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PERFORMANCE ASSESSMENT OF A MORPHING WINGTIP DEVICE

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Abstract. *The present work addresses the aerodynamic design of a reference aircraft and the assessment of the potential benefits that a morphing wingtip can bring in terms of the aircraft performance. The subject of the work is part of the NOVEMOR project (NOvel Air VEhicle Configurations: From Fluttering Wings to MORphing Flight) which is one of the many projects from the European Framework Programme. The reference aircraft is representative of a typical regional jet capable to carry 113 PAX in a single economic class and provide operational flexibility to fly different missions at the transonic regime. The variations of the wingtip toe and cant angles are evaluated in order to check the potential benefits in terms of aircraft performance. An aerodynamic database is created for both, the reference and the morphed configuration. Moreover, the generation of a representative high-by-pass engine deck allows the evaluation of different missions. The performance analyses are computed for the entire range versus payload diagram and the potential benefits are described in terms fuel saving.*

Keywords: *wingtip, morphing devices, aircraft performance, aerodynamic design, geometric parameterization.*

1. INTRODUCTION

The aeronautic industry, more precisely the aviation field, is characterized as a demanding business area in which the competition has become fiercer along the last years. Partially, the raise in the competition can be assigned to the emergence of economical containment and the imposition of more stringent airworthiness regulations to satisfy environmental aspects (IATA, 2011; Berlin, 2011; Branch, 2010; ACRE, 2011). The economical factor is intrinsically connected with the increase of the oil price over the last decade (European Commission, 2008), which imposes the need to have an aircraft design with the best operational performance and, at the same time, observing the important questions such as acquisition price, and the direct and indirect operating costs (Mechan, 2007). On the other hand, the environmental requirements are deeply connected with the noise and gas emission regulations. The main concerns about these two topics are their impact on the community situated around the runways and on the greenhouse gas effect.

In the last years a great amount of effort, from research institutes and aircraft manufactures, has been dedicated to study different active components for aircraft applications. These smart devices are capable of performing active flow control through changes in the geometric shapes of the lifting and non-lifting surfaces, and, hence, allowing potential improvements in the aerodynamic coefficients. Certainly, these promising aerodynamic enhancements can lead to improvements in the aircraft performance, thereby, easing the design of a more environmental friendly aircraft.

The present work is primarily focused in developing a reference aircraft in order to evaluate the potential benefits that wingtip morphing devices can bring in terms of aerodynamic performance. The work aims to develop a reference aircraft for the regional aviation segment and such activity is part of the NOVEMOR project, which is one of the many projects promoted by the 7th European Framework Programme. In particular, the referred project has a wider and more comprehensive scope, which encompasses different engineering analyses performed by academic institutions, research centers, and an aircraft manufacturing company. In the whole context of the NOVEMOR project a broader perspective, about the morphing devices, is expected to be approached. The project intends to evaluate not only the aerodynamic benefits but also the tradeoffs in terms of energetic balance, structural limits and aeroelastic effect.

ISSN 2176-5480

2. REFERENCE MODEL

The reference model is a typical regional airplane capable to provide operational flexibility to accomplish different missions at the transonic regime. In particular, the establishment of the operational requisites, for the reference aircraft, was obtained considering missions that encompass 600 nm. Nevertheless, the same reference aircraft is capable of accomplishing missions up to 2300 nm. In Tab 1 one can observe a brief description of the reference aircraft operational characteristics and in Fig 1 one can see the geometrical details.

The reference aircraft was designed to achieve an optimum cruise performance at the Mach number 0.78 and the lift coefficient, CL, of 0.47. The aerodynamic design was performed by means of an optimization process considering a medium fidelity solver, namely BLWF (Karas, 2002). The BLWF formulation contemplates the full potential equations coupled with a boundary layer subroutine. Indeed, the solver has a good compromise between computational efficiency and the accuracy provided by the numerical formulation. In terms of the geometrical representation of the wing, the optimization process considered the Parsec parameterization (Sobieczky, 1999) to define the respective profile shapes that constitute the wing. In the present work, the wing planform was not considered as part of the optimization process of the reference aircraft. The planform was defined through a geometric homothetic transformation imposed on the wing planform of a specific regional jet.

Table 1. General characteristics of the reference model.

Maximum Takeoff Weight	127,943 lb	58,034 kg
Maximum Landing Weight	116,920 lb	53,034 kg
Maximum Zero Fuel Weight	105,896 lb	48,034 kg
Basic Operating Weight	75,032 lb	34,034 kg
Maximum Payload	30,865 lb	14,000 kg
Maximum Fuel(1)	39,683 lb	18,000 kg
Maximum Operating Speed	Mach 0.82	
Time to Climb to FL 350, TOW for 600 nm	17 min	
Takeoff Field Length, ISA, SL, MTOW	4,889 ft	1,490 m
Takeoff Field Length, ISA, SL, TOW to 600 nm	3,780 ft	1,152 m
Landing Field Length, ISA, SL, MLW	5,334 ft	1,626 m
Range 113 pax @ 220 lb (100 kg), LRC	2,369 nm	4,387 km
Mean Aerodynamic Chord	12.66 ft	3.86 m
Reference Wing Area	1,184 ft^2	110 m^2
Reference Wing Span	51.61 ft	15.73 m

(1) Fuel density: 0.803 kg/l (6.70 lb/gal)

