BOX WING FLIGHT DYNAMICS IN THE STAGE OF CONCEPTUAL AIRCRAFT DESIGN

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Abstract

Different computational methods are available to evaluate the flying qualities of an aircraft in the stage of conceptual design. However, due to the unconventional configuration of the box wing aircraft, compatibility issues have been encountered with different software, the majority of which appear due to the influence of the second main wing. The independent use of different modules within CEASIOM (Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods) has proved to be a feasible option. The aerodynamic coefficients and derivatives are calculated with Tornado, a vortex-lattice method (VLM) implemented in MATLAB. The SDSA (Simulation and Dynamic Stability Analysis) module of CEASIOM, allows for the determination of the aircraft dynamic modes and the evaluation of the flying qualities based on MIL-F-8785C Specifications. An interface between Tornado and SDSA is programmed by means of MATLAB scripts that read the output data of Tornado, and build the appropriate input files for SDSA. The dynamic modes are also determined and evaluated by hand methods for cruise conditions, in order to compare the results with those obtained with SDSA. The flying qualities of the box wing aircraft are Level 1 for most of the dynamic modes, although the Short Period and Roll Subsidence modes present Level 2 and Level 3, respectively. However, the numerical values show that such modes are close to Level 1 and Level 2, respectively. The overall results can be considered relatively good for a first analysis, and important changes in the design are not needed. The handling qualities have also been evaluated, with the help of a Flight Dynamics Model (FDM) defined with JSBSim and integrated in the visual flight simulator FlightGear. The pilot's rating based on the Cooper-Harper rating scale is Pilot Rating 1, 3 and 5 for cruise, take-off and landing conditions, respectively.

1. INTRODUCTION

According to Flightpath 2050: "In 2050 technologies and procedures available allow a 75% reduction in CO2 emissions per passenger kilometer ... these are relative to the capabilities of typical new aircraft in 2000" [1]. However, these objectives do not seem to be realistic for conventional configurations. It is therefore necessary to investigate new unconventional configurations. One of these configurations is the box wing aircraft, a biplane with oppositely swept wings, which tips are connected by winglets (see FIG. 1). The main advantages it offers are the low induced drag and alleged structural superiority. The first feature allows this type of aircraft to achieve lower fuel consumption.

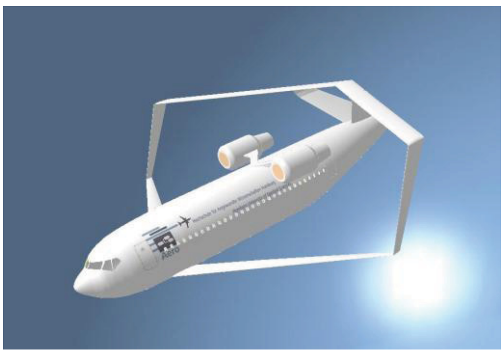

FIG. 1 Box wing aircraft prototype [2]

In order to save costs and time, it is important to determine, with certain level of accuracy, the flying and handling qualities of an aircraft in the early stages of the design. These qualities will allow the aircraft designer to correct and improve different parameters, in order to fulfill the final design requirements. This has a direct impact in the case of the box wing aircraft, as traditional aircraft design relies on statistical methods, which are based on conventional aircraft design. Thus detailed information regarding the flight dynamics of a box wing configuration is not yet known.

Due to the high cost of building and testing a real aircraft, the definition of an appropriate physical model is decisive. Nowadays, computer software allows for an easy determination of the aerodynamic coefficients and stability and control derivatives from the geometric model of an aircraft. CEASIOM (Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods) represents a very attractive option for this task, including all the necessary modules to define the geometric model of the aircraft, build the aircraft physical model, and evaluate its flight dynamics. However, compatibility problems were encountered due to the unconventional configuration of the box wing aircraft, most of them due to the influence of the second main wing. This deems CEASIOM unsuitable for the design evaluation. Other tools, such as Datcom+ or

Open Datcom, extensions of the original USAF Digital Datcom, presented similar problems. However, the independent use of different modules of CEASIOM has proven to be a feasible alternative.

2. BOX WING CONFIGURATION

In the conceptual design of the box wing aircraft [2], the Airbus A320 was used as a reference, having the same design mission. This allows for a comparison of the characteristics of both aircraft, in order to assess the potential of the box wing configuration. The Airbus A320 is a short to medium range aircraft with capability of accommodating up to 150 passengers in a two-class layout. FIG. 2 shows the three-view drawings of the box wing aircraft.

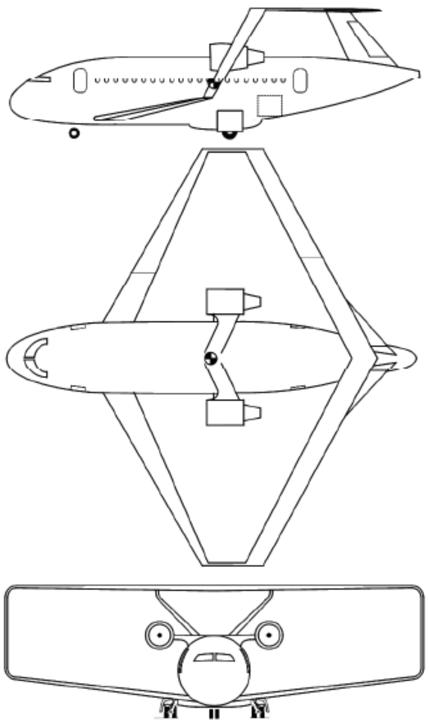

FIG. 2 Three view drawing of the box wing aircraft [2]

2.1. Wing Design

The total wing area of the box wing aircraft is equal to that of the reference aircraft, and is split into the forward and aft wings in equal parts. The chosen airfoils are supercritical, and belong to the second generation of NASA supercritical airfoils.

The forward wing is provided only with high-lift devices, and all the control surfaces are placed on the aft wing and V-tail. A second set of high-lift devices is located on the aft wing. FIG. 3 shows the control surfaces and high-lift system layout.

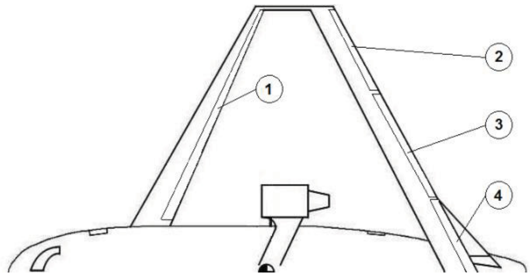

FIG. 3 Control surfaces and high-lift system layout of the box wing aircraft – 1,3: flaps; 2: aileron; 4: elevators [3]

The high-lift system consists only of trailing edge flaps, specifically fowler flaps, the standard for commercial aviation. As shown in FIG. 3, the fowler flaps are present on the forward wing and at the central section of the aft wing.

2.2. Empennage Design

The empennage of the box wing aircraft consists of a V-tail, with the stabilizers having 45º of dihedral. Since this element connects the aft wing with the fuselage, the V-tail design offers more structural strength compared with a simple vertical tail. The rudders will only provide the aircraft with yaw control, by means of asymmetric deflections.

2.3. Weight and Balance

The permissible CG range along the longitudinal axis for conventional aircraft is desired to be about 20 … 25% MAC. The mass and position of the different components of the aircraft were defined in the conceptual design [2], being the different values of the CG position within the permissible range. The longitudinal CG position for the empty aircraft (m_{OE}) is 16.4 m from the nose (structural axes), and 16.8 m for the fully loaded aircraft (m_{MTOW}).

2.4. Estimation of Moments and Products of Inertia

A method for the estimation of the moments of inertia is presented in [4], consisting of some simple steps. First it is needed to set up a reference frame. The CG of the aircraft lies in the plane of symmetry (X'Z'). The Y'Z' plane is placed ahead of the forward end of the aircraft, and the X'Y' plane below its lowest part and parallel to the thrust line. The X', Y' and Z' reference axes are the intersections of these planes. FIG. 4 shows the mentioned axis system, as well as the body-fixed reference frame (X_{BODY},Y_{BODY},Z_{BODY}).

