PSAA
AerospaceEurope Conference2021
WARSAW, POLAND | 23 -26 NOVEMBER 2021
CEAS
Council of European Aerospace Societies

A VARIABLE FIDELITY OPTIMISATION PROCEDURE FOR MULTI-AIRFOIL DESIGN

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Abstract

Designing and optimising multi-airfoil configurations require extensive tests in the wind tunnel and computationally expensive CFD simulations. This work proposes an accurate multi-airfoil optimisation procedure based on CFD with variable-fidelity algorithms to reduce the cost related to a pure CFD approach. Low-fidelity but faster steps are used to cut off the number of configurations to be analysed and quickly converge to an optimal solution. This allows for an efficient use of resources, especially when configuration and shape optimisations are conducted simultaneously. The tool proposed has been optimised on several configurations and generates high quality grids with limited user inputs. Compared to already existing methodologies for airfoil optimisation like the adjoint method, the proposed procedure is convenient because a new grid is generated for each configuration, instead of deforming the starting one, allowing large modification of shape, dimensions and relative position. CFD simulations are performed with compressible RANS and different turbulence models can be selected. The optimisation procedure supports several design variables, such as the shape and the configuration that can be optimised separately or simultaneously. The latter is the most interesting case but entails an increase in the number of design variables. Different optimisation methods are implemented, including Particle Swarm Optimisation (PSO) and Steepest Ascent (or Descent) Optimisation.

Keywords: multi-element, airfoil, CFD, optimisation, PSO, lift

1. Introduction

High performance wing configurations have always been one of the most important objectives in aeronautical designs. In particular, lift maximization becomes crucial for specific maneuvers like take-off and landing. The earliest designs proposed by aeronautics were typically wings with single-element configurations, but these setups were unable to reach high lift performances. To overcome these limitations, the most known and applied solution has been the design of multi-element airfoils which are capable of bringing several advantages in aerodynamic performances, especially in the maximum reachable lift, [1]. Nevertheless, the design and flow complexity drastically increase if compared to the much simpler single-element configuration, involving several challenges when an optimisation has to be performed. In particular, the *slot* dimensions (gap between each element trailing edge and leading edge of downward one) significantly influence the maximum lift of the configuration [2]; furthermore, the sensitivity to slots' changes is significant, such that a slot optimisation typically requires several candidates evaluations to reach the global optimum [3]. To optimise multi-airfoils configurations, the first methodologies historically adopted were using wind tunnel tests, like work proposed by D. Landman [2] as an example: although highly accurate, experimental optimisation methodologies in wind tunnels involve also high costs due to the high number of tests to be done. During the last 30 years, various works demonstrated the possibility to execute multi-airfoils optimisations adopting computational procedures, avoiding the high cost of wind tunnel tests but also allowing for handling a higher amount of design variables within the same optimisation problem. Since multi-elements airfoils typically involve large separated regions, inviscid computational methodologies are not the most accurate, requiring at least a viscid RANS approach. Klausmeyer and Lin [4] work highlighted the possible advantages and limitations of CFD optimisation of multi-element airfoils with RANS simulations, summarised by Rogers in the same reference; Trapani et al. [5], [6] and Iannelli et al. [7] demonstrated the feasibility of optimisation algorithms along with CFD to reach the optimal configuration of multi-element airfoils. However, all the previous analyses adopted in-house software and they were limited to one multi-element configuration. The present work is intended to provide an open-source optimisation tool for generic multi-element airfoils, guaranteeing a wide user customization on geometry, grid features, CFD details, optimisation methods and respective parameters.

2. Methodology

The procedure proposed in the present work is subdivided in three main intuitive blocks: geometry and grid file generation, CFD simulation run and optimisation. In particular, the adopted open-source software for grid generation is Gmsh, while SU2 is the one entrusted with the task of performing the CFD simulation; lastly, post-processing is performed by both ParaView and Python libraries. All the blocks are connected by a main Python3 script that manages the entire optimisation procedure.

