Optimization of Laminar Wings for *Pro-Green* Aircrafts

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Abstract

This work falls within the scope of aerodynamic design of *pro-green* aircraft, where the use of wings with higher aspect ratio and lower sweep angle than that usually employed in conventional configurations provides an opportunity to reduce the aerodynamic drag and, therefore, the emission of gases to the atmosphere. The objective is to optimize the shape of a wing with these characteristics, operating under transonic speeds. The Spalart-Allmaras model, the C_1 criterion and the genetic algorithm have been chosen as turbulence model, laminar-turbulent transition prediction method and optimization method, respectively. The latter is based on natural selection as an optimization process and it was applied to establish successive populations of candidate wing shapes.

Introduction

Over the past few years there has been a clear trend in industry towards more complex products spanning over several engineering domains. Simultaneously, there is a pressure on developing products faster, at competitive prices, and to a high quality standard. The aerospace industry, of course, is not an exception. It was with this intent that a group of personalities developed a set of measures to be taken in the future aiming to make aircrafts more efficient. This set of measures is compiled in the document Vision 2020 [5], which addresses, among other issues, some future challenges for areas such as quality and accessibility, safety, environment and transportation systems that will also become more efficient.

In these areas we highlight the environment and, more specifically, the reduction of the aerodynamic drag via new aircraft configurations. One of the new configurations is the so-called *pro-green* aircraft. In this configuration, the drag reduction is achieved through the use of wings with a significantly higher aspect ratio and a lower sweep angle than that usually employed in conventional configurations. The increase in aspect ratio allows a reduction of the total aerodynamic drag because the drag induced by the trailing vortex sheet also decreases [3]. The reduction in sweep angle opens an opportunity for the wing to be designed for large extensions of laminar flow. This is due to the lower occurrence of cross-flow instability in wings with smaller sweep angles. Such passive technique (based only on a geometric change) of laminar boundary layer control is called Natural Laminar Flow [NLF, 9]. In these cases, it is expected that the drag reduction can be up to 20%, leading to lower fuel consumption and, therefore, allowing large reductions in emissions of pollutant gases into the atmosphere.

The history of aircraft development has involved significant efforts to reduce the drag of an aircraft in order to minimize the amount of fuel burnt. The configurations that have been developed along with the major advances in design tools, such as Computational Fluid Dynamics (CFD), have lead to highly optimized designs. An example of these aircraft configurations based on the characteristics referred above is the new so-called High Aspect Ratio Low Sweep (HARLS) configuration. For this configuration, preliminary calculations have shown that the wing profile drag could be reduced by about 15%, corresponding to a reduction in fuel consumption of approximately 12% when compared to a more conventional configuration. As fuel costs can be up to 30% of aircraft direct operating costs, such a reduction in fuel burn will lead to significantly better, more cost effective aircraft.

Despite all the advantages associated with the HARLS configuration, there are other aerodynamic issues that are restrictive in the design process. One of such limitations relates to the structural constraints associated to wings with a higher aspect ratio. These wings are more susceptible, among others, to the occurrence of static and dynamic aeroelastic phenomena, such as divergence and flutter, respectively, which may eventually cause structural failure [11]. As a consequence, to operate at high subsonic speeds these wings cannot be too thin, which is a desirable characteristic to minimize the occurrence of shock waves and its corresponding wave drag. Hence, a trade-off is needed between aerodynamic and structural studies. In fact, the whole project of an aircraft is a trade-off!

Statement of the Problem

This work is based on the approach described above. Thus, our main objective is to optimize a wing with the characteristics presented by the HARLS configuration, i.e., a wing with high aspect ratio and low sweep angle. From the outset, it was known that the reference wing geometry was already fairly well optimized to operate in similar conditions to that of the conventional transport aircraft. For the design conditions, the wing operates in transonic regime, with a cruise speed corresponding to a Mach number of 0.74 and a cruise altitude yielding a Reynolds number of 20 million. The design value of the lift coefficient is relatively high, equal to 0.72. Such high lift coefficient is also characteristic of a HARLS configuration and it is due to the reduced area of the main lifting surfaces, i.e. the wings. The reference wing has a sweep angle of 19 degrees. As the wing to be optimized presents a high aspect ratio, the “infinite” swept wing approach is considered. The thickness of the reference wing is equal to 11.7% of the chord, relatively thin, as intended. The optimization process aims to reduce the aerodynamic drag of the reference wing for the prescribed lift coefficient and cruise conditions.

Note also that the CFD simulations required by the optimization process are carried out with the use of the commercial program FLUENT [6].

