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Aerodynamic shape optimization of rotary wing aircraft components using an advanced multiobjective evolutionary approach

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Abstract. *In the framework of my Ph.D. course, I developed a novel Multi-objective Evolutionary Algorithm (MOEA), namely the GeDEA-II, which features a Simplex-based crossover operator. The comparison among GeDEA-II and three modern elitist methods, on state-of-the-art multi-objective problems, clearly indicates that the performance of GeDEA-II is superior. Finally, a test case is presented, regarding the aerodynamic shape optimization of the AgustaWestland 101 helicopter left air intake.*

Keywords: evolutionary algorithms; simplex crossover; shrink mutation; multi objective optimization; aerodynamic shape optimization

1 INTRODUCTION

In the past, a number of powerful Multi-Objective Evolutionary Algorithms (MOEAs) were proposed, e.g. NSGA-II [1], SPEA-II [2] and IBEA [3]. GeDEA [4] algorithm, which was designed around the genetic diversity preservation mechanism called GeDEM, proved to be able to compete and, in some cases, to outperform, the aforementioned MOEAs as far as speed of convergence and covering uniformity of the Pareto Front are concerned. However, the common drawback of all of the previously mentioned multi-objective evolutionary algorithms concerns the huge amount of objective function evaluations (or number of generations) required to reach and sufficiently cover the Pareto Front.

To try to overcome this common weakness, during the last decade several authors started hybridizing evolutionary algorithms (EAs) with local search (LS) operators (some recent works are presented in [5] and [6]).

In the authors' opinion, the previously mentioned examples of hybridization with local search often degrade the global search ability of MOEAs. Moreover, local search based on the Nelder and Mead requires additional and several functions evaluations.

In this paper, GeDEA-II ([7], [8]) is presented, aiming at reducing the potential weaknesses of its predecessor and competitors, while retaining its very good performance, that is, a good balance between exploration and exploitation. In particular, the author propose a different approach to combine the Evolutionary algorithm-based global search and the Simplex theory, since global exploration and local search are intimately related and performed simultaneously, in such a way that they take advantage from each other. In order to judge the performance of the GeDEA-II, a comparison with other different state-of-the-art multi-objective EAs was performed. SPEA-2 [2], NSGA-II [1] and IBEA [3] were chosen as competitors, and their performance against GeDEA-II was measured on the ZDT_3 test function. The test function, the methodology and the metric of performance used in the comparison are deeply described in [4]. The original version of ZDT_3 presented in [9] featured 30 decision variables. Here we propose them with 100 decision variables. Moreover, the initial populations are evolved for only 30 generations. For

measuring the quality of the results, we employed the Hypervolume approach, due to its construction simplicity and reliability when it comes to judge the performance of a MOEA.

2 THE SIMPLEX CROSSOVER

In [10], a simplex crossover (SPX) is proposed, a new multi-parent recombination operator for real-coded GAs. However, in that work the authors did not consider the application of the SPX to multiobjective problems. Moreover, they did not consider the possibility to take into account the fitness of the objective function/s as the driving force of the simplex. Therefore, we decided to integrate in the GeDEA-II the simplex crossover with these and further new distinctive features. Unlike the Simplex-crossover presented in [10], in GeDEA-II only two parents are required to form a new child. These two parents are selected according to the selection procedure from the previous population, and combined following the guidelines of the simplex algorithm. *Reflection* coefficient is set equal to a random number ($refl \in [0, 1]$), unlike the elemental Simplex theory, which assumes a value equal to 1 for the *Reflection* coefficient. This new crossover operator was expected to combine both exploration and exploitation characteristics. In fact, the new formed child explores a design space region opposite to that covered by the worst parent, that means it explores a region potentially not covered so far. In the early stages of the evolution, this means that child moves away from regions covered from bad parents, while exploring new promising ones. In addition, the characteristics of the good parents are deeply exploited to accelerate the evolution process. During evolution, GeDEA-II makes use exclusively of the Simplex Crossover until three-quarters of the generations has been reached. After that, Simplex Crossover is used alternatively with the Simulated Binary Crossover [1].

3 RESULTS

In Figure 1, an excerpt of the non-dominated fronts obtained by the MOEAs on ZDT_3 test function and the Pareto-optimal fronts (continuous curves) is presented on the left, along with the boxplots (on the right).

