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MULTIOBJECTIVE AND MULTIPOINT OPTIMIZATION OF A HEAVY CLASS HELICOPTER ENGINE INSTALLATION USING EVOLUTIONARY ALGORITHMS

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Abstract. Aerodynamic design and optimization of engine installation is a pivotal part of the helicopter design process. To this purpose an adaptive, problem-independent and reliable optimization methodology would be particularly valuable in reaching such goal. The application of advanced evolutionary algorithms coupled with CFD solvers for the accurate flow solution of validated numerical models represents a very powerful tool for the parametric design and optimization of engine installation components. Within the JTI Clean Sky FP7 project “HeavyCopter” the consortium constituted by the University of Padova (UNIPD) and the spin-off company HIT09 developed an automatic optimization loop based on the home made genetic algorithm GeDEA, and applied it to engine installation design of a heavy-class helicopter, as well as to aircraft components optimization problems. This paper illustrates the application of the GeDEA-based optimization loop both at forward and hover reference flight conditions for such helicopter. The algorithm pursues the minimization of the total pressure losses at the inlets while keeping the flow distortion at the engine inlet at the lowest level; regarding the exhaust, the back-pressure is minimized in order to increase the power output of the engine while preserving the entrainment ratio. The results highlight significant improved performance margins in all the components.

1 INTRODUCTION

Within the Clean Sky framework, the joint technology initiative funded by the European Commission and industry, a specific activity is dedicated to the study of the engine installation of the AgustaWestland AW101 heavy helicopter. A consortium constituted by the University of Padova and the companies HIT09 and MDA submitted the HEAVYcOPTer project proposal in response to a specific Call on the subject [1]. The Call pertained a contribution and the supporting in accomplishing the aerodynamic optimisation of the intake and exhaust of the AW101 helicopter.

Efficient aerodynamic design of air intakes is a challenging objective for airframe manufacturers: inlet flow typically develops in adverse pressure gradient conditions, which leads to boundary layer instability and possible flow separation. Therefore inlet cross sectional area distribution along the central line should be optimized in order to minimize boundary layer "loading" and avoid separation [1]. In addition, for helicopter intake applications, an S-shaped duct is usually required to channel the air to the engine face; this is due to the presence of the engine shaft and the requirement for short and compact duct layout. From the fluid-dynamic point of view, a curved duct induces a secondary flow pattern, which essentially sets up pockets of swirling flow at the duct exit [2] and determines engines performance degradation [3]. In severe situations, these pockets can produce rotating stall instability of the compressor rotor [4]. Therefore, the internal shape of the curved duct should embody proper strategies in order to minimize total pressure loss and flow distortions at the engine face [5]. Finally, stability of boundary layer in turboprop and helicopter inlets may also be remarkably affected by the aircraft operating conditions and flight speed [6], [8], [8]. In such a context, CFD is a powerful tool which can be used to accurately evaluate the complex flow behaviour within inlet ducts: [10] and [11] are remarkable examples of CFD application to intake aerodynamics. When coupled with geometry parameterization techniques, CFD provides an effective automatic design methodology for inlet ducts.

Within the HEAVYcOPTer framework, the baseline intake CFD model has been built up and validated by means of a comparison against the available wind tunnel experimental data, starting from the existing AW101 engine installation geometry provided by AgustaWestland Ltd. via CATIA® CAD models. CFD analysis has been carried out for the nominal hover and forward flight cruise conditions; then, results have been analyzed in terms of total pressure losses, flow distortions, flow separations and all those aspects that affect the efficiency of the helicopter intake system. This analysis allowed to properly understand the aerodynamic behaviour of the actual design and to identify the most appropriate parametric changes to be applied to the geometry during the optimisation phase.

The baseline CFD solution and its associated parametric geometrical model are then the main inputs for the optimisation procedure selected, which involves the application of the GeDEA [12]. The GeDEA is the University of Padova home-made genetic algorithm able to perform multi-objective optimisation analysis with the general approach of the Pareto frontier search; it has been compared to others state of the art genetic algorithm with excellent results and, interfaced with flow solvers, it has been successfully used in several fluid-dynamics applications; in particular, within the clean-sky GRC2 research program [13], the GeDEA based optimisation loop has been successfully applied to several fuselage and engine installation components of the European tilt rotor ERICA [13].

The results obtained by the application of the above mentioned optimisation chain on the AW101 engine installation are presented in this paper, with focus on the air intakes and exhaust number one optimisation outcomes.

2 DESCRIPTION OF THE OPTIMISATION METHOD

The aerodynamic optimisation procedure which has been implemented and used for the project HEAVYcOPTer is structured in three phases as follows:

- Baseline model preparation and simulation phase;
- Automatic optimisation phase;
- Post-processing and optimized CAD model reconstruction phase.

