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COB-2021-0801 FLYING WING SHAPE MULTI-OBJECTIVE OPTIMIZATION USING GENETIC ALGORITHMS AND AVL SOFTWARE

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Abstract. *Flying wing is an aircraft with no tail, the lack of surfaces as horizontal and vertical stabilizers becomes the meeting of aerodynamic and stability requirements more difficult. In this work, the optimization of a flying wing UAVs is developed integrating a code in MATLAB with the aerodynamic software AVL. The number of variables involved in the optimization process of a flying wing is considerable, and the results not always obey proportional relations or trivial solutions, which can hinder the job of designing a UAV that needs to fulfill some purposes. So, the use of computational optimization methods is necessary to cover all possibilities and choose the best design variables configuration. The parametric model of the wing is generated via a code that allows to change dimensions and characteristics such as: span, dihedral angle, sweep angle, the chord and its position in reference to the different sections of the wing, allowing total customization of the flying wing. Aerodynamic characteristics such as wing lift and drag coefficients, and stability pitching/directional moment coefficients are extracted and utilized to be part of the fitness functions of a multi-objective optimization, in which the aerodynamic efficiency is maximized and both longitudinal and directional stabilities are considered. The optimization method utilized is Multi-objective Genetic Algorithm, that covers all the diverse regions of the solution space. Partial results shows a tendency of flying wing shapes similar to other flying wings found in the literature, that is, the wing geometry is like a delta wing configuration with accentuated sweep and dihedral angles. Results showed the impact of dihedral and swept angle in directional and longitudinal static stability of tailless aircraft configuration and the efficiency of NSGA II algorithm in the optimization of complex engineering problems involving large number of design variables.*

Keywords: *flying wing, optimization, aerodynamic efficiency, static stability*

1. INTRODUCTION

In recent years, advances in computer technology made possible the design of aircraft by mean of the solution of optimization problems involving, frequently, multiple objectives. A typical example consists in the maximization of the lift-to-drag ratio under a predefined flight condition by modifying the airfoil shape or wing plan-form, other cases include minimizing structural weight due to applied wind load. In more complex cases, not only aerodynamic or structural disciplines are involved, Multidisciplinary Design Optimization (MDO) is required. Flying wing configuration has been considered as an ideal configuration of the future Unmanned Aerial Vehicles (UAV) due to its potential benefits over conventional configurations in stealth capability, aerodynamic performance, and structural efficiency (Pan *et al.*, 2017), its design is facilitated when using MDO's techniques.

Tailless flying wing have attracted wide interest due to the combination of wings and fuselage into a unique lifting body without horizontal or vertical stabilizers, providing more internal space and structural stiffness in comparison with conventional aircraft configurations. From the aerodynamic point of view, approximately 50% reduction of the parasitic drag coefficient can be achieved for a flying wing aircraft compared to conventional aircraft (Northrop, 1947) and Bolsunovsky *et al.* (2001) estimated an approximately 20% increase in the lift-to-drag ratio (L/D) for a large passenger flying wing aircraft compared to a conventional one. The absence of a tail introduced some directional stability issues, the conventional vertical tail surface provides directional stability and control. In a tailless configuration some additional devices are used in order to directionally control the aircraft, such as, split drag rudders, in the other hand, to design a flying wing in order to guarantee directional stability without movable parts is a challenge task. A problems associated to the lack of a vertical stabilizer in a flying wing is its low yaw stiffness and damping compared to conventional configurations (Song *et al.*, 2014), as a consequence, tailless aircraft also exhibit poor lateral dynamic stability.

According to Tyan *et al.* (2017), the absence of a horizontal tail makes longitudinal control less efficient, which does not allow the aircraft to overcome a large nose-down pitching moment generated by high-lift devices, such as slotted flaps and slats at takeoff and landing. Longitudinal stability is also affected due to the short aircraft length of flying wings when compared to the conventional aircraft configurations. Despite all the mentioned advantages as less weight and parasitic drag, more internal space, etc. instability is the negative outcome of eliminating the tail (Zadeh and Sayadi, 2018).

It is clear that optimization of a single discipline cannot guarantee the overall optimum design in a flying wing, then, in order to overcome with stability issues and maintaining a good aerodynamic performance simultaneously, the use of MDO design and optimization reveals its necessity. In this work we conduct a Multi-Objective Optimization (MOO) tacking into account the maximization of the aerodynamic coefficient and the meeting of some static longitudinal and directional stability requirements, in this case, the optimization objectives belong to different disciplines always in conflict with each other.

