Design and analysis of the control and stability of a Blended Wing Body aircraft

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ABSTRACT

Future aircraft generations are required to provide higher performance and capacity with minimum cost and environmental impact. This fact calls for the design of revolutionary unconventional configurations, such as the Blended Wing Body (BWB), a tailless aircraft which integrates wing and fuselage into a single lifting surface with efficient and promising results. In this paper, a BWB aircraft baseline was designed and its aerodynamic behaviour and performance were analyzed with a special emphasis on its challenging stability and control features. This problem was approached by enhancing the CEASIOM software for conventional aircraft design by implementing DLR's CPACS, as an unified and more versatile software framework. This improvement enables the design and analysis of future unconventional aircraft configurations. A Vortex Lattice Method (VLM) and a 3D panel method were employed for the aerodynamic analysis and both showed a close agreement. The allocation and sizing of the control surfaces were then iterated to find the optimum winglet size for minimum drag and radar detectability conditions. A global 12% reduction of the control surfaces area was achieved, which implies lower weight and drag. All in all, the satisfactory performance of the BWB concept was confirmed and a new tool for unconventional aircraft design was obtained.

NOMENCLATURE

α = Angle of attack, [rad]
β = Sideslip angle, [rad].
δ = Control surface deflection angle, [rad].
λ = Eigenvalue.
ω = Oscillation frequency, [rad/s].
$\boldsymbol{A}$ = Complex aerodynamic influence matrix, [m];
AR = Aspect ratio.
b = Wing span, [m].
c = Reference length, [m].
$\boldsymbol{C}$ = Structural Damping Matrix, [kg/s].
FF = Form Factor [-].
$\boldsymbol{f_a}$ = Aerodynamic forces vector, [N].
k = Induced drag factor, [-].
$\bar{k}$ = Reduced frequency, [-].
$\boldsymbol{K}$ = Stiffness matrix, [kg/s^2].
$\boldsymbol{M}$ = Mass matrix, [kg].
q = Pitch rate [rad/s].
q_∞ = Dynamic pressure, [Pa].
r = Yaw rate [rad/s].
u = Air speed, [m/s].
$\boldsymbol{x}$ = Nodal displacement vector, [m].
x_{ac} = Neutral point position, [m].
x_{cg} = Center of gravity point position, [m].

1 INTRODUCTION

World air traffic has been increasing in a constant way over the last decades, and all forecasts predict that this pace will continue to accelerate in the near future due to the great economic development of China, India, Brazil and other areas. Some authors [2-5] estimate that the overall revenue passenger·kilometre figure will grow at a rate above 5%, well over the world economic growth. This process will require more than 35,000 new jet aircrafts and the reconversion of a large number of ageing airliners in the next 20 years (85% of the world fleet will be new by 2032[2]). However, this enormous demand will occur in a moment of high pressure to reduce both direct operating cost and environmental impact.

The conventional aircraft configuration has remained essentially unchanged for the last six decades and is approaching a productivity and capacity asymptote around the size of the Airbus A380. The continuously changing market and technology scenario is leading to new revolutionary unconventional designs and concepts to address this increasing air traffic demand. One of the most promising concepts is the Blended Wing Body (BWB) aircraft (see figure 2), a tailless aircraft design which integrates wing and fuselage into a single lifting surface, by thickening the wing in the central part of the airplane. Due to its efficient economic performance and its higher capacity, it is a promising candidate for the future large airliner. The feasibility, efficient performance and airport compatibility of the BWB concept have already been assessed in several previously publications [6-12] with encouraging results.

The main advantage of the BWB concept is its reduced wetted area to volume ratio compared to conventional aircrafts, which leads to a drag reduction and, therefore, to lower fuel burn and environmental impact. The lack of empennage reduces the weight and complexity of the aircraft. Other benefits are the significant structural and payload advantages, lower interference drag, reduced wing loading and the noise reduction (especially if the engines are located above the wing, requiring lower engine speed for landing). In general, this leads to the achievement of a lower operating cost. Authors such as Qin [7], estimated an increase in the maximum lift to drag ratio, $(L/D)_{max}$, of about 20% over the conventional aircraft configurations. This ratio can be estimated by the following equation:

$$\left(\frac{L}{D}\right)_{\max} = \sqrt{\frac{\pi AR}{4kC_{D_0}}} = b\sqrt{\frac{\pi}{kS_{D_0}}} \tag{1}$$

where C_{D_0} is the zero-lift drag, S_{D_0} is the zero-lift drag wetted area, k is the induced drag factor, and AR and b are the aircraft wing aspect ratio and wing span, respectively. As previously mentioned, the BWB's lower wetted area provides a substantial improvement in the aerodynamic performance. The rest of the parameters in equation 1 are considered similar to conventional aircrafts, e.g. the maximum span is limited to 80 m, considering the current airport capability (ICAO F category).

The most critical aspects in the BWB design process are its control and stability features, due to the lack of a tail and its unconventional shape. Several BWB models, such as the presented by Liebeck [6], had a largely negative static margin, requiring a fly-by-wire control system. Therefore, the design and allocation of the control surfaces becomes crucial. Unfortunately, this concept is quite novel and there are not enough data, experience or flight tests from previous BWBs to consider as reference. Furthermore, the design of the fuselage is a more complex problem than usual. Fuselage sections have to be carefully designed in order to fulfil both the structural and aerodynamic requirements. Finally, the size of the vertical surfaces, such as the winglets, which provide directional stability and control and increase the effective aspect ratio, condition the radar detectability of an aircraft, which is an important factor in case this aircraft is intended to serve military purposes. For this reason, as well as for drag reduction, the minimum size for these surfaces is a goal to achieve.

Traditional commercial aircraft conceptual design processes often employ handbook methods based on semi-empirical theory and data, which are not reliable enough for treating novel and unconventional designs and can easily lead to remarkable sizing errors. One option for improving the aircraft design process is to implement fast, high fidelity software frameworks earlier in the design process to apply physics based predictions of the performance and stability available. Obtaining highly accurate information earlier helps to avoid expensive redesign of the aircraft in the future and might allow being "first-time-right".