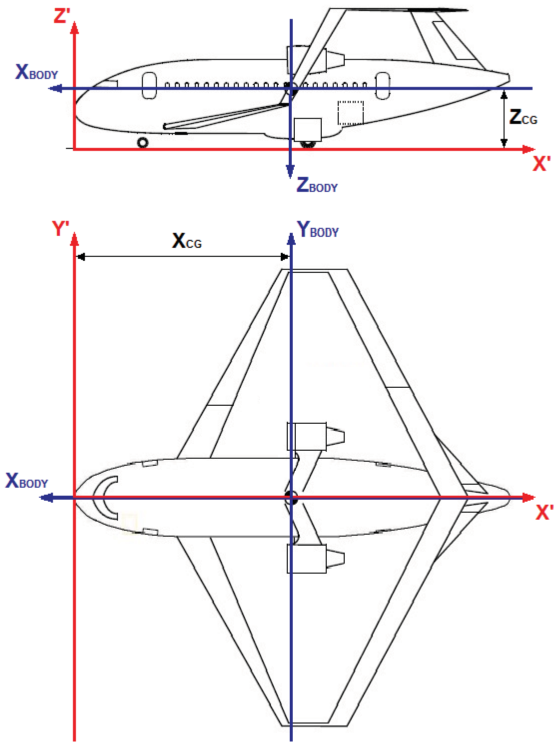

FIG. 4 Reference frames of the box wing aircraft [3]

The product of inertia of each element of the aircraft must be calculated. mxz and myz are zero, due to the symmetry of the aircraft with respect to the plane XZ.

The centers of mass of many elements of the aircraft of considerable size do not pass through the reference axes, and should not be neglected. According to the 'parallel axis theorem' or 'Huygens-Steiner theorem', it is necessary to add to the moment of inertia of the element, considered as a concentrated mass, its moment of inertia about an axis passing through its own center of gravity. These latter moments of inertia, parallel to the reference axes (ΔI_X, ΔI_Y, ΔI_Z), must be estimated, and depend on the geometry of each element.

The total moments of inertia of the aircraft about the three reference axes are:

(1) $I_{X'} = \Sigma my^2 + \Sigma mz^2 + \Sigma \Delta I_X$
(2) $I_{Y'} = \Sigma mx^2 + \Sigma mz^2 + \Sigma \Delta I_Y$
(3) $I_{Z'} = \Sigma mx^2 + \Sigma my^2 + \Sigma \Delta I_Z$

The product of inertia mxy is defined as:

(4) $I_{XZ'} = \Sigma mxz$.

The center of gravity lies in the X'Z' plane, but it is displaced from the Y'Z' and X'Y' planes by distances designated as x_{CG} and y_{CG}, respectively. The total moment of inertia of the aircraft with respect to the Y axis, passing through the center of gravity, is:

(5) $I_Y = I_{Y'} - m({x_{CG}}^2 + {z_{CG}}^2)$.

By substitution of (2) in (5), the expression can be reduced to:

(6) $I_Y = [\Sigma mx^2 - m{x_{CG}}^2] + [\Sigma mz^2 - m{z_{CG}}^2] + \Delta I_Y$.

In the same manner:

(7) $I_X = \Sigma my^2 + [\Sigma mz^2 - m{z_{CG}}^2] + \Delta I_X$
(8) $I_Z = [\Sigma mx^2 - m{x_{CG}}^2] + \Sigma my^2 + \Delta I_Z$

The final expression for the moment of inertia mxy is:

(9) $I_{XZ} = \Sigma mxz - \Sigma m x_{CG} z_{CG}$.

The accuracy of the method proposed in [4] is determined primarily by the accuracy with which the weight and position of the different elements is known. Another important factor is the accuracy with which the moments of inertia of the elements about their own centers of gravity are known. In general, these latter values are small relative to the total moments of inertia of the whole aircraft, and their accuracy does not need to be really high. In some cases it is possible to neglect these items, but the fact that the error due to neglecting them is accumulative should be taken into account. On the other hand, errors due to some mistaken estimates are probably random and tend to nullify each other.

The values calculated by this method have been shown to be lower than experimental values, by 6.5, 5 and 1 percent for the X, Y and Z axes, respectively. In the same way, it does not take into account the entrapped air. This would increase the calculated values by a small amount that can be neglected.

2.5. Static Stability and Controllability

Consider an aircraft in some state of steady flight. When disturbed from its position, either by a gust or by the pilot control, the aircraft will be statically stable if it returns to a sensibly steady state within a finite time, without any control input. The final state does not need to be identical to the initial state, although it often will be. In other words, the aircraft is statically stable if the disturbance generates forces or moments that tend to move the body back to the initial state.

For maneuvering, the aircraft needs to change its motion using its control surfaces. These surfaces apply moments which are resisted by the same restoring moments commented above. This means that an aircraft with a high degree of static stability also needs large control movements and vice versa. A trade-off exists between stability and controllability: the more stable the aircraft is, the less controllable, and vice versa.

The manner in which the aircraft returns to its initial position after a disturbance (directly or after an oscillation) is part of the flight dynamics analysis, and does not concern the static stability.

2.5.1. Static Longitudinal Stability and Controllability

The static longitudinal stability describes the behavior of the aircraft when disturbances affect its angle of attack, i.e., its pitch attitude. The aircraft will be statically stable in the longitudinal axis if it returns to its initial angle of attack, without any control input.

In the conceptual design [2], the box wing configuration was considered as a tandem-wing. In order to attain static stability with a tandem-wing, the CG should be generally forward of the location for an even weight split. This means that the forward wing must produce more lift than the aft wing.

The CG envelope of the box wing aircraft (the possible positions of the CG along the longitudinal axis) depends on the geometric and aerodynamic parameters of the aircraft. The most forward CG position is limited by controllability requirements, whilst the most aft position is limited by stability requirements. In other words, for the box wing aircraft to be more controllable, the CG needs to be moved backwards; to be more stable the CG needs to be moved forward.

The different forces and moments applied on the aircraft are shown in FIG. 5.

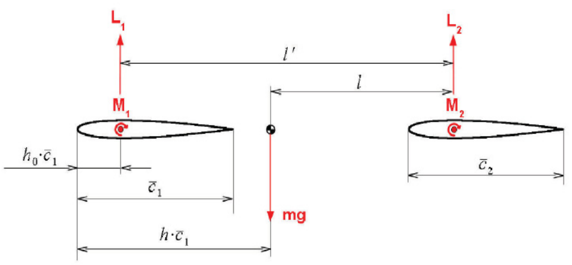

FIG. 5 Forces and moments acting on the box wing aircraft [2]

The initial conditions for static longitudinal stability are:

- *Stability condition:*

The slope of the pitching moment about the CG is negative:

(10) $\frac{dC_m}{dC_L} < 0$.

- *Trim condition:*

The pitching moment about the CG is positive at zero lift:

(11) $(C_m)_{C_L=0} > 0$.

The box wing aircraft should be trimmed in order to counteract the negative pitching moment produced mainly by the wings. In conventional tail aft configurations, such moment is counteracted by the horizontal stabilizer. However, in the case of the box wing aircraft, it is not possible to use exactly the same method. The fins of the V-tail could not be moved, since they are part of the overall structure of the aircraft, keeping the aft wing together with the fuselage. The aft wing could not be moved either, since it is connected to the V-tail and the forward wing through the winglets. In conclusion, it is not possible to trim the aircraft following methods similar to those of conventional configurations.

For a box wing configuration, the main factors that contribute to the negative zero-lift pitching moment are the wings, the fuselage, and in some cases the engines, when they are placed significantly above the CG. By modifying the wings or the fuselage, it is possible to obtain a positive zero-lift pitching moment. In the conceptual design [2], the wing twist was defined in such a manner that the highest value (positive) was at the wing root, and the lowest value (negative) at the wingtip. For the forward wing (positively swept), this means that parts of the wing that are more forward with respect to the CG produce more lift, contributing to a positive pitching moment. The opposite effect occurs on the aft wing, where parts that are more aftwards with respect to the CG produce more lift.