2.1 Baseline model simulation

Typically the starting point is represented by the CAD model of the baseline configuration. Starting from the geometrical model, the procedure moves into the "baseline simulation block" (see Figure 1), where the baseline configuration of the component under consideration is analyzed via CFD in terms of aerodynamic performance in the most relevant operating conditions. The assessment of the baseline solution allows the designer to proper understand the flow field characteristics of the object under analysis, gives fundamental indications for the optimisation objectives and constraints identification and make it possible to setting up the geometrical parametric model.

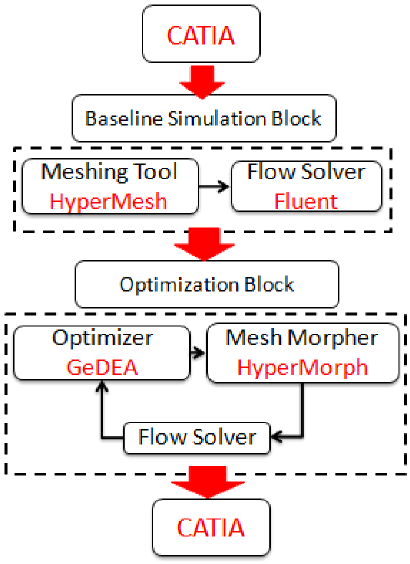

Figure 1: Optimisation method flow-chart

2.2 Automatic optimisation execution

When the preliminary operations have been completed, the optimisation can be carried out by means of the automatic optimisation loop in Figure 1: it is constituted by the following components:

- GeDEA (Genetic Diversity Evolutionary Algorithm): it is an advanced multi-objective optimisation algorithm developed at the University of Padova [12]. It is the selected optimisation engine;
- Altair HyperMorph®: it makes possible to convert the design parameters coming out from GeDEA into morphed CFD cases, suitable for the objective function evaluation;
- Ansys Fluent®: the selected flow solver; it takes in input the morphed CFD cases coming from HyperMorph® and gives back to GeDEA the corresponding values of the chosen objective functions.

During the optimisation process, GeDEA lets a population of individuals "evolve" (each one corresponding to a different set of design variables and so to a different geometrical configuration) until the convergence to the Pareto optimal frontier has been reached, being the Pareto frontier the set of non-inferior solutions, which represents the solution of a multi-objective optimisation problem; a non-inferior solution, also called Pareto optimal or non-dominated solution, is one in which an improvement in one objective requires the degradation of another [15].

2.3 Post-processing

The Pareto frontier in output from the automatic optimisation loop represents a multiple set of solutions equally optimal according to the Pareto concept but of course different form the aerodynamic and engineering point of view. In fact each solution over the Pareto frontier may present advantages and drawbacks with respect the other solutions. In order to choose among the optimal set the most appropriate solution a post-processing is necessary. Thanks to the intrinsic multi-objective approach adopted, the designer is allowed to select, among the Pareto optimal set, the solution which is more suitable for his needs: for example, choosing to privilege the improvement of one objective with respect to the other or even including other considerations such as non-aerodynamic requirements. The strength of the selected approach is that the designer can choose the proper trade-off between the objectives when the optimisation work has been completed and he is not forced to introduce his arbitrariness in the problem set up, as commonly happens using traditional optimisation approaches.

3 AW101 ENGINE INSTALLATION DESCRIPTION

The AW101 engine intake system is constituted by three side intake ducts feeding the three helicopter engines; from now on, we will refer to air intakes as "intake#1" and "intake#3" for the two symmetrical intakes on the fuselage sides, and "intake#2 for the intake placed at the top of the fuselage roof (Figure 2).

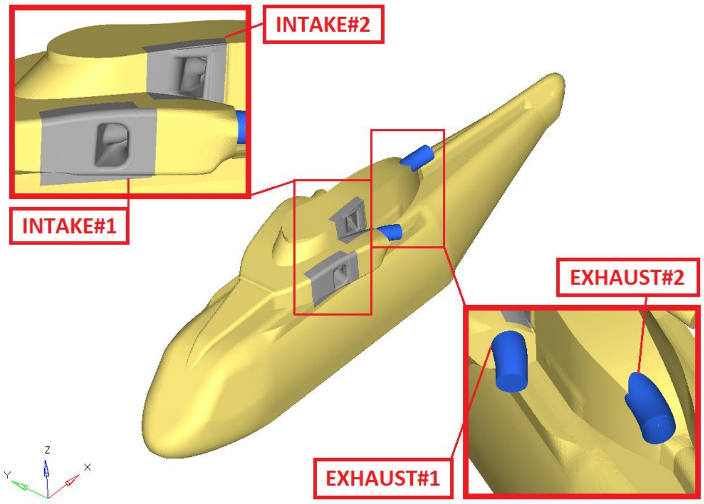

Figure 2: View of the engine installation on the AW101 CAD model.

An intake duct is an S-shaped duct connecting the side entry section with the engine compressor face, commonly referred as *Aerodynamic Interface Plane* (AIP). CAD layouts of engine#1 and engine#2 bay internal components were provided by AgustaWestland Ltd in order to allow the definition of geometrical modifications of the duct surfaces so as to be compliant with the installation architectural constraints (Figure 3).

