Effects of wing twist on lift and drag characteristics of blended wing body aircraft

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Abstract: Blended Wing Body is a revolutionary concept offering phenomenal performance advantages over conventional aircraft. There are various aerodynamic features that are added to the wing in order to adjust the lift distribution and wing twist is one of them. This paper presents a progressive study to examine the effects of twist angles on the aerodynamic characteristics of a Blended Wing Body (BWB) aircraft. CFD analysis is carried out on seven BWB models having wing twists ranging from +3° to -3°. Each model is analyzed at four different Mach numbers. The coefficient of drag ($C_d$) and coefficient of lift ($C_l$) is determined and plotted against the twist angle to obtain a trend. The $C_l/C_d$ ratio is also calculated to observe the overall aerodynamic performance of the BWB.

Keywords: Blended Wing Body, CFD, Aerodynamics, Twist angle, Coefficient of lift, Coefficient of drag.

1. Introduction:
To begin with the reference from Wright flyers in 1903 to the aircrafts which we see now, there has been large enhancement in the designs. In the past few decades, the need for better fuel efficiency and noise reduction for conventional aircrafts geared up for research of various designs. But recently, the configuration which has grabbed everyone’s attention is BWB aircraft. BWB aircrafts belong to the family of flying wing aircrafts which accommodate the crew, passenger and cargo inside the wing. Historically, the theory of flying wing aircraft dates back to 1910, when Hugo Junker patented the idea of wing-only aircraft. The Soviet’s Boris Ivanovich Cheranovskys started testing of tailless flying wing gliders in 1924. There were many other people and organizations who carried their research independently.

The most prominent contribution of the flying wing was given by American designer J.K. Northrop. In 1940, XB-35 strategic bombers were developed by Northrop, further XB-35 were transformed to YB-49 bombers [1]. In 1988, Northrop revealed a B-2 bomber which achieved a maximum L/D ratio of 22.5 which was 10% greater than the airliners developed during that period [1].
The tailless aircraft which unites cargo, propulsion system and passenger cabin into a single wing defines the BWB aircraft [2]. This leads to main aerodynamic advantages like low wetted area to volume ratio, productive use of wing span, ideal span loading and reduced interference and friction drag. Also, it is estimated that there is gain in $(\text{L/D})_{\text{max}}$ by 20% and 27% reduced fuel burn per passenger as compared to a conventional configuration [2, 3, 4]. Although a lot of literature is available on BWB in terms of its formulation and aerodynamics, there is no substantial data available on variation of $C_l$ and $C_d$ with twist angle. Hence, the objective of studying the trends of $C_l$ and $C_d$ with respect to twist angles is to understand the aerodynamic behaviour of BWB aircraft when twist angles are varied. It will provide insights on a particular twist angle where the BWB aircraft shows the best aerodynamic performance. This data might further help to reduce the drag of the BWB aircraft by incorporating the respective twist angles and lead to fuel savings [12-18].

2. Literature Review:
In 1990, Liebeck presented his work with a series of papers. Liebeck described the formulation of BWB in his paper [2]. The progress of BWB from streamlined disk plus wing was explained. For 800 passengers and $Ma=0.85$, the configuration evolved from 349ft wingspan (trapezoidal aspect ratio of 12) to 280ft wingspan (trapezoidal aspect ratio of 10). To compare with existing conventional aircrafts, the BWB-450 baseline aircraft was designed. When compared with Airbus A380-700, it resulted in 32% cutback in fuel burn per seat, 18% decrease in maximum takeoff weight and many more satisfactory results. Design constraints, the opportunities and challenges in BWB were also presented. Further, Liebeck et al. extended the work to design and analysis of BWB [2]. The study was distributed in phases starting from initial design of BWB to converting it to a workable design and redesigning it to reduce the flaws which could be addressed through simulation. Inverse design Navier Stokes codes were applied. With the help of CFD analysis and design methods, aerodynamic study of BWB was carried out including kink regions and inboard and outboard wing. Also, a study on thickness to chord ratio with respect to span was carried out. The analysis concluded that thick airfoils have minimal profile drag due to thickness and they must efficiently wrap the cabin and cargo areas in the centerbody region. Aerodynamic design challenges of BWB for subsonic transport were also discussed by Liebeck et al. [5]. Along with the applicability of Navier-Stokes analysis for this unconventional configuration, design constraints such as volume, deck angle, speed at landing approach, buffet and stall characteristics, etc. were also reviewed.