2.5.2. Static Lateral Stability and Controllability

The static lateral and directional stability describes the behavior of the aircraft when it is exposed to disturbances affecting its roll and yaw angles. According to [5], considering an aircraft disturbed in sideslip, elements like the fin tend to turn the aircraft into the direction of the resultant velocity. In other words, the sideslip is reduced by means of a yawing moment through the derivative $N_v > 0$. This is a stable response, known as ‘directional’ or ‘weathercock’ stability. Elements like the fin provide positive directional stability, whereas the fuselage and any engine nacelles or propellers ahead of the CG are destabilizing. In order to achieve directional stability, a restoring moment should be produced, for which the slope of the yawing moment (C_{n_β}) has to be positive, as shown in (12).

(12) $C_{n_\beta} = \frac{\partial C_n}{\partial \beta} > 0$.

Consider now an aircraft with a small angle of rotation in roll around its velocity vector. Since no surface of the aircraft has changed its incidence angle to the flow, there is not any restoring moment. However, a component of the weight along the Y-axis will produce a sideslip, resulting in a rolling moment through the derivative $L_v < 0$. A positive roll angle will produce a positive sideslip velocity, and so a negative rolling moment is necessary in order to attain static stability (13). This effect is known as ‘static lateral stability’.

(13) $C_{l_\beta} = \frac{\partial C_l}{\partial \beta} < 0$.

The sideslip will also produce a yawing moment, bringing the mechanism of the directional stability into play. These stability conditions are therefore coupled. However, such conditions are not enough for a complete evaluation, and the analysis of the dynamic stability is needed to fully evaluate the lateral and directional stability of an aircraft.

According to [6], the wing design is important for lateral and directional stability. Dihedral and positive wing sweep increase lateral stability, whereas anhedral and negative wing sweep reduce it. The position of the wings relative to the fuselage is also important. The higher the wing is placed with respect to the fuselage, the higher level of lateral stability.

Taking account of these considerations, a careful study of the wing parameters for the box wing configuration was carried out in the conceptual design [2]. The forward wing (low wing) was chosen to have positive dihedral. The aft wing does not have any dihedral, in order to avoid structural problems, since it is not directly connected to the fuselage.

3. FLIGHT DYNAMICS OF THE BOX WING AIRCRAFT

Due to the high cost of building and testing a real aircraft, the importance of building an aircraft physical model is crucial. By means of computer simulation, it is possible to evaluate the flying and handling qualities of the prototype aircraft, being this a starting point for the improvement of the design. It is important that such evaluation is carried out as early as possible in the design process, in order to save costs and time.

With data from the conceptual design of the box wing aircraft [2], it is already possible to build a physical model of the aircraft. However, the results may not be highly accurate, since some initial values are simple estimations. Nevertheless it will help perform a rough evaluation of the box wing aircraft flight dynamics, in order to draw some conclusions about its behavior, and improve the design in further stages.

Once the aircraft model is defined, it will be evaluated according to the requirements of civil aviation regulation (CS/FAR, ICAO, MIL). After that, it will be possible to determine the flying and handling qualities of the box wing aircraft, and make some decisions in order to improve its design. It will also allow for the design of a flight control system (FCS) in the future (it is not within the scope of this paper).

3.1. Vortex-Lattice Methods (VLM) and Tornado

Tornado is a 3D-vortex lattice program with flexible wake. It has been developed for linear aerodynamic wing design, mainly in the conceptual stage of the aircraft design, and training and education. Modeling all lifting surfaces as thin plates, Tornado can calculate a wide range of parameters for many different aircraft geometries: 3D forces acting on each panel, aerodynamic coefficients in both body and wind axis, stability derivatives with respect to angle of attack, sideslip angle, angular rates and control surfaces deflection, etc.

Tornado allows for multi-wing designs, as well as any number of control surfaces and high-lift devices, essentially important features in the case of the box wing configuration. Tornado also supports all kinds of wing parameters: sweep, taper ratio, camber, twist, dihedral, etc.

The code of Tornado is implemented in MATLAB, and distributed according to the GNU-Open license protocol. This allows the user for any change or improvement of the code. It works on any MATLAB-supporting platform: Win9x, Win7, Linux, etc.

The vortex lattice method (VLM) used by Tornado is only accurate in the potential flow domain, that is, the domain of linear aerodynamics. Because of this, the main assumptions for any analysis carried out with Tornado are: small angles of attack and small Mach numbers (subsonic range). Compressibility effects are therefore neglected, as well as thickness effects of the lifting surfaces. Fuselage effects and friction drag are not taken into account.

3.2. Implementation of the Box Wing Aircraft in Tornado

In order to obtain the aerodynamic coefficients and the stability and control derivatives, the box wing aircraft was implemented in Tornado.

The cruise conditions defined in the conceptual design [2] are: 12880 m, M0.76. FIGs. 6 and 7 show the geometric model defined with Tornado for cruise conditions, consisting of the lifting surfaces of the aircraft.

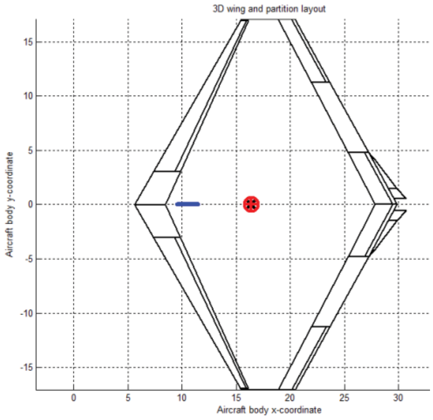

FIG. 6 Top view of the box wing aircraft in Tornado, cruise configuration

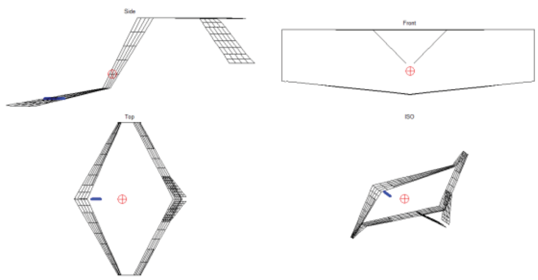

FIG. 7 Meshing of the box wing aircraft in Tornado

The take-off and landing conditions are: 0 m, 85 m/s (take-off) and 80 m/s (landing).

The box wing aircraft is provided with high-lift devices on the forward and aft wings, consisting of fowler flaps. Flap deflection angles of 5º, 10º and 20º are considered for take-off, and 30º and 40º for landing. Tornado allows only for the definition of plain flaps, with no increase of the wing chord. For this reason, it is necessary to modify the original geometric model of Tornado, increasing the wing chord as much as the flap chord. FIG. 8 shows the geometric model for take-off and landing conditions.

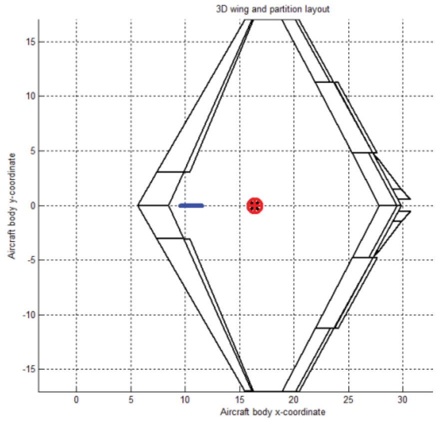

FIG. 8 Top view of the box wing aircraft in Tornado, take-off and landing configuration

The needed aerodynamic data is obtained, performing different analysis with the mentioned flight conditions. However, Tornado does not account for friction effects, and the zero-lift drag coefficient is therefore not considered. Thus, the value of the zero-lift drag coefficient obtained in the conceptual design [2] has to be added to the value of the drag coefficient computed by Tornado.

It has been found out that in order to obtain a lift force equal to the weight of the aircraft in cruise conditions, an angle of attack of 3.5º is necessary (for Tornado the angle of attack is defined as the angle relative to the fuselage centerline). This is due to the wing design, being necessary to modify the incidence angles of one or both wings in such a manner that the lift force equals the weight of the aircraft for an angle of attack of 0 º.

