International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:12, No:1, 2018

Aerodynamic Coefficients Prediction from Minimum Computation Combinations Using OpenVSP Software

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***Abstract*—**OpenVSP is an aerodynamic solver developed by National Aeronautics and Space Administration (NASA) that allows building a reliable model of an aircraft. This software performs an aerodynamic simulation according to the angle of attack of the aircraft makes between the incoming airstream, and its speed. A reliable aerodynamic model of the Cessna Citation X was designed but it required a lot of computation time. As a consequence, a prediction method was established that allowed predicting lift and drag coefficients for all Mach numbers and for all angles of attack, exclusively for stall conditions, from a computation of three angles of attack and only one Mach number. Aerodynamic coefficients given by the prediction method for a Cessna Citation X model were finally compared with aerodynamics coefficients obtained using a complete OpenVSP study.

***Keywords*—**Aerodynamic, coefficient, cruise, improving, longitudinal, OpenVSP, solver, time.

I. Introduction

NEARLY 14,000 airplanes share the sky every day, emitting on average 0.81 tons of carbon dioxide (CO_2) each [1]. Due to the constant increase of air traffic, an ecologic program has been implemented by the International Civil Aviation Organization (ICAO) aiming to reduce CO_2 emissions to 50% of the level measured in 2005 hence 30 years [2]. According to this statement, the aeronautical industry has the big challenge of considerably improving fuel consumption of aircraft. From this idea, researchers suggest several solutions such as improving or finding new trajectories, rehashing management of regular airlines, upgrading geometry shapes and materials, and many other solutions.

At the Research Laboratory in Active Controls, Avionics and Aeroservoelasticity (LARCASE) in Montréal, a project aiming to improve regular airlines trajectories has already shown an upgrade (reduction) on fuel consumption. Indeed, using different research algorithms, a reduction from 1.75% to 8% of fuel burn on a complete flight was found in references [3]-[12]. Furthermore, another project suggested that a smart wing can also decrease fuel consumption of an aircraft. In fact, this “smart” wing, better known under the name “morphing wing” has the purpose to change the shape of a wing during the flight. During the flight, several actuators can shift the shape of this wing and adapt it in the best way available for each flight condition. Hence, for each flight condition, drag and lift of the wing are optimized. This interesting technology has already shown successfully aerodynamic results, notably for an application on an Unmanned Aerial Vehicle (UAV), in the context of Consortium for Research and Innovation in Aerospace in Quebec (CRIAQ) 7.1 and CRIAQ Modelisation Simulation and Optimization (MDO) 505 projects [13]-[15]. In this idea, another new project conducted at LARCASE laboratory aims to evaluate performances of an aircraft equipped with modular wing for a cruise flight. In order to conduct regime investigation, a reliable numerical model able to compute aircraft aerodynamic characteristics from its geometry is required. To build this kind of model, an aerodynamic solver is needed. Aerodynamic solvers are software able to simulate an aircraft in its environment, and among those, some software give preference to a good accuracy of computations, and, other software favor rather a small time of computation. In this way, because it is the beginning of the project, OpenVSP software was chosen to perform this pre-study especially because of the fact that is enough reliable within a reasonable computation time. OpenVSP computes aerodynamic coefficients such as the lift coefficient and the drag coefficient for a given flight condition (an angle of attack α, a Mach number M and an angle of deviation β) [16]-[19].

As part of the project is conducted at the LARCASE, a given aircraft, the Cessna Citation X was arbitrary chosen. Moreover, as the cruise regime is the longest part of the flight, the geometry optimization by “Morphing-Wing” technology is focused for a range of Mach number between 0.6 to 0.9 and angles of attack from -2 to 14 degrees. To perform this study, 36 *α-Mach* combinations that take around 20 minutes are required. This is a small computation time for particularly studies, and it is long enough for pre-design studies.

In order to minimize the number of computations required by OpenVSP software for a complete study, this article presents a method to predict all combinations of angles of attack and Mach numbers from a minimum amount of computation combinations. This prediction is going to improve considerably computation time required for a pre-design study using OpenVSP. The paper is organized in two main sections: a methodology section and a result section. The methodology section is divided in two subsections: the first

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International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:12, No:1, 2018

subsection aims to present the model of the Cessna Citation X designed using OpenVSP and to show how accurate it is with a comparison using a reliable source, and the second subsection presents the prediction methodology aiming to improve computation required with an OpenVSP study.