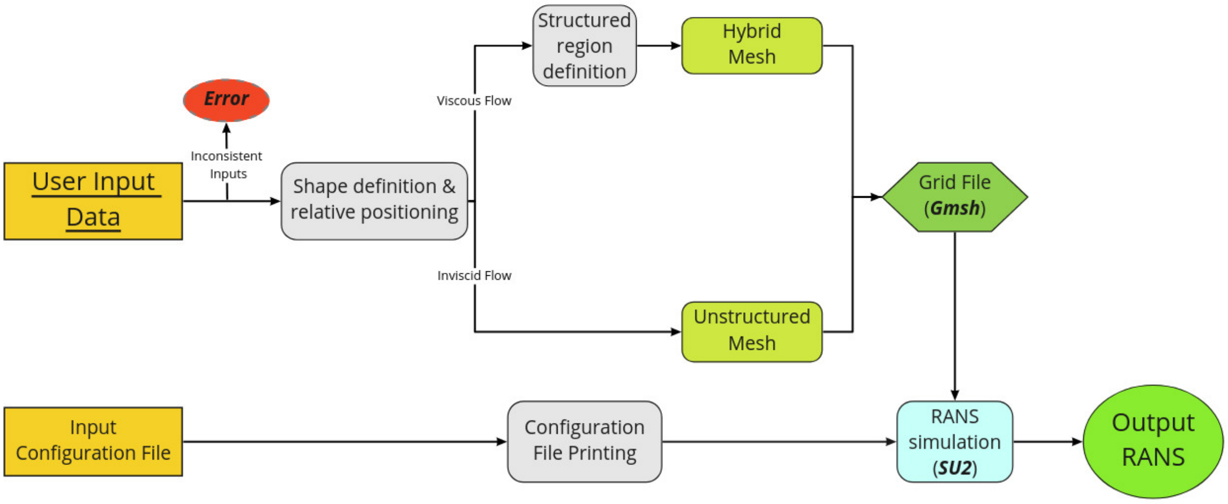

Figure 1 – Schematics of the proposed methodology

The methodology implemented for the optimisation of multi-airfoil configurations has a fundamental part that relies on geometry generation and CFD simulation. The schematics of these two blocks is provided in Figure 1. Each of the two blocks (geometry and simulation) is going to be explained in the following.

2.1 Grid generation

The grid generation procedure starts by reading the input geometry: the user can either select a parameterisation or provide a list of points, both options are valid for single or multi-element configurations. Once the geometry has been created, a template for mesh generation is filled with the information resulting from the geometry generation and starts a fully automatic procedure. The template is provided to Gmsh and the result is a high-quality grid for the CFD simulation with refinements that are adapted depending on the chosen geometry features and complexity.

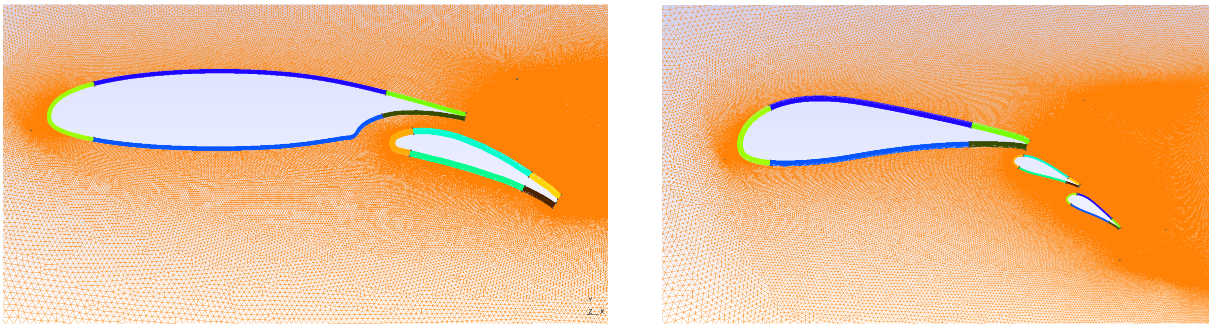

Figure 2 – Examples of grids generated for a NLR 7301 (left) and C-11 (right) airfoils.

