Aerodynamic design using genetic algorithms and application to rotor blades

D.G. Mourikis[1], V.A. Riziotis[1], S.G. Voutsinas[1]

Summary

Modern design strategies in aeronautics tend to incorporate into one compound procedure several aspects which in the past were considered separately, as for example aerodynamic performance, structural integrity and noise control. This is a direct consequence of the need for accelerating the time required up to commercialization of a new design concept. In this connection standard design tools based on differential optimization methods risk to fail either because they cannot treat in a uniform way different physical processes, or because during optimization they are trapped to local maxima (or minima). In this respect genetic algorithms offer a sensible way-out. They mimic the "optimization" procedure nature is using to constantly improve living species. Such an approach has been used in the aerodynamic design of airfoils and rotor blades under different kind of design requirements and constraints. The present paper provides a concise account of the design methodology and some representative results.

A brief account on GAs [1]

The basic characteristic of Genetic Algorithms (GA's) is their ability to locate the global optimum of a function if this exists. Populations of individuals (candidate solutions) evolve according to laws of natural selection, i.e. the individuals compete with each other and the best (fittest) gives a larger number of offspring in the next generation. Through simulated natural processes (parent selection, genetic crossover, mutation) the "fitter" children survive in successive generations while the "less fit" are led to extinction. In this way, the most favorable regions of the whole solution domain are investigated using the knowledge of previous solutions. Taking as example the design of an airfoil, a solution will correspond to an admissible profile shape. This means that given the geometry of the airfoil and the operational conditions (e.g. range of angles of attack, range of operational Ma and Re numbers) the model flow equations are solved and the set of exclusive constraints are fulfilled in order to accept a profile as admissible. Crossover and mutation will refer to the defining parameters of the profile, whereas parent selection will involve the evaluation of each solution against optimization in terms of an objective function (e.g. the drag integral over the range of operation).

The set of parameters that define a solution, are the design variables of the optimization algorithm. Crossover and mutation are carried out for each design variable

[1] National Technical University of Athens, School of Mechanical Engineering, Dept. of Fluids

by means of properly defined operators. Let *phusb* and *pwife* be the values of a design variable of the first and second parent respectively. Then for their child, the value of this variable will be given by the following crossover operator:

$$child = 0.5R_1\underbrace{(phusb + pwife)}_{P_m} + 0.5R_0\underbrace{|phusb - pwife|}_{P_d}, \quad R_1 = 1 + R_0 \cdot \sigma,\ R_0 = 1 - 2r,\ \sigma \approx 0.1 \qquad (1)$$

R_1 and R_0 are functions defining the range of variation of the parental characteristics, σ is the percentage of variation around 1 and r is a random range variable in [0,1].

Next as regards mutation, let $x=(x_1,\ldots,x_k,\ldots,x_n)$ be an offspring of n design variables. If variable x_k is chosen for mutation, then the offspring becomes $x_{mut}=(x_1,\ldots,x_{kmut},\ldots,x_n)$ where:

$$x_{kmut} = \begin{cases} x_k + \Delta\big(igen, UB(k) - x_k\big) & r < \dfrac{P_{mut}}{2} \\ x_k - \Delta\big(igen, x_k - LB(k)\big) & r > 1 - \dfrac{P_{mut}}{2} \end{cases} \qquad \Delta(igen, y) = y \cdot r \cdot \left(1 - \frac{igen}{mgen}\right)^b \qquad (2)$$

P_{mut} is the probability of mutation. Function Δ(*igen*,y) returns a value in the range [0,y] such that the probability of Δ(*igen*,y) being close to 0 increases as *igen* increases (*igen* is the generation index). This property causes the operator to initially search the domain of definition uniformly (when *igen* is small) and locally at later stages. In (2) *mgen* is the maximum number of generations and *b* (=5) is a system parameter determining the degree of non-uniformity. The crossover and mutation operators are illustrated in Fig. 1. The dark shaded area shows the effect of the crossover operator while the light shaded area shows the contribution of mutation.

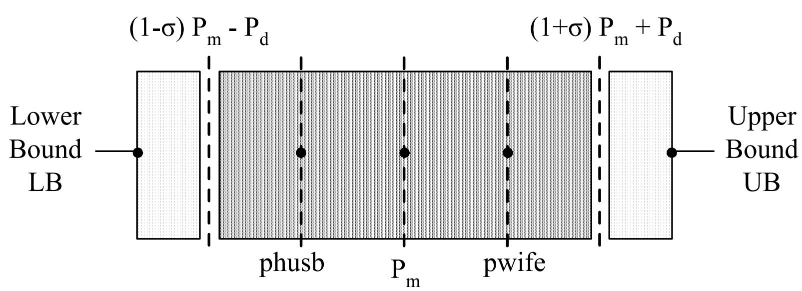

Figure 1: Genetic operators

GA's and aerodynamic design

<u>Parameterization:</u> In most cases, aerodynamic design concerns airfoils and wings either fixed or rotating. In this respect, a quite important aspect is the geometrical description or parameterization. For airfoils this is done by means of polynomials which

either follows the specific shape characteristics or use general purpose families of functions. In the first class a quite general parameterization is defined by the Parsec polynomials whereas in the second class usually b-splines are used.

