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EVALUATION OF DIFFERENT OPTIMIZATION STRATEGIES FOR THE DESIGN OF A HIGH-LIFT FLAP DEVICE

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Abstract. *The paper gives an overview of the optimization strategies studied within the MEGADESIGN project and their applications for solving the multi-point flap design defined within the European Eurolift II project. After a brief introduction of the test case definition, the solution procedure used at the DLR is depicted. More particularly, flap parameterization, mesh generation and flow solver are described. Three types of optimization strategy – evolutionary algorithm, deterministic gradient free approach and gradient based optimizer – are first tested on a coarse mesh to provide an insight into the design space and an assessment of their capability of finding the optimal solution. Finally, the most promising optimization strategies are used for the flap design on finer meshes. The optimized flaps are then analyzed to assess the meaningfulness of the design with respect to off design performance.*

1 INTRODUCTION

The wing of an aircraft is classically designed to reach the desired performance at cruise flight, which is a transonic condition for current commercial transport aircraft. At landing or take-off the aerodynamic conditions are so different that such wing can not fulfil the basic requirements without deployment of high lift devices. The basic idea of such a system is to increase the area of the wing in order to compensate the low velocity during the low-speed flight. Recently, the demands for noise reduction in the vicinity of the airport have led to stringent regulations which imply efficient and environmental friendly design of high-lift devices. The European project Eurolift II, started in 2004, is intended to provide advanced numerical tools and knowledge together with a thorough understanding of the flow phenomena for high-lift configurations. One of the tasks is devoted to the flap design of the DLR-F11 model in order to improve the take-off performance at 2 design points. At the same time, the CFD project MEGADESIGN [5] was initiated within the framework of the German aerospace research program. The main goal of this project is the development of efficient numerical methods for shape design and optimization.

This paper presents an evaluation of different optimization strategies for the design of a high-lift flap device. After a description of the test case in the second chapter, the main components of the aerodynamic optimization chain are outlined. More particularly, parameterization, mesh generation and flow solver are described and a brief introduction to optimization strategies concludes the third chapter. The evaluation of different optimization strategies on a coarse mesh gives a first insight into the design space and an assessment of their capability of finding the optimal solution. Finally the design of the flap using the most promising strategies is described in chapter five and the resulting geometries are analyzed in order to assess the meaningfulness of their design.

2 TEST CASE DESCRIPTION

The aim of the work is the flap design as defined within the Eurolift II project. Both the shape and position of the DLR-F11 wing-body model flap have to be designed in order to improve the take-off performance at 2 design points. A complete description of the optimization problem can be found in [17], here only the main steps are recalled.

The baseline geometry is a wing section, located in the middle of the outer wing part and between slat and flap brackets, so infinite swept wing assumptions are most likely to apply. While some partners are involved in the design using 2.5D flow infinite sweep wing, other calculations, like the DLR, carry out the design in 2D. In order to take into account the effect of the sweep angle of the wing, the selected streamwise wing section is normalized by scaling the vertical coordinate according to the sweep angle while keeping the retracted chord length equal to unity. In the same way, some normalization is necessary to simulate the related 2D aerodynamic inflow conditions and to retrieve the 2.5D aerodynamic coefficient. In order to perform a realistic design, 3D effects are taken into account by using the following relation:

$$CL_{3D} = \gamma_{CL} CL_{2.5D} \qquad (1)$$

$$CD_{3D} = \gamma_{CD} CD_{2.5D} + \frac{CL_{3D}^2}{\pi \lambda} \tag{2}$$

where γ_{CL}, γ_{CD} and λ are constant values, derived by correlation of 3D measurements and 2D computations [17].

The design focuses on an increase of the take-off performance within the complete flight range covered by the selected take-off setting. In order to achieve this, a two-points optimization has been defined, where each condition represent the limit of the design range (see table 1). The according objective function to minimize reads as follows:

$$F_{OBJ} = \sum_{i=1,2} w_i \times F_i \tag{3}$$

$$F_i = -\left(\frac{CL_{3D}^3}{CD_{3D}^2} \right)_{condition\, i} \tag{4}$$

and the weighting factors are set to $w_1 = w_2 = 0.5$.

Because the weight of the high-lift system kinematics depends on the horizontal flap deployment capability, a penalty is added to the objective function to avoid too heavy a mechanism. The relation between the horizontal displacement and the penalty is set according to industrial specifications. Also aerodynamic constraints are applied in order to avoid a decrease of lift and an increase of the pitching nose down moment.