3.3. "Dot" Derivatives

The aerodynamic derivatives with respect to angle of attack rate, or "dot" derivatives, characterize the "unsteady" flows that appear on the aircraft.

The "dot" derivatives cannot be computed with Tornado, and it is necessary to use empirical methods for their determination. Such derivatives are difficult to obtain, being still subject of research [1]. A highly accurate physical model of the aircraft would require non-linear differential equations with higher derivatives of alpha and beta. However, several methods exist to obtain estimations of these derivatives, being the results accurate enough for the conceptual stage of the aircraft design.

The so-called ‘lag-of-downwash’ method is presented in [1]. It assumes that the downwash behind the forward wing mainly depends on the strength of the trailing vortices of such wing near the aft wing. Since the vorticity travels with the flow, a change in downwash at the forward wing trailing edge, due to a change in angle of attack, will not affect the aft wing instantaneously. A time increment $\Delta t = x_2/U$ will be considered, where x_2 is the distance from the ¾ MAC of the forward wing to the aerodynamic center of the aft wing, and U is the aircraft forward velocity. The following approximation is considered:

(14) $x_2 \approx x_{ac_2} - x_{CG}$.

It is assumed that the downwash at the aft wing $\varepsilon(t)$, is equal to that downwash of the forward wing angle of attack $\alpha(t-\Delta t)$. Thus the following correction is made to the aft wing angle of attack:

(15) $\Delta\varepsilon = -\frac{d\varepsilon}{d\alpha}\dot{\alpha}\Delta t = -\frac{d\varepsilon}{d\alpha}\dot{\alpha}\frac{(x_{ac_2}-x_{CG})}{U}$.

The lift derivative with respect to angle of attack rate, or alpha “dot”, is given by the following expression:

(16) $C_{L_{\dot{\alpha}}} = 2C_{L_{\alpha_2}}\eta_2\bar{V}_2\frac{d\varepsilon}{d\alpha}$,

where $C_{L_{\alpha_2}}$ is the lift-curve slope of the aft wing, η_2 is the dynamic pressure ratio at the aft wing, and $\bar{V}_2$ is the aft wing tail volume coefficient.

η_2 is given by the following expression:

(17) $\eta_2 = \frac{\bar{q}_2}{\bar{q}_1}$,

where $\bar{q}_2$ is the dynamic pressure on the aft wing and $\bar{q}$ is the dynamic pressure of the entire aircraft.

$\bar{V}_2$ is defined as:

(18) $\bar{V}_2 = \frac{S_2}{S}\left(x_{ac_2} - x_{CG}\right) = \frac{S_2}{S}x_2$

where S_2 is the aft wing area and S the total wing area.

For these calculations the contribution of the V-tail was not considered for simplicity, as it does not have so much influence.

The pitching moment derivative with respect to angle of attack rate, or alpha “dot”, considering that lift-up on the aft wing produces a nose-down pitching moment, is given by:

(19) $C_{m_{\dot{\alpha}}} = -2C_{L_{\alpha_2}}\eta_2\bar{V}_2(x_{ac_2} - x_{CG})\frac{d\varepsilon}{d\alpha}$.

The beta “dot” derivatives are not considered in the present paper, as their influence in the results of the flight dynamics analysis may be neglected. In cruise the values of the lift and pitching moment derivatives with respect to angle of attack rate have the following values:

$C_{L_{\dot{\alpha}}} = 6.75$
$C_{m_{\dot{\alpha}}} = -52.4$

3.4. Aircraft Dynamics in State and Output Equation

In the linear simulation of flight dynamics, small perturbations about equilibrium or trimmed conditions are assumed. A linear system can be expressed in state space notation, in the form of the State Equation:

(20) $\dot{\boldsymbol{x}} = \boldsymbol{A}\,\boldsymbol{x} + \boldsymbol{B}\,\boldsymbol{u}$.

x is the state vector, with perturbations of the state variables. ***u*** is the control vector, with the control input of elevator and flaps, as well as disturbances due to gust inputs. ***A*** is the system matrix or state coefficient matrix, and ***B*** is the control matrix. They consist mainly of stability and control derivatives.

The State Equation form can be used for longitudinal and lateral-directional flight dynamics, varying the elements of the ***A*** and ***B*** matrices.

3.5. Stability for Longitudinal Flight Dynamics

The stability matrix ***A*** allows for the calculation of the eigenvalues, which are used for the determination of the dynamic stability of the aircraft. For this reason, only this matrix will be considered. The eigenvalues are calculated with the equation:

(21) $det|\lambda I - A| = 0$,

where ***I*** is a 4 x 4 identity matrix. The solution of (21) is the fourth degree characteristic polynomial:

(22) $\lambda^4 + a_1\lambda^3 + a_2\lambda^2 + a_3\lambda + a_4 = 0$.

With the values of the matrix **A**, (22) can be reexpressed as follows:

(23) $\lambda^4 + 0.867\lambda^3 + 1.86\lambda^2 + 0.0103\lambda + 0.0077 = 0$.

Solving the characteristic polynomial, the eigenvalues for (23) are the following:

$\lambda_1 = -0.432 + 1.29i$
$\lambda_2 = -0.432 - 1.29i$
$\lambda_3 = -0.0018 + 0.0647i$
$\lambda_4 = -0.0018 - 0.0647i$

λ_1, λ_2 correspond to the Short Period mode, and λ_3, λ_4 to the Phugoid mode. An aircraft is dynamically stable when all the real eigenvalues for the longitudinal and lateral motions are negative, and the real parts of the complex eigenvalues are negative. When represented in the S-plane, they should be placed to the left of the vertical axis (FIG. 9). The eigenvalues obtained for the box wing aircraft fulfill the stability requirements, being the aircraft **dynamically stable in the longitudinal axis**.

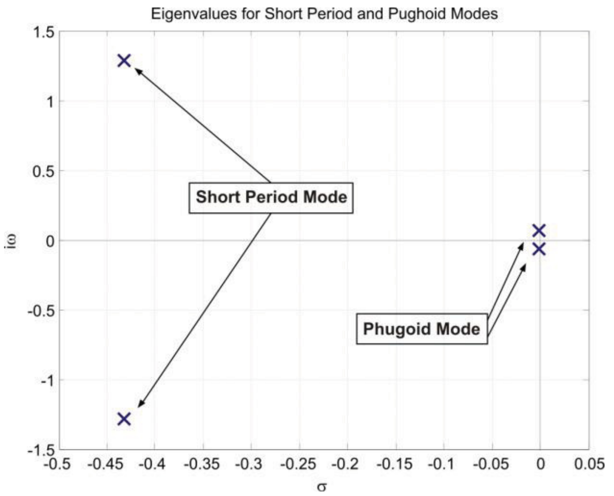

FIG. 9 S-plane for the longitudinal flight dynamics in cruise conditions

For the longitudinal flight dynamics, (22) can be factorized into two second order characteristic equations:

(24) $\left(s^2 + 2\xi_{ph}\omega_{ph}s + \omega_{ph}^2\right) \cdot \left(s^2 + 2\xi_{sp}\omega_{sp}s + \omega_{sp}^2\right) = 0$,

where the first factor belongs to the Phugoid mode and the second to the Short Period mode. ξ_{ph}, ξ_{sp} and ω_{ph}, ω_{sp} are the damping ratios and frequencies for both dynamic modes, respectively.

Considering any of the second order characteristic equations:

(25) $(s^2 + 2\xi\omega_n s + \omega_n^2) = 0$,

the solution will have the form:

(26) $s_{1,2} = \sigma \pm j\omega_d$,

where the real part is defined as:

(27) $\sigma = -\xi\omega_n$.

The damped frequency can be expressed as a function of the undamped natural frequency with the following equation:

(28) $\omega_d = \omega_n\sqrt{1 - \xi^2}$.

The damping ratio ξ depends on ω_d and σ:

(29) $\xi = \frac{1}{\sqrt{1+\left(\frac{\omega_d}{\sigma}\right)^2}}$.