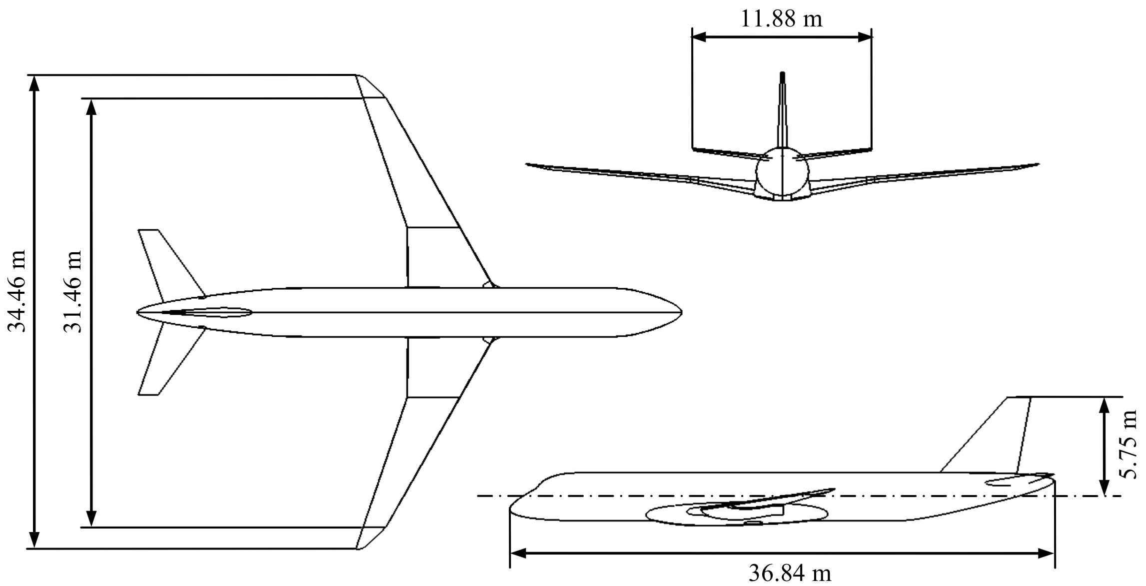

Figure 1. Reference aircraft 3-view.

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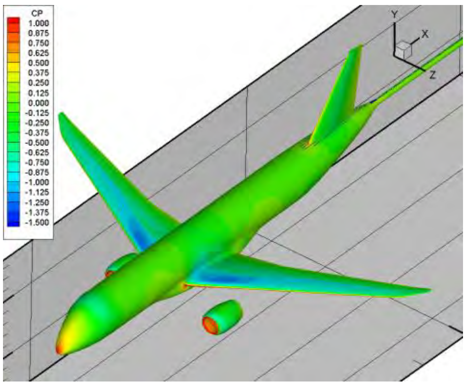
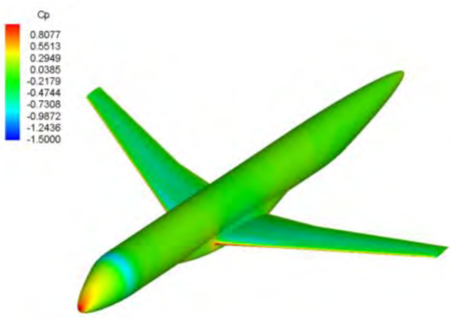
In the optimization process of the reference aircraft the Genetic Algorithms, GA, (Deb, 2003; Goldberg, 1989) was adopted as the main optimizer. Those prominent proposals, that outcome from the optimization process, were evaluated under different aerodynamic perspectives in order to define the best design for the reference aircraft. The selected design was later analyzed considering a higher fidelity approach in order to verify if there were some physical phenomena that were not captured with the medium fidelity solver. The higher fidelity analyses are performed with the CFD++ solver (Metacomp) and the referred check is absolutely necessary once subsonic and transonic wind tunnel campaigns are going to be performed to validate the numerical results and the morphing concepts.

Figure 2 shows the contours of the pressures coefficient, Cp, over the reference aircraft at the design point, M = 0.78 and CL = 0.47. In the presented case the simulations performed with the CFD++ do not have the wingtip and nacelle. In Fig. 3 one can observe a comparison between the Cp distribution, obtained with the BLWF and the CFD++, this comparisons are carried out for few station cuts along the wing spanwise. One can observe that, there is a good adherence among the results. This is a clear indication that BLWF is capable to reasonably predict the major aerodynamic behavior, as long as, we keep the project away from critical conditions such as those that can trigger the flow detachment caused by the interaction between the shock wave and the boundary layer.

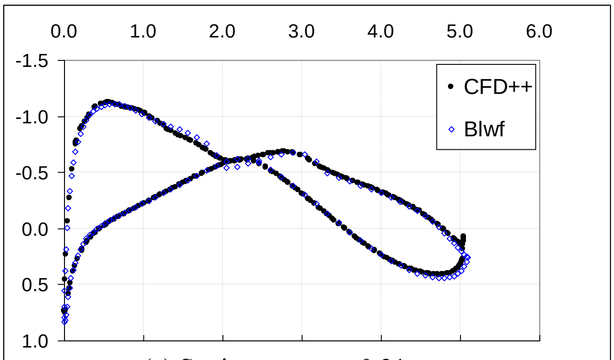


(a) Simulation performed with the BLWF solver.

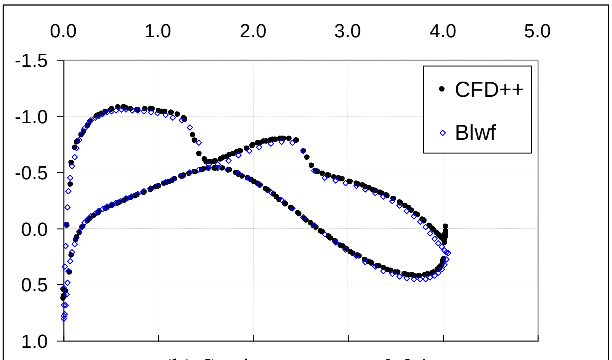


(b) Simulations performed with the CFD++ solver.

