Aircraft design optimization by means of Radial Basis Functions mesh morphing

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Abstract

This paper details an aerodynamic design method based on a numerical optimization procedure in which the problems of geometric parameterization and computational domain update were faced using a particularly efficient mesh morphing tool. The method was tested for the aerodynamic optimization of the well-known DLR-F6 aircraft model.

The automatic analysis procedure was developed within the ANSYS Workbench optimization environment coupling the RBF-Morph morphing software, as domain modification tool, and ANSYS Fluent as CFD solver.

The numerical configuration was validated comparing the CFD solutions obtained on the baseline geometry with the experimental data obtained in the ONERA S2MA transonic wind tunnel. A mesh morphing procedure was setup to generate a parametric mesh with witch to compute the Design of Experiments (DOE) solutions data set. An optimization criterion, based on Genetic Algorithms, was then applied on the computed Response Surface to drive the search toward the optimum.

The present research has been developed by the University of Rome Tor Vergata in partnership with D'Appollonia.

Introduction

Aerodynamic design and development of civil and military aircraft relies to an increasing extent on *Computational Fluid Dynamics* (CFD) analysis tools as time goes on. Aircraft design optimization driven by a CFD study combined with mesh morphing allows to improve aircraft performances in a reasonable time.

The design process starts defining the mission and the required performance of the aircraft. Commercial airliners require great aerodynamic efficiency in order to reduce fuel consumption and to increase the cruising range. Furthermore, the increase in the air traffic also means greater emissions. An higher aerodynamic efficiency contributes to reduce the environment impact.

The aim of this work is to provide a suitable method for aircraft design optimization by means of radial basis function (RBFs). The suggested workflow can be applied to a wide range of fluid dynamics studies where a shape optimization is needed.

In the present research the wing shape optimization of the *DLR-F6* model has been accomplished defining five *shape parameters* for the wing and three for the engine nacelle. The parameters are: the dihedral angle, the sweep and the twist angles of two wing regions, the vertical and horizontal rigid translations of the nacelle and its rotation along an axis perpendicular to the symmetry plane. The range of variation of each parameter represented the constraints of the optimization.

The first step of the work consisted in validating the numerical configuration against the experimental data measured in the French national aerospace research center (*ONERA*) S2MA transonic wind tunnel.

In order to test the performances of the mesh morphing tool the method was applied, to both a coarse grid (3 million of cells) and a fine one built with 14 million of cells.

In order to test the performances of the mesh morphing tool, the RBF procedure was applied, with the same setup, to two levels of meshes: a coarse grid with 3 million of cells and a fine one with 14 million of cells. Both meshes were hybrid and unstructured. The commercial morpher software used (RBF-Morph) showed to be very efficient also with the fine mesh which was then used in the optimization procedure. The defined parametric computational domain was used to analyse the set of solutions selected by a DOE (Design of Experiment) method. The whole procedure has been automated using *ANSYS Workbench.*

RBF Tool description

Radial Basis Functions (RBF) are powerful mathematical functions able to interpolate, giving the exact values in the original points, functions defined at discrete points only (source points). The interpolation quality and its behaviour depends on the chosen RBFs. In the field of mesh morphing radial basis functions find their natural application.

Using RBFs can be indeed modified the displacement at discrete points, and interpolated congruently every nodal position of the grid in a mesh independent fashion, as it deals with points positions only.

Radial Basis Functions are the ideal tool for the grid generation problem in a design optimization. Instead of having to rebuild the mesh at every step to take into account new a configuration of the wing, the new shape can be obtained imposing the displacement required by the user to the source points, and morphing accordingly to the wing shape and the fluid domain using RBF. An important amount of time and computational resources can be saved integrating the RBF morpher into the workflow.

