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Cessna Citation X Performances Improvement by an Adaptive Winglet during the Cruise Flight

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***Abstract*—**As part of a 'Morphing-Wing' idea, this study consists of measuring how a winglet, which is able to change its shape during the flight, is efficient. Conventionally, winglets are fixed-vertical platforms at the wingtips, optimized for a cruise condition that the airplane should use most of the time. However, during a cruise, an airplane flies through a lot of cruise conditions corresponding to altitudes variations from 30,000 to 45,000 ft. The fixed winglets are not optimized for these variations, and consequently, they are supposed to generate some drag, and thus to deteriorate aircraft fuel consumption. This research assumes that it exists a winglet position that reduces the fuel consumption for each cruise condition. In this way, the methodology aims to find these optimal winglet positions, and to further simulate, and thus estimate the fuel consumption of an aircraft wearing this type of adaptive winglet during several cruise conditions. The adaptive winglet is assumed to have degrees of freedom given by the various changes of following surfaces: the tip chord, the sweep and the dihedral angles. Finally, results obtained during cruise simulations are presented in this paper. These results show that an adaptive winglet can reduce, thus improve up to 2.12% the fuel consumption of an aircraft during a cruise.

***Keywords*—**Aerodynamics, Cessna Citation X, optimization, winglet, adaptive, morphing, wing, aircraft.

I. Introduction

NOWADAYS, increasingly sensitive to the global warming, the aerospace industry is committed to reduce its toxic gas emissions. According to International Civil Aviation Organization (ICAO) emissions calculator, more than 18,500 kg of fuel is burnt for a single trip connecting San Francisco to New-York [1]. This amount of fuel leads to a considerable emission of 73,000 kilograms of carbon dioxide (CO_2) in the atmosphere for an aircraft carrying around 250 passengers. To limit these unwanted emissions, the aerospace industry aims to halve aircraft CO2 emissions registered in 2005 before 2050 [2]. As part of this ecological program, some improvements take place, especially using aerodynamic optimizations. The "Morphing-Wing" that is a technology aiming to control the shape of an aircraft wing during the flight is particularly interesting in this context [3]. Indeed, by changing their shapes, wings may have the best aerodynamic parameters during the whole flight [4]-[8]. As part of a "Morphing-Wing" idea, the following research consisted in measuring how an adaptive winglet that is going to move during the flight can be effective.

Conventionally, winglets are fixed-vertical platforms at the wingtip designed to reduce the drag generated by a wing for the average cruise regime profile of the aircraft [9]-[13]. Indeed, during a cruise phase, the altitude can vary from 30,000 to 45,000 ft. It is supposed that this variation should completely change atmospheric conditions around the aircraft. As a consequence, the fixed-winglet is supposed to generate some drag, and performance should not be as excellent as expected. From this point of view, it is supposed that, for a selected cruise condition, there exists a winglet position able to minimize the drag. Because of the fact that the drag is going to be reduced, global aerodynamic performances of the aircraft should be consequently enhanced [12].

In this way, this research consists in find an optimal winglet position for each cruise condition. This objective was reached according to the methodology presented in **Section** II. Results obtained are available in **Section** III of this paper.

II. Methodology

This paper aims to highlight that an adaptive wing (equipped with moveable winglets) allows an aircraft to optimize its performance. In this way, fuel consumption required for a conventional aircraft with a wing equipped with fixed winglets, and for an aircraft equipped with an adaptive wing will be simulated, and further compared [14]-[18]. To ensure that the comparison is as fair as possible, it is necessary to compare exactly the same aircraft evolution in the same environment (i.e. same flight conditions, same engines) [19]-[22]. As a result, this study is turned towards the business type airplane Cessna Citation X. Indeed, studies at our Laboratory of Active Controls, Avionics and AeroServoElasticity (LARCASE) with a Research Aircraft Flight Simulator (RAFS) allowed establishing a reliable mathematical model of the Cessna Citation X [23]-[26]. For a selected flight condition, this model is able to give the fuel consumption during the cruise regime, as shown in Fig. 1.