Design Point	Mach	Reynolds Number	α
Condition 1	0.1715	14.70×10^6	9.6°
Condition 2	0.1715	14.70×10^6	14.785°

Table 1: Aerodynamic flow conditions

3 COMPONENTS OF THE OPTIMISATION CHAIN

3.1 Parameterization

In order to perform a realistic design of the flap, both coordinates and shape are considered. Three designs variables are assigned to the displacement of the flap: the x and y coordinates displacement of the flap and its angular deflection (figure 1). For the shape, only the part of the flap which is hidden when the flap is retracted is free for design. The test case specification imposes that the new shape must be smooth and must retrieve, at least tangentially, the baseline flap at specific points marked with circles in figure 1. The local flap chord is not allowed to increase. The maximum extent of shape variation is limited by a bounding box, representing the shape of the clean wing. Of course, this bounding box has to be properly moved when the flap is displaced and deflected. In order to automatically fulfill all these requirements, the free-form deformation [8] approach is adopted. The design space has been defined within the specified bounding box (right of figure 1) within which the shape is free to move smoothly. The space of the design is split in upper and lower parts which are continuously connected at the leading edge of the flap. The latter is free to move in such a way that the chord length remains constant. Special care is taken to ensure that the upper and lower parts of the flap are continuous, at least in the first order, at the leading edge. In total 7 design variables are defined for the new shape, one for the position of the leading edge and five plus one to control the upper part and the lower part respectively.

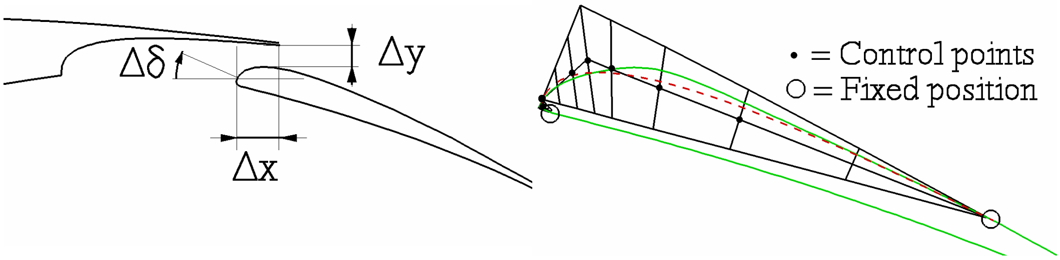

Figure 1: Parameterization of the flap.

3.2 Mesh procedure and flow solver

The quality of the computational grid plays a crucial role for the correct resolution of the complex flow which occurs around the 3-element airfoil. Furthermore, a grid generator applicable for optimization should allow the generation of grids of constant quality, in terms of smoothness and boundary layer resolution, around changing geometries in an automatic way. At the DLR, the grid generator MegaCads has been developed, which is able to fulfill these requirements [3]. MegaCads offers basic geometric operations like projection and intersection of spline curves and surfaces. The generation of grids includes algebraic, elliptic and hyperbolic techniques that guarantee smooth grids. Furthermore, the parametric and script concepts allow an automated generation of a new mesh from scratch for each geometry ensuring constant mesh quality, in contrast to mesh movement techniques. All new meshes are based on the same topology, a multi-block type mesh with 9 blocks, 90,065 points and designed for 3 levels of multigrid. Special care is taken to discretize the boundary layer and the wake of each element (figure 2).

The flow simulation software used is the DLR FLOWer code [6], which is a structured finite-volume RANS solver. For the discretization of the governing equations a central scheme of second order accuracy in space is used. From several algebraic and transport turbulence equation models, the Spalart-Allmaras model with Edwards modification is preferred for its accuracy and robustness. The steady RANS equations are integrated in time using a time-marching 5-stage Runge-Kutta scheme and typical convergence acceleration techniques, like multigrid, implicit residual smoothing and local time stepping are applied.