CEASIOM[1] (Computerised Environment for Aircraft Synthesis and Integrated Optimisation Methods) is a multidisciplinary support tool for the conceptual aircraft design, developed within the SimSAC[2] project. This software provides higher fidelity during the beginning of the product definition, were approximately up to 80% of the life cycle budget is expended, with the consequent saving of resources and time. CEASIOM stability and control characteristics (which are crucial in tailless aircrafts) are well defined since the beginning, avoiding expensive situations where the whole subsystem has to be redesigned due to a design error. Previous experience [13] has proven that inadequate design of these features can even cause the demise of any project. This way, the definition of a virtual aero-servo-elastic aircraft model is possible earlier in the design process, which is also more fluid and is based on modelling and simulation, instead of being rigid and strictly based on design, like in the classical methods. However, the current geometry module of CEASIOM, AcBuilder, is very limited and has several constraints, such as the necessity of having only one tubular fuselage, reduced number of kinks in the wing, and, in general, usual restrictions for conventional aircraft configurations. These restrictions render the current state of the CEASIOM platform largely, making it inapplicable for the study of unconventional configurations, such as the BWB.

The aim of this paper is to design and analyze a BWB baseline and study the optimal control surface design, regarding its aerodynamic, stability and control features. To overcome CEASIOM limitations, the Common Parametric Aircraft Configuration Scheme (CPACS)[3], a design and analysis tool for unconventional aircraft configurations developed by the DLR (German Aerospace Center) are implemented, enhancing CEASIOM, in order to be able to design the BWB geometry. The scope of this work is focused on the conceptual design stage and the start of the preliminary definition, but it is sufficient to create an initial view of the BWB aircraft and make a first analysis.

The rest of the paper is structured as follows: Section 2 gives an explanation of the software used and the improvements made in this research to enable the study of the BWB. Section 3 gathers the geometrical description of the final BWB model, the main aerodynamic results, the stability analysis and the optimization process of the control surfaces. Finally, section 4 is devoted to the conclusions and the most important statements of the paper.

2 METHODS AND TOOLS

CEASIOM gathers into an application the main aircraft design disciplines (geometry, structures, aerodynamics, aeroelasticity, stability, control, propulsion, etc.) in different interconnected simulation modules that share an unified geometrical description. The most relevant modules used for this paper are introduced below:

- **AcBuilder (Geometry)**: This module can be used for creating a parametrized geometry of the aircraft, defining the components and their dimensions. The user can also calculate the materials, fuel tanks, cabin, luggage, weight and inertia parameters and visualize the sketch of the aircraft while changing the geometry parameters. However, as stated before, this module only considers conventional aircraft configurations with several rigid constraints (one cylindrical fuselage, one main wing, one horizontal tail, etc.), and therefore, a more versatile tool should be implemented, such as CPACS.

[1] CEASIOM is offered as a freeware, according to the EULA conditions and it is downloadable free of charge from the official website: [http://www.ceasiom.com]
[2] SimSAC: Simulating Stability And Control Characteristics for Use in Conceptual Design, funded by the European Commission 6th Framework Programme. Website: [http://www.simsacdesign.org]
[3] CPACS website: [https://code.google.com/p/cpacs]

- **SUMO (Geometry mesher)**: The graphical surface modelling tool SUMO (SUrface MOdeler) can be used to quickly define an accurate aircraft geometry employing b-spline surfaces. SUMO is able to automatically generate surface and volume unstructured meshes, using the Tetrahedral Mesh Generator TetGen, for using them in CFD solutions based on the Euler equations. SUMO also performs automatic CAD repair by closing wingtips and fuselage noses and tails, if necessary. An example of the outcome of SUMO is illustrated in figure 2 (c).

- **Weight & Balance**: The weight and balance parameters of non-structural masses and their location can be estimated using semi-empirical methods (Howe, Torenbeek, Raymer, USAF and Cessna) mainly based on statistical handbooks. This way, the centres of gravity of the different components can be obtained and visualized and the inertia moments of the aircraft can be calculated, as depicted in figure 2 (d).

- **AMB-CFD (Aerodynamics)**: In the Aerodynamic Model Builder module, tabular data with several parameters values can be obtained for the considered aircraft geometry and then generate an aerodynamic database with forces and moments for flight dynamic analysis. Within this module, there are four different available methods for calculating the results, depending on the fidelity required:

    1. DATCOM (Data Compendium): Handbook methods which have shortcomings in the transonic speed envelope and are only available for certain conventional types of aircraft which exist in the handbook. It estimates the aerodynamic derivatives based on geometric details and flight conditions.

    2. TORNADO: Tool based in the potential Vortex Lattice Method (VLM) which can be used for steady and unsteady low-speed aerodynamic cases. Zero-lift drag is modelled according to Eckerts flat plate analogy. Viscosity can be approximately taken into account by an empirical extension and incompressible fluid conditions can be calculated using the Prandtl-Glauert correction. Trailing edge devices (TED) deflections are generated by mesh deformations during the modification of the horseshoe vortices.

    3. Edge: Inviscid 2D/3D CFD Euler code used for high-speed aerodynamic cases and aero-elasticity calculations, including compressibility effects. Edge is based on Navier-Stokes equations for viscous and inviscid compressible flow problems in unstructured grids. The aerodynamic of control surface deflections is computed by using the transpiration boundary conditions instead of deforming the grid.

    4. RANS (Reynolds Averaged Navier-Stokes): high-fidelity flow simulator for extreme flight conditions analysis including viscous effects. The computational cost of this method is too high for this research, so it will not be further explained.

  The choice of the most suitable method is a compromise between fidelity and computational cost (time). In this project, the VLM code TORNADO was used, due to the low-speed and low-angle of attack conditions of the analysis. This tool achieves reasonable accurate results employing low computing time, compared to the much larger time required by higher fidelity tools.

