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Influence of Winglets Design Parameters on Aerodynamic and Stability of a Blended Wing-Body Aircraft

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Abstract. The Blended Wing Body (BWB) aircraft is a non-conventional aerodynamic configuration that merges the fuselage and wings into a seamless structure, offering significant advantages in fuel efficiency, payload capacity, and aerodynamic efficiency. However, the absence of conventional tail units introduces aerodynamic and stability challenges that require careful design optimization. This study investigates the aerodynamic and static stability characteristics of a baseline BWB design from the European Distributed Multi-Disciplinary Design and Optimization (EU MOB) project. The analysis is performed using a mid-fidelity numerical tool based on the vortex lattice method, incorporating geometric and mass properties from previous studies. Aerodynamic curves and static stability derivatives are evaluated across a specific flight regime and compared with existing literature verifying the suitability of the used tool for preliminary aerodynamic and stability assessments. Subsequently, a parametric study is conducted to assess the effects of varying winglet design parameters, including height, sweep, cant, and toe angles, on aerodynamic efficiency and static stability characteristics. The results demonstrate that optimized winglet configurations can enhance lift-to-drag ratio and improve static stability characteristics without significantly increasing drag. These findings provide valuable insights into the role of winglets in improving BWB aircraft performance and contribute to the optimization of next-generation aerodynamic designs.

1. Introduction

The Blended Wing Body (BWB) configuration integrates the fuselage with the wing, eliminating the need for a tail by Replacing the well-known tube configuration for fuselage by large chord and high thickness to chord ratio airfoil, Inboard Wing. It used to obtain its privilege as a lift producer part and the same role as the fuselage. This smooth blending creates a wide, flat fuselage that contributes significantly to lift generation. Research indicates that the BWB design can substantially reduce fuel consumption, leading to lower operational costs. Additionally, its aerodynamic efficiency is enhanced by minimizing drag, allowing the entire aircraft to generate lift more effectively, which improves both fuel economy and range. By removing the tail and transforming the structure into a unified lifting body, the wetted area-to-volume ratio decreases, resulting in reduced interference drag. The BWB layout also offers environmental benefits and

unique safety advantages. Positioning the engines above the wing helps mitigate engine noise by preventing interaction with the lower wing surface, leading to a lower acoustic signature.
Despite its advantages, the BWB design presents certain challenges. One major concern is stability and control, primarily due to the absence of a tail and the aircraft's unconventional shape. Proper design and placement of control surfaces are critical to ensuring manoeuvrability. Furthermore, since the BWB merges the fuselage and wing, defining a central structural framework becomes complex.

Therefore, careful optimization of the fuselage section is essential to meet both aerodynamic and structural requirements [12]. it is a tailless aircraft design that seamlessly merges the wings and fuselage. Unlike conventional tube-and-wing configurations, BWBs eliminate the distinct separation between the fuselage and wings, resulting in a more aerodynamically efficient shape. Originally conceptualized in the late 20th century, the BWB was developed as a promising platform for high-speed subsonic commercial airliners [1,2,3]. In general, the Blended Wing Body (BWB) design features a central section (Center body or fuselage) and an outer section (wing). The transition between these two is the blending area, where the Center body seamlessly merges with the wing structure (Fig.1) [1].

The Blended Wing Body (BWB) concept has been in the design field for a long time. Northrop first introduced a BWB-like design in 1947, developing an all-wing aircraft shape. In 1965, Lee explored the potential cost reductions associated with an all-wing aircraft. By the late 1980s, NASA Langley advanced the development of subsonic transport designs, envisioning an aircraft capable of carrying 800 passengers over a 7,000 nautical mile range at a cruise speed of Mach 0.85. However, none of these configurations progressed beyond the design stage due to various challenges. In the early 2000s, Russian designers Bolsunovsky et al. integrated research on BWB aerodynamic configurations and structural concepts to align with FAR-25 regulations. Comparisons with conventional aircraft designs confirmed BWB's advantages. In 2004, Liebeck et al. proposed a BWB subsonic transport concept and documented its technical development. Later, Roman et al. analyzed the aerodynamics of high-subsonic BWB configurations, concluding that a cruise speed of Mach 0.93 resulted in performance penalties compared to Mach 0.85. As the cruise Mach number increased, the lift-to-drag ratio (L/D) decreased, making the design less feasible. Also in 2004, Qin et al. evaluated the aerodynamic performance of BWB aircraft, optimizing three-dimensional aerodynamic surfaces for various configurations and improving performance at cruise conditions [7].

