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AERODYNAMIC INTERFERENCE OF WINGTIP AND WING DEVICES ON BWB MODEL

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Abstract

*This work presents a computational analysis of the behavior of different devices coupled on a non-conventional configuration model called the Blended Wing Body (**BWB**). Two wingtip devices (winglet and C-wing) and two wing devices (fence and gurney flap) were analyzed in order to recognize both their properties and their interference on the pattern of the fluid over the model. During the evolution of aircraft many devices have been studied and implemented in conventional airplanes. These devices have several advantages, such as improving aerodynamic efficiency and reducing induced drag, which in turn produce positive effects on aircraft performance. On the other hand, the BWB could offer better aerodynamic characteristics than a conventional aircraft. The simulations for the different configurations were carried out to get the aerodynamic characteristics of the BWB model. The results show that adding devices to the BWB could improve the aircraft performance as well as the aerodynamic efficiency, decreasing the drag coefficient at higher angles of attack.*

1 Introduction

The Blended Wing Body (**BWB**) is an aeronautical concept, where the fuselage, wings, tail and engines are smoothly integrated as one single body which could resemble the flying wing concept [1]. The **BWB** was proposed as a potential solution to the environmental restrictions at the airports and the market economy, where alternatives have been sought to develop an aircraft that generate lower operating costs, lower ecological climatic and acoustic impacts [2]. Furthermore, different studies have showed that non-conventional configurations, as **BWB** [3, 4] or Box wing [5, 6] could have aerodynamic efficiency than a conventional aircraft.

Technological advances and new materials have made viable the possibility of implementing and operating this sort of aircraft for civil transport in the near future. Being so, the different areas of aeronautical engineering are committed to developing and optimizing of the **BWB** configuration.

On the other hand, the noise emission has been reduced more than 20 dB for current jet aircraft, through the implementation of the turbofan engine with high by pass ratio [7], there have been no important reductions in noise emission in the last two decades [8]. The conventional configuration is approaching a limit in terms of productivity and performance characteristics. As a result, different studies are in development to find alternatives that allow for be more efficient, lucrative and better aircraft, meeting the environmental requirements [17].

Several devices can improve the aerodynamic efficiency when installed on conventional wings. Wing-tip devices make use of the flow generated in that region to develop an additional thrust force. Other interpretations are that, vortexs strength decreased or that the wing has an increase in the effective span [10, 11].For some particular wings, it is used to avoid or restrict the presence of cross flow on the surface wing. This is a typical pattern of flow that can be observed for sweep wings. Also, some small passive devices, called Gurney Flaps which are located at the trailing edge of the wing, can aid in the increase of lift without heavier penalties in regards to weight and maintenance.

Ceron and Catalano [2, 12] have carried out experimental studies about the interference of power plant over a **BWB** model. Although the **BWB** presented good aerodynamic behavior at low angles of attack, less than 8^o, the existence of flow cross and detachment at higher angles was observed. Although this phenomenon can be overcome through a new wing design, the use of some conventional devices was studied. The devices analyzed were: Winglets, C-Wing, Fences and Gurney Flap. Even though there is an extensive literature about these devices, this work aims at studying their influence in order to see potential benefits on the **BWB** configuration.

2 The Blended Wing Body

2.1 The BWB configuration

The **BWB** configuration promises to reduce aircraft fuel consumption and lower pollution [13], for this reason, in the last years the **BWB** has attracted great interest of the aviation industry, government and researchers [14, 15, 16]. The elimination of high-lift systems and the placement of the power plant airframe over the upper surface of the lifting body, is classified as a low noise setup for large transport aircraft [17]. The Tailless aircraft has advantages compared to the conventional configuration. The cargo and passengers can be transported inside a spacious structure with a wing shape. The elimination of the stabilizers reduces the weight of the aircraft, generating less drag and greater maneuverability. In the first **BWBś** these advantages, was practically annulled by a longitudinal and lateral instability of the aircraft.

Liebeck et al.[18] compared a conventional wing-fuselage configuration with the **BWB**. It had an aerodynamic efficiency $L/D = 27.2$, 32% higher than the conventional configuration. The TOGW and OEW ware 14% and 10% lower respectively. Liebeck [6] makes a brief historical review of the aircraft evolution until the **BWB** and the **BWB**-450, with the capacity of 468 passengers and a range of 7750 miles and compares it with similar conventional aircraft requirements, as the B747, the A340 and the A380. Kehayas [19] concluded that the conventional configuration would be better than the **BWB**, but he warns that the possible technological advances were not evaluated.

