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GA Optimization Design of Multi-Element Airfoil

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Abstract: The CFD analysis and optimization of multi-element airfoils are presented. Window-Embedment technique is used to automatically generate the grids along with the geometry evolving. The CFD code named NSAWET is employed for performance and flow field analysis. The Genetic Algorithms are used in along with gradient methods to get a good compromise of global optimization capability and efficiency. Man-in-loop idea is realized in the process to make the computer automated process practical and realizable. The results of single-point and dual-point optimization are compared.

Keywords: Multi-element Airfoil, Optimization, Navier-Stokes, Genetic Algorithms

1 Introduction

With the great improvements in CFD, optimization algorithms and computer power, the automatic Aerodynamic Geometry Optimization (AGO) is becoming more and more feasible in modern aircraft design. However, "try and error" is still overwhelming in the industry's engineering design. The efficiency and the engineering applicability of the AGO still need to be improved to make it fully accepted by the designers.

In the civil transoprt aircraft aerodynamics design, the design of high lift devices is a critical part. Dam C. P. [1]pointed out that an 1% increment in the maximum lift will lead to a 2-ton improvement in payload, with the same approaching speed. Although its results can not be directly applied to the 3-D design, the 2-D multi-element airfoil design remains an imortant procedure of the high-lift design. The experience and design concepts gained in the 2-D process can form the basis of 3-D design. There have been many research works on the 2-D multi-element airfoil design.

The deflection and displacement of the slat and flap, as well as the geometry profiling of them from the baseline airfoil, form the design parameter set, which is relatively small when compared to that of airfoil design or wing design. Therefore the modern optimization methods are able to be more frequently applied in the 2-D multi-element design.

To realize a computer automated optimization design, on the CFD side, the efficiency and accuracy of the CFD analysis, the automation of the geometry definition and grid generation are the problems that must be well solved first. On the optimization side, besides the optimization algorithms, the design objectives and design restrictions need to be carefully specified to achieve good convergence and get a rational design results. Even though, optimization practises are often complained to give impractical results. Everyone dreams that someday computer can do everything automatically for us. However, until now, the designer's expertise and experience must be able to be incorporated in to the automated design process.

This paper will introduce the authors' recent efforts on incorporating the Navier-Stokes analysis with Genetic Algorithm for the AGO of multi-element airfoils.

2 CFD Analysis and Optimization method

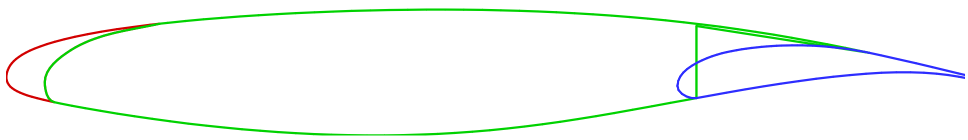
2.1 Geometry definition

The design of high-lift configuration always begins with a well defined baseline airfoil. The Profile Cutting (PC) for the slat from the leading edge and the flap from the trailing edge of the baseline airfoil are conducted by using the 3rd order spline. See fig.1a. Usually in engineering design, such PC is defined by cones curves or elliptical curves. Since the PC will shape the leading edge of the main element and the flap, which are essential to the performance of the high-lift configuration, splines are expected here to improved the controbility and smoothness of the curves. The location and orientation of the flap and slat are defined by Deflection angles, Overlap and Gap (DOG).

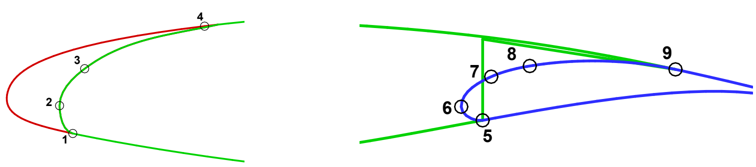
The coordinates of the PC control points, as well as the DOG parameters, form the design parameter set for the optimization. As an example shown in fig.1b left, there are 4 spline nodes to define the curve for the slat cutting. Among them, point 1 and 4 are stationary points, nothing needs to be changed. Point 2 is the leading edge of the main element. Since the chord length is settled, only the y coordinate is variable. Both x and y coodinates of Point 3 can be changed during the optimization. So there are 3 design parameters for this curve. For the flap cutting, five points with 5 design parameters are used to define the curve. The slopes on the two ends of each curve are set to be tangiential to the local baseline airfoil. Restrictions should be introduced to ensure the convexity of the curves.