II. Methodology

In this section, the methodology used to reduce time of an aerodynamic computation with OpenVSP is developed. Firstly, an aerodynamic model of the Cessna Citation X is designed using OpenVSP, and is validated by means of a Level D Research Aircraft Flight Simulator (RAFS). The level D is the highest degree of certification given by Federal Aviation Administration (FAA) [20]. Then, this model is used to improve time computation for several conditions of Mach numbers and angles of attack.

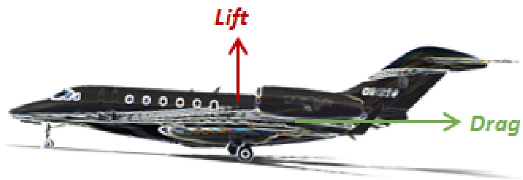

Fig. 1 Lift and drag forces applied on an aircraft

A. Conception and Validation of an Aerodynamic Model of the Cessna Citation X Using OpenVSP

OpenVSP software is an aerodynamic solver that enables the computation of aerodynamics coefficients of an aircraft from its geometry. Because lift L and drag D forces depend on lift C_L (1) and drag coefficients C_D (2), an aerodynamic comparison can be established from these aerodynamic coefficients C_L and C_D [21], [22]. Hence, the effectiveness of the Cessna Citation X model built using OpenVSP software is only measured by computed aerodynamic coefficients.

$$L = \frac{1}{2}\,\rho\, S\, V^2\, C_L \quad (1)$$

where L is the lift force (N), ρ is the fluid density (kg/m^3), S is the reference area of the aircraft (m^2), V is the fluid velocity (m/s^2) and C_L the lift coefficient.

$$D = \frac{1}{2}\,\rho\, S\, V^2\, C_D \quad (2)$$

where D is the drag force (N), ρ is the fluid density (kg/m^3), S is the reference area of the aircraft (m^2), V is the fluid velocity (m/s^2) and C_D the drag coefficient.

Because of the fact that the RAFS gives aerodynamic coefficients for two components: the "Wing-Body" and the "Horizontal Tail" component, it is required to design one of these components in order to, validate the model. The "Wing-Body" component is composed of a wing, a fuselage and a vertical tail. Because of the fact that the global goal of the project is to change the shape of the wing, the "Wing-Body" component model is required.

The design of the Cessna Citation X "Wing-Body" model using OpenVSP consisted in reproducing its geometry on the solver interface. By default, OpenVSP has already wing and fuselage basic components. Consequently, to design the model of the "Wing-Body" of the Cessna Citation X, it is required to set two wings and a fuselage component with Cessna Citation X geometrical properties shown in Table I. The Cessna Citation X "Wing-Body" model is presented in Fig. 2.

TABLE I
Geometrical Properties of the Cessna Citation X

Designation	Value	Unit
Fuselage		
Medium Diameter	1.71	m
Length	18.90	m
Wing		
Wingspan	19.38	m
Aspect Ratio	7.80	m
Dihedral	2.0	deg
Airfoils	*CESS-CX-W0*	-
	CESS-CX-W4	-
Vertical Tail		
Wingspan	3.41	m
Area	10.31	m^2
Airfoil	NACA0009	-

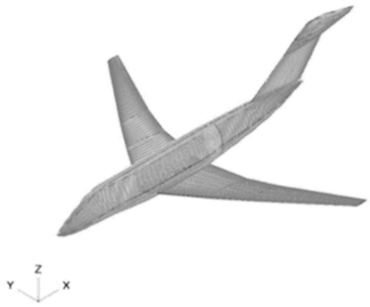

Fig. 2 Cessna Citation X designed on OpenVSP interface

To compute aerodynamic coefficients C_L and C_D, OpenVSP needs an angle of attack α, an angle of deviation β, and a Mach number M. In this global project, the objective is to simulate only the longitudinal behavior of the aircraft. More precisely, the study here conducted is based on a cruise trajectory exclusively. That is why the angle of deviation β is considered equal to zero, the angle of attack α was taken between -2 degrees to 14 degrees and the Mach number M was taken from 0.6 to 0.9. Moreover, OpenVSP software offered two computational methods, the Vortex Lattice Method (VLM) and the Panel Method (PN). Because of the fact that the PN cannot give all aerodynamic coefficients needed, the VLM method was chosen by default. Aerodynamic coefficients C_L and C_D obtained by OpenVSP simulation of the model designed (Fig. 2) are presented in Figs. 3 and 4 for Mach numbers, angles of attack, and angles of deviation described previously.