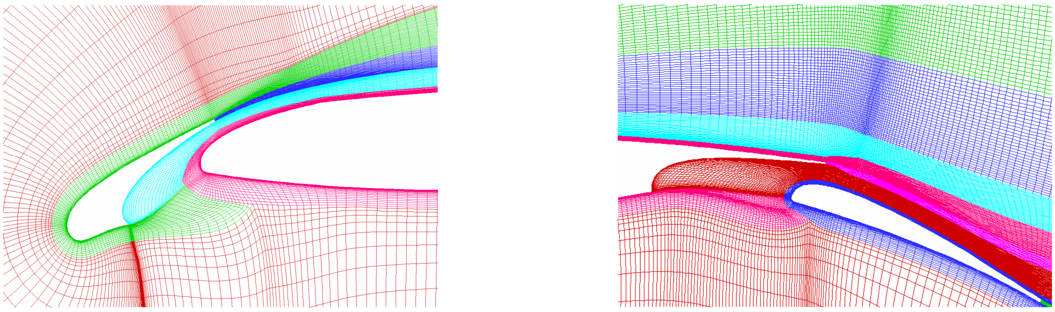

Figure 2: Details of the mesh around the elements.

3.3 Optimization strategies

Optimization techniques for numerical problems are very well-explored and several hundred algorithms exist, which makes it difficult to test them all for high-lift design. We voluntary limit our investigation to three representative classes of optimization strategies: a non-deterministic approach, a deterministic gradient free approach (GFA) and a gradient based strategy (GBS).

The non-deterministic approach is particularly suited to multidimensional global search problems where the search space potentially contains multiple local minima. Various approaches are available and one promising strategy seems to be Differential Evolution (DE) [11] which belongs to the group of evolutionary algorithms (EA). The EA models the development (mutation, recombination, selection) of a population over a number of generations, where the individuals are vectors of design variables. These strategies are called non-deterministic because they use random numbers to create new candidates (children). In contrast to standard EA, DE combines the mutation and recombination phases to one operation. The main idea is to use vector differences (mutation) and a variant of uniform crossover (recombination) for the creation of the children. The last phase (selection) is straightforward and very simple: the child replaces his parent if it is better. DE has been tested both on benchmark problems [14] and on real problems [12] and it often appears to be the best performing algorithm for finding the global optimum.

The simplex method [7] is a deterministic gradient free strategy, so called because it uses neither random number nor derivatives. The main idea is to build up a regular body with n+1 points in the design parameter space, with n the dimension of the design space: for two design parameters this will be for instance a triangle. At each vertex, the function is evaluated. The worst point is mirrored with respect to the geometric mean of the other points. The algorithm performs additional stretching and shrinking while moving through the domain. At the end, the simplex collapses into one single point. One possible extension of this approach is the subplex method [9] which first determines an appropriate set of subspaces and then uses the simplex to find a minimum in each subspace. This is repeated until convergence. Such an approach performs well when the sensitivities differ considerably between design variables and was successfully used at the DLR to carry out various high-lift optimizations [15,16].

Other approaches to minimize the objective function use the derivatives as a “search direction”. The optimum is then sought in this searching direction and new derivatives are computed. This procedure is repeated until all derivatives vanish. The steepest descent method is the simplest method, since it directly uses the negative gradient as searching direction. In the case of a constrained problem, following the steepest descent does not guarantee that the optimum is feasible in the sense that the constraints are not violated. Several ways to handle a constrained problem exist and good experience with the modified method of feasible direction [13] has been achieved at the DLR [2]. This strategy computes a search direction based on gradient of the objective function and the active constraints. This will reduce the objective function without violating the active constraints. For the present study, all required gradients are evaluated using forward finite differences.

For both the evolutionary algorithm and the gradient free optimizer, the constraints are handled by using penalties on the objective function.

These three optimization strategies are connected to the SynapsPointer® Pro optimization framework [4] which manages the run of the optimization process.

4 PRELIMINARY STUDY - EVALUATION OF OPTIMIZATION STRATEGIES

The main goal of this section is to evaluate the capabilities of the three optimization strategies to design the flap. In order to reduce the computing time, only the first design point is considered and the aerodynamic flow is evaluated on the coarser mesh which is the third multigrid level. A single evaluation of the aerodynamic chain requires then only 6 minutes on a single Pentium 4 3.4 GHz processor. Each of the three optimizations presented are deeply converged, more than is usually necessary, in order to ensure that the optimum is reached.

Optimization with an evolutionary algorithm. The population considered here consists of 10 individuals, allowed to evolve during 1,000 generations. Of the 10,000 required evaluations, only 143 individuals were not successfully computed. The best individual is obtained after 9,649 evaluations with an improvement of 7.3% of the objective function. Figure 3 presents the evolution of the best individuals according to the generation.