The methodology of this study is based on the mathematical model presented in Fig. 1. Aerodynamic data are given to the mathematical model using tables of lift and drag coefficients variations with the Mach numbers and the angles of attack. These aerodynamic tables given by the RAFS for the Cessna Citation X wing can be replaced by other tables relevant to the wing equipped with adaptive winglet (Fig. 2). In this way, two aerodynamic models able to build further give tables of aerodynamic coefficients according to the Mach numbers and

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the angles of attack are required. Therefore, the first model will correspond to the reference wing (with fixed winglet), and the second model will correspond to the test wing (with adaptive winglets), as shown in Fig. 2.

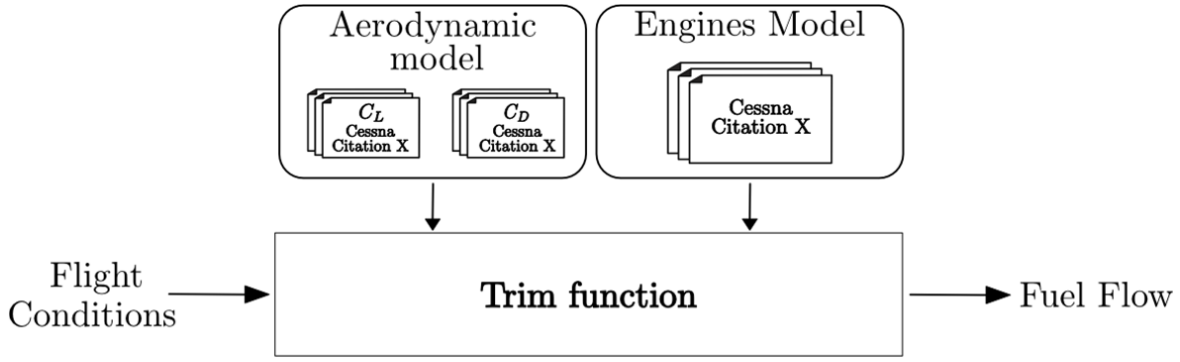


Fig. 1 Original mathematical model

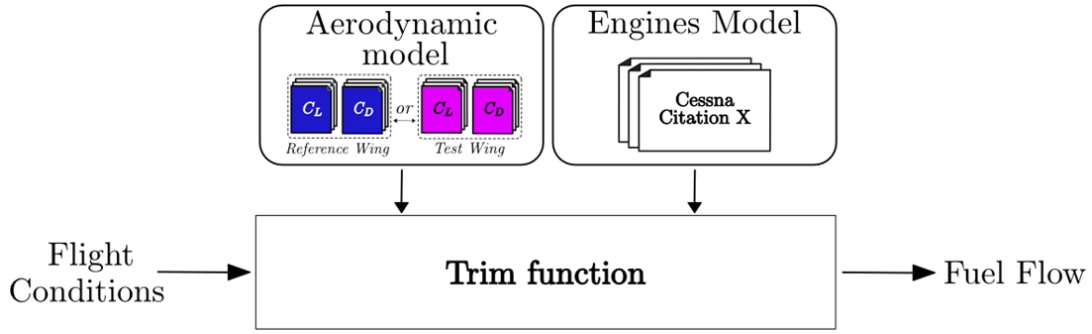


Fig. 2 Mathematical model used for this study

In order to reduce computation mistakes, these two aerodynamic models are designed using the same aerodynamic solver. OpenVSP software is a reliable solver available under NASA Open Source Agreement (NOSA) since 2012 [27]. This software has a user-friendly interface and allows to computes lift and drag coefficients for a given combination of Mach number and angle of attack. Moreover, with OpenVSP, a wing is modeled with a succession of several wing-sections that is the most convenient way to design a winglet. Each wing-section can be set by a span value, a root and a tip chord value, a sweep angle value, a dihedral angle value, and an airfoil.

Sections II.A and II.B of this methodology are devoted to present how the two models were designed using OpenVSP. The first subsection is dedicated to the reference wing model design, and the second subsection presents how the model for the adaptive wing with moveable winglets was designed.