2.2 The geometry of the BWB model

The **BWB** model is composed of a central lifting section and two tapered and swept wings that provide a smooth combination of the elements that compose it. Adopting the proportions suggested by Qin et al. [20], the model consists of the following sections:

- A thick streamlined central body: 0 to 0.21 m (hypothetical payload).
- A pair of inner wings: 0.21 m to 0.38m (hypothetical fuel tanks).
- An outer wing: 0.38 m to 0.64 m.

The leading edge sweep angles are sweep back 56^o at the central body and 38^o at the outer wing. The aspect ratio of the model is $AR = 6.68$ and the wetted area ratio is $S_w/A_{ref} = 3.06$. The aspect ratio and the mean chord, taken as reference for the aerodynamic coefficients, are $A_{ref} = 0.23\ m^2$ and $c_{ref} = 0.20\ m$. The central body of the aircraft is defined by five airfoils sections from the plane of symmetry of the aircraft, moving spanwise, located at: $y/b = 0$; 0.32; 0.64; 0.125 e 0.17 respectively.

Two factors were relevant to the choice of airfoils: thickness and the aerodynamic performance at low Reynolds numbers. Eppler airfoils were chosen with a thickness distribution similar to that of Quin N. et al [20]. An isometric view is shown in Fig. 1. more detailed information is available in Ceron-Muñoz and Catalano [2, 12].

2.3 Wing-tip devices: Winglet and C-wing

The Winglets were developed in the last decades and aim the reduction of induced drag. There are different types of Winglets which have been

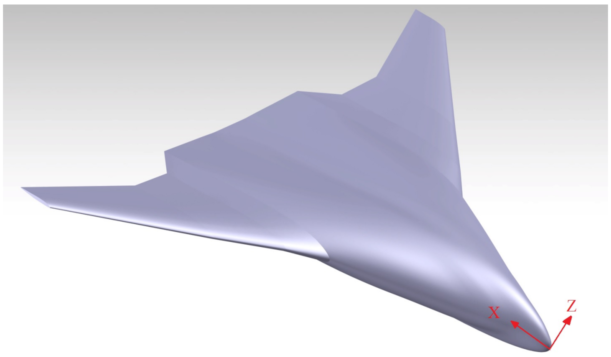

Fig. 1 Isometric view of **BWB** model

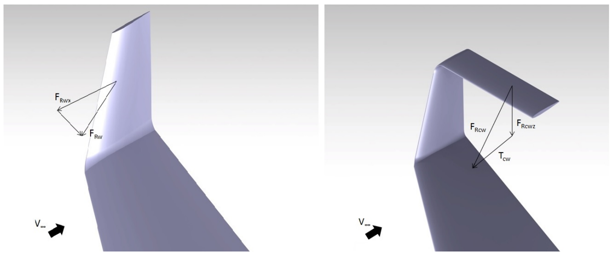

Fig. 2 Winglet (a) and C-winglet (b)

used in a wide range of aircraft [21]. At the first glance, the working principle of these devices is not so complex. The Winglet takes advantage of the flow existent around the wingtip. In short, there will be an resultant aerodynamic force which will have a component in the flight direction that, with the appropriate design could result in drag reduction [22, 23, 24].

In the current case, both the Winglet profile and its chord were the same used in the wingtip as an extension of the external wing. The cant and sweep angles were 72^o and 37^o respectively, $c_{rw}/c_{tw} = 0.55$, and 0.627 m of semi-span. Finally, the twist in the Winglet root is 2.2^0 (outward), and the twist of the Winglet tip is 1^o (inward). In this way, an effective angle of attack of 4^0 is expected along the Winglet span.

Regarding the c-wing, an horizontal surface is added to the Winglet. In the wing tip vortex, there will be the respective downwash above the upper surface of the wing therefore, the airfoil is set conveniently in order to get a resultant force with a horizontal component in the flight direction, (see Fig.2(b)). The profile used in the horizontal surface was a NACA 0012 with a twist angle of 2^o (downward) and 11 cm in span. Different studies have shown that the C-wing device could decrease the induced drag like the closed-wing system, consequently, this concept could reduce fuel consumption and gas emissions of the aircraft [25].

