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Multi-Objective Sizing Design Optimization of an Airfoil via Genetic Algorithms

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Abstract. One of the problems with optimization in aeronautical engineering, with various formulations, refers to searching for the best airfoil geometric shapes to reach countless objectives for several finalities. Between the formulations of these optimization problems, there are single and multiple objective problems. The multi-objective optimization generally contains conflicting objectives. The final solutions generate a Pareto curve that will enable the decision-maker to choose the one that best suits their expectations. In this work, the formulation and solution to the problem of multi-objective optimization of a beam with an airfoil as a cross-section with two conflicting objectives are presented. The maximization of the first mode of natural frequency of vibration and the minimization of the airfoil structural weight are the conflicting objective functions. The maximization of the first mode of natural frequency aims to avoid resonance problems with possible loads and minimize the weight, for an efficient airfoil. The airfoil is modeled in 2 dimensions, and the variable in the project is the thickness of the cross-section. To solve the optimization problem, it is used the MOGA - Multi-objective Optimization Genetic Algorithm, available in the software ANSYS®. The model developed and its complexity is presented, obtaining interesting results, and the desired expectations.

Keywords: Airfoils, Multi-Objective Optimization, Genetic Algorithms.

1 Introduction

Optimization techniques reach more and more space with the advent of more powerful computers. One of the areas that most involves optimization processes is aeronautic, in the fields of aerodynamics, control, and aeroelasticity, as shown in Deshmukh and Collopy [1], Caixeta Jr. [2] and Marinus [3]. There is also a demand for studies on wind turbines, a clean and renewable form of energy, which still needs efficiency improvements [4]. Satisfying the constraints in these areas describes highly complex problems, being the constant alternative to the solution by using multi-objective optimization. This technique presents expressive results for problems with conflicting objectives, as in this work is presented, which aims to explore the structural limits of an aerofoil. The study's motivation was due to the urging for larger structures that demand less consumption of resources, such as aircraft aerofoils and wind turbines.

There are dozens of variables that allow the structural optimization of an airfoil (i.e., shape, material, type of manufacture, weight relief, etc.), as shown in Mukesh et al. [5] and Molinari et al. [6]. The optimization techniques are comprehensive, many of them based on mono and multi-objective genetic algorithms and topological optimization.

The MOGA is used as a technique, which deals with highly complex problems. The work seeks to optimize two essential design variables to the design of aerodynamics surfaces: the first natural frequency of vibration and structural weight. The maximization of the natural frequency is aimed at avoiding problems of large loads at high speeds, and the weight must be minimized to increase the structural efficiency of the equipment and reduce manufacturing costs. However, these are conflicting objectives, which lead to the problem being treated as multi-objective. As a design variable, the thickness of the model's cross-section was used.

The modal analysis available in the software was used to find the natural vibration frequencies of the system. Suppose the frequency of the structure reaches the natural vibration frequency. In that case, the system's amplitude of response reaches an extremely high-value Clough [7], resulting in high values of displacement that could damage the structure. This is the reason why it is desired to maximize these frequencies. In this study, the first natural frequency was chosen as the parameter.

The model was chosen based on a widely studied airfoil belonging to the National Renewable Energy Laboratory - NREL, the NREL 5 MW Base Wind Turbine [8].

The paper is organized as follows: Section 2 defines multi-objective optimization, focusing on MOGA; in section 3, the algorithm operation in ANSYS® and the model developed are exposed; section 4 discusses the numerical results; ending in section 5 with the conclusion and future work.

2 Multi-objective Genetic Algorithm

Genetic algorithms are the most used bio-inspired metaheuristics for optimization. They are part of the stochastic algorithms and are based on Darwin's evolutionary theory. Arora [9] describes the main terms associated with the problem as follows:

- Population. Represents a group of possible initial solutions generated randomly, and that explore the entire search space.
- Generation. Describe the iteration of the procedure, each generation a population of defined size is developed.
- Chromosome. This term is used to describe a candidate solution, feasible or not.
- Gene. Represents the value of a design variable.

2.1 Multi-objective optimization

Arora [9] describes multi-objective optimization as being the following:

$$f(x) = (f_1(x), f_2(x), ..., f_k(x)), \tag{1}$$

subject to

$$h_i(x) = 0; i = 1 \ to \ p \tag{2}$$

and

$$g_j(x) \leq 0; j = 1 \ to \ m, \tag{3}$$

where k is the number of objective functions, p is the number of equality constraints $h_i(x)$ and m is the number of inequality constraints $g_j(x)$. The function $f(x)$ is a vector of feasible solutions that respect the constraints. Compared to a single-objective problem, determining and global maximum point for this problem is usually more complex. In most cases, the minimum point of $f_1(x)$ does not allow the minimization of $f_2(x)$, making it impossible to choose an ideological point, such as all minimized functions.

