wind turbine performance. New airfoils tailored on specific requirements can help to obtain outstanding performance, while reducing loads and mass.
The present work is focused on the design of a new family of airfoils. This is done by adopting an approach based on numerical optimization coupled with the ECN solver RFOIL. The numerical results show good potentialities in terms of performance and consistent geometrical properties along the family. However, wind tunnel test have been performed to validate those results. The 21% thick section has been selected to be tested in the Low Speed Low Turbulence Wind Tunnel at TU Delft. The tests have been carried out in free and fixed transition at different Reynolds numbers. Despite a general good agreement with the numerical results, in one case the stall behavior was sharper than expected in the simulations.
The final part of the work is focused on evaluating the impact of the new airfoils on the performance of a very large offshore wind turbine. In this phase, the 10MW reference wind turbine of the European project INNWIND.EU has been used for comparisons. The results show that the blade equipped with new airfoils can have the same annual energy production but with visible decrease in axial force and root bending moment.

Keywords: airfoil, wind tunnel testing, aerodynamic design, numerical optimization

1 Introduction

In order to maximize the ratio of energy capture and reduce the cost of energy, the selection of the airfoils to be used along the blade plays a crucial role. This is because the twist and chord distributions are optimized based on the aerodynamic characteristics of the airfoils. From a structural point of view, the characteristics of the blade are strongly dependent on the thickness distribution and other typical geometry parameters (i.e. internal area).
In the modern wind turbines, some airfoils for aeronautical applications (i.e. NACA63xxx and NACA64xxx) are still quite used; however, due to the particular requirements in terms of design/off design properties and structural properties, there is an increased interest in develop dedicated airfoils for wind turbines. Starting from the mid-1980s, quite some work has been done at NREL [1], FFA [2], Delft University [3], Risoe [4].
The target design characteristics for the airfoils have been updated during the years and tailored to the specific type of power control and the need for off design operation. The desirable airfoil characteristics can be divided into structural and aerodynamic properties, and the wind turbine blade can be divided into the root, middle, and tip parts, where the root part is mainly determined from structural considerations. In contrast, the tip part is determined from aerodynamic considerations.
Despite the above mentioned distinction between different blade areas/requirements, it is important to have a good blending of the different sections so that the blade has a smooth surface. In terms of design, the aerodynamic and structural properties should vary very gradually along the blade. As immediate consequence, families of airfoils have been and are in development.

Some work has been done also at ECN [5-7] by using modern design techniques and advanced tools. Despite the promising results however, the numerical accuracy and the reliability of such design strategies is still a crucial point in order to obtain outperforming products.
In order to assess the value of ECN design methodology and its robustness, a research project has been performed in close collaboration with Blade Dynamics Ltd. The aim of the project was to design a new family of airfoils for a large offshore wind turbine, validate the numerical predictions in wind tunnel tests and finally evaluate the impact of these new airfoils on the performance of a new very large wind turbine.
In the next section, the design methodology is presented together with the characteristics of the airfoils calculated numerically. Then the results of the wind tunnel tests are illustrated and discussed. Finally the design of a new rotor for a 10MW wind turbine is performed and the characteristics are compared to the reference wind turbine (RWT) designed in the European project INNWIND.EU [8].

2 Design of new airfoils

2.1 Methodology

In the present work, a numerical optimization based approach has been used in order to have an efficient design method able to deal with multiple requirements coming from different disciplines. In particular, a gradient based algorithm (GBA) [9] has been used. The shape of the airfoils is described by 4 Bezier curves of third order, in accordance with the formulation proposed by Grasso [10]. An example of the parameterization is sketched in figure 1. The design variables are the vertical and horizontal positions of the control points.

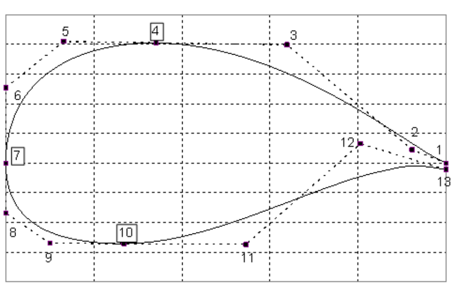

Figure 1 Geometrical parameterization example.