Fig. 3 presents comparison of the lift coefficient C_L obtained by OpenVSP (in the red line) and the C_L given by the flight simulator (in blue line). For Mach number equal to 0.6

and Mach number equal to 0.7, data match very well under an angle of attack $\alpha = 14°$. The difference over $\alpha = 14°$ is due to the stall of the aircraft, in fact, OpenVSP does not take into account the stall characteristics and therefore cannot predict the aerodynamic coefficients associated with this phase of flight, and after it.

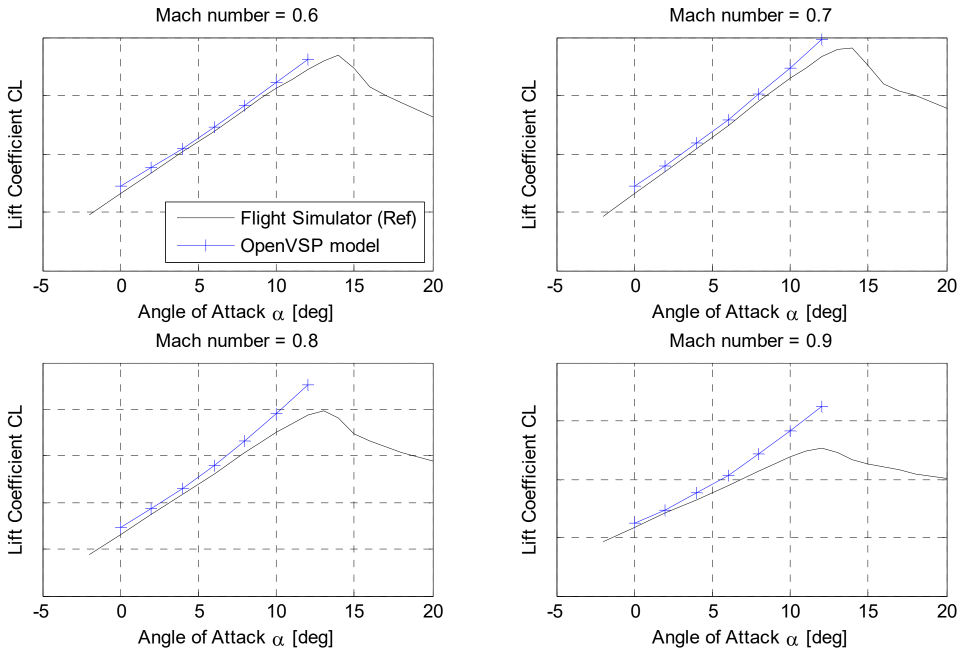

Fig. 3 Comparison between lift coefficients obtained by the simulator and the model build with OpenVSP for Mach numbers 0.6 to 0.9 and for α -2 to 12 degrees

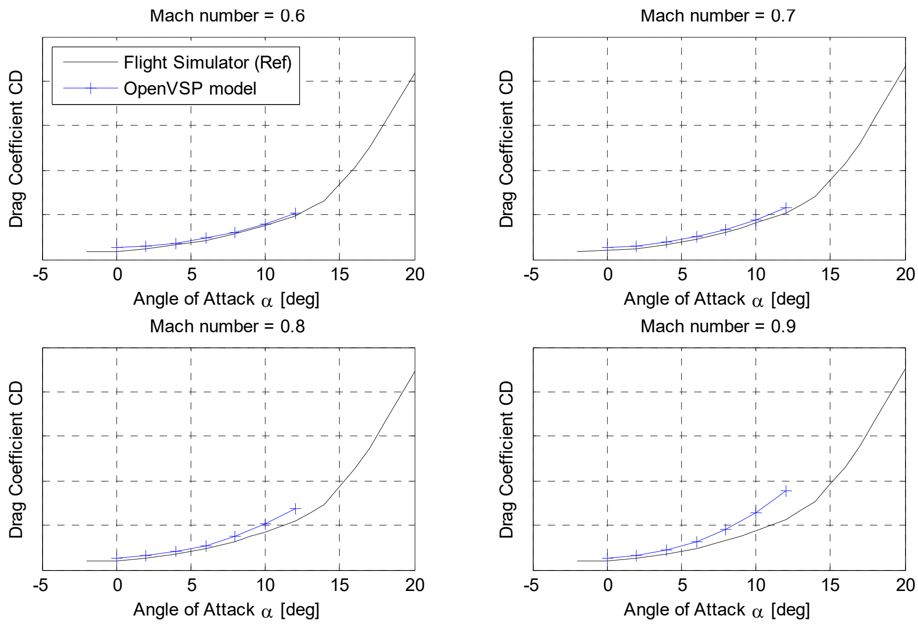

Fig. 4 Comparison between drag coefficients obtained by the simulator and the model build with OpenVSP from Mach number 0.6 to 0.9 and from α -2 to 12 degrees

Fig. 4 presents the comparison of drag coefficient C_D obtained by OpenVSP (in the red line) and C_D given by the flight simulator (in blue line). For Mach number equal to 0.6 and Mach number equal to 0.8, such as in the case of previous comparison for the lift coefficient C_L, data match very well for all the range of angle of attack α defined. For Mach number of 0.9, data do not watch well which is explained by the existence of transonic regime for which OpenVSP does not give accurate enough results.

