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# Design of after-market wind turbine blade add-ons for noise reduction

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ABSTRACT: As a result of the continous growth of Wind Turbines (WTs) implementation worldwide, the problem of WT noise has become more relevant than ever. The increase of noise legal constraints and their non uniformity across different countries and/or regions make it important to address this problem early in the design phase of a WT. However, one might want to reduce the noise produced by WTs that are already in use to comply with new stricter noise limits. In the present work, this problem is addressed by using a WT blade optimization framework to obtain the shape of blade add-ons that could be attached to the blade of a WT (for example, by using some kind of adhesive) to reduce its noise without compromising the performance. Blade Element Momentum (BEM) theory was used to compute the aerodynamic performance of the WT and semi-empirical models were used for the airfoil self-noise and turbulence interaction noise prediction. The aerodynamic analysis of the cross sectional airfoil shapes, required for both the BEM calculations and noise predictions, is performed using the viscous-inviscid interactive code XFOIL. Non-dominated Sorting Genetic Algorithm-II was used as the optimization algorithm. Two NURBS curves were used to define the baseline cross sectional airfoil shape of the blade at certain control sections and another two to define a variation from the baseline, totalling up to 54 design variables. The framework was used to optimize the AOC 15/50 WT, a commercial downwind, three bladed WT. Optimal solutions were selected from the Pareto front and discussed in detail. These solutions ranged from an increase in energy production of 5.2% to a decrease in noise levels of 5.9%. The results demonstrated that, while it is preferable to address noise concerns in the design phase of the WT, it is possible to address them with favourable results after its construction.

## 1 INTRODUCTION

Wind Turbine (WT) noise has been studied for many decades as a result of the continuous growth of the WT implementations worldwide (Stephens et al. 1982, Pedersen and Waye 2004, Colby et al. 2009). With the increase in noise legal constraints and the non uniformity of these across the different countries and/or regions, it's important that the aeroacoustic properties of a WT are addressed in its design phase, when it is still possible to fully optimize the blade to achieve greater energy production to generated noise ratios. It might however be the case that an existent wind turbine park, at a certain point of its lifespan, generates noise levels which need to be reduced, either to comply with regulations or complaints. A simple and cost effective method for achieving the desired reduction in noise levels, without compromising the performance of the wind turbines, would then be advantageous.

While previous work consisted in optimizing the geometry of the blade by varying simultaneously the chord, twist and cross sectional airfoil shapes at specific locations of the blade (Rodrigues & Marta 2014), in the present paper the WT optimization framework is used to obtain the shape of blade add-ons which could be attached to a WT blade (for example, by using some kind of adhesive) to reduce its noise without compromising the performance.

The WT aeroacoustic prediction tool used to compute the noise and performance of the WTs is described in Section 2. The optimization framework and the shape parametrization approach are described in Section 3. Results of the optimization of the blades of a commercial WT are presented in Section 4.

## 2 AEROACOUSTIC PREDICTION TOOL

There are many models and methods of varying complexity and fidelity one can use for the prediction of aerodynamic performance of WTs, going from the simplistic actuator disk theory to full Computational Fluid Dynamics analysis of the entire turbine geometry. For the purpose of this work, a fast turnaround tool was necessary, as the optimization algorithms have the necessity to call the analysis functions many times and the optimizations were to be computed using an average workstation.

The Blade Element Momentum (BEM) theory (Hansen 2008) was chosen as the prediction model of the aerodynamic performance of the WT to address the previously described requirements. It is a simple (and of fast execution) model, but with the right corrections and good aerodynamic data, it has been shown to produce good agreement with experimental data. The airfoil aerodynamic data used in the BEM

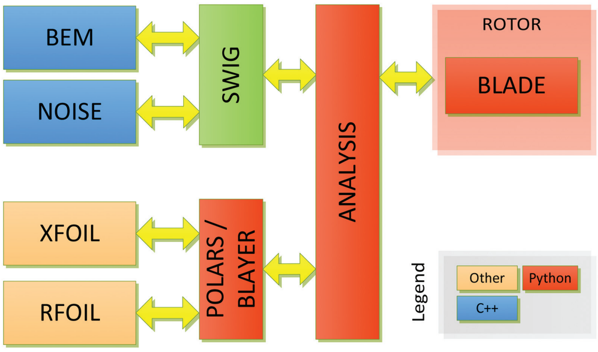


Figure 1. Structure of the WT aeroacoustic prediction tool.

iterations was obtained from the viscous-inviscid interactive code XFOIL (Drela 1989) and corrected for 3D effects using the stall delay model from Du & Selig (1998) with drag adjustments from Eggers et al. (2003). The data was extrapolated using a method developed by Viterna & Janetzke (1982).

