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Evolving aerodynamic airfoils for wind turbines through a genetic algorithm

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Abstract. Nowadays, genetic algorithms stand out for airfoil optimisation, due to the virtues of mutation and crossing-over techniques. In this work we propose a genetic algorithm with arithmetic crossover rules. The optimisation criteria are taken to be the maximisation of both aerodynamic efficiency and lift coefficient, while minimising drag coefficient. Such algorithm shows greatly improvements in computational costs, as well as a high performance by obtaining optimised airfoils for Mexico City's specific wind conditions from generic wind turbines designed for higher Reynolds numbers, in few iterations.

1. Introduction

The efficiency of a wind turbine depends heavily on the geometry of the airfoils used to design the blades. Historically, AO is a process that has been mainly performed in a trial and error basis in wind tunnels [1]. Actually, as many other areas of science, aerodynamics has been benefited from the vertiginous advancements in computing power. These advantages have taken two different directions:

- In CFD, to simulate more realistic flows, or flows not achievable in wind tunnel facilities.
- In the area of AO to increase their desirable physical features and response.

In the subject of CFD, there has been an enormous amount of research [2, 3, 4, 5] that has led to several open source, proprietary as well as commercial software to simulate almost any flow, for instance, flows in a wide range of Reynolds numbers.

The AO is part of what constitutes actually the field of CA, a branch of the airfoil design process [6, 7, 8]. Despite the existence of several computational techniques to optimise airfoil, most of them heavily rely on the analytical theory of aerodynamics; also, some of them are designed specifically to optimise the performance of airfoils used as wings for airplanes, helicopters, etc. The main difference between an airfoil used as a wing and those used in wind turbines is that they appear inverted in the blade. This is due to the fact that the lift force they provide in a wing, when inverted, provides the torque necessary to rotate the turbine. Some of the traditional methods to optimise airfoils are the ones that use differential gradients of functions representing the parameters to optimise; this way, one is able to modify iteratively the parameters or variables of the design being performed. This allows to map systematically the space of solutions, but they are slow to converge and are not reliable when the optimization problem is complex due to a multi-modal behaviour, non-continuities or non-



differentiabilities in the physical behaviour of the parameters, etc. Due to such slowness, some efforts have focused in reducing execution times [9]; however, is not a common target in their development. Modern algorithms that overpass these difficulties are evolutive algorithms [9, 10, 11, 12, 13, 14, 15].

In this work we propose a novel genetic algorithm that relies on the arithmetic of lineal combinations of the theory of algebra. This algorithm is used to obtain airfoils with new geometries and with superior aerodynamic features by taking the crossover of previous airfoils already optimised for their usage in wind turbines. This set of parent-airfoils will produce son-airfoils; the latter are analysed in a flow which reproduces the mean conditions of air flows in Mexico City. The son-airfoils overpassing the efficiency criteria are taken as the new optimal airfoils.

This paper is organised as follows: in section 2 we briefly describe the algorithm we propose to obtain new airfoils through crossover techniques. In section 3 we present the most relevant results we obtained along with their corresponding aerodynamic analyses. In the last section, we present a discussion of the results as well as the main achievements in computational and human times in AO.

Listing 1. Pseudo-code for the proposed genetic algorithm

- Define a set of linearly independent one-dimensional functions.
- Generate a new bigger set of functions by performing all the possible compositions of the initial set.
- Take two parent airfoils previously known to be optimal (for wind turbines).
- Apply the crossover operator (see eq. (1)) to both parents with each of the functions previously defined, so to obtain son-airfoils.
- Do until N generations final fitness criteria met:
 - * Apply fitness criteria to each airfoil in current generation.
 - * Get the two fitness individuals and set them as parents.
 - * Apply crossover operator to both parents and replace current generation with new airfoils.

2. Genetic algorithm

The optimization method is based on a genetic algorithm, which starts with a selected initial population, to then proceed on applying cross-over and/or mutation operators. These operators generate a new population (generation) over which, again, fittest individuals are taken. The approach taken varies in the standard genetic algorithm in that an initial set of non-random individuals are taken.