- **SDSA (Stability and Control)**: The Simulation and Dynamic Stability Analyzer module allows a six-degree-of-freedom flight simulation of the stability and control characteristics, and assesses about the flying quality and performance. It requires the aerodynamic coefficients and control surfaces parameters for the total flight envelope as well as the center of gravity coordinates and inertia moments. The aircraft mathematical model is transformed into a matrix form. The non-linear equations of motions are formulated and linearized computing the Jacobian matrix of state derivative around the trimmed condition (state of equilibrium). The eigenvalues and eigenvectors for the equilibrium state are then computed.

Finally, the modes of motion and the stability characteristics (damping and frequency coefficients, damping ratio, period, etc.) are calculated. With the recorded data, the SDSA module can provide the stability motion modes characteristics. It can also provide the trimmed angle of attack, the trimmed angle of deflection and the drag coefficient. The stability analysis results are presented as figures of merits based on JAR/FAR, ICAO and MIL regulations.

As commented before, the major problem of CEASIOM is its geometry module, AcBuilder, which is greatly limited to conventional aircraft configurations. Since 2005 the DLR has been developing the Common Parametric Aircraft Configuration Scheme (CPACS), a standard XML syntax definition for the exchange of data within conceptual and preliminary aircraft design stages, including all the parameters necessary to describe the aircraft configuration, and process and tool specific data for the connected analysis modules.

In this research CPACS was implemented in CEASIOM, providing a common language for all the modules and a more unified version of CEASIOM. This way, design teams in various institutions benefit from standardized product descriptions and from identical coupling of analysis modules. In this unified data-centric setup, the number of interfaces required decreases to a minimum, establishing a more effective and flexible communication between the modules. CPACS is able to define aircrafts with several levels of fidelity and complexity and to overcome any eventuality which might occur in future aircraft configurations. CPACS describes the characteristics of aircrafts, rotorcrafts, engines, climate impact, airports, flight plans, fleets and mission in a object-oriented, structured, hierarchical manner. Geometric elements such as aircraft, wings, sections, elements, profiles, points, and transformations are defined covering the bandwidth of the named projects. CPACS offers several advantages compared to the old CEASIOM XML files, such as being more versatile and accurate for the geometry definition and containing more task specific details which are highly accessible by several coupled tools. Appendix A includes the flowchart of the new software.

Therefore, a new geometry module, called CPACSCreator, was implemented in CEASIOM, in substitution for the AcBuilder module, and connected to the other modules via wrappers, using CPACS as syntax. A comparison between examples of both geometry modules output is depicted in figure 1.

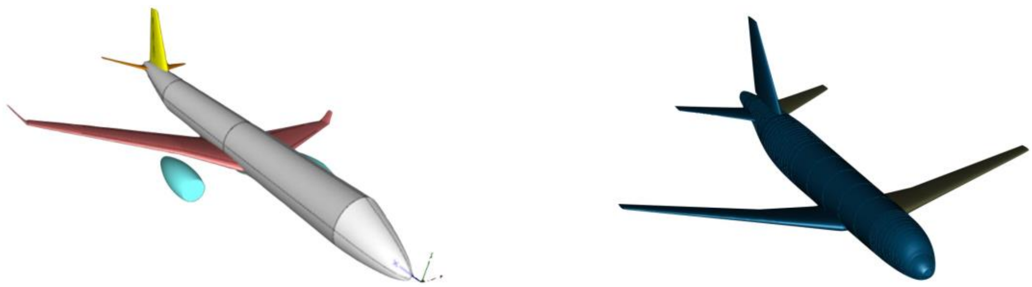


Figure 1: Example of a traditional airliner configuration as defined in: (left)CEASIOM AcBuilder. (right) CPACSCreator (enhanced module allowing more accurate and smoother surface definition).

A special emphasis should be laid on the fact that some modifications were made in the code of TORNADO so that it can also handle a larger number of control surfaces and be compatible with CPACS. In order to confirm the performance of these variations, an example case of a Boeing 747-100 was analyzed and compared with the experimental and numerical results published by Da Ronch et al. [14]. The outcome of that experience was very satisfactory and is also included in the full text of this research [1]. Other successful validations were made with examples provided by CEASION. In order to get more data to compare with, the BWB geometry was also implemented in the XFLR5[4] software, for studying its aerodynamic characteristics using a VLM method and a 3D panel method.

[4] XLFR5 is an open source program based on an improved version of the XFOIL code developed by Mark Drela at MIT. Website: [http://www.xflr5.com||http://www.xflr5.com]

3 RESULTS AND PERFORMANCE

3.1 BWB baseline design

The BWB baseline is required to have two engines, winglets instead of empennage or vertical fins, and dimensions of approximately 3x2x0.5 m (with enough capacity for the fuselage). The model should be designed for low speed conditions and be statically stable in all the directions and dynamically stable in all the modes, if possible. As stated before, the allocation and sizing of the control surfaces needs to be optimized to a minimum size with acceptable performance. After CEASIOM was enhanced with CPACS, the BWB baseline geometry was created, taking into account some guidelines from other BWB references, such as NASA's X-48B[5], the MOB BWB [7-11], the SAX-40[6] and especially the ELSA BWB, designed by Carlsson [12] in 2002. In general, this BWB design would correspond to a UAV, approximately 1:30 scale of a real size prototype, see figure 2 (a).

After a simple aerodynamic shape optimization process, the *Wortmann fx 60-126* airfoil was selected for the BWB wing due to its high lift to drag ratio. The fuselage was first considered as a body defined by the first *N2Asta072* airfoils (which have a suitable shape for the required capacity) in the wing direction and later as cross sections of that body in the fuselage direction, as illustrated in figure 2 (b). The non-circular shape of the fuselage implied a slightly larger structural weight, but offered a higher capacity. The rest of the geometric parameters were selected according to the design requirements, taking into account typical values for other BWB models. Once all the design features were defined, an iterative shape refinement process was performed using a combination of SUMO and the CAD tool CATIA, in order to smooth the outer surface and eliminate bumps and irregularities. Table 1 gathers some geometric characteristics and table of the BWB model obtained.