Methodology

- Turbulence Modeling

In this work, due to the computational limitations and the high value of the Reynolds number, the methodology used for the calculation of turbulent flow regions was the numerical solution of the Reynolds-Averaged Navier-Stokes [RANS, 3]. Thus, a turbulence model based on this methodology must be chosen to obtain the closure of the governing system of equations. Among the existing models, the Spalart-Allmaras turbulence model was selected. This model implements the one-equation approach to the closure, which is less complex and therefore computationally less expensive than classical two-equation and Reynolds-stress models (five equations). In addition, the fact that this model was originally developed for aerospace applications was also an important factor in its choice.

- Prediction of the Laminar-Turbulent Transition

The transition in infinite swept wings occurs mainly via two mechanisms. The first mechanism is due to flow instabilities in the direction of the velocity vector external to the boundary layer. These instabilities are due to the appearance of disturbances in the form of a two-dimensional harmonic wave known as Tollmien-Schlichting wave [3]. The second mechanism is due to flow instabilities in the transverse direction to the external velocity vector. A feature of the latter mechanism is that the transverse velocity profile intrinsically presents an inflexion point, making it inherently unstable. As a consequence, the transition process can also be triggered by harmonic waves propagating in a transverse direction to the external flow. This type of flow instability in three-dimensional boundary layers is called cross-flow instability [3].

Due to the computational limitations involved in the present work, an empirical method for the calculation of the transition from laminar to turbulent flow was chosen, namely the C_1 criterion [1]. This criterion only predicts transition due to cross-flow instability, thus, by adopting it, the hypothesis of transition by Tollmien-Schlichting instability is excluded. In this work, where the calculations focus on swept wings defined by laminar airfoils (characterized by large flow extensions subjected to a favourable pressure gradient), this is an acceptable hypothesis, as transition due to Tollmien-Schlichting instability generally occurs when the flow is subjected to mildly adverse or zero pressure gradients. Therefore, it is likely that the leading transition mechanism present in the configurations studied is, in fact, cross-flow instability.

For an accurate application of the C_1 criterion, it is desirable to calculate the velocity profiles of the laminar boundary layer. To achieve this purpose, the corresponding RANS pressure distribution (less sensitive to the high resolution required by the numerical calculation of a three-dimensional boundary layer at high Reynolds numbers) was used in an intermediate calculation of the laminar boundary layer profiles. For this calculation, a program originally developed by Kalle Kaups and Tuncer Cebeci [10] was used.

- Numerical Methods and Computational Mesh

The numerical method chosen for solving the RANS equations in the commercial program FLUENT was the "density-based" method based on an implicit formulation. This method was specifically developed for compressible flows. So, the choice of this numerical method was due primarily to the fact that the simulations carried out in this work were in the compressible regime (coupled equations). One could state that the "pressure-based" method was also a credible alternative for compressible flow calculations, using the "coupled" algorithm. Though this is known to be true, the "density-based" method has a better performance in the presence of shock waves due to the conservative form of the governing equations, which constituted an important rationale for the choice of the numerical method.

The computational mesh used in this work is a structured *C*-mesh. After several preliminary studies and a "study of mesh independence", the resolution of the mesh constructed for this work is equal to $512 \times 128 \times 1$ control volumes. The computational mesh used is illustrated in Figure 1.

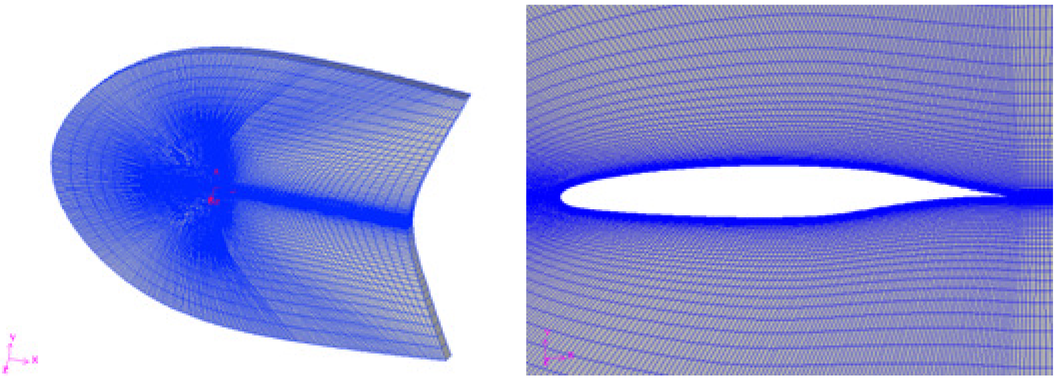

Figure 1. Computational mesh with a resolution of $512 \times 128 \times 1$ control volumes

- Optimization Methods

The optimization methods can be divided into derivative methods and non-derivative methods. The non-derivative methods are more robust in locating the global optimum and are applicable to a broader set of problems [7]. Another advantage of non-derivative methods is that they do not require the derivation of the objective function (function to maximize or minimize in an optimization process) in order to find the optimal solution of the problem. In this study, it was deemed that the optimization method to be used should belong to the class of non-derivative methods, because the objective function is not a continuous function, thus preventing the immediate application of the derivative methods. The objective function chosen for this work was the lift-to-drag ratio and, of course, the objective was to maximize it. The non-derivative method selected for this work was the genetic algorithm [8], due to its increasing popularity in the aerodynamic optimization. Furthermore, the genetic algorithm presents greater robustness in locating the global optimum of the problem, when compared to other methods, such as the complex method [2].

