LOW COST AERODYNAMIC OPTIMIZATION FOR LIGHT AVIATION FINITE WING USING PATTERN SEARCH AND APAME 3D PANEL CODE

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Abstract. *The present work makes reference to a low cost procedure for aerodynamic optimization of a finite wing for general and sport aviation. The general scheme of the procedure is presented, tools and methods are described and its pertinence to low cost purposes is explained. APAME 3D panel method is used as solver,MATLAB® Psearch Toolbox is implemented as optimizer and PARSEC 11is the geometry generator included in the optimization structure. Design strategy through optimization is described and considerations made to compensate for lack of fidelity of the solver are showed. Optimization is made for a specific case of study related with a general aviation type aircraft. Optimization progress is shown and finally FLUENT solver is used to provide a high fidelity evaluation to check for consistency of the method.*

Keywords*: Aerodynamics, APAME, Pattern Search, PARSEC11, General Aviation, MATLAB®*

1. INTRODUCTION

Optimization techniques represent a progressively defined boundary that splits apart two different ages of aerospace design, ruled by principles so different between each other that turn design usual evolution based on experience into knowledge based process.

Actually several approaches have been developed by enthusiastic researchers and results obtained have shown practical and reliable implementation, allowing to guess a wide and solid future for this kind of methods.

When considered, aerospace applications are founded on multiple objective approaches, due to the complexity of aerospace systems that take into account the relations between components and its particular physic considerations such as aerodynamic-structural interaction or main effects of propulsive components. Nevertheless this approach, robust indeed, is expensive and is usually implemented with complex models in order to take real advantage to reduce uncertainty or handle economical risk.

Despite optimization literature is extensive and varied, most of it is focused on transport design at transonic and even supersonic regimes. Thus, is unusual to find literature relative to low speed light aviation applications that make emphasis in less significant fidelity but still valid models.

While major manufacturers and engineering companies can afford the cost of complex optimization structures, some general aviation and sport aviation manufacturers cannot afford the cost of these models, constraining their designs, and consequently performance, to traditional approaches that are broadly used but adds little value to a product aimed for a highly competed market.

In this paper a first stage of simplified optimization tools and approaches for multi-point low cost optimization is proposed mainly for wing aerodynamic design. The strategy is based on affordable software and hardware tools combined with proper considerations to compensate for lack of fidelity aiming for adequate robustness in the process.

2. LOW COST OPTIMIZATION TOOLS

Generally, optimization methods for aerospace applications are structured around three main modules that respectively cover the geometry of the problem, the physics phenomena analysis and the optimal search. According to needs, these three optimization aspects have been explored by several researchers in order to define sensitivities of optimal results to selected models (Oyama 2008) (Verburg 2008) allowing for a given criteria to select proper tools for the specific scope of the problem. Then it seems a logical option to select a geometry generator like NURBS when a complex shape, like wing to fuselage junction, is to be handled, selecting a full Navier-Stokes solver when optimizing for transonic and supersonic conditions, or selecting a very robust unconstrained evolutionary algorithm when dealing with highly sensible and uncertain operational concepts like Mars atmospheric flight (Shimoyama 2006). As usual for engineering cases, the selection of tools and methods is related with the well known cost to benefit ratio, and the practicability of implementation for light aviation is not an exception. For this type of scope, tools and models must meet proper cost to benefit criteria too, thus following very complex, possibly expensive, approaches would probably waste valuable resources as the application requires more simple considerations to obtain proper results.

2.1. Parametric geometry generator

From results observed from researchers like Sobieczky (1998) and Oyama (2008) among others, PARSEC 11 was considered fairly appropriate for the intended implementation. The simple structure and level of flexibility allows for proper geometry control and definition of airfoil sections trough a simple sixth grade polynomial definition given by

$$y(x) = \sum_{i=1}^{6} \alpha_i x^{i-\frac{1}{2}} \tag{1}$$

Where α_i term represents real coefficients that are obtained by solving a linear system which contains eleven variables related with airfoil parameters. .

The advantage of using PARSEC is the intuitive relation provided by parameters with airfoil aerodynamic performance, thus allowing for inclusion of designers criteria into curvature control. Additionally the linear nature of PARSEC method allows for rapid computation. Finally, wing planform parameters are kept as those of a simple tapered swept wing. Parameters are showed in Fig. 1.

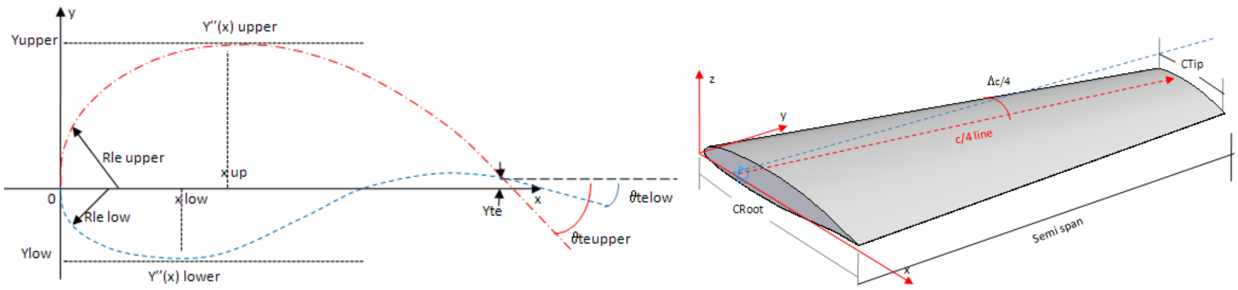

Figure 1. PARSEC 11 geometrical parameters (left) and wing planform parameters (right)