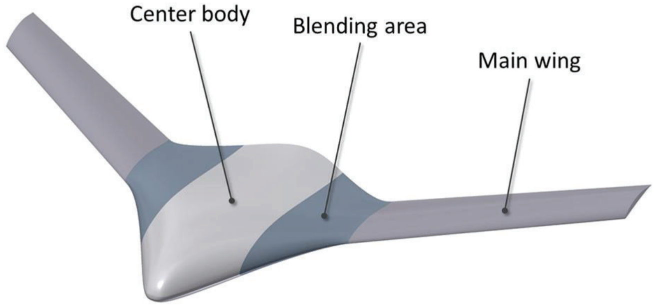

Figure 1. BWB Concept [1]

In recent decades, there has been considerable interest in enhancing the performance of transport aircraft. Unconventional designs, like the Blended Wing Body (BWB), are expected to significantly improve efficiency in civil aviation [4]. One of the key advantages of the BWB configuration is its aerodynamic efficiency [12]. The smooth transition between the Center body (fuselage) and the outer wing sections reduces drag, leading to a higher lift-to-drag ratio compared to traditional aircraft [14]. This efficiency translates into lower fuel consumption, reduced carbon emissions, and improved range and payload capacity [5]. Additionally, the wide-body design allows for flexible internal layouts, making it well-suited for both passenger and cargo transport [13].

Despite these advantages, the BWB design presents several challenges, particularly in terms of aerodynamics and stability. The absence of a conventional tail unit, which in traditional aircraft provides essential pitch and yaw stability, makes it difficult to achieve natural static stability [15]. Without a horizontal stabilizer, BWB aircraft must rely on carefully designed aerodynamic shaping and advanced flight control systems to ensure pitch stability and trim control. Similarly, the lack of a vertical tail compromises yaw stability, increasing susceptibility to Dutch roll and adverse yaw. Additionally, the integration of control surfaces such as elevons and rudder split surfaces becomes more complex, requiring sophisticated flight control systems to compensate for the missing tail [6]. Another challenge in BWB aircraft design is cabin pressurization.

Conventional cylindrical fuselages are structurally optimized to withstand internal pressurization, whereas the wide, blended structure of a BWB may require reinforced structures to maintain passenger safety. Furthermore, winglet design plays a crucial role in stability and efficiency, as variations in cant angle, sweep, and height can significantly affect aerodynamic performance.

This study aims to analyse the aerodynamic and stability characteristics of a baseline BWB configuration (for the EU MOB project [9]), evaluating its behaviour across different flight conditions. Furthermore, a parametric study will investigate the influence of winglet design parameters on aerodynamic efficiency and stability, offering insights into optimizing BWB performance.

The following sections provide description of the selected BWB case-study aircraft, including its geometric and mass properties. Subsequently, an aerodynamic and stability assessment is conducted using numerical simulation tools to evaluate key performance metrics such as lift, drag, and stability derivatives. To further understand the impact of design modifications, a sensitivity analysis is performed on various winglet parameters, including cant angle, sweep angle, and height, to assess their influence on aerodynamic efficiency and stability.

2. Description of the BWB Case-Study

Due to data availability, the selected case-study aircraft is the baseline BWB design (EU MOB) project. The following subsections introduce its geometric properties, mass and inertia properties, and the airfoil for different sections of the aircraft, which are essential for evaluating its aerodynamic behaviour and static stability characteristics.

2.1 Geometric Properties

The BWB aircraft in this study consists of a central body, inner wing, and outer wing with an attached winglet, all seamlessly blended to form the integrated BWB structure. Based on the figures given in [10, 11] and the available limited data, the three-view drawing of the aircraft is reproduced to obtain all necessary geometric characteristics of the case-study aircraft as shown in Figure 2. A summary of the most important geometric properties of the aircraft is presented in Table1.

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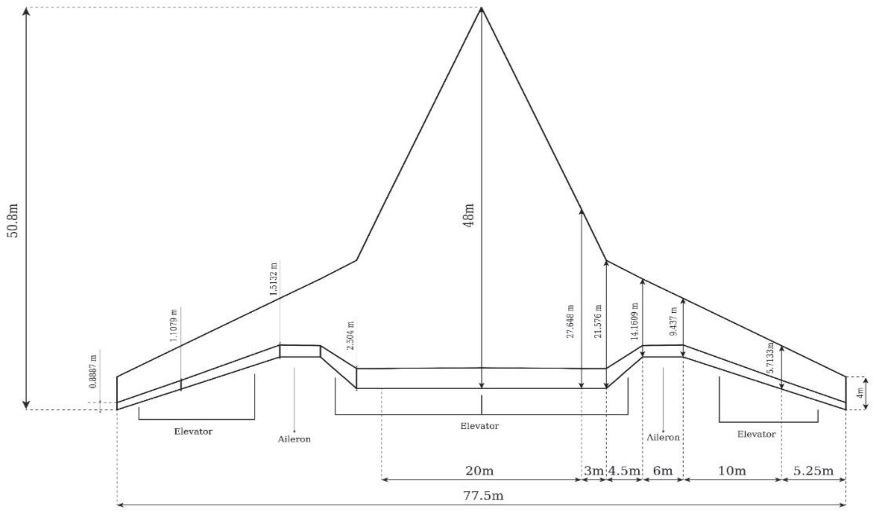