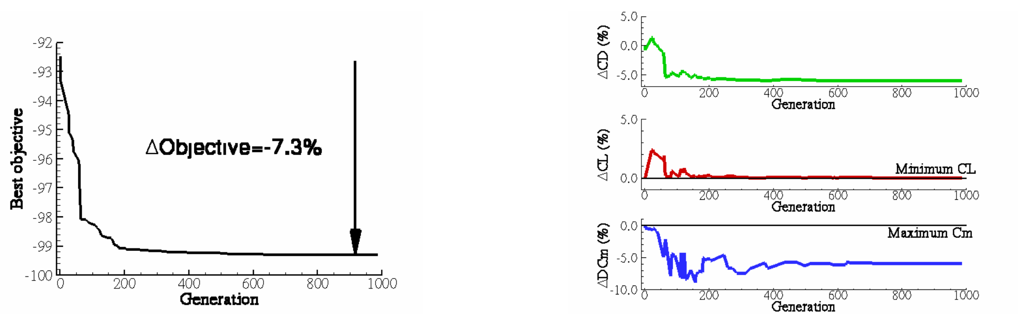

Figure 3: Evolutionary algorithm - Evolution of the optimization with the number of generation.

The DE rapidly converges after few hundred generations - 95% of improvement is reached after 200 generations - and then reaches a plateau where thousands of evaluations are required to slightly improve the solution. The aerodynamic coefficients for the best individuals are plotted on the right of figure 3. While during the 200 first iterations best candidates are those with a higher lift coefficient than the baseline configuration, the final best individual retrieves the initial lift with the lowest drag. The constraint on the pitching moment is fulfilled without problem.

Optimization with gradient free approach. Here, we define a cycle as a single resolution of all sub-problems. For the current flap design, 8 cycles are required to converge which represent 549 evaluations of the cost function. The optimum is found after 514 evaluations and its objective function is improved by about 6.4%. Figure 4 presents the evolution of the goal function and the aerodynamic coefficients according to the number of cycles. Here also, convergence is quickly obtained and 96% of improvement is already attained after the second cycle. The best solution exhibits a lower drag coefficient at the same lift as the baseline configuration and the pitching moment is decreased. However, the DE is able to find a better optimum, due to a greater decrease of the drag.

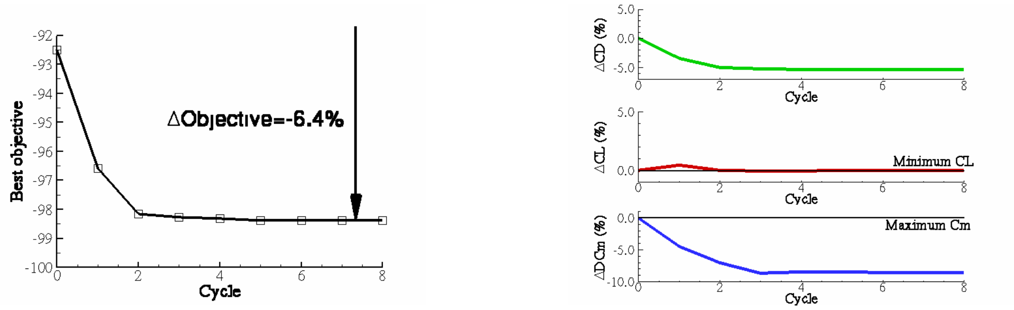

Figure 4: Gradient free strategy - Evolution of the optimization with the number of cycles.

Optimization with gradient based strategy. In contrast to the two previous strategies, optimization using gradients requires a rather long preliminary study. Firstly the best suited step size must be found for accurately evaluating the gradient with finite differences. A too small step might result in a change of aerodynamic of the same order of magnitude as the truncation error of the flow solution and in contrast, a too large step does not allow neglecting second order effects. A second problem arises from the big variation of the sensitivities toward the design variables. While the flap setting produces large variations of the aerodynamic coefficients, the shape variation introduces only small effects. Without any care, the optimization is not well conditioned and only a poor optimum is obtained. One way to avoid this is to artificially scale the variables in order to reduce the variation of the sensitivity. This requires some “trial and error” to succeed. After finding the right scaling, the optimization run is extremely fast and only 195 evaluations are necessary to find the minimum. Figure 5 presents the evolution of the optimization parameters according to the stage, where a stage includes a gradient evaluation and a line search. After 14 cycles, 6.0% of improvement is reached and at least 5 cycles are required to reach more than 95% of this level. This may be due to the accuracy of the gradient which degrades as the optimizer converges to the optimum and/or the optimizer gets trapped in a local optimum. A look at the aerodynamic coefficients confirm the trends obtained so far: the optimum is obtained by decreasing the drag at constant lift. In fact, a violation of about 0.3% of lift is allowed here in order to ease the optimization process and the optimum solution is at the limit of this tolerance.