Workflow

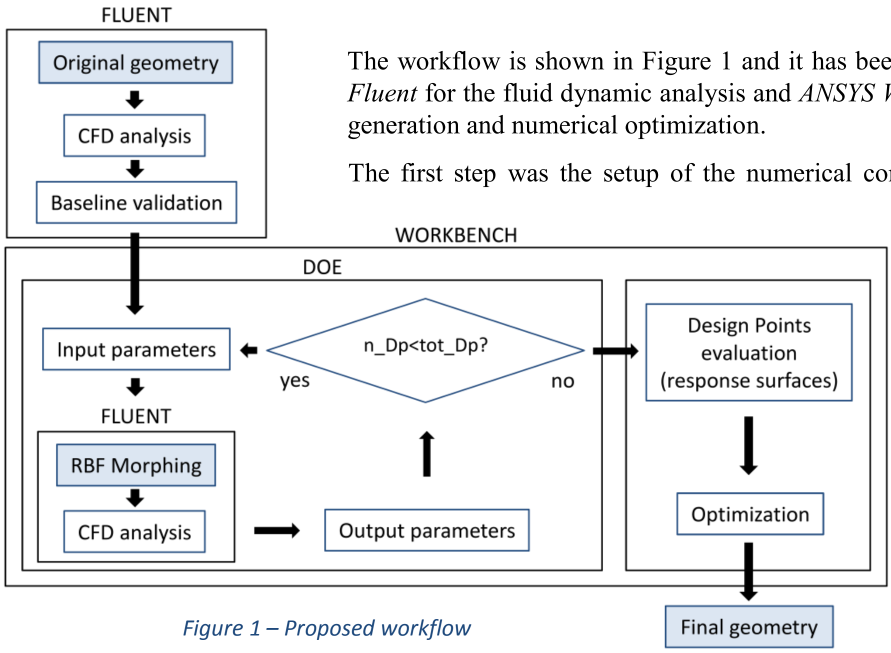

Figure 1 – Proposed workflow

The workflow is shown in Figure 1 and it has been implemented using *ANSYS Fluent* for the fluid dynamic analysis and *ANSYS Workbench* for the DOE table generation and numerical optimization.

The first step was the setup of the numerical configuration and the analysis, with *ANSYS Fluent*, of the baseline geometry in cruising condition. The results was compared with the experimental values from wind tunnel tests at the *ONERA* facility. The mesh morphing has been then applied using *RBF-Morph* in order to obtain parametric meshes.

The optimization process follows with the computation of the DOE table solution, the generation of the Response Surface and the application of the search algorithm.

DLR-F6 geometries

Since 2001, several case studies were proposed by AIAA (American Institute of Aeronautics and Astronautics) in order to involve a large number of aeronautical experts and software developers in a common assessment session of Navier-Stokes solvers. These kind of studies were called Drag Prediction Workshop (DPW).

The aircraft model used for the work presented in this paper is the DLR-F6 which was proposed as a test case for the second Drag Prediction Workshop held in Orlando in 2003. Details of the model are shown in figure 2 (dimensions in millimetres). The configuration consists in a complete aircraft with fuselage, wing, nacelle and pylon (WBNP) excluding the tail. This model is representative of a typical modern twin-engine passengers aircraft and was extensively used as a base of validation for CFD codes.

The wing sweep angle at the leading edge is 27.1°, the aspect ratio is 9.5 and the dihedral angle is 4.8°.

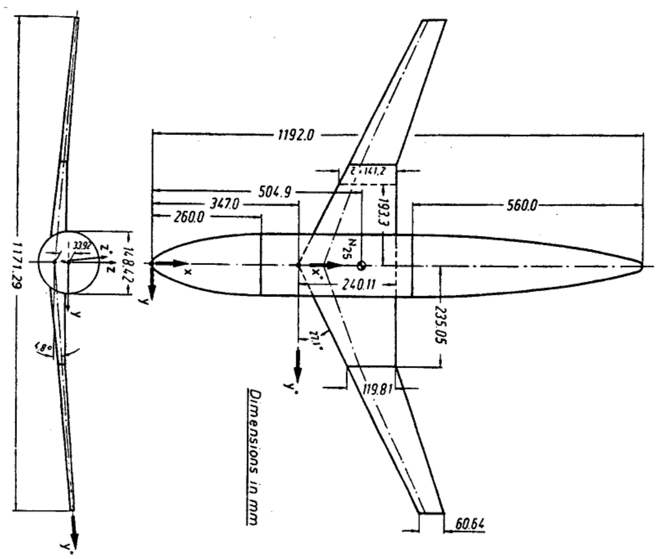

Figure 2 – DLR-F6 geomery

RBF Morph Setup

A brief description of the parameters that have been selected for the DLR-f6 wing optimization is presented in the following section.

The limits in the range of variation for each parameter constituted the constraints of the optimization problem. It was assumed a fixed angle of attach and the aerodynamic efficiency (ratio between lift and drag) was defined as objective function.