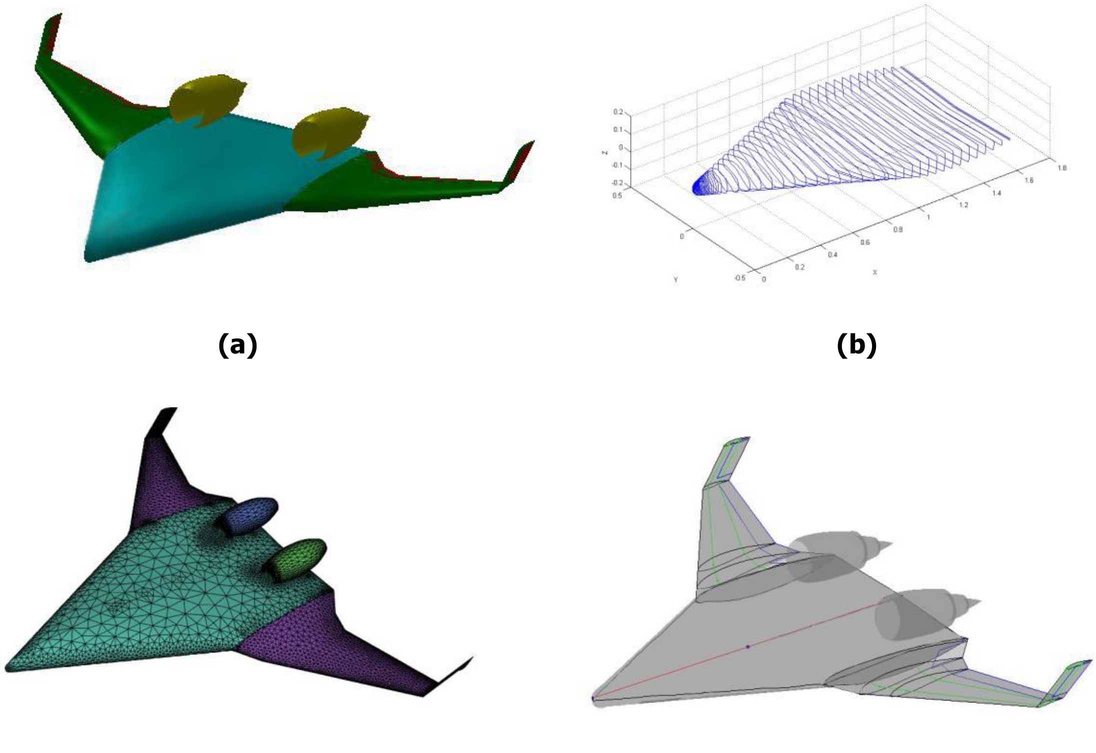
Parameter	Value
Wing span, b	3.095 m
Wing area, S_{wing}	1.5164 m^2
Mean Aerodynamic Chord, MAC	0.961 m
Mean Geometric Chord, MGC	0.655 m
Total length, L_{BWB}	1.734 m
Fuselage length, L_f	1.609 m
Total height, h_{BWB}	0.326 m
Fuselage height, h_f	0.253 m
Aspect ratio, AR	3.53
Taper ratio	0.083
Dihedral angle, Γ	5º(BWB) and 80º(winglet)
Leading edge sweep angle, Λ_{LE}	63.51º (fuselage) and 39.05º (wing)
MTOW	22.5 kg
Thrust to Weight ratio, T/W	0.41
Center of gravity coordinates	(0.9651, 0, -0.0378) m
Thrust per engine	45 N

Table 1: Geometric characteristics of the optimised BWB model designed.

The control surface design issue is critical so, for the baseline geometry, four sets of trailing edge devices of considerable area were implemented:

- A pair of inner elevators and a pair outer elevators for pitch control.
- A pair of elevons (which can operate as elevator or as aileron when needed) for pitch, roll control and secondary yaw.
- A pair of winglet rudders for yaw control.

[5] NASA X-48B website: [http://www.nasa.gov/centers/dryden/research/X-48B]
[6] Aero-Astro Magazine Highlight website: [http://web.mit.edu/aeroastro/news/magazine/aeroastro-no4/silentaircraft.html] MIT Department of Aeronautics and Astronautics.



(a) (b) (c) (d)

Figure 2: Final BWB geometry after the optimization process: **(a)** Final BWB model, including the engines and the control surfaces (in red) as seen in CPACSCreator. **(b)** Fuselage cross sections as seen in CPACSCreator. **(c)** Refined mesh of the BWB geometry using SUMO automatic mesh generator. **(d)** Final BWB geometry as seen in the Weight & Balance module, showing the position of the center of gravity (blue dot), control surfaces (in blue) and spars (in green).

3.2 Optimization process

An iterative optimization process was performed in order to achieve the minimum size of the control surfaces which still offers satisfactory flight performance and stability characteristics. The objective function to minimize combines the overall drag and the BWB weight. During the iteration process, special attention was paid to the Dutch roll and spiral motion modes, which are critical due to their dependence on the size of the winglet rudders (which we are trying to minimize). A configuration without rudders was also studied but determined to be too unstable in the lateral motion.

The geometric characteristics of the control surfaces of the final model are gathered in table 2 and show an average control surface area reduction of 12 % and a winglet span reduction of 20 % with respect to the baseline model, which implies lower weight, drag and radar detectability. See appendix B for the sketches of the control surfaces allocation.

Control Surface	c_1 (m)	c_2 (m)	Span (m)	Surface (m^2)	Baseline Comparison
Inner elevator	0.119	0.129	0.151	0.0187	-20.43%
Outer elevator	0.092	0.069	0.140	0.0113	-14.59%
Elevon	0.074	0.049	0.639	0.0393	-8.82%
Rudder	0.096	0.096	0.120	0.0115	-4.17%

Table 2: Geometric characteristics of the optimised BWB model designed.