2.2 Aerodynamic solver

During the design, the ECN panel code RFOIL [11] has been implemented to calculate the performance of the candidate shapes. RFOIL is a modified version of XFOIL [12] featuring an improved prediction around the maximum lift coefficient and capabilities of predicting the effect of rotation on airfoil characteristics. Regarding the maximum lift in particular, numerical stability improvements were obtained by using the Schlichting velocity profiles for the turbulent boundary layer, instead of the Swafford velocity profiles. Furthermore, the shear lag coefficient in Green's lag entrainment equation of the turbulent boundary-layer model was adjusted, and deviation from the equilibrium flow has been coupled to the shape factor of the boundary layer.

2.3 Airfoil requirements

The novelty of the present work is that the goal of the design process is not to obtain a single airfoil, but a complete set of geometries with good aerodynamic and structural characteristics. In addition to this, those characteristics and the geometrical properties should vary in a consistent and gradual way so that they are compatible with each other and the blending of the sections is not affected by strange bumps or irregularities.
Using numerical optimization approach during the design implies that all the above mentioned properties and characteristics must be "translated" in terms of requirements. In order to have a family of airfoils, these requirements should be general to be applicable to the complete set of airfoils but, at the same time, able to describe a certain need at a specific area of the blade.
In the present work, a weighted combination of the aerodynamic efficiency and sectional moment of resistance has been adopted as objective function, where the aerodynamic efficiency takes into account the aerodynamics while the moment of resistance counts the structural requirements. Depending on the value of the weighting factor, the design can be driven by aerodynamics or structure.
In terms of requirements, a good robustness for roughness has been considered, together with good off design performance. A sufficient margin between the design condition and the stall is also taken into account to avoid that the airfoil works in stall conditions in case of gusts. High lift performance can be advantageous because

for a certain aerodynamic load, the chord can be reduced if the lift produced by the airfoil increases. Reducing the chord is positive to decrease the loads in parked condition. Manufacturing aspects have been included by prescribing a finite value for the trailing edge thickness.

2.4 Numerical results

In the figure 2, a sketch of the new airfoils (named ECN-G1-XX) is illustrated, while in the figures 3 and 4, the aerodynamic characteristics of the ECN-G1-XX airfoils are shown. It should be noticed that not only the geometrical characteristics of the airfoils, but also the performance are consistent along the family so, no irregularities should be expected on the complete blade.

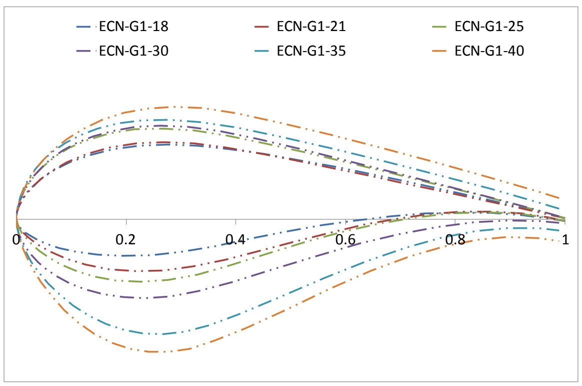

Figure 2 Sketch of the ECN-G1-XX airfoils.

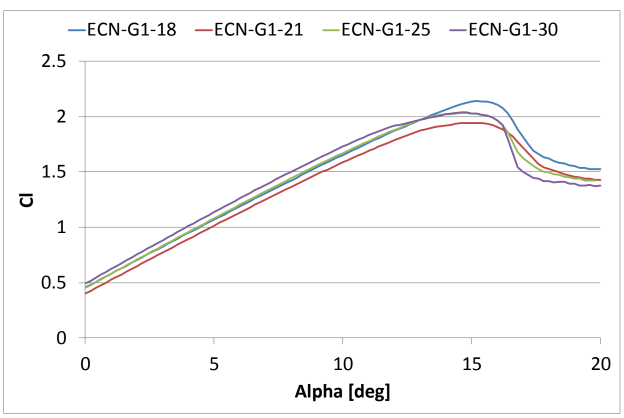

Figure 3 Numerical prediction for the lift curve of the ECN-G1-XX airfoils. 6 millions Reynolds number, free transition.

