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# 'A CASE OF SUCCESS: MDO APPLIED ON THE DEVELOPMENT OF EMBRAER 175 ENHANCED WINGTIP'

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## Abstract

*This paper presents the roadmap for the development of the new wingtip for the EMBRAER 175 aircraft, and how Multi-Disciplinary Optimization (MDO) was applied on its definition and design.*

*In order to succeed in current aeronautical industry development, manufacturers must not only aim on creativity and innovation, but also on state of the art processes and fast response to market requirements. MDO methods have been proven as a useful and efficient methodology to overcome those challenges.*

*The short term development and certification of the EMBRAER 175 aerodynamic improvements can be considered as a great example of how MDO can provide a, not only optimum, but also fast and robust solution. The work consisted on optimizing an existing product by integrating several multi-fidelity analysis tools (from preliminary design to certification phase), and applying an efficient optimization algorithm.*

*An overview of the MDO process development by EMBRAER is presented. Then a brief introduction of the market requirements rationale is described. Next, it is showed how the MDO framework for the problem was assembled as well as the causality relations between all the involved technologies. A summary of the process and tools of each discipline integrated at the framework will be presented.*

*Regarding the optimization process, some lessons learned are discussed as well as how the objectives and constraints were defined, aiming on an optimum, robust and feasible solution, leading to the selected geometry.*

*Further, some stand-alone high-fidelity analysis were conducted in order to validate the lower-level fidelity tools used in the framework.*

*To conclude, flight test results and its accuracy with the proposed methodology will be discussed as well as how the final result meets the market expectations.*

## 1 The MDO Background at Embraer

The MDO technology has been constantly developed and applied at Embraer. The multidisciplinary analysis and optimization methodology started as a research and development project (R&D). The main goal was on identifying processes that could be efficiently used on the application of multidisciplinary analysis and optimization in the development and improvement of products, as well as identifying the major trade-offs that are inherit to the aeronautical design (as represented in Figure 1).

**Fig. 1: Trade-offs challenges in the aeronautical design.**

A case study consisting of applying MDO on the preliminary design of regional transport aircraft was proposed, in which some multi-fidelity tools were integrated to perform a multi-disciplinary sensitivity analysis and optimization. During this stage, a benchmark of integration tools were performed as well as several fidelities tools were tested during the workflow integration, aiming on identifying the more suitable fidelities of the analysis tools and integration and iteration strategies of the disciplines, depending on the design phase of the aircraft.

The MDO core team was assembled and several best practices for disciplines integration and optimization were tested and mapped (see references [1] and [2]).

One of the branches of the MDO R&D Project was the application of the MDO methodology on the design of wingtip devices.

## 2 Wing Tip Design

Wingtip devices are usually intended to improve the efficiency of fixed-wing aircraft. There are several types of wingtip devices, and though they function in different manners, the intended effect is always to reduce the aircraft's drag by altering the airflow near the wingtips (as shown in Figure 2).

Fig. 2: Different existent wingtip devices.

Designing wingtip devices is inherently a multidisciplinary challenge. If in one hand it can improve significantly fuel burn and take-off performance by reducing drag, on the other hand it can drastically penalize the aircraft by increasing the wing loading, thus adding weight (due to structural reinforcements) and, therefore, increasing fuel burn.

Additional attention must also be taken in evaluating possible impacts on several other aspects, such as aeroelastic margins, aircraft trimming capability, buffeting issues and stall characteristics.

## 3 MDO Strategy Applied to Wing Tip Design

As stated previously, part of the scope of the MDO R&D project at Embraer was to identify key objectives, constraints and integrated technologies, as well as to have a pool of easy “plug and play” tools, in order to provide a fast and reliable multidisciplinary analysis environment for each specific upcoming design challenge.

The high level design strategy consisted of building a general integrated multidisciplinary framework with multi-fidelity level capabilities using ESTECO-modeFRONTIER©, a commercial software integration tool.

The framework consisted of integrating a pool of tools aiming on modeling the main aspects of the technologies involved in the preliminary design of a wingtip, such as aerodynamics, structure, loads and performance (as shown in Figure 3). High performance computing (HPC) cluster and high throughput computing (grid computing - HTC) were extensively used.

