Usage of advanced thick airfoils for the outer part of very large offshore turbines

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Abstract. Nowadays one of the big challenges in wind energy is connected to the development of very large wind turbines with 100 m blades and 8-10MW power production. The European project INNWIND.EU plays an important role in this challenge because it is focused on exploring and exploiting technical innovations to make these machines not only feasible but also cost effective. In this context, the present work investigates the benefits of adopting thick airfoils also at the outer part of the blade. In fact, if these airfoils are comparable to the existing thinner ones in terms of aerodynamics, the extra thickness would lead to a save in weight. Lightweight blades would visibly contribute to reduce the cost of energy of the turbines and make them cost effective. The reference turbine defined in INNWIND.EU project has been adjusted to use the new airfoils. The results show that the rotor performance is not sacrificed when the 24% airfoils are replaced by the ECN 30% thick airfoils, while 24% extra thickness can be obtained.

1. Introduction

Looking at the current trend in wind turbine development, the size of the blades becomes larger and larger. European projects like INNWIND.EU [1] and AVATAR [2] are focused on improving the modeling for very large wind turbines (10MW) and explore/exploit innovative solutions to make such machines not only feasible to produce but also cost effective.

A key parameter in this sense is the cost of energy (CoE). Being able to significantly decrease the CoE is the breakthrough that research Institutes and Industry try to achieve. A possible way to obtain that, is to develop lightweight rotors, so the tower top mass is reduced and also the tower can be less expensive.

The present work aims to explore the possibility to extend the usage of thick airfoils up to the tip of the blade, without sacrificing visibly the annual power production by taking into account the positive aspects of operating in higher Reynolds numbers of the turbine or changing significantly the loads over the blade. If this would be possible, the mass of the blade could be reduced.

In the next section the design requirements are presented and the design scheme is illustrated. Then, the design of a new ECN 30% airfoil is shown and the performance are compared to existing geometries.

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2. Design of thick airfoils for the outer part of the blade

The design of new thick airfoils is presented in this paragraph. In particular, two specific aspects are described that introduce a source of novelty with the existing geometries: design requirements and large wind turbines up-scaling effects.

2.1. Design requirements.

The 10MW reference wind turbine (RWT) defined in INNWIND.EU project is used in the present work as term of comparison and baseline of the investigation. The rotor diameter is 178.3 meters with 6.2 meters maximum chord. The blade is equipped with FFA airfoils [3], ranging from 24% thickness at the tip to 60% thick section at the root. So the thinner airfoil, used at the outer part of the blade, is the 24% thick FFA-W3-241 geometry, while the middle part is equipped with the FFA-W3-301 and FFA-W3-360 airfoils and the inner part adopts the FFA-W3-600 airfoil.

This choice of airfoils is quite different from what can be normally observed in existing blades up to 3-5MW power. Typically, 15% - 18% thick airfoils are used at the outer part of the blade, while 24-30% thick geometries are used in the inner - middle part of the blade.

However, apart from the thickness values themselves, what makes really the difference between the airfoils is the set of requirements they have to accomplish. In fact, at the outer part of the blade the aerodynamics is predominant, while at the inner part the structural properties are instead more important. In order to have thicker airfoils at the outer part of the blade, one could think of using existing thick airfoils and "move" them more outboard. In that case, the result would be a poor performance because those thick airfoils are mean to provide good structural properties but not necessarily good aerodynamic performance. Instead, what is necessary to do, is to design new airfoils with the proper requirements for the outer part of the blade, but larger thickness values.

