FSI optimization of industrial airplanes: the P180 Avanti EVO study

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Summary

This paper describes a fluid-structure interaction (FSI) optimization carried out for the P180 Avanti EVO vehicle, designed and manufactured by Piaggio Aerospace. This study is performed in the framework of the Experiment n. 906 of the Fortissimo project. In particular, the effect of a set of modifications of the winglet shape, that were applied by means of a mesh morphing technique based on the use of radial basis functions, was numerically investigated adopting the mode superposition approach. The CFD analyses were carried out with both commercial (CFD++, ANSYS Fluent) and open-source (SU2) solvers employing the cross-platform FSI solver implemented in the RBF4AERO suite.

Keywords

Aerodynamics, aircraft optimization, RBF, mesh morphing, FSI, mode superposition

Background

The RBF4AERO project [1], funded by the EU Seventh Framework Programme (FP7/2007-2013) under the Grant Agreement n° 605396, aimed at creating software, referred to as RBF4AERO platform [2][3], conceived to handle the high-demanding requirements of aircrafts design and optimizations, so as to considerably shorten the time needed to finalise Computer-Aided Engineering (CAE) analyses in view of improving aircraft and its components performances.

After the completion of the RBF4AERO project, some among the components of the partnership with the support of Piaggio Aerospace company [4], agreed to undertake some exploitation activities including the participation in the Call of the Fortissimo 2 project [5], which has received funding from the EU Horizon 2020 research and innovation programme under Grant Agreement n° 680481, with the main purpose to offer CAE services using the RBF4AERO platform through the Fortissimo Marketplace.

The key elements of the platform are tools that existed prior to the RBF4ERO project, which have been improved and suitably integrated in a single comprehensive working environment during its duration [6]. Specifically these are the morpher tool (MT), namely the commercial standalone version of the RBF Morph technology [7], the optimization Manager (OM) employed to run Single- and Multi-Objective Optimization (SOO and MOO) problems using Evolutionary Algorithms (EA) assisted by off-line trained surrogate evaluation models (metamodels) and the in-house developed adjoint solver for the OpenFOAM suite [8].

The basic idea of the platform functioning is to make the CAE model parametric through a meshless morphing technique based on radial basis functions (RBF) [9][10] in order to enable the computational studies the RBF4AERO platform has been conceived for, which are:

- EA-based optimizations, including constraint SOO or MOO [11]-[20] which can be coupled with the FSI option [21];
- Icing studies [22];
- Adjoint-morphing coupling optimizations [23].

The results obtained with the EA-based operative scenarios can be reviewed and post-processed using an embedded post-processing module. Furthermore, the platform can schedule and monitor simulation jobs and has the support to multi-user and multi-hardware management.

With particular reference to FSI studies, a solver called rbf4aeroFSI has been designed, validated and implemented to work with both commercial and open-source solvers. The rbf4aeroFSI solver allows designers to run SOO or MOO using EA assisted by metamodels taking also into account the elasticity of the deformable components of interest in steady state conditions, according to two approaches: two-way and mode-superposition. It is worth specifying that two-way approach is based on the exchange of data between the Computational Fluid Dynamics (CFD) (loads) and Computational Structural Mechanics (CSM) (displacements) models, whilst the mode-superposition one is based on the import of the natural modes and frequencies of deformable parts, and the calculation of modal forces and actual displacement directly in the CFD model.

Main Objectives of the 906 Experiment

In the Fortissimo Experiment n. 906 [25], called "Cross-Solver Cloud-based Tool for Aeronautical FSI Applications", the proposed aeronautical application consists of the aero-elastic optimization of the winglet of the P180 Avanti EVO (see Figure 1), a business aircraft designed and manufactured by Piaggio Aerospace [26].