Figure 2. Reproduced BWB model identifying main dimensions, control surfaces and its dimensions

Table 1. The key geometric properties of the baseline BWB aircraft [11]

Wing Parameter	Value	Units
Gross Area (S_{gross}**)**	1390.6	m^2
Wing reference area (S_{ref}**)**	841.70	m^2
Wing span (b**)**	80	m
Mean aerodynamic chord ($\bar{C}$**)**	12.31	m
Trapezoidal aspect ratio (AR**)**	7.14	–
Root chord (C_{root}**)**	48	m
Tip chord (C_{tip}**)**	4	m
Leading edge sweep (Λ_{LE}**)**		
• Center	63.8	deg
• Trapezoidal wing	38.0	deg
Thickness to chord ratio (t/c**)**		
• Center	16.5%	
• Maximum	18.0%	
• Outboard	8.0%	
Dihedral (Γ**)**		
• Center	0.0	deg
• Kink	1.5	deg
• Outer Wing	3.0	deg

The geometric characteristics of the winglets, which were not available in [11], were sourced from Qin et al. and are presented in Table 2. The blended wing configuration was divided into multiple sections, as illustrated in Figure 3, where each section corresponds to either a distinct airfoil profile, a variation in sweep angle, or the beginning of a new control surface.

Table 2. Geometrical parameters for the BWB winglet [8]

Parameter	Value	Parameter	Value
Airfoil Type	NACA 0012	**t/c ratio**	0.12
Root chord	4.0 m	**Tip chord**	1.35 m
Fin height	5.0 m	**Sweep (Λ_0)**	28.0°
Rudder chord ratio	0.25	**Fin taper ratio**	0.6

2.2 Mass and Inertia Properties

The mass and inertia properties of the BWB aircraft were obtained from previous studies conducted at Cranfield University [9, 10, 11]. Table 3 lists the mass and inertia values at the maximum take-off weight (MTOW). The maximum landing weight (MLW) was estimated by extrapolating a mass reduction from 371,280 kg to 322,600 kg, to provide an assessment of weight variations across different flight phases [10].

Table 3. BWB mass and inertia properties [11]

Parameter	BWB (MTOW)	BWB (MLW)	Unit
Aircraft mass, m	371,280	322,600	kg
Inertia about X axis, I_{xx}	47.03×10^6	40.72×10^6	$Kg.m^2$
Inertia about Y axis, I_{yy}	25.06×10^6	21.7×10^6	$Kg.m^2$
Inertia about Z axis, I_{zz}	99.73×10^6	86.36×10^6	$Kg.m^2$

2.3 Spanwise Airfoil Distribution and Aerodynamic Considerations

The BWB airfoil distribution of the case-study is carefully designed to balance lift, drag, and stability requirements. The Center-body section (shown in Figure 4a) employs a reflexed camber airfoil, generating a positive pitching moment ($Cm_0 > 0$) to improve longitudinal stability, though at the expense of a reduced sectional lift coefficient. From y = 0 to y = 10 m, the reflexed profile transitions linearly into a nearly symmetric airfoil, which remains unchanged up to y = 13 m. Beyond this spanwise location, two distinct supercritical airfoil profiles are introduced to optimize high-speed aerodynamic performance. The airfoil selection and optimization were originally conducted by R.H. Liebeck [2] and later utilized in Ref. [10]. Each section's airfoil profile was extracted and reproduced using SolidWorks to allow the extraction of airfoil data for each respective section. Figures 3 and 4 present the different wing sections used along the BWB span.

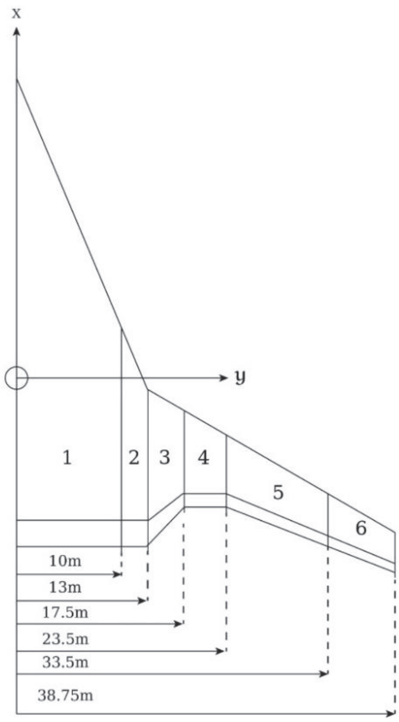
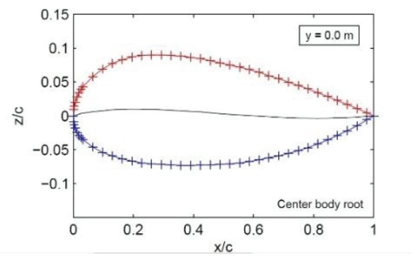
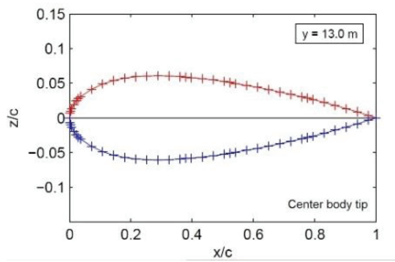