3.3 Performance analysis and discussion

The aerodynamic characteristics of the final model are presented in table 3, where C_L is the lift coefficient, C_D the drag coefficient, C_Y the side force coefficient, C_m the pitching moment coefficient, C_l the roll moment coefficient and C_n the yaw moment coefficient. The subscripts α, β, q and r represent the derivatives with respect to the angle of attack, sideslip angle, pitch rate and yaw rate respectively. In table 4 the aerodynamic derivatives with respect to the control surfaces deflections (δ) are gathered, confirming the influence of the deflections of the different control surfaces.

Coefficient	Value
C_L	0.1989
C_D	0.0037
C_m	-0.0169
C_{L_α}	2.7312 rad^{-1}
C_{D_α}	0.617 rad^{-1}
C_{m_α}	-0.1139 rad^{-1}

Coefficient	Value
C_{Y_β}	-0.2712 rad^{-1}
C_{l_β}	-0.1089 rad^{-1}
C_{n_β}	0.0379 rad^{-1}
C_{m_q}	-24.2 s/rad
C_{Y_r}	-0.0953 s/rad
C_{l_r}	-0.0781 s/rad
C_{n_r}	-0.1098 s/rad

Table 3: Aerodynamic coefficients derivatives for the BWB final model and α=2º and u=40 m/s obtained in TORNADO.

Coefficient	Value
$C_{L_{\delta InnerElev}}$	0.5124 rad^{-1}
$C_{D_{\delta InnerElev}}$	0.0217 rad^{-1}
$C_{m_{\delta InnerElev}}$	-0.2622 rad^{-1}
$C_{L_{\delta OuterElev}}$	0.3897 rad^{-1}
$C_{D_{\delta OuterElev}}$	0.0038 rad^{-1}
$C_{m_{\delta OuterElev}}$	-0.1873 rad^{-1}

Coefficient	Value
$C_{Y_{\delta Elevon}}$	0.0194 rad^{-1}
$C_{l_{\delta Elevon}}$	-0.3281 rad^{-1}
$C_{n_{\delta Elevon}}$	-0.0061 rad^{-1}
$C_{Y_{\delta Rudder}}$	0.0812 rad^{-1}
$C_{Y_{\delta Rudder}}$	0.0384 rad^{-1}
$C_{Y_{\delta Rudder}}$	-0.0295 rad^{-1}

Table 4: Control surfaces deflection derivatives for the BWB final model and u=40 m/s obtained in TORNADO.

It is important to notice that TORNADO (and in general the VLM method) fails to predict the parasite drag, C_{D_0}, whose values are extremely low $C_{D_0} \approx 0.0015$ for the three methods) compared to typical values of around 0.02. This is due to the fact that TORNADO does not consider properly the viscosity, which is one of the main causes of the parasite drag. Therefore, an alternative procedure for estimating the parasite drag, the so-called flat plate method, was employed. The parasite drag of each component (BWB and engines) can be estimated with the following empirical formula [15]:

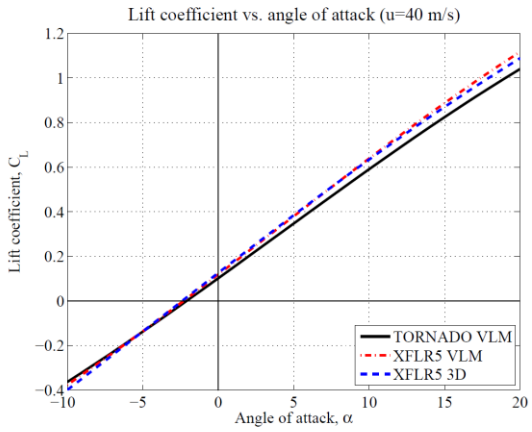
$$C_{D_{0_{component}}} = \frac{C_{f_{component}} S_{wet_{component}} FF_{component}}{S_{reference}} \tag{2}$$

where $C_{f_{component}}$ represents the skin friction coefficient of the component, $S_{wet_{component}}$ refers to the wetted area of the component, $FF_{component}$ represents the form factor of the component and $S_{reference}$ is the reference area (selected to be the wing area). Therefore, the new value of the parasite drag of the BWB model (considering the whole fuselage-wing body and the engines) is:

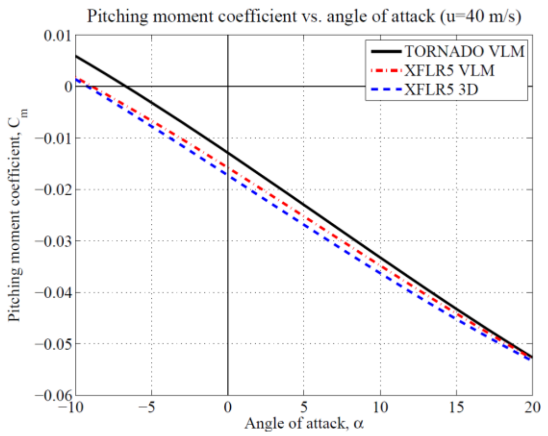
$$C_{D_0} = C_{D_{0_{BWB}}} + C_{D_{0_{engines}}} = 0.01113 + 0.00092 = 0.01205 \tag{3}$$

Which is around 8 times larger than the one considered by TORNADO and has more physical meaning. Therefore, it was added to the obtained data before any further aerodynamic analysis, in order to get a closer view of the actual performance.

In figure 3, an overview of the aerodynamic results of the BWB model is presented. The variations of the lift coefficient, C_L , and the pitching moment coefficient, C_m, with the angle of attack, α, obtained for the three methods (VLM from TORNADO and VLM and 3D panel method from XFLR5) are compared in figures 3 (a) and (b), which have the typical linear values for these methods. Furthermore, the drag polar (drag coefficient vs. lift coefficient) and the local lift force spanwise for different angles of attack are also depicted in figures 3 (c) and (d). The local lift force spanwise distribution is approximately elliptical, which is considered to have minimum drag for the subsonic regime. All the three methods show a very close agreement between them, which is encouraging and confirms the accuracy of the results. The aerodynamic efficiency (lift to drag ratio) has maximum values of 50 for low angles of attack, but for typical operating points, this value varies between 25 and 35, which is still remarkably higher than usual values from conventional aircraft configurations, such as the Boeing 747 which has a lift to drag ratio of approximately 17.