The Annual Energy Production (AEP) of the WT is computed as the product of its power curve and the probability function of the wind, which is assumed to follow a Weibull distribution.

Semi-empirical models developed by Brooks, Pope, & Marcolini (1989) are used for the airfoil self-noise prediction and a model formulated by Lowson (1993), based on the work of Amiet (1975), is used to predict the noise due to turbulent interaction between the flow and the airfoil. To the latter, a correction to account for the shape of the airfoil is applied (Moriarty et al. 2004, Moriarty et al. 2005). The boundary layer parameters used by these models were also computed with XFOIL.

The code was developed using the C++ and Python languages, as indicated in Fig. 1, where the analysis tool structure is schematically represented. Integration of the C++ classes in the Python language was implemented through the use of SWIG (Beazley et al. 1996). Validation was performed against experimental data of a commercial WT and proved to provide good qualitative results, sufficient for the conceptual design framework that it is intended for (Rodrigues & Marta 2014).

## 3 OPTIMIZATION FRAMEWORK

A Multidisciplinary Optimization (MDO) framework was developed using pyOpt (Perez et al. 2012) and the aeroacoustic prediction tool described in the previous section. The Non-dominated Sorting Genetic Algorithm-II (Deb et al. 2002) was chosen as the optimization algorithm and was used with the parameters presented in Tab. 1. They are the probability of occurrence of crossover and mutation and distribution indexes for the same two operations. NSGA-II solves non-convex, non-smooth single and multi-objective and has been used in the WT optimization field (Petrone et al. 2011, Wang et al. 2011).

Table 1. GA parameters used in the optimization.

| Parameter | Value |
|---|---|
| P(Crossover) | 0.6 |
| P(Mutation) | 0.2 |
| $\eta_c$ | 10.0 |
| $\eta_m$ | 20.0 |
| seed | 0.0 |

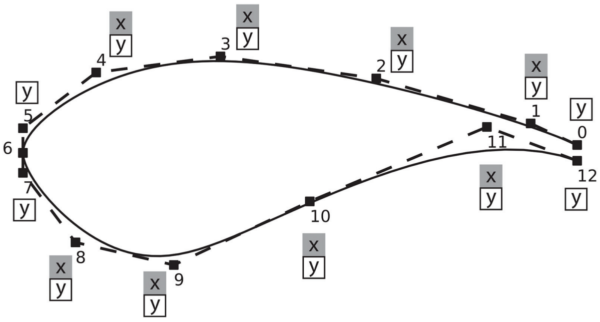


Figure 2. NURBS airfoil parametrization control points and respective degrees of freedom.

### 3.1 *Shape parametrization*

The shape of the blade is defined by control sections distributed along the blade span, defining the normalized cross-sectional airfoil shape at their locations. Between them, this shape is linearly interpolated. This normalized geometry is then scaled and rotated according to the specified twist and chord distributions, also defined by control points along the blade span.

In authors previous work, the airfoil shapes were parametrized directly using with two Non-Uniform Rational B-Splines (NURBS) curves, for the upper and lower sides of the airfoil (see Fig. 2).

As the goal of the approach presented in this paper was to design add-ons for the turbine blade, constraints to the new airfoil shape needed to be imposed, in order to obtain airfoils thicker than the originals. To easily handle these, instead of parametrizing the airfoil shapes directly, two extra curves were introduced, to define the upper and lower added thickness to the baseline shape. The final airfoil shape is then defined, as the sum of each pair of curves (baseline + difference).

