

Improvement of the Regional Jet CRJ700 Winglet Design based on Morphing Wing Principles

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Introduction – A high increase in carbon dioxide (CO₂) emissions in the atmosphere was observed during the last years in terms of 859 million and 915 million tonnes of CO₂ in 2017 [1] and in 2019 [2]. The aerospace sector has for goal to reduce these emissions in the near future. To achieve this goal, the International Civil Aviation Organization (ICAO) decided to reduce the CO₂ emissions recorded in 2005 by half in 2050 [3]. To support this effort, the ICAO set up the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) program in January 2019, funded by polluting actors in proportion with to their CO₂ emissions [4]. Thanks to the CORSIA program, aviation professionals are joining the efforts to develop environmentally friendly aircraft.

Among the most innovative and promising advances, those dedicated to the improvement of winglets are particularly interesting. Indeed, it has already been shown that the addition of a winglet to the wingtip of an aircraft allows to considerably improve its aerodynamics and consequently aims to reduce its fuel consumption and/or to increase its operational range [5].

Since their first design in 1969, many winglet shapes have been studied in order to make them as efficient as possible [6–9]. However, the new generation of winglets which equips the new Boeing 777x aircraft is of high interest to us. It is a folding winglet [10]. The new Boeing aircraft has been designed with a particularly large wingspan, initially limiting it to airports with adapted infrastructures (called Code-F airports) [11]. To enable their aircraft to compete with existing medium and long-range aircraft, Boeing engineers chose to use a folding wing tip, which would be able to reduce the aircraft's wingspan for both taxiing and docking phases [12].

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Finally, to move this winglet between the flight phases (unfolded winglet), and the ground phases (folded winglet), a mechanism has to be installed, which represents a certain weight at the tip of the wing for only a very short part of a flight.

We are therefore interested in the benefits that an adaptive winglet could offer during the flight compared to a conventional (i.e., fixed) winglet. This aspect is all the more interesting as the winglet mechanism has already been installed to allow its motion for the ground phases (for the Boeing 777x). Therefore, no extra weight would be added to allow its motion during the flight.

The advantages of an adaptive winglet were firstly studied at the Laboratory of Applied Research in Active Controls, Avionics and AeroServoElasticity (LARCASE) using aerodynamic models based on low fidelity computation methods, such as the Vortex-Lattice Method (VLM) [13,14]. Coupled with an aircraft performance model, it has been noticed that an adaptive winglet would increase the lift-to-drag ratio of the aircraft. This coupling makes the adaptive winglet particularly interesting during climb phases, where the rate of climb may increase up to 26 ft/min. For the cruise phase, it has been shown that the required fuel consumption can be reduced by up to 20 lb/h with an adaptive winglet (compared to the use of a fixed winglet). Following these successful results, it was decided to continue these studies, in particular by using higher fidelity methods, such as Computational Fluid Dynamics (CFD) based on Navier-Stokes equations [15,16].



Figure 1. Flight simulator of the CRJ700 aircraft located in the LARCASE laboratory (ÉTS)

Methodology – The Bombardier CRJ700 aircraft was selected in order to apply this research especially because of the fact that the LARCASE team has all needed data for this aircraft. Indeed, the LARCASE is equipped with a level D flight simulator of the CRJ700 aircraft, which is a valuable tool to perform validation of models. This flight simulator, shown in Figure 1 was developed for the LARCASE research needs by CAE Inc. and Bombardier. The level D is the highest certification degree that the Federal Aviation Administration is using to

qualify the flight dynamics of a flight simulator; it signifies that the data provided by the simulator has a maximum relative error of 5% compared to the data measured in-flight on the real aircraft. Moreover, the LARCASE has also a detailed Computer-Aided Design (CAD) drawing of this aircraft, which means that its geometry is perfectly known. Furthermore, this aircraft choice will allow us to project the benefits that an adaptive winglet could bring to a regional fleet that represent 58.2% of all flights performed daily [17].

The original CAD drawing of the CRJ700 aircraft, was thus modified in order to add the adaptive winglet system. A "pod" was then added at the junction between the wing tip and the winglet root. As the study concerned only the aerodynamic performance aspect, and not the mechanical aspect, the hypothesis that this "pod" could accommodate an adequate mechanism was made. This "pod" is remarkable under various angles of view shown in Figure 2.