Pambagjo et al. studied the aerodynamic design of medium sized BWB aircraft [4]. The main objective of the study was to verify if the BWB configuration could be extended to the design which accommodates 200 passengers cruising $Ma=0.8$. He presented the process to design BWB aircraft for...
200 passengers. The design process resulted in configuration of 50m wingspan and an aspect ratio of 7.7. The interesting result to note was that the wetted area of this BWB configuration was found to be greater than that of conventional aircraft of the same mission requirements. Thus it can be concluded that not all BWB configurations can extract the originally claimed aerodynamic advantages. The design process resulted in an L/D ratio of 18.87 indicating a comparable performance with conventional aircrafts from an aerodynamic point of view.

Roman et al. presented the study of aerodynamics of high subsonic BWB configurations [6]. CFL3DV6, a CFD code was developed to design BWB configuration at Mach 0.93. However, Multidisciplinary Design Optimization was also used in conjunction with CFD. BWB 6-250B was designed on the basis of Ma=0.93, range of 7500 nmi WingMOD optimized configuration.

Aerodynamic study of this design was carried out. It was observed that at design cruise, \( (L/D)_{\text{max}} \) of Ma=0.93 BWB was 92% of \( (L/D)_{\text{max}} \) of the Ma=0.85 configuration. Also, compressibility drag drastically increases beyond cruise Ma=0.93. Thus it can be concluded that although the design at Ma=0.93 is feasible, it has some performance penalties with respect to design at Ma=0.85.

Wisnoe et al. discussed the aerodynamic behavior of BWB Unmanned Aero Vehicle (Baseline I) by CFD analysis and wind tunnel experiments [7]. Aerodynamic characteristics such as \( C_l \), \( C_d \) and pitching moment obtained at various velocities are compared. Also, pressure contours are plotted to study the flow behavior whereas mini tuft is used for visualization in wind tunnel to study the flow pattern. Maximum lift for the prescribed design was obtained around 34°- 39° of angle of attack (AOA). Thus, it was concluded that this type BWB can be operated at higher AOA. Further in 2009, Baseline II (the latest design of BWB) was investigated[8]. The studies on Baseline I indicated a few obstacles in the use of elevator as control surface. Hence the new design had canard configurations. From wind tunnel experiments of Baseline II, it was observed that the stall conditions occurred at higher AOA as compared to Baseline I. In 2010, further modifications were made in the Baseline II, where a certain twist angle was incorporated in the wing and the improved design was named as Baseline II E2. Ali et al. studied the aerodynamic performance of Baseline II E2 [8]. The CFD results were compared with experimental wind tunnel results.

By surveying various research papers and relevant material, it was identified that there is limited data available on effects of twist angle of BWB on \( C_l \) and \( C_d \). This also restricted the study on improvising the lift and drag characteristics of BWB aircraft by varying the twist angle. The present study elaborates the effects of varying twist angles of BWB on \( C_l \) and \( C_d \) at various velocities. Since 2005, MARA University of Technology (UiTM) has commenced research on BWB aircraft [7]. The baseline geometry considered for this study is the one developed at UiTM. Propulsions, weight, stability and control of aircraft and structures is not considered. Aerodynamic shape of BWB is emphasized. Numerical analysis at velocities of 25m/s, 30m/s, Ma=0.1 and Ma=0.3 is carried out at various twist angles. Changes in \( C_l \) and \( C_d \) are plotted against twist angle to study the trend. In addition, pressure distribution is also plotted to investigate behavior of flow around aircraft. Figure 2 shows the half model of BWB aircraft by UiTM.
In this paper, aerodynamic characteristics like $C_l$ and $C_d$ are obtained at velocity 30 m/s, 35° AOA and 0° twist angle for the Baseline I design developed by MARA University. The results are compared and verified with the one obtained in the paper by Wisnoe et al.[7]. The study was further extended to analyze the $C_l$ and $C_d$ by varying the twist angles at various velocities.

3. Methodology:
In the present article, the effect of varying twist angle on the aerodynamic characteristics of BWB was studied numerically at velocities of 25m/s, 30m/s, Ma=0.1 and Ma=0.3. Airflow over the BWB was simulated and analyzed using ANSYS Fluent. Data obtained from pressure distribution was used to estimate the values of $C_l$ and $C_d$, which are plotted against the twist angle.

3.1. Generation of CAD model
The BWB prototype developed by UiTM, namely Baseline I was chosen for the study [7]. Figure 3 shows the 2D geometry of the Baseline I.