The automation of the procedure for the grid generation avoids the typical time-consuming meshing procedure and becomes particularly useful whenever a large set of simulations has to be prepared, namely during optimisations. The meshing tool applies a peculiar refinement strategy (the numbering corresponds to Figure 2):

1. External grid semi-circle to guarantee a refinement ahead of the entire configuration
2. Ellipse enclosing the multi-airfoil configuration, guaranteeing a second level of refinement.
3. Structured regions close to the surfaces to guarantee $y^+ < 1$.
4. Grid points located inside each slot for accurately describing wake-element interaction.
5. Wake refinement between two lines, whose point spacing increases using a geometrical series.

The grid generation algorithm has been tested with several geometries, both single or multi-elements and it is able to mesh robustly a very large set of airfoil geometries. The size of the domain has been tuned with a sensitivity analysis on different geometries, resulting in a good farfield size of 300 chords; as for the wake refinement, using 50 times the major ellipse axis as refinement length is sufficient not to see the grid influence on aerodynamic performances.

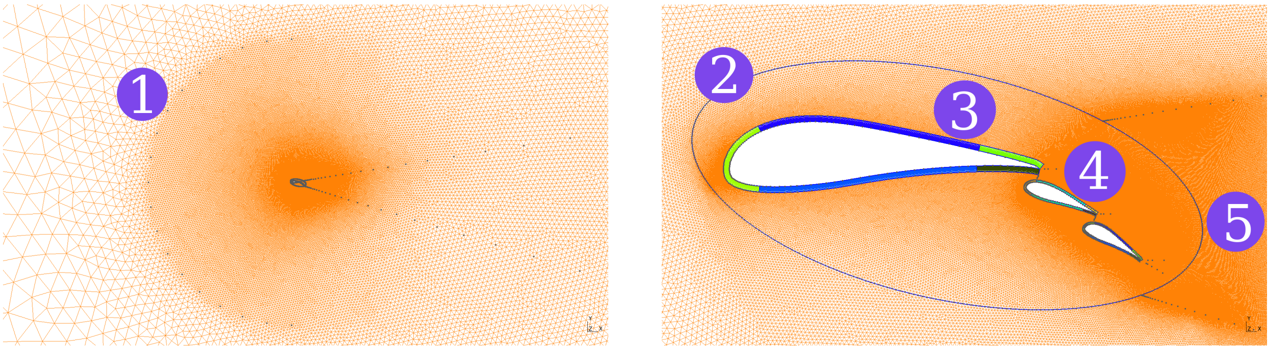

Figure 3 – Grid details.

3. CFD module

The CFD module implemented in this methodology collects the grid generated during the previous step and creates an SU2 simulation case. The user has the possibility to customize all the typical CFD aspects on SU2 [8] (such as flow conditions, turbulence model, CFL, fully turbulent or transitional boundary-layer, convergence criterions) by editing an input CFD configuration file. Whenever a viscous flow is considered, the structured region close to airfoil surfaces are generated using the flat plate analogy [9] for ensuring the desired y^{+} value. In most of the tests, it has been set to $y^{+}0.1$ to be sure that everywhere $y^{<}0.1$. The user can further customize the details of the structured region, such as thickness, element progression in normal direction and the amount of nodes on airfoil surfaces. As for convergence criteria, the user can adopt the various options provided by SU2. Since the amount of fitness evaluations is relevant during a typical optimisation procedure, and since candidates could consider any possible configurations within design space, the procedure has to face possible "spurious" candidates with oscillating CFD simulations. An example can be a multi-airfoil candidate with the flap too far from main element, which consequently cause stall condition since not protected from upward element downwash [10]. Within an optimisation, these candidates could affect the optimum found if the CFD convergence criterions have been selected too permissive. To increase procedure's robustness and face the cited topic, whenever candidate's RANS history has a standard deviation higher than a value (chosen in input) the simulation will be automatically excluded from optimisation. About the optimisation test cases presented in this work, the CFD setup considers compressible RANS and the Spalart-Allmaras turbulence model [11] with fully turbulent boundary-layer, but other turbulent models can be easily selected from those ones available in SU2. The chosen convergence criteria are the Cauchy series convergence criterion for both lift and drag along with density residual, imposing to the RANS simulations to exit whenever all the criteria are satisfied after a minimum of 1500 iterations.