2.2. Aerodynamic solver APAME 3D panel code

In order to attain a low computational cost optimization, a three dimensional panel method was selected for aerodynamic solving purposes. APAME© is a code originally written by Daniel Filkovic (2008) under GNU General Public License. The code is structured around a combination of constant source and constant dipole panels under Dirichlet boundary condition and handles a flat vortex trail. Far field consideration is replaced with a distanced point singularity.

The code is easy to handle and straightforward for data extraction. It is able to handle the required parameters for wing planform and inclusion for airfoil generation is easily added by code manipulation.

From Filkovic code development, a series of considerations for paneling densities are available for convergence studies allow for proper implementation. Despite of its inviscid model, results obtained from APAME are considered to be acceptable for optimization purposes. Moreover Laplace nature of the code allow for rapid solutions (around 5s to 15s in a 2Gb ram notebook depending on practical paneling densities), compared with time needed for Navier-Stokes solvers.

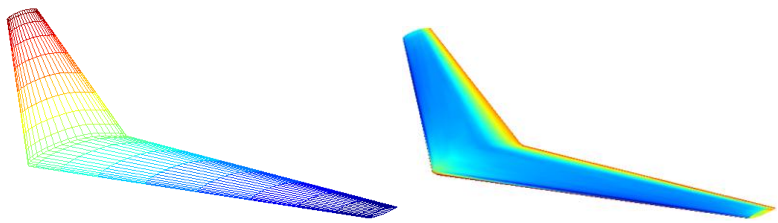

Figure 2. APAME paneling scheme (left) and pressure coefficient distribution (right) for swept wing.

2.3. Optimization tool MATLAB® PSEARCH Toolbox

Implementation of Pattern Search is made trough MATLAB® PSEARCH Toolbox (Mathworks 2008). This toolbox was found proper for the aim and scope of this work, showing faster processing than Genetic Algorithm tool also available in MATLAB®.

Relatively simple, Pattern Search method works by searching optimal into a certain region according to specified constrains that could be defined by bounds setting or by definition of nonlinear constrains functions.

The way Pattern Search works is defined by the following algorithm (LEWIS et al. 1998)

$Given\ x_0 \in \mathbb{R}^n, f(x_0), D_0 \in \mathbb{R}^{n\times p0}, and \Delta_0 > 0,$
$for\ k = 0,1, \ldots..\ until\ done\ do\{$
$1. Find\ a\ step\ s_k = \Delta_k d_k\ using\ the\ procedure\ Exploratory\ Moves\ (\Delta_k, D_k)$
$2. if\ f(x_k, \Delta_k d_k) < f(x_k), then\ x_{k+1} = x_k + \Delta_k d_k; otherwise, x_{k+1} = x_k$
$3. Update(\Delta_k, D_k)\}$

For a given case the shown structure states that for iteration k the algorithm will search possible solutions around a current vector solution $x_k \in \mathbb{R}^n$by moving around at a given step-length parameter $\Delta_k > 0$ and oriented by unit basis vector $e_i, i = 1, \ldots., n$. Algorithm evaluates the surrounding points $x_{k+1} = x_k \mp \Delta_k e_i$ until a certain x_{k+1} point is found for which$f(x_{k+1}) < f(x_k)$. If no x_{k+1} is found such that $f(x_{k+1}) < f(x_k)$ then the algorithm reduces Δ_k by a half and continue; otherwise the current step-length parameter remains. Alternatively for the latter case Δ_k may be increased by a factor of 2 when justified. The process is repeated until Δ_k is sufficiently small.

PSEARCH Toolbox includes several settings (Mathworks 2008) in order to improve solution by minimizing objective function (or maximizing if needed). Among other, options include two main search modes. General Pattern Search and Mesh Adaptive Direct Search, both with two different positive basis. 2N positive basis explores the mesh by defining a number 2N of direction vectors (being N the number of variables) and NP1 that generates a number of N+1 directions vectors for mesh exploration. Complete or partial Poll is also available, when off the algorithm will stop searching at a given iteration when it finds a lower value for objective function, when on, the algorithm explores the whole mesh searching for the lowest value in order to proceed with next iteration. The mesh contraction is controlled by setting its value as well as its expansion if required.

Stopping criteria includes Mesh Tolerance, X tolerance (the minimum distance from the previous best point to the current best point), function tolerance (lowest allowed value for objective function), nonlinear constrain tolerance (similarly to function tolerance) and blind tolerance (used for constrained problems, specifies how close explored points get to feasible region borders before a linear constrain is active).

3. OPTIMIZATION STRATEGY

3.1. General considerations

With tools defined, finding how to properly implement these tools into a coherent procedure is a main concern if low cost is intended with consistent results.

