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Numerical Prediction of Blended Wing Body Aerodynamic Characteristics at Subsonic Speed

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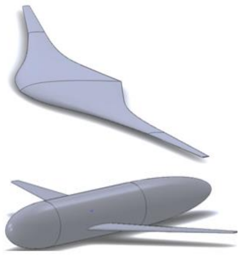
Graphical abstract



Abstract

The need for high performance and green aircraft has brought the blended wing (BWB) aircraft concept to the centre of interest for many researchers. BWB is a type of aircraft characterized by a complex blending geometry between fuselage and wing. Recently, many researches had been performed to unlock its aerodynamic complexity that is still not well understood. In this paper, aerodynamic characteristic of a baseline BWB configuration derived from simple conventional aircraft configuration was analysed using the Reynolds-averaged Navier-Stokes computational fluid dynamics (CFD) solver. The main objectives of this work are to predict the aerodynamic characteristics of the BWB concept at steady flight conditions and at various pitch angles. The results obtained are then compared against a simple conventional aircraft configuration (CAC). The results show that the BWB configuration used has 24% higher L/D ratio than the CAC. The increment to the L/D however is mainly due to lower drag than the improvement in the lift.

Keywords: Blended wing body; conventional aircraft; l/d ratio; computational fluid dynamics

■1.0 INTRODUCTION

Lift-to-drag (L/D) ratio of an aircraft is the parameter used to describe the aircraft's aerodynamic efficiency. The L/D is also one of the main parameters required in the aircraft flight performance estimation. The higher the L/D value reflects better flying performance, often targeted by aircraft designers for longer flight duration, endurance and for better fuel consumption.

To improve the L/D value of an aircraft, several design concepts were introduced (e.g. aircraft with planar wing concept, blended-wing-body and etc). Blended Wing Body (BWB) is a type of aircraft configuration which has an aerofoil shaped body which contributes to the overall lift during flight. The BWB fuselage is blended to the wing in such a way that the fuselage-body interference that exists in the conventional aircraft configuration (CAC) can be eliminated. Earlier applications of the BWB were found in the military aircraft designs leaving very good track records [1,2]. Due to its advantage of higher lift-to-drag, and the need for high performance and low pollution to meet the green sky program promoted in Europe, the BWB concept could be introduced for civilian transport in the near future. The aerofoil-like fuselage that replaces the conventional body-empennage arrangement was reported to contribute to the higher L/D ratio of the BWB.

Most of researches and development on BWB designs for the last 10 years are focused for large scale (up to 800 passengers) and long range designs, intended to replace or supersede the capability of the current jumbo CAC [1-5]. One of the notable works on BWB for subsonic transport was reported by Liebeck [4, 5]. Similar study was performed at TsAGI, Russia [6] which looked at the problems and decisions related to the development of advanced large-capacity BWB and the rationale of selecting design solution for BWB, its aerodynamic configuration, structural concept, as well as analysis of alternative configurations [4,5].

Conceptually, the main aerodynamic advantages of the BWB are the lower wetted area to volume ratio and lower interference drag and higher lift-to-drag (L/D) ratio as compared to the conventional aircraft configuration (CAC) [4, 7]. This higher L/D ratio theoretically gives the aircraft better aerodynamic efficiency leading to better fuel efficiency. However, with the design lacking both vertical and horizontal stabilizers and the tail that a typical conventional aircraft has, is more difficult to control the BWB [6]. It is also found that the BWB needed much more rigid body since the lift from the body will support most of the BWB's weight [8].

Another study on BWB aircraft under a European project was the MOB project [4]. In the MOB, the baseline BWB geometry used was derived from the MSc student project at Cranfield College of Aeronautics. The inverse design approach combining both panel method and multiblock Reynolds-Averaged Navier-Stokes solver, used MERLIN code to predict the effect of spanwise distribution on the aircraft aerodynamic efficiency.

The changing demand of air traffic from hub-and-spoke to point-to-point created a new demand for small aircraft that can accommodate 100-200 seats. To support this transition in air traffic demand, a small BWB concept has been studied at the Japan Aerospace Exploration Agency (JAXA) and Japan Metropolitan University [9]. In their work, the unstructured CFD solver was used to predict aerodynamic characteristics of BWB with several wing positions (high, mid and low wing). Aerodynamic shape optimisation was also performed to find the blending coefficients for higher L/D ratio.

The BWB concept is still new and more research is needed to find out its aerodynamic performance under various flight conditions and the problems posed by the design. Therefore, in this study, a baseline mid-wing BWB design is presented as an initial study and to predict its aerodynamic characteristics at various flight conditions.