The deflection angles are defined relative to the stat and flap's stowed orientations (see fig.1a). If the trailing edge of the slat overlap the main element by some x extent, we define the overlap to be x/c, where c is the chord length of the baseline airfoil. A negative value of overlap means the trailing edge of the slat is apart from the leading edge of the main element by some x extent. For the flap, the overlap is similarily defined. For the slap, gap means the shortest distance between the slat trailing edge and the main element. For the flap, gap means the shortest distance between the main element's trailing edge and the flap.

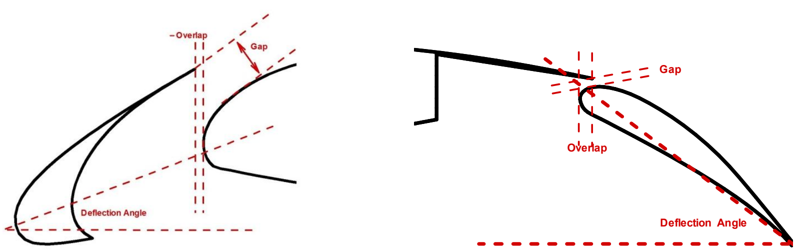
All together, 14 design parameters are used to define the geometry of the high lift configurations. Such a relatively small number makes the optimization design methods better applicable.



a. Baseline airfoil



b. Profile Cutting(PC) definition



C. Deflection，Overlap and Gap(DOG) definitions of the slat and flap

Figure 1: Geometry definition of the high-lift airfoil

2.2 Grid Generation and CFD code

The Window-Embedment strategy[2] is employed in the grid generation. A C-grid is first generated about the baseline airfoil. Then two windows are opened for the slat and flap respectively. Two H-grids are generated for them, as well as the cutted geometry of the main element, in the windows. With this grid generation strategy, during the optimization process, the evolution of the geometry and the regeneration of the grid are localized in the windows. The grid regeneration is greatly accelerated. The effects of the grid change to the CFD results are also minimized. It is well known that the optimization evolution relys heavily on the tendency of the performance change. The unphysical change to the performance brought by the grid should be eliminated as much as possible.

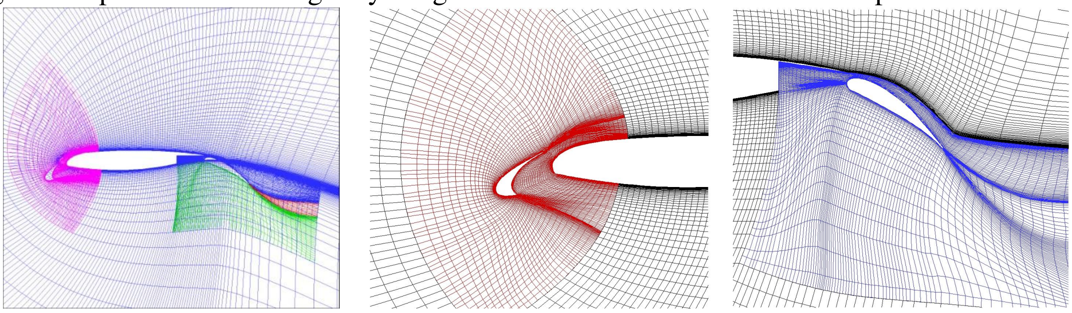


Figure 2: Geometry definition of the high-lift airfoil

The in-house developed CFD code NSAWET (Navier-Stokes Analysis based on Window Embedment Technology) is used as the performance analyzer [2-5]. It's a structural grid RANS solver based on cell-centered finite volume method. Multiple spatial and time advancing schemes and several widely used turbulence models are integrated in this code. According to the past experiences of using NSAWET[2-5], in the present numerical simulation, Roe's FDS spatial discretization and LU-SGS time stepping, as well as SST turbulence model are selected.

In order to make the optimization be directed to a correct direction and produce a "real" optimum design, the performance analyzer must be a relizble one. In the present paper, the Window-Embedment grid and NSAWET code are both verified by the standard Douglas 3-element airfoil test case (fig.3) first. From the pressure distrubution and the streamline plots in fig.2, for angles of attack ranging from small value to poststall value , the CFD results agree very well with the test data. The separation on the flap and its effect to the Cp distribution is well captured.