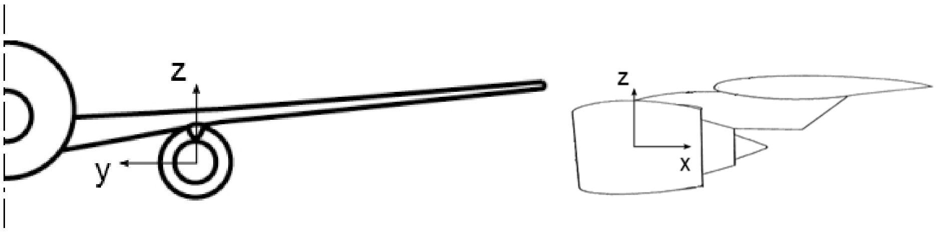

Figure 3 – Nacelle local axes

The presence and the position of the nacelle effects the aerodynamics of the wing and plays a role in the overall aircraft performance. The nacelle position is defined by three design variables: translation along z axis and x axis and rotation around y axis (figure 3).

Amplification values, which are implemented with *RBF Morph*, must be multiplied by the displacement used in mesh parametrization. The increment in the displacement is 1 mm for translations and one degree for rotation.

Aircrafts approaching transonic speeds need swept wings to reduce the fluid compressibility effects and its consequent increase of drag. Such configuration contributes to delay the Drag Rise and to increase the speed without raising the thrust. The aerodynamic efficiency, however, is in general negatively affected by the introduction of the sweep angle. Furthermore the inner and the outer region of the wing have different structural and aerodynamic requirements that often would involve the opportunity to apply different sweep angles.

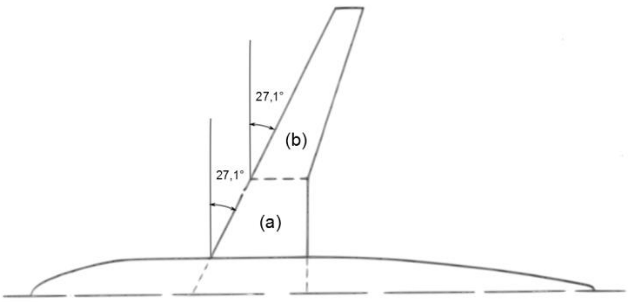

Figure 4 – Sweep angles definition

In the present research two sweep angles was considered. The wing shape modification consisted in the variation of the sweep of the inner wing section **(a)** and of the outer section **(b)** as depicted in figure 4. The range of variation for both sweep angles was ±1°.

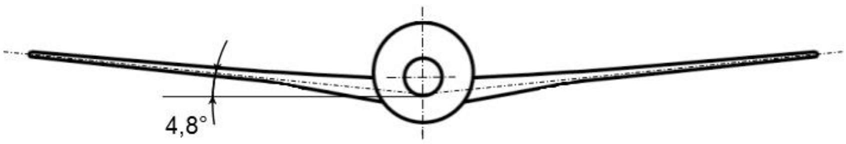

Figure 5 – Dihedral angle definition

The angle that the wing form with the horizontal plane is called *dihedral angle*. Dihedral is added to the wings for roll stability; a wing with some dihedral angle will naturally return to its original position if it encounters a slight roll displacement. Dihedral angle influences dihedral effect and stability, moreover nacelle size should be considered in order to be sure to have enough space between the ground and the wing. DLR-f6 has a dihedral angle of 4,8° as depicted in figure 5. This shape modification will take place from 3,8° to 5,8°.

Wing twist is a geometric feature which, in combination with the sweep angle, wing planform and airfoils shapes, have a strong effect on lift distribution along the wing. The opportune spanwise load distribution is defined by a complex combination of several requirements. Generally speaking, the first and more evident influence is on the induced drag for which an elliptical load distribution represents the theoretical optimum.

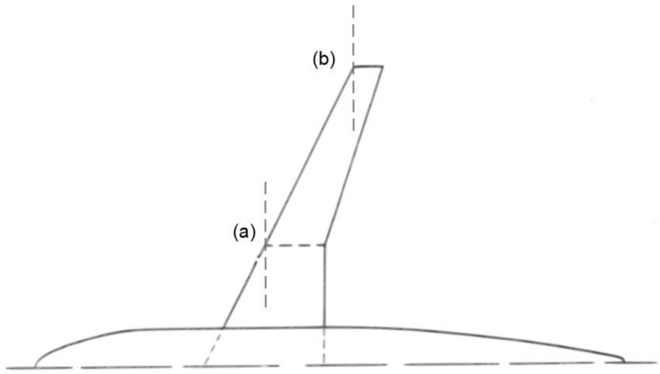

Figure 6 - Axes definition for twisting: (a) kink, (b) tip

In the present work the modification of the twist angle consists in a rigid rotation of two sections (both sections are parallel to the symmetry plane) at the kink and at the tip of the wing around two axes. Both axes are orthogonal to the symmetry plane of the aircraft and intersect the wing at the leading edge, the first one at the kink **(a)** and the second one at the tip **(b)**. Both twist angle ranges was ±1° from the baseline configuration.