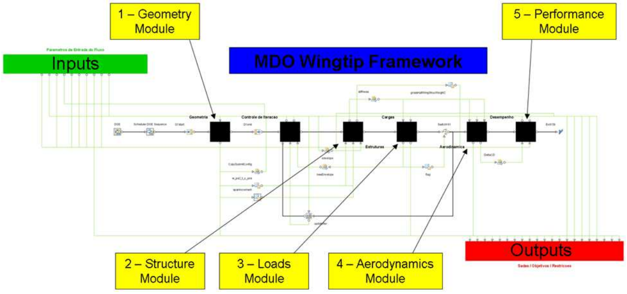

Fig. 3: Multidisciplinary framework assembled for the MDO Project.

Then, after some integration checks, an optimization was performed in order to select optimized trade-off solutions along the Pareto front, as shown in Figure 4.

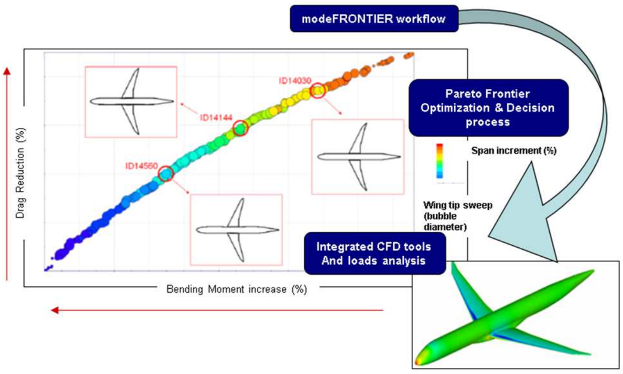

**Fig. 4: High level design strategy for the wingtip multidisciplinary optimization.**

Some key aspects were considered in the development of the multidisciplinary framework and executing the optimization:

- The main technologies involved and their respective level of fidelity;
- The adequate formulation of the optimization problem;
- Extensive use of parallel processing;
- Aero-structural optimization;
- Identification of several optimized trade-off solutions for further detailed analysis;

A wind tunnel test was executed in order to perform a calibration of the aerodynamic tools implemented in the multidisciplinary framework. The selected configurations in the Pareto front and their respective wind tunnel models are shown in Figure 5.

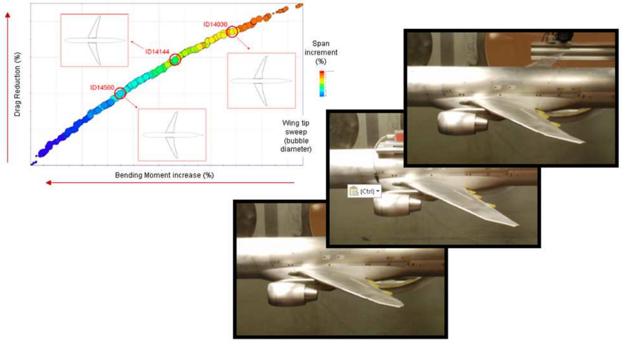

**Fig. 5: Optimized trade-off solutions selected for wind tunnel test.**

Finally, with the integration and optimization strategies tested, wind tunnel tests executed and framework models calibrated, the readiness to apply MDO on a product definition was achieved.

## 4 The Scope Clause and the Embraer Portfolio

A scope clause is part of a contract between an airliner and a pilot union. Generally, these clauses are used by the union of a major airline to limit the number and/or size of aircraft that airline may contract out to a regional airliner.

By the year of 2012, the Embraer E-Jets family consisted of 4 aircraft:

- Embraer 170 (E170), up to 78 passengers and a maximum take-off weight of 35990kg (STD);
- Embraer 175 (E175), up to 88 passengers and a maximum take-off weight of 37500kg (STD);
- Embraer 190 (E190), up to 114 passengers and a maximum take-off weight of 47790kg (STD);
- Embraer 195 (E195), up to 124 passengers and a maximum take-off weight of 48790kg (STD);

By the year 2012, there was a renegotiation of the scope clauses in the USA regional aviation market. Briefly, this renegotiation allowed an increase of the total number of large regional jets (up to 76 passengers) that could be operated by regional carriers under capacity purchase agreements with Major Airlines. The introduction of 76-seaters, with lower operational cost per seat, brought a new level of efficiency in this segment, improving the industry profitability.

The combination of the new scope clauses with the E175 range of passengers capabilities and operational weight, proved to be very attractive to the market, however a demand for fuel burn reduction was identified, in order to make the product even more attractive.

In order to achieve the required fuel burn reduction, several improvements in the E175 were proposed and some of them were implemented, with the re-design of the wingtip playing a major role on the fuel consumption reduction objective.