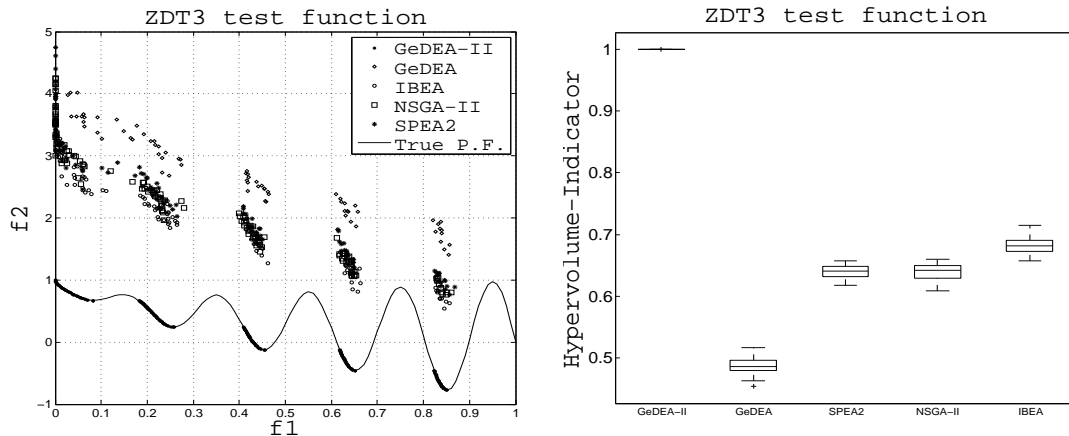


Figure 1: Final Approximation Set reached by the GeDEA-II on test function ZDT_3 (ON THE LEFT), and box plots based on the *Hypervolume* metric (ON THE RIGHT), referring the five algorithms.

4 AERODYNAMIC SHAPE OPTIMIZATION OF THE AW101 AIR INTAKE #1

The scope of the present work was the optimization of the full scale AW101 engine intake#1, located at pilot left-hand side: the CATIA® model of the intake#1 mounted on the AW101 fuselage is illustrated in Figure 2. The optimization problem considered was of the multi-point type, since the total pressure losses occurring in both forward flight and hover conditions were requested to be minimized simultaneously. In addition, the optimization problem featured some constraints, both of the functional and geometrical type.

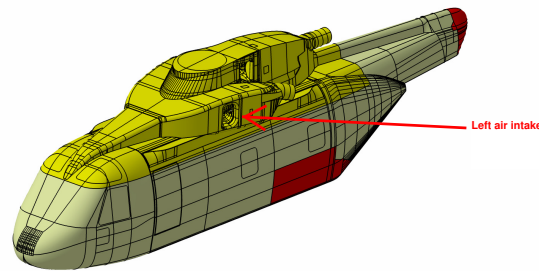


Figure 2: CATIA® V5 models of AW101 model without main and tail rotors.

Specifically, the functional constraints were related to the necessity of maintaining the flow distortions at the Aerodynamic Interface Plane (AIP) within acceptable values: a Penalty Function approach was used to deal with this type of constraint. On the other hand, the requirement that the final intake design is both able to be manufactured and installed into the aircraft led to the definition of a series of geometrical constraints that were considered in this preliminary optimization as well.

As far as the mesh generation is concerned, the software used to carry out the meshing operations was respectively Hypermesh® [11] for surface meshing and Ansys Tgrid® [12] for the volume mesh generation. A pressure-based solver [13] type with absolute velocity formulation and steady approach was adopted for the tiltrotor simulations. The $\kappa - \omega$ SST model was selected for turbulence treatment. As far as the solution algorithm is concerned, a COUPLED scheme was adopted, which solves the pressure and moment equations simultaneously. A Second Order Upwind discretization scheme was considered sufficient for this work purposes. It was selected for all the fluid dynamics variables, since it guarantees a high accuracy of the numerical solution, due to its potential to improve sufficiently spatial accuracy by reducing numerical diffusion, particularly for complex three-dimensional flows, while not negatively affecting the total time requested for simulations when compared to the third order upwind scheme. A total amount of nine design variables were considered. All the design variables were generated using the so called domains-handles approach in order to satisfy global morphing requirements. In particular, this approach allows for the application of mesh nodes displacements within a geometrical region (domain) by changing the location of specific, user defined, control points (handles) ([11]). The ultimate Pareto front after 20 generations is illustrated in Figure 3. In Table 1, the values of the objective functions of the

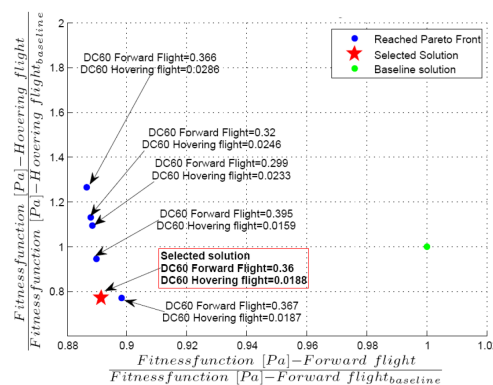


Figure 3: Final Pareto front after 20 generations.

optimized solution are reported and compared with the baseline. As apparent, a remarkable reduction of the total pressure losses along the intake duct was obtained with the optimized solution, especially in hover conditions; in addition, regarding the flow distortion at the AIP, a large reduction of the $DC(60)$ at the engine face was achieved in forward flight and, to a lesser extent, in hover conditions.