The setup has been developed analysing several simulations on single and multi-element configurations. Numerical results have been compared with experimental tests [12], [2], [3]. The procedure supports multi-processing for distributed computing to take advantage of HPC.

4. Optimisation module

The innovative module of the procedure is the optimisation block, where the optimum solution is searched within the design space through a methodology chosen by the user. A schematics of the optimisation methodology is provided in Figure 4.

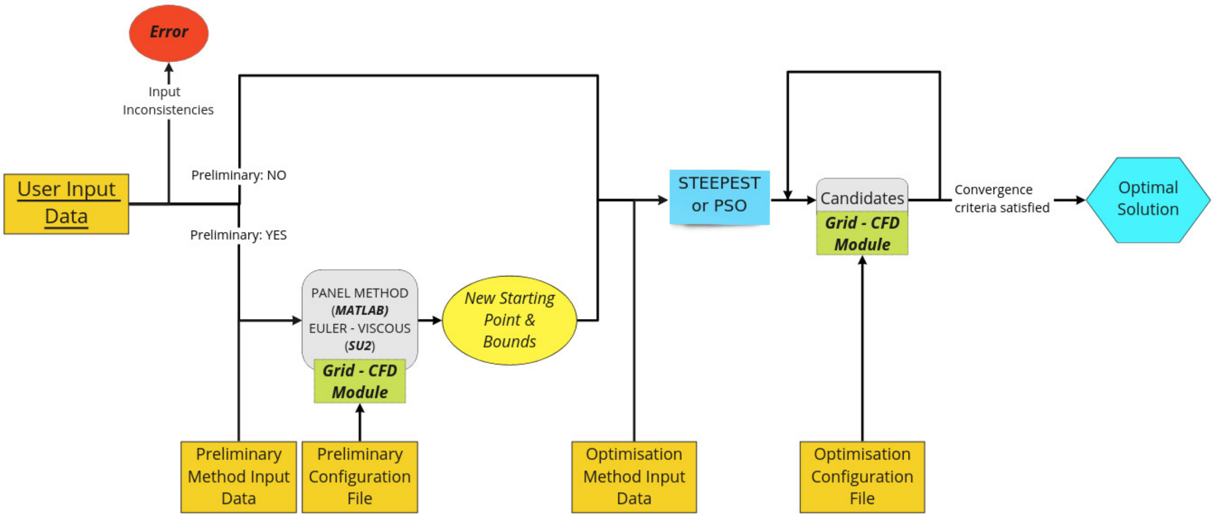

Figure 4 – Schematics of the optimisation methodology

At the current stage, two optimisation algorithms have been implemented:

- the Particle Swarm Optimisation (PSO), based on the standard version proposed by Clerc [13]. It belongs to the evolutionary optimisation methodologies: at each iteration, each candidate displacement is influenced by the optimum found previously by the entire swarm and by the specific particle, plus the previous iteration displacement and a random factor.
- the Steepest Ascent (or Descent) Optimisation, which is a gradient-based methodology already adopted in experimental multi-airfoils optimisations [2]. The user defines a starting point which moves within the design space driven by the fitness gradient, which is calculated based on fitness evaluation of an amount of candidates close to the centroid. Depending on the design space dimensions, these candidates are the vertexes of an hyper-pyramid with the centroid located on the previous iteration optimum.

Besides their respective definitions, the two implemented methodologies differ also about the performances: in particular, PSO is expected to have higher accuracy by improving the probabilities to find global optimum thanks to the larger population and random features related to each particle displacement and velocity. On the other side, Steepest Ascent requires less computational power since it typically requires a lower amount of fitness evaluations at each iteration. Anyway, the Steepest Ascent disadvantage is the higher risk to convergence to local optimum and consequently, PSO is expected to be more accurate. Steepest Ascent is suggested whenever high computational power is not available, meeting both sufficient accuracy and computational speed.

The tool guarantees again a wide customization: along with the details of the chosen optimisation methodologies cited above, the user can define maximum or minimum lift, drag, lift-to-drag-ratio and a combination of lift and drag as objective function; furthermore, the user can select constraints on the design variables, defining a custom design space for the analysis.