3.6. Stability for Lateral Flight Dynamics

In the same manner as for the longitudinal dynamics, the characteristic polynomial of lateral motion is expressed as follows:

(30) $det|\lambda I - A| = 0$,

where *I* is a 4 x 4 identity matrix. The solution of (30) is the fifth degree characteristic polynomial:

(31) $\lambda^4 + d_1\lambda^3 + d_2\lambda^2 + \lambda d_3 + d_4 = 0$.

With the values of the matrix *A*, (31) can be reexpressed as follows:

(32) $\lambda^4 + 0.499\lambda^3 + 1.06\lambda^2 + 0.264\,\lambda - 0.0033 = 0$.

The eigenvalues for (32) are the following:

$\lambda_1 = -0.117 + 0.993i$
$\lambda_2 = -0.117 - 0.993i$
$\lambda_3 = -0.277$
$\lambda_4 = 0.0119$

λ_1, λ_2 correspond to the Dutch Roll mode, λ_3 to the Roll subsidence mode, and λ_4 to the Spiral mode. FIG. 10 shows these eigenvalues represented in the S-Plane. The real values of the Dutch Roll and Roll Subsidence modes are negative, positioned to the left of the vertical axis, thus being **stable**. The real value of the Spiral mode is positive, positioned to the right of the vertical axis, being **unstable**. However, such a value is relatively small, being this characteristic common in most aircraft.

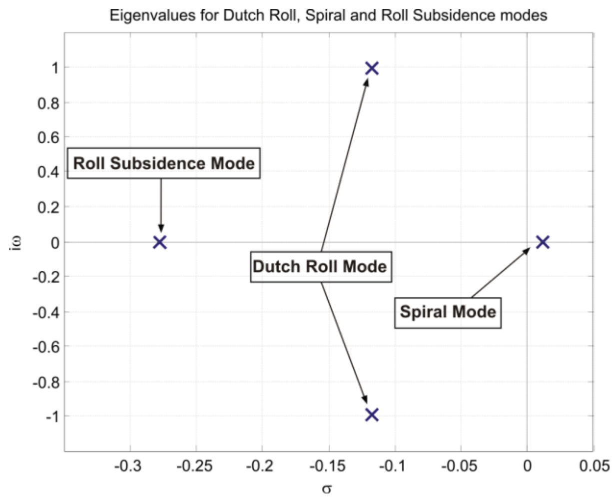

FIG. 10 S-plane for the lateral flight dynamics in cruise conditions

4. FLYING AND HANDLING QUALITIES OF THE BOX WING AIRCRAFT

A distinction between flying and handling qualities can be found in [6], being the "flying qualities" determined by those parameters of the aircraft physical model related to the complex frequency domain, such as damping ratio. On the other hand, "handling qualities" refer to the easiness with which a pilot can perform a particular mission. However, both concepts are connected, and an aircraft with good flying qualities will be nice to maneuver by the pilot, thus having good handling qualities.

The Cooper-Harper rating scale is a criteria used by test pilots and engineers, to evaluate the handling qualities of an aircraft. It consists of a scale from 1 to 10, where 1 represents the best handling qualities and 10 the worst. It is therefore a subjective evaluation, based on the opinion about the behavior of the aircraft of test pilots and engineers. Table 1 shows the equivalence between the levels defined by the MIL-F-8785C Specifications and the Cooper-Harper rating scale.

TAB 1. Equivalence between MIL-F-8785C and Cooper-Harper rating scale [6]

Pilot state	Level MIL-F	Cooper-Harper rating
	1	1 2 3
	2	4 5 6
	3	7 8 9
Control partially lost	Unacceptable	10

4.1. Evaluation of Flying Qualities by Hand Methods

The characteristic values of each dynamic mode, as well as the classification according to MIL-F-8785C Specifications, are summarized in Table 2.

TAB 2. Characteristic values and classification of the dynamic modes

DYNAMIC MODES	Characteristic values	MIL-Spec.
Short Period	$\xi_{sp} = 0.318$	Level 1
Phugoid	$\xi_{ph} = 0.028$	Level 2
Dutch Roll	$\xi_D = 0.086$ $\omega_D \xi_D = 0.117$	Level 1 Level 2
Roll Subsidence	$T_{\xi R} = 3.61\ s$	Level 3
Spiral	$T_s = 58.0\ s$	Level 1

The Control Anticipation Parameter (CAP) has the following values:

$\boldsymbol{n_{z\alpha}} = 5.84$
$\boldsymbol{CAP} = 0.316$

According to the CAP Flight Quality Level Definition chart for Category B (FIG. 11), and considering the values above, the CAP is classified as **Level 1**.

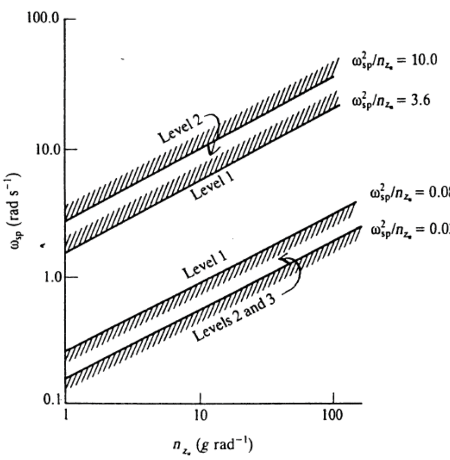

FIG. 11 Chart of the CAP Flight Quality Level Definition, Flight Phase Category B [7]

According to MIL-F-8785C Specifications, for flight phase category B, the flying qualities for the Roll Subsidence mode are classified as **Level 3**.

4.2. Evaluation of Flying Qualities with SDSA

The evaluation of the flying qualities of the box wing aircraft was accomplished with the software SDSA (Simulation and Dynamic Stability Analyser), with the purpose of having a second assessment, in order to compare the results with those obtained in the previous chapter.

4.2.1. SDSA Input Files

The CEASIOM environment is the interface between the different modules. The input data of SDSA are then processed by CEASIOM in the appropriate format, with data from the different modules. However, since the whole CEASIOM environment cannot be used for the box wing configuration, the input files of SDSA must be created manually. In the same manner as CEASIOM, the input data of SDSA are managed in the MATLAB environment, with data obtained from Tornado.

According to the Input Data Manual of SDSA [8], two different types of input data structures are accepted, named *XML* and *TEXT*. *XML* is a single file structure, with an *.xml* file containing all the necessary data. *TEXT* is a multiple text file structure, with several text (*.txt*) and configuration (*.cfg*) files. In the present analysis, the ***TEXT multiple file data structure*** was chosen. Therefore the needed input data are: dimensionless stability and control derivatives, aerodynamic coefficients and $Alpha_{max}$.

For the *TEXT* file structure, the different files are located in appropriate directories:

- Input_data\BWA\... *- input data root directory*
aero.cfg *- aerodynamic input data configuration file*
controls.cfg *- control system input data*
gmas.cfg *- mass input data*
landing_gear.cfg *- landing gear input data*
power.cfg *- power unit input data configuration file*
thrust.cfg *- thrust properties input data*
- Input_data\BWA\aero\... *- input data subdirectory for aerodynamic data*
aero.txt *- main dimensionless aerodynamic coefficients*
ctrl.txt *- main dimensionless aerodynamic coefficients vs. control surfaces deflections*
alfamax.txt *- max. angles of attack*

In the case of the text files (*.txt*), arrays containing all the necessary data were created with MATLAB, from the data obtained with Tornado. The input files ***Alfa_max.txt***, ***Czda_prim_ma.txt***, and ***Cmda_prim_ma.txt*** contain the max. angles of attack (also defined with Tornado) and the "dot" derivatives $C_{L_{\dot{\alpha}}}$ and $C_{m_{\dot{\alpha}}}$, respectively. In each file, these data are defined for a specific range of Mach numbers, in this case from M0.3 to M0.8 (6 values).

The ***aero.txt*** file contains the main dimensionless aerodynamic coefficients. Each line of data contains the state vector and vector of the dimensionless coefficients, in the following manner:

[alpha, Ma, beta, q, p, r] $[C_{L(lift)}, C_{D(drag)}, C_{M(pitch)}, C_{Y(lateral\ force)}, C_{l(roll)}, C_{N(yaw)}]$

The data are written in Mach series for a specific range of angles of attack *α*, varying the other input parameters (*alpha, Ma, beta, q, p, r*). The values for these input parameters depend on the user. The higher the number of values the more accurate the final results will be.