In first place, by studying the proposed tools and models, it is observed that method structure is mainly constrained by solver fidelity, which means that optimization must be framed into the valid results range of APAME code. Such a range is defined by two factors, paneling density and limit angle of attack. The former factor is mainly related with the paneling density in the chordwise direction and its effects in description of pressure coefficient distribution along the chord for airfoil design. The second factor represents the limit angle at which optimization can be requested from the proposed structure without invalid solver evaluation.

Second, PARSEC 11 method requires the definition of bounds for the eleven parameters involved in optimization in order to avoid generation of unreal geometries or geometries that do not meet specific requirements. Additionally, settings for optimization toolbox needs for definition in order to take advantage of its different features. To test both, geometry generation and optimization routine, a simple test could be made by requesting PARSEC 11 to imitatespecific airfoil geometry with control of Pattern Search toolbox.

To obtain an efficient optimization structure, additional constrains may be included along the structure, thus avoiding waste of computational time by allowing the routine to run APAME evaluation only for approved geometries, leaving rejected geometries apart. This consideration may be also included for lift and drag requirements as optimization is intended for multi-point optimization, then a first check of aerodynamic performance is made before proceeding with other optimization points, thus saving time and costs.

3.2. Climb, cruise and stall behavior considerations

When considering aerodynamic optimization the usual definition is related with lift to drag ratio for specified conditions. For climb case optimization is made at a given climb angle and given velocity (usually that for best rate of climb), but consideration of a minimum power requirement is also desired as this allow to use the remaining power as excess power for climb. Such a condition is given when $C_L^{\frac{3}{2}}/C_D$ is maximum. This condition is related with an specific velocity, but is usually too low for practical cases, nevertheless optimization routine could be forced to optimize this term to be maximum for a different velocity, even if it is not a global maximum (the velocity at which minimum power is given could still be different) it will improve the performance at a more practical velocity.

Now cruise condition shows a similar situation and for this case minimum drag is given when C_L/C_D is maximum, again for a given velocity optimization could increase wing efficiency for that specific situation.

Stall behavior requires more detailed attention. Stall behavior is directly related with operational safety and its qualitative analysis could become complex if fine detail is required. For design purposes, stall behavior is related with providing a smooth progression, growing from the trailing edge at root towards wingtip, leaving enough flow attached at tip vicinities to allow for lateral control during high angle of attack maneuvers or low speed handling. Now to include that criterion into an automated optimization process Load Distribution Factor (*LDS*) is included. This factor, proposed by Pinelly and Sereno (2005) deals with load distribution along span trough a centroid like definition that pulls the resultant load back to the root. This simple factor is given by

$$LDS = \sum_{i=1}^{N} \frac{C_{li}\ y_i\ \delta y_i}{C_L\left(\frac{b}{2}\right)^2} \tag{2}$$

Where C_{li} is the local lift coefficient, y_i is the local station along semispan (b/2), C_L is the global lift coefficient and δy_i is the spanwise direction step towards tip. The control provided by this factor is observed in Fig. 3.

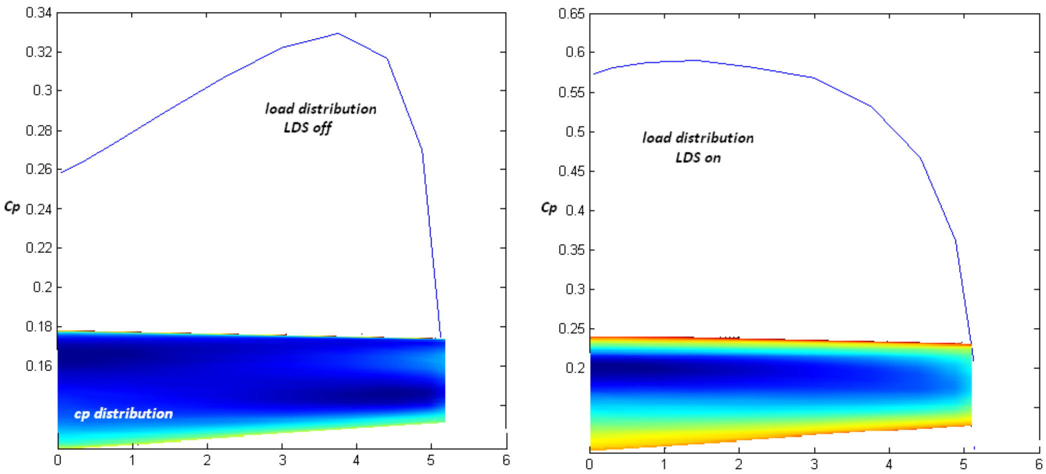

Figure 3. LDS factor influence in load distribution along semispan

3.3. High fidelity evaluation

A final consideration is made into strategy proposal. In order to provide reliability check of the process, high fidelity solver runs could be made in order to check for consistency. Despite this kind of analysis is made only with checking purposes, and high fidelity solver is not included into the optimization routine it does provide fair judgment of results obtained from optimization process. This judgement was made with FLUENT solver coupled with GAMBIT for geometry meshing.