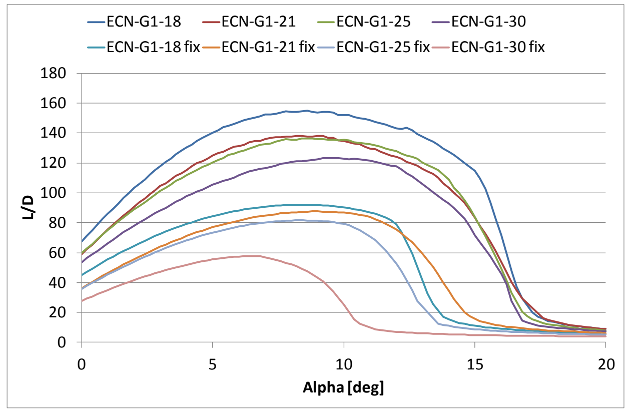

Figure 4 Numerical prediction for the lift curve of the ECN-G1-XX airfoils. 6 millions Reynolds number.

3 Wind tunnel testing

In order to validate the numerical predictions, a wind tunnel test campaign has been performed on the 21% thick ECN-G1-21 airfoil. The Low Speed Low Turbulence Wind Tunnel (LSLTWT) at the Delft University has been used. The LSLTWT is an atmospheric tunnel of the closed-throat single-return type. The dimensions of the tunnel are enormous, since the fan and engine are on ground level, whereas the settling chamber and the test section are on the second floor. The six-bladed fan is driven by a 525 kW DC motor, giving a maximum test section velocity of about 120 m/s. The maximum Reynolds number for two-dimensional testing is about 3.5 million (based on 0.6m chord model). Due to the large contraction ratio of 17.8, the free-stream turbulence level in the test section varies from only 0.015% at 20 m/s to 0.07% at 75 m/s. The corner vanes that rotate the flow in the corners of the tunnel, are equipped with a cooling system to control properties of the flow. The main characteristics of the LSLTWT are summarized in table1.

The measurements have been done by pressure measurements. The 0.6m chord model used during the tests has been manufactured in glass fiber and it has been equipped with 101 pressure points. The pressure points are distributed in such way that the distance between them is reduced at the leading edge and the trailing edge. This is because in these areas, a high accuracy is required, especially to measure the change in the location of the transition and the separation points when the angle of attack is changing.

The model static pressures 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 127 samples during a total averaging time of 10 seconds. The data were on-line reduced to pressure and force coefficients. The pressures in the wake were measured with a static and a total pressure wake rake, both 504 mm in width. 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.

Table 1 Wind tunnel main characteristics.

Type of wind tunnel	Closed loop, closed test section
Test section size (W x H x L) [m]	1.8 x 1.25 x 2.6
Max speed [m/s]	120
Turbulence Intensity	0.015% at 10m/s, 0.07% at 70m/s
Pressure measurements (max number of pressure points)	150
Wake rake pressure points	67 total and 16 static
Balances	Available but not used during these tests

3.1 Experimental results

The tests have been performed at 1 million and 3 millions Reynolds number, in clean and rough conditions. In figures 5-7 the comparisons with the numerical predictions are illustrated in terms of lift coefficient (Cl), drag (Cd) and aerodynamic efficiency (L/D). As it can be observed, the general agreement in terms of Cd and L/D is good for both Reynolds numbers. However, at 3 millions Reynolds number the stall is quite sharp, while a smoother response was expected according to the RFOIL data. A possible reason for it could be that the leading edge is sensitive to turbulence. So when the Reynolds number increases, the turbulence level of the LSLTWT increases, leading to a sharp stall.
Looking at the pressure distributions (figs. 8-10) for several angles of attack (AoA), it can be seen that RFOIL is capable to capture correctly the response of the airfoil, including the location of the transition up to 13 degrees. For larger values of AoA, the experiments show the transition moving fast to the leading edge with consequent sharp stall. In this sense, a more convex upper surface could improve the performance.

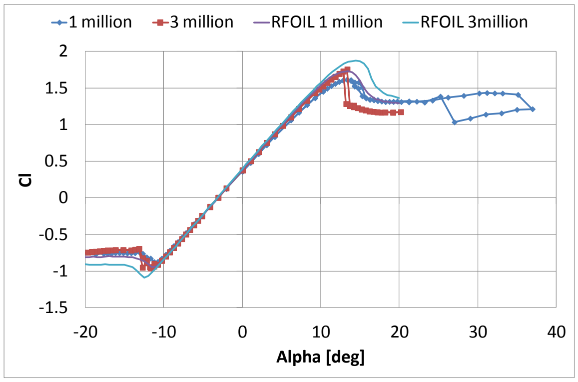

Figure 5 Lift curve measured in clean condition. Comparison with RFOIL results.