### 3.2 *Problem statement*

The multi-objective optimization problem solved can be stated as

$$\begin{aligned} \underset{\mathbf{x}}{\text{minimize}} \quad & f_1(\mathbf{x}) = -AEP \\ & f_2(\mathbf{x}) = OASPL \\ \text{subject to} \quad & \mathbf{g}(\mathbf{x}) \leq \mathbf{b},\ i = 1, \ldots, m, \end{aligned} \tag{1}$$

Table 2. Design variable boundaries of used in the optimization problems.

| | lb | ub |
|---|---|---|
| $\mathbf{x}_{\text{lower/upper}}$ | $0.9\mathbf{x}_{\text{baseline}}$ | $1.1\mathbf{x}_{\text{baseline}}$ |
| $\mathbf{y}_{\text{upper}}$ | 0.0 | $0.3\mathbf{y}_{\text{baseline}}$ |
| $\mathbf{y}_{\text{lower}}$ | $0.3\mathbf{y}_{\text{baseline}}$ | 0.0 |

where $f_1$ and $f_2$ are the aerodynamic and acoustic components of the objective function vector $\mathbf{f}$, and $\mathbf{g}$ is the vector of constraints. The design variables $\mathbf{x}$ are the x- and y-coordinates of the control points of the *difference* NURBS curves (see Fig. 2). Each control section introduced 18 design variables, relative to the 20 degrees of freedom minus the trailing edge ones (control points 0 and 12), which were maintained at zero. This totals 54 design variables (three control sections). The search space was defined by the bounds indicated in Tab. 2.

The constraint vector is defined as, for each control section $j$,

$$\begin{aligned} x_i^{cp,j} &\geq x_{i+1}^{cp,j}, \quad \text{on the upper curve} \\ x_i^{cp,j} &\leq x_{i+1}^{cp,j}, \quad \text{on the lower curve,} \end{aligned} \tag{2}$$

thus ensuring that the control points of the NURBS curves do not intersect.

## 4 OPTIMIZATION OF THE AOC 15/50 WIND TURBINE BLADES

The AOC 15/50 is a commercial downwind, three bladed WT, with a diameter of 15 m and a rated power production of 50 kW (Seaforth Energy 2010). Its blades use the NREL S821, S819 and S820 profiles, defined at 40%, 75% and 95% of blade span, respectively.

A Weibull curve with parameters $A = 6.48$ and $k = 1.99$ as used in the simulations to model the wind distribution in the municipality of Vila do Bispo, in the south west of Portugal (Costa 2004). In each simulation, the BEM code was run for wind speeds raging from 2 ms$^{-1}$ to 25 ms$^{-1}$, in 1 ms$^{-1}$ intervals. The aeroacoustic simulation of the turbine was run for a wind speed of 6 ms$^{-1}$ and assuming the observer at ground level, 96 meters (three times the height of the tip of the blade at its higher position) downwind of the turbine, in the direction of its rotation axis. The ground roughness was taken as 0.5 ms$^{-1}$, corresponding to a type of terrain with many bushes and obstacles. Both boundary layer parameters and airfoil polar data were computed using XFOIL. The TE was assumed to have a thickness of 1% of the chord and a constant angle of 6°. Due to the non-aerodynamic shape of the sections up to 40% of the blade span, the noise was only computed in the 60% outer part.

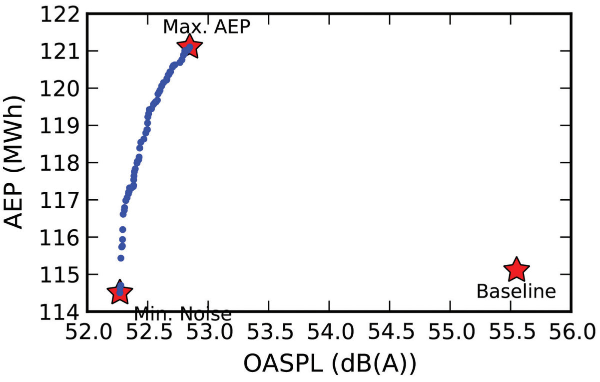


Figure 3. Pareto front resultant from the optimization.

Table 3. Comparison between optimal solution values of "design phase" and "add-on" optimizations.

| | | AEP [MWh] | | OASPL [dB(A)] | |
|---|---|---|---|---|---|
| Baseline | | 115.11 | | 55.55 | |
| Add-on | Min Noise | 114.51 | −0.5% | 52.27 | −5.9% |
| | Max AEP | 121.10 | 5.2% | 52.85 | −4.9% |
| Design Phase | Min Noise | 115.45 | 0.3% | 50.38 | −9.3% |
| | Max AEP | 134.76 | 17.1% | 53.19 | −4.3% |