In short, genetic algorithms are modelled by mechanisms of natural selection based on the evolutionary theory of Darwin [4]. Each optimization parameter is encoded by a *gene*, using an appropriate representation, such as a real number or a sequence of bits. The genes corresponding to all parameters form a *chromosome* which describes a single possible solution, usually called by *individual*. A set of chromosomes form a *population*, where individuals are evaluated by a *fitness function* to select, as the name implies, the fittest (*parents*) in order to mate and generate the new individuals (*offspring*). The generation of new individuals is performed through crossover and mutation of the parents' genes. The offspring forms a new generation and the process resumes.

For this work, the structure chosen for the chromosome consists of five geometric parameters of the wing with significant influence on its aerodynamic characteristics. The selected geometrical parameters are as follows: $1st$ - sweep angle; $2nd$ – relative thickness, $3rd$ - position of maximum thickness, $4th$ - relative camber; $5th$ - position of maximum camber. The specific values considered here for each of these parameters (in percent of chord where applicable) are written below in the same order they were presented above:

$\mathbf{1st}$	$\mathbf{2nd}$	$\mathbf{3rd}$	$\mathbf{4th}$	$\mathbf{5th}$
$1 - 16\ degrees$	$1 - 10.7\%$	$1 - 40\%$	$1 - 1.78\%$	$1 - 69\%$
$2 - 19\ degrees$	$2 - 11.7\%$	$2 - 44\%$	$2 - 2.28\%$	$2 - 71\%$
$3 - 22\ degrees$	$3 - 12.7\%$	$3 - 48\%$	$3 - 2.78\%$	$3 - 73\%$
		$4 - 52\%$		$4 - 76\%$

The selected ranges vary around the parameters characterising the reference wing (represented by the chromosome 2 2 2 1 2). It should also be noted that the deviations from the reference geometry are not very high. This decision is justified by the fact that the reference wing is known to be already designed for the flight conditions under consideration, as concluded in the preliminary study (carried out in this work) of its basic aerodynamic characteristics. Another constraint on the choice of these values is placed within the context of structural studies and refers to the choice of the values of the relative thickness of the wing section. For this reason, the deviation from the reference value (11.7%) is only ± 1%.

In the implementation of the genetic algorithm, an initial population of 23 wings and subsequent generations of 10 wings were considered. The chosen fitness function is the difference between the ratio $L/_D$ (L is the lift and D stands for the aerodynamic drag) of the evaluated wing (identified by index i) and a (lower) close value of the minimum ratio $L/_D$ (identified by C_{min}) present in the generation where the evaluated wing is inserted, as follows:

$$f_{fitness_i} = \left(L/_D\right)_i - C_{min} \qquad (1)$$

Results and Discussion

After the completion of the optimization process, it was concluded that for a relative thickness of 12.7%, the values of the drag coefficient are much higher than those observed for the reference wing. Hence, wings presenting this feature did not generate any offspring past the first generation. In addition, for a fixed relative thickness of 11.7%, the maximum reduction in the drag coefficient was about 3%. This result clearly indicates that the reference wing was already fairly well optimized, with respect to the geometrical parameters chosen to be optimized here. This conclusion is also supported by the deductions taken from the preliminary study of the influence of the geometrical parameters on the aerodynamic characteristics of the wing, carried out in this work as well. From this study, it was concluded that the optimum value for the position of maximum thickness was 44% of chord (corresponding to the value presented by the reference wing). Concerning camber, the optimum value reached by the optimization procedure was 1.78% of chord (again the value displayed by the reference wing). Regarding the position of the maximum camber an optimum value could not be found so explicitly. However, it was concluded that its influence on the drag values of the wing was not very strong (especially for values higher than that presented by the reference wing). With respect to sweep angle, it was also concluded that the gain in total drag obtained by the prescribed variation was not very significant. Based on these observations, it was deduced that the geometrical parameter (from the set of parameters selected for the optimization process) showing greater influence on the drag values was the relative thickness. In fact, it was shown that by reducing the thickness of the reference wing by just 1% of chord (to 10.7%), a set of wings presenting an aerodynamic behaviour clearly better than the reference wing could be obtained. This set of wings also exhibits a better aerodynamic performance in the operating conditions of interest than the set of wings characterized by a relative thickness of 11.7%.