About the required computational time for the optimisation, various features have been implemented to guarantee a quick convergence to optimal solution. First of all, the procedure supports multiprocessing; secondly, low-fidelity preliminary studies have been additionally implemented in the tool: at the current stage, the user can select between Hess-Smith panel method or inviscid CFD simulations as preliminary study. These low-fidelity methods can be adopted to delineate a possible starting point for the design variables and to reduce design space by excluding all the candidates with not interesting fitness. Secondly, the preliminary studies can also involve a general reduction in computational time required for the entire optimisation. Whenever the selected objective function is maximum or minimum lift and the chosen preliminary study is Hess-Smith panel method, the user can also select the Valarezo-Chin criterion [1] to filter stalled configurations.

5. Validation Test case

In this section a demonstration of the procedure's potentiality is reported. The test case under analysis is the optimisation of a GA(W)-1 airfoil with maximum lift as objective function. The flow conditions are Re = 2.2e6 and Ma = 0.21. The starting configuration is with absolute angles of attack 7.7 deg and 37.7 deg for the elements; the flap element has a 30% starting relative chord.

The starting geometry has been reconstructed using a IGP parametrisation from the external data point to then initialize the optimisation. Consequently, the total amount of design variables is 21, composed as follows:

- the angles of attack of each element (2);
- flap element relative chord (1);
- slot dimensions, that is the distance between the main element trailing edge and flap element leading edge (2);
- IGP shape parameters of each element in the configuration (16).

Therefore, 5 design variables describe the configuration, while 16 defines the entire shape for a double-element configuration like the NLR 7301 in Figure 2 (left). Before the present test case, a validation of the procedure was executed by several optimisations about the slot of GA(W)-1 airfoil [14] with various methodologies: PSO appeared more accurate providing an error of about 3.3 % on the lift coefficient, if compared with experimental data [3] as best performance; Steepest Ascent was anyway sufficiently accurate, since the worst case provided an error of about 5.5%.

Instead, the test case presented in this section is thought to show the full potentiality of the procedure, with much more design variables. Also, the investigation is aimed at understanding whether the design variables of configuration and shape can be decoupled or not. For this reason, various optimisation strategies have been adopted for comparisons, as reported in Table 1.

The optimisation is subdivided in two steps, where the design variables under inspection are changed. Apart from the differences between the various tests, a preliminary study with Euler CFD with 80 candidates was considered in the first step to better initialise the optimisation and speeding up procedure. PSO has been the optimisation methodology chosen for each test, with 40 swarm particles. Lastly,

Test ID	**1^{st} Step**		**2^{nd} Step**	
	`Preliminary`	`Design variables`	`Preliminary`	`Design variables`
A	✓	Configuration	✓	Shape
B			×	
C	✓	Shape	✓	Configuration
D			×	
E	✓	All	×	All

Table 1 – Double-element configuration of GA(W)-1 optimisation: performed tests' details.

each optimisation step will exit after 11 iterations, guaranteeing a direct comparison between the optimisation strategies and possibly delineating the most efficient one thanks to the equal total amount of iterations (22).

5.1 Results

Table 2 and Figure 5 provide the main results and the optimisation history respectively.

Test ID	**AOA** [deg]		**Slot coord.** [%]		**Flap Relative Chord** [%]	$C_{L_{opt}}$ [-]	**Optimum improvement** [%]
	Main	Flap	Main	Flap			
A	9.254	46.321	1.97	-1.97	40.0	3.406	24.11
B	9.254	46.321	1.97	-1.97	40.0	3.469	26.40
C	6.530	45.673	0.80	-2.28	40.0	3.455	25.91
D	4.070	46.425	-0.19	-2.41	39.7	3.398	23.82
E	7.150	50.000	2.00	-2.57	40.0	3.538	28.92

Table 2 – Double-element configuration of GA(W)-1 optimisation: final tests' configurations details.