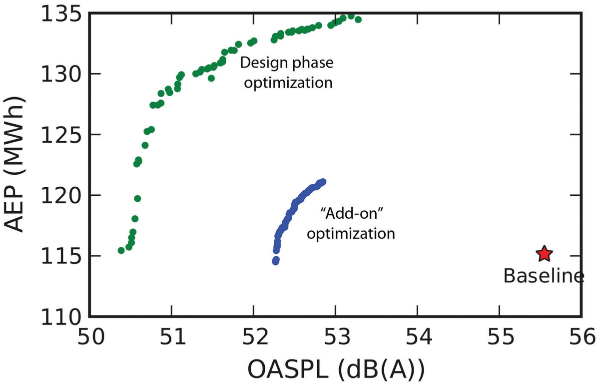
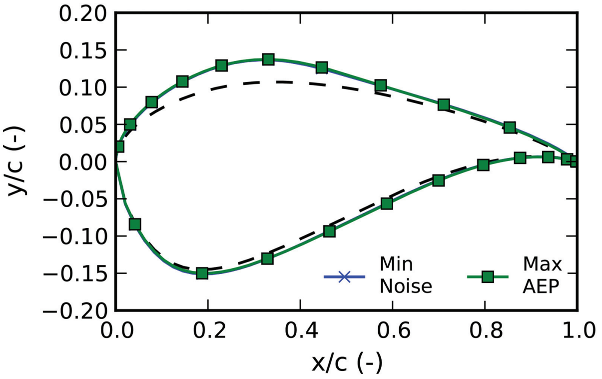


Figure 4. Comparison between Pareto fronts obtained with "design phase" and "add-on" optimizations.

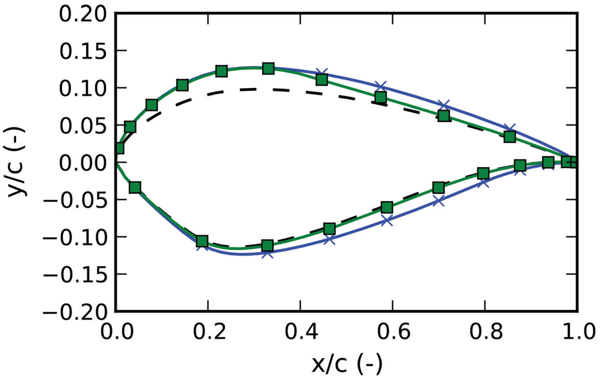
The optimization was run for 140 generations of 68 individuals and the resultant Pareto front is shown in Fig. 3, where two different solutions are highlighted: one producing the *minimum noise* level and another the *maximum AEP*.

The AEP and OASPL values of the solutions highlighted in the previous figure are presented in Tab. 4 (top part). The minimum noise blade is able to reduce the noise by about 3 dB(A), or 5.9%, with a negligible cost in energy production of 0.5%. The maximum AEP blade, while increasing the AEP by 5.2% is still able to reduce the noise levels by 4.9%.

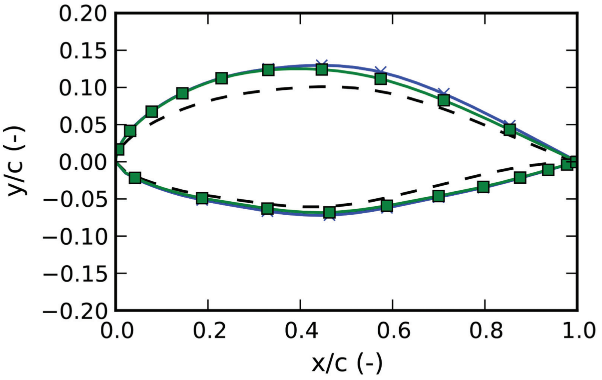
In Fig. 4, the same Pareto front presented in Fig. 3 is compared to the one obtained from the full "design phase" optimization of the same blade, which is described in detail in (Rodrigues & Marta 2014). The latter approach, with much more freedom to vary the shape of the blade, was able to move the Pareto front



(a) Control section at 40% of blade span



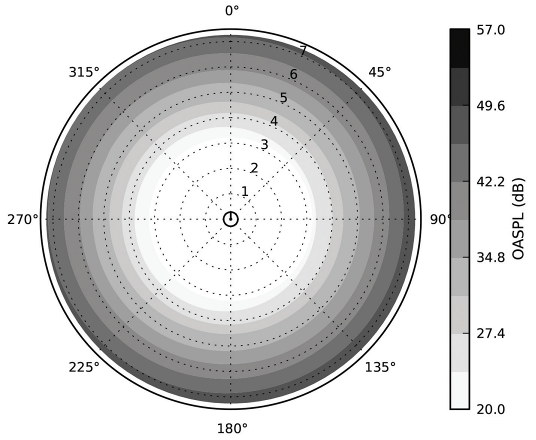
(b) Control section at 75% of blade span