From the numerical modelling and computational implementation point of view, Athena Vortex Lattice (AVL) was chosen as the main software. It is a freeware, FORTRAN-based linear VLM solver written first by Drela and Youngren at MIT and is widely used for this kind of preliminary analysis of aerodynamic surfaces. The linear vortex lattice method (VLM) for predicting aerodynamic flow solutions provides a computationally efficient and reasonably accurate solution to wing models and thus is especially helpful for parametric exploration. AVL is a linear aerodynamic solver that uses the extended vortex lattice method to predict the aerodynamic characteristics of lifting surfaces (Tyan *et al.*, 2017). AVL simplifies the Navier-Stokes equations by assuming steady, attached, incompressible, non-rotational and inviscid flow (Salam and Bil, 2016). Then, it can only be used to estimate the behaviour of subsonic flows at low angles of attack in order to avoid over-predicted aerodynamics values showing good precision estimating lift coefficient under these conditions and poor accuracy to predict parasitic (skin friction) and pressure drag, as a a result, only induced drag is tacked into account. A Parametric model of the flying wing is created through the link of AVL and Matlab software. AVL has been used in a number of different design studies and experiments, and been verified as reasonably accurate (Salam and Bil, 2016). The Non-dominated Sorting Genetic Algorithm (NSGA II) was chosen as the main optimization algorithm of the present problem. NSGA II is an elitist strategy which can be used to solve a multi-objective, multi-constrained problem with mixed (discrete-continuous) design variables (Bharti *et al.*, 2006).

2. METHODOLOGY

2.1 Design variables and baseline configuration

The flying wing is composed by a unique NACA airfoil along its wingspan, the wing has three segments/sections: inner, central and outer (see figure 1). All segments are taper sections with trapezoidal planforms with tip chords x_1, x_2 and x_3, and wingspan x_4, x_5 and x_6, respectively. The six previously mentioned parameters are the first design variables of the optimization problem. It is worth to mention that neither geometric/aerodynamic twist nor incidence angle of airfoils are considered as design variables, then, they are considered as null constants.In comparison with other works as Zadeh and Sayadi (2018) and Pan *et al.* (2017) were the swept and dihedral angles of each section are constants, the present work differs by the consideration of the dihedral and swept angles of each wing section (x_7 to x_12) as design variables. It is expected high values of these last parameters in the optimized wing design due to the necessity of higher and after area to tackle with longitudinal and directional stability issues. Upper and lower parts of figure 1 show, respectively, the after and upper view of the right flying wing.

The baseline wing planform was adopted from Zadeh and Sayadi (2018), the flying wing aircraft has 4.38 m wingspan (b) a 2.44 m chord (c) and a constant swept angle of 42 degrees along all its wing sections, these parameters are fixed for analysis. From the AVL analyses using VLM method, the lift and drag coefficients of the flying wing are computed, fig. 2 shows the drag polar and lift coefficient of the baseline configuration.

The drag polar curve was created along an angle of attack (α) range between $-20°$ and $25°$. Figure 3 presents the basic static longitudinal and directional stability curves. The pitching and yawing moments are presented, the first as a function of the angle of attack previously mentioned and the last as a function of the sideslip angle (β). From this figure, it can be concluded that the flying wing is statically stable around lateral axis (longitudinally), because the pitching derivative $\frac{dC_m}{d\alpha} < 0$, but, instable regarding to yawing moment due to the directional stability derivative is $\frac{dC_n}{d\beta} < 0$.

Following and justifying the previous idea, Cook (2012) mentioned that the directional stability is stablished when the yawing moment causes the aircraft to yaw to the direction which makes the sideslip angle to be reduced to zero, that is, $\frac{dC_n}{d\beta} > 0$. In a similar way, longitudinal static stability is guaranteed when pitching moment tends to reduce angle of attack under up and down wind disturbances.