2.4 Gurney flap and fences

The Gurney flap (**GF**) is a flat plate that is located along section of the wing span and it is placed at the trailing edge. The GF width is around $1\% - 3\%$ of the wing chord and it is set with affixed forming a right angle with respect to the chord line [26, 27]. In the beginning, the **GF** was used to increase the downforce in race cars. However, Liebeck [28] suggested that if the **GF** worked in cars, it should be capable of enhancing the lift generated by conventional wings.

The **GF** studied is 25.4 cm long with 0.4 cm at the internal chord and 0.2 cm at the external chord. **GF** thickness is 0.5 mm. Following the recommendation of Lance W.T[27], the **GF** was set with an inclination of 45^o. A **GF** sketch is shown in Fig 3 (a).

Other device used in this study was the fence or “Boundary Layer Fence”, which is a flat plate attached perpendicularly on the wing surface in the chordwise direction. The fence produces an interaction of the several factors working together in order to increase lift at high angles of attack. When the cross flow, on the upper surface of the wing, is decelerated by the incidence of the fences, the load over the wingtip is reduced and the boundary layer separation is delayed.

Care should be taken regarding to the height of the fences. If the height is less than the boundary layer thickness, there will be no effects, however if the fence is too high, the device could not be an efficient alternative. Finally, in order to increase the effectiveness, the fences continue around the leading edge and are extended on the lower wing surface. In this work, the use of three fences with $0.3c$ on the lower surface and $0.75c$ on upper surface is proposed. Each fence has 0.5

cm in height and 1 mm of thickness. The spacing was of 11.6 cm $Sf/s \approx 0.18$. The Fences are shown in Fig.3(b).

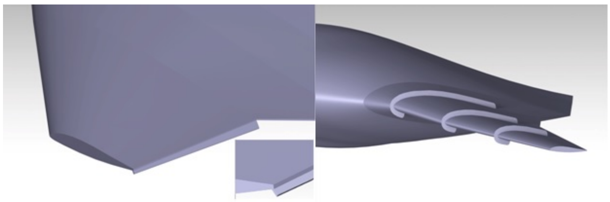

Fig. 3 Gurney flap (a) and (b) Fences

3 Methodology

3.1 Computational Domain

The computational domain was $3m\,x\,7m\,x\,1.3m$. There is an oval subdomain where the model was located. This subdomain was used for mesh refinement in order to get more accurate results. The computational domain used can be seen in Fig. 4.

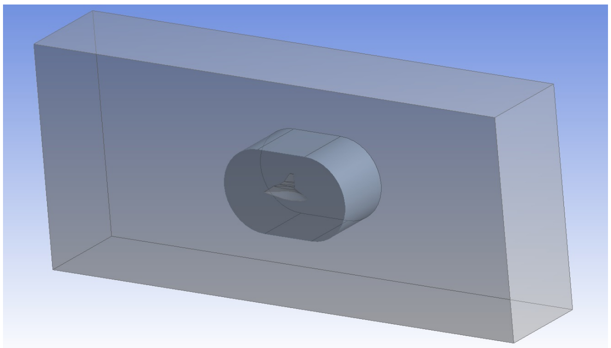

Fig. 4 Computational Domain with **BWB**

All simulations were performed with the ISA (International Standard Atmosphere) parameters at sea level. The variation of angle of attack was of -4^o to 20^o at Reynolds number of $3.9x10^5$. The SST (Shear Stress Transport) turbulence model was chosen [29, 30].

3.2 Grid Generation

In CFD analysis the computational domain is discretized both in space and time through of nodes and elements where the appropriate equations are solved. To achieve an accurate solution, a grid independence analysis was carried out. In Fig.5 the grid independence analysis for the clean model is shown. The convergence criteria chosen for this case was 0.001 N and this value was achieved for the clean model with $5x10^6$ nodes.

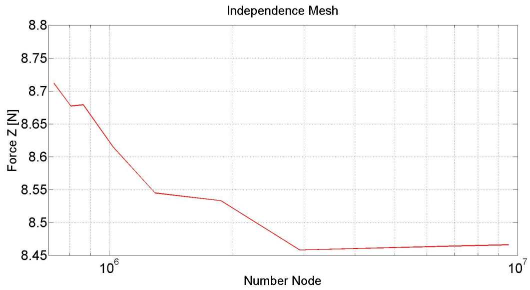

Fig. 5 Analysis of mesh independence

The grid was generated using an unstructured mesh (tetrahedral). The different values for each model are shown in Table 1. The variations of the values are due to additions of the new surfaces of the devices analyzed.The mesh generated for each device used is shown in Fig.6. Only half of the model was analyzed.

