Design of advanced airfoil for stall-regulated wind turbines

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Abstract. Nowadays, all the modern MW-class wind turbines make use of pitch control to optimize the rotor performance and control the turbine. However, for kW-range machines, stall-regulated solutions are still attractive and largely used for their simplicity and robustness. On the design phase, the aerodynamics plays a crucial role, especially concerning the selection/design of the necessary airfoils. This is because the airfoil performance should guarantee high wind turbine performance, but also the needed machine control capabilities. In the present work, the design of a new airfoil dedicated for stall machines is discussed. The design strategy makes use of numerical optimization scheme where a gradient-based algorithm is coupled with XFOIL code and an original Bezier-curves-based parameterization to describe the airfoil shape. The performances of the new airfoil are compared in free and fixed transition conditions. In addition, the performance of the rotor is analysed comparing the impact of the new geometry with alternative candidates. The results show that the new airfoil offers better performance and control than existing candidates do.

1. Introduction
Looking back in wind turbines history, pitch-regulated machines gradually substituted stall-regulated systems. In fact, the possibility to optimize the power production for each wind condition by regulating the pitch angle of the blade, proved to be a key feature to maximize the Annual Energy Production (AEP) of the wind turbines. Nowadays, all the modern MW-class wind turbines are “by default” pitch-regulated and several innovations are implemented by Industry to improve the pitch performance (e.g. individual pitch control, fine regulation mechanisms/algorithms) and extract more power.

In apparent contradiction with MW machines however, small and medium kW wind turbines are still largely stall-regulated machines. The reasons of this are easy to explain. In fact, the advantages of the pitch system come with some costs. The first is the direct cost of the pitch system and its maintenance. Secondly, the pitch system increases the general complexity of the system, together with the development costs and the issues related to the system robustness/reliability. Extra components, such on-board anemometers, pitch bearings are necessary to operate correctly the pitch of the blade. All these costs and complications can be very relevant for small machines and it explains why a robust and easy-to-maintain solution is preferred even with some AEP sacrifice.

From the design point of view, the stall-regulated machines offer still a challenging task, especially concerning the aerodynamics of the blade that should ensure the power performance but provide the machine control. In practice, the design of the blade should obviously aim to maximize the AEP, but it is also the only component to keep the turbine under control and stopping it when necessary. To do so, the stall and post-stall characteristics of the airfoils play a crucial role. From this angle, the
selection/design of the airfoils and the blade shape design are more delicate than pitch-regulated turbines.

The present work focuses on the design of a new airfoil specifically designed for stall-regulated turbines. The next section illustrates the design of the new airfoil in comparison with existing geometries. Then, its impact on the overall turbine performance is discussed.

2. Design of a new airfoil

2.1. General requirements

The selection of the proper airfoils is very relevant to achieve satisfactory wind turbine performance. Depending on the area of the blade, the requirements change quite a lot; in fact, the outer sections are optimized for high aerodynamic performance, while the inner sections are designed to provide low-weight, structural integrity to the blade.

The focus of the present investigation is the outer region of the blade, so the airfoils should have high aerodynamic efficiency (L/D). This is the primary parameter to increase the annual energy production of the rotor, but it is not the only one. Besides that, the stall behaviour should be considered, avoiding sharp stall. This would lead in fact to load problems to the blade (e.g. fatigue issues and additional noise) and other components. The impact of roughness on the rotor performance should be also addressed when the airfoil is designed/selected. Normally, the annual production decreases when the blade is contaminated by dirtiness (e.g. mosquitos), damages (e.g. erosion) or imperfections. Designing an airfoil that is robust (or less sensitive) to roughness would contribute to maintain a stable performance on the long run.

Looking at the blade construction, it must be buildable and lightweight to save the production costs, so the airfoils adopted should not have critical features which may compromise those aspects (e.g. too thin trailing edge, very concave-complex areas). Thin airfoils have better aerodynamic performance but the thicker ones have less weight and so are cost-effective. A complete discussion can be found in [1].

2.2. Aerofoils for stall-regulated wind turbines

In addition to what presented in the previous paragraph, special considerations should address the peculiarity of stall-regulated wind turbines. As mentioned, the big challenge of these machines is their control. While the pitch-regulated turbines can change the pitch angle of the blades, so to optimize the performance for each wind speed, the stall-regulated turbine are much more simple and rely on the aerodynamics of the airfoils.

Two aspects are particularly important: the first is the stall margin and the airfoil post-stall behaviour. A certain stall margin is beneficial and necessary to the machine to operate at its best without introducing fatigue problems due to permanence in stall region. However, for stall-regulated turbines, this margin must be carefully calibrated and normally reduced compared to the values for pitch-regulated machines. In fact, the stall mechanism stops the turbine when the loads are becoming too large; postponing the stall would lead to excessive forces on the blades and the other components of the turbine. Directly connected, also the post-stall behaviour of the airfoil plays a crucial role. The capability of the machine to slow down the rotor and avoid over-power issues depends on this. A slope of the lift curve excessively “flat” could be insufficient to control the turbine (and so prevent over-power), while sharp stall would make more difficult to re-start the machine and would cause sudden changes into the loads faced by the blades. Figure 1 illustrates these two cases.
Two generic airfoils are considered, with different stall behaviour. Airfoil 2 has softer post-stall region. The two power curves are visibly different and have different aerodynamic damping coefficient (DC).