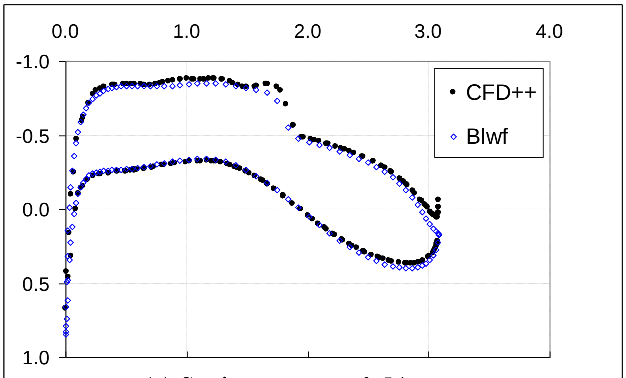
Figure 2. Pressure coefficient contours at Mach number = 0.78 and CL = 0.47.



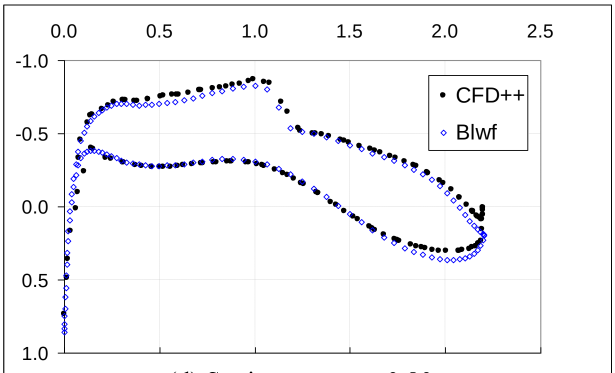
(a) Station cut eta = 0.21



(b) Station cut eta = 0.34



(c) Station cut eta = 0.54



(d) Station cut eta = 0.80

Figure 3. Pressure coefficient contours at Mach number = 0.78 and CL = 0.47.

An engine deck was generated in order to supply the necessary data for the performance assessment of the mission with the without the morphing wingtip device. The generated deck is in accordance with an engine capable to deliver 21000 pounds of thrust, weighting 6300 kilograms and with the following geometric characteristics: diameter of 2.07 meters, a total length of 3.73 meters. In Fig. 4 and 5 on can observe the thrust and fuel flow for maximum cruise rating considering different flight Mach number and altitude levels. Figure 6 shows the thrust at takeoff conditions.

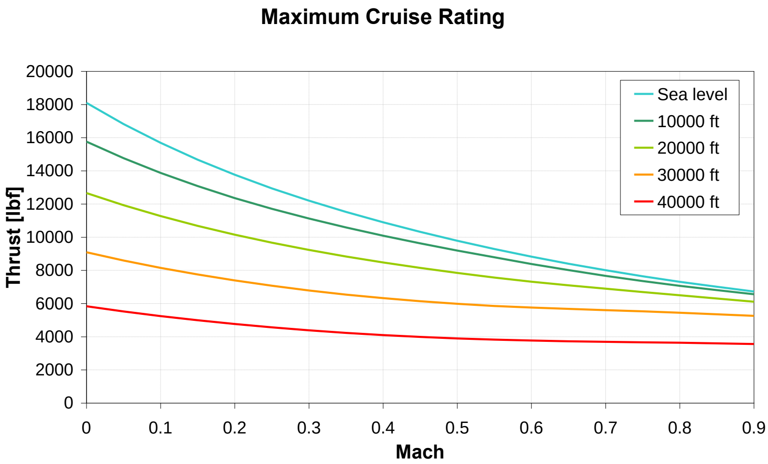


Figure 4. Variation of the thrust as function of the Mach number and the altitude.

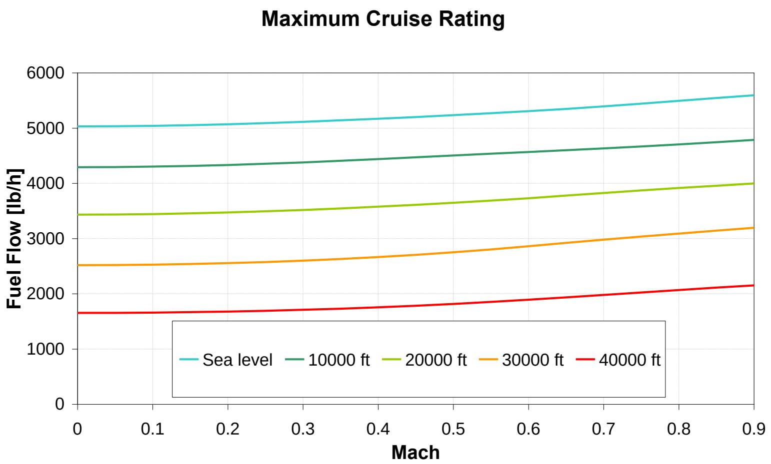


Figure 5. Variation of the fuel flow as function of the Mach number and the altitude.