Airfoils are defined by their x , y coordinates and their chord's length c , so we propose the crossing-over operator to be a linear combination of a pair of individuals as

$$f_i y_{p1} + f_j y_{p2} = y_s \quad (1)$$

where y_{p1} , y_{p2} and y_s are the y coordinate of both of the parent-airfoils and of the resulting son-airfoil respectively, $\{f_k\}_{k=1}^n$ is a set of n continuous and differentiable functions such that $f_k : [0,1] \rightarrow [0,1]$, and with the constriction $f_k + g_k = 1$ so to avoid extremely thick airfoils. In listing 1 we show the pseudo-code of this algorithm.

1.1. Airfoil input for the algorithm

There exist a huge amount of airfoils, each specially designed for specific purposes, which can be found on databases and in the literature [17, 18, 19, 20, 21]. We took the set of parent-airfoils for wind turbines from the S-series provided in the public database of the NREL, designed to exhibit a maximum C_L while being relatively insensitive to roughness effects. We particularly chose an initial parent-airfoil set of 2 individuals, S809 and S804 airfoils (which can be appreciated in figs. 1 and 2), whose aerodynamic features are shown in table 1 and 2.

Table 1. Nomenclature and units.

Symbols	Abbreviations		
C_L	Lift coefficient (adimensional)	CFD	Computational Fluid Dynamics
C_D	Drag coefficient (adimensional)	CA	Computational Aerodynamics
C_P	Pressure coefficient (adimensional)	AO	Airfoil Optimization
C_M	Moment coefficient (adimensional)		
C_L/C_D	Aerodynamic efficiency parameter (adimensional)		

Table 2. Top aerodynamic parameters for the selected parent airfoil set (see figs. 1 and 2).

Airfoil	C_L	C_D	C_M	C_P	C_L/C_D
S809	1.0271 ($\alpha = 14.7$)	0.0166 ($\alpha = 7.8$)	-0.0019 ($\alpha = 14.5$)	-6.445 ($\alpha = 15.6$)	58.920 ($\alpha = 7.8$)
S814	1.3743 ($\alpha = 10.2$)	0.0202 ($\alpha = 6.9$)	-0.0842 ($\alpha = 13.4$)	-6.081 ($\alpha = 18.3$)	64.964 ($\alpha = 9.6$)

To increase the crossing-over possibilities, we actually define an initial set of functions with the above features, so $\{f_k\}_{k=1}^n$ is the set of all the possible compositions between them that preserve such properties. Our initial set of functions is $\{\sqrt{x}, e^x, \ln x, \text{sech } x, \tanh x, \sin x, \cos x, \arctan x, J_4, J_5\}$, where J_k is the Bessel function of k order.

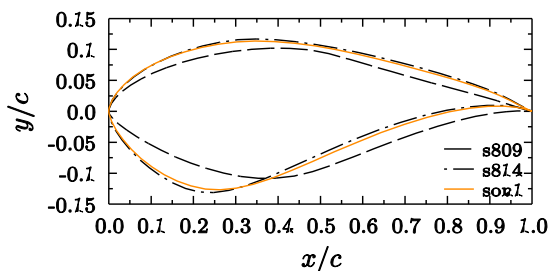
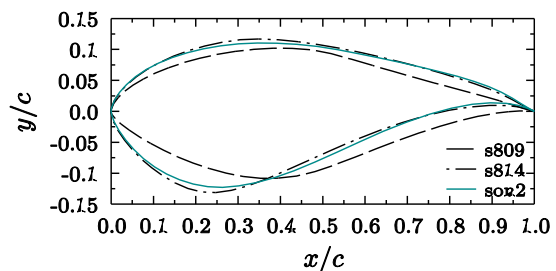
Table 3. Mexico City mean wind parameters

Parameter	Mean speed (m/s)	Density (kg/m ³)	Temperature (C)	Kinematic viscosity (Pa s)
Value	14.816	0.98	20	1.845×10^{-5}

3. Aerodynamics of optimised airfoils

For the purpose of this work, we simulated in XFOIL software [16] an air flow corresponding to the mean conditions in Mexico City, which are summarised in table 3.

