An Integrated Preliminary Approach Elaboration for the Analysis of a Blended Wing Body Aerostructure Concept

Mohamed Hakim(✉) and Saad Choukri

Mechanical Engineering and Energetics Research Team: Modeling and Experimentation, Mohammadia School of Engineers, Mohammed V University, Agdal, Rabat 10090, Morocco
mohamed_hakim@um5.ac.ma, choukri@emi.ac.ma

Abstract. Growing interest in UAVs applications pushed the researchers to study new conceptual designs that should meet specific requirements and aerodynamic performances. In this context, the aim of our present paper is the elaboration of a preliminary approach for a blended wing body (BWB) concept analysis and validation. For this goal, reference is made to the general aircraft design cycle and then focused on the main first phases; mainly the conceptual and the preliminary designs and their associated requirements. In this proposed approach, design tasks and tools are integrated. Our interest was then put on static longitudinal stability as an advanced requirement involved in preliminary analysis. We showed that this advanced analysis can be carried out early in the preliminary phase. Using XFLR5 software, which is a medium fidelity numerical tool for aerodynamic plane analysis, a parametric study is conducted on planform geometry and wing twist. The findings are BWB aerostructure that fit the cruise flight requirements.

Keywords: Aeronautics · UAV · Design cycle · Blended wing body · Numerical testing

1 Introduction

The use of UAVs (Unmanned Aerial Vehicle) for civil and tactical applications is gaining interest with the emergence of new aeronautical project developers [1]. We already distinguish two categories of UAVs. The first category is that of fixed-wing UAVs, where applications cover fields such as observation and surveillance, mapping, precision agriculture, and all missions requiring to cover long distances. We qualify this category; of mini UAV, where the altitude ceiling is around 5000 m with an autonomy beyond 1 h. In addition to this, there are the medium and high altitude UAVs reserved mainly for military or scientific applications. The second category is that of rotary-wing UAVs, such as multi-rotors,

Mohamed Hakim and Saad Choukri contributed equally to this work.

L. Azrar et al. (Eds.): CIP 2022, LNME, pp. 331–340, 2023.
https://doi.org/10.1007/978-3-031-23615-0_34

and is dedicated to the inspection of engineering or industrial structures and the taking of aerial photos or videos, where the range is relatively limited. This classification by type of missions leads us to adopt, during the development of mini UAVs, the design cycle of conventional aircraft with, certainly, different constraints in terms of regulations and safety, but a greater freedom of choice of new concepts; Fig. 1. For example, the absence of the pilot and passengers does not require a cockpit, nor a tubular fuselage and reduces the space management to the payload, propulsion and control modules. But, contrary to the conventional construction of light civil aircraft, freighters or airliners, where the references of comparisons exist, the "Baselines", and whose performances are known [2], the mini UAVs are characterized by a variety of quasi unique missions. In this case, the engineering of new concepts requires intensive studies and analyses, necessitating a multitude of tests and iterations. Our approach is to adopt the design cycle methodology and its deliverables, and to integrate the numerical tools adapted to the preliminary analysis. It is in this sense that we undertook this work where we based our preliminary design on the XFLR5 software, and analyzed the stability in level flight (cruise flight) for different configurations of an aerostructure with integrated fuselage.

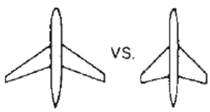
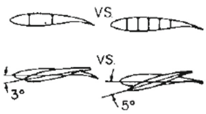
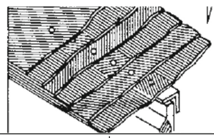
Fig. 1. Various unmanned aerial vehicles

2 Basis for a Preliminary Approach

The preliminary approach consists, in general, to validate the concept and to establish the configuration of the aerostructure responding the various requirements, such as; the mission, the dynamic and aeroelastic stability, the strength, etc.

The elaborated methodology is based on the aircraft design cycle and the different associated tasks, as presented in [2], where we integrate, Table 1, known numerical methods and adapted to each phase of the cycle [3]. For an aircraft of conventional type and mission, where many requirements are generally known or estimated from a similar reference and baselines, the validation phase of concept only concerns the application of DATCOM (Data Compendium) procedures, based on analytical methods (Lifting Line Theory; LLT) [4], for the estimation of weight or drag among others. This is not the case for UAVs where the mission requirements are unique and without aeroelastic or mass distribution similarities, for example. In this case, it is necessary to iterate on the shapes, aerodynamic profiles, mass distribution... This is not easy with the DATCOM tools, even digitized, and justifies our choice to introduce numerical tests and analysis of candidate configurations very early in the cycle. The numerical methods adopted in these simulations are mainly based on the equations of potential flows (Laplace, Glauert-Prandtl for compressibility effect) and discretized by $2D$ (VLM) or $3D$ panels [5–7]. They allow at least to capture the geometrical and functional complexity of the aircraft with a low computational cost, but with limitations inherent to the modeling assumptions. These methods cover a good part of the preliminary design with a transition to high fidelity methods, based on Navier-Stokes/finite volumes, generally used in the phase of detailed design or optimization, but require large amount of modeling efforts and high computational costs. It should be noted that this cycle also concerns structural design and its numerical tools, from beam theory to non-linear finite elements, but they are not concerned in our present application.