CFD Setup

In according with the second DPW, DLR-F6 has an attack angle of 1°, Reynolds number and Mach number are respectively $3*10^6$ and 0,75 in cruise conditions (about 260 m/s) so *in* (inlet), *bot*, *top* and *side* surfaces of the wind tunnel have been set as *pressure-far-field* with related angles for velocity components.

Symmetry has been applied for the symmetry plane and the whole aircraft surfaces has been set as wall with the aluminium default values with no-slip conditions.

RANS Simulations were carried out with the *ANSYS Fluent* solver using a density based technology solved in double precision. The turbulence was modelled with the one equation *Spalart-Allmaras* model. The flow has been considered steady and air as ideal.

The CFD computation of the candidates, during the optimization process, was performed restarting the computations from the solution obtained on the baseline geometry. Such technique permitted to reduce the computational effort.

Design of Experiments

DOE is a fruitful technique used when a large number of experiments have to be accomplished. This method consists in defining a test plan with a restricted number of simulation in order to optimize computational time and simultaneously to obtain a wide and satisfactory range of design configurations**.**

DOE table with 81 design points has been generated using *ANSYS Workbench* with the *Optimal space filling (OSF)* method. Essentially, *OSF* is a Latin Hypercube Sampling Design (*LHS*) that is extended with post-processing. It is initialized as an *LHS* and then optimized several times, remaining a valid *LHS* (without points sharing rows or columns) while achieving a more uniform space distribution of points (maximizing the distance between points).

OSF shares some of the same disadvantages as *LHS*, though to a lesser degree. Possible disadvantages of an *OSF* design are that extremes (i.e., the corners of the design space) are not necessarily covered and that the selection of too few design points can result in a lower quality of response prediction. In this manner a *DOE* table with equidistant points is gained. Figure 7 shows efficiency for each generated design point.

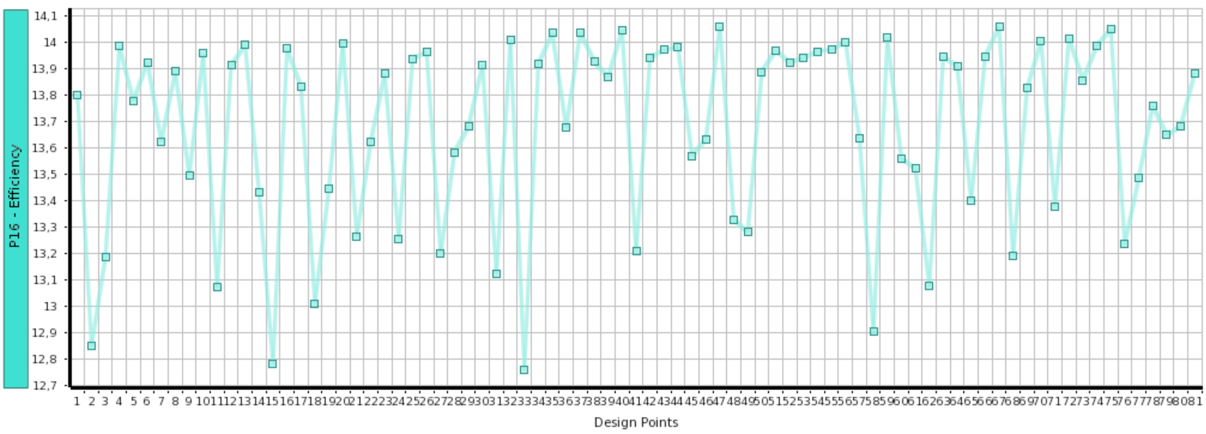

Figure 7 - Design points vs. efficiency

A useful tool of DOE in *ANSYS Workbench* is the sensitivities chart which shows the sensitivities of the output parameter with respect to the input parameters. The larger the change of the output parameter, the more significant is the role of the input parameters that were varied. As depicted in figure 8, the feature which most influences output parameter (*Efficiency*) is the twist at the kink of the wing. Also twist tip and dihedral angle lead to a change of the lift-to-drag ratio. Moreover, nacelle displacements have a lower effect than wing features, however, the horizontal displacement along X-axis and the rotation around Y-axis of the nacelle appreciably distort efficiency.