As results shown in Figs. 3 and 4, an aerodynamic model of the Cessna Citation X designed on OpenVSP software was validated.

B. Lift and Drag Coefficients Prediction Methodology

The computation of C_L and C_D of the "Wing-Body" geometry for one Mach number and one angle of attack by OpenVSP takes around 30 seconds. In order to obtain all 36 aerodynamic coefficients for combinations of Mach numbers (0.6 to 0.9) and angles of attack (-2 to 14 degrees), 20 minutes are taken. That is really a long time of computation for a pre-design analysis. The global objective of this paper consists in dividing this time of computation without impacting accuracy acquired by Vortex Lattice Method to compute coefficients through OpenVSP software. Therefore, the method of reducing time is equivalent to computing aerodynamic coefficients C_L and C_D with OpenVSP for a minimum of *α-Mach* combinations.

The method here presented for reducing computation time consists in the "use" of basic aerodynamic equations which expressed the lift coefficient C_L and the drag coefficient C_D with (3) and (4) respectively. It is well known from the literature [22], the lift coefficient C_L can be described by a linear relationship with respect to the angle of attack α in the absence of stall conditions.

$$C_L = C_{L_0} + \alpha * C_{L\alpha} \quad (3)$$

where C_{L0} is the zero-incidence lift coefficient dependent of the airfoil shape and the Mach number, $C_{L\alpha}$ is the slope coefficient dependent on flight conditions, and α is the angle of attack of the aircraft. In the same way, the drag coefficient C_D (4) is described by a second degree polynomial curve.

$$C_D = C_{D_0} + \frac{{C_L}^2}{\pi * AR * \varepsilon} \quad (4)$$

where C_{D0} is the zero-lift drag coefficient, expressed as an offset that depends on the fluid parameters and the geometry of the aircraft's wing, C_L is the lift coefficient, AR is the aspect ratio and ε is the Oswald coefficient.

1) Lift Coefficient Prediction for a Given Mach Number M_1

According to (3), because the lift coefficient C_L is in a linear relationship with the angle of attack α, if the offset C_{L0} and the slope coefficient $C_{L\alpha}$ are known, it is easy to compute all angles of attack desired for a same Mach number M_1. It is important to consider M_1 the smallest possible, for instance, M_1 equal to 0.2 gives good results.

a. Slope Coefficient $C_{L\alpha}$

The coefficient $C_{L\alpha}$ is the slope of lift coefficient C_L, in the other words, using two values of lift coefficient C_L computed by OpenVSP for a same Mach number, it is easy to obtain $C_{L\alpha}$ for the same Mach number M_1 (5).

$$C_{L_\alpha}(M_1) = \frac{C_L(\alpha_1, M_1) - C_L(\alpha_2, M_1)}{\alpha_1 - \alpha_2} \quad (5)$$

where $C_{L\alpha}$ is the slope coefficient of the lift coefficient for a Mach number M_1 ($M_1 \leq 0.9$), $C_L(\alpha_1, M_1)$ is the lift coefficient computed by OpenVSP software for α_1 and Mach number M_1, in the same way, $C_L(\alpha_2, M_1)$ is the lift coefficient computed for α_2 and Mach number M_1. Angles of attack α_1 and α_2 must be distinct between -2 to 14°.

b. Zero-Incidence Lift C_{L0}

The coefficient C_{L0} is given in (6).

$$C_{L_0}(M_1) = C_L(\alpha = 0°, M_1) \quad (6)$$

where $C_{L0}(M_1)$ is the zero incidence lift coefficient for a Mach number M_1, and C_L ($\alpha = 0°$, M_1) is the lift coefficient computed by OpenVSP for an angle of attack equal to zero degrees and a Mach number M_1.

For lift coefficient prediction, for a given Mach number M_1, two computations (one for $\{M_1, \alpha_1\}$ and one for $\{M_1, \alpha_2\}$) are needed to predict the $C_{L\alpha}$ (5). Among these two different angles of attack α_1 and α_2, it is imperative to choose an angle of attack α equal to zero degrees.