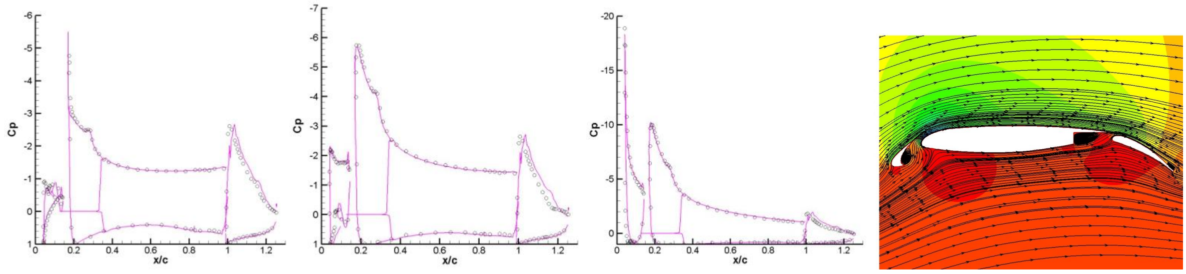


Figure 3: Validation of the NSAWET code and Window-Embedment grid by MD 3-element airfoil

2.3 Optimization Procedure

The deflection of slat will delay the airfoil's leading edge seperation and increase the airfoil's curvature, enhance its capability of producing the circulation. The deflection of the flap will also increase the curvature of the airfoil, increase the linear lift. However, with the increase of the curvature, flow will tend to seperate on the main element and flap because it has to go through turns to follow the "bended" upper surface. To increase the stall angle of attack, multi-elements design are proposed to creat suction peaks and segment the pressure recovery. Gaps between the elements are designed to create jets to energize the boundary layer for separation control. The jets' direction and strength control the effect of stall delaying. They are governed by overlap, gap together with the local surfaces of the elements.

According to the above analysis, the performance of the high-lift configuration are determined comprehensively and nonlinearily by all the design parameters. Such a situation posts great difficulties to the optimization methods. This is especially true when multi-objective or multi-point design are required.

Theoretically Genetic Algorithms (GA) are good at handling such type of nonlinear, multi-parameter, multi-objective optimization. It has excellent capability of global optimal value searching. The property that the GA optimization can be seperated from the flow solver especially makes it attractive to aerodynamics designers. However its excessive computer resource consumption and sometimes irrational results are still preventing it from being widely applied in engineering.

To solve these problems of GA optimization, the typical optimization process in the present research is illustrated in fig.4. GA optimization is used at the beginning of the optimization process to make it possible to get solutio close to the global optimum value. During this GA "phase", monitoring and artificial controlling of the optimization are conducted by the designer. The generated individuals can be killed or modified. New individuals can introduced into the population. The weights of the design ojectives and restrctions can be adjusted. This approach can help the experienced design better control the evolvement direction, and better realize their design idea. For designer who wants to get some ground breaking results, such an approach can also help to improve the diversity of the population and raise the possibility of finding new design peak. The GA is not treated as a black box. Such an idea is called " men in loop". Such an engineering treatment to the GA is proved to be effective in acclerating the convergence and producing more engineering applicable solutions.[3]

When genetic optimization is about to converge, the optimization is shifted to gradient methods. This will help to greatly shorten the whole iteration process.

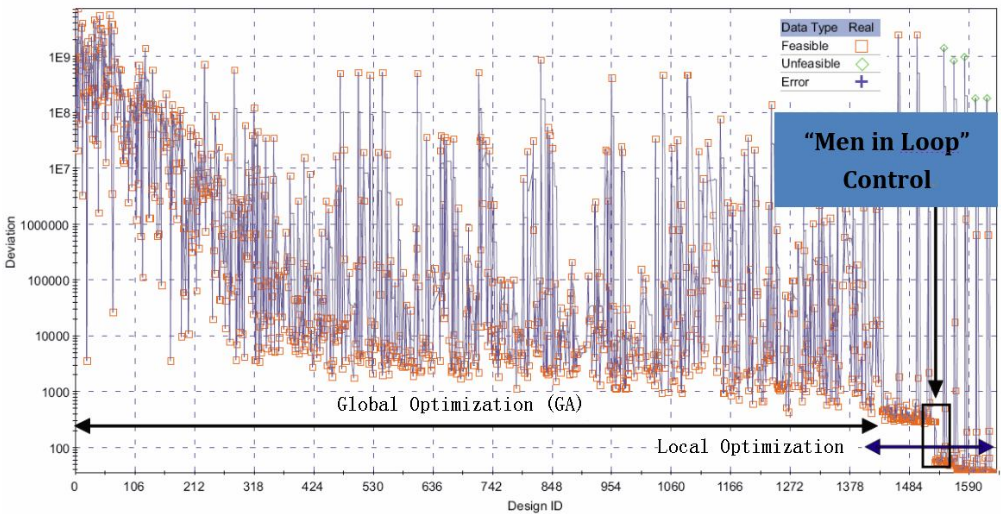


Figure 4: Flow chart of optimization procedure

3. Optimization Results

For the landing configuration, usually a larger maximum lift coefficient is pursued. However it is prohibitively expensive for the CFD to capture the maximum lift in the optimization process. Therefore the design point is set to be M=0.20, Aoa=18deg. At such an Aoa, the flow should be close to stall but still with some margin. The maximum Cl at this point is set to be the design objective. An improvement on this point's lift is expected to drive the peak value of the lift curve up.