2.2 Pareto optimality

The most common concept for solving multi-objective optimization problems is *Pareto Optimality*. A point x^* belonging to the feasible sample space is called the Pareto optimal point if there is no other point x that reduces at least one objective function without increasing another one. It can be described as follows:

$$f(x) \leq f(x^*) \tag{4}$$

with at least one

$$f_i(x) \leq f_i(x^*). \tag{5}$$

When there are only two objective functions, the minimum points of each one define the endpoints of the Pareto curve, if there are minimums. In this situation, Pareto's condition explores the limits of the search space, given the non-dominated solutions between these endpoints.

The Pareto optimization concept applied to MOGA determines which potential solutions (i.e., non-dominated solutions) can be identified to evaluate the solutions. In this paper, a GA is used to evaluate each candidate solution demanding a simulator. To do that, the ANSYS® was used in this paper.

3 Analysis Description

3.1 Geometry

The geometry used in this study is a section of the NREL 5 MW Base Wind Turbine. The model has varying cross-sections with the airfoils DU30 and DU35 airfoils depicted in Figure 1.

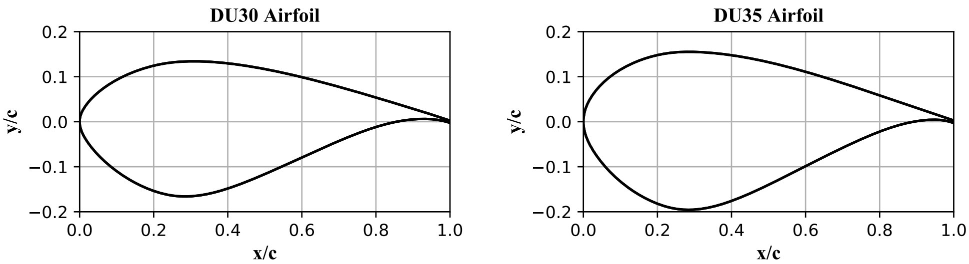

Figure 1. Airfoil cross-sections coordinates in ratio of chord

Each cross-section is equally distanced and has a different airfoil chord and twist angle. The airfoils are aligned considering a straight line going through the each airfoils' aerodynamic center, considered to be at 25% of the chord-line starting at the leading edge. For this analysis, similar to a cantilever beam, a fixed support was applied along the first airfoil curve, as displayed below. The airfoil was modeled as a hollowed shell, as illustrated in Figure 2.

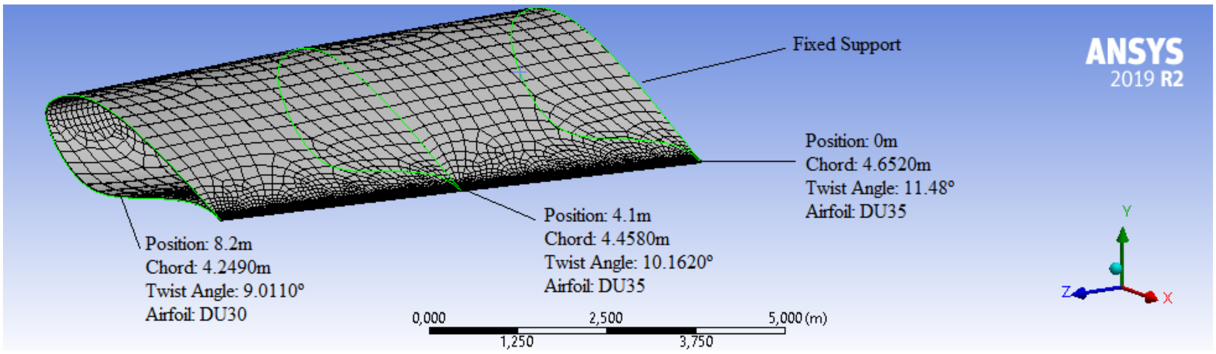

Figure 2. Model displayed in ANSYS® with geometry description

3.2 Mesh and material properties

Table 1. Material properties

Property	Value	Unit
Density	79.644	$kg.m^{-3}$
Young's Modulus	710.56	MPa
Poisson's Ratio	0.3	-

For the modal analysis, a mesh consisted of quadrangular and triangular elements was generated by the program, with an element size of 0.3 m. This results in a number of 38250 elements and 37569 nodes.

An isotropic material was considered in this study based on this blade's section properties described by Jonkman et al. [8]. The material properties necessary for the modal analysis are presented in Table 1.

3.3 ANSYS® procedure

To illustrate how MOGA works in ANSYS®, the flowchart of Fig. 3 was developed. MOGA was chosen from the available optimization options, and the settings were adjusted to the desired parameters, as shown in Fig. 2.