4. METHODOLOGY VALIDATION

Validation was made at three different levels. First FLUENT and GAMBIT were validated according to results obtained from Bollech (1948) for a series of test of finite wings with different aspect ratios and airfoil sections. By validating FLUENT first it is possible to compare data that is not available in the experimental report like pressure distribution at span stations along the chord. Moreover, Bollech results include a qualitative analysis of stall progression that can be used to compare simulation fidelity for such a condition (Fig.5). Validation was achieved with a 742101 elements mesh (Fig.5) for NACA (2.5-10-44, 20) finite wing proposed by Bollech.

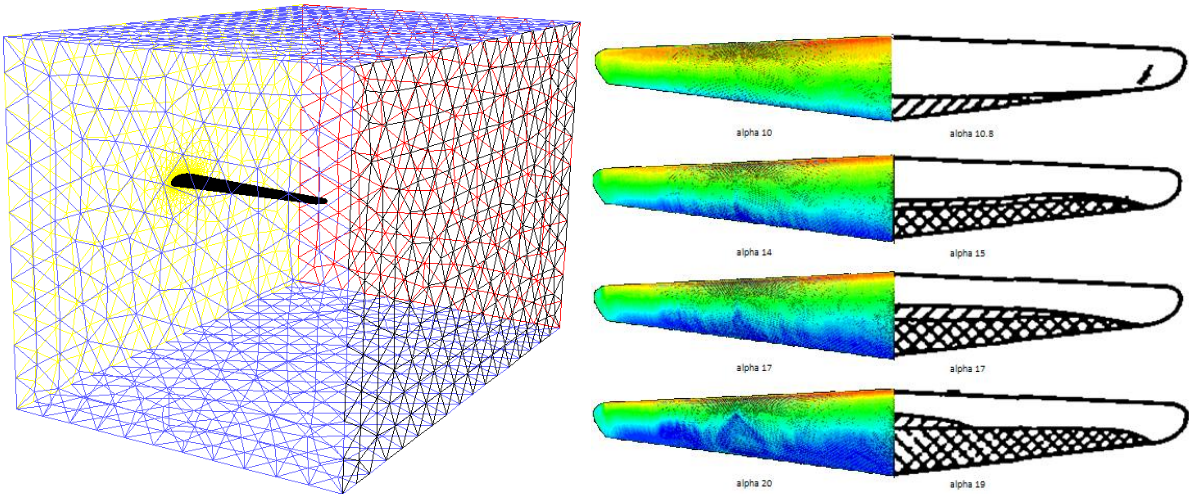

Figure 5. Volume meshing for finite wing simulation and qualitative comparison of stall progression

APAME code validation is related with limit angle of attack and paneling density in the chordwise direction to achieve proper description of pressure coefficient distribution. Finally, starting with Filkovic (2008) paneling studies, 35 panels for each, upper and lower surfaces, were required to properly describe pressure distribution. By simulating a quasi-infinite wing in APAME, two dimensional comparison for a LS(1)-413 (GAW-2) (McGhee et al. 1973) airfoil with 35 panels was made against FLUENT results for the same airfoil for inviscid and viscous conditions (Fig.6). With distribution established, limit angle of attack is defined by comparing APAME results with those results previously obtained from FLUENT and Bollech (1948) (Fig.6), obtaining a limit angle of 10 degrees with a percentual difference under 10%.

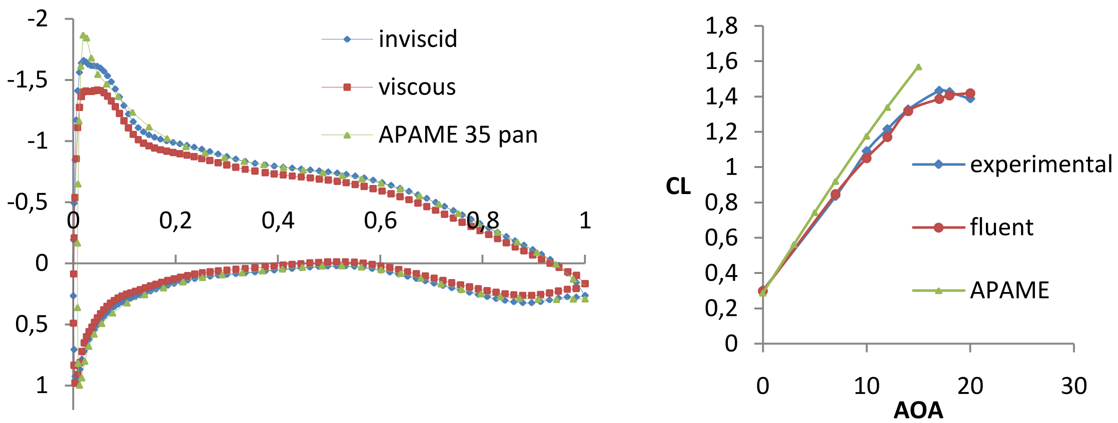

Figure 6. Pressure coefficient distributions comparison for airfoil (left) and limit angle definition (right)

Final level of validation has to do with testing of optimization tool and geometry generator. Since optimizer tends to minimize the value of a specified objective function, then it is possible to ask the optimizer to minimize the difference between an initial airfoil geometry points and a target airfoil (LS(1)-413 (GAW-2)) geometry points. This test allowed for definition of a first requirement to avoid unreal geometries by requesting that upper surface were always above the lower surface of the airfoil, results are shown in Fig.7.