2.2 Mesh convergence study

In order to achieve a proper accuracy and reasonable time for calculations, the number of panels (elements) along the wing surface of the numerical model in AVL were varied and the aerodynamic coefficients measured. Figure 4 shows the

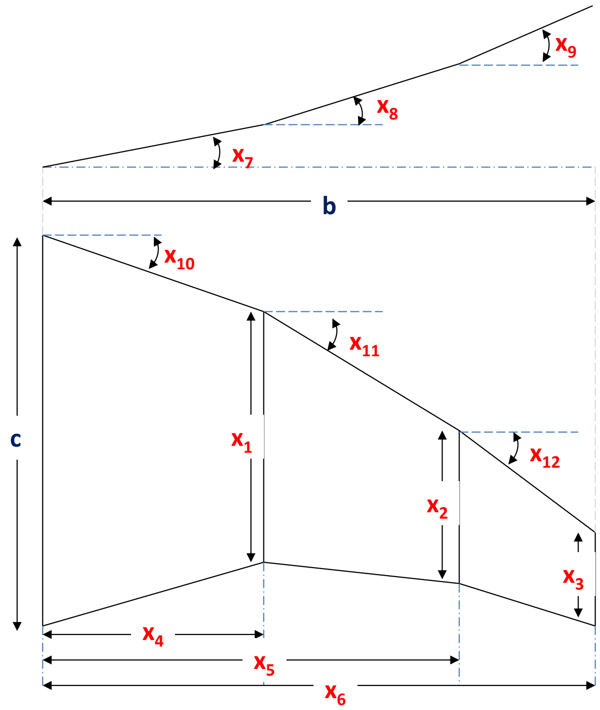

Figure 1. Flying wing planform and design variables

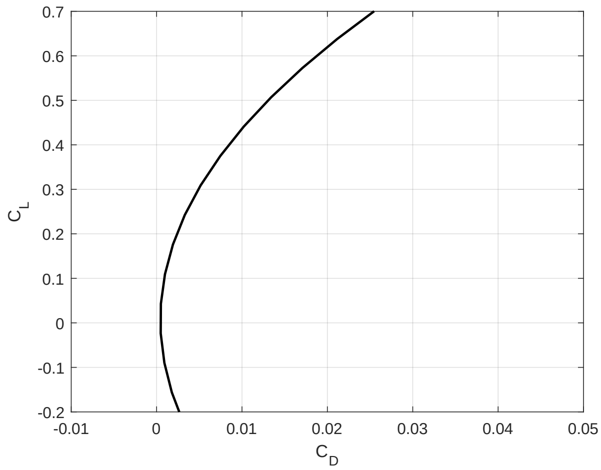

Figure 2. Drag polar of baseline configuration

mesh convergence of these parameters to the baseline configuration at $\alpha = 10$ for different numbers of elements. The mesh convergence study concluded that $n = 200$ elements are accurate enough and ensure a good resolution for the wing mesh panels, being 10 panels chordwise and 20 panels spanwise.

2.3 Methodology framework

Figure 5 illustrates the framework of the proposed optimization method for the aerodynamic and stability optimization a flying wing shape. According to this, the methodology process is partitioned into two stages. In the first stage (left blocks column), the initial wing planform geometry is parameterized and using AVL software, the numerical model is derived. The aim of the second step of first stage is the computation of the force and moments coefficients, associated to the aerodynamic and stability behaviour of the aircraft, these coefficients are: C_L, C_D, C_m and C_n. The third and final step of the first stage will be the construction of curves $C_{m\alpha}$ and $C_{n\beta}$ by varying angle of attack and sideslip angle, the objective of this step is to determine the gradients $\frac{dC_m}{d\alpha}$ and $\frac{dC_n}{d\beta}$, used as stability criteria. At second stage the objective functions to the Multi-Objective Optimization (MOO) process are created, the first one is related to the aerodynamic efficiency and the second with to some static stability criteria (more details will b given at next section). Then, the configuration of the NSGAII optimization algorithm is defined, elitism, population and generation number are the main