2) Drag Coefficient Prediction for a Given Mach Number M_1

Then, to predict the drag coefficient C_D, a second degree curve is required (4). It is considered that the drag coefficient C_D can be predicted from lift coefficient C_L, the coefficient dividing the term ${C_L}^2$, and, the zero lift drag C_{D0}.

a. Zero-Lift Drag C_{D0}

The zero lift drag C_{D0} can be obtained for $\{M_1, \alpha=0°\}$ (7).

$$C_{D_0}(M_1) = C_D(\alpha_0, M_1) \quad (7)$$

where C_{D0} (M_1) is the zero lift drag coefficient for a Mach number M_1, and C_D (α_0, M_1) is the drag coefficient computed by OpenVSP for an angle of attack $\alpha = 0$ and a Mach number M_1.

b. Induced Drag C_{Di}

Considering the coefficient dividing the term ${C_L}^2$ in (4), it depends on flight conditions and aircraft wing's shape. Because of the difficulty to compute independently this coefficient, it is necessary to throw it. To reach the objective, a polynomial equation is estimated from three points computed by OpenVSP software given in (8).

$$C_D(M_1) = A_0 + A_1 * C_L(\alpha_1, M_1) + A_2 * C_L(\alpha_2, M_1)^2 \quad (8)$$

where C_D (M_1) is the drag coefficient for a Mach number M_1, coefficients A_0, A_1, and A_2 are polynomial coefficients, $C_L(\alpha_1, M_1)$ and $C_L(\alpha_2, M_1)$ are respectively lift coefficients computed by OpenVSP for angles of attack α_1 and α_2 and for a Mach number M_1. Once polynomial coefficients A_0, A_1, and A_2 were found for Mach number M_1, the drag coefficient C_D can be predicted for a large range of angles of attack and a given Mach number M_1.

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:12, No:1, 2018

3) Aerodynamic Prediction for All Mach Numbers

Finally, from three computations $\{M_1, \alpha_0\}$, $\{M_1, \alpha_1\}$, and $\{M_1, \alpha_2\}$ using OpenVSP, it is possible to predict all lift and drag coefficients for a large range of angles of attack and Mach numbers (in the cruise phase of flight), using (9) and (10).

$$C_L(M_2) = \frac{C_{L\alpha}(M_1)}{\sqrt{1-M_2^2}} * \alpha + \frac{C_{L_0}(M_1)}{\sqrt{1-M_2^2}} \quad (9)$$

where $C_L(M_2)$ is the lift coefficient predicted for a given Mach M_2, $C_{L_\alpha}(\alpha, M_1)$ is the lift slope computed for Mach number M_1, $C_{L_0}(M_1)$ is the zero incidence lift coefficient also computed for Mach number M_1 and finally, M_2 is the Mach number which coefficients are predicted for.

$$C_D(M_2) = A_0 + A_1 * C_L(\alpha_1, M_2) + A_2 * C_L(\alpha_2, M_2)^2 \quad (10)$$

where $C_D(M_2)$ is drag coefficient predicted for a given Mach M_2, coefficients A_0, A_1, and A_2 were found in (8), finally $C_L(\alpha_1, M_2)$ and $C_L(\alpha_2, M_2)$ are lift coefficients predicted for M_2 and respectively angles of attack α_1 and α_2 in (9).

III. Results

This section exposes results obtained for several combinations of angles of attack and Mach numbers. A comparison is given between aerodynamic coefficients obtained by the Cessna Citation X Wing-Body model using OpenVSP (presented in the first part of the methodology), and aerodynamic coefficients predicted by the method described in the second part of the methodology. Data obtained by the RAFS are also presented in graphs shown in Figs. 5-8.

The methodology previously presented aims to improve the computation time required for an aerodynamic study on OpenVSP. To expose results of this study, figures are presented by charts depending on angles of attack α included from -2° to 14° and Mach number M from 0.6 to 0.9.

First, for M equal to 0.6, the difference observed between the lift and the drag coefficients C_L and C_D obtained by the model on OpenVSP, and by the prediction method is shown in Fig. 5. Moreover, data of the RAFS are also presented on this figure to show how accurate are the results. By the same way, results obtained for Mach equal to 0.7, 0.8 and 0.9 are respectively given in Figs. 6-8.