The ***ctrl.txt*** file contains the main dimensionless aerodynamic coefficients vs. control surfaces deflections. As in the previous case, each line of data consists of the state vector and vector of the dimensionless coefficients, in the following manner:

[alpha, Ma, elevator, rudder, aileron] $[C_{L(lift)}, C_{D(drag)}, C_{M(pitch)}, C_{Y(lateral\ force)}, C_{l(roll)}, C_{N(yaw)}]$

The data are also written in Mach series for a specific range of angles of attack *α*, varying the deflection of the control surfaces (*elevator, rudder, aileron*).

4.2.2. Results of SDSA

The evaluation of the flying qualities was performed for cruise conditions, as well as for different values of altitude (0 m … 14000 m) and airspeed (100 m/s … 240 m/s).

Table 3 shows the results obtained for cruise conditions with SDSA, compared to those obtained by hand methods.

TAB 3. Characteristic values and classification of the dynamic modes

	Hand Methods		SDSA	
DYNAMIC MODES	**Characteristic values**	**MIL-Spec.**	**Characteristic values**	**MIL-Spec.**
Short Period	$\xi_{sp} = 0.318$	Level 1	$\xi_{sp} = 0.267$	Level 2
Phugoid	$\xi_{ph} = 0.028$	Level 2	$\xi_{ph} = 0.029$	Level 2
Dutch Roll	$\xi_D = 0.086$	Level 1	$\xi_D = 0.202$	Level 1
	$\omega_D \xi_D = 0.117$	Level 2	$\omega_D \xi_D = 0.196$	Level 1
Roll Subsidence	$T_{\xi R} = 3.61\ s$	Level 3	$T_{\xi R} = 3.39\ s$	Level 3
Spiral	$T_s = 58.0\ s$	Level 1	$T_s = 31.9\ s$	Level 1

The recognition of the different dynamic modes is carried out by SDSA taking into account the eigenvector of the aircraft. Due to the unusual eigenvector of the box wing aircraft, SDSA presented some problems recognizing the Roll

Subsidence and Spiral modes. These modes were confused, being the Roll Subsidence mode considered as Spiral mode, and vice versa. Since the box wing is a non-typical configuration, it is reasonable that non-typical results may appear. Nevertheless, considering the numerical output of SDSA, it is possible to calculate the correct parameters for these modes.

In the case of the Spiral mode, it is only necessary to change the sign of the value of $T_{1/2}$:

$$\boldsymbol{T_{1/2}} = 31.9\ s$$

In the case of the Roll Subsidence mode, the time to half is considered as follows:

$$(33)\quad T_{1/2} = \frac{ln2}{|T_{\xi R}|}$$

where $T_{\xi R}$ is the time constant, the parameter that is needed. Considering $T_{1/2} = 2.33\ s$, the numerical value of the roll damping time is:

$$\boldsymbol{T_{\xi R}} = 3.39\ s$$

Some plots were obtained, representing the flying qualities for the specified ranges of altitude (0 m … 14000 m) and airspeed (100 m/s … 240 m/s).

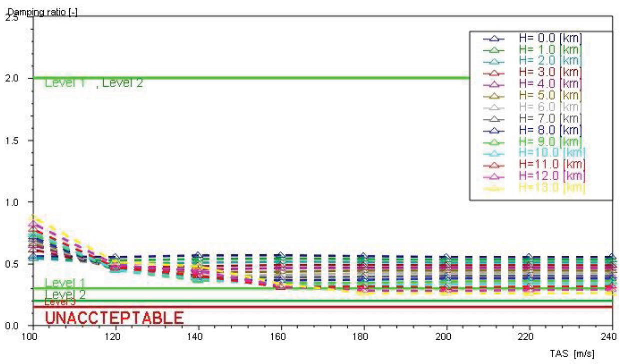

FIG. 12 Short Period mode, 0 m … 14000m, 100 m/s … 240 m/s

It can be observed in FIG. 12 how the damping ratio decreases with altitude, thus making worse the behavior of the aircraft. Nevertheless the values remain in Level 1 until about 12000 m of altitude, where they slightly drop to Level 2.

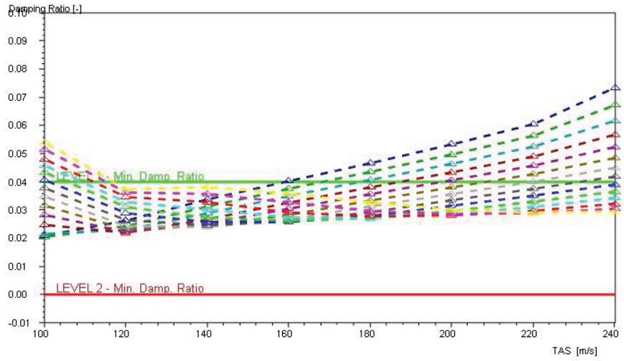

FIG. 13 Phugoid mode, 0 m … 14000 m, 100 m/s … 240 m/s

It can be observed in FIG. 13 how the flying qualities of the aircraft are classified as **Level 1** for lower altitudes, decreasing to **Level 2** when the altitude increases. The aircraft airspeed contributes to an improvement of the flying qualities at any given altitude, when it is higher than 140 m/s. Such an improvement is more noticeable for higher altitudes.

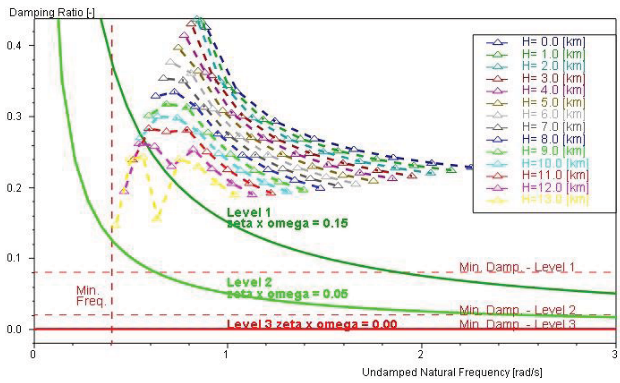

FIG. 14 Dutch Roll mode, 0 m … 14000 m, 100 m/s … 240 m/s

It can be observed in FIG. 14 how the flying qualities of the aircraft for the Dutch Roll mode are classified as **Level 1** for the whole altitude range. However, at the highest altitudes (12000 m … 13000 m) the flying qualities decrease to **Level 2** for lower airspeeds.

Due to the problem of SDSA recognizing the Spiral and Roll Subsidence modes, the results of such modes cannot be correctly plotted by SDSA.

4.3. Evaluation of Handling Qualities with JSBSim

A Flight Dynamics Model (FDM) is a physical model (a set of equations) that defines the movement of an aircraft, rocket, etc., under the forces or moments applied to it due to the control surfaces and the forces of nature. A flight simulator relies on an FDM, in order to simulate the flight of an aircraft.

JSBSim in an open source FDM, which models the aerodynamic forces and moments based on the classic coefficient buildup method. *JSBSim* has no native graphics, and can be run as a standalone program, using several scripts and vehicle configuration files as input. On the other hand, it can also be implemented into a flight simulator with a visual system. *JSBSim* is currently the main FDM of the open source flight simulator *FlightGear*.

The FDM on *JSBSim* is defined with several scripts in *.xml* format, allowing for fully configurable flight control system, aerodynamics, propulsion, landing gear configuration, etc. *JSBSim* can be compiled and run under several operating systems, such as *Microsoft Windows*, *Apple Macintosh*, *Linux*, *etc.*

FIG. 15 shows how the different files that define the FDM are arranged in different directories.