A discussion about these requirements can be found in the works presented in [4-7] and it is here summarized. The most important parameter to be considered is the aerodynamic efficiency (L/D) that should be maximized. However, beside this other parameters should be taken into account. The stall for instance, should be gradual and smooth: abrupt stall would cause fatigue problems when the local angle of attack (AOA) varies during the operations. Associated with fatigue problems, it is also the need of a safety margin between the design condition and the stall. In case of gusts, the local AOA can suddenly change bringing the airfoil closer to stall. If the margin is not sufficient, there could be a local stall. The sensitivity to roughness plays an important role. Due to sand, mosquitos, blade erosion and/or manufacturing imperfections the shape of the airfoil can be not completely smooth. As a consequence, the real performance will deviate from the nominal ones. A reduction of the airfoils sensitivity to the roughness is important to preserve the rotor performance.

2.2. Large wind turbines up-scaling and high Reynolds number effects.

Due to the up-scaling of the rotor sizes for 10MW+ machines, the local Reynolds number increases as well. For 2MW machine, a local Reynolds number of 4 million could be expected. In case of 10MW wind turbine, the local Reynolds number could be expected in the range of 10-12 million. This brings to a first conclusion: all the current airfoils are designed for lower Reynolds numbers and tested for limited Reynolds numbers only. The effect of high Reynolds numbers on the airfoil performance is primarily the change of Cl and Cd curves and the change in the location of laminar-turbulent transition. This influences the power performance of the wind turbines and would result in non-optimum shapes of the blades, if not taken into account during the design. These aspects are explained more in details in [8] and they are so important that wind tunnel tests are planned to be performed in DNW-HDG as a part of Avatar project to investigate the airfoil performances in 10-15 million Reynolds numbers.

For several airfoils and a range of Reynolds numbers, the airfoil characteristics can improve with higher Reynolds numbers. For instance, Cl_{max} and Cl_{max} angle could increase, while minimum drag could reduce for the same airfoil. In the same way, Cl and Cd performances in rough conditions could also improve. Using the positive aspects of operating in higher Reynolds numbers for very large blades, thick airfoil sections are applied to the outboard part of a large blade using existing thick airfoils [9]. It is shown that for larger blades, it can be feasible to adopt thicker airfoils to the outer part of the blade. Normally, this is not a preferred option because thick airfoils are known for having bad performances in terms of early stall, high drag, and strong sensitivity to roughness. These negative aspects are somewhat reduced by operating in high Reynolds numbers.

2.3. Design scheme
In the present work a design scheme based on numerical optimization approach has been used. In this scheme an advanced gradient based algorithm [10] is used, in combination with the ECN tool RFOIL [11] as aerodynamic solver. The geometry of the airfoil is parameterized with third order Bezier curves based on [12].

2.4. Design problem
The focus has been concentrated on the design of a 30% thick geometry for high efficiency. Keeping in mind what described above, the design has been performed at 10 million Reynolds number in free transition. A minimum trailing edge thickness of 1.5% of the chord has been required (the same value is used in the FFA-W3-301 airfoil).
Considering that the efficiency is defined as ratio between lift and drag, large values can obtained either by adopting high lift solutions or low drag configurations. Due to the constraint on the airfoil thickness, low drag solutions are hard to achieve so high lift geometries are expected. In pursuing high lift performance the stall is expected to occur for lower AOA, while the design point can move to high AOA values. As bad consequence, the margin between design condition and stall can be significantly reduced. To preserve a minimum value for this margin, a limit should be imposed for the cambering of the airfoil. From geometrical point of view, camber and camber location are the two parameters driving the cambering of the shape. However, instead of prescribing a constraint on these two quantities, a constraint on the moment coefficient (Cm) of the airfoil has been introduced (to be greater than -0.15). In this way, only one parameter is used instead of two and the design domain is preserved since the optimization is free to explore all the possible combinations of camber and camber location in order to satisfy the condition.