We obtain the performance features of the parent-airfoils set as well as the best sons up to the tenth generation. The fitness criteria is set as to overcome the average of both the aerodynamic efficiency C_L/C_D and the lift coefficient C_L of parents, while not overcoming the average of C_D of parents. In figures 1 and 2, we show the coordinates of the two best son-airfoils obtained, called son1 and son2.

**Figure 1.** Shape of son1 optimised airfoil with respect to the original airfoils.**Figure 2.** Shape of son2 optimised airfoil with respect to the original airfoils.

In figures 3, 4, 5 and 6 we show the plots of the aerodynamic efficiency parameter, the lift coefficient, the drag coefficient and the pressure coefficient against the attack angle, from where it is possible to observe the improvements we had in such parameters up to the tenth generation of airfoils.

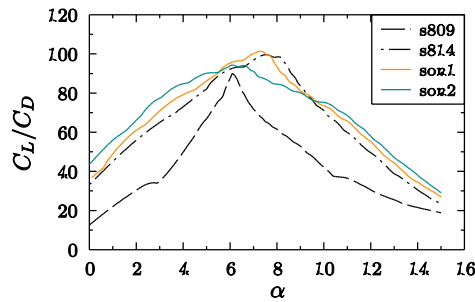


Figure 3. Efficiency parameter of the 2 optimised airfoils with respect to that of their parents.

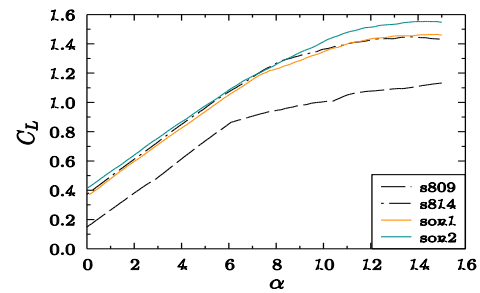


Figure 4. Lift coefficient of the 2 optimised airfoils with respect to that of their parents.

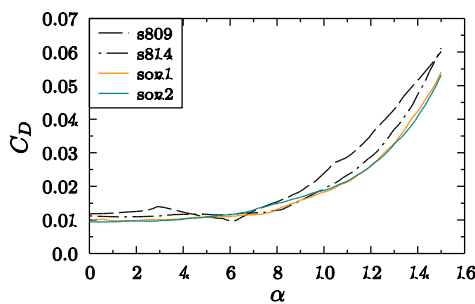


Figure 5. Drag coefficient of the 2 optimised airfoils with respect to that of their parents.

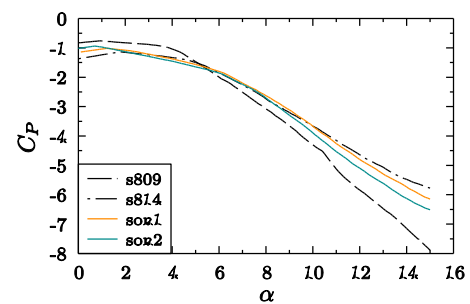


Figure 6. Pressure coefficient of the 2 optimised airfoils with respect to that of their parents.

4. Conclusions

From the two specially-designed wind turbine initial airfoils (optimal to be driven by a 100,000 Re flow), we executed 10 generations of son-airfoils in order to observe improvements in the aerodynamics of optimised airfoils. With the proposed genetic crossover rule, as early as in the tenth generation we found son-airfoils which perform better in the low angle of attack range, as can be observed from figures 3 to 6; despite son1 have a max aerodynamic efficiency greater than both parents, in the range $0 \leq \alpha \leq 6$ the performance of son2 is better than both son1 and the original parents. At this stage, son1 and son2 are the best sons of tenth generation, which already possess superior aerodynamic features for their applications on wind turbines at low Reynolds numbers as those of Mexico City. To obtain optimised airfoils with just 10 iterations is something remarkable, as other genetic algorithms report improvements only with many more iterations [22, 23], saving computing time just by taking suitably the set of parent-airfoils. It is also remarkable to be able to drive an AO process with mono-CPU programming technique. Further research on the parallel implementation of this algorithm must be conducted in order to increase the sets, both of parent-airfoils as well as of functions to augment the crossing-over possibilities so to explore a wider space of solutions to the AO problem.

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