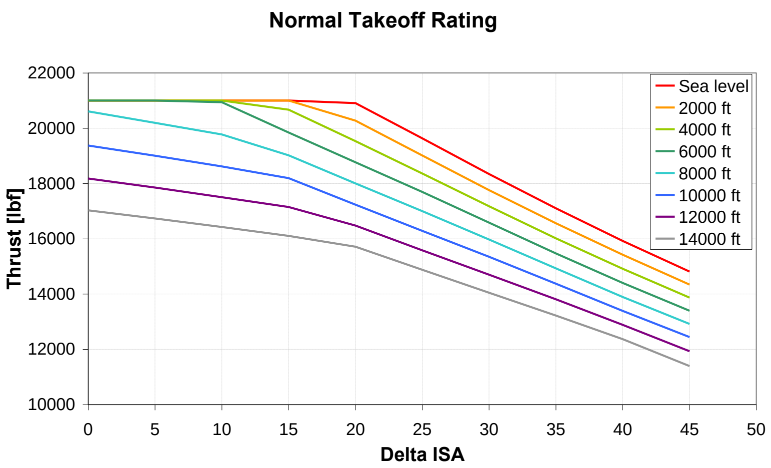
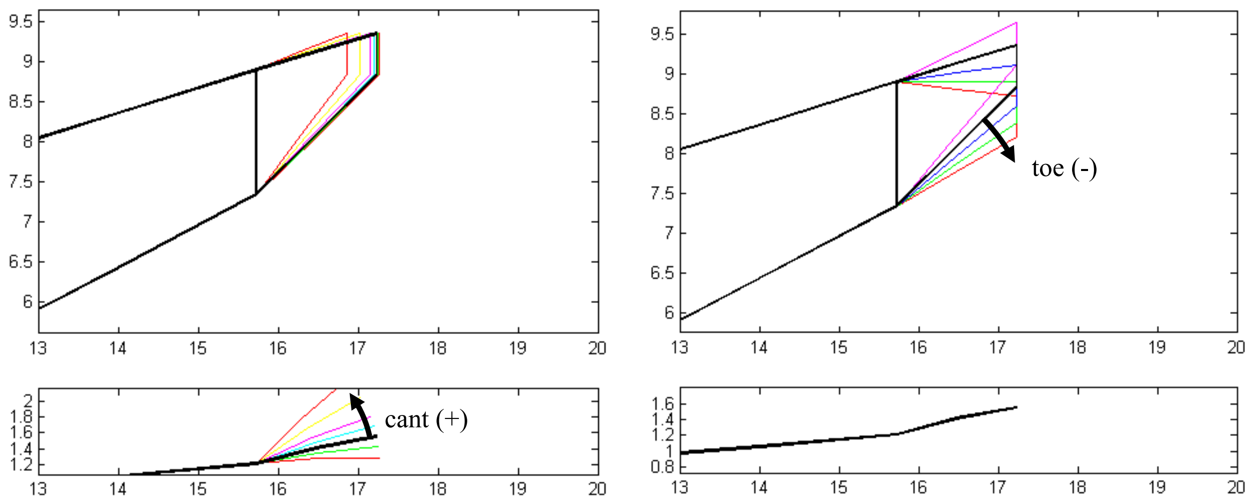


Figure 6. Variation of the thrust as function of the Delta ISA and the altitude.

ISSN 2176-5480

3. MORPHING WINGTIP

The evaluation of the morphing wingtip was achieved through modifications in the cant and toe angles. These two angles are graphically represented in Fig. 7 and their definitions have some similarity with the wing dihedral and sweep angles. In the present study the cant angle is allowed to vary from -10° to 30°, whilst the range of the toe angle goes from -15° up to 5°. The wingtip area was kept constant in order to maintain the same total wetted area and, even though the projected area varies depending on the morphing configurations, the reference area was also kept constant.



(a) Cant angle. (b) Toe angle

Figure 7. Definition of the cant and toe angles.

It was adopted a step of 5° during the generation of the all possible combinations of cant and toe angle to be analyzed. An aerodynamic database, taking into account different values of lift coefficient and Mach number, was created for each of the respective morphing proposals. In the end, a total amount of 35 configurations, including the reference wingtip, were simulated for a vast number of flight conditions. Due to the great amount of cases to be evaluated the simulations were performed with the aid of a distributed grid computing environment. It is worth mentioning that these analyses were conducted for the wing/body/nacelle/vertical tail configuration and the evaluation of the horizontal tail, which is responsible for the longitudinal stability of the aircraft, was performed by a separated numerical procedure. This procedure was responsible to create the respective trimmed drag polar of the many analyzed proposals.

Figure 8 illustrates the adopted procedure that guided the elaboration of an optimum aerodynamic database. The optimum and unique database has not only the information about the optimum drag coefficient, at the respective Mach number and lift coefficient, but also the morphed wingtip device associated with each pair (Mach, CL). Certainly, there are some situations in which the best configuration is given by the reference wingtip and, thereby, there is no mention to any cant and toe angle deflections.

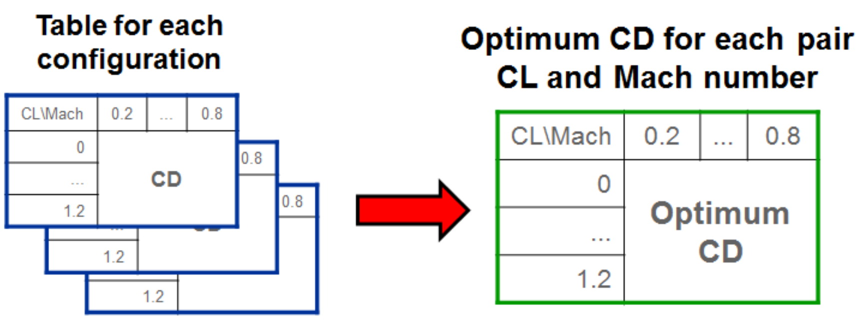
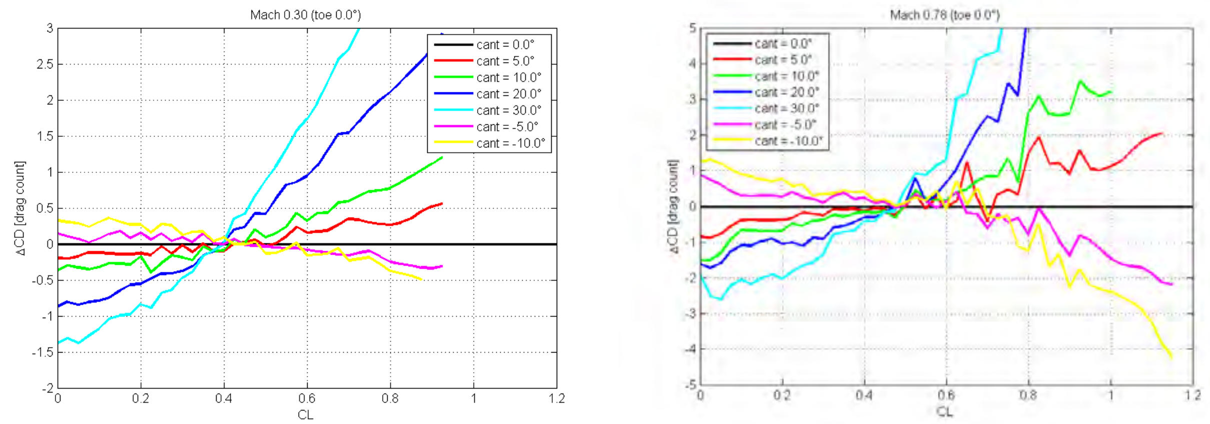