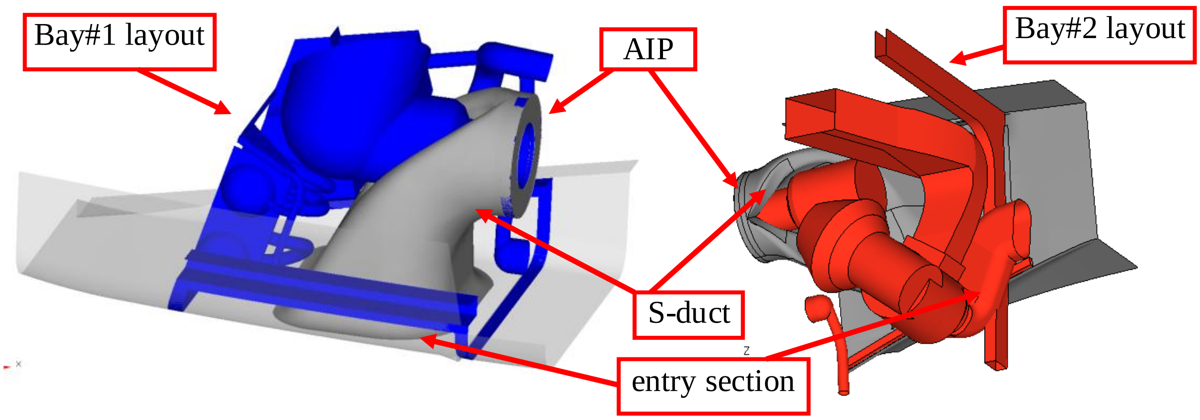

Figure 3: Internal view of intake S-duct and bay internal components layout for engine#1 and engine#2.

AW101 engine bay and exhaust are replaced by a simplified rig configuration, which was tested at the AWL wind tunnel facility in order to get cold flow data on current engine system and to validate CFD models. The CAD layout of the exhaust internal components was provided by AgustaWestland Ltd in order to allow the definition of geometrical modifications of the daisy nozzle and central body surfaces so as to be compliant with the installation architectural constraints (Figure 4). The swirl generator blades are replaced by a flat surface normal to the main flow direction, where a FAN boundary conditions is applied in order to reduce mesh size and to make the model more representative of the real exhaust installation. Only the primary nozzle and the central body installed on Engine#2 is optimised.

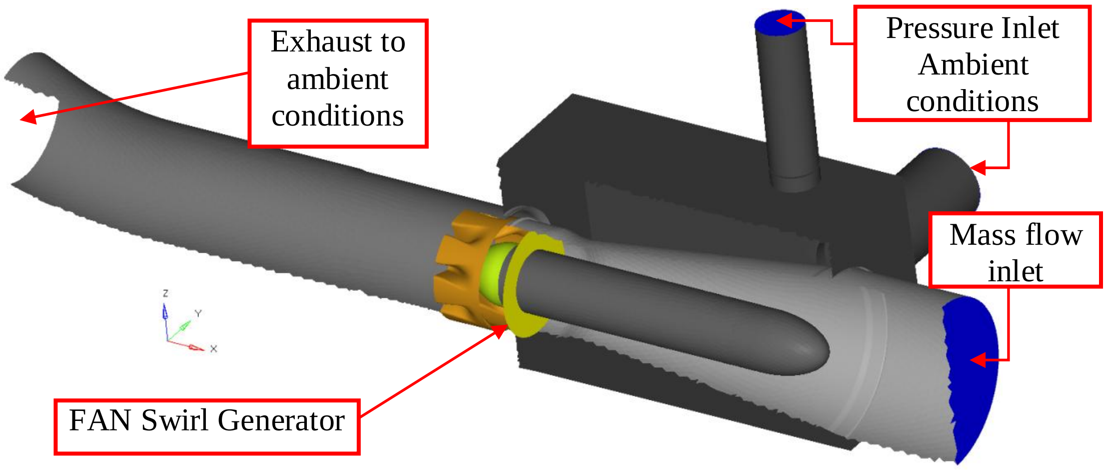

Figure 4: Boundary Conditions applied to full scale Rig model.

4 SET UP OF THE PARAMETRIC MODEL

Once the main geometrical features characterising the baseline designs are identified, design parameters are generated for the complete geometrical control of the intake#1 and intake #2 duct shapes and of the exhaust daisy nozzle and central body shapes. Those parametric shapes are generated using the Altair software HyperMesh® by means of the mesh morphing and parameterisation techniques available within the morphing toolbox HyperMorph®, utilizing a combination of different free form techniques available within the tool. When applied, the nodes displacements can be saved as perturbation vectors and then be reapplied to the baseline model with any given scaling factor. Shape scaling factors become then the design variables for the optimisation problem; the morphed geometry results therefore from the linear combination of the user defined shapes multiplied by their own scaling factors:

$$v = \sum_{i=1}^{n} \alpha_i Sh_i \quad (1)$$

where:

- v is the global displacement vector;
- Sh_i are the i^th basic shapes defined within HyperMorph®.
- α_i is the i^th shape scaling factor generated by GeDEA.
- n is the number of parameters for the current application.