Figure 3: Dimensions of half model of BWB. [7]

These specified dimensions were used to generate a CAD model of the BWB using Solidworks. Isometric and top view of the 3D model is shown in Figure 4. The wingspan of the Baseline I was 666mm with a leading-edge sweep angle of 60°. The root chord and tip chord were 336mm and 41.63mm respectively. The reference area of the aircraft was 75,000mm². Similar models were created by varying the wing twist between -3° to 3°, in steps of 1°. The angle of twist was measured between the central and the outermost airfoil. It was ensured that while the wing twist is varied, the main parameters of the aircraft remain constant.
Based on the XFLR5 results presented by Paudel et al., HS-522 airfoil was chosen for the BWB profile [9]. The coordinates of the airfoil were obtained from the Hartmut Siegmann airfoil database. Table 2 enlists the principal characteristics of the airfoil.

| Airfoil Characteristics | Values |
|-------------------------|--------|
| Cl max                  | 1.35   |
| Alpha max               | 140    |
| (Cl/Cd) alpha max       | 42     |
| (Cd)alpha max           | 0.032  |
| (Cm)alpha max           | 0.019  |

Table 1. HS-522 airfoil characteristics

3.2. Mesh generation
For simulating the flow characteristics, a cuboidal domain was defined around the main geometry. The domain walls were positioned at a distance of 0.7m from the surface of the Baseline I. Discretization of the domain was carried out using an unstructured tetrahedral mesh. Unstructured mesh was found to be an appropriate choice as it has the potential to be adapted according to the geometry [10, 11]. Thus, flow around the complex geometry of the aircraft could be captured accurately. The grid consisted of a maximum of 5,20,000 cells. The quality of the mesh was examined based on the parameters given in Table 2.

| Sr.no | Mesh metric     | Average value |
|-------|-----------------|---------------|
| 1     | Skewness        | 0.23          |
| 2     | Orthogonal quality | 0.77        |
| 3     | Aspect Ratio    | 1.86          |
| 4     | Element quality | 0.83          |

Table 2: Parameters for Mesh Quality.

3.3. Simulation of flow characteristics
Fluid flow is governed by the momentum, continuity, and energy conservation equation. The continuity equation is given by-
For incompressible flow, the above equation reduces to
\[ \nabla . \mathbf{V} = 0. \]

The momentum conservation equation is given by-
\[ \frac{\partial}{\partial t} (\rho \mathbf{V}) + \nabla . (\rho \mathbf{V} \mathbf{V}) = -\nabla . \mathbf{P} + \nabla . (\mathbf{T}) + \rho g + \mathbf{F} \]  

These governing equations were resolved by the solver using the Finite Volume Method (FVM) so as to get a numerical solution to the problem.

The discretized model was imported into the ANSYS Coupled solver. For simulating the flow, velocity inlet, pressure outlet and no slip walls were used as boundary conditions. To determine the flow regime of the problem, the Reynolds number was estimated for all four velocities of \( \text{Ma}=0.072 \) (25 m/s), \( \text{Ma}=0.086 \) (30 m/s), \( \text{Ma}=0.1 \) (34.4 m/s) and \( \text{Ma}=0.3 \) (103.85 m/s). The values obtained\(^a\) lay between 71248(at 25m/s) and 295965(at \( \text{Ma} \) 0.3). Thus, the problem was contained within the laminar region of fluid flow, as the range of Re was less than 5,00,000. The flow was assumed to be incompressible and steady state analysis was carried out using the realizable k-epsilon turbulence model. Coupled solver was used to solve the mass and momentum conservation equations. All models were analyzed at AOA of 35\(^o\), as the \( C_{\text{lim}} \) at \( \text{Ma}=0.3 \) is attained at 35\(^o\) AOA [7]. The solution was obtained using the second order upwind scheme for better accuracy. From the results, the values of \( C_l \) and \( C_d \) were calculated from the obtained values of lift and drag forces using the following formulae-
\[
C_l = \frac{2L}{\rho \nu^2 A} \\
C_d = \frac{2D}{\rho \nu^2 A}
\]

Where A is the reference area (75,000mm\(^2\)) and L and D are the lift and drag force respectively. The values of \( C_l \) obtained at \( \text{Ma}=0.3 \) at 0\(^o\) twist were verified by comparing with the values given by UiTM. Similar analysis was carried out for twist angles of -3\(^o\), -2\(^o\), -1\(^o\), 1\(^o\), 2\(^o\) and 3\(^o\). The pressure distribution was observed and the variation of \( C_l \) and \( C_d \) was plotted against the twist angle at each velocity.

4. Results and discussions:
The lift and drag results produced on the Baseline I at twist angles between -4\(^o\) to 4\(^o\) are presented in Figure 5 and Figure 6 respectively.