## 5 The Wingtip MDO Workflow

With the readiness of the processes regarding wingtip design and optimization, an experienced and skilled team and the correct product and time to market opportunity, a workflow was adapted aiming on optimizing fuel consumption on the E175.

Additionally, since the wingtip design was not for an application on a clean sheet design, several constraints regarding structural margins and aeroelastic issues must be considered, in order to accommodate the new design at the already existent wing structural topology.

The workflow consisted on integrating several tools concerning geometry generation, aerodynamics analysis, loads envelope generation, weight estimation and performance analysis. The causality relation between those disciplines and the integration environment assembled in modeFRONTIER© is shown in Figure 6.

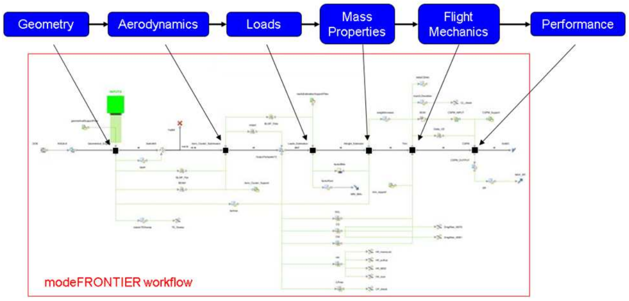

**Fig. 6: Multidisciplinary workflow applied on the design of the E175 new wingtip.**

Next, a brief description of the analysis performed by each discipline will be presented.

### *5.1 Geometry Module*

The geometry parameterization of the wingtip was performed using a modified CST formulation [3]. This formulation provides a very generic geometry generation capability, from simple wing extension to complex winglet devices.

Through straight linear construction lines, it also provides control of the geometry definition variables degree of freedom, allowing the generation of complexes continuous nonlinear curves and surfaces, hence providing a high level of freedom for the optimization to define the aircraft final geometry. The continuous and smooth surfaces produced through this methodology can also bring advantages to the manufacturing process. Figure 7 ilustrates some geometries built using the modified CST formulation.

The design variables selected for the optimization were the wingtip planform related (such as sweep, taper and span) and airfoil definition variables (such as camber, thickness and twist). The wingtip dihedral angle was also selected as a design variable.

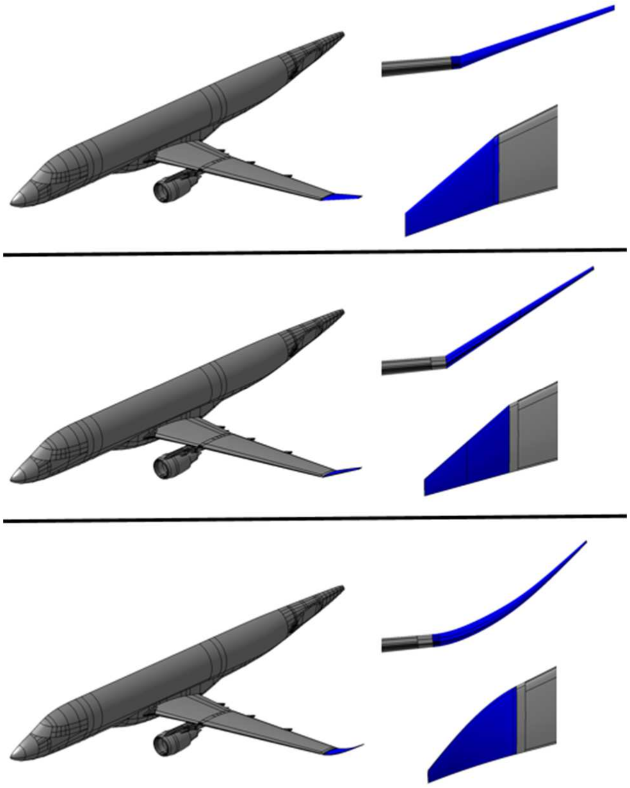

**Fig. 7: Examples of wingtip geometries**

### *5.2 Aerodynamics Module*

The aerodynamics analyses were performed using a full potential CFD code with boundary layer correction, as showed in Figure 8.

In order to evaluate important aeroelastic effects, a structural beam model was coupled in the CFD code.

Different aerodynamics conditions were simulated in order to evaluate the drag, for fuel consumption calculation purposes, and check several aerodynamics constraints, such as drag rise, buffeting and stall speeds and characteristics.