During the automatic optimisation process, the scaling factor α_i represents the set of design parameters controlled by the genetic algorithm.

Some examples of shapes are shown in Figure 5 and Figure 6.

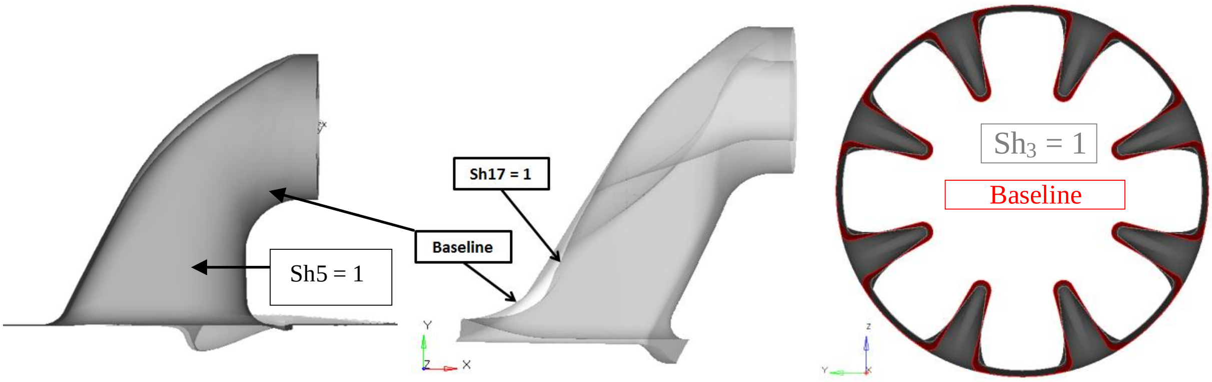

Figure 5: Examples of shapes respectively for intake#1, intake#2 and exhaust#2

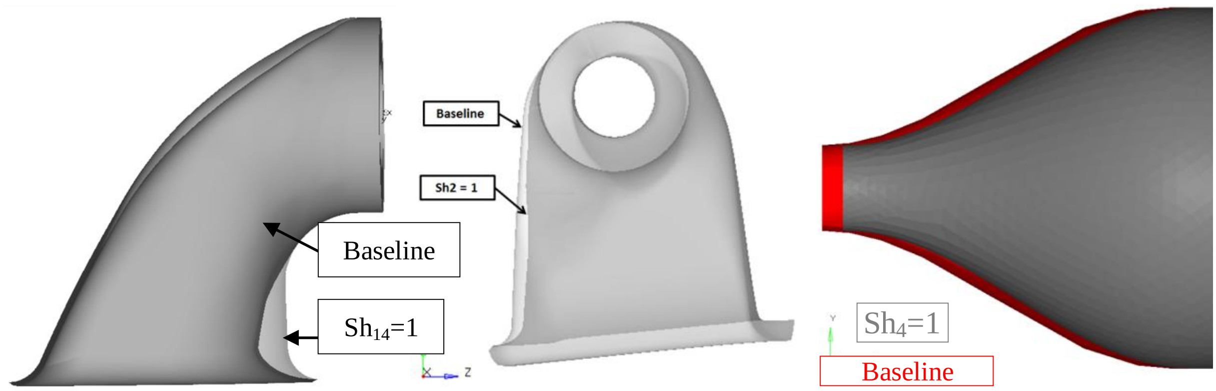

Figure 6: Examples of shapes respectively for intake#1, intake#2 and exhaust#2

5 FORMULATION OF THE OPTIMISATION PROBLEM

The GeDEA-based optimization loop has already been successfully applied to several fuselage and engine installation components of the European tilt rotor ERICA [14]: the interested reader can find an extensive description of the main achievements of the Clean Sky GRC2 projects CODETilt [16] and TILTOp [17] in the conference papers [18], [19] and [19]. Two different objective functions are formulated to pursue the HEAVyCOPTer optimization, one for the air intakes and one for the exhausts, respectively.

The former is a two-objective and two-component vector function; it is obtained from the sum of the total pressure loss term and a *penalty function* term. It can be formally expressed as:

$$minimize\ \{G(x) = [F(x) + PF(x)]\} \tag{2}$$

Where *F(x)* accounts for aerodynamic total pressure loss (ΔP_T) within the intakes at the two reference flight conditions:

$$F(x) = \begin{bmatrix} \Delta P_T(x) \,|\, @hover \\ \Delta P_T(x) \,|\, @cruise \end{bmatrix} \tag{3}$$

The penalty function *PF(x)* introduces a functional constraint on the flow distortions at the engine inlet by worsening the score of a new configuration with an additional term that is proportional to the DC60 factor difference with respect to the baseline configuration:

$$PF(x) = \begin{bmatrix} 0 & \text{if DC60(x)} \le \text{DC60}_{\text{baseline}} \\ \beta \left| \dfrac{DC60(x) - DC60_{baseline}}{DC60_{baseline}} \right|^{\gamma} & \text{if DC60(x)} > \text{DC60}_{\text{baseline}} \end{bmatrix} \tag{4}$$

where the coefficients β and γ control the intensity and shape of the penalty function respectively. Again, this term is evaluated at the two flight conditions.