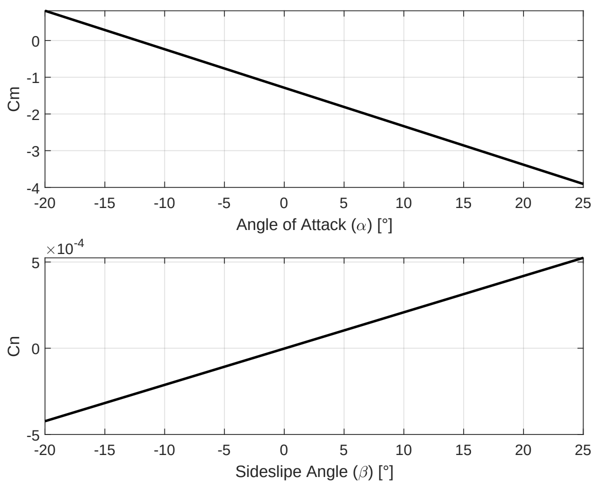

Figure 3. Static stability curves of baseline configuration

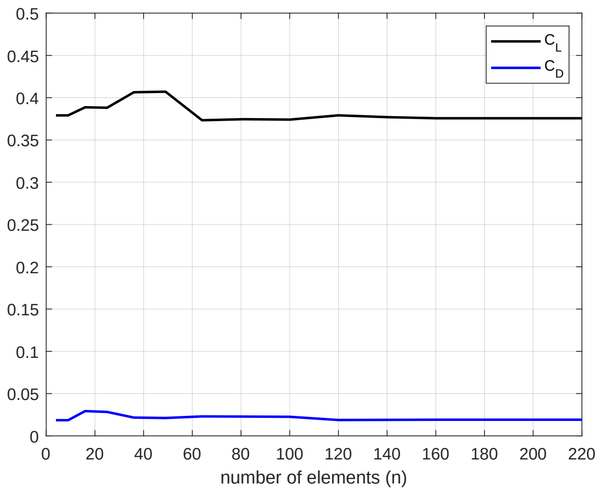

Figure 4. Flying wing mesh convergence

modified parameters. Geometric constraints are also defined in order to attribute boundaries to physical wing dimensions. Finally, the MOO is performed and objective functions evaluated, this process generate new design variables to the next generations. This process is repeated until a previously predefined stopping criteria is achieved.

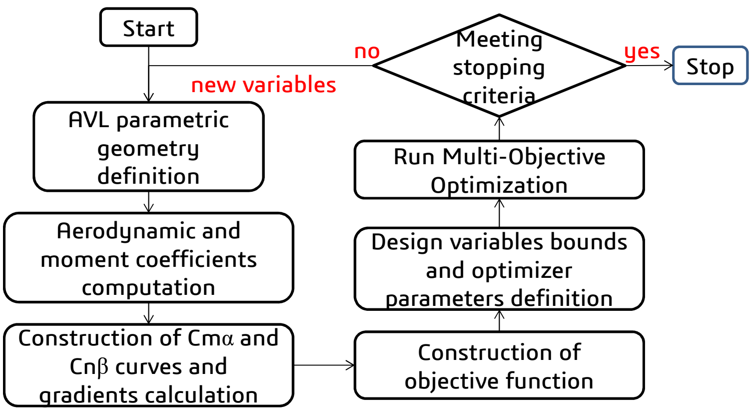

Figure 5. Flying wing mesh convergence

3. Optimization problem formulation

In the present paper, optimization will help to find the optimum flying wing shape that allows the meet of some static stability requirements while guarantees the maximum aerodynamic efficiency. This objectives will be achieved by adjusting some physical wing dimensions as chord and length of wing span sections. Another adjustable parameters are the dihedral swept angles of each section.

Regardless of the optimization nature, each optimization problem begins with the mathematical definition of the problem objectives and its constraints. It can be highlighted that how the problem is defined, i.e. optimization problem definition, affects the solution process and the final optimal solution. In MOO, there often exists a set of optimal solutions, and none can be said to be better than any other without any further information.

In the optimization strategy, the Multi-Objective Non-dominated Sorting Genetic Algorithm (NSGA-II) is adopted for system optimization. The formulation of optimization problem is stated as follows:

- Objectives:
  1. Maximize aerodynamic efficiency C_L/C_D, that is, minimize its inverse C_D/C_L. It is worth to mention that to the construction of the first optimization objective, C_L and C_D selected, were chosen at $C_m = 0$ and $C_n = 0$ condition, that is, at equilibrium (trim point).
  2. Minimize the difference between the gradients $\frac{dC_m}{d\alpha}$ and $\frac{dC_n}{d\beta}$ between them and some predefined gradients called "targets".
- Design variables: design variables are the parameters which are used to define the plan-form of the flying wing along its three sections, such as: sections chords x_1, x_2 and x_3 and section span ratio x_4, x_5 and x_6 and the dihedral and swept angles of each section.
- Constraints: only physical lower and upper bound of design variables were considered as official constrains, the geometric constraints are required to prevent the wing from becoming with a extremely high aspect ratio, due to the natural lift increment caused by it. During the optimization process, several subroutines were also programmed in order to discard individuals whose configuration does not meet aerodynamic constrains, for example, flying wing designs that shows aerodynamic stall or negative lift coefficients. Finally, the optimization problem can be formulated as follows:

Given: $X = \{x_1, ..., x_{12}\}$

Minimize:

$$\frac{C_D(X)}{C_L(X)}, \left(\frac{dC_m(X)}{d\alpha} - \frac{dC_m}{d\alpha}_{target}\right)^2 + \left(\frac{dC_n(X)}{d\beta} - \frac{dC_n}{d\beta}_{target}\right)^2 \tag{1}$$