Figure 8.Illustration of the elaborated procedure to generate the optimum aerodynamic database.

4. RESULTS

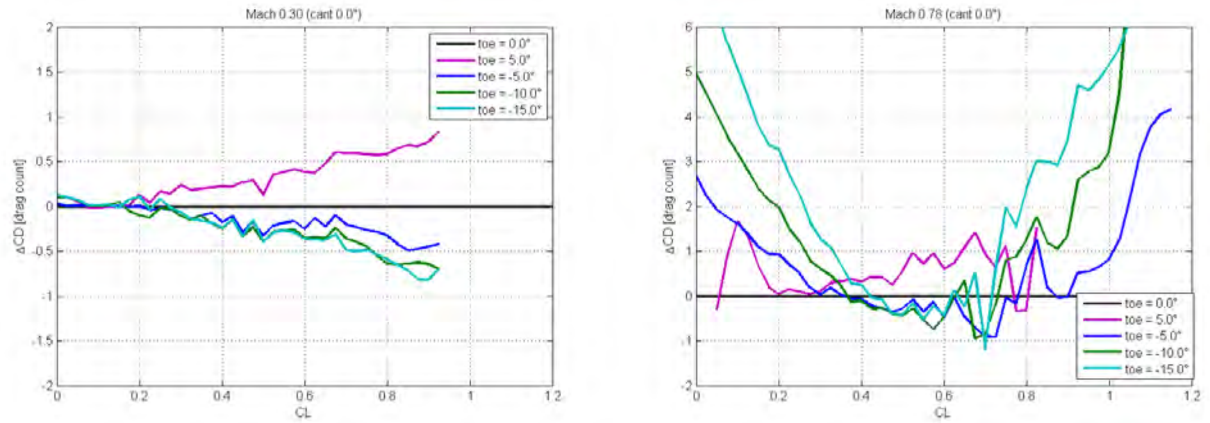
In this section, initially it is presented some limits that stipulate both, the aerodynamic benefits and the aerodynamic disadvantage attained with the adoption of the morphing wingtip device. In a second moment, the effect of the application of the morphing devices, now considering only the potential benefits, is shown in terms of fuel block savings. In order to obtain the information about the fuel saving a performance program is employed to simulate the analysis of the aircraft mission.

Figure 9 shows the delta drag coefficient, CD, as function of the lift coefficient for different deflections of the cant angle. The result that lies above the abscissa represents an increase in the drag coefficient with respect to the values obtained by the reference aircraft. It is important to notice that, the best cant angle, which gives lower CD, changes as the value of the CL is modified. This means that, to get the best aircraft performance, the morphing device should be constantly modifying its configuration along the flight mission. In Fig. 9(a) one can observe the results obtained for a lower Mach number, M = 0.30, considering the toe angle fixed at zero degree and in Fig. 9(b) one can see similar results now for a higher Mach number, M = 0.78. Figure 10 shows the same delta CD as function of the CL, however, in this case, the cant angle is fixed at zero and the toe angle is allowed to vary. Here, the results are also shown for two flight regimes.



(a) Lower Mach number. (b) Higher Mach number.

Figure 9. Effect of the cant angle in the drag coefficient as function of the CL.



(a) Lower Mach number. (b) Higher Mach number.

Figure 10. Effect of the toe angle in the drag coefficient as function of the CL.

The deflections of the cant angle, for a wide range of Mach number and lift coefficient, are represented in Fig. 11(a) by different colors and specified in the sidebar legend. Those regions in Fig. 11(a), that are associated with non-zero values for the cant angle, represent flight conditions where improvements are obtained in the drag coefficient by the adoption of the morphing wingtip. Nonetheless, those regions defined by the cant angle equal to zero means that, the reference wingtip provides a lower drag coefficient. Similarly, the same sort of information can be observed in Fig. 11(b), but in this case for the toe angle.

The addition of the cant and toe angle benefits can be observed in Fig. 12. However, the results presented in Fig. 12 are shown in terms of reduction in drag coefficient. It can be observed that, in the region close to the design point of the reference aircraft the benefits of the morphing wingtip is not considerable. The benefits of the morphing wingtip are more expressible in the flight envelope region that encloses a very low lift coefficient and Mach number above 0.70.