The design variables vector, **x**, is given by the set of scaling factors, subject to the variable bounds which will differ between Intake#1 and Intake#2:

$$\mathbf{x} = [\ \alpha_1 \ldots \alpha_n] \tag{5}$$

The exhausts objective function E(**x**) is a bi-objective two component vector function, evaluated at the forward flight condition only:

$$\text{minimize} \left\{ E(x) = \begin{bmatrix} BP(x) \,|\, @cruise \\ \left| ER(x) - ER_{baseline} \right| \,|\, @cruise \end{bmatrix} \right\} \tag{6}$$

where *BP(***x***)* and *ER(***x***)* represents the back-pressure and the entrainment ratio respectively:

$$BP(x) = \frac{P_{T,exhaust-inlet} - P_s}{P_s} ; ER(x) = \frac{\dot{m}_{cold}(x)}{\dot{m}_{hot}} \tag{7}$$

where P_s represents the free-stream static pressure.

As mentioned before, *G(***x***)* and *E(***x***)* are evaluated and passed to the algorithm by means of CFD simulations of the individual **x**.

6 SUMMARY OF THE OPTIMISATION RESULTS

The both intakes and exhaust#2 optimisation results are discussed within in this section: the optimization loop had completed 7, 5 and 5 evolutionary generations on Intake#1, Intake#2 and Exhaust#2 respectively. Remarkable improvements on the objective functions are achieved. Figure 7, Figure 8 and Figure 9 show the final Pareto frontiers calculated by the GeDEA algorithm for Intake#1, Intake#2 and Exhaust#2 respectively: despite the number of generations is relatively small, significant improvements in both hover and forward flight objective functions can be observed.

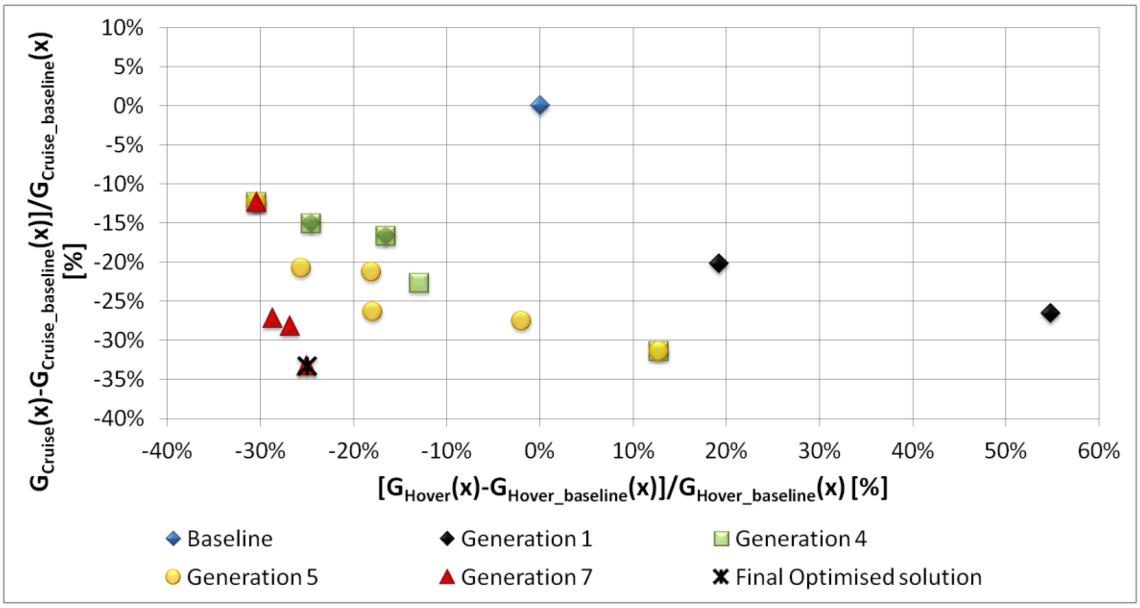

Figure 7: Intake#1 GeDEA Pareto frontier, 7th generation and evolution of the Pareto front through the generations; the selected optimal individual is highlighted.