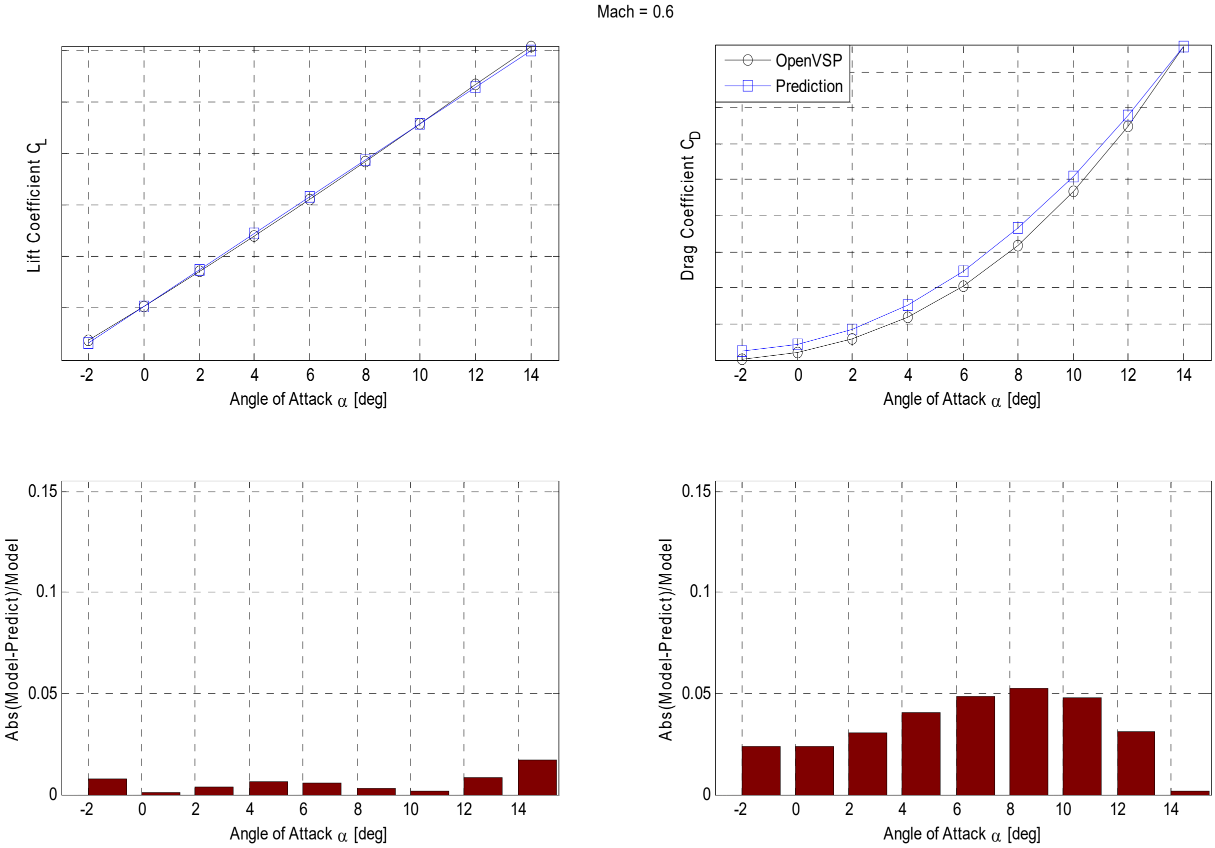

Fig. 5 Lift and drag coefficient comparison for Mach number equal to 0.6

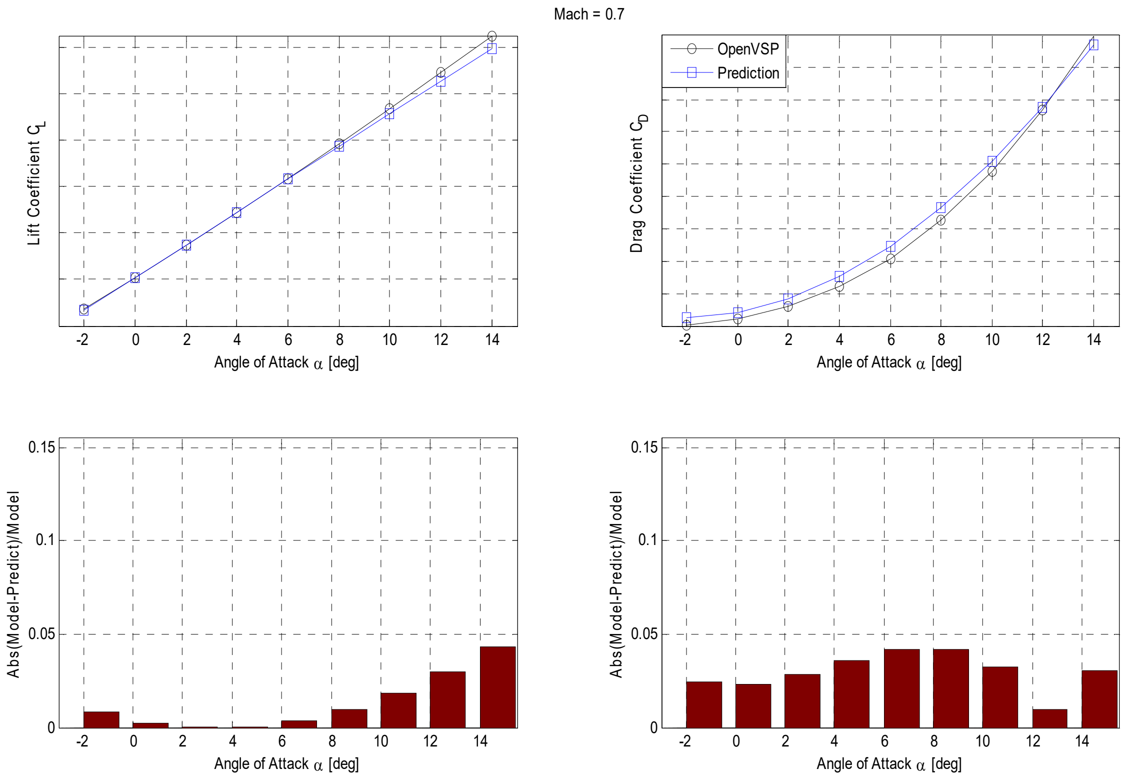

Fig. 6 Lift and drag coefficient comparison for Mach number equal to 0.7.