Table 1. Major design phases and methodologies in UAV development

		Phase 1 Conceptual design	Phase II Preliminary design	PHASE III Detail design
	Known	Basic mission requirements Range Altitude Speed Basic material properties	Aeroelastic requirements Fatigue requirements Flutter requirements Overall strength requirements	Local strength requirements Producibility Functional requirements
Numerical testes	Candidate configuration			
	Analysis	DATCOM Lifting line VLM 2D 3D panels	DLM RANS	URANS FEM
	Results	Geometry and design objectives : Airfoil type Drag level AR Weight goals λ Coast goals	Basic internal arrangement Complete external configuration Local flow problems solver	Detail design Joints, fitting, attachments Design refinements as results of test and operation

3 Application to the Blended Wing Body

3.1 Definition

As shown in Fig. 1, the fuselage is integrated in the wing for the Parrot, AgEagle and ATyges UAVs, this configuration called the Blended Wing Body [8–10]. This concept was developed to encounter various economic and environmental constraints. In fact, it offers a reduction in structural weight, drag with a higher lift-to-drag ratio and therefore a decrease in fuel consumption compared to the existing generation. Also, a notable reduction in greenhouse gas emissions and noise as well as an increase in carrying capacity. On the other way, there're also some disadvantages for the BWB, one of them is the lack of the traditional horizontal tail and vertical fin which lead to a difficulty in longitudinal control and stability [11,12] subsection. The longitudinal stability is discussed in Sect. 3.2.

In this study, we are interested in the mini UAV which Davis and McMaster had classified them in their works [13–15]. We can see clearly from their classifications that mini UAVs had mass (aerostructure + payload) values of 10–100 kg, flight speed of 10–100 m/s, wingspan < 10 m, with flight altitudes up to 5000 m and Reynolds number around 10^5. The latter has been studied in previous works [15,16], which showed that the performance of most conventional airfoils decreases significantly at this critical Reynolds number range. Thus, the determination of an aerodynamic airfoil that circumvents this constraint is essential, which is the subject of our study [17], where from thirty-two airfoils existing in the literature we were able to select five. Among these, the NACA63(3) - 018 airfoil was chosen for the comparison between the configurations developed in the following. Those configurations will have a maximum speed of $V_{max} < 35$ m/s, a dimension of $3 * 2$ m^2 and a maximum weight of 15 kg evaluated by a study on the structure.

3.2 Longitudinal Stability and Cruise Flight

The longitudinal stability is the quality that stabilizes an aircraft about its lateral axis. It involves the pitching motion as the nose of the aircraft rises and falls in flight. In analyzing stability, it is important to remember that a body that is free to rotate will always rotate about its center of gravity. To achieve the static longitudinal stability, the wing moment must be such that, if the airplane is suddenly pitched up, the wing moment will change so that will provide unbalanced but restorative moment which, in turn, will bring the nose down. Likewise, if the aircraft nose drops, the resulting change in moment will bring the nose up Fig. 2. Equation 1 that describes the static longitudinal stability of wing only is defined as:

$$C_{m_{cg}} = C_{m_{ac}} + C_{L_0}\left(\frac{x_{cg}}{\bar{c}} - \frac{x_{ac}}{\bar{c}}\right) + C_{L_\alpha}\left(\frac{x_{cg}}{\bar{c}} - \frac{x_{ac}}{\bar{c}}\right)\alpha \tag{1}$$

So for the BWB to be statically stable, Fig. 2 give us the idea that the aerodynamic center must be aft of the center of gravity and the restorative moment must counteract the disturbance which leads to $C_{m_\alpha} = C_{L_\alpha}\left(\frac{x_{cg}}{\bar{c}} - \frac{x_{ac}}{\bar{c}}\right) < 0$ and $C_{m_0} = C_{m_{ac}} + C_{L_0}\left(\frac{x_{cg}}{\bar{c}} - \frac{x_{ac}}{\bar{c}}\right) \geq 0$. Where $C_{m_{cg}}$, $C_{m_{ac}}$,C_{L_0}, C_{L_α}, x_{cg}, x_{ac}, α and $\bar{c}$ are respectively the pitching moment coefficient at center of gravity, the pitching moment coefficient at aerodynamic center, lift coefficient at zero angle of attack, the lift curve slope, position of gravity center, position of the aerodynamic center (neutral point), angle of attack and the mean chord.