3. Results and discussion
As result of this investigation, a new airfoil (named ECN-GX30) has been designed (Figure 1).

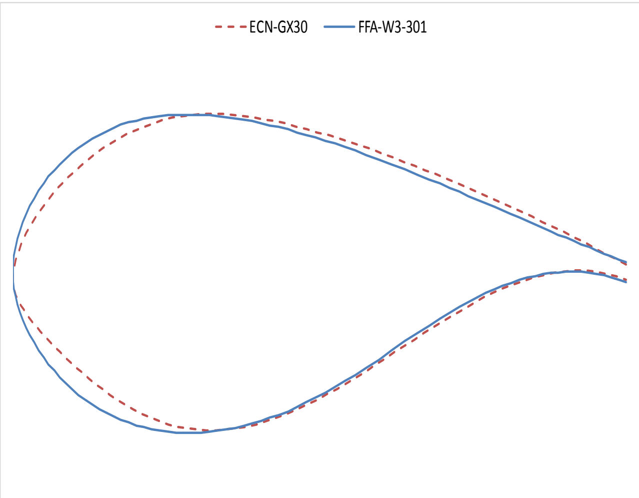

Figure 1 Sketch of the ECN-GX30 airfoil in comparison with the FFA-W3-301 airfoil.

The figures 2-5 show the comparisons between its characteristics and the ones of FFA-W3-241 and FFA-W3-301 airfoils. Those are used on the INNWIND.EU RWT. The analyses have been performed in clean and rough conditions. The e^n transition model is implemented in RFOIL code. Figure 6 shows the transition location predicted by RFOIL for the above mentioned geometries. For what concerns the rough condition, this is simulated by fixing the transition location. 1% of the chord from the leading edge has been chosen as location on both sides of the airfoils because this would be a sort of worst scenario to compare the airfoil performance.

In clean condition, the lift produced by the ECN-GX30 airfoil is in line with the FFA-W3-241, but lower than FFA-W3-301; however, the efficiency is visibly higher. In fixed transition, the FFA-W3-241 airfoil outperforms the other two but the ECN-GX30 is still very in line with the FFA-W3-301. In the previous paragraph, the margin between stall and maximum L/D has been mentioned. From this point of view, the ECN-GX30 has 4 degrees of margin in free transition, against 5 degrees of the FFA-W3-301 and 6 degrees of the FFA-W3-241. So some improvements is still possible in this case. However, in fixed transition the margin of the FFA airfoils is reducing to 4 degrees, while the ECN airfoil keeps the same margin.

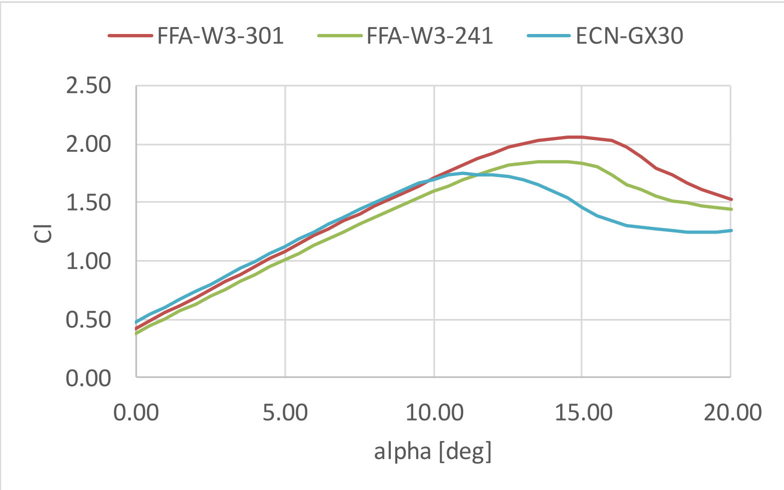

Figure 2 Lift curve comparison. RFOIL predictions. 10million Reynolds number, free transition.