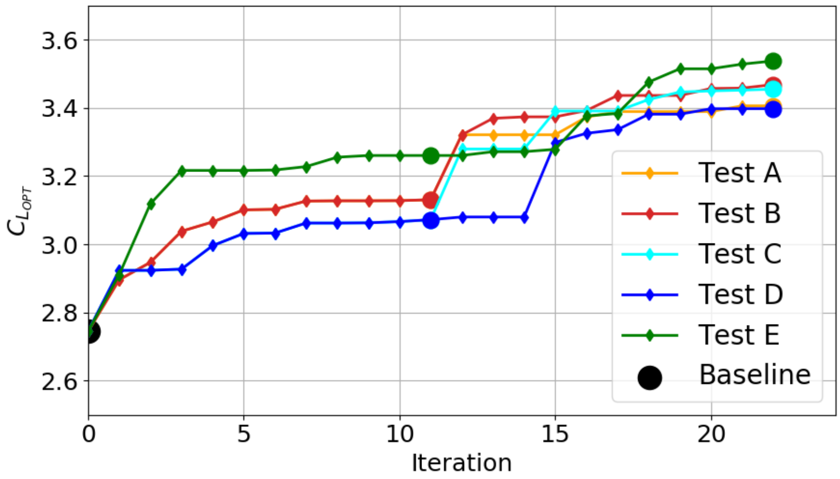

Figure 5 – Tests' optimisation histories.

Comparing the results, each strategy guarantees an improvement in the lift coefficient of about 20-30 % from the baseline configuration, highlighting the effectiveness of the tool for any adopted strategy. Anyway, the best performance is reached by Test E, which provides the configuration with the highest lift coefficient.

Consequently, considering all the design variables (both regarding shape and configuration) at the same time can be considered as the best strategy. Looking at the history plot, Test E provides the optimum airfoil with best performances at both first and second step ends (iterations 11 and 22). Decoupling shape and configuration design variables (such as in Tests A, B, C and D) is not the best-performing strategy, but it can however be considered to reduce the total amount of design variables considered contemporaneously during the optimisation. This reduction would provide the possibility to reduce the population size, and consequently the computational power required to perform the optimisation. Anyway, performing the optimisation at first on shape and then on configuration or viceversa makes no relevant difference. Lastly, Tests A and C can be compared respectively to Tests B and D about the adopted preliminary study's performance. Looking again at Figure 5 between step 1 and 2 (iterations 11-12), the Euler CFD preliminary study provides no benefit in Tests A-B comparison since the fitness provided at iteration 12 is almost equal. On the other hand, by comparing Tests C and D it can be noted a strong benefit provided by Euler CFD preliminary study: at iteration 12, adopting or not an additional iteration with inviscid simulations makes a difference of 6.5 % on fitness.

Since designed with different optimisation strategies, each test finds its own optimal configuration and shape. The only detail confirmed by each test is the flap relative chord, which reaches the imposed upper bound of 40 %. Higher flap relative chords were expected since they contribute in higher lift coefficient by increasing the total lifting surface. Similarly, the higher main and flap elements angles of attack were expected, getting closer to stall conditions. About the slot, the optimums agreed with the typical results of multi-element configurations: the distance between the two configuration elements is low enough to guarantee a benefit effect of main element down-wash on downward element, protecting it and delaying stall condition as consequence.