Parsec polynomials parameterize the upper and lower airfoil surfaces in x,y coordinates as in (3) where α_k are real coefficients. Instead of taking these coefficients as design variables, the parsec airfoils are defined through six basic geometric parameters (degrees of freedom) for each side of the airfoil: the leading edge radius, the crest location including curvature, the trailing edge y ordinate and the wedge angle and thickness as shown in Fig. 2.

$$y(x) = \sum_{k=1}^{6} a_k \cdot x^{k-\frac{1}{2}} \quad (3)$$

The b-spline curves are defined by (4) where *p(s)* is the position vector of a point along the curve, given as a function of the arc-length s, b_i are the position vectors of the n+1 vertices of a defining polygon (Fig 3) and N_i^k are normalized basis functions of order k, $2 \le k \le n+1$, defined by the Cox-de Boor recursion formula [1]. The main advantage of b-spline curves is their flexibility in treating local geometry changes. For example, it is possible to keep unchanged the leading region of an airfoil while allowing changes in the rear part of the airfoil and vice-versa.

$$\mathbf{p}(s) = \sum_{i=1}^{n+1} \mathbf{b_i} N_i^k(s) \quad (4)$$

For wings and blades, the parameterization concerns the chord and twist distribution as well as the span-wise distribution of the profile shape. The last is usually realized by defining an appropriate data-base with a search-engine which at every radial station will restrict the selection over a subset of the complete data-base. If structural integrity is part of the design procedure, the natural choice is to use the relative thickness in order to define the search engine.

<u>Constrains:</u> There are several types of constraints. Clearly some acceptability criterion for the shape is necessary. Thus shapes with multiple changes of curvature are discarded. Then “operational” constraints could be necessary. For example when considering the design of blades and structural integrity is included, the maximum normal loading must be limited. Another example of aerodynamic constraint concerns the position of the transition point which is critical if the range of angles of attack will approach (or even exceed) the stall limit. In such cases the appearance of a laminar bubble will deteriorate the aerodynamic performance. Quite easily one can add more complicated constraints such as the sectional rigidity, or even the noise footprint. In such cases it is necessary to solve not only the flow equations but also the equations that describe the structural or the acoustic performance of the design.

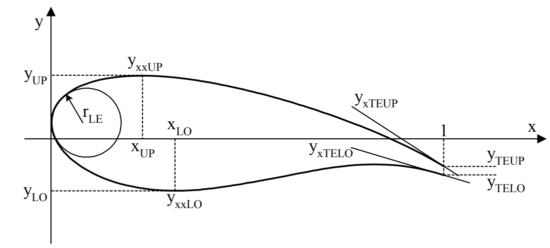

Figure 2: Design variables for the parsec parameterization

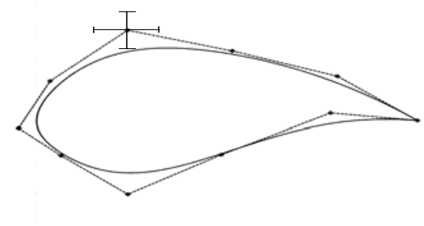

Figure 3: Airfoil parameterization with b-spline curves

Cost function: The cost function depends on the application considered. For fixed wings and blades used for generating thrust, it is important to minimize the drag penalty. Let W(.) denote a probability distribution function defined over the range of operational conditions (e.g. the angles of attack). So for a fixed wing the cost function will be the W-weighted integral of the drag force, whereas for a rotor blade the W-weighted integral of the rotorshaft torque (or power). The above examples of cost functions are purely aerodynamic. In case the design also involves other physical aspects such as structural flexibility or noise it is possible to define compound cost functions. For example if aerodynamic performance and structural design must be combined, then the cost function would have two terms, one for each contributing mechanism (with an appropriate normalization). Of course there is always the option of including some aspects of the optimization in the form of constraints.

The flow solvers: A very important property of GA's is that the whole procedure will solve a large number the equations describing the physical mechanisms considered. This means that the corresponding solvers cannot be very sophisticated. For the flow over 2D airfoils, a good choice is to use boundary layer approximations. A flow solver has been developed based on the strong viscous-inviscid interaction coupling first introduced by Drela [2]. In order to also include stalled situation, the model was extended to fully separated flows based on the double-wake concept [3], resulting the FOIL2W code. The code is fast and robust and provides good predictions for the lift and drag even in post stall conditions. As regards the structural part, thin-wall theory was used to define a code that provides the structural properties of a profile [4]. Again the computational cost is very low. Finally as regards noise, Ffowcs-Williams Hawking's equation is used [5]. For rotor blades, the simplest aerodynamic model is the one based on actuator disk theory. In this connection every radial station is independently considered. Its application will provide the range of effective angles of attack to be input in the design of airfoils [6]. The next model in increasing complexity is the lifting line model, which will also provide the range of angles of attack but now the different radial stations are no longer independently treated.