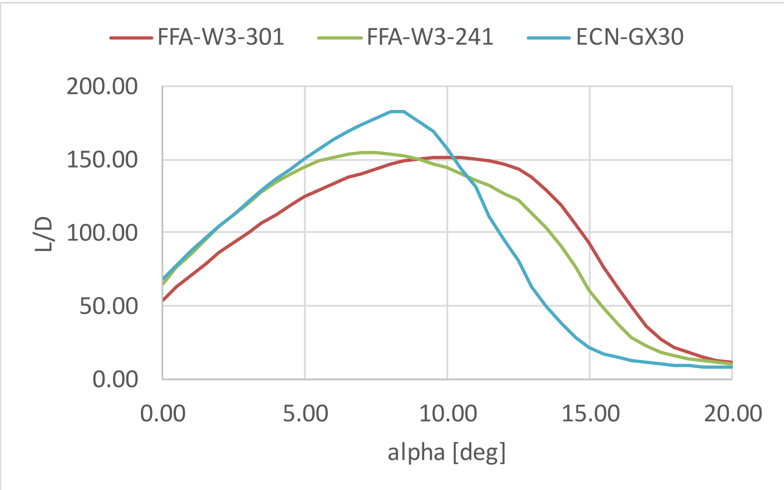

Figure 3 Efficiency curve comparison. RFOIL predictions. 10million Reynolds number, free transition.

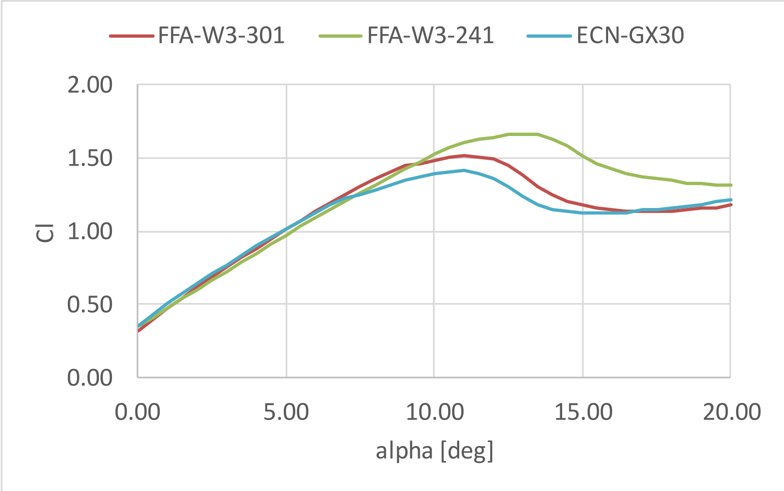

Figure 4 Lift curve comparison. RFOIL predictions. 10million Reynolds number, fixed transition.

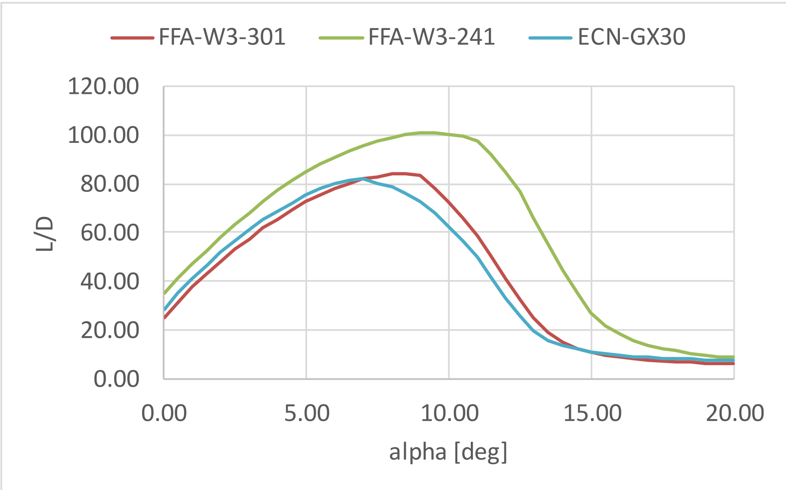

Figure 5 Efficiency curve comparison. RFOIL predictions. 10million Reynolds number, fixed transition.