Wing	C_D	**Transition Upper surface,** x/c	**Transition Lower surface,** x/c
32214	0.00817	0.33	0.22
32213	0.00819	0.33	0.21
32212	0.00829	0.32	0.22
22212	0.00845	0.30	0.30

Table 1. Aerodynamic characteristics of the three “best” wings with a relative thickness of 11.7% and the reference wing 22212

Wing	C_D	Transition Upper surface, x/c	Transition Lower surface, x/c
21212	0.00711	0.48	0.32
21214	0.00717	0.42	0.33
21213	0.00721	0.42	0.32
11212	0.00736	0.41	0.43
11213	0.00741	0.38	0.44
22212	0.00845	0.30	0.30

Table 2. Aerodynamic characteristics of the five "best" laminar wings with a relative thickness of 10.7% and the reference wing 22212

The basic data obtained for the "best" laminar wings with relative thicknesses of 11.7% and 10.7% given in Tables 1 and 2, respectively, seems to indicate that wings showing larger laminar flow extensions on the upper surface present lower values of drag coefficient (C_D). Not underestimating the influence of shock waves (wave drag contribution to total drag) and the positions of the transition point on the lower surface, it was concluded that the laminar extension on the upper surface plays a dominant role in the aerodynamic optimization of these wings.

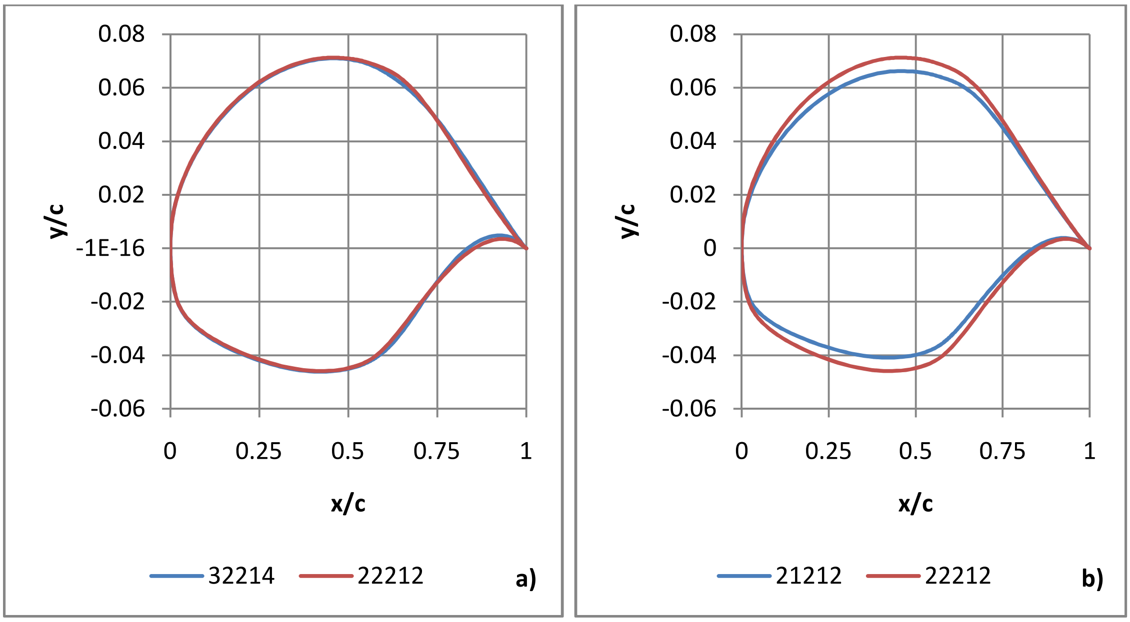

Figure 2. Wing sections showing better aerodynamic behaviour for relative thicknesses of 11.7% (a) and 10.7% (b)

In short, at the end of this study, a set of wings with relative thickness of 11.7% showing drag coefficients lower than that presented by the reference wing (Table 1) was obtained. However, the maximum reduction achieved was only 3% for the wing 32214, where its section is shown in Figure 2a together with the section of the reference wing 22212. For wings with a thickness of 10.7% (Table 2), a maximum reduction of 16% in the drag coefficient was achieved, corresponding to wing 21212. Hence, this wing is considered to be the optimal solution for this optimization process. The airfoil corresponding to wing 21212 is portrayed in Figure 2b.

Conclusion

To conclude, in a structural study of the wing following the present aerodynamic study, one must take into account that by reducing the thickness of 1% of chord, a 13% reduction in the drag coefficient may be achieved (comparing the "best" wing with a relative thickness of 11.7% and the "best" wing with a relative thickness of 10.7%). However, the advantages from the thickness reduction should not be offset by the resulting loss of structural rigidity, particularly noticeable in the case of wings with high values of aspect ratio. It is thus evident that, in the choice of the wing to use, a trade-off between these two points of view is needed.

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