Subject to:

- geometric constraints: $X_{lower} \leq X \leq X_{upper}$
- trim constraints: $C_D(X)/C_L(X)$ calculated at: $\partial C_m(X)/\partial\alpha = 0$ and $\partial C_n(X)/\partial\beta = 0$
- aerodynamic constraints: $C_L(X) > 0$

Where X is the vector of design variables with length $n = 12$, being n the number of design variables and X_{lower} and X_{upper} are the lower and upper limits of the variables, respectively. $\frac{dC_m}{d\alpha}_{target} = -0.05$ and $\frac{dC_n}{d\beta}_{target} = 0.005$, are defined in order to guarantee longitudinal and directional static stability. The $\partial C_m(X)/\partial\alpha = 0$ and $\partial C_n(X)/\partial\beta = 0$ constraints guarantee that aerodynamic coefficients C_L and C_D to the first objective be taken at level flight condition with constant altitude and $C_L(X) > 0$ false minimum at low or negative angle of attacks.

4. RESULTS

First of all, the details about optimizer set-up is discussed, afterward, the results are presented and analyzed. In the MOO problem, the NSGA II algorithm is configured such that the population and number of generations are, 120 and 100 respectively. As recommended by literature, the population has to be, at least 10 times the number of design variables n. It was considered elitism as a mean to always get better results along generations and the crossover and mutation fractions were defined as 0.7 and 0.05 respectively. In order to stop the optimization process, the tolerance of the fitness function was chosen as 1×10^{-9}, it also were defined a maximum number of stall generations (to stop when no improvement in fitness functions is found). The geometric constraints are given by the following bounds:

$$X_{lower} = \{1.90, 1.30, 0.70, 0, 2.13/3, 2.13 * (2/3), -5, -5, -5, 0, 0, 0\} \quad (2)$$

$$X_{upper} = \{2.40, 1.90, 1.30, 2.13/3, 2.13 * (2/3), 2.13, 20, 20, 20, 30, 30, 30\} \quad (3)$$

Once reached the 40 generations, the multi-objective optimizer found a set of possible solutions about the minimization of both, $f_1(X)$ and $f_2(X)$ fitness functions. Figure 6 provides the Pareto fronts in which are the solutions of minimizing both the inverse of the aerodynamic efficiency and the difference between stability derivatives and predefined static stability requirements. An optimal point can be selected from the Pareto optimal solution set according to the design criteria.

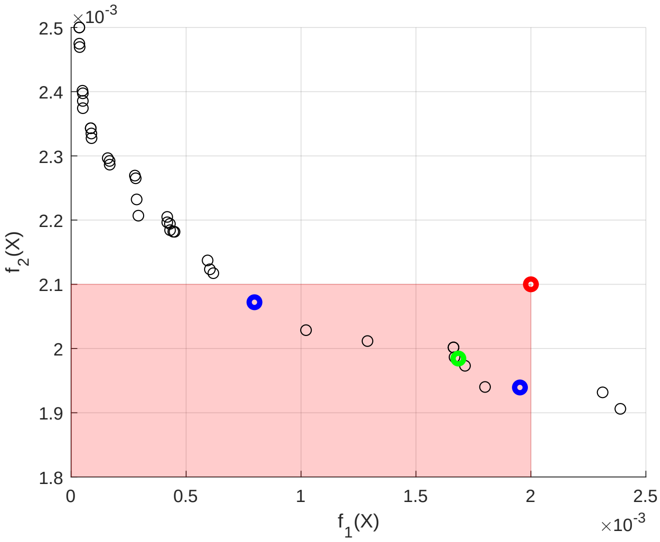

Figure 6. Pareto front

As can be seen at Figure 6, the non-dominated solutions at Pareto front are defined by a red region. Three of these solutions were compared, an optimal point (p_2 in green color) which demonstrated better fitness function values for both objectives and two blue points. The p_1 blue point located at the left side of p_2 which provided a better $f_1(X)$ value (better aerodynamic performance) and a second blue point (p_3) located at the right side of p_2 which represents an optimal solution with better stability performance ($f_2(X)$). The numerical values of the design variables at all points inside the non-dominated solutions region are illustrated at Figure 7 and compared to the baseline configuration.