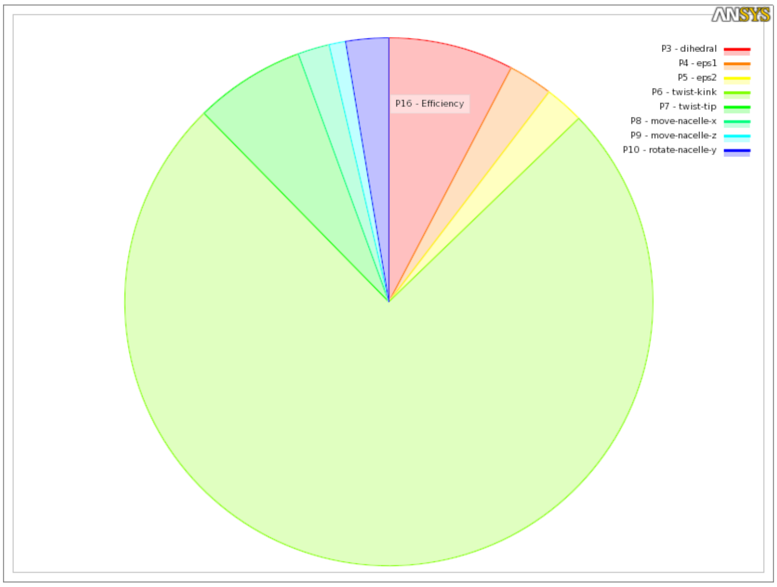

Figure 8 - Sensitivities chart

After the creation of the design points, a response surface has been generated by means of Kriging method. MOGA algorithm (Multi-Objective Genetic Algorithm) has been used to find 3 candidate points on the response surface (candidate A, B, C). In a genetic algorithm, a population of candidate solutions to an optimization problem is evolved toward better solutions. Each candidate solution has a set of properties which can be mutated and altered. The evolution usually starts from a population of randomly generated individuals and it is an iterative process, with the population in each iteration called a generation. In each generation, the fitness of every individual in the population is evaluated; the fitness is usually the value of the objective function in the optimization problem being solved. The more fit individuals are stochastically selected from the current population, and each individual's genome is modified (recombined and possibly randomly mutated) to form a new generation. The new generation of candidate solutions is then used in the next iteration of the algorithm. Commonly, the algorithm terminates when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached for the population.

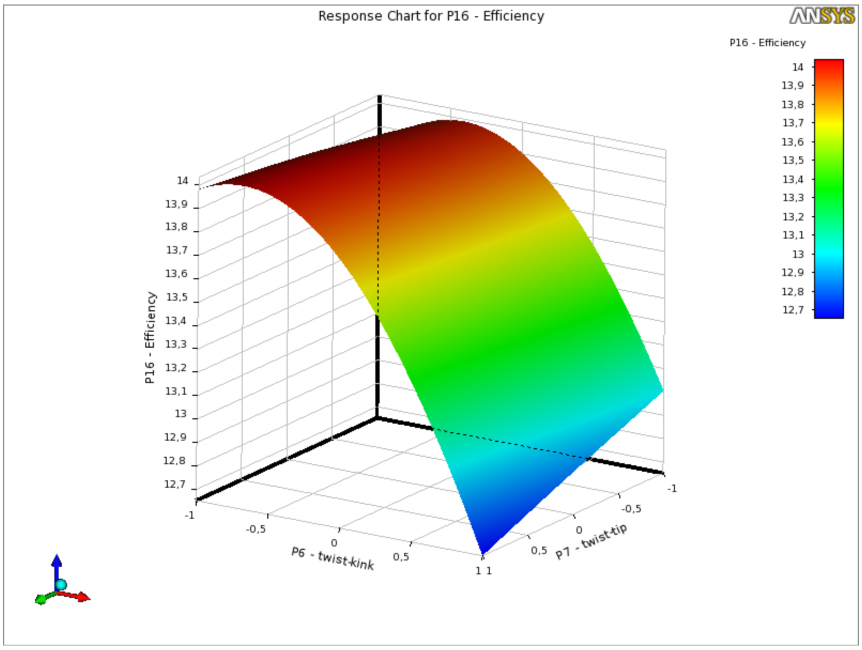

Figure 9 – Efficiency vs. twist kink and tip response surface

As result of the mono-objective optimization, 3 possible candidates are shown in following tables. Candidate B represents the best configuration which can be obtained; it is important to notice that all candidate have a higher lift compared to the baseline value and drag is quite increased. Even though all candidates have a similar objective function values, candidate B should be preferred because it has the highest efficiency value. It is also important to remind that baseline values for both meshes have been compared with the same ones of the wind tunnel experimentation.