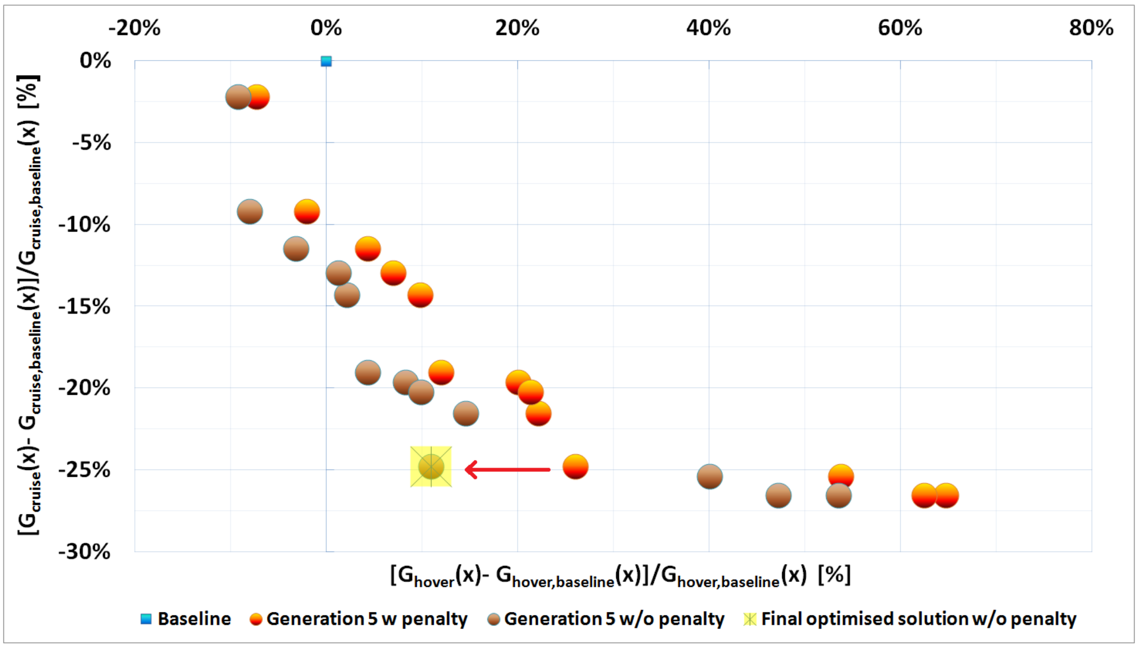

Figure 8: 5th generation Intake#2 GeDEA Pareto frontier, including (orange dots) and excluding (brown dots) the penalty function (**Error! Reference source not found.**) in the computation of the fitness value. The no-penalty fitness score of the optimised solution is highlighted in yellow.

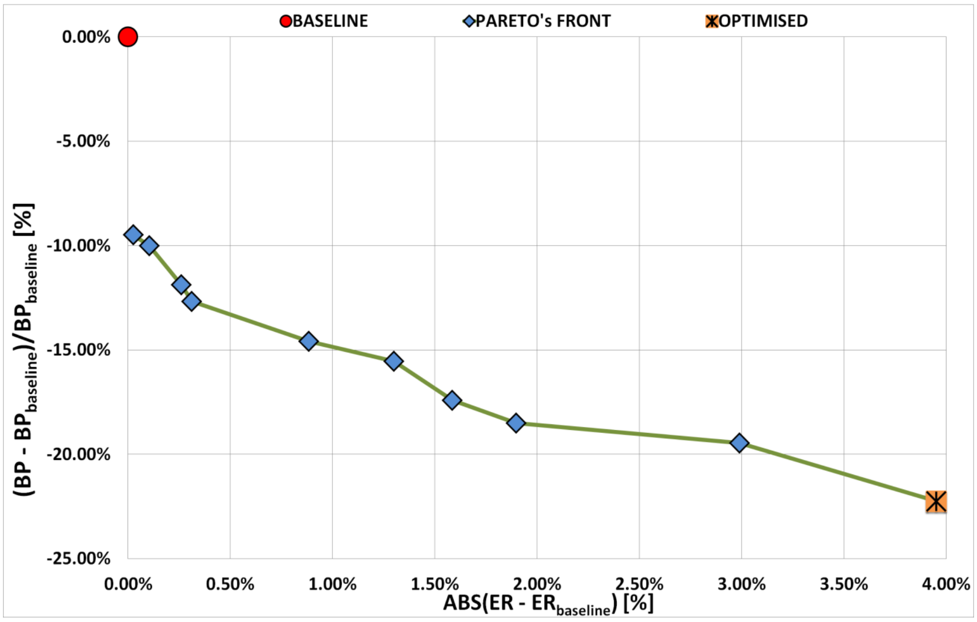

Figure 9: 5th generation Exhaust#2 GeDEA Pareto frontier; the selected optimal individual is highlighted.