3.3 Numerical Testing Tool: XFLR5

XFLR5 [18] is an open-source software that couples the $2D$ airfoil analysis of XFOIL [19] with a $3D$ solver to simulate the performance of an aircraft configuration at any time during the design process. It includes:

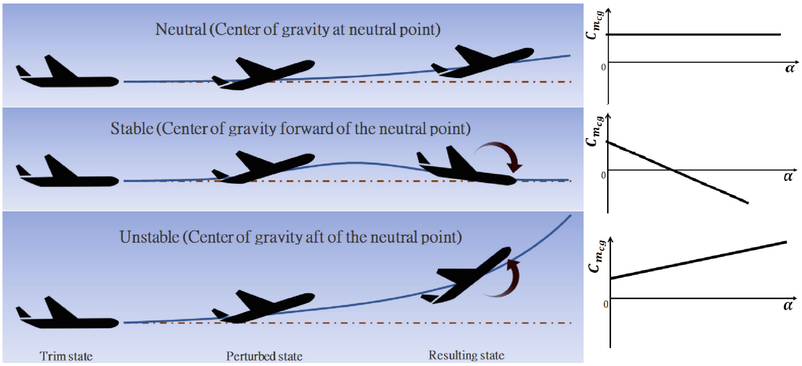


Fig. 2. Pitching moment coefficient $C_{m_{cg}}$ versus angle of attack α for different center of gravity positions

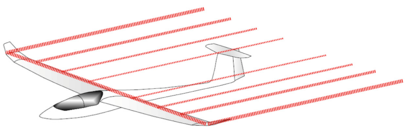
- XFOIL which is an interactive program for the design and analysis of subsonic isolated airfoils. The XFOIL code is a combination of a panel method and an integral boundary layer formulation for analyzing the potential flow around airfoils. The code was developed to quickly predict airfoil performance at low Reynolds numbers and its convergence is achieved by iterating between outer and inner flow solutions on the boundary layer displacement over the thickness of the boundary layer displacement. Thus, the XFOIL code calculates the viscous pressure distribution and captures the influence of limited trailing edge separation and laminar separation bubbles. It had shown an excellent result comparing to other tools [20,21].
- Wing design and related analysis based on tree numerical methods, Fig. 3, the non linear Lifting Line Theory (LLT), the Vortex Lattice Method (VLM), and a 3D Panel Method.

The XFLR5 software is intensively used [22,23], and thus has been verified and validated within the potential methods validity. In our case of flying wing where the wing is everything, the software is suitable for our intended use to get trends, and to understand sensitivity to design parameters. It is also noted that increasing panel density may overcomes some limitations of constant strength singularities giving reliable results.

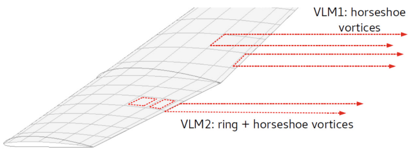
3.4 Design and Solution Validation Process

Many requirements are involved in the preliminary design. These are fulfilled by evaluating corresponding performance. Some of the important requirements are of flight stability concern. This may be the case of the basics as take off, landing, level flight, turn manoeuvre... Every one of these should follow a requirement fitting process as described in Fig. 4. In this study, our primary requirement, is cruise flight or trimmed level flight.

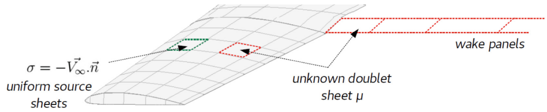
Three candidate configurations, Fig. 5, had been developed and discussed in terms of performances and stability, Fig. 6, to select the best configuration for



(a) Lifting line horshoe



(b) VLM panels



(c) 3D panel

Fig. 3. Numerical methods in XFLR5

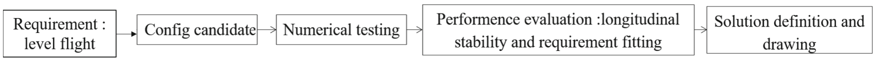
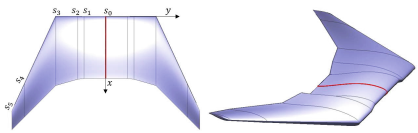
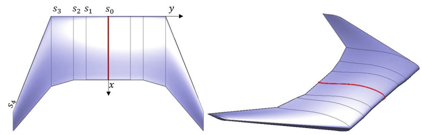


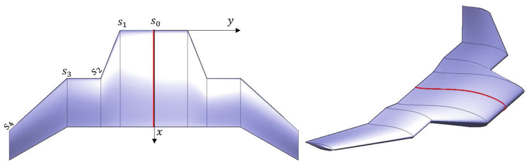
Fig. 4. Requirement fitting process



(a) Configuration 1 ($-4° <$ twist $< 10°$)



(b) Configuration 2 ($0° <$ twist $< 4°$)



(c) Configuration 3 ($0° <$ twist $< 4°$)

Fig. 5. The candidate configurations

our requirements. The main geometric parameters of those configurations are listed in Table 2.