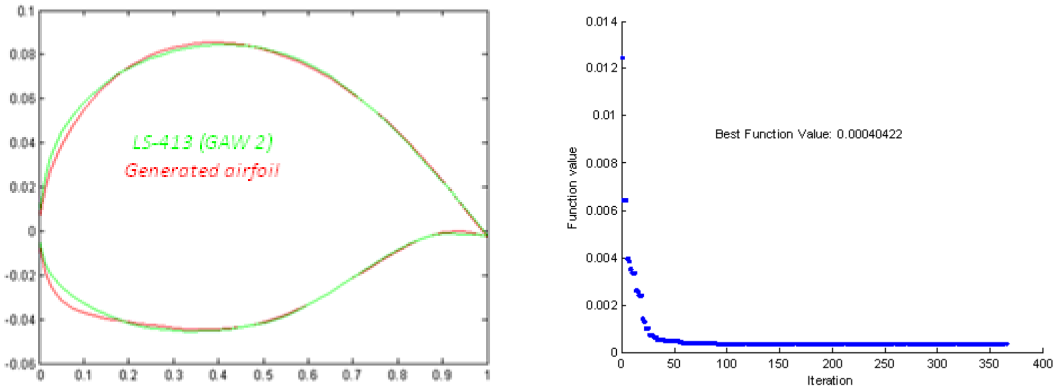

Figure 7. Imitation of LS(1)-413 (GAW-2) test, geometry comparison (left) and optimization progress (right)

5. CASE OF STUDY

Considering a mountain operational environment like Andean geography, operations could be quite demanding, requiring some special features usually related with power increments, leaving aerodynamic changes relegated to minimum or nullity levels due to mayor alteration complexities or interference with aeronautical authority regulations. For light aviation, the impact of this kind of operational environment is reflected in their mission profiles (Fig. 8) that change from having a mayor portion related with cruise to having a mayor portion related with climb.

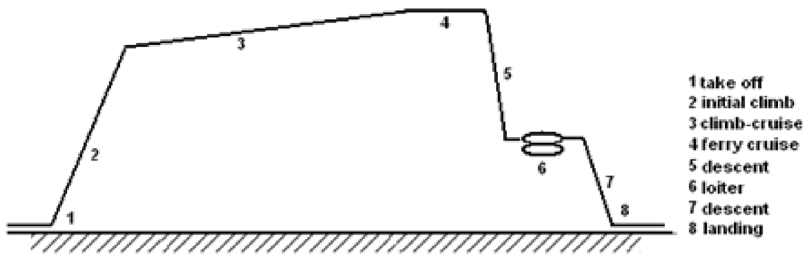

Figure 8. Mission profile under mountain environment

Additionally while operating at airports that could be located as high as 3000 m over sea level, high lift and stall characteristics are fundamental if safety and practical operations are expected.

In order to implement these considerations for optimization aims, a simple case of study is proposed at conceptual level intended for wing aerodynamic design. Related with general aviation, requirements were set in accordance to efficiency in climb, proper stall progression and acceptable cruise performance. Additionally, aiming to take advantage of optimization, some geometrical requirements are considered in order to include some of the typical constrains found in general aviation like airfoil thickness to increase internal volume for structure and fuel.

From conceptual design, initial weight estimation and definition of wing area allowed for definition of optimization conditions, nevertheless some special consideration are made for stall. Due to the inviscid model used in APAME, nonlinear range evaluation is beyond its capabilities, thus alternative considerations are made expecting to obtain proper results. Using the limit angle of attack previously defined, stall velocity (for clean configuration) is considered to provide some level of robustness for conditions beyond this angle than if considering lower angles only. Furthermore, due to PARSEC flexibility, camber of the upper and lower airfoil surfaces can be controlled if thickness constrains are specified for different chord stations aiming to avoid large velocity gradients and the consequent flow detachment.

With these considerations in mind, stall and initial climb considerations are made under the assumption of operation at high altitude airports (2590 m, El Dorado International Airport, Bogota) while cruise is kept to a more conventional altitude. Optimization conditions are given in Tab. 1.

Table 1. Optimization Conditions for climb cruise and limit angle

	Altitude [m]	Speed [m/s]	Angle º
Limit AOA	2590	31,33	10
Climb	2590	37,04	7
Cruise	3048	84,99	-2

5. WING OPTIMIZATION

5.1. Three level Optimization

Following the optimization strategy, optimization routine is to be structured in such a way that computational cost be reduced, thus a three level optimization is proposed including different constrains and objective functions for each level.