A. Design of a Reference Wing Model Using OpenVSP

In this study, the reference wing needs to be a wing that highlights the efficiency of an adaptive winglet. For that, the reference wing must have winglets. However, the Cessna Citation X, the aircraft for which the wing geometry is perfectly known, does not have any winglets.

To use the mathematical model presented in Fig. 2, design from the model presented in Fig. 1 which was validated by data provided by the Cessna Citation X RAFS, it is required to use data which are close to those provided by the Cessna Citation X.

(a) Cessna Citation X (b) Cessna Citation X+

Fig. 3 Cessna Citation X and Cessna Citation X+ wing model

For this purpose, the “engines model” used in the mathematical model presented Fig. 2, is the same model as the engines model use in the original mathematical model (Fig. 1). In the same way, the aerodynamic model should be the same as the one used for the original mathematical model (Fig. 1). However, because the Cessna Citation X (Fig. 3 (a)) does not have any winglets, another aerodynamic model has to use the “reference aerodynamic model”. The reference aerodynamic model design was inspired by the Cessna Citation X+ wing geometry (Fig. 3 (b)). The Cessna Citation X+ is a Cessna Citation X evolution that is wearing winglets. This reference aerodynamic model was designed from the Cessna Citation X wing dimension given in Table I, and by 2 additional wing sections that represent the winglet, called respectively, “section 1” and “section 2”, see Fig. 4. These two additional wing sections are set by fixed values shown in Table II.

TABLE I
GEOMETRICAL PROPERTIES OF THE CESSNA CITATION X WING

Designation	Value	Unit
Wingspan	19.38	m
Mean Aerodynamic Chord	2.65	m
Root Chord	4.85	m
Tip Chord	0.81	m
Sweep angle (2 % Chord)	36.0	deg
Area	48.96	m^2

Fig. 4 Designation of winglet sections

TABLE II
GEOMETRICAL PROPERTIES OF THE REFERENCE WINGLET

Designation	Value	Unit
Wing-section 1		
Section-Span	0.30	m
Root Chord	0.81	m
Tip Chord	0.76	m
Sweep	40.0	deg
Dihedral	40.0	deg
Airfoil	NACA 64-008A	
Wing-section 2		
Section-Span	1.21	m
Root Chord	0.76	m
Tip Chord	0.27	m
Sweep	30.0	deg
Dihedral	80.0	deg
Airfoil	NACA 64-008A	

Finally, Fig. 5 shows the reference wing model in OpenVSP software interface. Fig. 5 (a) shows the front view, and, Fig. 5 (b) shows the side view.

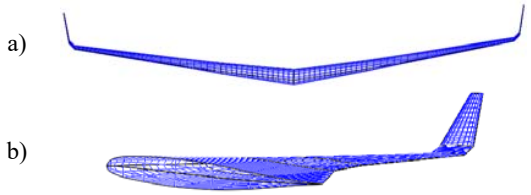


Fig. 5 Wing reference for the study using OpenVSP

B. Design of an Adaptive Wing with Moveable Winglets

In order to design the adaptive wing, it is supposed that, for a selected flight condition, there is an optimal winglet position that keeps the same lift force of the reference wing (established in Section II. B), but provides the smallest drag force possible with respect to the reference wing drag force. Indeed, because the drag increased proportionally with the lift, the optimized wing should keep the same lift force that the reference wing can generate.

To set the adaptive winglet shape, OpenVSP software needs some of its geometrical characteristics such as span, chord, sweep and dihedral of wing-sections 1 and 2. Therefore, 10 parameters have to be set, corresponding to a moveable winglet with 10 degrees of freedom corresponding to these parameters. From a mechanical point of view, it is unrealizable because the number of parameters is too high. As a consequence, a pre-study is done, consisting of quantifying which are the geometrical characteristics of the first and the second wing-sections with the highest influence on aerodynamic coefficients.