■2.0 METHODOLOGY

Preliminary study for selected aerofoils was performed to determine a suitable aerofoil design for the BWB fuselage design. The criteria for the aerofoil are 1) high L/D ratio 2) high speed aerofoil 3) high stall angle and 4) reasonable thickness. The two-dimensional aerodynamic data of aerofoils (Fig. 1) used in this work is summarised in Table 1. The aerodynamic data presented are obtained using the viscous panel method solver, XFOIL [10].

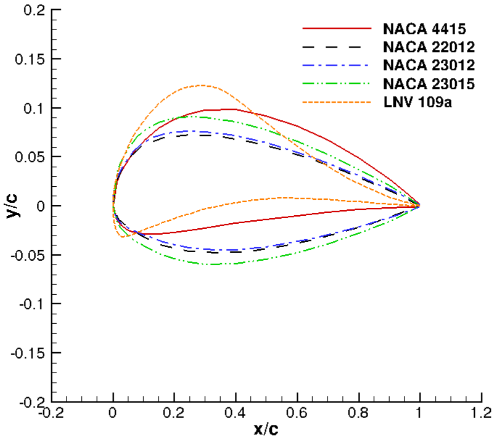


Figure 1 Geometry of Aerofoil candidates for BWB Fuselage Design

Table 1 shows that the LNV 109A aerofoil produces highest L/D among the chosen aerofoils. The LNV 109A aerofoil is a type of aerofoil designed to produce natural laminar flow for high L/D ratio. However, the drawback of the LNV109A aerofoil is its low thickness profile near the trailing edge making it not suitable for fuselage design. The five-digit NACA aerofoil produces the lowest L/D in the table but with high stall angle and thicker cross-section. The requirement for an aerofoil with high stall angle is required so that the fuselage does not stall before the wing. Taking a compromise of all the requirements, the NACA 23012 aerofoil was found to be the best aerofoil configuration to be used as an initial fuselage profile for the baseline design of the BWB presented in this work (Fig. 2).

Table 1 Aerodynamic characteristics of selected aerofoils

Parameters	NACA 4412	NACA 22012	NACA 23012	NACA 23015	LNV 109A
$C_{L_{max}}$	1.62	1.62	1.58	1.65	1.82
$Max(\frac{C_L}{C_D})$	132	89	99	96	151
AoA $at\ max.(\frac{C_L}{C_D})$	6.0°	9.0°	9.5°	9.0°	10.0°

* *AoA is angle of attack*

The geometric specifications of the BWB wing (taper ratio, leading and trailing edge sweep angles, span, tip and root chord) are developed based on a simple, generic conventional aircraft configuration (CAC) as shown in Fig. 3. For comparison purposes, a simple geometry of CAC model was developed based on the external geometry of the Airbus A380. The CAC aircraft has 38^o swept angle measured from the ¼ chord line. It can be seen that the BWB can offer wider and shorter fuselage than the CAC configuration.

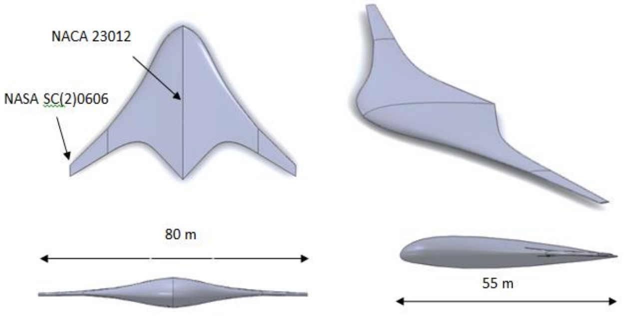


Figure 2 BWB geometry

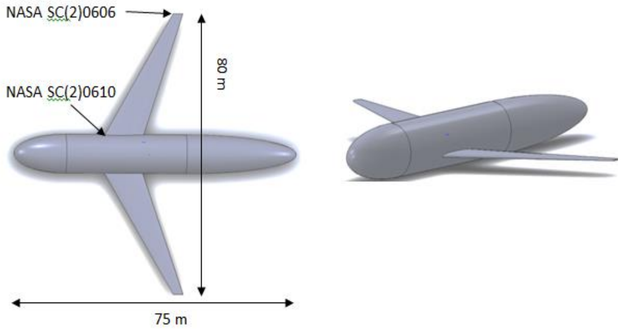


Figure 3 CAC geometry

In this work, the prediction of aerodynamic characteristics of the BWB and CAC design was done using commercial CFD solver, Ansys Fluent. The Reynolds-averaged Navier-Stokes is solved using finite volume on unstructured meshes and for all cases, the turbulence closure is modelled using the standard 2-equation k-ω turbulence model.