First level has to do with geometrical filter, thus only wings with real (non crossed curves) geometry airfoils and the minimum required thicknesses are approved for evaluation in APAME solver. Additionally thickness specifications at 25% and 65% of the chord are also included to provide some control on velocity gradient. The related objective function for this level is given by

$$dl = 20 - \{maxthick_{root} + R_{leroot} + X_{uproot} + R_{letip} + maxthick_{tip} + X_{uptipt} + (\mathrm{Surf}_{\mathrm{upper\ root}} - \mathrm{Surf}_{\mathrm{lower\ root}}) + (\mathrm{Surf}_{\mathrm{upper\ tip}} - \mathrm{Surf}_{\mathrm{lower\ tip}})\} \quad (3)$$

Note that this first level function is minimized by increasing airfoil features like leading edge radius or thickness for root and tip airfoils keeping the real geometry condition.

Second level request from optimizer to find a configuration that matches the required lift coefficient for a given weight first at climb condition and additionally it includes the *LDS* factor to control load distribution since the initial iterations, thus forcing the algorithm to follow a path that minimizes objective function considering with some priority climb and stall condition. Second level objective function is given by

$$dl = 10 + abs(C_{Lgen} - C_{Lreq}) + LDS \quad (4)$$

Third level is finally the one that couples climb, stall and cruise conditions plus the required geometrical conditions. At this level, optimizer searches for configurations that improve the respective C_L/C_D ratios for the three required conditions while pulls load towards wing root. Objective function is given by

$$dl = 1 + \left(\frac{C_D}{C_L}\right)_{cruise} + \left(\frac{C_D}{C_L^{\frac{3}{2}}}\right)_{climb} + abs(C_{Lreq} - C_L) + \left(\frac{C_D}{C_L}\right)_{limit\ AOA} + LDS \quad (5)$$

5.2. Results

With a initial point that included a NACA 2412 airfoil, optimization required about one hour and seven minutes with a mesh limited in size to 10^{-3} as main stopping criteria, for a personal laptop with 2.2 GHz processor and 1.75 Gb ram memory. It has to be noted that selection of initial configuration was made to mismatch design requirements like thickness (a minimum 13% thickness was required) or required lift coefficient (greater lift coefficients than those possible with initial configurations was set) then optimizer was forced to go through the three different levels. Results extracted from APAME show matching for lift coefficient while accomplishing with geometrical requirements, results for lift coefficient matching and lift to drag ratios are shown in Tab. 2. Evolution, final geometries, load distributions and optimization progress at the three proposed levels are shown in Fig. 9, Fig. 10 and Fig. 11.

Table 2. Results for required CL (a) matching and lift to drag ratios (b)

a	
Original	**Optimized**
Climb condition a= 7	
($CL^{3/2}$)/CD	**($CL^{3/2}$)/CD**
21,3778	20,6801
Cruise condition a= -2	
CL/CD	**CL/CD**
1,3465	21,7132
Limit AOA stall a= 10	
CL/CD	**CL/CD**
21,2889	16,9987

b		
Original	**Optimized**	
Climb condition a= 7		
CL	**CLopt**	**CL req**
0,7778	1,1224	1,1217
Cruise condition a= -2		
CL	**CLopt**	**CL req**
-0,0136	0,3105	0,224
Limit AOA stall speed a= 10		
CL	**CLopt**	**CL req**
1,0389	1,3888	1,4008