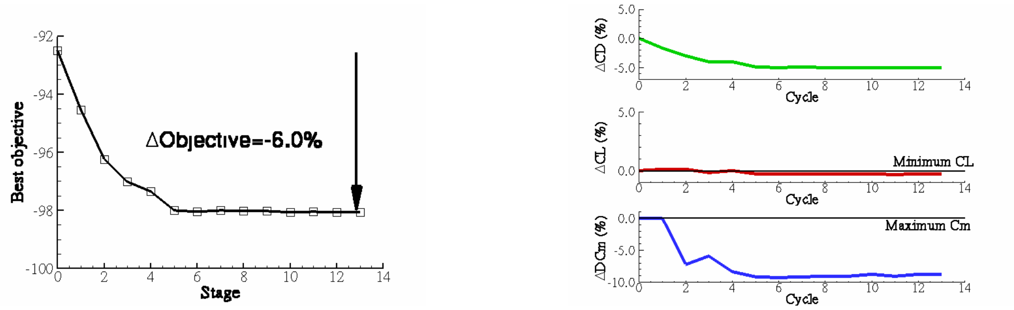

Figure 5: Gradient based strategy - Evolution of the optimization with the number of cycles.

The comparison of the flap position and shapes in figure 6 allows distinguishing the different designs. Compared to the baseline configuration, all three optimized flaps are more deployed, closer to the main wing, about 1 degree less deflected and with a sharper nose. More particularly, both deterministic approaches converge to almost the same setting and the same shape: it can be guessed that they converge to the same optimum. The discrepancy may come from the inaccuracy of the gradient computed during the GBS to retrieve the same optimum as the GFA. In contrast, the best flap obtained with the evolutionary strategy is 2 times more deflected and the flap is thicker: the DE finds a different optimum, better than those obtained with the deterministic approaches. It can be deduced that the design space has several minimums and only the EA is able to find the globally best solution.

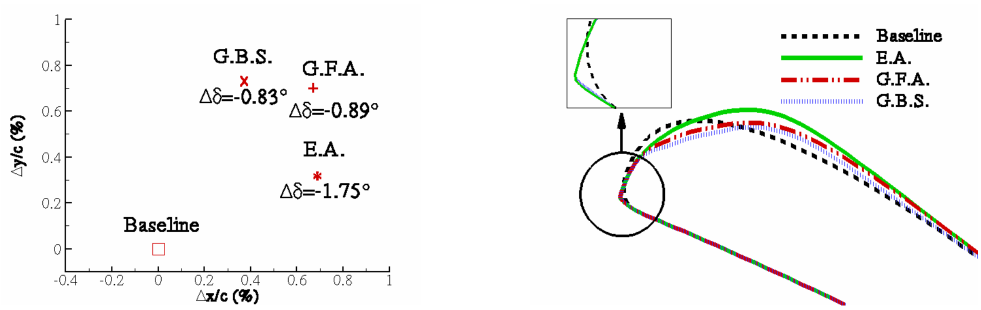

Figure 6: Comparison of the different optimized flap settings and shapes.

Table 2 compares the performance of the different optimization strategies. The wall clock time indicates the equivalent number of flow evaluation on one or 10 processors. By using 10 processors, the time needed for gradients computation is for instance of the same order as using the adjoint approach [1]. In the same way, the time needed for one DE generation with a population of 10 individuals would be equivalent to a single evaluation. According to table 2, the gradient based strategy requires 20 times less time than the DE on a single processor. Thanks to the inherent capability of the evolution strategy to be parallelized, this ratio can be decreased to 12 if one uses 10 processors. The GFA is badly parallelized and it is of better interest to try to decrease the wall clock time by computing the flow solver in parallel.

A last important criteria concerns the robustness of the optimization strategies toward noise and failure. It has been found that the gradient based strategy is highly sensitive to noise in the objective function. This implies for instance high convergence of the flow solver. In the same way, a failure during the evaluation stops the optimization. In contrast, the gradient free and the evolutionary algorithm easily handle failures and are more robust to noise.