The vibrations induced by rotating blade generate a force component that acts as aerodynamic damping force [2]. After the stall, the slope of the lift curve has negative value. The flow supplies energy to the blade and the amplitude of vibrations increases causing fatigue loads on the blade, in case the structural damping cannot compensate this energy. A sharp stall leads to lower damping force and so larger vibrations. DC is a coefficient that summarizes the damping potential of a certain airfoil/blade combination. In the present work, a linearized formulation is used to retrieve the value of DC.

Looking at figure 1, it can be noticed how a gentle slope of lift coefficient curve of the airfoils results in a higher value of damping coefficient but in a less control of the power.

So overall, it is important that the stall margin is reduced but with gentle and continuous stall. To limit the problem of power control the airfoils along the blade should have a low lift coefficient beyond stall and the drag coefficient as high as possible.

In addition, the airfoils of stall regulated turbines work in a quite wide range of angles of attack so a sound performance comes from the fact that they achieve high aerodynamic efficiency over the entire angle of attack range.

To complete the challenging scenario, these characteristics must be achieved both in clean and rough conditions. This introduce more complexity for the designer because special attention should be put also to avoid that the characteristics of the lift curve do not change significantly to influence the stall and post-stall behavior.

Finally, it should be kept in mind that a higher value of AEP can be obtained not only with a higher maximum efficiency of the airfoils, but also with a lower power peak wind speed, that means with a stall angle of attack closer to the maximum efficiency angle of attack.

2.3. Design methodology

Multidisciplinary Design Optimization (MDO) [3] has been adopted in this work. In fact, when compared to a traditional design technique (e.g. inverse design), MDO leads to a more accurate and computational-time saving design product, while covering constraints coming from different disciplines. A gradient-based algorithm controls the design procedure, where the popular tool RFOIL [4] is used to evaluate the aerodynamic performance of the airfoil. In fact, RFOIL accuracy for stall
region is significantly better than XFOIL [5] and, as mentioned in the previous chapters, stall is quite crucial parameter in this case. The geometry of the airfoil is parameterized with a combination of four Bezier curves of third order distributed along the airfoil contour (figure 2). Each Bezier curve covers one quarter of the shape with 13 control points free to move in chord and normal-to-the-chord directions (i.e. 26 design variables). To appreciate and understand the choice of four Bezier curves, the reader should consider that third order polynomial is needed to describe inflection points; however higher degree can lead to wavy shapes. Dividing the airfoil contour in four pieces is a smart move to divide the complexity of the parametrization and ease the control of the shape. This formulation is C2 continuous. 15 design variables are active in the present work; in fact, the leading edge cannot move, while the neighbours and the trailing edge can move only in vertical direction. In addition, the control points 4 and 10 are internally controlled to ensure C2 property also in those points. The complete mathematical formulation can be found in [6].

![Figure 2 Airfoil shape parameterization scheme. From [6].](image)

3. Results

3.1. Airfoil performance

The blade in development has two airfoils only (one main and one at the inner part, excluding the blending area at the very root of the rotor) in order to simplify the blade construction. This work focuses on the main airfoil design where the main target is the aerodynamic efficiency (L/D) maximization at the operative Re number of 1 million. At the same time, appropriate stall behaviour needs to be achieved in order to provide good control to the wind turbine. To cover this aspect, a combination of constraints focused on maximum lift coefficient (<1.4) and moment coefficient (> -0.12) has been adopted. In fact both constraints act on the camber line of the airfoil and their combined effect is to get soft stall with no excessive cambered shape. The airfoil thickness (t/c) of 0.25 has been selected, rather than a thinner value. Although the pure aerodynamic performance could be better with thinner (e.g. t/c 0.15, 0.18) airfoils, thicker sections offer the advantages of saving blade mass and provide higher strength to the blade structure.
Figure 3 S819 and S821 shapes.

Figure 4 Lift curves for S819 and S821 airfoils. Free and fixed transition data, 1 million Re number. RFOIL predictions.

Figure 5 Aerodynamic efficiency curves for S819 and S821 airfoils. Free and fixed transition data, 1 million Re number. RFOIL predictions.
Considering existing airfoils, the S821 and the S819 have been used as reference. Figure 3 shows the shapes, while figures 4 – 6 show the aerodynamic performance of these airfoils in free and fixed transition, as calculated with the RFOIL code. The Reynolds number used for the simulations is 1 million, in accordance with the average real Reynolds number value expected for a 60kW-range machine. It should be noticed the stall and post-stall behaviour that is soft but monotonically decreasing in the indicated angle of attack range. In addition, it should be noticed the relative small margin between the design point and the stall; for stall-regulated turbines, this is an important feature to avoid excessive loads once the design condition has been passed (e.g. in case of wind gust).