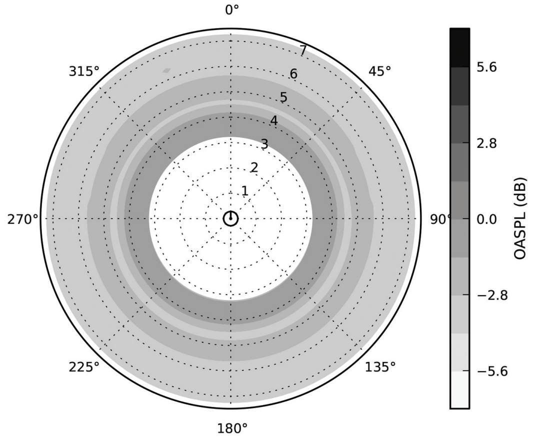
(c) Control section at 95% of blade span

Figure 5. Initial and optimized airfoil shapes.

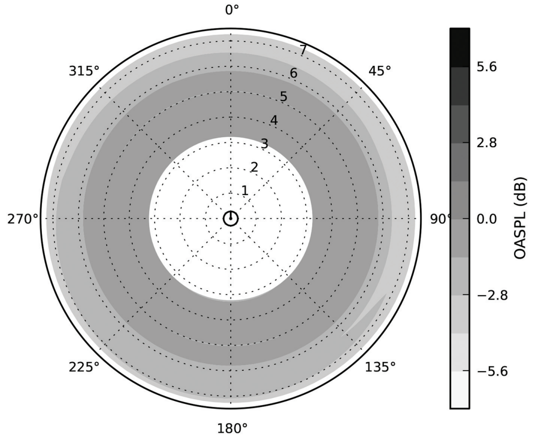
farther to the upper left region of the chart, meaning higher AEP values and lower noise levels. Table 4 also presents AEP and OASPl obtained in the design phase optimization. Comparing the minimum noise solutions, while the AEP variation is similar (0.5% loss with the add-on approach vs. 0.3% gain with the optimization at the design phase), a much larger reduction in noise levels can be achieved if the optimization



(a) Baseline



(b) Minimum noise



(c) Maximum AEP

Figure 6. Differences in overall sound pressure level across the rotor for selected optimal blade geometries, using the baseline blade as reference.

is performed in the design phase (9.3% vs 5.9% reduction). In the case of the maximum AEP solutions, the noise reduction is similar, while the increase in AEP is larger with the design phase optimization approach (5.2% vs 17.1% increase).

The optimized airfoil shapes relative to the three highlighted solutions of Fig. 3 are presented in Fig. 5. All the optimal profiles present shapes thicker than the baseline, which is in accordance to the requirements for the add-ons. At 40% of blade span, both airfoils present a larger fore camber and thickness. At 75% and 95%, the same change is visible in the optimized shapes and the minimum noise airfoils also present a larger aft thickness, compared to the maximum AEP.

Figure 6 presents the difference of noise generated by the blades in the rotor plane between the baseline and the two selected Pareto solutions highlighted in Fig. 3, as well as the baseline noise distribution. The non-symmetric behaviour is visible as the noise levels are higher between 90° and 180°, corresponding do the blade downward movement. In the minimum noise solution, the reduction of generated noise is clearly visible, with the majority of the rotor plane generating lower noise levels. The maximum AEP blade, although presenting noise levels slightly higher than the minimum noise, is also able to reduce noise levels across the rotor plane.

## 5 CONCLUSIONS

A new approach to parametrize the blade was introduced in the previously developed optimization framework, which simplified the handling of the constraints specific to the optimization problem treated in this paper.

The optimization framework was able reduce the overall sound pressure level (maximum decrease of 5.9%) with small reduction, or even increase in energy production (maximum increase of 5.2%) of the AOC 15/50 WT, by adding volume to its blade.

Although asserting the importance of addressing noise constraints in the design phase of a wind turbine, the results indicate that it is possible to improve an existent blade with small changes to its geometry, through the use of skins made of lightweight materials glued to the outer surface of the existing blade using structural adhesives.

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