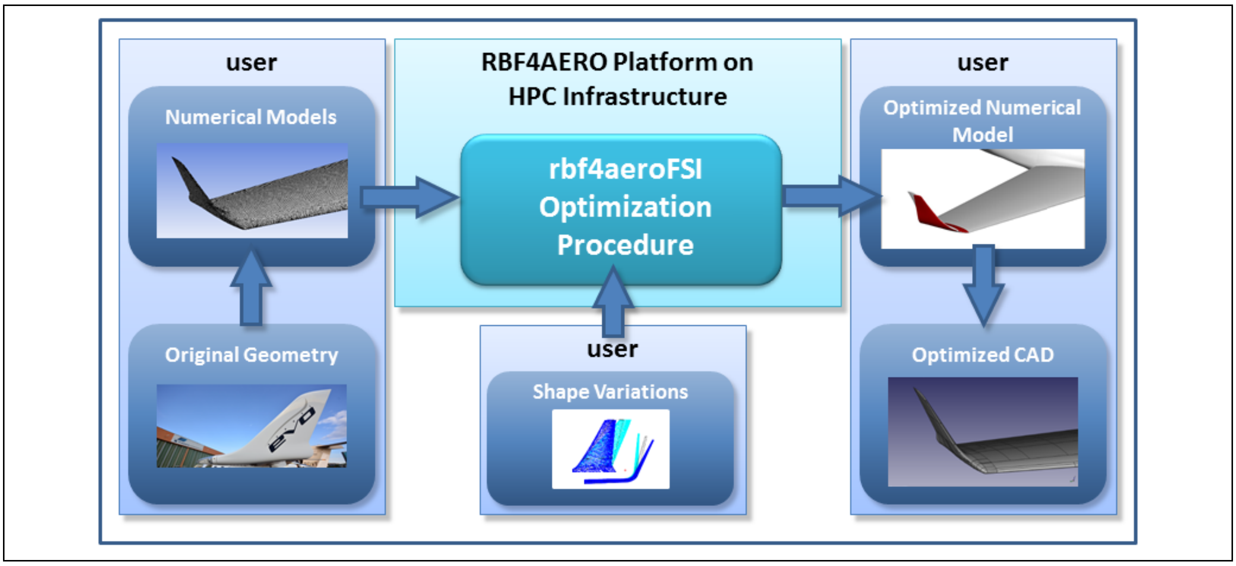

Figure 1: Workflow of the proposed FSI optimization

In particular, the optimization takes into consideration the shape modifications of the winglet and involves aerodynamic objective functions (e.g. aerodynamic coefficients). Such an optimization has been accomplished using the native coupled (multi-physics) rbf4aeroFSI solver on the industrial models provided by the stakeholder Piaggio Aerospace.

FSI Optimization

Shape modifications

The three shape modifications are twist, cant and sweep angles. In particular, the twist angle variation concerns the rotation of the winglet tip around the trailing edge maintaining its root fixed, the cant angle shape modification changes the winglet angle with respect to the wing, whilst the sweep angle geometrical variation is achieved by translating the winglet position along the wing chord.

The RBF set-up controlling the surface mesh is shown in Figure 2, in which the red points on the left image represent the moving ones, whereas the green ones those do not change their position during morphing. On the right of Figure 2, the final position of source points, amplified 10 times to ease the comprehension, is shown. The portion of the winglet between moving and fixed points is left free to deform by the morphing action.