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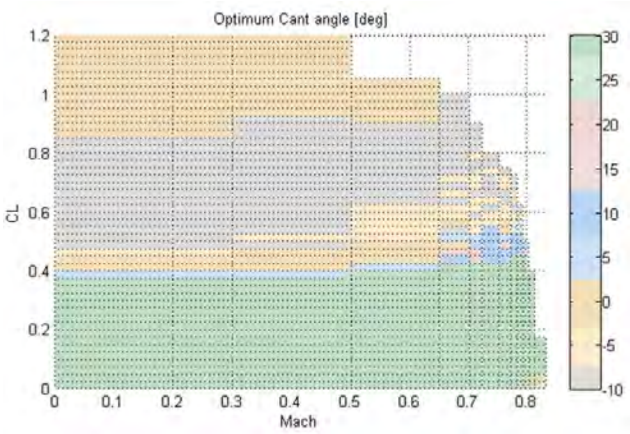
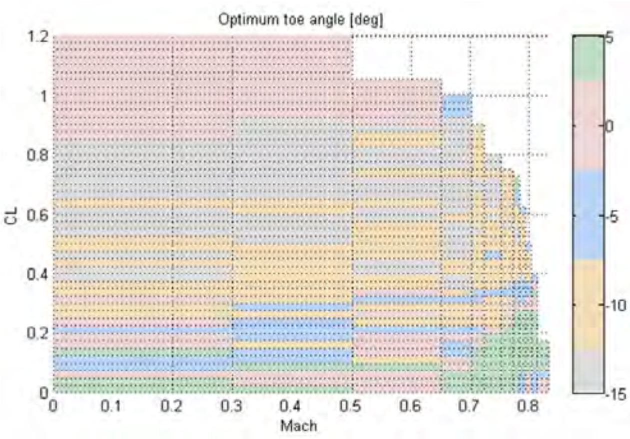


(a) Optimum cant angle



(b) Optimum toe angle.

Figure 11. Definition of the best cant and toe angle over the aircraft flying range of Mach number and CL.

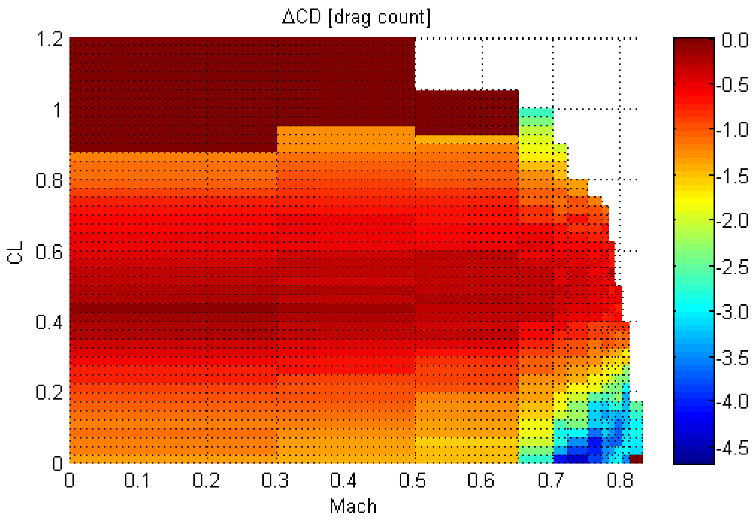


Figure 12. Drag reduction due to the application of the wingtip morphing.

The constructed optimum aerodynamic databank and the engine deck were adopted in the flying simulation of a typical 600 nm mission. In this flight mission the following flight schedule was considered:

– Climb
 (a) 250 KCAS from 1.500 feet until 10.000 feet;
 (b) linear increase in the velocity up to 290 KCAS at 12.000 feet;
 (c) maintain the velocity at 290 KCAS until it reaches Mach 0.75;
 (d) maintain the velocity at Mach 0.75.

– Cruise
 (e) velocity fixed at Mach = 0.78 in the flight level of 38.000 feet.

– Descent
 (f) constant Mach 0.77 until the velocity reaches 290 KCAS;
 (g) maintain the velocity at 290 KCAS until 12.000 feet;
 (h) linear decrease in the velocity up to 250 KCAS at 10.000 feet;
 (i) maintain the velocity at 250 KCAS at 1.500 feet.

Figure 13 shows the mission profile and the details about the lift coefficient, the Mach number and the corresponding cant and toe angle along the respective flight phase. It is possible to see that, at climb and descent segments the best configurations is the one that requires a cant angle of 30°, which was the highest angle simulated. This shows that if higher angles for the cant angle were allowed, higher gains would be obtained. Furthermore, it is

ISSN 2176-5480

possible to note that there are basically three optimal configurations: one for climb and descent (positive cant); one for cruise (slightly positive cant) and one for hold (negative cant). Figure 13 show how the lift coefficient and Mach number vary along phases of the 600 nm mission. Moreover, the sidebar on the graph shows the respective cant and toe angles demanded from the morphing device along the mission segments. Taking the typical 600 nm mission and considering 12.000 kg of payload, it was possible to observe a reduction of 3.8 kg in block fuel, which represents a reduction of 0.1%. This result is inside the error margin from the adopted tools, and, hence, at least for the present analyzed flight mission, no practical improvement could be observed. It is important to reinforce that this result does not consider any additional weight in basic operational weight, BOW, caused by the additional weight of the actuators of the morphing device.