<u>Hover</u>: total pressure distribution along the duct

<u>Hover</u>: AIP total pressure distribution

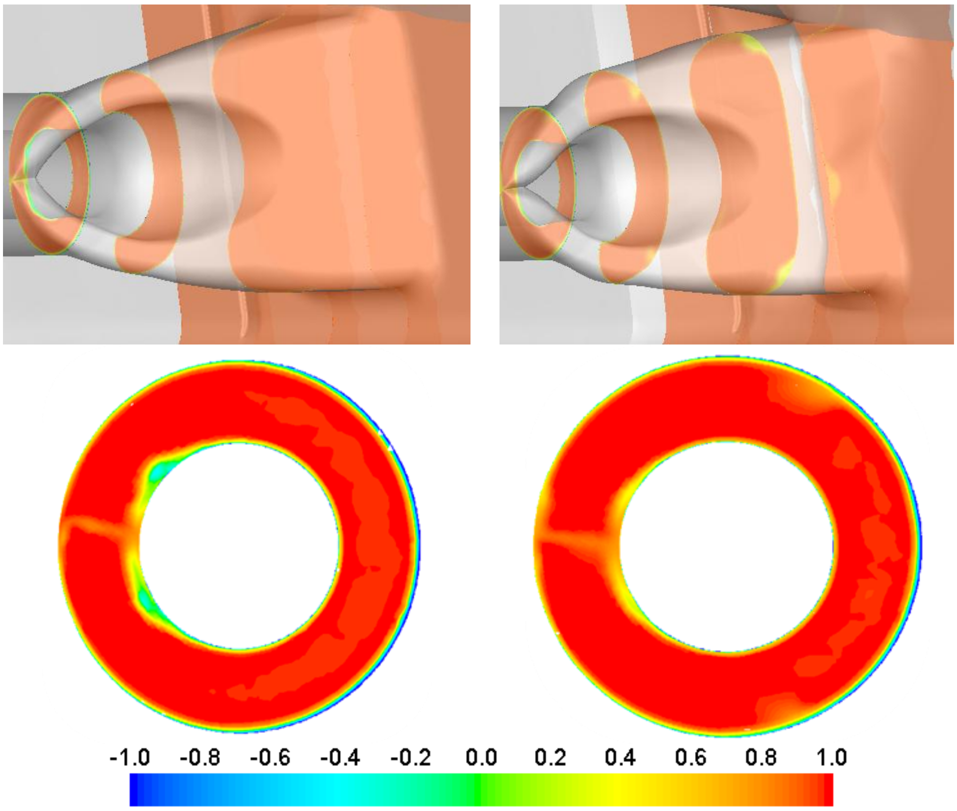

Figure 10: Hover AIP Total Pressure distribution comparison (normalised by free stream total pressure value) for intake#1; baseline (left) and optimal solution (right).

Forward flight: total pressure distribution along the duct

Forward flight: AIP total pressure distribution

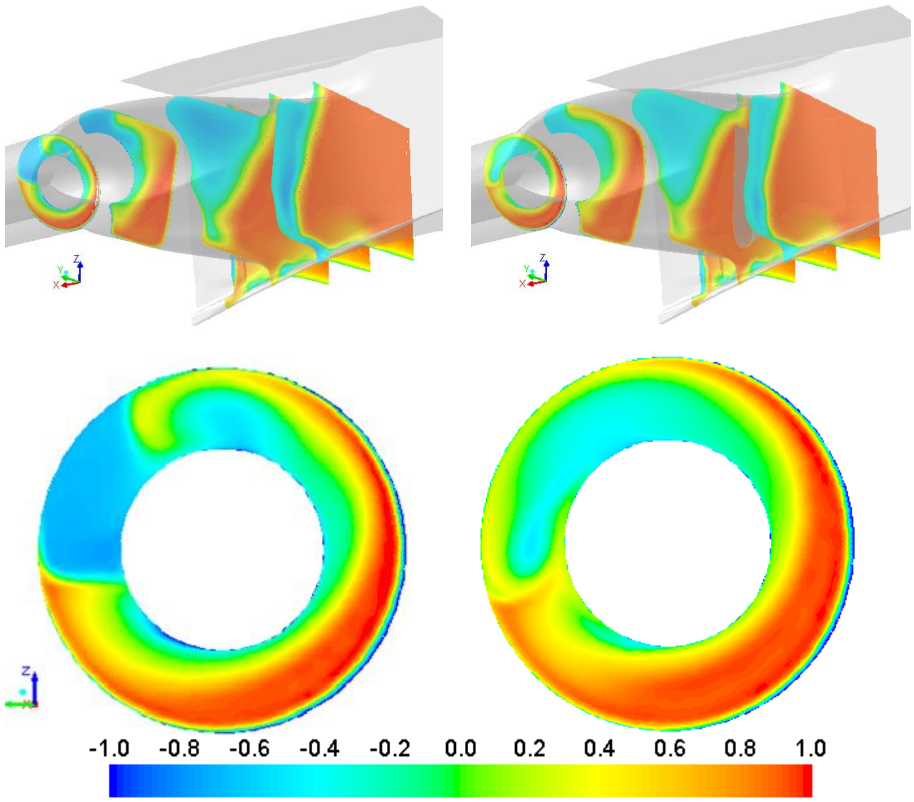

Figure 11: Forward flight AIP Total Pressure distribution comparison (normalised by free stream total pressure value) for intake#2; baseline (left) and optimal solution (right).