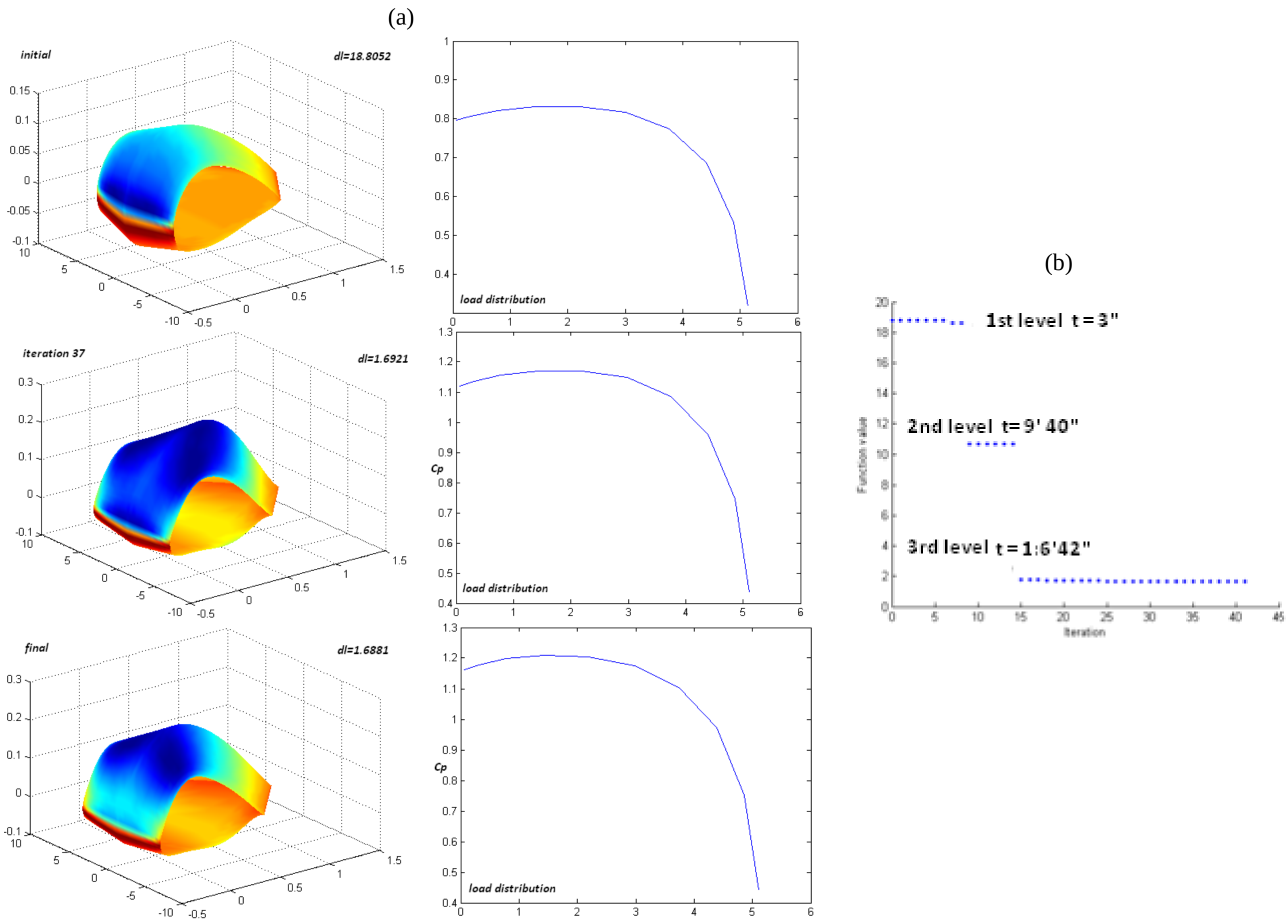

Figure 9. Mission profile under mountain environment (a) and three level optimization progress (b).

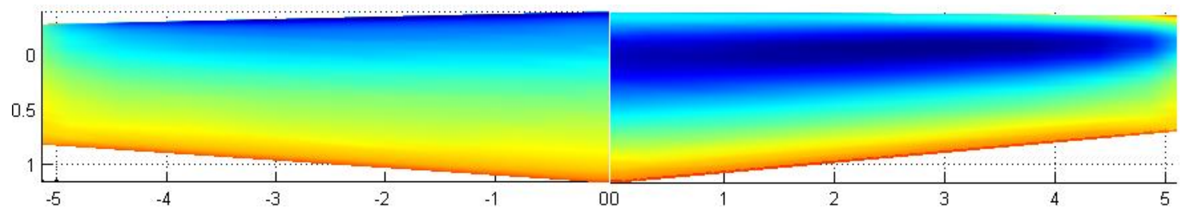

Figure 10. Planform comparison, original wing (left) final wing (right)

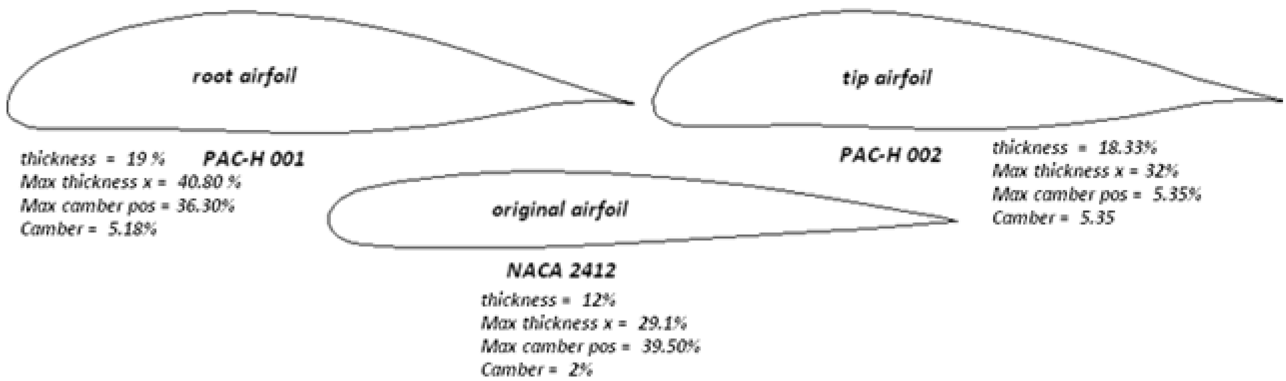

Figure 11. Airfoil comparison, original airfoil NACA 2412 and generated airfoils

6. FLUENT CHECK

To provide a final analysis, FLUENT runs were made to check for general performance and stall progression qualities. From this results a smooth stall is observed as well as a slope comparable to those of NASA's low speed family airfoils, also good behavior for aerodynamic moment generation was noted, favoring the reduction of required tail. Polar plots for stall speed are shown in Fig. 12a, stall progression is shown in Fig. 12b.