(a)



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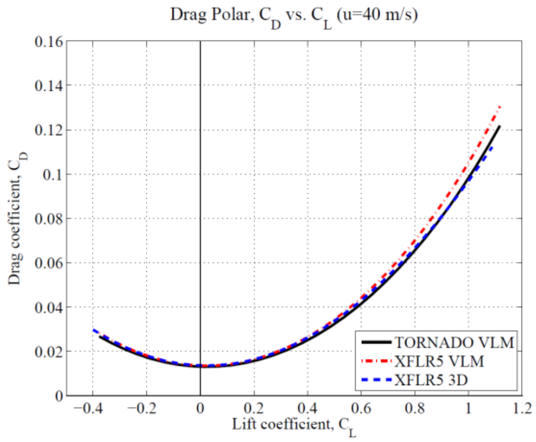

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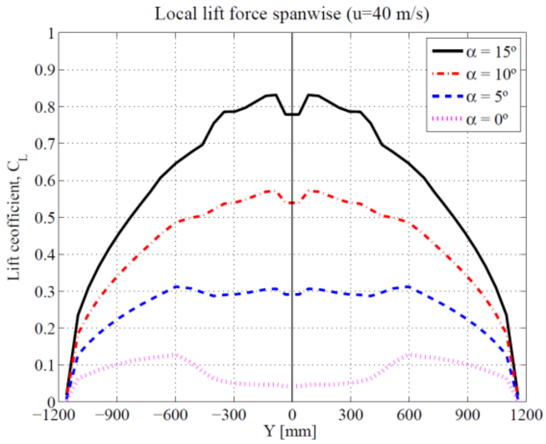


(d)

Figure 3: Final BWB model aerodynamic performance results for all methods and an air speed of u=40m/s: **(a)** Lift coefficient variations with the angle of attack. **(b)** Pitching moment coefficient variations with the angle of attack. **(c)** Drag polar (including the empirical parasite drag). **(d)** Local lift force spanwise for different angles of attack (without considering the winglets)

The placement of the engines over the wing was carefully designed and oriented in a way that they do not induce a high pitch down moment, especially during take-off. The possibility of flight with one engine out was also studied and confirmed to be satisfactory.

The static stability of the BWB in all modes is confirmed with the fulfilment of several conditions with respect to some values from table 3:

- For longitudinal static stability C_{m_α} has to be negative and, in this case, its value is $-0.1139\ \mathrm{rad}^{-1}$.
- For lateral static stability C_{l_β} has to be negative and, in this case, its value is $-0.1089\ \mathrm{rad}^{-1}$.
- For directional static stability C_{n_β} has to be positive and, in this case, its value is $0.0379\ \mathrm{rad}^{-1}$.
- For sideslip static stability C_{Y_β} has to be negative and, in this case, its value is $-0.2712\ \mathrm{rad}^{-1}$

The static margin, K_n, is defined as the longitudinal distance between the center of gravity and the neutral point of the aircraft normalized to the Mean Aerodynamic Chord: $K_n = (x_{ac} - x_{cg})/MAC$. The normal requirement states that, for commercial airplanes, this value should be approximately 5%.The static margin in typical operating points for the BWB model tends to a value between 5 and 6%, confirming this way the satisfactory stability performance.

After solving the dynamic equations of motion [16], presented in equation 4, an eigenvalue problem is obtained (equation 6) that provides the characteristics of the motion modes. Here, $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{C}$ the structural damping matrix, $\boldsymbol{K}$ the stiffness matrix, $\boldsymbol{x}$ the nodal displacement vector and $\boldsymbol{f_a}$ is the vector or aerodynamic forces. A dot, $(\dot{\ })$, represents differentiation with respect to the time, t. Using a linear incompressible aerodynamic model, such as the VLM, the aerodynamic forces can be expressed as a function of the nodal displacements of the structure and the free-stream dynamic pressure, q_∞. $\boldsymbol{A}$ is the complex aerodynamic influence matrix and $\bar{k}$ is the reduced frequency, defined as the quotient between the oscillation frequency, ω, multiplied by a reference length, c (typically the Mean Aerodynamic Chord of the wing), and the free-stream velocity, u_∞.

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{f_a}(t) = q_\infty \boldsymbol{A}(\bar{k})\boldsymbol{x} \quad (4)$$

$$\bar{k} = \frac{\omega c}{u_\infty} \quad (5)$$

$$\det|\lambda \boldsymbol{I} - \boldsymbol{A}| = 0 \quad (6)$$

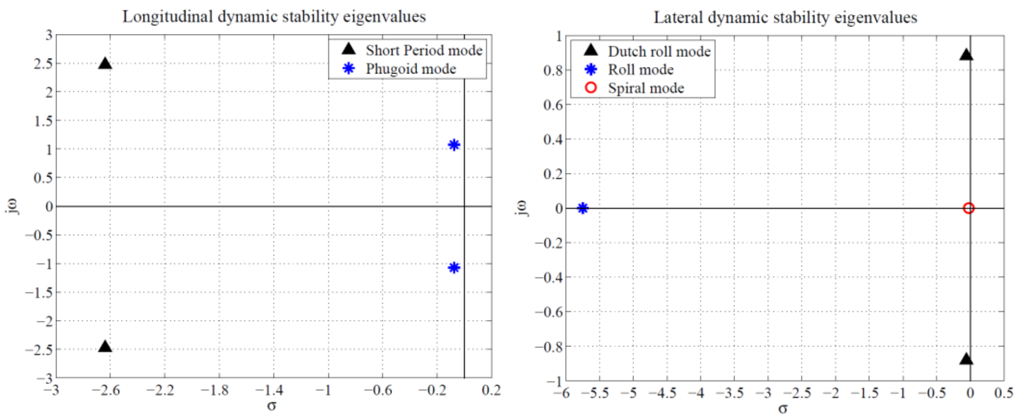


Figure 4: Dynamic stability complex conjugate eigenvalues for the BWB: **(a)** Longitudinal direction. **(b)** Lateral direction.