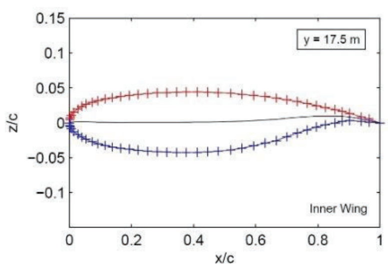
Figure 3. Wing sections for the BWB [10]



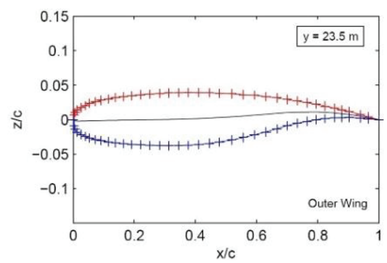
Center body root. y= 0 m



Center body tip. y= 13 m



Inner wing. y= 17.5 m



Outer wing. y= 23.5 m

Figure 4. Different wing sections along the BWB [10]

3. Aerodynamics and Static Stability Analysis

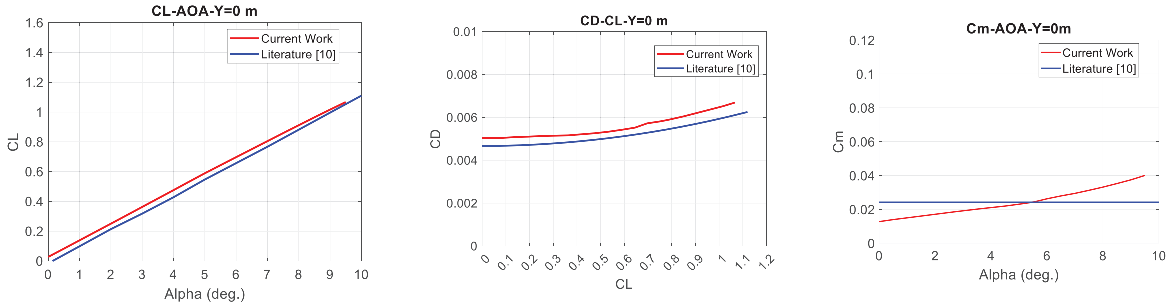
This section presents aerodynamic and static stability analysis of the Blended Wing Body (BWB) aircraft. The analysis is conducted using a mid-fidelity numerical tool (XFLR5) Which is considered a mid-fidelity tool because it utilizes the Vortex Lattice Method (VLM), which offers a higher accuracy than simple analytical solutions but it has less accuracy compared with experimental methods like wind tunnel testing, to evaluate aerodynamic performance and relevant static stability derivatives.

The results are verified (where available) by comparing them with data from Ref. [10]. The analysis is divided into three parts: individual airfoil analysis, evaluation of the complete BWB aircraft without winglets, and assessment of the complete BWB aircraft with winglets to determine their influence on aerodynamic and static stability characteristics.

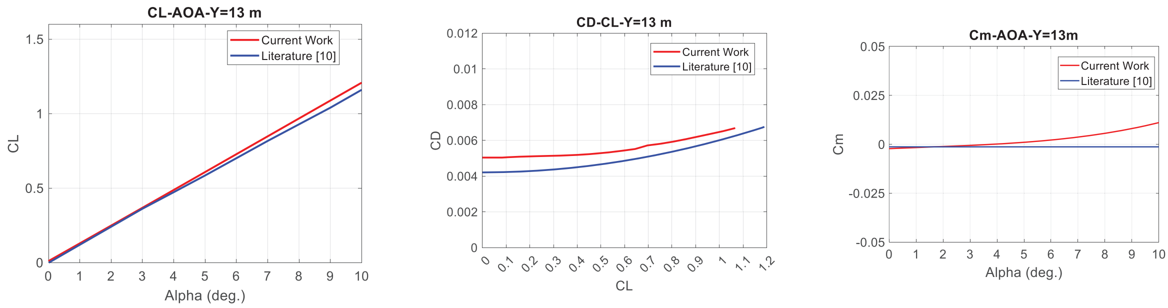
3.1 Airfoils Analysis

The aerodynamic performance of the airfoils used in different sections of the BWB aircraft was analyzed using XFLR5 at multiple Reynolds numbers for each section and Mach = 0.3 to ensure their suitability for full aircraft analysis. Each airfoil was evaluated using XFLR5's analysis type.1, and the BWB model was drawn in XFLR5 using dimensions obtained from the generated SolidWorks CAD.