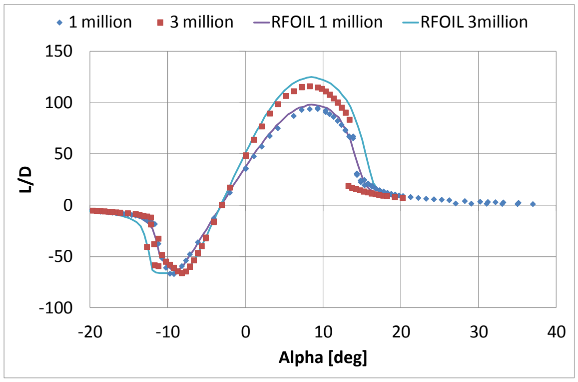

Figure 6 Aerodynamic efficiency curve measured in clean condition. Comparison with RFOIL results.

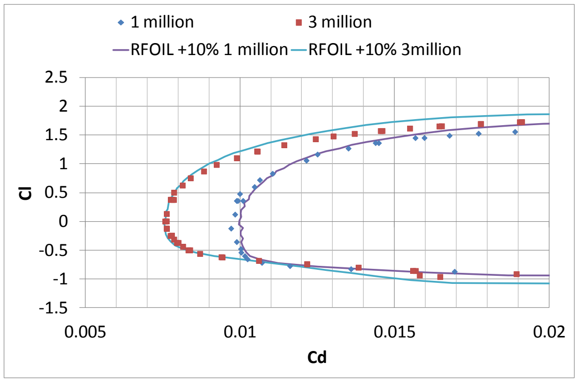

Figure 7 Drag curve measured in clean condition. Comparison with RFOIL results.

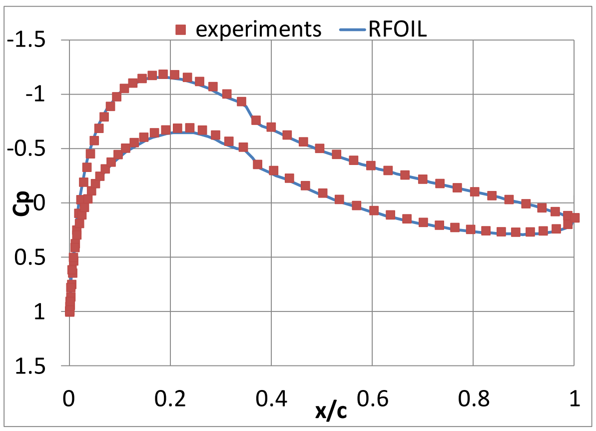

Figure 8 Pressure distribution in clean condition at 3 millions Reynolds number and 0 deg.

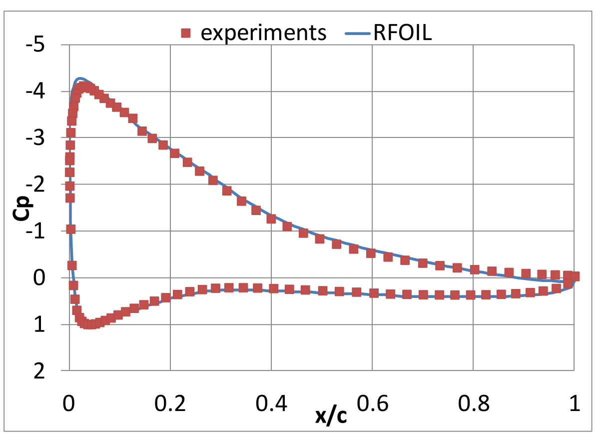

Figure 9 Pressure distribution in clean condition at 3 millions Reynolds number and 13.3 deg.