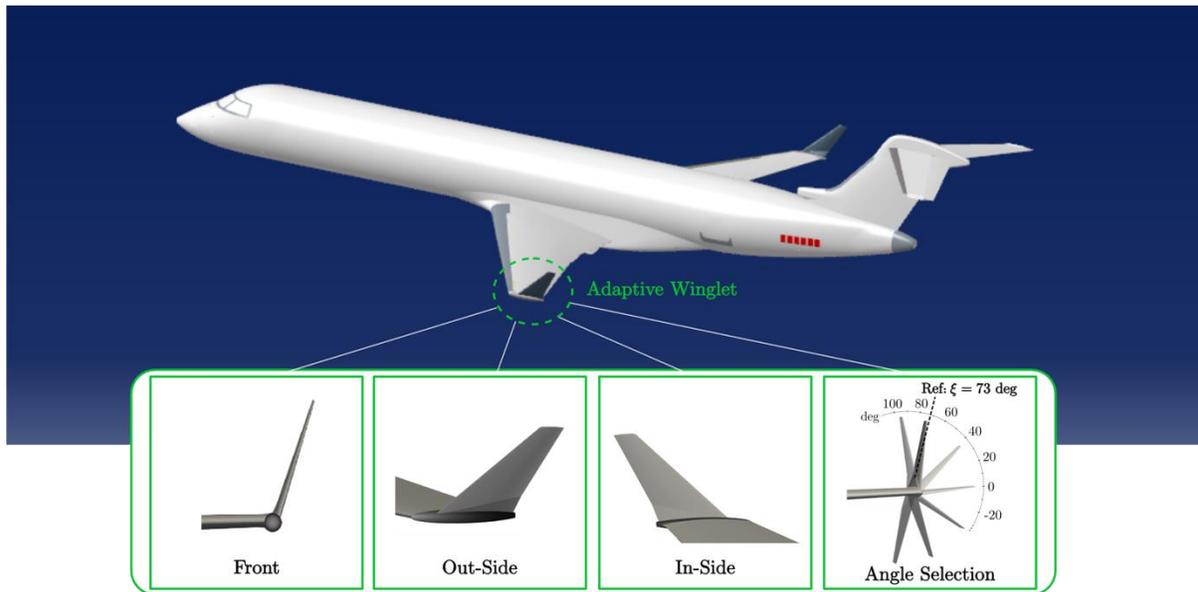


Figure 2. Design of an adaptive winglet for the Bombardier CRJ700

On Figure 2, it can be assumed that the only geometrical change carried out on the aircraft design is the "pod". Indeed, the wing and the rest of the aircraft remain unchanged, as well as the winglet shape, except its base.

This new winglet has 1 degree of freedom around the rotation axis located along the wing tip chord (in the center of the pod). The winglet can rotate from -93 deg to +93 deg. The position of 73 deg allows the new winglet to be geometrically superimposed on the original winglet of the Bombardier CRJ700. Considering that the study aims to highlight the advantages of an adaptive winglet with respect to those of a fixed winglet, it was chosen that the geometrical reference of the study would be the new winglet parameterized at its position of 73 deg. This

reference was chosen in order to take into account the possible aerodynamic performances changes brought by the pod.

Then, in order to study the aerodynamic benefits of this new winglet design, a high fidelity aerodynamic model designed with the OpenFoam toolbox (CFD) was used. The whole mesh was realized using successively the tools *blockMesh* and *snappyHexMesh*. For the simulations (CFD), the incompressible and compressible flow solvers *simpleFoam* and *rhoSimpleFoam* were chosen, and were coupled with the Spalart-Allmaras and $k - \omega$ Shear Stress Transport (SST) turbulence models, respectively. The whole methodology has been developed and validated with flight test data from the CRJ700 aircraft, provided by the level D flight simulator (Figure 1). Statistical results obtained for 35 different flight conditions, exposed in Figure 3, show that the aerodynamic model was able to well predict the lift coefficients within a margin error of -0.007 ± 0.045 and the drag coefficients within a margin error of -0.00015 ± 0.00114 , both in 95% of cases [18].