To ensure the data calculated in CFD are independent of the mesh, the mesh convergence study was first performed. This mesh sensitivity analysis was performed in the direction normal to the surface of geometry and the first cell height was set to 1×10^{-4}. Using this setting gives the y+ value of 100 which implies that the viscous effect may not be well captured. The effect of mesh size used on the aerodynamic prediction was presented in term of L/D or C_L/C_D (Fig. 4 and 5).

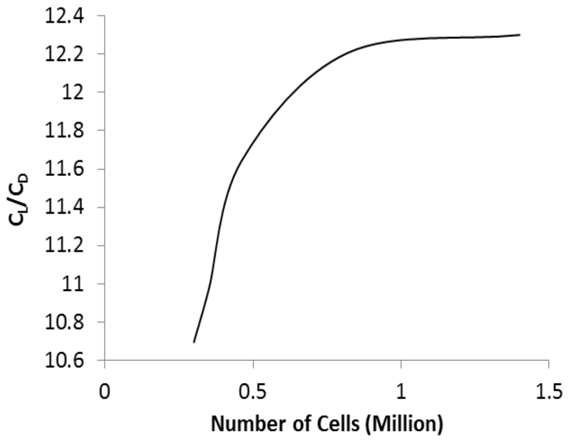


Figure 4 Mesh convergence of the CAC model

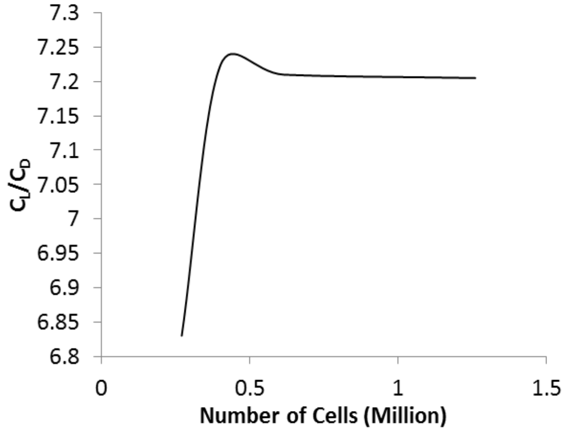


Figure 5 Mesh convergence of the BWB model.

3.0 RESULTS AND DISCUSSION

A series of computations of aircraft at different incidence angles of -5°, 0°, 5°, 10° and 15° at approach speed (Mach = 0.16) and cruise speed (Mach = 0.80) were performed. The results for the aerodynamic characteristics for both aircrafts are summarized in Tables 2 and 3. The results show that, for all range of positive pitch angles, the BWB configuration generates lower drag and higher L/D ratio compared to the CAC design. At the angle of attack of five degrees nose down, the present BWB design is predicted to produce negative lift of 164% higher than the CAC model for both speed cases.

As reported in many literatures [3-8], the BWB design presented produces higher L/D ratios. In this work, the BWB design used produces 24% higher L/D values compared to the CAC. This is achieved at the angle of attack five degrees nose up condition. It is also noted that huge improvement in the L/D of the BWB design is contributed from a large reduction in drag which is up to 32% rather than improvement in the net lift force. The comparison of the L/D ratio is depicted in Figure 6. Also it can be highlighted that the best cruising angle for the BWB is with 5° nose up condition which at this angle, the aircraft is flying at the highest value of the L/D ratio.

Figure 7 shows the side-by-side comparison of the aircraft geometry for both CAC and BWB models. Initially, both models share the same wing geometry. However, due to wing-body blending, only small portion at the outboard section of the BWB wing remain the same as the CAC design. Blending the wing and body is found to greatly alter the wing geometry by increasing the wing leading edge sweep angle, longer chord at the inboard sections of the wing span. This is expected to affect the distribution of surface pressures on the wing and body, thus changing the overall aerodynamic performance.