This pre-study has shown that the tip chord, the section-span, and the twist angle of the first wing-section have not a high influence on aerodynamic coefficients for a computation using OpenVSP software. In the same way, concerning the second winglet-section, the section-span has no more influence either on aerodynamic coefficients. Because these geometrical properties have not a high influence on aerodynamic coefficients, it is not necessary to consider them as varying in the study, thus they can be considered constant. Moreover, the airfoil type influence on winglet sections was also part of this pre-study. Because of the fact that the airfoil seems not very much influencing aerodynamic coefficients with an OpenVSP computation, the same airfoil of the wing reference was imposed to wing sections 1 and 2 for the whole study.

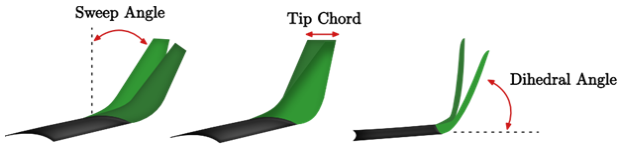


Fig. 6 Winglet degrees of freedom

Varying parameters of winglet sections are therefore displayed in Fig. 6. Another pre-study allowed determining bounds of the geometrical parameters presented in Fig. 6. These bounds values are presented in Table III.

TABLE III
GEOMETRICAL PROPERTIES OF THE ADAPTIVE WINGLET

Designation	Value	Unit
Wing-section 1		
Sweep – *S1*	5 to 85	deg
Dihedral - *D1*	*D2*/2	deg
Airfoil	NACA 64-008A	
Wing-section 2		
Tip Chord - *T2*	0 to 0.7	m
Sweep – *S2*	5 to 85	deg
Dihedral-*D2*	5 to 100	deg
Airfoil	NACA 64-008A	

To find the best position of the winglet for a given flight condition, a *fitness function* coupled to an *algorithm* were used (Fig. 7). Thus, for a given flight condition, the fitness function received a vector with values for parameters *S1*, *T2*, *S2* and *D2*. With these parameters, OpenVSP can build the corresponding wing, which can now be named the "test-

wing". To measure how this "test-wing" is efficient for the selected flight condition, aerodynamic coefficients such as it lift and drag coefficients are computed using OpenVSP. Afterwards, aerodynamic coefficients obtained for the "test-wing" are compared with aerodynamic coefficients of the reference wing, provided by the reference wing model designed in Section II.A. This comparison is evaluated by an error *err* given in (1), and returned by the fitness function.

$$\min_{S1,T2,S2,D2}\left(\left[C_{L_w}-C_{L_{Ref}}\right]^2+10*C_{D_w}\right) \quad (1)$$

$$\textbf{Subject to:}\quad C_{D_w}<C_{D_{Ref}},\quad C_{L_w}=C_{L_{Ref}}$$

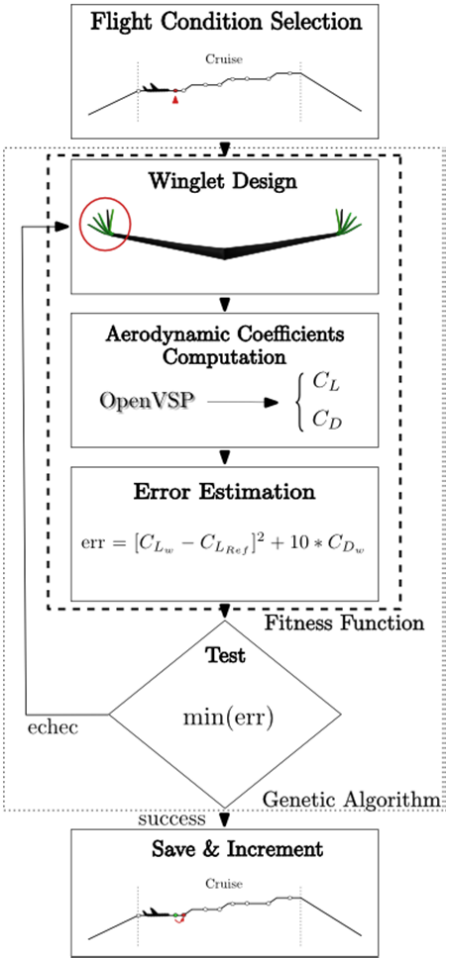


Fig. 7 Fitness function coupled with GA in charge of finding winglet geometry that optimizes aerodynamic coefficients characteristics of a wing for a selected flight condition