For the longitudinal and lateral dynamic stability modes, a set of complex conjugate eigenvalues define each motion mode. These eigenvalues are presented in the S-plane (real part in the horizontal axis and imaginary part in the vertical axis) in figure 4 and they are all stable because they all have negative real part [16]. It can be observed that the Dutch roll and spiral modes eigenvalues are very close to the vertical axis (very small negative real part) in the S-plane and, therefore, their stability will be critical.

CEASIOM provides a visualization of the assessment of these motion modes according to certification criteria from ICAO, EASA CS-23, Cooper-Harper, MIL-F-8785C, etc. The analyses in the SDSA module were performed for altitudes from 0 to 5000 m with values every 1000 m, and airspeeds from u=20 m/s to u=120 m/s with values every 20 m/s. Figure 5 illustrates the assessment of the dynamic stability of the BWB model in the following modes: short period, phugoid, Dutch roll, roll and spiral. The BWB model performs in a satisfactory way in all of them, but, as commented previously, the Dutch roll and spiral modes are the most critical ones and are in the limit to be unacceptable. This fact is due to their dependency on the rudder, which has been notably reduced in size in the optimization process.

All in all, both the static and dynamic stability characteristics of the BWB model, which are one of the major concerns, are confirmed, as well as satisfactory aerodynamic and flight performances.

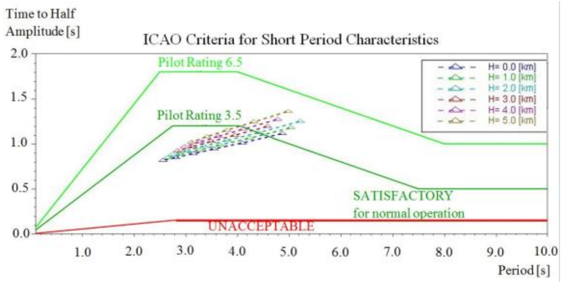
4 CONCLUSIONS

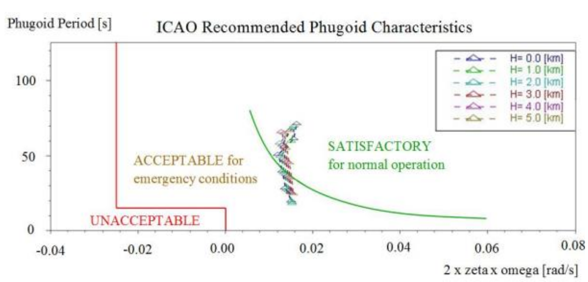
The aim of this paper was the design of a BWB baseline and the study of the optimal control surface design, regarding its aerodynamic, stability and control features. This was approached by implementing CPACS into the CEASIOM framework to obtain a new design and analysis tool for unconventional aircraft configurations. This tool was employed to design a Blended Wing Body aircraft baseline and to perform a study and an optimization process for the allocation and sizing of the control surfaces. The research conducted in this paper is the first use of these tools to design and analyze an unconventional aircraft. CPACS will be implemented in the following version of CEASIOM, enabling the study of other unconventional aircraft configurations.

The most critical aspects of the BWB configuration, its stability and control, were addressed and solved, and even a 12% reduction in the area of the baseline's control surfaces was achieved, with the consequent weight and drag reduction. The agreement between the outcomes of the different analyses used is very encouraging. Furthermore, the radar detectability was also decreased due to the 20% reduction in the winglet span, which is an interesting factor for military purposes.

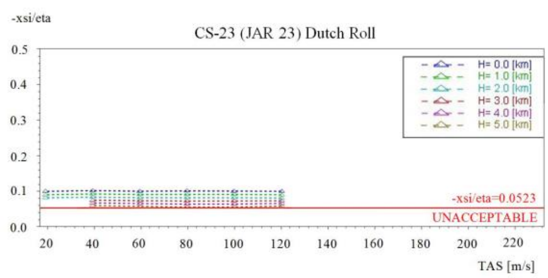
Despite the fact that references and previous experiences about the BWB concept are not abundant, nowadays several research teams are developing this idea. A broader study of the BWB model in other fields such as aeroelasticity or aeroacoustics would also be greatly interesting. Larger computational capabilities would enable higher fidelity numerical analysis and optimisation processes, with tools such as Edge or RANS, could be performed in order to get a more realistic view of the actual aerodynamic and flight performance. In addition, experimental validation with a 3D model in a wind tunnel and flight tests would be very useful and necessary for the next design steps. Future work may also include the implementation of CPACS in other computational tools to obtain a unified cross-compatible framework.

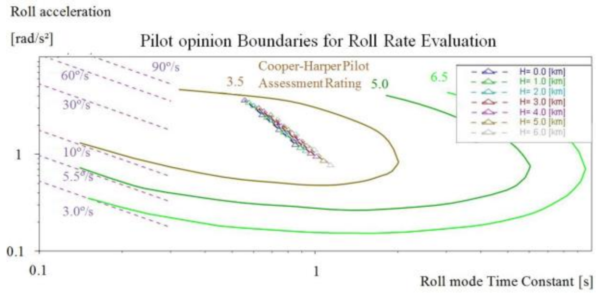
All in all, CPACS and CEASIOM have confirmed their useful potential in the aircraft design process as new improved tools and the BWB has proven to be a very promising option for solving current and future air traffic problems.



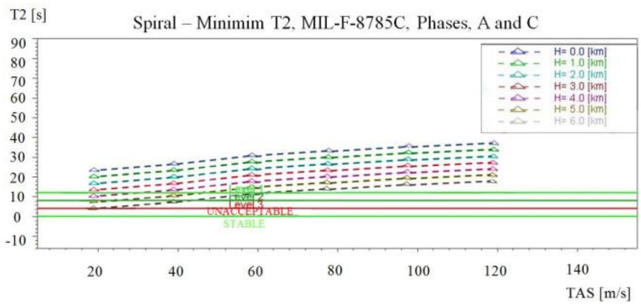


(a) **(b)**





(c) **(d)**



(e)

Figure 5: Assessment of the dynamic stability modes of the final BWB model in CEASIOM: **(a)** Short Period mode. **(b)** Phugoid mode. **(c)** Dutch roll mode. **(d)** Roll mode. **(e)** Spiral mode.