Table 1 Element and Node number for the models

Model	Elements Numb.	Nodes Numb.
Clean	5088111	7014523
Gurney Flap	5495523	7585763
Fence	5326826	7336902
Winglet	6740283	9275393
C-wing	6284088	8668683

3.3 Convergence Criteria

The residuals, imbalances and forces were monitored as solution convergence targets. The convergence history, for clean model at 0^o attack angle and steady flow, is shown in Fig.7.

The maximum residue, which is better that Root Mean Square [29], the target level was set at $1e^{-5}$. The maximum iteration number that was used for analysis was 350 for all models. A target imbalance for the conservation equations was set at 1%. In this case, the solvers only stop before the maximum number of iterations if the residual criteria and global balances are met.

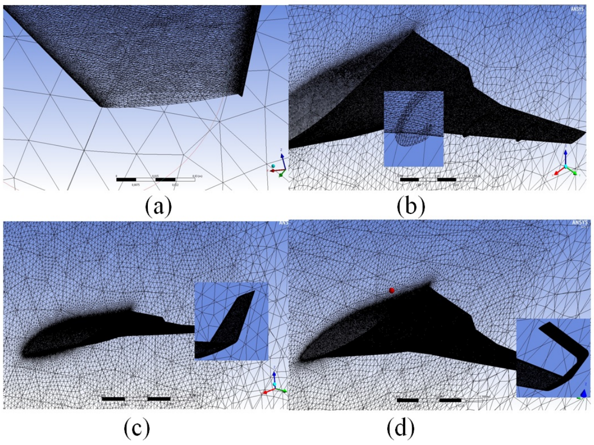

Fig. 6 Grids for devices: Gurney Flap (a), Fence(b), winglet (c), C-wing (d)

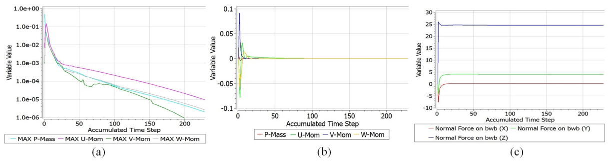

Fig. 7 Residual (a), Imbalance(b), Monitoring forces(c)

4 Results

In this section the curves of drag and lift coefficients are presented. These values were obtained from the simulation results in ANSYS®.

4.1 Lift coefficient

The curve of Lift coefficient (C_L) is shown in the Fig.8. All models show the same trend, but the effect of **GF** considerably higher. The $C_{L_{max}}$ for **GF** was 1.17, while than the $C_{L_{max}}$ for all other devices was 1.05 on average.

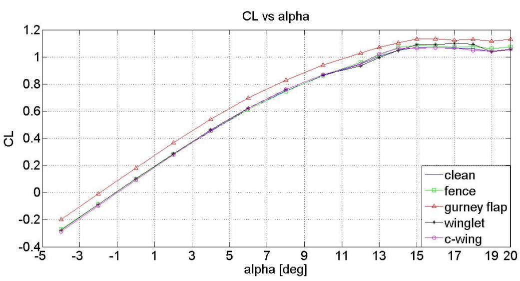

Fig. 8 $C_L x \alpha$

All other devices have the same behavior up to an angle of attack of 12^o. The Winglet produced a $C_{L_{max}} = 1.1$.

There is an alteration in slope for all the curves from $\alpha = 8^?$ to $\alpha = 12^?$, due to flow separation, which occurs on the external wing as shown in Fig.9. This happens in all models in this range of angles of attack. Nevertheless, it can be observed that the central body still maintains an attached flow and continues to produce lift for the whole aircraft.