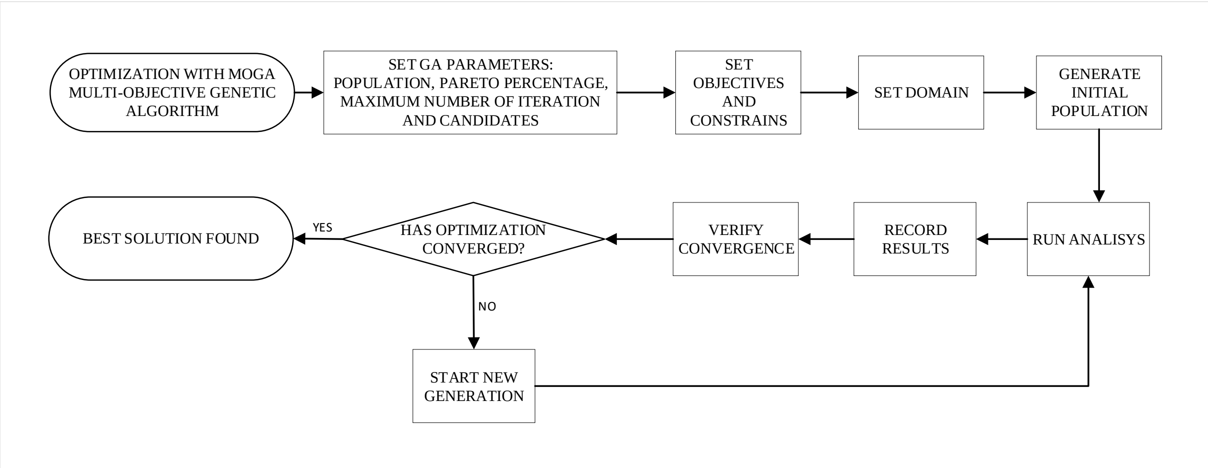

Figure 3. MOGA procedure flowchart

The GA parameters were adjusted according to Table 2. The Maximum Allowable Pareto Percentage measures the rate of the number of Pareto points per iteration, relative to the number of models, and the Convergence Stability Percentage refers to the percentage of the population considered stable.

Table 2. Parameters used in the analyzes

Optimization terms	Value
Number of Initial Solutions	350
Number of Samples per Iteration	100
Maximum Allowable Pareto Percentage	70
Convergence Stability Percentage	2

4 Numerical Results

The conflicting objectives between aerofoil weight and the first natural frequency of vibration were investigated in this paper. For this, the thickness of the cross-section was used as a design variable. The thickness of the shell was allowed to vary from 0.01 to 0.3 m. The obtained Pareto curve is shown in Figure 4.

Figure 4 shows the maximum frequency happens close to the 0.10 m thickness. Based on the results, it can be observed that the results found was according to the expectations for this study, showing that, based on structural dynamics, the thickness of the cross-section has an, at least, an attractive local optimal value. After reaching convergence, the software was considered the best candidate to be a 0.087786 m thick shell, with the first natural frequency of vibration of 9.8177 Hz.

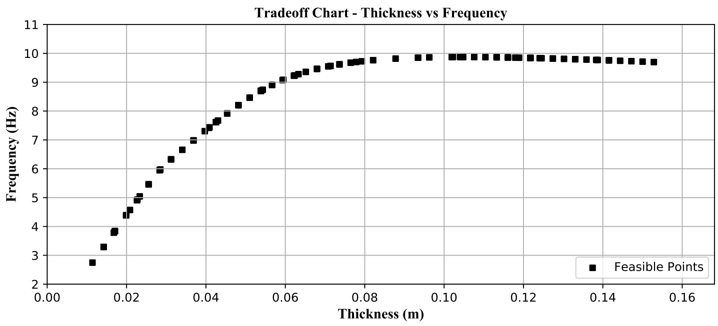

Figure 4. Pareto curve obtained for the optimization process

5 Conclusions

The potential for conducting structural analyzes using MOGA was discussed in this study. ANSYS ® software was chosen because it can model and analyze complex geometries such as, for instance, the cross-section of a aerofoil presented in this paper. Modal analysis is fundamental in the design of large structures to prevent mechanical damages. It is important to remark that it was possible to speed up the time for modeling and solve the multi-objective optimization problem addressed here, without losing quality, using the shell model. From the results presented in this paper, it is possible to conclude that the work was within expectations.

5.1 Future works

This work was the beginning of the search for aeronautical and wind aerofoils optimization considering dynamic structures. In future works, the model of a complete blade will be used with a cross-section of variable thickness and displacement constraints.

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