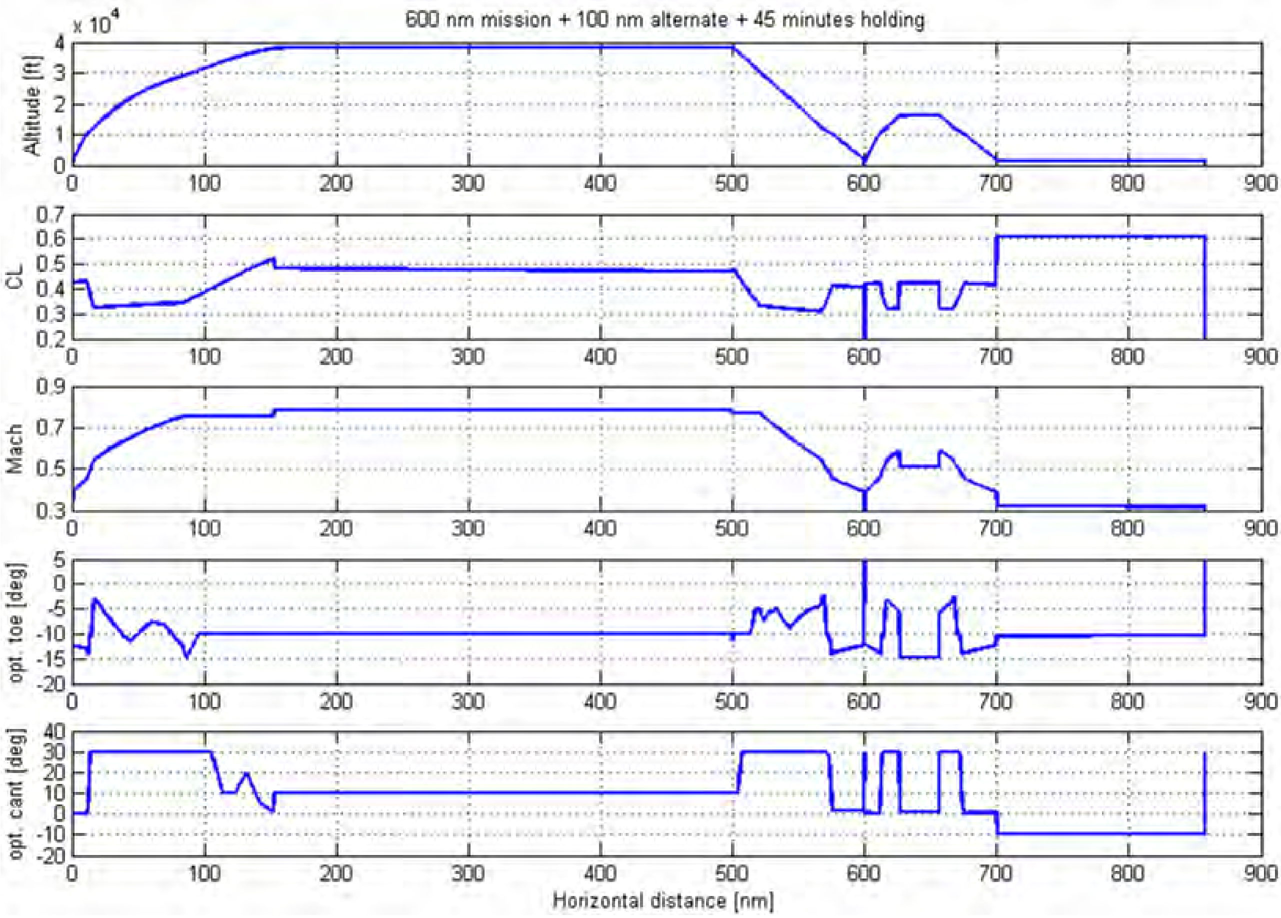


Figure 13. Mission profile with optimum cant and toe angles.

Figure 14 shows in a plot containing the Mach number and the lift coefficient the flight phases of the 600 nm mission. It can be seen in Fig. 14(a) how the cant angle is varying along the mission phases, similarly, in Fig. 14(b) the observed information is relative to the toe angle. Both angles are constantly changing along the mission in order to provide the best flight performance.

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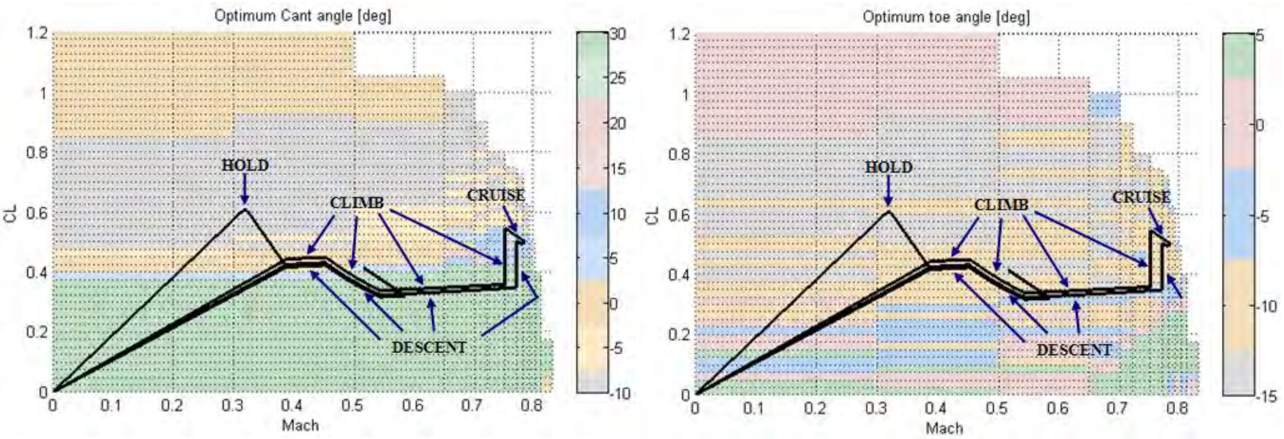

(a) Optimum cant angle variation (b) Optimum toe angle variation

Figure 14. Variation of the cant and toe angles required at the different phases of the 600 nm mission.

The aircraft range versus payload graph provides an overview about the aircraft flexibility to accomplish different missions. Figure 15 shows the achieved amount of saved fuel for different situations of the range versus payload graph of the aircraft. It is quite clear that the benefit of the morphing increases with the raise of the mission range, however, such long range is only possible with a very lower payload.