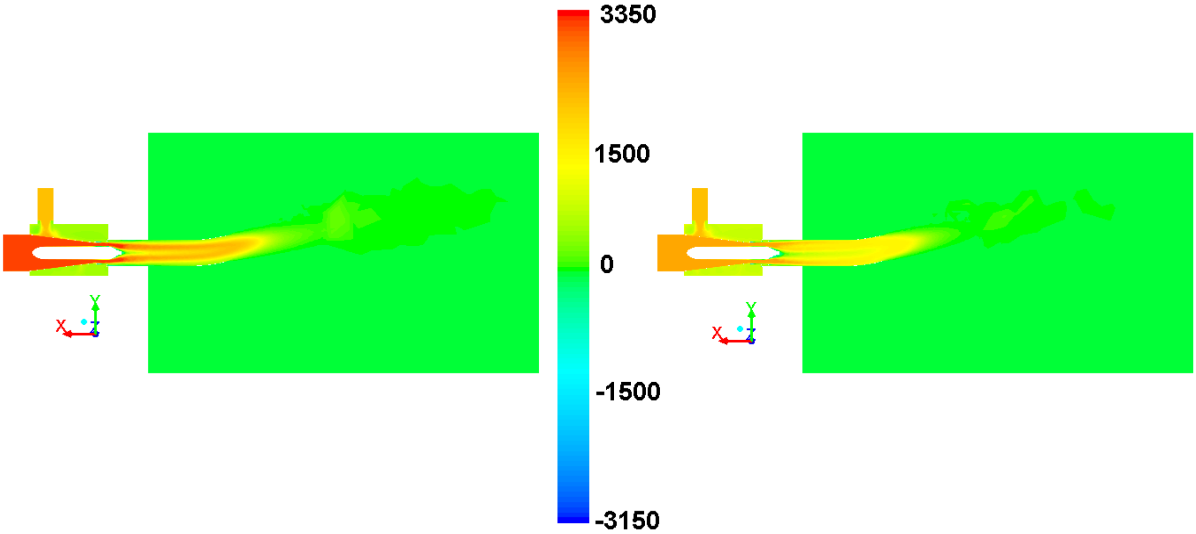

Figure 12: Forward flight Total Pressure [Pa] contours over x-y plane section comparison for exhaust#2; baseline (left) and optimal solution (right).

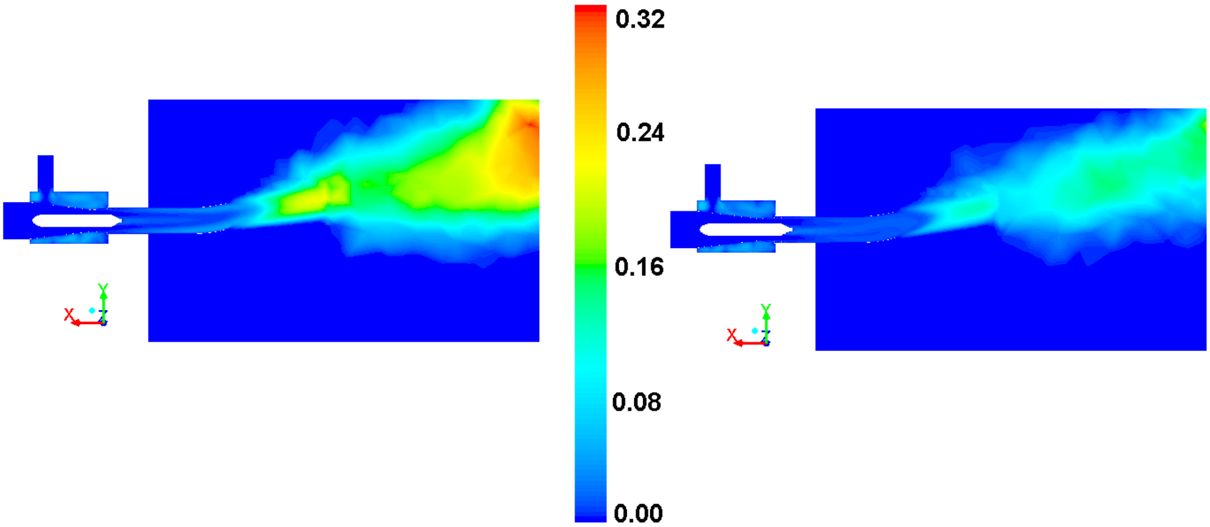

Figure 13: Forward flight Turbulent Viscosity [kg/s] over x-y plane section comparison for exhaust#2; baseline (left) and optimal solution (right).

7 CONCLUSIONS

The selected optimised geometry for Intake#1 displays a -25/-33% total pressure loss reduction from the baseline in hover/forward flight respectively, without any detrimental flow distortion effect.

The cruise-optimized geometry of Intake#2 does worsen the hovering performances to a limited extent, while significantly improving the forward flight efficiency: a +10/-25% total pressure loss drop is obtained (hovering/cruise).

Back-pressure on Exhaust#2 was lowered by the 22% from the baseline, while maintaining the entrainment ratio (which increases by the 4%).

The paper demonstrate the strength of the parametric approach chosen: the genetic algorithm GeDEA provides an efficient search procedure for alternative designs and optimal solutions while the morphing technology adopted allows solution compatibility with feasibility considerations and industrial constraints.

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