This fitness function is coupled to a genetic algorithm (GA) and its role is to minimize the error *err* while proposing a logical combination of parameters *S1*, *T2*, *S2* and *D2*. These different steps are repeated until the GA finds a combination of $S1_f$, $T2_f$, $S2_f$ and $D2_f$, that leads to the minimal error *err*. When the GA gives final parameters $S1_f$, $T2_f$, $S2_f$ and $D2_f$, the optimum winglet position for the selected flight condition is found, and its aerodynamic coefficient data are saved in a database. The study then starts again with a new flight condition until it finds an optimum position of the winglet for another cruise regime, and finally, the optimum positions of winglet are found for the complete cruise profile, as detailed in Fig. 7.

Finally, an aerodynamic table is dynamically built according to Mach numbers from 0.6 to 0.9 and angles of attack α from -2 to 8 degrees. This aerodynamic table is then put into the mathematical model (Fig. 2), and the behaviors of the wing with an adaptive winglet for different cruise phases are simulated.

III. Results

Results obtained for this study are divided into three sections. The first section is going to show aerodynamic data obtained as outputs of the algorithm presented in section II.B. The second section presents fuel consumption required for 22 fixed cruise conditions for an airplane equipped by a fixed wing, and by the adaptive wing. Finally, the third section presents the fuel burnt for different cruise phase simulations.

A. Aerodynamic Results

Aerodynamic results of the reference wing and the adaptive wing are compared in Fig. 8. Indeed, Fig. 8 presents aerodynamic polar of the reference (in blue), and of the adaptive (in magenta) wing for Mach number from 0.6 to 0.9. Each aerodynamic polar is defined by a drag coefficient on the horizontal axis and a lift coefficient on the vertical axis.

Aerodynamic coefficients seem to be the same for angles of attack below 2 degrees and for Mach number from 0.6 to 0.9. As a consequence, for low angles of attack, below 2 degrees and for cruise Mach number, from 0.6 to 0.9, the adaptive wing here designed does not show any aerodynamic improvement.

Concerning higher angles of attack, above 2 degrees, markers of the adaptive and the reference curves are at the same y-level. Furthermore, the adaptive wing curve is shifted to the left of the reference curve. These observations can be made for Mach number from 0.6 to 0.8. A shift on the left is typically the consequence of a drag reduction, which is meaning the adaptive wing allows a drag improvement (in terms of drag reduction) in comparison to the reference wing.

For Mach number = 0.9, OpenVSP seems to not take into account different winglet positions, thus, results are the same for both cases.

Generally, from these aerodynamic results, the adaptive wing seems to be most effective at higher angles of attack, above 4 degrees.

B. Fixed Cruise Simulations

Fixed cruise conditions were simulated. Simulating a fixed cruise condition is the same as computing the fuel consumption of the aircraft with the mathematical model (Fig. 2), for a given point during the cruise.