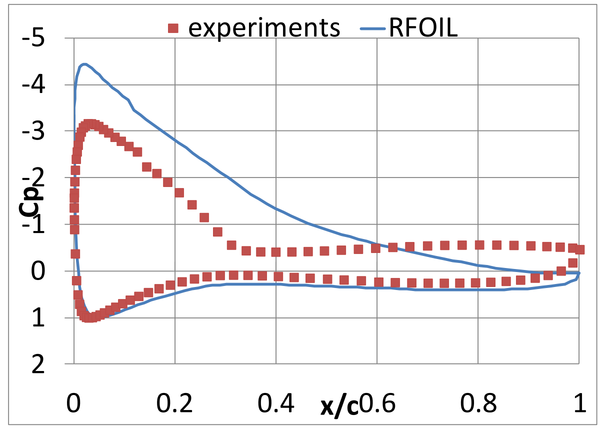

Figure 10 Pressure distribution in clean condition at 3 millions Reynolds number and 13.7 deg.

The tests have been performed also in fixed transition by using zig-zag tape (ZZtape) on the leading edge. Depending on the model and the velocity, the proper thickness for the ZZtape should be selected. For these tests, a 0.3mm (0.28mm measured with micrometer) thick ZZtape with 60 degrees zig-zag profile has been used. The preliminary tests performed with stethoscope proved this tape to be effective in generating the transition. The goal of the tests was to evaluate the performance of the airfoil with fixed transition at the 1% of the chord on both upper and lower surface. To obtain this effect correctly simulated with the ZZtape, the ZZtape has been put at 1% on the upper side and on the 5% on the lower side for the positive angles of attack and in opposite way for the negative angles of attack. The reason of this procedure is to avoid that the stagnation point for some angles of attack is behind one of the stripes,that would result in a flow that encounters two stripes on one side of the model and no strip on the other side. Figures 11 and 12 show the results.

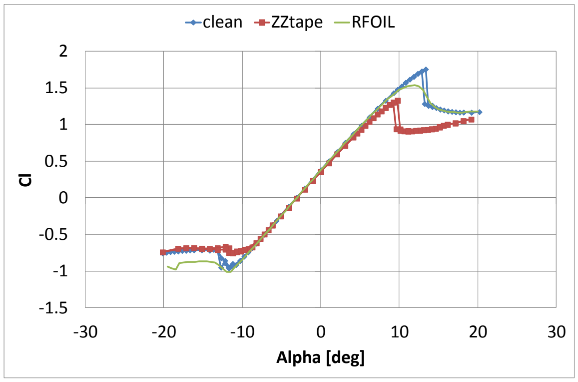

Figure 11 Lift curve measured in fixed transition condition. 3millions Re number.

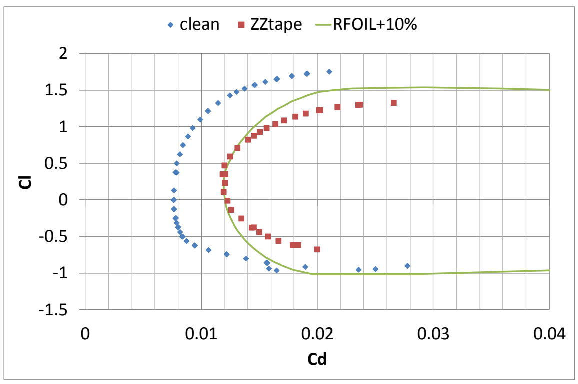

Figure 12 Drag curve measured in fixed transition condition. 3millions Re number.

4 Effects of the new airfoils on the blade performance

One of the goals of this research is to evaluate the effects of the ECN-G1-XX airfoils on a complete turbine rotor. The 10MW wind turbine defined in the European project INNWIND.EU has been used as reference. On this blade, the FFA airfoils have been used. Starting from it, the airfoils have been replaced with the ECN-G1-XX geometries and chord and twist have been re-optimized according to the characteristics of the new airfoils. The BEM based ECN tool BOT [13] has been used to design the new blade planform maximizing the annual energy production. In order to compare in fair way the results, the original data provided for the aerodynamic properties of the FFA airfoils have been replaced by the ones obtained with RFOIL and the performance of the complete rotor have been calculated also with BOT. The twist has been adjusted to consider the modified polars. In addition, the original pitch settings have been replaced by the ones calculated by BOT. These values are determined to produce an optimal axial induction factor for each wind speed. In figures 13 - 15 the axial force and root bending moment comparisons are shown, together with the chord distributions. A decrease in axial force and root bending moment around 5% can be achieved with the new airfoils, keeping the same annual energy production.

Table 2 Main characteristics of the blade in comparison with the RWT.