Figure 5 represents variation of \( C_l \) with changing twist angles. \( C_l \) is observed to be depending on the amount of twist produced. On varying the twist from 0\(^o\) to 1\(^o\) or -1\(^o\), a sharp increase in \( C_l \) is observed at velocities of 25m/s and 30m/s. The increase in \( C_l \) at 25m/s is found to be the greatest as compared to other velocities; i.e. 72.12% at +1\(^o\) and 55.35% at -1\(^o\) as that of 0\(^o\). As the velocity is increased, the percentage increase in \( C_l \) on varying the twist from 0\(^o\) to +1\(^o\) and -1\(^o\) tends to reduce. \( C_l \) further increases in a non-linear fashion between -1\(^o\) and -3\(^o\). Maximum \( C_l \) is achieved at -3\(^o\) for all four velocities. The increase in \( C_l \) is 80.61% as that of 0 at 25m/s and -3\(^o\) twist. This increase gradually reduces with increase in velocity, dropping to 11.6% at \( \text{Ma}=0.3 \). On further increasing wing twist beyond -3\(^o\), \( C_l \) decreases. On giving a positive twist beyond 1\(^o\), the \( C_l \) decreases and tends to stabilize after 2\(^o\) twist, decreasing only slightly. Thus, lift characteristics of the Baseline I improve with inception of negative twist up to -3\(^o\).

Figure 6 shows the variation for drag coefficient with twist angle. The variation of \( C_d \) with wing twist is found to be similar to that of \( C_l \). The \( C_d \) increases abruptly on giving a twist of +1 and -1 at
velocities of 25m/s and 30m/s. The maximum Cd is attained at 1° twist at all four velocities, increasing by 73.21% as compared to 0° at 25m/s. This percentage of increase is gradually reduced to 6.69% at Ma 0.3. There is a significant decrease in Cd from 1° to 2°, after which it starts increasing at a steady rate. The drag coefficient increases between -1° and -3°, beyond which it decreases.

To examine the effect of twist angle on overall aerodynamic performance of the Baseline I, the C_l/C_d ratio is calculated. Figure 7 shows the variation of C_l/C_d with twist angles. It is observed that on varying the twist from 4° to -3°, C_l/C_d increases non-linearly. The pressure contour plots at 0° and -3° twist and 25m/s are shown in Figure 8. At 25m/s and 0° twist, a low pressure of 703.7Pa is generated on the upper surface of the aircraft whereas a high pressure of 283.3Pa is generated on the lower surface, giving a C_l/C_d ratio of 1.468. The aircraft with 3° twist showed change from 259 Pa to 1066 Pa at 25 m/s, giving a C_l/C_d ratio of 1.563. It is thus observed that the C_l/C_d ratio increases by 6.58% at Ma=0.1 on varying the twist from 0° to -3°. There is a substantial increase in Cd as compared to C_l from -3° to 4° which results in maximum C_l/C_d at -3° twist angle. By further increasing twist angle on the negative side, C_l/C_d is found to decrease. Thus, the aerodynamic performance of the Baseline I is the best at -3° twist.
4.1 Validation of Results

The CFD results for aircraft at 350 angle of attack, 00 twist angle and velocity of 103.85 m/s (Ma=0.3) were cross checked with the results for the same parameters from the paper by Wisnoe et al [7].

| Aerodynamic parameters | Obtained CFD results | Results from the research paper [7] |
|------------------------|-----------------------|-------------------------------------|
| Cl                     | 0.96104               | 1.031                               |
| Cd                     | 0.65426               | 0.65                                |
| Cl/Cd                  | 1.46889               | 1.586                               |

**Table 3. Validation of results**
There is little variation in the obtained results which can be attributed to selection of a different airfoil. But these results validated our mesh model and mathematical model which helped us in finding the further results by varying the parameters like twist angle and velocity.

5. Conclusion

Blended Wing Body aircraft offer several advantages but with certain design challenges. The progressive aerodynamic study of BWB design highlighted the importance of selection of airfoil section and twist angles. The effects of varying twist angle on lift and drag of BWB has been investigated in this paper. The analysis was carried out by changing the twist angles from -3° to 3°.

The results showed potential aerodynamic benefits of UiTM Baseline I at twist angle of -3°. The maximum $C_l$ is attained at -3° and maximum $C_d$ is attained at 1°. The study also concludes that with increasing twist angles, $C_l$ and $C_d$ both increase but the increment in $C_l$ is higher than that of $C_d$. For UiTM Baseline I BWB there is a 10.9% increase in $C_l/C_d$ when twist angle is changed from 3° to -3°, which indicates the better performance of BWB when twist angle is -3°. The results are particularly promising and will encourage further investigation of various other aerodynamic parameters which will affect the performance of BWB.

List of Abbreviations:

1. $C_l$ – Coefficient of Lift
2. $C_d$ – Coefficient of Drag
3. Ma – Mach Number
4. nmi – Nautical miles
5. AOA – Angle of Attack
6. p – Static Pressure
7. V – Velocity vector
8. T – Stress tensor
9. $\rho g$ – Gravitational body force
10. F – Sum of external body force
11. A – Reference area
12. L – Lift
13. D - Drag
14. Re – Reynolds number

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