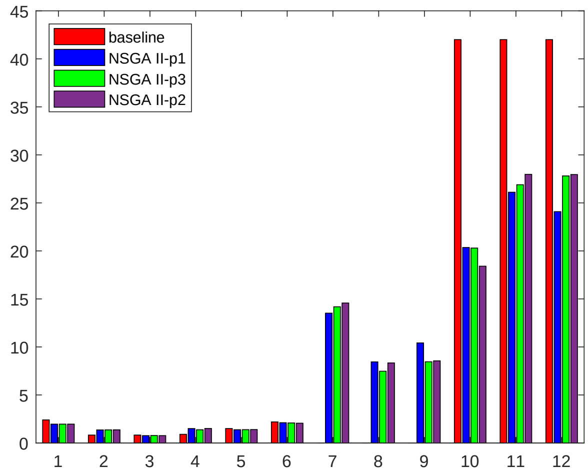

Figure 7. Resultant design variables

It is worth to highlight that swept angles at the last wing sections (design variables 11 and 12) almost achieve the upper bounds (30°) predefined in Eq. 3, then, it is expected that better results could be obtained with more swept at that sections (a more detailed explanation will be done below). The results also demonstrated the necessity of dihedral and swept angles in order to meet the optimization objectives when compared to the baseline configuration. A gradual increase at these angles along the wingspan direction allows to reduce the induced drag and increase the vertical and horizontal surface of the aircraft behind the center of gravity, which makes it possible to obtain greater longitudinal and directional restorative moments. The geometric configuration of the optimized (in green) and baseline (in black) flying wing is illustrated at Figures 8, 9 and 10 for the three points p_1, p_2 and p_3.

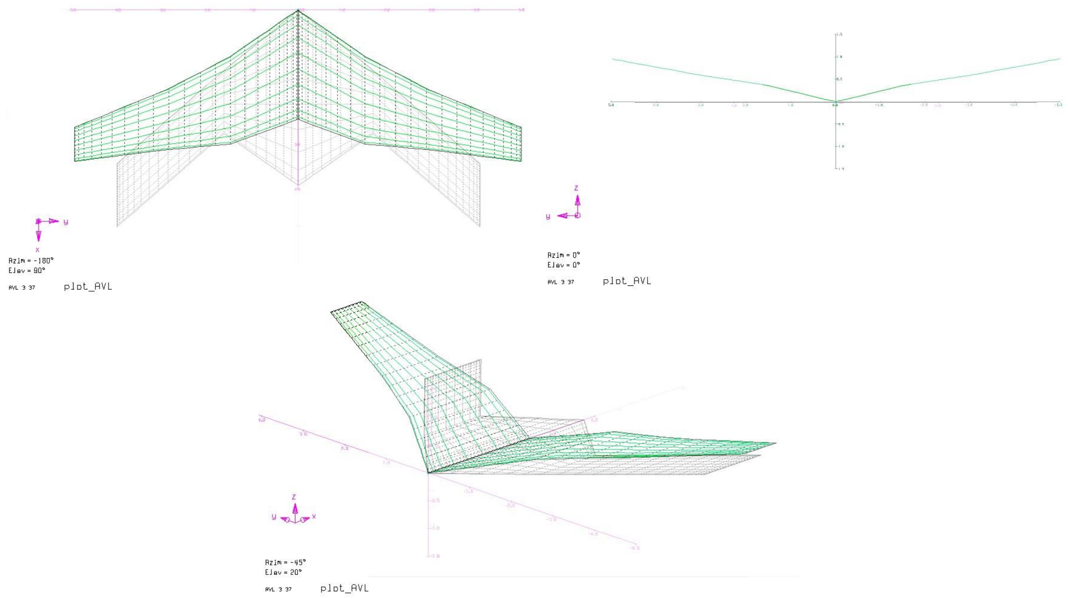

Figure 8. Optimized flying wing - p_1
baseline (black) / optimized (green)