		RWT	ECN
Yield:	GWh/yr	53.41	53.41
P_{rated}:	kW	10000	10000
U_{rated}:	m/s	12.00	12.00
C_{Pmax}:	(mech)	0.4980	0.4987
λ_o:	-	7.500	7.500
Q_{start}:	kNm	89.113	93.141

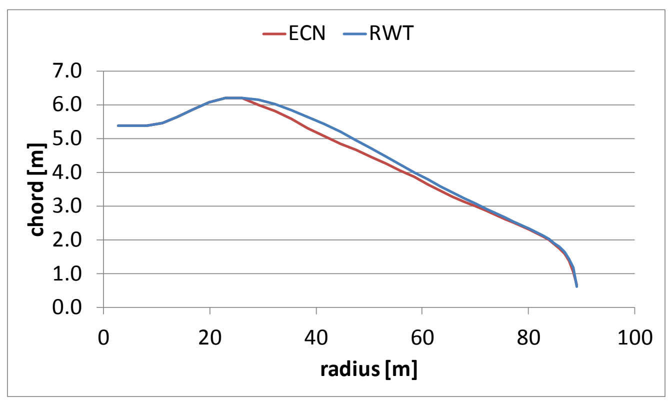

Figure 13 Chord distribution for the complete blade. Comparison with the RWT.

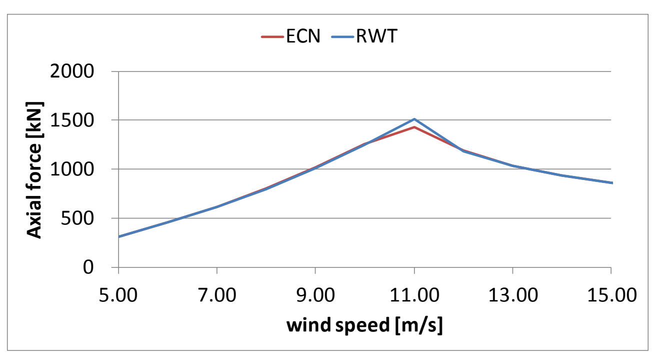

Figure 14 Axial force for the complete rotor. Comparison with the RWT.

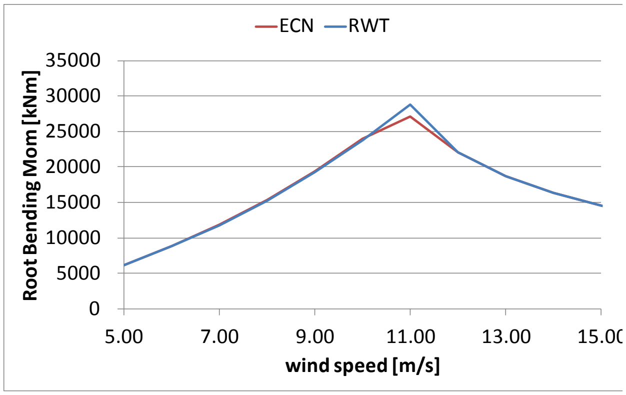

Figure 15 Root bending moment for the complete rotor. Comparison with the RWT.

5 Conclusions

A new family of ECN airfoils has been developed with the scope of assessing the overall quality of the design strategy and ECN expertise. These activities have been carried out in a research project in cooperation with Blade Dynamics Ltd. Detailed wind tunnel tests have been performed at TU Delft on one of the sections. The results showed a general good agreement with the predictions. This means that the design strategy implemented is also robust and reliable. However, in one of the tests the stall behavior appeared to be sharper than expected. In terms of airfoils performance, this is an undesired feature because it could lead to vibration problems for the blade, with consequent fatigue problems. From the design point of view it means that the robustness of the implemented scheme should be further improved.

The final part of the work has been focused on assessing the impact of these new airfoils on the performance of a 10MW wind turbine. The RWT of the European project INNWIND.EU has been used as term of comparison. The results showed that the same annual energy production is obtained with visibly lower axial force and root bending moment. This proves that the development and implementation of new airfoils can contribute to design advanced blades with reduced cost of energy.

Acknowledgement

This work is the result of a research project in collaboration with Blade Dynamics Ltd. The author would like to acknowledge Paul Hayden for giving permission to publish part of the experimental data and Jelmer Cnossen for the useful discussions during the project.

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