Table 1 - Candidate points and baseline input values

DESIGN POINT	dihedral	eps1	eps2	twist-kink	twist-tip	move-nacelle-x	move-nacelle-z	rotate-nacelle-y
Baseline	0	0	0	0	0	0	0	0
Candidate A	-0,81	0,135	-0,916	0,690	-0,378	0,646	0,395	0,0689
Candidate B	-0,874	-0,397	-0,688	0,706	0,446	-0,086	0,264	0,881
Candidate C	-0,068	-0,389	-0,982	0,521	-0,662	0,162	0,37262	0,137

Table 2 - Candidate points and baseline output values

DESIGN POINT	Cd	Cl	Efficiency	**Δ-Efficiency**
Baseline	0,0381	0,528	**13,86**	---
Candidate A	0,0397	0,559	**14,07**	**1,56%**
Candidate B	0,0407	0,573	**14,09**	**1,67%**
Candidate C	0,0398	0,560	**14,06**	**1,44%**

A valid method to evaluate the goodness of the present work is to compare the values of the pressure coefficient along the wingspan. Eight section of the wing have been studied and compared with the results from wind tunnel experiment.

As depicted in graphs, Cp values, which are related to the optimized configuration (green marker), decrease as you move from root to tip on the upper surface of the wing. This phenomenon proves that lift is really increased in the optimized configuration.

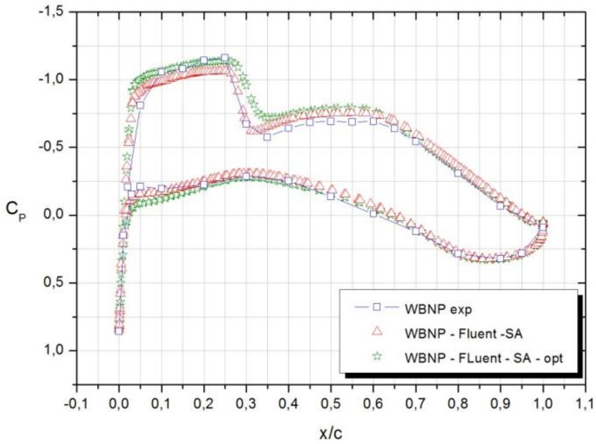

Figure 10 – Cp value at kink (η=0,377)

Conclusions

In this paper an aircraft design optimization procedure, based on the use of *Radial Basis Function* for geometric parameterization and as computational domain modification tool, has been presented. The aim of this research consisted in evaluate the capability of the methods to approach a typical complex aeronautical design problem finding a better aerodynamic configuration of the well-known DLR-F6 test case. Eight geometric parameters, referred to the wing shape and the engine nacelle position, was used as variables of the optimization problem.

The starting geometry was successfully improved and the procedure proved to be efficient and robust. The workflow can be used to face shape optimization problems in a wide range of fluid dynamics cases.

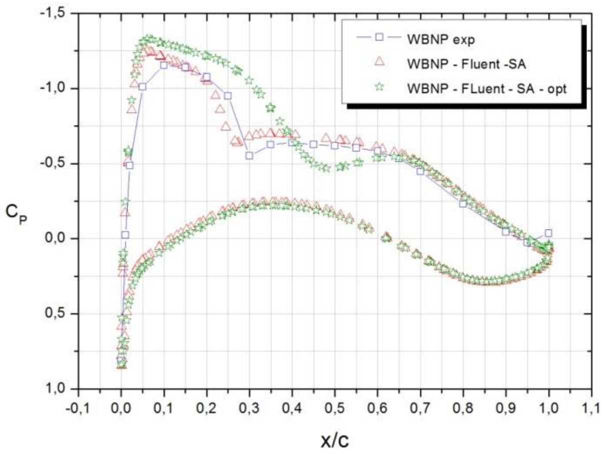

Figure 11 – Cp value near wing tip (η=0,847)

Radial Basis Functions have proved to be a valid tool for mesh morphing application, granting both speed and quality and allowing to define the displacement of the interested nodes only. *RBF Morph* has demonstrated to be a *grid independent* add-on for *ANSYS Fluent* and its integration into design optimization workflow seems feasible.

Acknowledgments

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