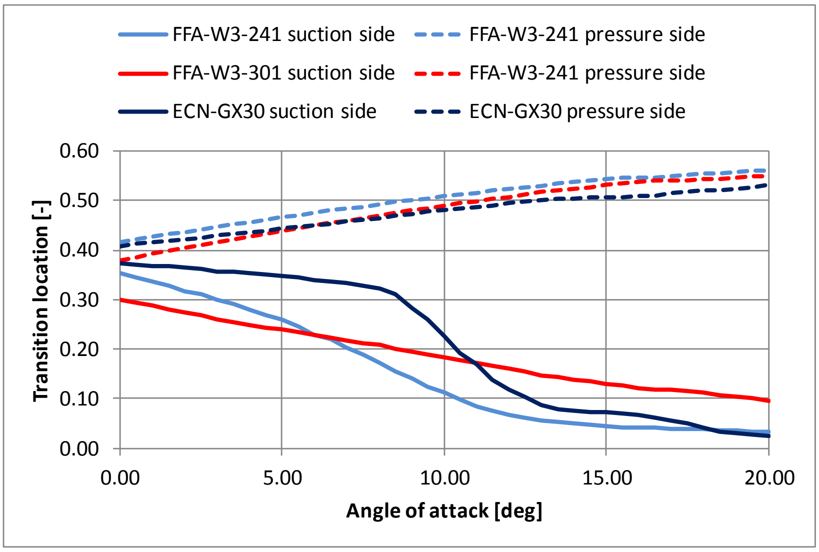

Figure 6 Transition location comparison.

The impact on rotor performance has been assessed also. Starting from the RWT where both FFA airfoils are used, one variant has been designed where both are replaced by the ECN airfoil. The chord distribution has been kept as the original, but the twist has been optimized to fit with the new airfoil. A comparative analysis has been performed by using the ECN tool BOT [13] that is based on BEM theory. As it can be observed in Table 1, the annual energy production (AEP) is almost the same. However, looking at the thickness distribution along the blade (Figure 7), a 24% of extra thickness has been achieved with the new airfoil. In order to have a complete overview of the new airfoil impact, a second variant of the RWT has been designed by adopting only the FFA-W3-301 airfoil (named RWT30). The AEP is reduced (-0.5%) and the Cp_{max} is also lower.

The same analyses have been performed by using the data related to the airfoil characteristics in fixed transition. This should provide a more complete idea on the potentialities of thick airfoils used at the outer part of the blade because the performance in realistic conditions is simulated (so including erosion, manufacturing imperfections, mosquito, sand). As expected, the energy production decreases due to the drop in airfoil performance. In this case, the energy production of the RWT is higher than the ECN concept about 0.47%. The ECN concept performs anyway slightly better than the RWT30. In Table 1, also the maximum axial force (Fax) and the maximum root bending moment (Root_bend_mom) are reported. It should be noticed that a reduction in both parameters is achieved by adopting the ECN concept (-1.5% in axial force, -1% in root bending moment).

In reality, 30% airfoil gives higher lift in the linear Cl region. Moreover, the blade stiffness values are further improved due to the increase in section thickness with the application of a thicker airfoil. As a result of these improvements, it is possible to reduce the chord length further without making the blade more flexible than the reference. This brings several advantages: the blade will be slender but not necessarily too flexible, better dynamic response of the blade and less parked loads due to the shorter chords. The increase in sectional stiffness lead also to thinner skin thickness and so saving in weight. These advantages connected to thicker airfoils at the outer part of the blade should also be taken into account while considering longer blade designs.