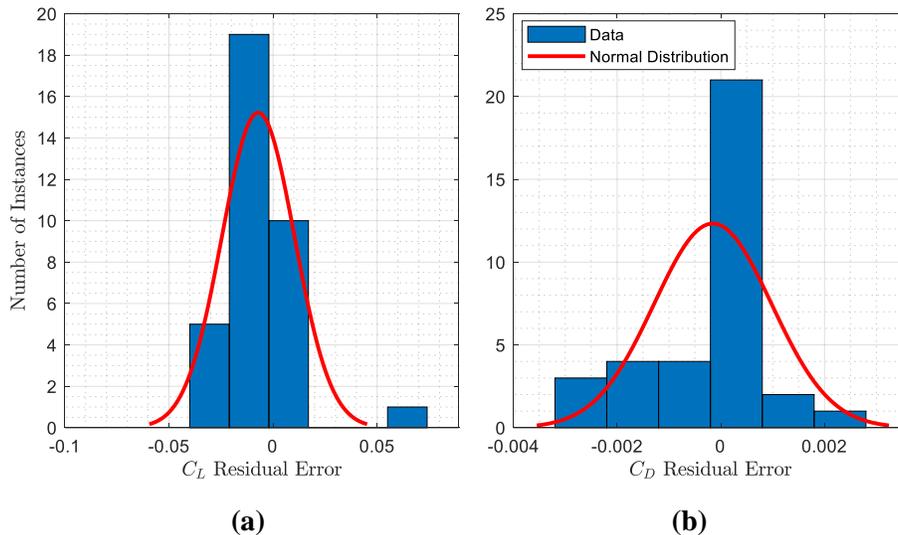


Figure 3. Statistical results obtained for the validation of the aerodynamic model versus level D flight simulator data of the Bombardier CRJ700

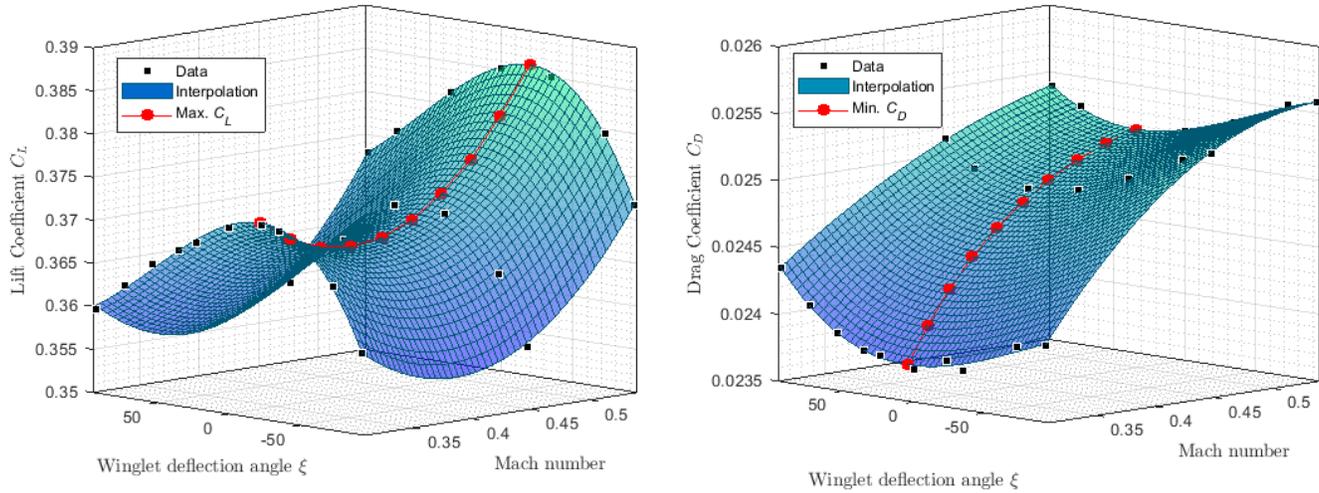
Using this validated aerodynamic model, aerodynamic coefficients (C_L and C_D) were evaluated for different flight conditions frequently used by the aircraft that were expressed by Mach numbers varying between 0.31 and 0.79, as well as altitudes varying between 5,000 ft and 30,000 ft. For these flight conditions, different winglet positions were tested, ranging from -93 deg to +93 deg.

After obtaining all needed aerodynamic coefficients C_L and C_D , a behavioral study was performed in order to establish a selection criterion of the "best winglet" position for a certain flight condition (i.e., minimum drag, maximum lift, etc.). Then, by use of surface interpolation tools presented in Figure 4, a surface was found to

predict variation of C_L or C_D coefficients for a given angle of attack, as a function of the winglet angle ξ and the Mach number M . This surface was expressed by Eq. (1), as follows:

$$C_k(M, \xi) = \sum_{i=0}^2 \sum_{j=0}^3 a_{ij} \cdot M^i \cdot \xi^j \quad (1)$$

where C_k represents an aerodynamic coefficient (C_L or C_D), i and j are indexes used in the sum development, and a_{ij} are polynomial coefficients that depend on the angle of attack and on the type of coefficient C_k desired (i.e., lift or drag coefficient).