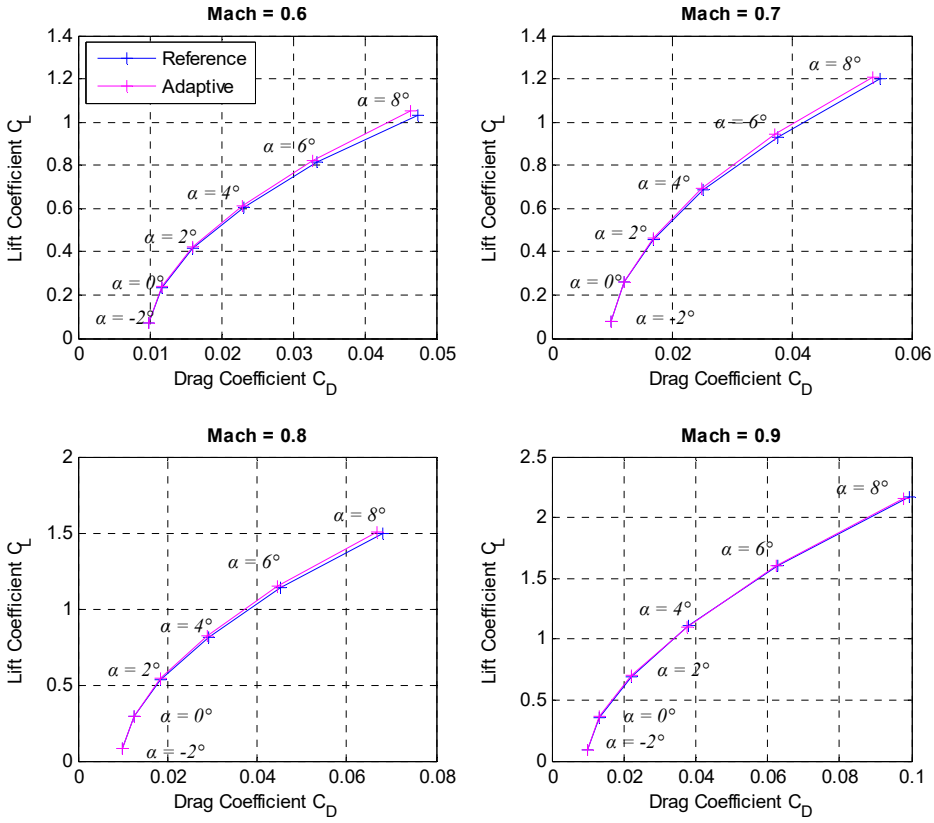
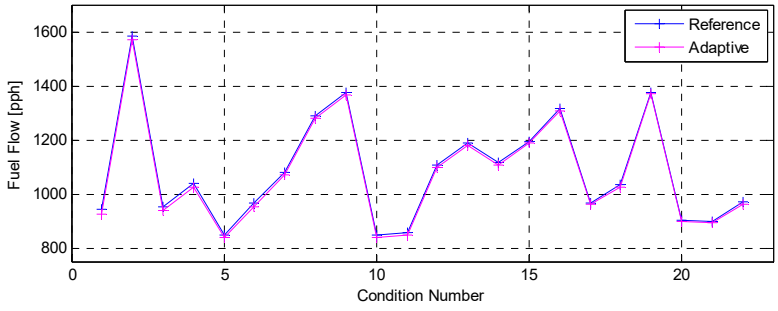
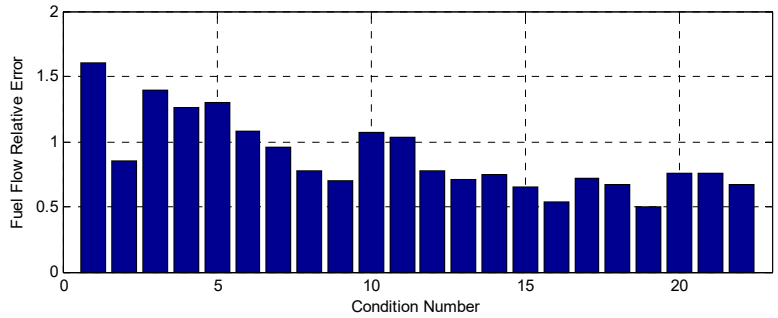


Fig. 8 Aerodynamic polar of the adaptive and the reference wing for Mach number 0.6 to 0.9



(a)



(b)

Fig. 9 Fuel flow relative error obtained for fixed cruise condition for an airplane equipped with a reference, and an adaptive wing

Fuel consumptions finally obtained by the mathematical model (Fig. 2) for the reference wing, and for the adaptive wing aerodynamic models are presented in Fig. 8. Fuel flow in pounds per hours [pph] required by the airplane wearing the adaptive (magenta line), and the reference wing (blue line) are presented in Fig. 9 (a) depending on 22 number of flight conditions referred in Table IV. These 22 conditions number correspond to fixed cruising condition for the Cessna Citation X in terms of three parameters: Mach numbers, altitudes and weights. For its better representation, the relative fuel flow gain was computed in Fig. 9 (b) for each condition number.