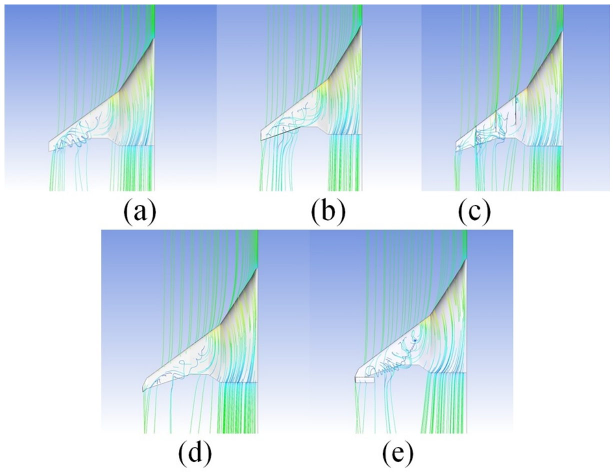

Fig. 9 Streamlines: Cleam (a), Gurney(b), Fence(c), Winglet(d) and C-wing (d)

4.2 Drag coefficient

The variation of drag coefficient (C_D) versus angle of attack (α) is shown in Fig.10. All curves show a approximated value of C_D of around 0.05 from -4^o until 9^0. The **GF** presents a significant increase in the lift coefficient, however it has a considerable increase in drag in comparison with the others configurations. This is in agreement with Liebeck [14], who concluded that flaps with height of more than $0.02c$ will significantly increase the drag. On the other hand the C-wing showed the lower drag coefficients.

4.3 Drag Polar

The drag polar curves can be seen in the Fig.11. It can be observed that the **GF** has larger C_L, with lower values of C_D for $C_L > 0.6$. The other devices had a similar behavior.

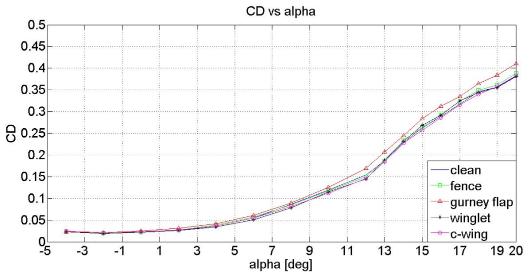

Fig. 10 $C_L x \alpha$

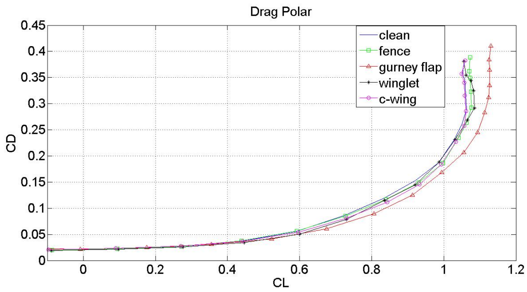

Fig. 11 Polar drag curves

4.4 Lift-to-Drag Ratio

The Lift to Drag ratio curves are presented in the Fig.12. It is shown that **BWB** configuration with Winglet has maximum efficiency at 6^o ($C_L/C_D = 13.5$), while for the **GF** the maximum efficiency is achieved at 4^o ($C_L/C_D = 13.$). Until $\alpha = 4^o$, the **GF** presents better aerodynamic efficiency than the other configurations, which have similar behavior up to this angle of attack. From $\alpha = 4^o$ on,the Winglet is more efficient until $\alpha = 13^o$. For higher angles all configurations showed identical tendency.

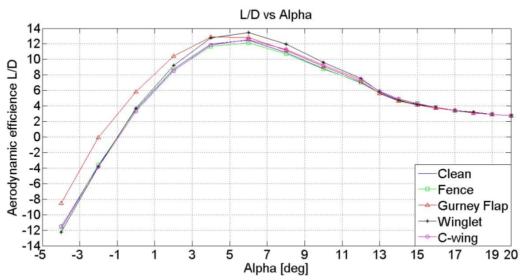

Fig. 12 Aerodynamic Efficiency

5 Conclusions

The BWB is a promising nonconventional configuration that aims at increasing the payload, as well as decreasing the fuel consumption, and could be considered as an alternative more ecologically correct.

The twist of the external wings of the **BWB** was not satisfactory, for this reason, this work was aimed in order to study, numerically , the interference of the Winglet, C-wing, Gurney flap and Fences devices in the current model.

Regarding the wingtip devices, the c-wing showed lower drag coefficient. Nevertheless the Winglet presented greater aerodynamic efficiency. For this specific wing, the fences were not an appropriate solution to the cross flow presence. On other hand, the Gurney flaps modified lightly the camber on the trailing edge of the wing. In this way both lift and drag coefficients were increased. Finally, Experimental analysis must be carried out in wind tunnel to compare the present computational results.

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