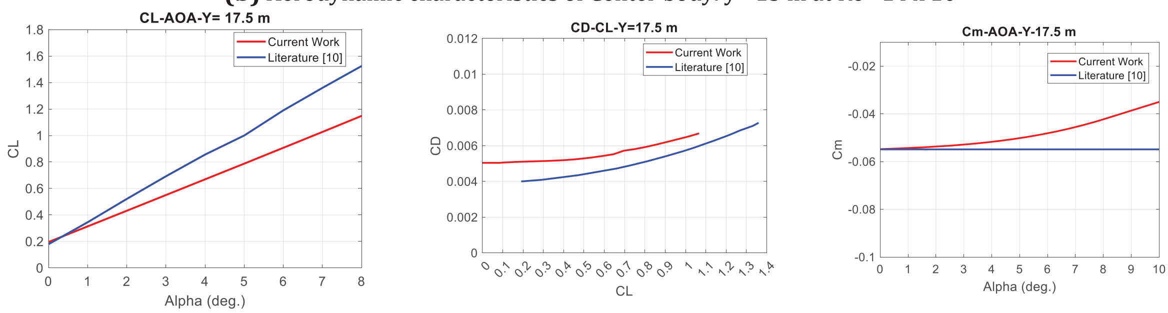
The results from this analysis provide key aerodynamic characteristics, such as lift, drag, and moment coefficients, which serve as the foundation for further aerodynamic and static stability evaluations. Figure 5 presents the calculated aerodynamic characteristics of different wing sections along the BWB Compared with the the ESDU calculations of PhD [10] under the same conditions specified in this section.



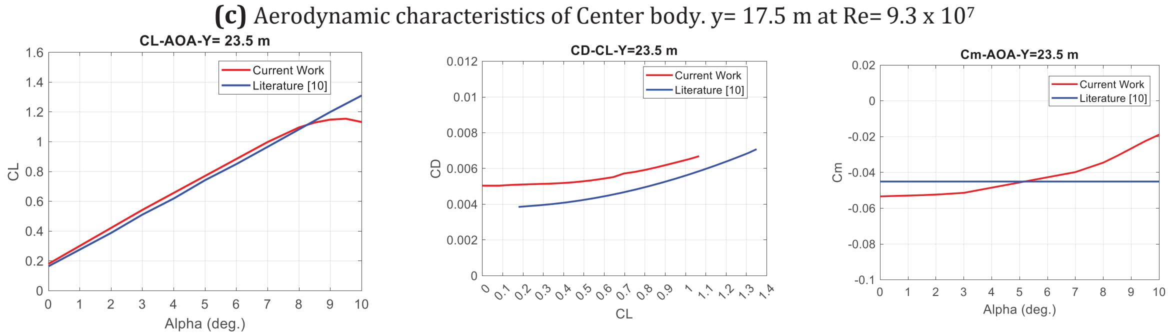
(a) Aerodynamic characteristics of Center body root. y= 0 m at Re= 32 x 10^7



(b) Aerodynamic characteristics of Center body. y= 13 m at Re= 14 x 10^7



(c) Aerodynamic characteristics of Center body. y= 17.5 m at Re= 9.3 x 10^7



(d) Aerodynamic characteristics of Center body. y= 23.5 m at Re= 6.3 x 10^7

Figure 5. Aerodynamic characteristics of different wing sections along the BWB

3.2 Complete Airplane Analysis (Without *Winglets*)

A complete aerodynamic and static stability analysis of the complete BWB aircraft without winglets was conducted using VLM2 analysis method in XFLR5. The simulations were performed at a free-stream velocity of 400 knots and an altitude of 10,000 feet, covering a range of angles of attack (α) from −6° to 10° at a sideslip angle (β) of 0°. Additionally, the effect of sideslip was examined by varying β from 0° to 10° at α = 0°. The results were verified by comparing them with those obtained from Ref. [10], showing a acceptable degree of agreement. The results are presented in Figure 6.