On Fig. 9 (a), the magenta line is below the blue line for all conditions. This observation means that the airplane which is wearing the adaptive wing needs less fuel than the airplane wearing the reference wing to accomplish the same cruise.

Fig. 9 (b) shows also the same fuel consumption gain as the one represented in Fig. 9 (a), but in terms of relative error numbers *err* (2). Indeed, up to 1.61% can be saved for an aircraft wearing an adaptive wing, with an average fuel gain of 0.89%.

$$err = \frac{Fuel(Reference) - Fuel(Adaptive)}{Fuel(Reference)} . 100 \qquad (2)$$

C. Cruise Simulations

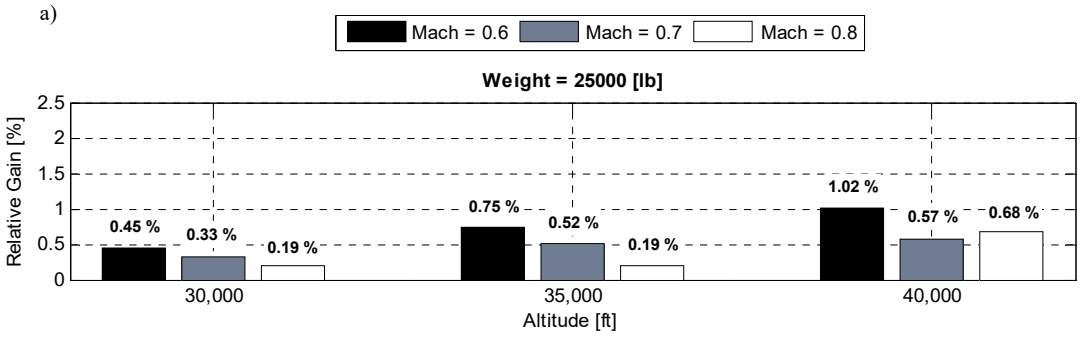
In this last part, real cruise was simulated. A real cruise is simulated according to initial conditions such as an initial weight, an initial altitude, and an initial speed (given through a Mach number). To operate this cruise simulation, the aircraft state is updated with the mathematical model (Fig. 2) every minute until complete simulation duration between 3 and 4 hours. During a cruise, the altitude and the Mach number are constant, only the weight of the airplane is updated.

Fuel required to perform different cruise phases by an airplane wearing the reference wing, and the adaptive wing have been simulated with different initial weights (i.e. from 25,000 lb to 35,000 lb), and different altitudes (i.e. from 30,000 ft to 40,000 ft). In the same way, cruises are performed for different Mach numbers from 0.6 to 0.8.

TABLE IV
FLIGHT CONDITIONS FOR CRUISE SIMULATION

Condition Number	Mach Number	Altitude	Weight
#	-	ft	lb
1	0.60	35000	35000
2	0.79	30000	35000
3	0.67	40000	35000
4	0.67	35000	35000
5	0.67	40000	30000
6	0.75	45000	35000
7	0.61	30000	35000
8	0.81	35000	30000
9	0.81	35000	35000
10	0.75	45000	30000
11	0.60	35000	30000
12	0.74	35000	30000
13	0.74	35000	35000
14	0.82	40000	30000
15	0.82	40000	35000
16	0.73	30000	30000
17	0.75	40000	30000
18	0.75	40000	35000
19	0.73	30000	35000
20	0.83	45000	25000
21	0.75	40000	25000
22	0.83	45000	30000

a)



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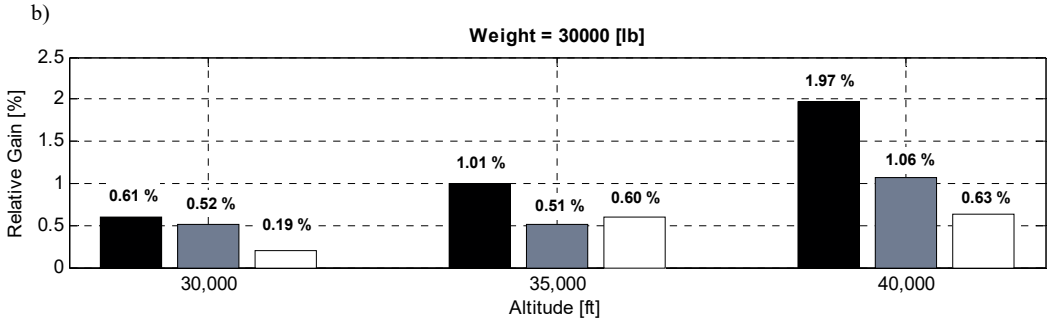