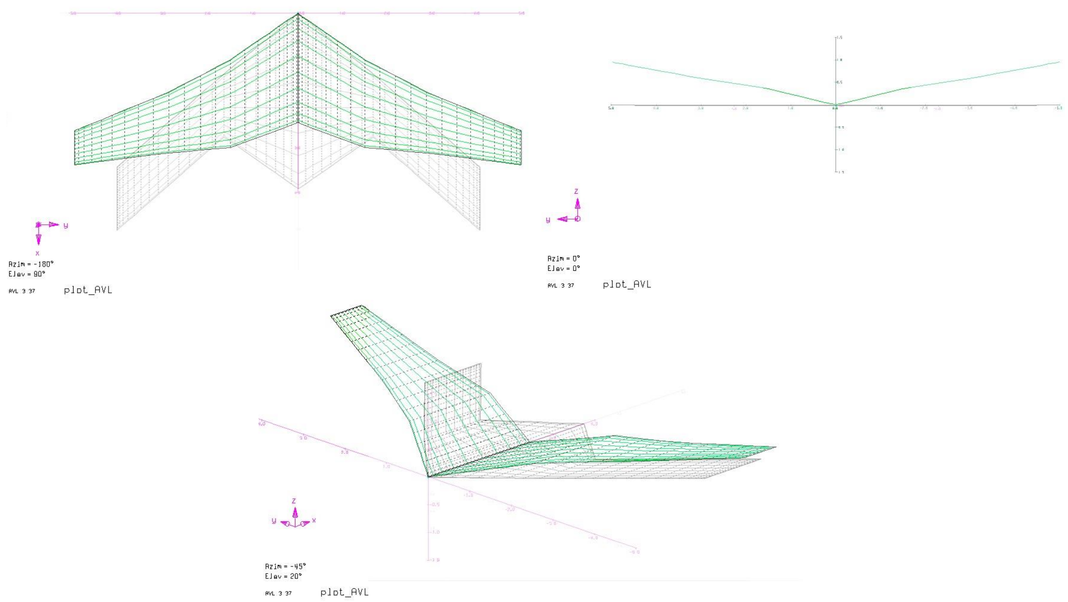

Figure 9. Optimized flying wing - p_2
baseline (black) / optimized (green)

In order to quantitatively compare the aerodynamic improvement after the optimization process, the drag polar of all configurations were plotted (see Figure 11). It can be seen at the zoom view that flying wing aerodynamic efficiency is improved at p_1 and p_2 configurations, the C_L is higher for the same drag coefficient (C_D) around almost all the angles of attack. The previous affirmation is evident in the Pareto front (Fig. 6), by the position of p_1 and p_2 in terms of $f_1(X)$ when compared to the baseline configuration.

From stability point of view, the NSGA II algorithm founds more and better results (feasible solutions), as can be

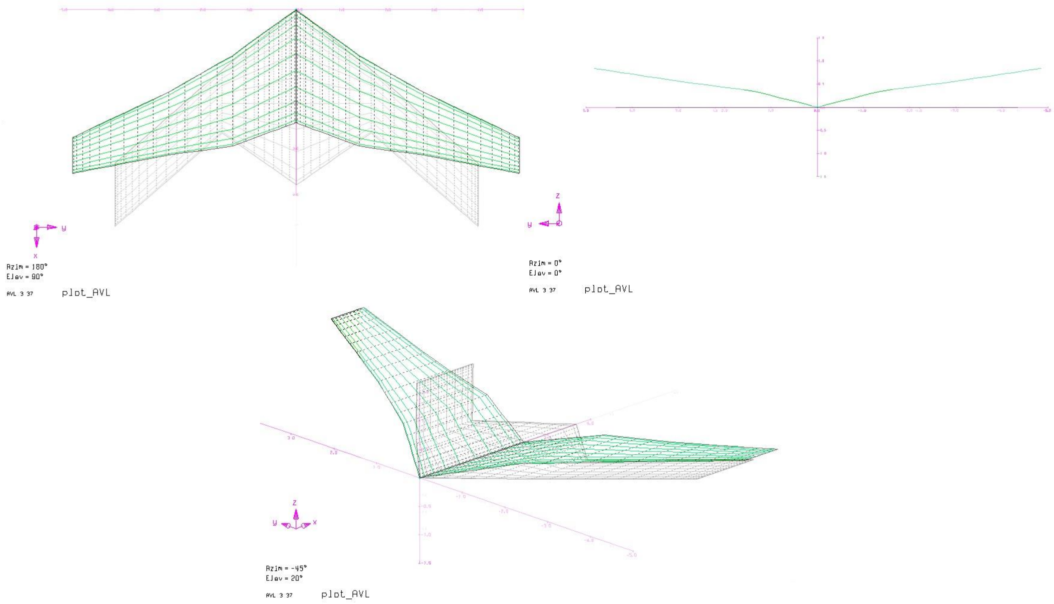

Figure 10. Optimized flying wing - p_3
baseline (black) / optimized (green)