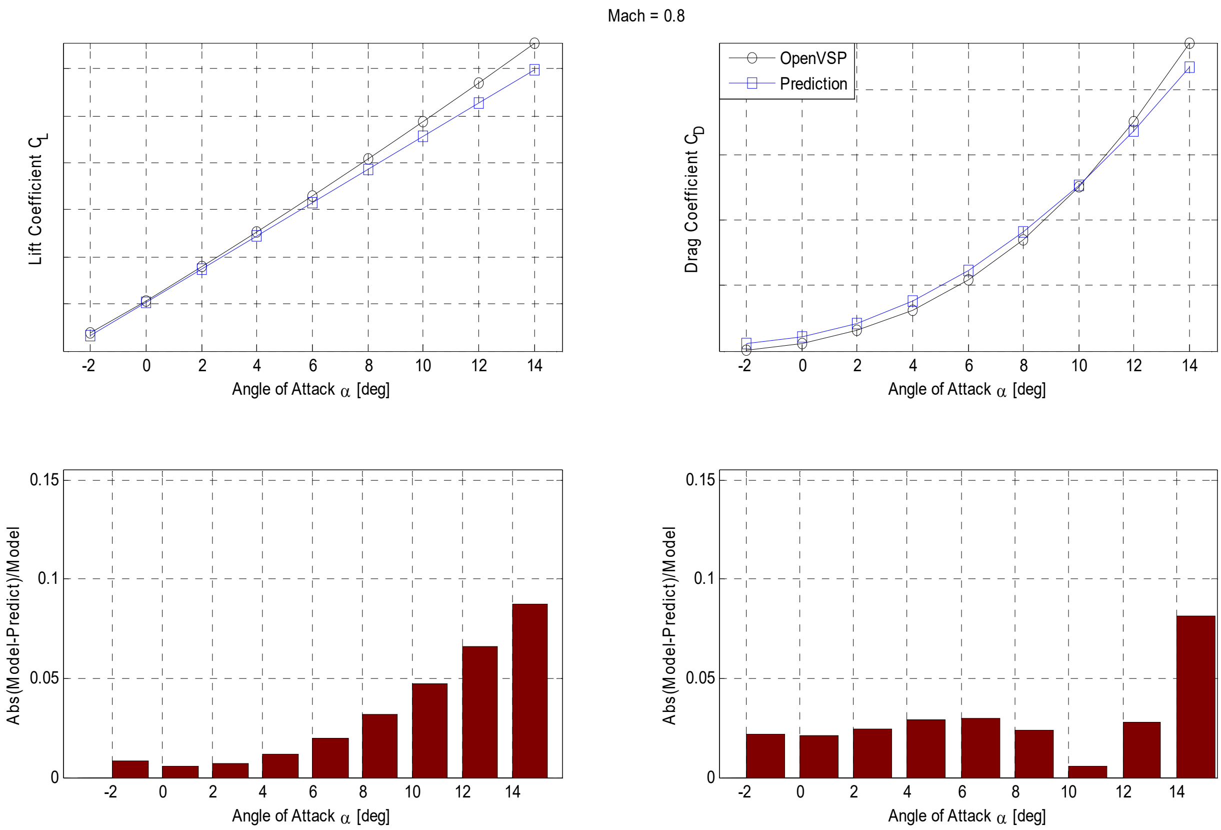

Fig. 7 Lift and drag coefficient comparison for Mach number equal to 0.8

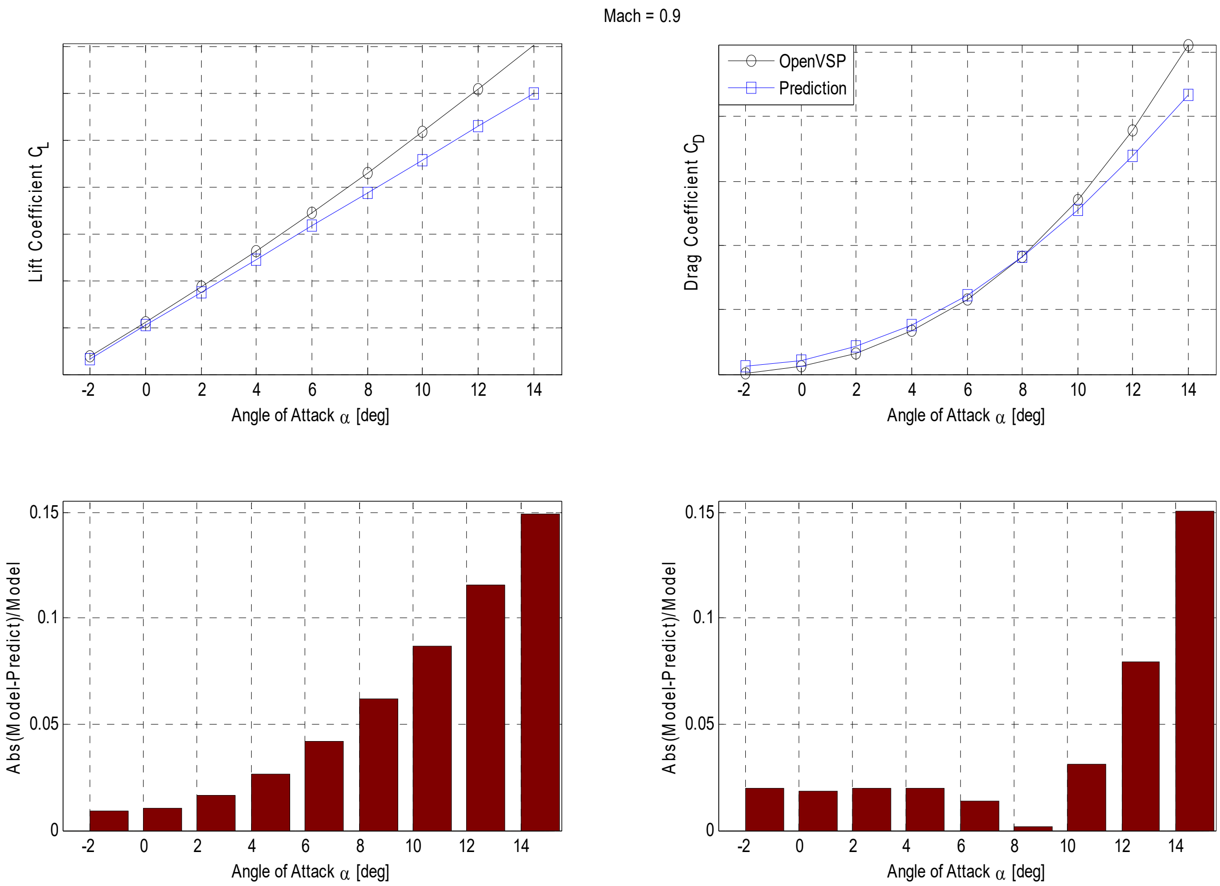

Fig. 8 Lift and drag coefficient comparison for Mach number equal to 0.9

IV. Conclusion

A computation time reduction was required for a pre-conceptual study using OpenVSP software. Some equations were established to reduce OpenVSP computation time for a complete study. Finally, aerodynamic coefficients were calculated for three computation combinations of: three angles of attack where one of them needs to be zero degrees and one Mach number equal to 0.2. From these three cases, all lift and drag coefficients for each angle of attack and Mach number can be predicted by the methodology detailed in this paper. As a conclusion, this method allows to reduce a complete study that takes around 20 minutes using OpenVSP to 90 seconds.

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