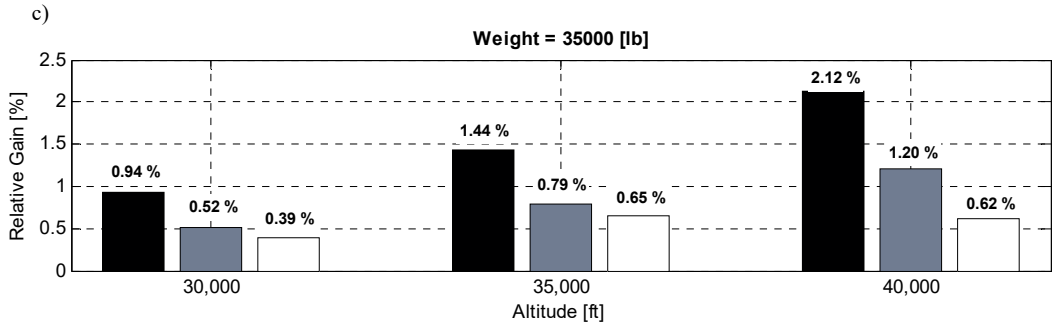

Fig. 10 Fuel gain obtained with an airplane equipped with an adaptive wing compared to fuel burn by an airplane equipped with the reference wing for several cruise simulations, and a fixed duration of 4 hours

Results obtained for this last study are presented in Fig. 10 and they are arranged in forms of three graphs accordingly to three initial weights: 25,000 lb, 30,000 lb, and 35,000 lb. Each graph shows the variation of the relative error with the altitudes and Mach numbers. The highest gains are obtained when the initial weight of the airplane is the heaviest, 35,000 lb, as shown in Fig. 10 (c). For this initial weight, the highest gain of 2.12% for all considered cases is obtained for an altitude of 40,000 ft, and a Mach number equal to 0.6.

According to these last observations, conditions when the gains are the greatest, are obtained when the airplane is heavy and subject to high angles of attack, above 4 degrees. Indeed, take-off and climb phases seem to be interesting to study for this adaptive wing because of the fact that they will offer a fuel gain much more important.

IV. Conclusion

To conclude this study, an adaptive wing has been designed from several degrees of freedom: the sweep angle, the dihedral angle and the tip chord length. Best combination values of these geometrical parameters have been founded from a Genetic Algorithm, and for several combinations of Mach numbers and angles of attack. Mach numbers were chosen from 0.6 to 0.9, and the angles of attack were considered from -2 to 8 degrees, in accordance with angles of attack and Mach numbers used in a cruise phase.

Aerodynamic coefficients of the adaptive and the reference wing have been compared. This comparison shows that the adaptive wing generates less drag force than the reference wing, thus less fuel consumption; for this reason, this adaptive wing is more efficient. Moreover, the adaptive wing keeps the lift force that the reference wing generates. Nevertheless, adaptive winglets have shown that the biggest aerodynamic improvement occurred at high angles of attack for a cruise phase. As a consequence, the cruise study, using only low angles of attack, seems to give much lower results than one can hope for a climb study, where the angle of attack is bigger than in cruise.

A mathematical model of a Cessna Citation X, coupled to aerodynamic coefficients of the adaptive, and the reference wings allows determining the fuel consumption during complete cruises with these wings. Results showed that an average fuel gain of 0.76% can be made by an adaptive wing for a cruise phase. It was also seen that highest fuel gains have been made when the aircraft was the heaviest. As a consequence, this study can be also very interesting for the take-off and climb phases.

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