(a) (b)

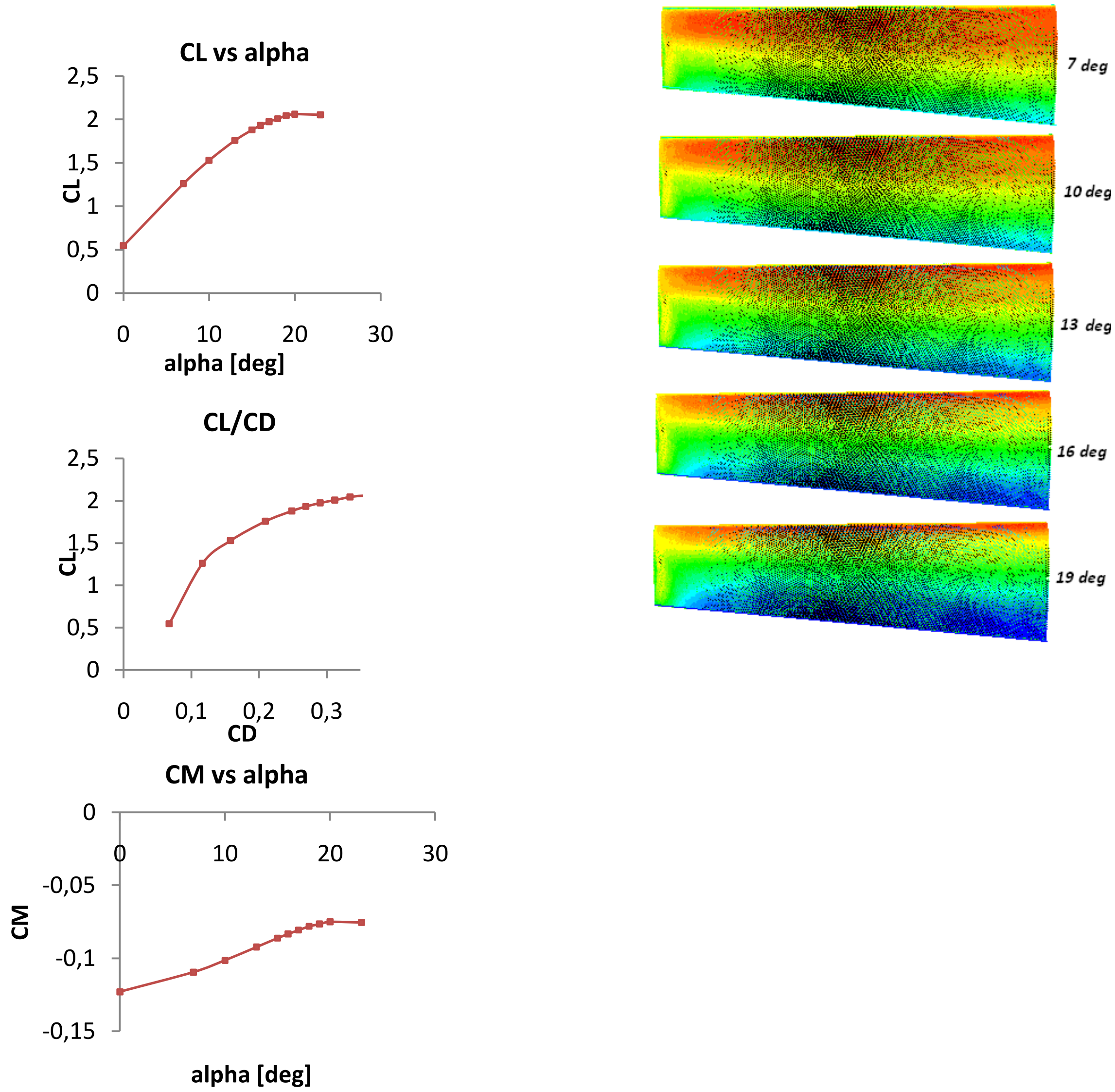

Figure 12. FLUENT results for general performance at stall speed (a) and stall progression for different angles (b)

7. CONCLUDING REMARKS

Implementation of numerical optimization process was made following usual structure found for this kind of approaches. A geometry generation module was implemented in the form of PARSEC11 method, coupled with tridimensional wing planform parameters. This method resulted to be flexible enough to generate different airfoils for tip and root, while following geometrical constrains hypothetically implemented to prove the method in more real conditions.

An evaluation module was included into the optimization loop with requirements of acceptable fidelity and low computational cost. The implemented method was a three dimensional panel based code called APAME. Despite being an inviscid solver, proper considerations and careful study of its limitations allowed for results that went beyond the initial expectations, providing enough similarity for results when compared with high fidelity solvers such as FLUENT Navier-Stokes solver.

Optimization was performed with PsearchTool. This MATLAB® toolbox, based on direct search method, specifically Pattern Search technique, resulted in a fast optimization approach, robust enough if the right consideration is included and proper definition of objective function is performed. Even more, the process was improved by structuring the algorithm such that expensive calculations were performed only when needed.

Despite results were acceptable, increased solver fidelity would be desired, a viscous model like boundary layer strips would keep computational cost low while improving results as skin friction would be considered. Furthermore, even though geometrical considerations paid off this time, an extended study would be proper to add consistency to the method, again a wake model inclusion would significantly improve results. Finally, while PARSEC 11 was flexible enough, the dependence of upper and lower curves may have lead to, perhaps, excessive thickness and to increased drag as a consequence, including manipulation of lift generated through mean camber line may reduce this excessive thickness.

8. ACKNOWLEDGEMENTS

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