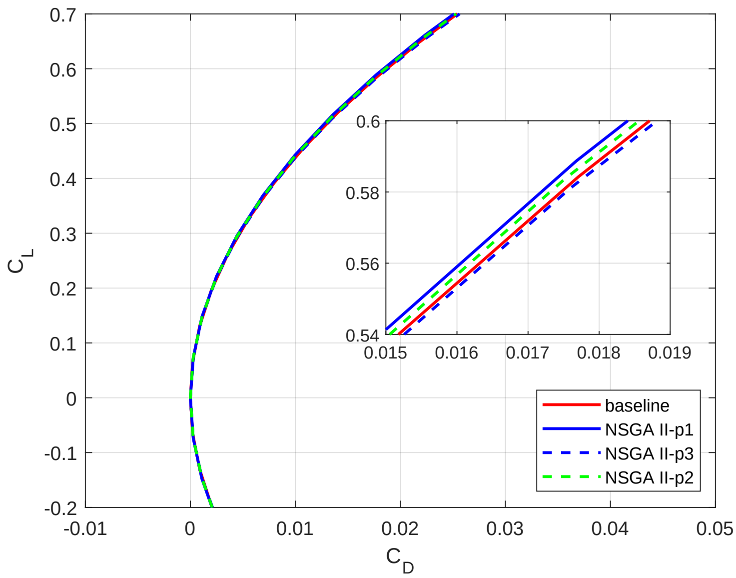

Figure 11. Drag polar comparison

noted at Pareto front (Figure 6). Figure 12 confirms this result. The $Cm-$ curve reveals a better agreement between the optimized flying wing configurations (p_1, p_2 and p_3) than the baseline one in terms of $C_{m\alpha}$ derivative (target and NSGAII curves almost parallel). In terms of static directional stability, the optimized (NSGA II) configurations showed a difficulty to find feasible solutions in order to improve the directional stability (find $C_{n\beta} > 0$). This difficulty can be explained by the low upper bounds of swept angles defined in the optimization problem.

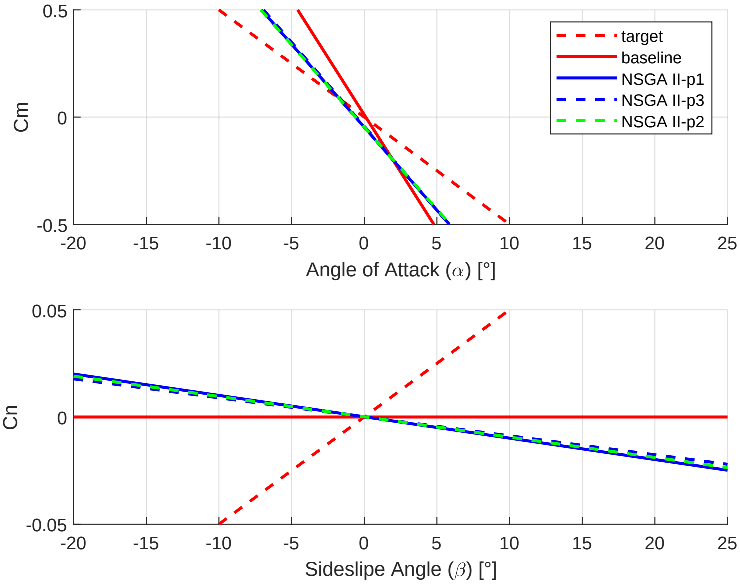

Figure 12. Stability criteria comparison

5. CONCLUSIONS

In this paper, an investigation has been made to study the improvement the design of flying wings by the optimization of geometric variables which define the flying wing shape in order to enhance the aerodynamic and stability characteristics of a Flying Wing aircraft. The AVL software was used as platform for modelling the flying wing surfaces and to extract the necessary aerodynamic coefficients required to evaluate the aircraft aerodynamic efficiency and static stability derivatives, both used as fitness functions. In order to solve the MOO problem, the NSGA II multi-objective algorithm was chosen. Results revealed the efficiency of the multi objective genetic algorithms in the search for global possible solutions.

The optimized flying wing configurations found, showed to be in accordance to the constraints and requirements imposed and demonstrated to improve the aerodynamic efficiency and the augmentation of longitudinal stability. Problems were found in terms of directional stability of the whole aircraft probably associated to the low upper bounds os swept angle at the wing sections. It is worth to emphasize that high swept and dihedral angles provide more vertical and lateral surface after the aircraft CG position, improving the directional aircraft behavior due to the absence of a vertical stabilizer. Results also showed the impact of dihedral and swept angle in directional and longitudinal static stability of tailless aircraft configurations and the efficiency of NSGA II algorithm in the optimization of complex engineering problems involving large number of design variables.

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