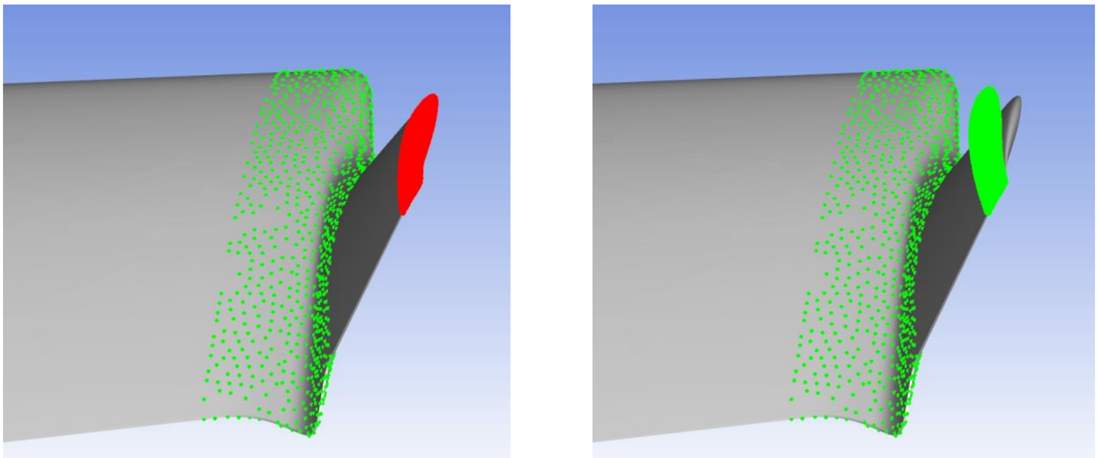

Figure 2: Winglet twist angle RBF set-up for surface mesh morphing

The RBF set-up managing the volume mesh foresees the definition of a domain into which the morphing action is delimited. Because of the cell quality degradation due to the morphing, the combinations of the created shape modifications were verified by evaluating the resulting mesh quality over the interval of variations of the selected angles.

Mesh and CFD model set-up and results for the baseline case

A hybrid unstructured computational grid with about 21 million cells was generated according to the specifications and settings typically adopted by Piaggio Aerospace to create a medium accuracy grid. Specifically, a surface mesh formed by triangular elements only was first generated starting from the imported CAD model. Then a set of layers were inflated from the surfaces to properly resolve the boundary layer to finally generate tetrahedral cells in the remaining portion of the simulation volume.

Transonic regime cruise conditions commonly adopted by Piaggio Aerospace were selected to perform the CFD simulations included in the FSI optimization. In particular, the flow regime enables the identification of the main settings assigned in the CFD set-up such as the angle of attack, the Mach number and the altitude conditions, while the influence of the engine was simulated through proper boundary conditions applied at its inlet and outlet.

Figure 3 depicts from a front (left) and bottom (right) view respectively, the comparison between the pressure coefficient (Cp) distribution over the aircraft surfaces gained with SU2 [26] and CFD++ [27] in the steady state cruise conditions.

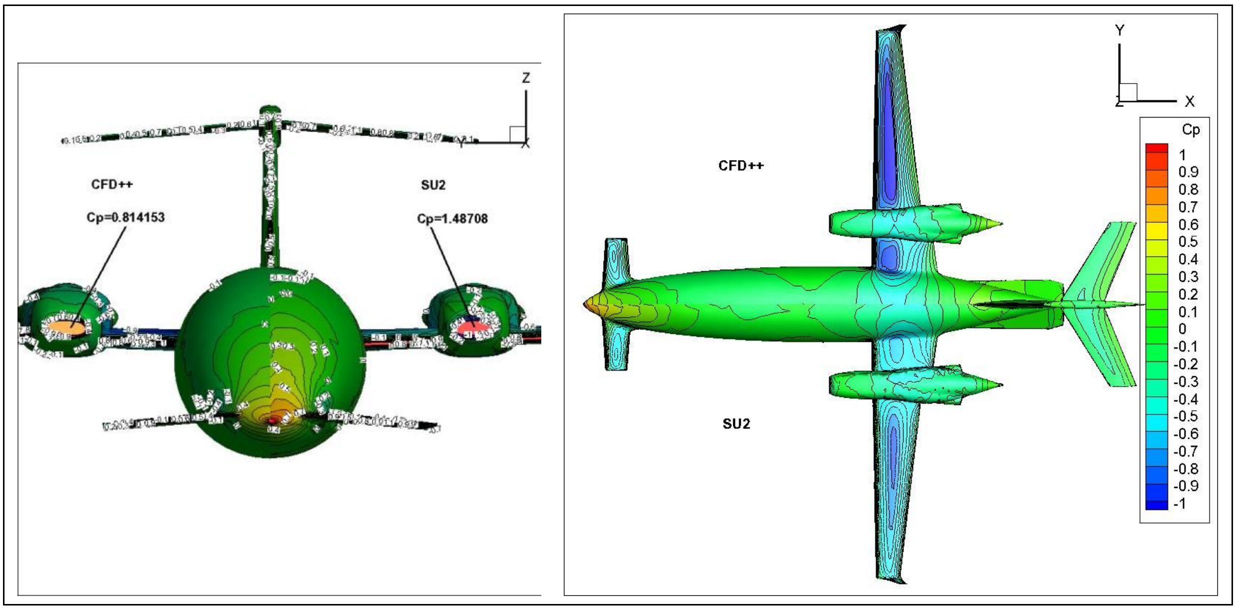

Figure 3: CFD results obtained for the baseline configuration of the P180 model

The fully developed solution gained for the baseline configuration was employed to initialise the computing of each design point (shape variant of the baseline) of the FSI optimization thus allowing to save computing time.