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APPENDIX A

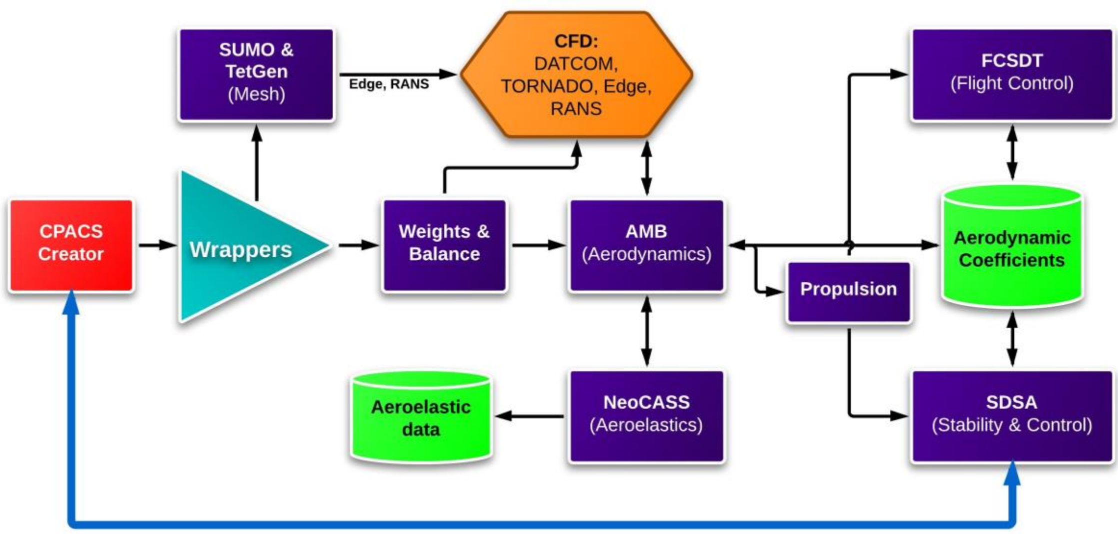

Figure 6: Flow chart of the different modules of the enhanced version of CEASIOM including CPACS as a data file language and CPACSCreator as a geometry module.

APPENDIX B

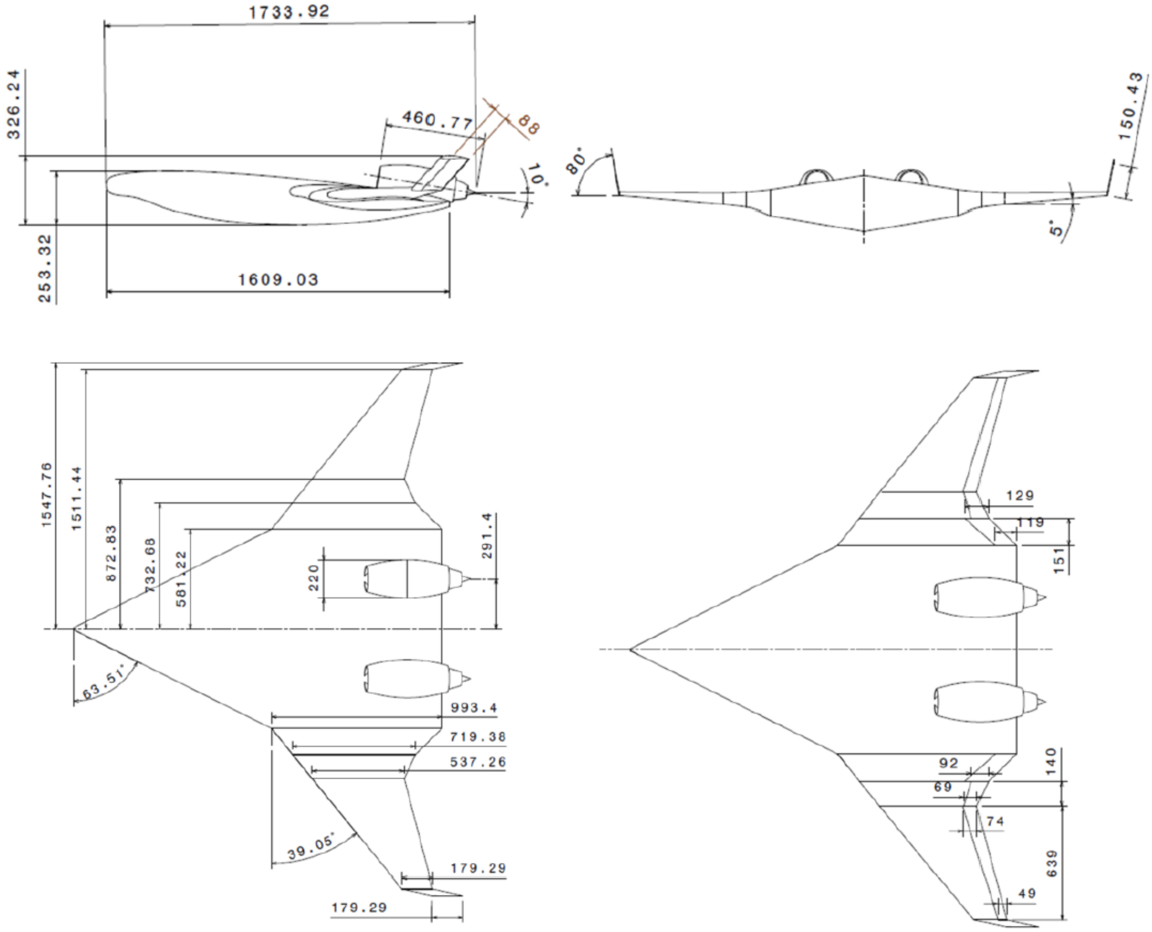

Figure 7: Final BWB model sketches, including the size and position of the control surfaces.