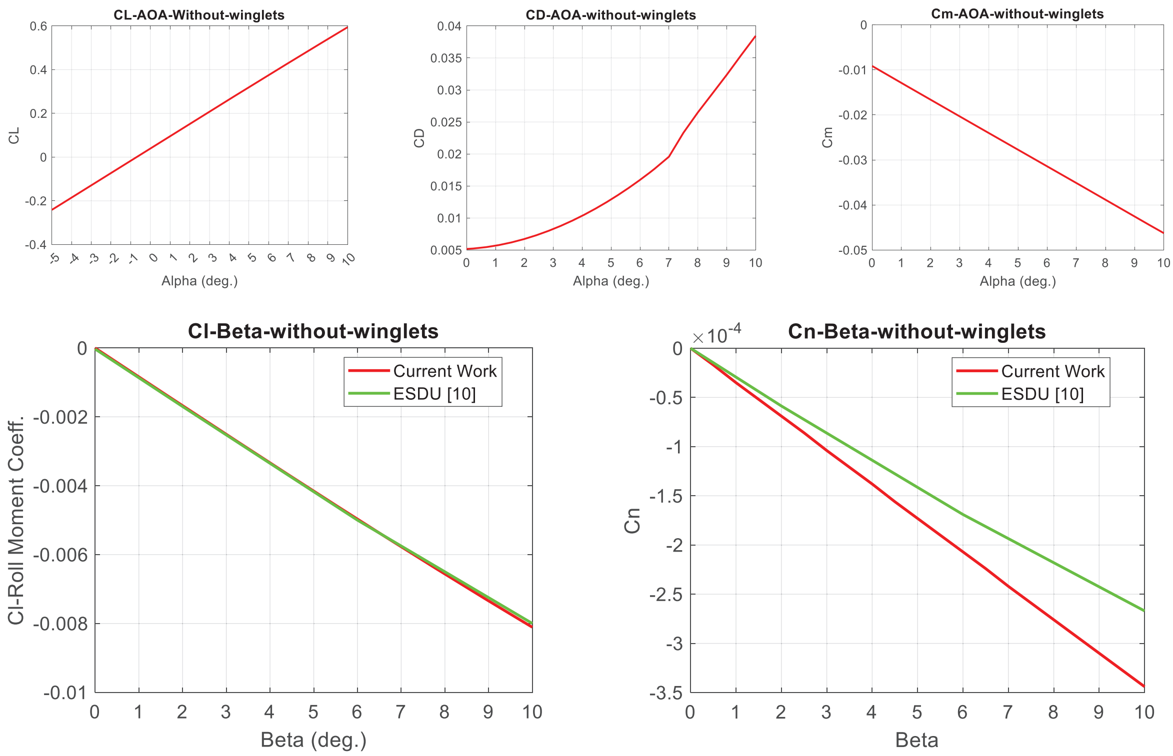


Figure 6. Aerodynamic characteristics of the case-study BWB (without winglets).

3.3 Complete Airplane Analysis (With Winglets)

Following the baseline analysis, the influence of winglets on aerodynamic performance and static stability was assessed. The same VLM2 methodology was applied, maintaining consistent flight conditions to enable direct comparisons. The integration of winglets aimed to improve the lift-to-drag ratio (L/D) and enhance static stability derivatives, particularly in yaw stability. The aerodynamic effects of winglets were evaluated by examining changes in lift, drag, and pitching moment, while static stability enhancements were analyzed through roll and yaw stability derivatives. The findings highlight the potential benefits of optimized winglet designs in improving overall aerodynamic efficiency and static stability without significantly increasing drag. Figure 7 presents the calculated aerodynamic and static stability curves for the current study compared with data from Ref. [10], which are indicated in the figure by the method used to obtain them in the Ref. (i.e., panel, ESDU, baseline).