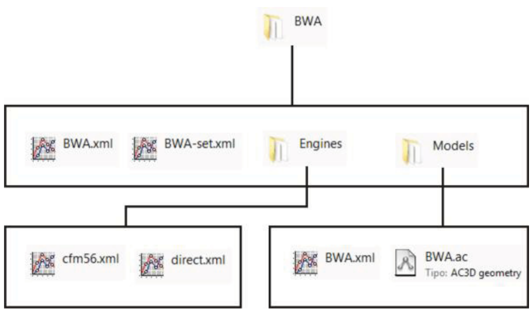

FIG. 15 Files and folders of the box wing aircraft FDM

The main folder contains the files *BWA.xml* and *BWA-set.xml. BWA.xml* (*aircraft* file) is considered as the main file of the FDM. It fully describes the aircraft, taking into account metrics, mass balance, ground reactions, propulsion, flight control and aerodynamics. *BWAset.xml* is intended for the implementation of the FDM into a visual flight simulator, and defines the 3D model of the aircraft, including information regarding the different views and virtual cockpit, sound, etc. The folders *Engines* and *Models* include files defining the aircraft power plant (*engine* file) and the 3D model, respectively.

4.3.1. 3D Aircraft Model

In order to integrate the FDM of the box wing aircraft in a visual flight simulator, such as *FlightGear*, it is necessary to define a geometric model of the aircraft. This task is performed with *Datcom+* and *AC3D*.

Digital Datcom is a computer software written in the 1960's – 1970's, based on the original *Datcom*. *Datcom+* represents an extension of *Digital Datcom*, including some tools for making it easier to use. *Datcom+* generates a 3D model of the aircraft, which is used in the present case.

AC3D is a well-known 3D design software, for modeling 3D graphics for games and simulators. Its modeling technique is polygon/subdivision-surface based, referring to "surfaces" instead of "polygons", like other 3D software.

The aircraft 3D model obtained with *Datcom+* consists in an *.ac* file that is rather simple (FIG. 16), since *Datcom+* does not offer the possibility of defining elements such as winglets, V-tail, landing gears, etc. The 3D model must therefore be modified with *AC3D*, for the implementation of the elements commented previously.

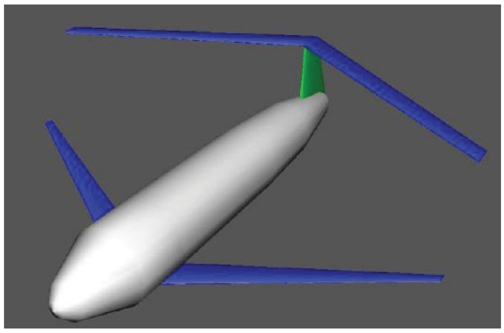

FIG. 16 3D model of the box wing aircraft generated by Datcom+

The 3D model of the box wing aircraft created by *Datcom+* is manually modified with *AC3D*.

The file *BWA_model.ac* can be found in the folder *Models.* The following elements are added: winglets, V-tail, landing gear, engines, control surfaces and high-lift devices.

Elements such as the engines or the landing gear are taken from sample aircraft 3D models included with *FlightGear*, being later modified for their integration in the box wing aircraft.

In addition, some other tasks were performed with the aim of making the aircraft 3D model look more realistic, such as adding textures and colors. The final 3D model is shown in FIG. 17. As it can be observed, the aircraft is defined in body axes, with the origin in the CG.

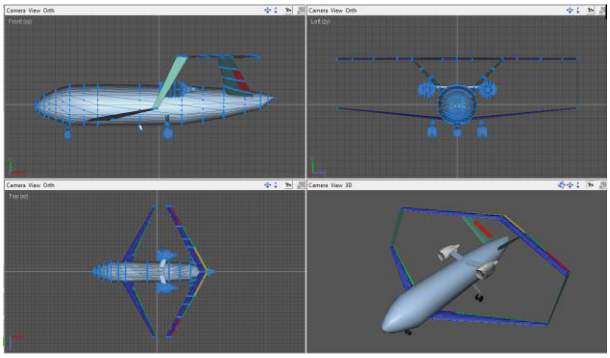

FIG. 17 Final 3D model of the box wing aircraft

The hierarchy of the elements in which the 3D model of the aircraft is divided is also defined with *AC3D*. In the file *BWA_model.xml,* the kinematics of such elements was defined, in order to provide them with a defined movement (rotation or displacement) in a visual flight simulator. This feature contributes to a more realistic experience while flying the aircraft in a flight simulator.

4.3.2. JSBSim and FlightGear

FlightGear is an open-source flight simulator, developed by volunteers around the world. The source code is available and licensed under the GNU General Public License, and is supported by the most popular operating systems (Windows, Mac, Linux, etc.)

JSBSim is currently the main flight dynamics model (FDM) of *FlightGear*. The integration in *FlightGear* of any aircraft FDM created with *JSBSim* is a simple task. A folder with the files that define the FDM is to be placed in the *FlightGear* directory *data/Aircraft,* and when the simulator is started the new aircraft is automatically recognized.

FIG. 18 Screenshot of the box wing aircraft in FlightGear

4.3.3. Cooper-Harper Rating Scale

According to [9], the term “pilot evaluation” refers to the subjective assessment of the handling qualities of an aircraft made by pilots. It consists of two different parts: pilot’s comments and rating. Both sources of information are the most important data on the closed-loop pilot-aircraft provided to the engineer.

The pilot’s comments can provide the engineer with information about something that is wrong, as well as possible changes to improve the handling qualities of the aircraft.

Regarding the pilot’s rating, the Cooper-Harper Handling Qualities Rating Scale has been the standard for measuring handling qualities since 1969. It consists of a scale from 1 to 10, where 1 represents the best handling qualities and 10 the worst. The levels defined by the MIL-F-8785C Specifications and the Cooper-Harper rating scale was shown in Table 1.

The Cooper-Harper rating scale has a “decision tree” structure, as shown in FIG. 19. The pilot needs to answer a series of two-way choices which lead him/her to three ratings, from which one of them must be chosen. However, this rating scale has no meaning if the dimensions of interest are not specified. Therefore the tasks the pilot needs to accomplish should be defined, as well as the conditions under which the operation is to be conducted.

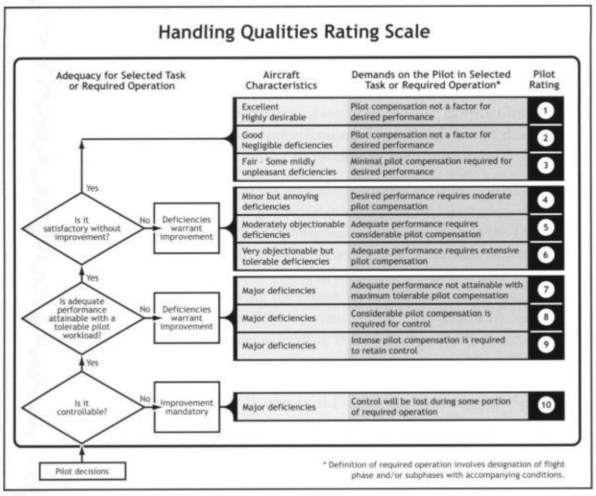

FIG. 19 Cooper-Harper Handling Qualities Rating Scale (www.nasa.gov)

The following text refers to the number of pilots needed for conducting the flight tests:

"A classic handling qualities experiment showed that a few pilots evaluating for a longer period of time produced the same central tendency of the rating excursions as a larger group conducting shorter evaluations. What was lost with the larger group, however, was the quality, consistency, and meaningfulness of the pilot comment data. Based upon this and other experiences, it is generally recommended to use only a few pilots (sometimes only one) until the experiment has matured through the engineer's understanding of the comment and rating data." [9]

Taking into account the above considerations, and given the early stage of development of the flight dynamics model, only one test pilot is used in the present project. A student with a deep knowledge and experience in flight simulation was selected.

4.3.4. Evaluating Cruise Flight

The box wing aircraft is set in *FlightGear* at cruise conditions: M0.76, 12880 m. Different tasks are defined for the pilot:

- Maintain constant altitude and attitude
- 360º turn at constant altitude
- 90º turns left/right at constant altitude
- 1000 ft climb
- 1000 ft descend
- Keep bank angle of 30º
- Descend: 0% throttle

<u>Pilot's comments:</u>

The handling qualities of the box wing aircraft in cruise conditions are very satisfactory. The aircraft is stable and nice to maneuver.