The single point design for DOG is conducted first. The optimized result is shown as the red line in fig.5a. The lift at the design point do increased by only a little amount, but the maximum lift is improved by about 0.1. An unexpected non-linear jump can be found near Aoa=16 deg. Apparently the single point optimization does not improve the Cl on the linear section of the lift curve and even decreased the lift at Aoas from 10 degree to 16 degree.

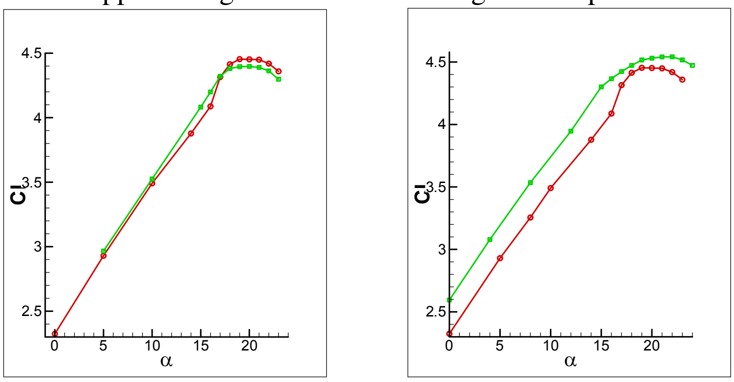
In order to improve the linearity, dual-point optimization is conducted. Maximum Cl at M=0.20, Aoa=8 deg is added as another design objective. 8 degree is an Aoa for normal approaching, the lift improvement at this point is also benificial. With this effort, as shown in fig.5b, on Cl curve of the dual-point optimized configuration (green line in fig.3b, corresponding to the circled point 1 in fig.6), the lift at 8 degree increased harmoniously with that at 18 degree. The lift curve shows much better linearity than the single point one (red line). The optimized DOG paramters are compared between single-point and dual-point design, as is listed in table.1.

Table 1: DOG parameters of optimized results

	Slat			Flap		
Parameter	Gap	Overlap	Deflection	Gap	Overlap	Deflection
Single Point	0.03	-0.005	20°	0.018	0.004	37°
Dual Point	0.03	0.005	23°	0.014	0.006	40°

A 16-individual population is used for the GA opimization, usually 50 generations need to be evolved for convergence. As an example, for the single point optimization, all together 660 effective configuations are computed.

When the DOG and PC are coupled in the optimization, the Pareto front of the dual-point optimization (fig.6) can be greatly extended. As is shown in fig.6, A, B and C are 3 candidate configurations for engineers to select. A has the largest peak Cl. C has the best performance for normal approaching. B can be seen as a good compromise of the two ends.



a. Single-point optimized configuration vs. baseline configuration

b. Single-point optimized configuration vs. dual-point optimized configuration

Figure 5: Optimization results

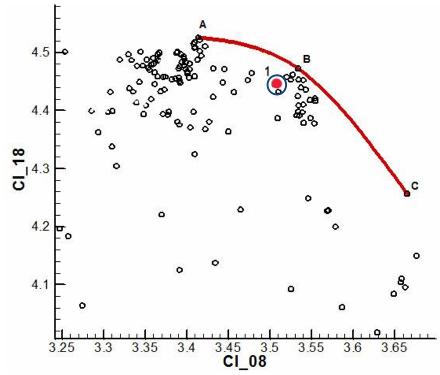


Fig. 6 Extended Parleto front by DOG/PC integrated optimization

4. Conclusion and Future Work

The NS analysis is integrated into the automatic Aerodynamic Geometry Optimization of multi-element airfoil. Window-Embedment technology greatly simplified the grid generation and the numerical simulation in the process. Man-in-loop idea can accelarate the convergence of the optimization iteration and make the process able to produce more practical results. Dual-point optimization shows obvious advantages when compared to the single point design. The DOG/PC coupled optimization can produce multi-element airfoil configurations with better performance.

Acknowledgments

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