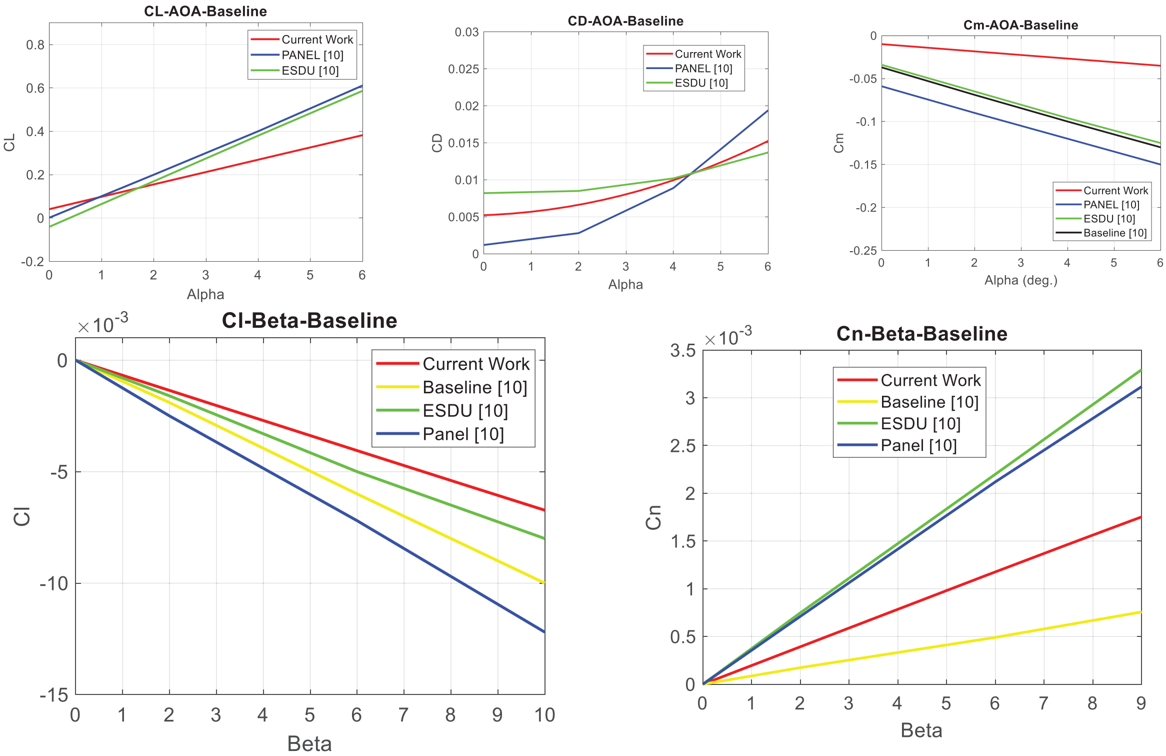


Figure 7. Aerodynamic characteristics of the case-study BWB (with winglets).

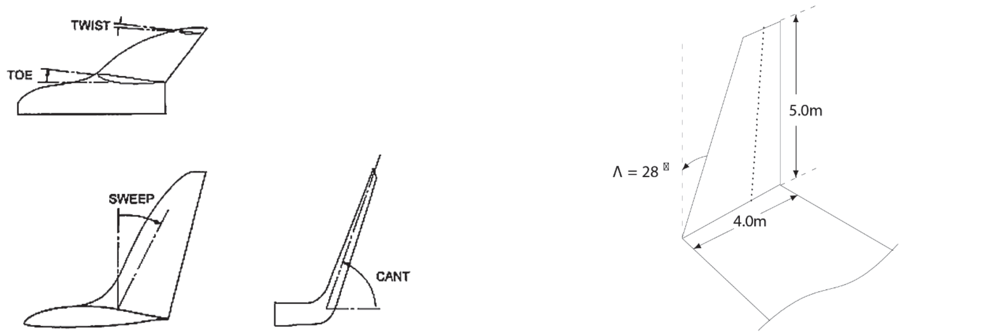
4. Sensitivity Analysis of Winglets Design Parameters

This section investigates the impact of various winglet design parameters on the aerodynamic performance and static stability of the Blended Wing Body (BWB) aircraft. By systematically modifying key winglet characteristics, the study aims to identify configurations parameters that enhance aerodynamic performance and maintain static stability.

4.1 Methodology

Following the verification of the used analysis tool, the same aerodynamic model was employed under different winglet configurations. The baseline model with its original winglets is used as reference values for the following key aerodynamic/static stability parameters: maximum lift-to-drag ratio $(CL/CD)_{max}$, lift curve slope (CL_α), minimum drag coefficient (CD_{min}), pitching moment coefficient at zero lift (Cm_0), pitching moment curve slope (Cm_α), yaw stability derivative (Cn_β), and roll stability derivative (Cl_β).

Figure 5 illustrates the key winglet design parameters and their respective values for the baseline configuration of the Blended Wing Body (BWB) aircraft.



(a) Definitions of winglets angles **(b)** Winglets Geometry with Dimensions on BWB wing tips [10]

Figure 8. Definition of winglets Parameters and their values for the baseline configuration [10],[11]

4.2 Winglet Parameter Modifications

To assess the influence of winglet geometry, the following parameters were systematically varied:

- Winglet span (increased to 110% and reduced to 90% of the original value).
- Taper ratio (increased to 110% and reduced to 90%)
- Cant angle (adjusted to 70° and 80°)
- Sweep angle (increased to 110% and reduced to 90%)
- Toe angle (adjusted by +10° and -10°)

Additionally, a configuration without winglets was also included to serve as a comparative reference.

4.3 Analysis and Results

Each modified configuration was re-evaluated, and the new aerodynamic and static stability derivatives were recorded. The results were systematically compared in Table 4 to identify the changes that led to the most favourable aerodynamic and static stability characteristics.