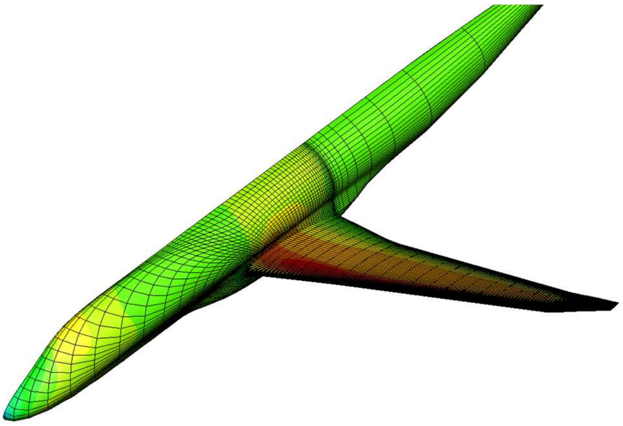

**Fig. 8: Full potential CFD code mesh and solution.**

### *5.3 Loads & Weight Module*

Critical load flight conditions were simulated using the same CFD tool of the aerodynamics module.

The lift distributions was then used to compute the shear, bending and torsion loads. These loads were then used to calculate the new in-flight loads envelope.

The wing load full envelope is then used in the mass properties module to estimate the wing additional weight due to structural reinforcements.

An additional analytical model was created in order to consider the increase in moment of inertia of the wing main box necessary to meet the same structural margins previously applied in the original design, thus estimating the increase of weight.

### *5.4 Flight Mechanics Module*

With the wing main aerodynamic coefficients computed, it is possible to compute the aircraft trimmed drag.

The trimmed drag was computed by obtaining the wing lift, drag and pitch moment coefficients at several conditions near the design condition and then performing a mathematical fitting on those curves, in order to obtain an analytical expression for those coefficients as a function of the lift. With these analytical expressions it was possible to compute the total trimmed aircraft drag by a simple trimming algorithm. The drag of the horizontal stabilizer was estimated through semi-empirical formulations.

### *5.5 Performance Module*

With the computation of the total aircraft weight and drag it is possible them to estimate the fuel consumption.

It can be shown that, for long range cruises, the fuel consumption has a very high correlation with the aircraft specific range (SR), described in equation (1):

$$SR=M*L/(D*W) \qquad (1)$$

where M is the cruise Mach number, L is the aircraft lift, D is the aircraft drag and W is the aircraft weight.

Henceforth, the aircraft specific range, computed at a medium cruise point, was selected as one of the objective function for the optimization.

## 6 Optimization Results

With the mathematical models integrated in the framework, and several sensitivity analysis evaluated, in order to check possible integration issues, an optimization was performed.

The non-sorting genetic algorithm [4] (NSGA-II) was selected for optimization. Additionally to the constraints and objective function already mentioned, an additional objective function was selected aiming on minimizing the bending moment at a critical wing station, characterizing the problem as multi-objective optimization.

Optimization results were obtained after heavy usage of a high efficient computational pool, and the Pareto front can be seen in Figure 9. The cross shape design points in Figure 9 represents the unfeasible design due to not complying one or more optimization constraints, and, therefore, not applicable for selection.

Based on engineering judgment and considering several multi-disciplinary aspects not modeled in the workflow, such as dynamics aeroelastics and manufacturing issues, a design point that best fit all engineering needs was selected along the Pareto front.

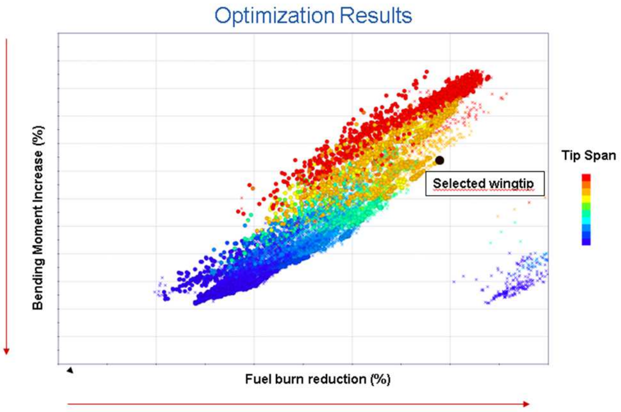

Fig. 9: Optimization result for the E175 new wingtip design.

## 7 High Fidelity Analysis

With a design point selected in the Pareto front, a high fidelity aerodynamic analysis was performed in order to confirm transonic characteristics, such as drag and pitch moment computed in the optimization. Subsonic aspects, such as maximum lift and stall characteristics, were also analyzed at this point.