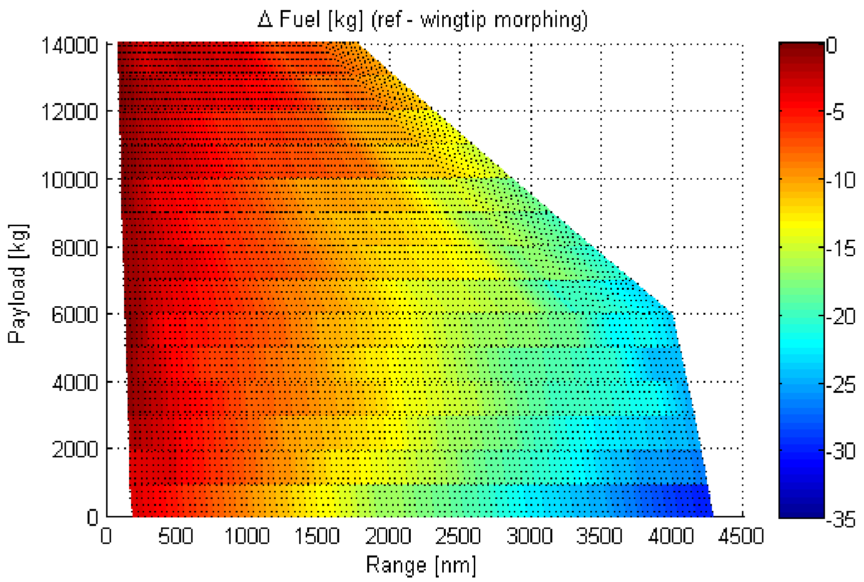

Figure 15. Fuel reduction with wingtip morphing for the entire payload x range.

The evaluation of the morphing benefits considered in this work did not take into account the real weight of the necessary actuators to perform the geometrical displacements of the morphing devices. Hence, a sensibility study considering different increase in the BOW weight caused by the morphing actuators was accomplished for different mission ranges. The objective of such study consisted in have some idea about the maximum tolerable actuator weight for different missions, which means that above this maximum weight it is not beneficial to have the morphing device.

Figure 16 is showing that the long range mission, 2000 nm, it worth adopt the morphing devices if they weigh less than 70 kg, otherwise, there is an increase in the block fuel to accomplish the mission. The 600 nm mission has a threshold of 100 kg; however, the benefits are lower in terms of saving fuel. In general, the longer the mission the higher is the possibility to obtain improvements in the performance.

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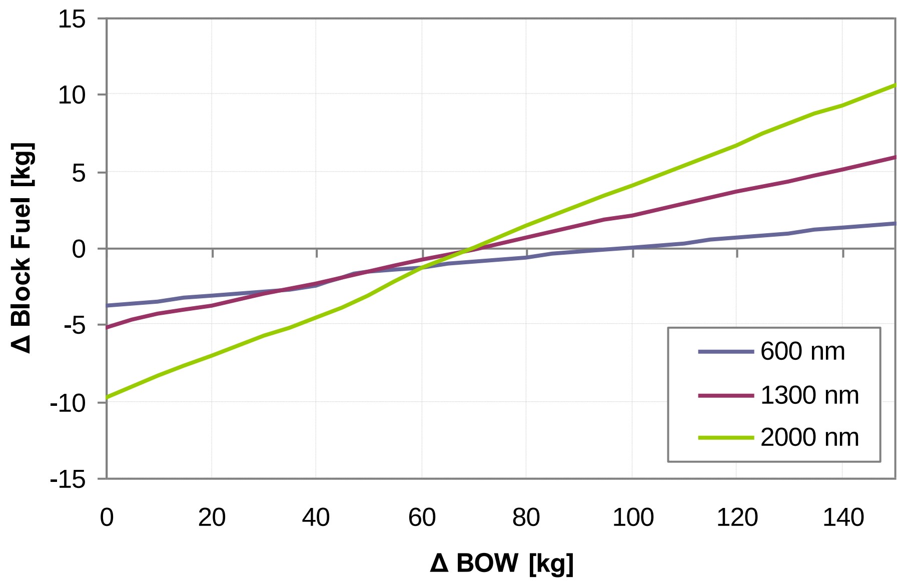

Figure 16. Impact of BOW increase on block fuel reduction for missions with 12.000 kg of payload.

5. CONCLUSION

The present work has presented some information about the construction of the reference aircraft and a performance comparison between the morphed wingtip and the baseline aircraft. In such comparison only the aerodynamic considerations were taken into account, i.e. no penalization provoked by the extra weight due to the need to carry morphing actuators has been considered. However, an abacus was constructed in order to define, for different missions, the total amount of extra weight that would still make the morphing devices beneficial.

The obtained benefits were small for the considered typical mission, but it tends to increase with the increase of the mission range. Therefore, it is quite possible that, for long range aircraft, the benefits of such technology might be really expressive.

6. REFERENCES

ACRE, 2011, *Report of the High Level Group on Aviation Research*, Flight Path 2050 Europe's Vision for Aviation.
Berlin, I., 2011, *World Travel Trends Reports 2006-2007*, Technical Reports, The World Travel Monitor Company.
Branch, E., 2010, *International Civil Aviation*, Technical Report, ICAO Journal – vol.64 n.03.
Deb, K., 2003, *Multi-Objective Optimization Using Evolutionary Algorithms*, Wiley, New York.
European Commission, 2008. *European Energy and Transport – Trends to 2030*. Belgium.
Goldberg, D.E., 1989, *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley, New York.
IATA, 2011, *Technical Report, International Air Transportation* – Annual Report.
Karas, O. and Kovalev, V., 2002, *BLWF 43 User's Guide*, Report, Tsagi.
Mecham, M., 2007, *No Time to Wait*, Aviation Week & Space Technology, June 2007, pp.52-54.
Metacomp Technologies Inc., CFD++, http://www.metacomptech.com/.
Sobieczky, H., Parametric Airfoils and Wings, *Recent Development of Aerodynamic Design Methodologies: Inverse Design and Optimization*, Friedr. Vieweg & Sohn Verlagsgesellschaft, Braunschweig, Germany, 1999, pp. 72-74.

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