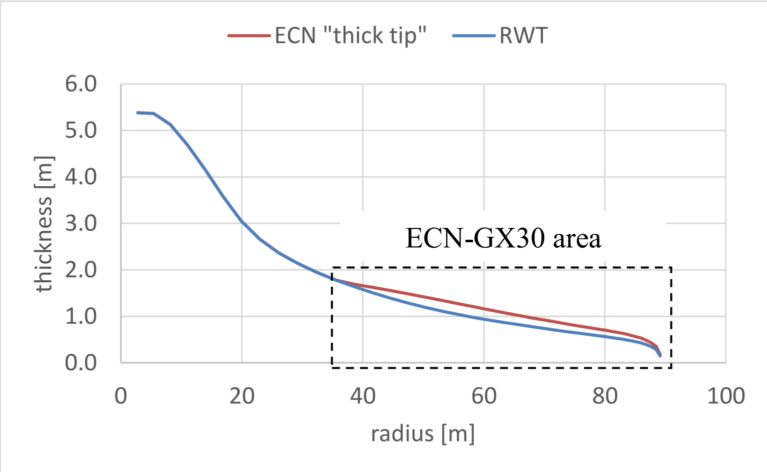

Figure 7 Thickness distribution comparison.

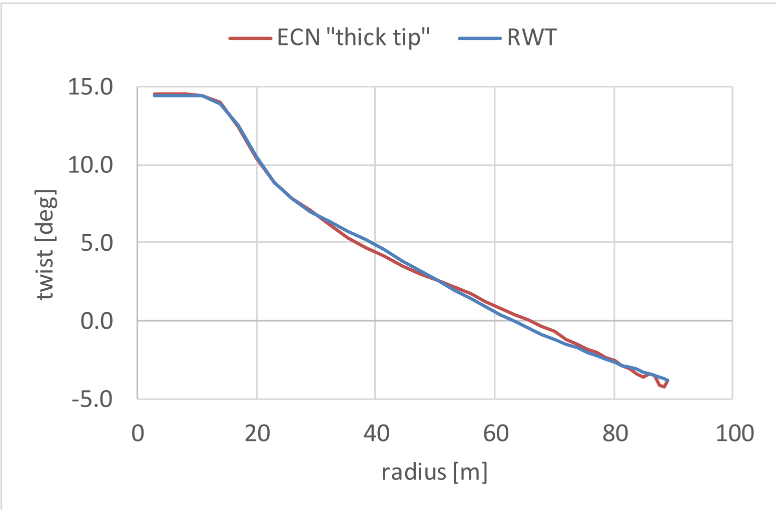

Figure 8 Twist distribution comparison.

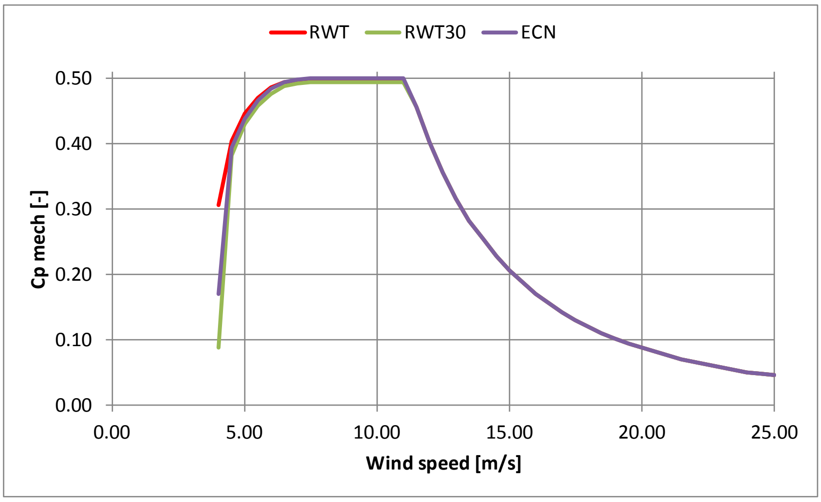

Figure 9 Mechanical Cp comparison in clean conditions.

Table 1 Rotor performance summary.