A Reynolds average Navier-Stokes code simulation was used for the simulations, as shown in Figure 10.

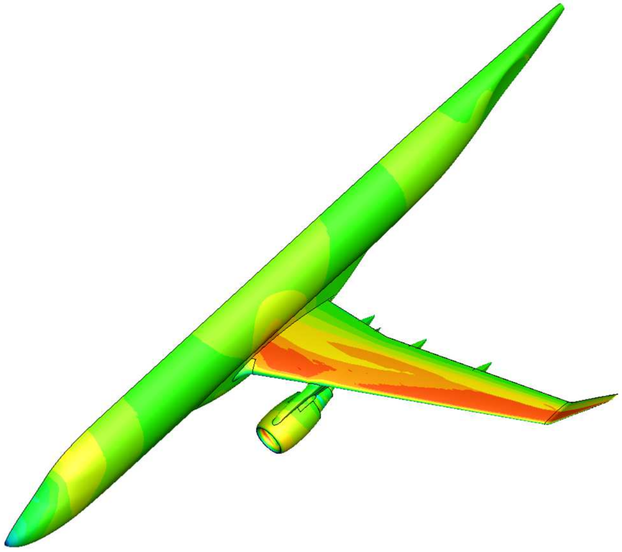

Fig. 10: CFD RANS simulation result

The high fidelity CFD analysis confirmed all the results predicted with the lower fidelity tools used in the optimization framework concerning drag, buffeting and stall issues

Henceforth, with the technical go-ahead, the project was cleared for the next design steps, such as detailed design and joint definition phases and, finally, flight tests and certification.

## 8 Flight test results and market acceptance

The first flight, flight tests and certification of the improved E175 were successfully accomplished in the year of 2013. A lean and efficient flight test campaign was executed, meeting all costs and date targets. All the aspects predicted in the optimization, such as fuel consumption and lift characteristics, were confirmed.

Fig. 11: Embraer 175 plus prototype

The aircraft was released in the market, by the name of Embraer 175 plus (E175+). It has achieved excellent acceptance, with more than 400 aircraft orders since its certification (see Figures 12 and 13).

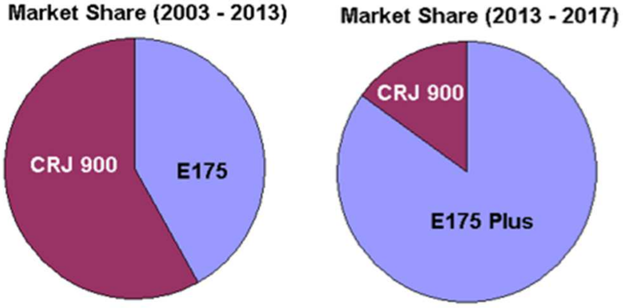

Fig. 12: Market share of the main competitors in the 70 seat aircraft market.

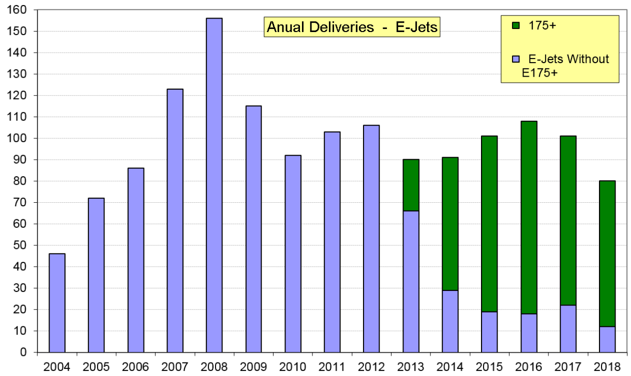

**Fig. 13: Embraer commercial aircraft deliveries.**

## 9 Conclusion

The multidisciplinary optimization strategy applied in the design of the E175+ new wingtip was briefly described.

The fuel consumption reduction obtained in flight test matched with the predicted values by the tools applied in the optimization, proving the accuracy of the method.

The aircraft sales number show how the product was well received by the market, and its reflection in the market share on the 70 seats aircraft market.

Much of the market success is not only due to the fuel consumption reduction, in great part obtained by the new wingtip, but also due to the correct time to market on releasing the product.

The timeframe of less than two years between the change in scope clauses and the final product certification shows how agile and efficient both the design and the flight test team reacted to a change in the market scenario.

In that sense, MDO proved to be not only a good solution in order to design global "optimum" products, but also to be a good methodology to provide fast response to new upcoming challenges, as long as if you have a good maturity of both, tools and personnel.

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