<u>Pilot's rating:</u>

The rating given for cruise flight is **Level 1**, which according to the Cooper-Harper rating scale means "Excellent/Highly desirable", referred to the aircraft characteristics. According to Table 1, such level corresponds to **Level 1** of MIL-F-8785C specifications.

4.3.5. Evaluating Take-Off

The following tasks are defined for take-off and second segment:

- Climb at constant airspeed
- 90º turns left/right
- Climb with pitch angle of 10º … 15º

<u>Pilot's comments:</u>

The rotation of the aircraft could be performed at the standard speed (160 kt … 180 kt) with the fully loaded aircraft (m_{MTO}). However, when the amount of fuel in the aircraft was reduced, in order to decrease its take-off weight below m_{MTO}, the rotation speed did not decrease accordingly, remaining at about 160 kt. Flaps deflections of 20º and 40º were used, and the rotation speed was noticeable lower in the latter case. In the opinion of the pilot, the rotation speed is within acceptable limits for such type of aircraft, but it should be slightly lower when $m < m_{MTO}$.

Regarding the second segment, the box wing aircraft climbed at constant airspeed for a pitch angle of about 10º. For higher pitching angles (until 15º), the airspeed decreases slightly. However, the aircraft should be able to climb slightly faster, according to the pilot.

<u>Pilot's rating:</u>

The rating for take-off and second segment is **Level 3**. According to the Cooper-Harper rating scale, such level means "Fair – Some mildly unpleasant deficiencies". At this level, a minimal pilot compensation is required to attain the desired performance. As shown in Table 1, the Level 3 in the Cooper-Harper rating scale corresponds with **Level 1** of MIL-F-8785C Specifications.

4.3.6. Evaluating Landing

The following tasks were defined for landing:

- Normal approach and landing
- Missed approach
- Landing with initial horizontal path offset

<u>Pilot's comments:</u>

The main issue encountered by the pilot was the control efficiency of the aircraft, especially for roll and pitch. Regarding roll control, the ailerons did not move quickly enough as to perform the necessary corrections, especially with gusty weather. To solve this problem, the gain of the aileron control was increased. After this change, the roll control of the aircraft improved considerably, being able to perform the necessary corrections.

Regarding pitch control, it was difficult to lose altitude pitching down. The range of deflection of the elevator was increased, as well as the gain. After such changes, the pitch control improved considerably, and the pitch down of the aircraft became more effective.

According to the pilot, it was not easy to maintain the desired pitch angle with the stick, and it was necessary to use the trim for landing. It was not possible to flair the aircraft, i.e. reduce gradually the descent rate until the landing gear gently touches the ground. Thus the landing could not be performed as smoothly as wished.

The speed of deflection of the flaps was too high, resulting in a sudden pitching up moment when the flaps were deflected, being the pitch control partially lost for several seconds. As the landing speed was relatively low, this could lead the aircraft to a stall with fatal consequences. The speed of deflection of the flaps was therefore decreased in such a manner that 60 seconds were needed for a fully deflection of the flaps (40º).

The pilot also missed more instrumentation, necessary for a more objective distinction among rating levels. The only instruments in use for the flight test were those included in the head-up display (HUD) embedded in *FlightGear*. Important instruments for landing, such as the vertical speed indicator, were unfortunately not available.

Pilot’s rating

The rating for landing is **Level 5**. The definition of such level in the Cooper-Harper rating scale is “Moderately objectionable deficiencies”, referred to the aircraft characteristics. Considerable pilot compensation is required for an adequate performance. According to Table 1, the Level 5 in the Cooper-Harper rating scale corresponds with **Level 2** of MIL-F-8785C Specifications.

5. CONCLUSIONS

According to MIL-F-8785C Specifications, the flying qualities of the box wing aircraft are classified as Level 1 for most of the altitude range of the aircraft. However, with an increase of altitude, the flying qualities decrease, dropping to Levels 2 and 3 for the highest altitudes in some cases. This is due to the decrease of air density with altitude.

According to the conceptual design of the box wing aircraft [2], the cruise altitude is 12880 m, above the limit mentioned previously. The Levels 2 and 3 of the flying qualities of an aircraft is defined as follows:

“Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.” [7]

“Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A flight phases can be terminated safely, and Category B and C flight phases can be completed” [7]

Since the flying qualities of the box wing aircraft are good enough, being always within acceptable limits, important changes in the design are not needed. Therefore the addition of stability augmentation systems (SAS) for the improvement of the flying qualities represents the best option.

The control systems of modern aircraft generally rely on *fly-by-wire* technology, and thus the implementation of SAS would not represent any inconvenience. In the event of a failure of the SAS, when flying at altitudes of more than about 10000 m, the flying qualities of some dynamic modes of the box wing aircraft would drop to Level 2 (the Roll Subsidence mode probably to Level 3), which is still within safety and operational limits. The pilot then would decide to descend to lower altitudes, where the flying qualities of the aircraft are classified as Level 1.

The safety requirements for aircraft systems are listed in section 1309 of the certification requirements CS-25 and FAR Part 25. Table 4 shows the acceptable probabilities for the different levels of flying qualities according to MIL-F-8785C Specifications, for civil aircraft.

TAB 4. Levels of acceptability for civil aircraft [6]

MIL-F Level	Probability of encountering within “normal” flight envelope
1	Required under “normal” conditions
2	After failure $<10^{-4}$ per flight
3	After failure $<10^{-6}$ per flight
Unacceptable	Total loss of control $<10^{-9}$ per flight hour

In conclusion, the box wing aircraft presents Levels 1, 2 and 3 flying qualities. The probability of the aircraft to drop to Levels 2 or 3 may only occur at higher altitudes, generally above 10000 m, in the event of a failure of the *fly-by-wire* system, thus being such a possibility relatively low. In such a case, although with some increase in the pilot workload, the aircraft can still be flown in direct mode, and descending to lower altitudes would improve the flying qualities. The box wing aircraft would be then suitable for certification without the necessity of performing any important change in the design, but only by implementing the necessary SAS.

Regarding the handling qualities, the rating given by the pilot has been Pilot Rating (PR) 1 for cruise conditions, PR 3 for take-off, and PR 5 for landing. The pilot's comments have been generally positive, having some remarks regarding landing maneuverability. Several modifications have been introduced in the FDM, specifically in the flight control system. After these modifications, the pilot emphasized the noticeable improvement of the handling qualities for landing conditions. However, his evaluation was limited by the available instrumentation of the flight simulation, as well as the hardware.

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NOMENCLATURE

Symbols

C	Aerodynamic coefficient
C_D	Drag coefficient
C_L	Lift coefficient
C_Y	Side-force coefficient
C_l	Roll rate coefficient
C_m	Pitch rate coefficient
C_n	Yaw rate coefficient
p	Roll rate
q	Pitch rate
r	Yaw rate
$n_{z\alpha}$	Acceleration sensitivity
$\bar{q}$	Free-stream dynamic pressure
I	Moment/product of inertia, identity matrix
v	Velocity, airspeed
$\bar{V}$	Tail volume coefficient
x	Longitudinal position/distance
y	Lateral position/distance
z	Vertical position/distance
S, S_w	Wing reference area
U	Longitudinal component of velocity
ε	Downwash angle
α	Angle of attack
β	Sideslip angle
η	Relative half span
λ	Taper ratio, eigenvalue
ξ	Damping ratio
ω_n	Natural frequency

Abbreviations

CG	Centre of Gravity
FAR	Federal Aviation Regulations
CS	Certification Specifications
ICAO	International Civil Aviation Organization
MAC	Mean Aerodynamic Chord
MIL	Military Specification
SDSA	Simulation and Dynamic Stability Analyser
USAF	United States Air Force
VLM	Vortex-Lattice Method

Indices

MTOW	Maximum Take-Off Weight
OE	Operating Empty
1	Forward wing
2	Aft wing
ph	Phugoid
s	Spiral mode
sp	Short Period mode
D	Dutch Roll mode
R	Roll Subsidence mode

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