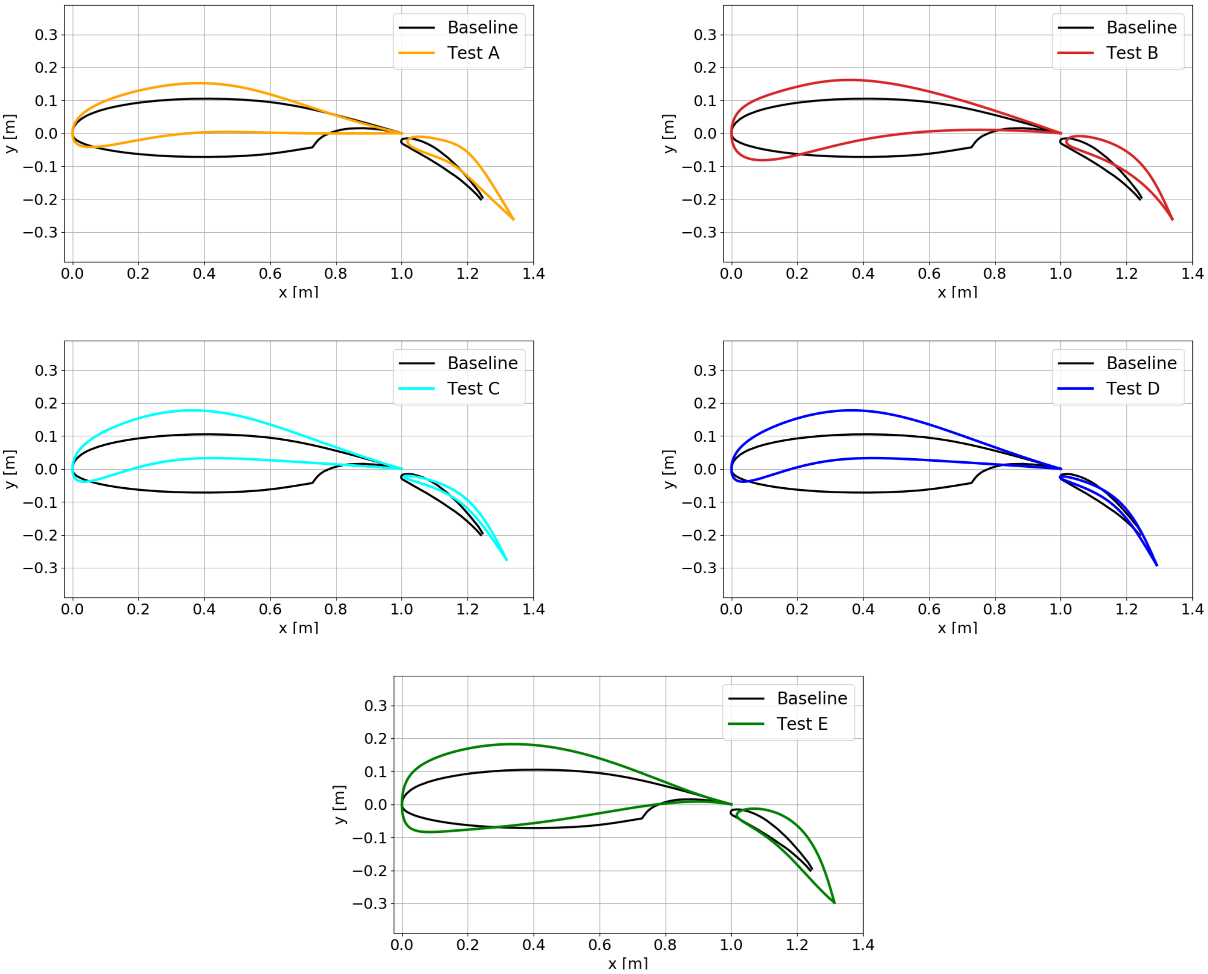

Figure 6 – Comparison between each test's optimised shape and starting one.