The results of the sensitivity analysis, presented in Table 4, reveal variations in aerodynamic performance based on winglet geometry. The key findings include:

- Decreasing the cant angle has the significant effect on increasing the lift-to-drag ratio and the lift curve slope, longitudinal static stability, and decreasing CD_{min} (where cant angle of 70° yielded the highest lift-to-drag ratio with $(CL/CD)_{max}$ = 26.7427, the maximum lift curve slope of CL_{α} = 0.0573, $Cm_{\alpha} = -0.0046$, and the minimum CD_{min} = 0.00519).
- The lowest drag coefficient (CD_{min} = 0.005103) was recorded in the model without winglets. Where, when adding winglets, decreasing the cant angle results in decreasing CD_{min}
- Decreasing the toe angle improves the directional and roll static stability, while significantly decreasing Cm0 (where toe angle of -10° yielded the minimum pitching moment coefficient Cm0 = 0.1754, and the maximum directional stability derivative $Cn\beta$ = 0.0005, and the highest roll stability derivative $Cl\beta = -0.0014$).

The sensitivity analysis in Table 4 demonstrates how modifications to winglet geometry impact aerodynamic efficiency and static stability. Reducing the cant angle significantly improves the lift-to-drag ratio (CL/CD), lift curve slope (CL_{α}), and longitudinal stability (Cm_{α}) while lowering minimum drag (CD_{min}), with a cant angle of 70° yielding the most favourable performance (CL/CD= 26.7427), ($CL\alpha$ = 0.0573), and (CD_{min}= 0.00519). However, the lowest overall drag (CD_{min}=0.005103) occurred in the model without winglets, suggesting that while winglets enhance aerodynamic efficiency, they introduce some additional drag. Additionally, decreasing the toe angle to -10° significantly improves directional stability (Cn_β = 0.0005) and roll stability (Cl_β=0.0014) while reducing the pitching moment coefficient (Cm_0 = -0.1754), indicating improved control characteristics. These results highlight the importance of optimizing winglet cant and toe angles for achieving the best balance of aerodynamic efficiency and static stability.

Table 4. Aerodynamic Parameters and Static Stability Parameters

Configuration	Aerodynamic Parameters				Static Stability Parameters		
	$(\frac{CL}{CD})_{Max.}$	CL_α	$CD_{Min.}$	Cm_o	Cm_α	Cn_β	Cl_β
No Winglets	25.487	0.056	0.005103	-0.10107	-0.0037	0.00004	-0.0008
Baseline Winglets	26.368	0.0569	0.005228	-0.10182	-0.0042	0.0003	-0.0012
span 110%	26.420	0.0569	0.00524	-0.10182	-0.0042	0.0003	-0.0012
span 90%	26.312	0.0568	0.005216	-0.10182	-0.0042	0.0002	-0.0012
Taper Ratio 110%	26.369	0.0569	0.00523	-0.10182	-0.0042	0.0003	-0.0012
Taper Ratio 90%	26.366	0.0569	0.00523	-0.10181	-0.0042	0.0002	-0.0012
Cant Angle 80°	26.5562	0.057	0.005207	-0.10179	-0.0044	0.0003	-0.0012
Cant Angle 70°	26.742	0.0573	0.00519	-0.10193	-0.0046	0.0002	-0.0012
Sweep Angle 110%	26.369	0.0568	0.005219	-0.1018	-0.0042	0.0003	-0.0011
Sweep Angle 90%	26.368	0.0569	0.00524	-0.1018	-0.0042	0.0003	-0.0012
Toe Angle +10°	24.739	0.0564	0.005588	-0.0275	-0.0042	0.0003	-0.001
Toe Angle -10°	17.103	0.057	0.00643	-0.1754	-0.0042	0.0005	-0.0014

5. Conclusions and Future Work

In this study, the mid-fidelity numerical tool XFLR5, which is suitable for preliminary aerodynamic and stability assessments, was employed to analyse the aerodynamic and static stability characteristics of a case study BWB aircraft. This tool was further utilized to evaluate the impact of winglet design modifications on the aerodynamic performance and static stability of the aircraft. The analysis confirms that modifications to winglet geometry significantly influence aerodynamic efficiency and static stability. Reducing the cant angle leads to a higher lift-to-drag ratio, increased lift curve slope, and improved longitudinal stability, while also contributing to a reduction in minimum drag. However, results indicate that the lowest overall drag occurs in the absence of winglets, suggesting that while winglets enhance aerodynamic efficiency, they introduce a minor drag penalty. This finding highlights the necessity of an optimized winglet configuration to achieve an optimal aerodynamic balance.

Furthermore, adjustments to the toe angle demonstrate a notable enhancement in directional and roll stability. These findings emphasize the importance of precisely tuning winglet cant and toe angles to optimize both aerodynamic efficiency and static stability in BWB aircraft. For future work, a higher-fidelity tool, such as Computational Fluid Dynamics (CFD), will be employed to more accurately assess the effects of winglet design modifications on aerodynamic performance and stability. Additionally, a full dynamic stability analysis will be conducted to evaluate the impact of winglet design on aircraft dynamic modes, including phugoid, short-period, Dutch roll, roll, and spiral modes. These analyses will further refine the optimization of BWB winglet configurations for enhanced performance and stability.

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