CSM model and model analysis results

The CSM model includes the central parts of the aircraft. Such a model and its position and room with respect to the CAD model is shown in Figure 4. While the winglets are modelled in full detail down to the composite material employed, the rest of the model is simplified using plates and beams for the wing and rigid elements for the engines, and using springs elements to link wing and fuselage maintaining fixed the two extremal sections of the fuselage.

Since the wetted CFD and CSM surfaces were not matching, it was impossible to accomplish an FSI optimization by adopting the standard 2-way method. Exploiting the meshless property of the morpher tool, however, it was possible to interpolate the structural displacements in order to propagate them onto the CFD mesh with a good level of accuracy. For this reason, the modal superposition method, that foresees the embedding of structural modes in the CFD model, was chosen to carry out the FSI analysis. According to this approach, FSI is solved as a reduced order method in which the structural behaviour of the system is condensed using a chosen number of modes, also called retained modes, each one allowing a single degree of freedom problem directly solvable in the CFD solver.

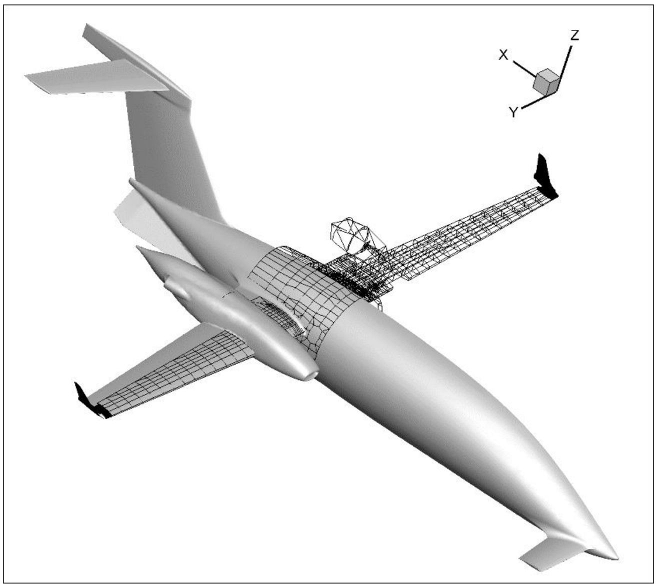

Figure 4: CSM model and its position with respect to the CAD model

In particular, the first 30 modal shapes were extracted but most of them were discarded being relative to local vibrational modes of the plates.

The modal shapes extracted from the CSM solver were used to generate a shape parameter for each one, adopting a strategy for the RBF solutions set-up similar to the one followed for the shape modifications previously detailed.

Optimization Results

Relating to the optimization analysis, a two-objective optimization ran choosing the drag as objective function to minimize and lift as objective function to maximise exploring the three shape modifications between +/-15°. As far as optimization settings are concerned, the full factorial method was selected to run the 27 design points identifying the design of experiment (DoE) exact evaluations, namely CFD-based evaluations. Other settings concerned the number of the offspring population size set to 60, the parent population size set to 20, the elite size set to 5, the maximum number of exact evaluations set to 40 and the maximum approximations set to 500.

Figure 5 shows the comparison between the baseline (bottom-grey) and the deformed configuration (coloured-top) of the wing for the baseline configuration.