In Figure 4 the total pressure contours over a series of transversal sections along the optimized intake

Table 1: Trial intake optimization results: Total pressure drop and DC60 reduction with respect to the baseline geometry

	Baseline configuration	Forward Flight	Hovering Flight
Total pressure drop reduction[%]	\	10.85%	23.4%
DC60 reduction[%]	\	19.6%	8.29%

duct are depicted for both the hovering and forward flight conditions and they are compared with the baseline. As apparent, in hover conditions the region of low total pressure occurring in the final portion of the intake duct is less extended in the optimized geometry, and total pressure losses are less severe.

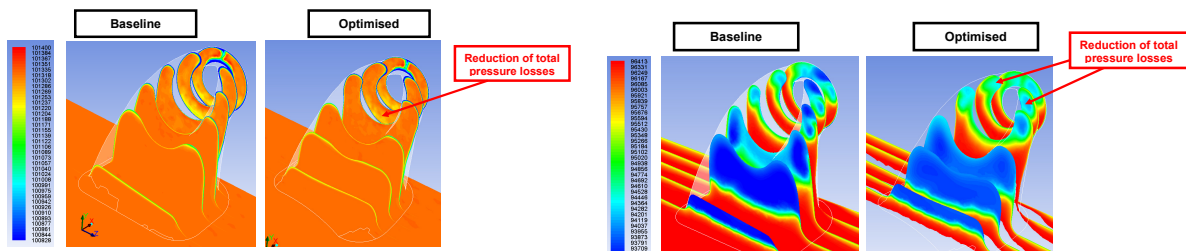


Figure 4: Contours of total pressure ([Pa]) over a series of transversal sections along the intake duct: forward (on the left) and hovering flight conditions (on the right) solutions.

Furthermore, also in forward flight conditions a reduction of the total pressure losses with respect to the baseline is evidenced, especially in the upper portion of the intake duct and towards the AIP. As expected, also the flow behavior over the AIP is improved in the optimized solution with respect to the baseline, for both hovering and forward flight conditions, as apparent from Figure 5: in fact, the total pressure field is much more uniform over the engine face in both the considered flight conditions, and the most severe total pressure drops are eliminated in the optimized geometry. Results presented here

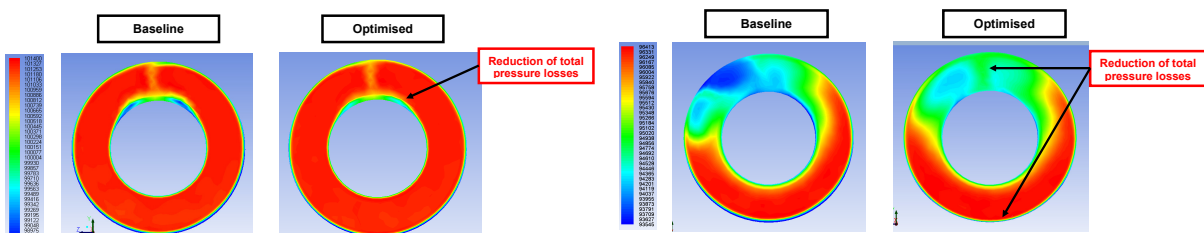


Figure 5: Contours of total pressure ([Pa]) over the AIP: forward (on the left) and hovering flight conditions (on the right) solutions.

are owned by the CleanSky Partner Consortium *HEAVYcOPTer* (led by University of Padova), aimed at studying enhanced engine installations for improved performance and lower noise specifically designed for heavy helicopters configuration.

5 CONCLUSIONS

In this paper, I have presented GeDEA-II, an improved multi-objective evolutionary algorithm that employs novel genetic operators compared to its predecessor GeDEA. Extensive numerical comparisons of GeDEA-II with GeDEA and with NSGAI, SPEA-2 and IBEA, three state-of-the-art recently proposed algorithms, have been carried out on two test problems. The key results of the comparison show the outstanding performance of the GeDEA-II, when compared to the competitors algorithm, in terms of both

exploration and exploitation capabilities. Boxplots shows that the reproducibility of results of GeDEA-II is high-level, when compared to that of the NSGAII, SPEA-2 and IBEA. In extremely high dimensional spaces, GeDEA-II clearly shows excellent performance. In addition to these characteristics, GeDEA-II performs these tasks with a reduced number of objective functions evaluations, which is not negligible when considering its application to real-world engineering problems. Also on a challenging real-world engineering problem, the proposed algorithm showed excellent performance.

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