Equivalent wall clock time	EA	GFA	GBS
on 1 processor	9,857	549	195
on 10 processors	1,000	477	78

Table 2: Comparison of the peformance.

The current study was done on the coarser mesh which can not accurately predict the aerodynamic coefficient and the according design space may not be representative of the aerodynamic problem. However, it has been checked that these results remain almost valid on the finest mesh (table 3). Indeed, the improvement is confirmed and the flap designed by DE on the coarse mesh has the best improvement while the flaps designed by deterministic approaches provide close results. It can be concluded that the optima found on the coarse mesh are aerodynamically meaningful and the conclusion drawn using the coarse mesh is also valid on the finest mesh. Of course, the optimum found here is not guaranteed to be the optimum for the flap design and new optimizations have to be performed on finer meshes.

To conclude, the gradient based optimization strategy is the most efficient strategy but difficult to apply for high-lift configurations. In contrast, DE is the most robust approach and the only one able to find the best optimum on this multi-modal design space. Finally, the gradient free strategy presents the best compromise between efficiency and robustness.

Flap designed with	ΔF1 (%)	ΔF2 (%)
Evolutionary algorithm	3.5	2.5
Gradient free approach	2.7	1.8
Gradient based strategy	2.7	2.0

Table 3: Verification on the finest mesh.

5 FLAP DESIGN

This chapter is dedicated to the aerodynamic flap design, as defined in chapter 2. In the preliminary study, good results have been obtained by optimizing the flap on the coarsest mesh at only the first design point. However, verifications on the finest mesh show that the constraints on lift are no longer satisfied. The design must therefore be done on finer meshes with preferably the EA. A single aerodynamic evaluation takes about 1 hour wall clock time on the finest mesh by computing the flow in parallel on 4 processors, and 30 minutes on the middle mesh on a single processor. Because the multi-point optimization with DE would take too much time on the finest mesh, only the first condition and the middle mesh is considered. The population is composed of 10 individuals spread on a cluster of 5 processors and allowed to evolve during 500 generations which should be enough according to the preliminary study. For purpose of comparison, a multi-point optimization is performed with the gradient free approach, each condition computed on the finest mesh. The procedure is speed up by using 2 clusters of 4 processors, each cluster solving independently a design point.

The comparison of the different optimization results is given in table 4, where results obtained with EA are recomputed on the finest mesh. Here again, the best design with the differential evolution (EA-Best ID) outperforms the deterministic approach (GFA) for both design points.

A look at the results confirms the trends obtained so far (figure 7): the optimized flap is more deployed, closer to the main wing, less deflected and presents a sharp nose. The shape designed by the subplex is rather surprising with its double bump and this may be due to the strong penalty applied on the flap deployment. In fact, this constraint is acting as a “barrier” and artificially favors a displacement close to the main wing. The shape modifications tend to locate the minimum pressure peak of the flap right behind the main wing trailing edge (figure 8) and the flow in the duct is of only minor importance for the aerodynamic performance. This allows a transfer of lift to the main wing and a drag improvement on the flap. At a given lift coefficient, a decrease of around 14 drag counts is obtained with GFA and almost 20 drag counts is reached with EA (left of figure 9).

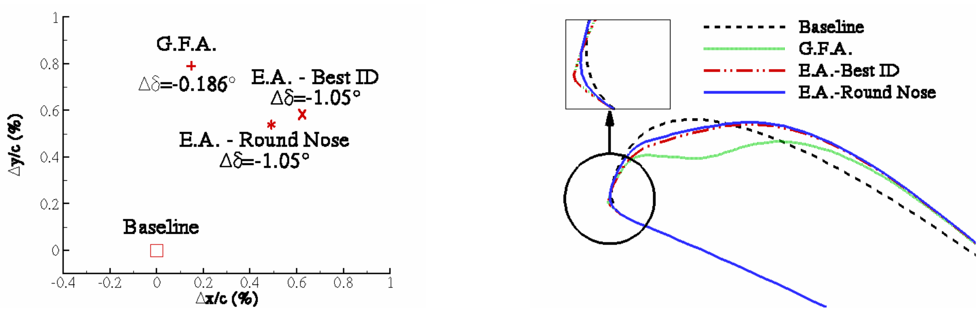

Figure 7: Comparison of the different optimized flap settings and shapes.