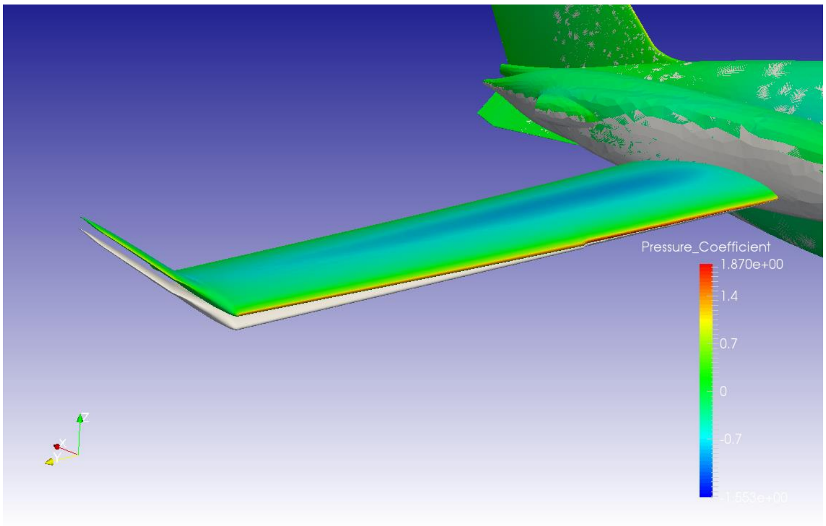

Figure 5: Comparison between the baseline (bottom-grey) and the deformed configuration

Figure 6 shows the most important output of the optimization, namely the distribution of the exact evaluations highlighting with a different marker both the baseline configuration and the non-dominated individuals (data are confidential). As visible, the FSI optimization showcased that there is room for effectively optimizing the winglet in cruise conditions.

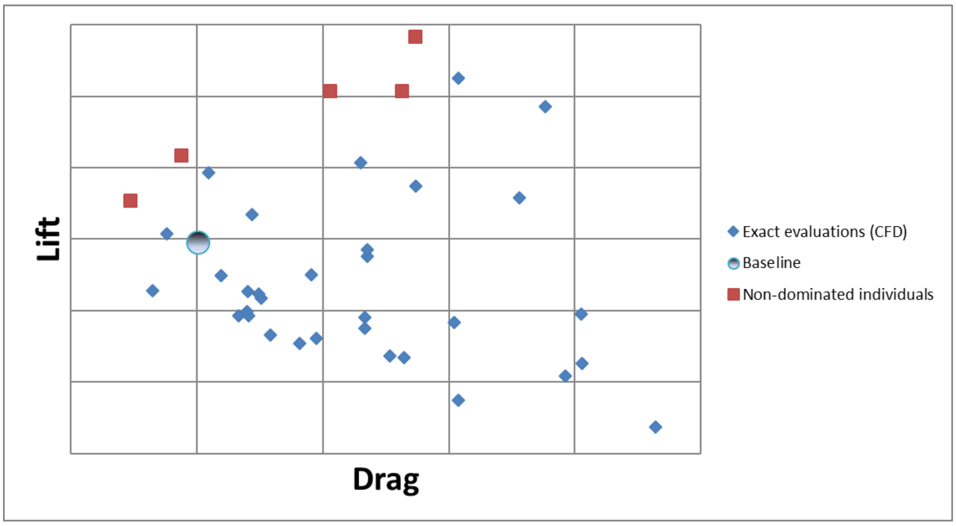

Figure 6: Optimization main outputs. Front of non-dominated solutions along with all the candidate solutions evaluated in the course of the optimization.

Considering that non-dominated individuals can be generated using known combinations of shape modifications, one of these can be then chosen as optimal configuration to improve the aircraft performance in cruise conditions.

Conclusions

The effectiveness of the use of the RBF4AERO platform to perform an highly automated optimization study concerning a mid-size business aircraft winglet in cruise conditions, also accounting for the effect of the elasticity of the wing, was demonstrated. Such an optimization was carried out adopting the mode superposition approach even if the wetted surfaces of the CFD and FEM models were not matching. The optimization study described in this paper showcased margins to improve the aerodynamic efficiency of the industrial vehicle. Given that, the mesh morphing methodology can help in optimizing the winglet shape to gain, for instance, a reduction of fuel consumption in cruise conditions. The RBF4AERO platform confirms to be a potential numerical means to offer CAE services through cloud infrastructures, such as the Fortissimo Marketplace, according to the software as a Service (SaaS) paradigm.

Acknowledgments

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