So the ideal airfoil is a 25% thick airfoil (like the S821) with L/D performance similar to S819, reduced stall margin and maximum lift coefficient ($C_{\text{max}}$), but also small roughness sensitivity and contained moment coefficient ($C_m$); the latter to avoid excessive torsional loads.

With these parameters in mind, three airfoils have been developed to offer better performance than the reference geometries. The airfoils have been preliminary named A, B and C and are all 25% thick (the shapes are not shown because of confidentiality issues). Their aerodynamic characteristics, evaluated with RFOIL, are illustrated in figure 7 and 8.

The airfoil A has more camber than the other airfoils. This is evident from the lift curve. It achieves better efficiency in clean condition. However, its behaviour is very sensitive to the roughness; in fixed transition, the efficiency drops significantly and the lift curve changes completely, making impossible the control of the wind turbine. The differences are smaller for the airfoil B, but the post-stall characteristics of the lift curve make difficult the control of the turbine. The airfoil C (from now on, called G25sx6) is instead a good compromise between good performance and good control properties.

The lift curve is in practice almost unchanged from free to fixed transition. In addition, the stall angle of attack unchanged. In terms of efficiency, the G25sx6 exhibits the best performance in fixed transition and a quite flat plateau in both free and fixed transition. As mentioned, this is quite convenient for stall regulated turbines because the airfoil will operate in a range of angles of attack rather than a specific value like in the pitch controlled machines. Combining lift and efficiency performance, the stall margin is almost unchanged between free and fixed transition.
Comparing the G25sx6 with the S821 airfoil (figures 9 and 10) it can be notices a similar value of efficiency in free transition but better performance in fixed transition. In addition, the efficiency curves keep a good level over a wider range of angles of attack and the stall margin is reduced, that is an advantage for stall regulated wind turbines (i.e. avoiding excessive loads in case of wind gust).
3.2. Impact on rotor performance

In order to assess the value of the new airfoil, its impact on wind turbine performance has been evaluated with a numerical analysis.

A 60kW stall-regulated wind turbine has been used as reference and the S821 and G25sx6 airfoils have been adopted as main airfoil. The reference wind turbine is a three blades machine designed to product energy in sites characterized by a very low mean wind speed, such as coastal regions but also many hinterland areas. Thus, its main characteristics are very low values of cut-in and power peak wind speeds (about 2.5 m/s and 8.5 m/s respectively) and a high AEP with a mean wind speed of about 4 m/s. To obtain this performance a generous rotor radius and particularly slender blades are adopted: the radius is 13.7m, the maximum chord is 1.2m and the RPM is 34 (fixed).

Figure 11 shows the (non-dimensional) power curves for the blade optimized based on the S821 airfoil and G25sx6 airfoil. The BEM-based tool WtPerf [7] developed by the NREL has been used for these analyses. The chord and thickness distributions have been kept unchanged but the twist distribution has been adjusted to optimize the performance based on the actual airfoil installed.

Both free and fixed transition conditions have been included, as representative of clean and rough blade conditions. The power curves related to free and fixed transition in the figure refer to different
values of the blade pitch, which is the value necessary to achieve the desired power peak in each case. In fact, due to uncertainties on the real behaviour of the airfoils the possibility to modify the pitch of the whole blade can provide the desired maximum power in case of inaccuracy in numerical simulations.

The necessary pitch will be higher in fixed transition than in free transition. In other words, at each wind speed, the airfoils will work at a lower angle of attack; this means lower airfoil lift coefficients and lower wind turbine power. In fact, in fixed transition the maximum lift coefficient is lower, so a higher value of wind speed is needed to achieve the desired peak power. The maximum lift angle of attack has to be achieved at this higher wind speed, and consequently the pitch necessary in fixed transition will be higher than in free transition.

![Figure 11 Effect of the new airfoil on the wind turbine's power curve.](image1)

![Figure 12 Angle of attack distribution along the blade.](image2)

**Table 1 Impact of the new airfoil on the wind turbine AEP.**

| Airfoil | Free transition | Fixed transition |
|---------|-----------------|------------------|
|         | AEP [kWh] | Δ [%] | AEP [kWh] | Δ [%] |
| S821    | 136000      | -     | 129000    | -     |
| G25sx6  | 143000      | +5.15 | 132000    | +2.3  |
Considering the overall Annual Energy Production (AEP, see table 1), the new airfoil provides a considerable gain in free (+5.1%) and fixed (+2.3%) conditions. More in detail, the turbine reaches the maximum power for lower wind speed and the post-peak region is smoother. In addition, the production at very low wind speed increases thanks to the new airfoils.

4. Conclusions
Despite the pitch controlled wind turbines cover the complete large MW machines market, stall regulated solutions are still diffused for small power production. A new airfoil specifically designed for this class of wind turbines has been developed and presented in this work. Compared to existing geometries, the new airfoil can increase visibly the annual energy production of the machine, both in clean and rough conditions. In terms of rotor performance, the new airfoil brings a visible benefit on the punctual power production and on the overall AEP (+5.1% in free transition and +2.3% in fixed transition).

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