However, the configurations with a sharp nose, well suited for the take-off design case, have poor performance in a landing configuration, where the maximum lift at higher flap deflection is of main importance (right of figure 9). Instead of starting a new optimization, the best candidate with a round nose is searched within the solutions explored during the DE run. To ensure that this new configuration is optimal, a subplex run is performed and an improvement of only 0.05% is achieved. The aerodynamic state for this geometry is then checked on the finest mesh and the corresponding performances are reported in table 4 (EA-Round Nose). This new geometry exhibits good performance, not only in take off condition where the drag is reduced by about 17 drag counts but also in landing configuration where the maximum lift is improved by 4 lift counts (figure 9). This last geometry is then retained as the best geometry for the flap design.

Design	ΔF1 (%)	ΔF2 (%)
GFA	-2.2	-1.7
EA-Best ID	-3.1	-2.2
EA-Round Nose	-2.8	-2.0

Table 4: Comparison of the peformance.

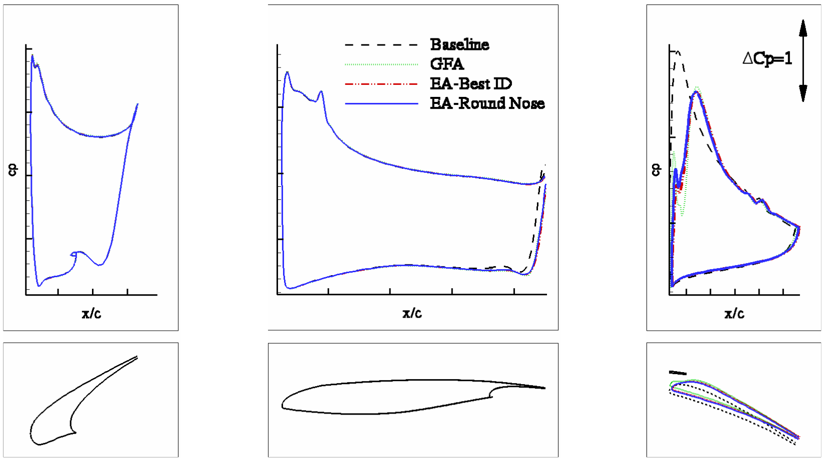

Figure 8: Comparison of pressure distributions for initial and optimized flap (Condition 1).

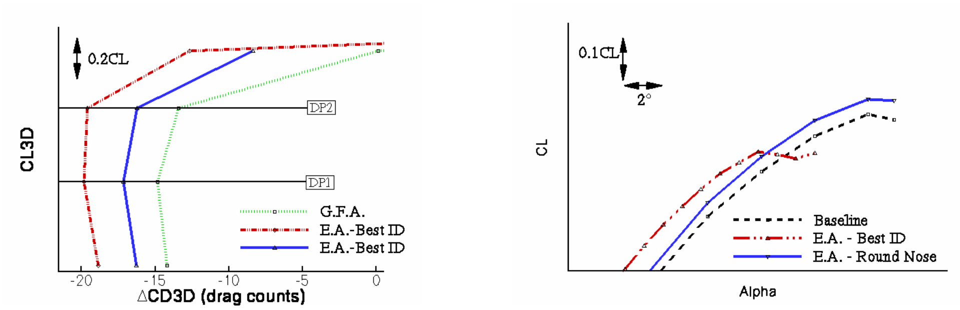

Figure 9: Drag improvement in take-off and polar in landing configuration for the initial and optimized shape.

6 CONCLUSION

The multi-point flap design defined within the European project Eurolift II was presented. Three different optimization strategies (gradient based and gradient free optimizers, evolutionary algorithm) have been evaluated for the design of a flap in high-lift configuration. Calculations on a coarse mesh have given a first insight into the design space and an assessment of their capability of finding the optimal solution. It is seen that the evolutionary algorithm outperforms deterministic approaches but requires up to one order of magnitude more time than gradient based strategy. However, the latter is tedious to use for a high-lift configuration. The deterministic gradient free approach obtains the best compromise between efficiency and robustness. Finally the flap was designed on a finer mesh with EA. By taking into account recommendations for landing configuration, a realistic design was obtained and the corresponding flap reduced the drag by about 17 drag counts in the take off phase. This work is pursued now in the frame of the MEGADESIGN project. The gradient approach will be improved by using the discrete adjoint and promising results have already been achieved [1]. Coupling strategies or mixing levels of mesh will be also investigated in the near future.

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