Table 2 Aerodynamic characteristics of BWB and CAC at approach speed

Angle of Attack	Blended Wing Body			Conventional Body		
	C_L	C_D	$\frac{C_L}{C_D}$	C_L	C_D	$\frac{C_L}{C_D}$
-5°	-0.830	0.0857	-9.69	-0.314	0.0800	-3.92
0°	0.191	0.0386	4.94	0.598	0.0697	8.58
5°	1.219	0.0972	12.54	1.446	0.1428	10.13
10°	2.137	0.2700	7.92	1.972	0.2872	6.86
15°	2.945	0.5830	5.05	2.181	0.5262	4.14

Table 3 Aerodynamic characteristics of BWB and CAC at cruise speed

Angle of Attack	Blended Wing Body			Conventional Body		
	C_L	C_D	$\frac{C_L}{C_D}$	C_L	C_D	$\frac{C_L}{C_D}$
-5°	-0.841	0.0739	-11.38	-0.317	0.0659	-4.80
0°	0.195	0.0319	6.10	0.617	0.0584	10.56
5°	1.237	0.0854	14.48	1.484	0.1269	11.69
10°	2.135	0.2503	8.53	1.991	0.2643	7.53
15°	3.0245	0.5715	5.29	2.293	0.5224	4.39

The variation of chordwise surface pressures, C_p plotted against normalized chord length for both BWB and CAC models for various angles of attack and flight conditions are presented in Figures 8 to 11. For comparison, the C_p values presented are extracted at the mid-section of the half wing span (½ b) where the wing and the body are blended together (Figure 7). At this particular section, it is apparent that the blending of the wing and body alters the original sectional profile of the wing hence the chordwise C_p. Overall, the results clearly show that the BWB produces a higher chordwise C_p distribution than the CAC for all pitch angles considered.

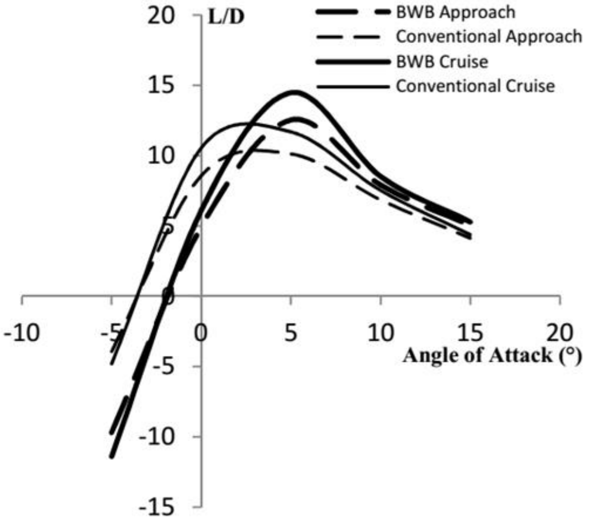


Figure 6 Comparison of L/D ratio for different aircraft angles of attack

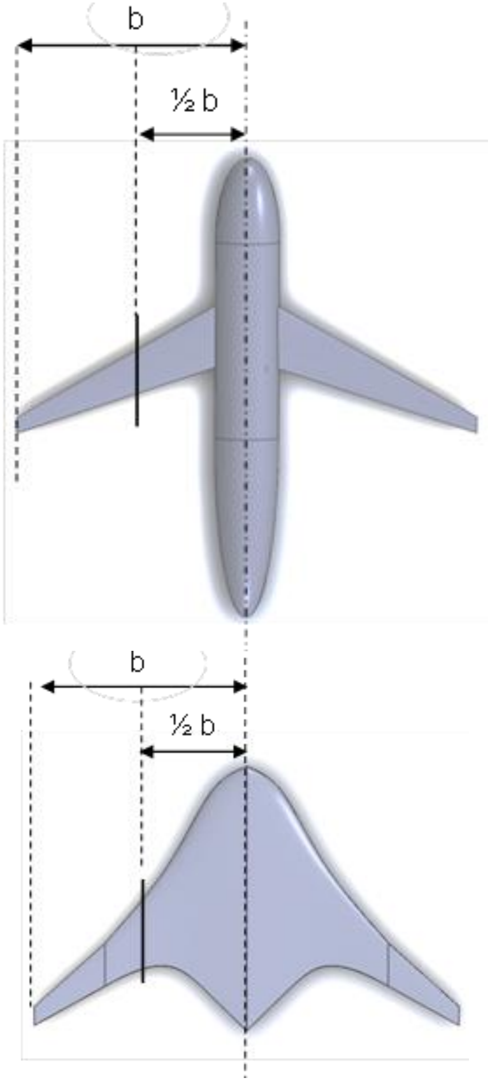


Figure 7 Location of plane on the wing surface for surface pressure extraction (solid line)