		RWT	ECN	RWT30	RWTfix	ECNfix	RWT30fix
Yield:	GWh/yr	53.27	53.29 (+0.037%)	53.10	52.69	52.44 (-0.47%)	52.40
P_{rated}:	MW	10					
U_{rated}:	m/s	11.50					
C_{Pmax}:	(mech)	0.498	0.500	0.495	0.482	0.475	0.475
λ_o:	-	7.5					
Fax_{max}:	kN	1509	1487 (-1.46%)	1514	1510	1488 (-1.46%)	1508
Root bend. Mom max:	kNm	28579	28321 (-0.9%)	28849	28678	28172 (-1.76%)	28647

4. Conclusions

The development of very large offshore wind turbines is big challenge. Research projects showed that move to large sizes is convenient and feasible, but not yet cost effective. Decrease in cost of energy is needed. A way to achieve that is to design lightweight rotors.

The present work investigated the possibilities to design thick airfoils with high aerodynamic performance by including the advantages of operating in higher Reynolds numbers so they could be adopted at the outer part of the blade and save some weight without scarifying the wind turbine performance.

The numerical results show that the new airfoil ECN-GX30 has good potentialities in comparison with existing geometries, although the stall margin could be still improved. Looking at the blade performance, the new airfoils would lead to slightly higher AEP values with better Cp_{max}. In addition to this, the same airfoil would be used on large part of it, so then the manufacturing and surface blending would be simplified.

Nevertheless, more investigations are needed regarding the structural design connected to the new airfoils. Also, all the results are based on RFOIL numerical predictions. Wind tunnel tests are necessary to validate them.

Acknowledgements

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References

[1] www.innwind.eu

[2] www.eera-avatar.eu

[3] Björk, A., “Coordinates and Calculations for the FFA-W1-xxx, FFA-W2-xxx and FFA-W3-.xxx Series of Airfoils for Horizontal Axis Wind Turbines”, FFA TN 1990-15, Stockholm, Sweden 1990.

[4] Grasso, F., “Usage of Numerical Optimization in Wind Turbine Airfoil Design”, AIAA, Journal of Aircraft, AIAA, Vol.48, No.1, Jan.-Feb. 2011, DOI: 10.2514/1.C031089.

[5] Tangler, J.L., Somers, D.M., “NREL Airfoil Families for HAWT’s”. Proc. WINDPOWER’95, Washington D.C., 1995; pp. 117–123.

[6] Timmer, W.,A., van Rooij, R.P.J.O.M., “Summary of the Delft University Wind Turbine Dedicated Airfoils”. AIAA-2003-0352.

[7] Fuglsang, P., Bak, C., “Design and Verification of the new Risø-A1 Airfoil Family for Wind Turbines”. AIAA-2001-0028.

[8] Ceyhan, O., "Towards 20MW wind turbine: High Reynolds number effects on rotor design", AIAA, 50th AIAA ASM conference, Nashville, Tennessee, USA, 9-12 januari 2012.
[9] Ceyhan O., "High Reynolds number effects on 20MW wind turbine rotor design", ECN-L--12-058, The Science of Making Torque from Wind, Oldenburg, Germany, 9-11 October 2012.
[10] Schittkowski, K., "NLPQLP: A new Fortran implementation of a sequential quadratic programming algorithm - user's guide, version 1.6", Report, Department of Mathematics, University of Bayreuth, 2001.
[11] van Rooij, R.P.J.O.M., "Modification of the boundary layer calculation in RFOIL for improved airfoil stall prediction", Report IW-96087R TU-Delft, the Netherlands, September 1996.
[12] Grasso, F., "Multi-Objective Numerical Optimization Applied to Aircraft Design", Ph.D. Thesis, Dip. Ingegneria Aerospaziale, Università di Napoli Federico II, Napoli, Italy, December 2008.
[13] Bot, E.T.G., Ceyhan, O., "Blade Optimization Tool BOT, User Manual", ECN, ECN-E-09-092, 2009.