Results

The first example concerns the design of an 18% thick airfoil at Re=2 10^6. The performance of the optimized profile is compared with the NACA63418 airfoil in Fig 4 in case the flow is assumed fully tripped. This specific airfoil was designed for a wind turbine targeting maximum power extraction over the complete range of inflow velocities (usually ranging from 4-25m/s). The corresponding range of angles of attack will exceed stall, and so the aim is two fold: maintain high lift values and decrease drag. The improvement is clear: both targets are met. Also important is the post stall behavior of the optimized profile. Separation will start at 8deg but drop in lift will not occur up-to 20deg. This suggests a good behavior in dynamic stall.

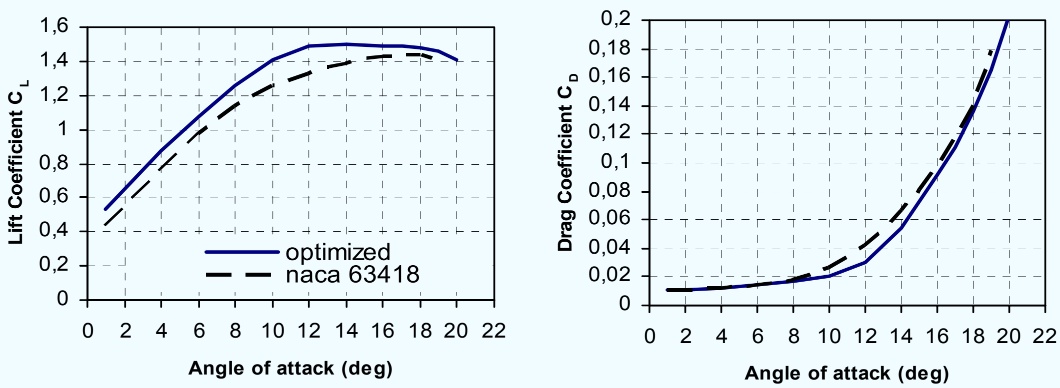

Figure 4: Lift and drag curves of an 18% thick airfoil: comparison with NACA63418

Next the design of a blade is considered for which a complete data-base of airfoils was used. The data base is indexed with respect to relative thickness, Re number and range of operational angles of attack. This last point is important if the rotor is pitchable (in this case the pitch can be a design variable possibly depending on constraints related to the trim over the range of operation considered). This particular case again concerns a wind turbine. The optimization aimed at improving the performance of an existing machine equipped with blades formed with NACA 6_series airfoils. It is noted that the particular blade is one of the best in the market. Fig 5 shows the improvement in power extraction as compared to the existing one for two different pitch settings. Constraints to the design process were the maximum load at blade root, the length of the blade, the plan form area and the weight. The plan form area was used as an indicator of the cost of the blade, whereas the weight was an important parameter for the overall dynamics of the machine.

Concluding remarks

Genetic algorithms offer a sound and flexible basis for interdisciplinary design procedures. Their main advantage is that they combine very different mechanisms in a unified context offering the possibility of obtaining global solutions. Their main drawback is the large number of iterations, which prohibit the use of sophisticated models. Fortunately in aerodynamic design simple but still reliable flow solvers are available.

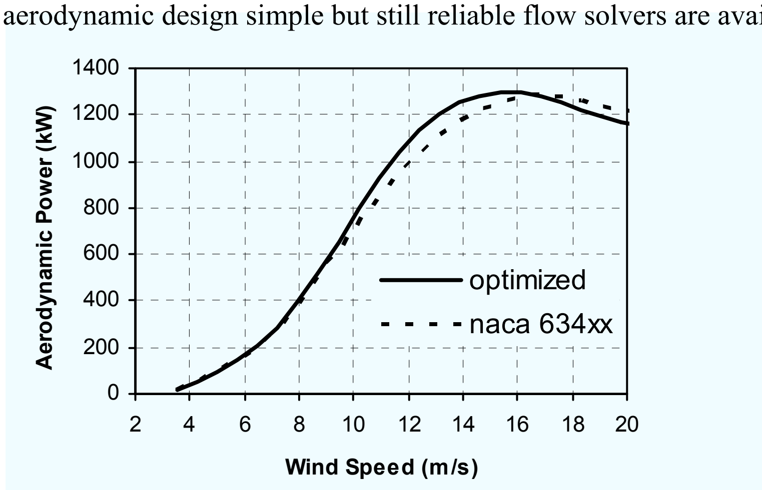

Figure 5: Comparison of an optimized and existing wind turbine blade

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