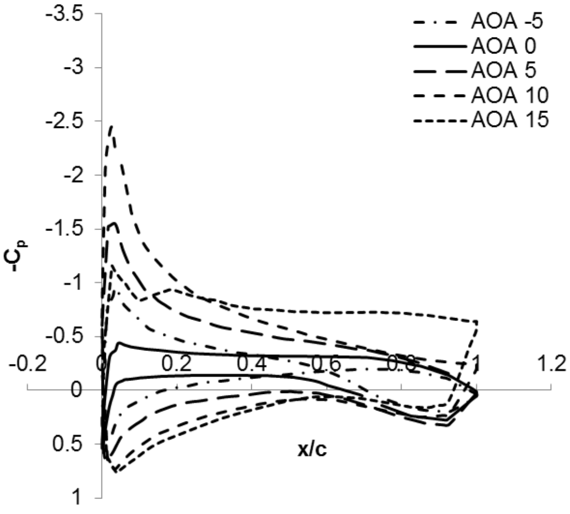


Figure 8 Chordwise surface pressure distribution of the CAC at Mach = 0.16

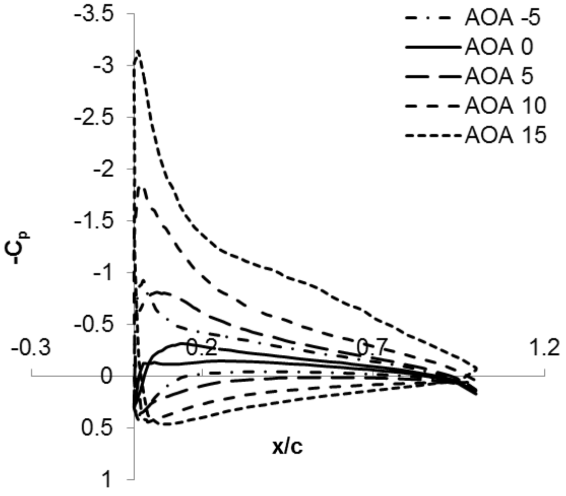


Figure 9 Chordwise surface pressure distribution of the BMach = 0.16

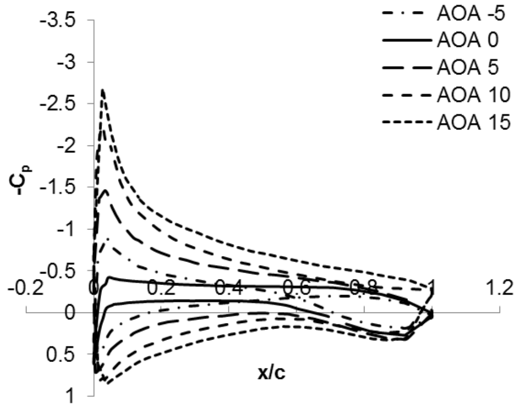


Figure 10 Chordwise surface pressure distribution of the CAC at Mach 0.80

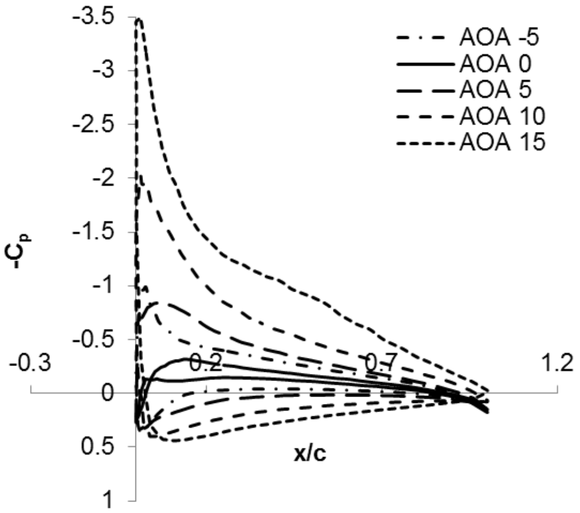


Figure 11 Chordwise surface pressure distribution of the BWB at Mach = 0.80

■4.0 CONCLUSION

The conceptual design and the aerodynamic characteristics of the blended-wing-body (BWB) at normal cruising and approach speeds for large aircraft at various angles of attacks were studied and compared with a simple conventional aircraft configuration (CAC). In this work, the centre section of the fuselage is based on NACA23013, while the wing tip is NASA SC(2) 0606. The section from the fuselage centre towards the tip are a blend of these two aerofoils. The CFD results showed that the BWB configuration proved to have aerodynamic features superior to the CAC. The BWB configuration shows huge reduction in the total drag of up to 32% and about 24% improvement in the lift-to-drag ratio compared to the CAC design. For aircrafts of the same weight, the small drag and high L/D ratio of the BWB will result in extra flight endurance and range for the same amount of fuel. Consequently, this can make the BWB more environmentally friendly. From the aerodynamic point of view, the BWB is shown to be more attractive than the CAC aircraft. However, poor understanding of the aerodynamics and controllability of BWB requires more research to be carried-out.

Acknowledgement

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