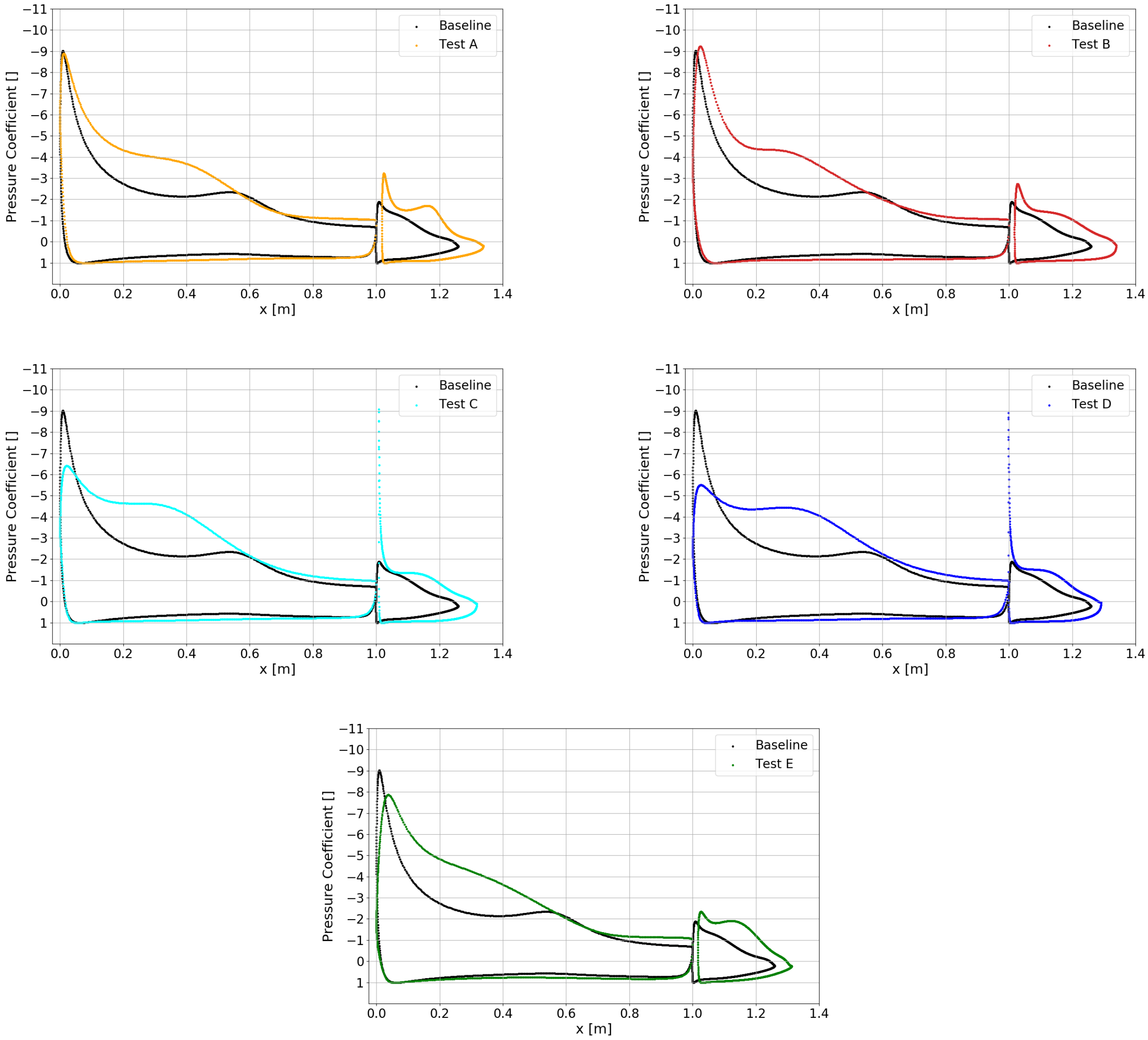

Figure 7 – Pressure coefficient distribution Comparison between each test's optimised airfoil and starting one.

Figure 6 reports the geometrical differences between the optimum shapes found by each test. Test E can be immediately noted as different: its optimum differs from the other tests by higher thickness in shape, both on main element and flap element. Figure 7 reports the comparison between the pressure coefficient distribution of optimums found and baseline configuration: an important extension of depression region can be immediately noted on both configuration elements.

6. Conclusions

After a successful test with a limited design space, the feasibility of the procedure has been demonstrated with a high number of design variables. The test case results show the potentiality of the tool, which is capable to tackle an optimisation of a multi-element configuration considering several design variables and guaranteeing a wide customization on several aspects (such as grid design, optimisation parameters etc). Compared to other methodologies, like adjoint method, the present procedure is convenient because it allows large modifications thanks to an automatic new grid generation instead of deforming the starting one. Although different strategies have been considered to optimise the same baseline double-element airfoil, each optimisation provides a strong lift coefficient improvement of about 20-30%. Comparing the strategies, considering all the available parameters as design variables (Test E) has appeared to be the best-performing approach, providing the optimum with the highest lift coefficient in less than 46 hours. Various developments can further improve the accuracy, applications, speed, customization and accessibility. For example, since entirely written using the open-source language Python, updates could easily investigate implementations of different and various optimisations methodologies (such as genetic algorithm or simulated annealing). They could be compared to PSO and Steepest Ascent to investigate the most efficient methodology with respect to speed and accuracy. Secondly, future developments could also provide access to different software, both for grid generation and for CFD simulations. Another important planned development regards the procedure extension to 3D wings with more complex features, which would improve the transfer of results to aeronautical and automotive applications.

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8. Copyright Statement

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