(a) Lift coefficient

(b) Drag Coefficient

Figure 4. Lift and Drag coefficient variation versus the Mach number and the winglet deflection angle (angle of attack of 0 deg)

From Figure 4, it was observed that the coefficients do not vary symmetrically on either side of the 0 deg winglet position. Moreover, the minimum drag (interesting to minimize fuel consumption), does not necessarily correspond to a winglet position offering the reference lift offered initially by a winglet at 73 deg. In order to take into account the lift and drag advantages that the adaptive winglet could offer, the criterion of the highest lift-to-drag ratio was chosen to select the "best winglet" position for a flight condition.

Results – Results obtained for flight conditions corresponding to Mach numbers of 0.31 and 0.54 are shown in Figure 5. Thus, the lift-to-drag ratio is indicated on the y-axis while the angle of attack is specified on the x-axis. Each bar color is corresponding to a winglet position studied: -93, -73, -35, 0, 35, 73, and 93 deg.

It can be noticed that the winglet positions located between -35 deg (in “white” color) and +35 deg (in “dark pink” color) are particularly interesting for these flight conditions (M0.31 and M0.54). Indeed, for these flight conditions, the adaptive winglet allowed to increase the lift-to-drag ratio up to 3.91% compared to a fixed winglet set with a 73 deg angle (represented with a “black” bar).

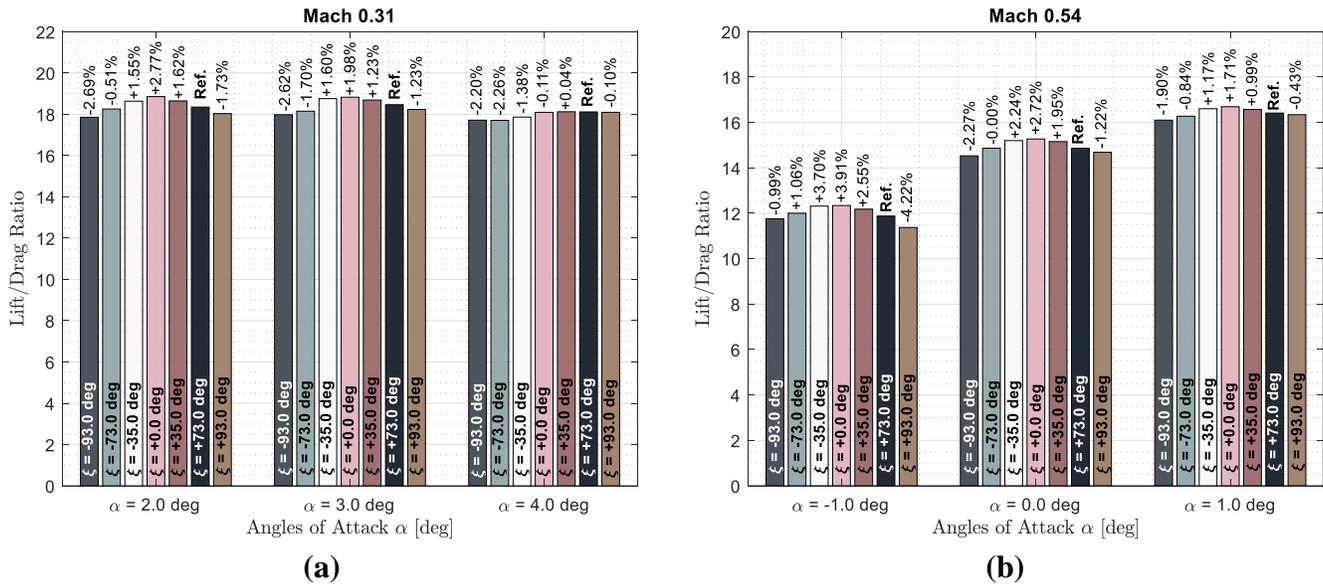


Figure 5. Results obtained for flight conditions corresponding to Mach number 0.31 and 0.54

From the results, we can assume that by using the interpolation surfaces estimated in Figure 4, the winglet position corresponding to the maximum value of the lift/drag ratio could be more accurate (within 1 degree for example). As well, the lift to drag ratio could be slightly higher than the “best” ratio shown on Figure 5 (a) and (b).

Conclusion – Results obtained using high fidelity CFD methods have confirmed results that were obtained during preliminary studies, using VLM methods. In consequence, it is expected that the use of a performance model of the CRJ700, would conduct to benefits such as fuel flow reduction, an increasing operational range, or higher rate of climb. It is important to mention that the winglet research here developed was applied on the CRJ700 aircraft because the LARCASE team has data of this aircraft to validate models; but the methodology used can be applied on other aircraft.

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