The first (initial) configuration for the mini UAV BWB, Fig. 5a, was developed taking into account the requirements mentioned in Sect. 3.1. The surface of the wing and its geometry are determined in order to produce a sufficient lift in cruising flight (at zero angle of attack), to have a sufficient volume for storing all the payload and to make the aerostructure stable. It's noticed on Fig. 6a and b that the aerostructure respects the requirement of mission speed for the level flight and that the maximum lift to drag ratio is at 4°. Meanwhile, Fig. 6c shows

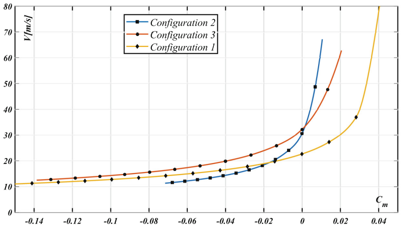
Table 2. Geometric parameters of all configurations

	Section	Chord (m)	y position (m)	x position (m)	x_{np}
Configuration 1	S_0	1 m	0	0	0.5 m
	S_1	1	0.35	0	
	S_2	1	0.45	0	
	S_3	1.1	0.8	0	
	S_4	0.528	1.3	1.072	
	S_5	0.3	1.5	1.5	
Configuration 2	S_0	1	0	0	0.445
	S_1	1	0.35	0	
	S_2	1	0.55	0	
	S_3	1.1	0.9	0	
	S_4	0.3	1.5	1.5	
Configuration 3	S_0	1	0	0	0.568
	S_1	1	0.35	0	
	S_2	1	0.55	0.5	
	S_3	1.1	0.9	0.5	
	S_4	0.3	1.5	1.041	

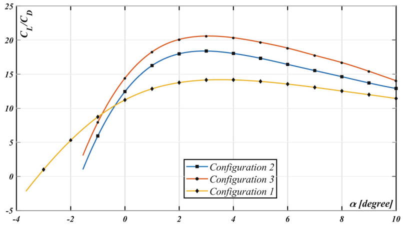
that the aerostructure verifies the criteria of the longitudinal stability (Sect. 3.2). We note that $x_{cg} = 0.258\,\text{m}$.

In order to have more freedom for maneuvering in flight, the aerostructure twist had to be reduced to the minimum possible while increasing the lift to drag ratio in level flight. For this purpose, the configuration 2, Fig. 5b, has been developed in order to take into account the above modifications. The comparison between the polars of the configuration 2 and the initial one shows that the speed for the cruising flight has increased due to the decrease of the twist, unlike the lift to drag ratio which has been improved, $|C_{m_\alpha}|$ has decreased and $x_{cg} = 0.335\,\text{m}$ has been shifted backwards whereas x_{np} has been pushed forward. So according to these results, we have succeeded to increase the lift to drag ratio for the cruise flight but at the same time speed and stability were affected.

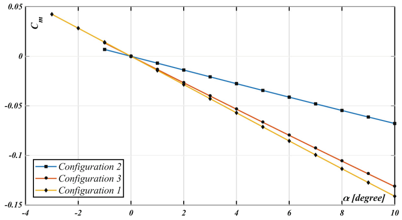
To overcome the disadvantages of the configuration 2, a third one is set up, Fig. 5c, which is based on the achievement of a compromise between the highest lift/drag ratio for the cruise flight and the most aft position that is possible for the neutral point. We can see clearly that the performance is better at the level flight despite the increase in speed and that the stability has been improved with a more static margin ($x_{cg} = 0.430\,\text{m}$ and $x_{np} = 0.568\,\text{m}$).



(a) Speed versus pitching moment coefficient



(b) Lift to drag ratio versus angle of attack



(c) Pitching moment coefficient versus angle of attack

Fig. 6. Polars of the candidate configurations

4 Conclusion

In this work, we were interested in the aerodynamic design study of a mini UAV BWB. An initial design was developed to satisfy the requirements and then improved its aerodynamics and longitudinal stability based on a numerical testing. Graphs and tables are used to show the progression of the configurations that have been developed based on wing sections positions (sweep) and twist variations. The proposed approach has proved to be useful in design tasks, definitions and scheduling, and in performance evaluation efficiency. The resulting configuration is not an optimized design by any means but may constitute a good starting design for more advanced optimization of the external layout using a multidisciplinary optimization approach, and calculation of stability derivatives could be very useful in refining the stability and control characteristics of the UAV.

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