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Research on stability for blended-wing-body aircraft

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Abstract

The primary goal of this research is to research the stability properties of a blended-wing-body (BWB) aircraft. This section examines the assessment and selection of aircraft design parameters, planform design, and reflex wing and conducts a complete aircraft stability analysis. A BWB aircraft conceptual design has been completed and the design. To attain static stability, it was examined and refined. The BWB aircraft's study was performed at three distinct values. The analytical findings were used to calculate the angle-of-attack (AOA) and the stall AOA. We determined the estimated initial departure angle of attack and departure region by assessing the results of the trials and a set of stability criteria.

Keywords: Blended-Wing-Body Aircraft (BWB); Stall Departure; Static Stability; Dynamic Stability; Stability Modes; Computer-Aided-Design

1. Introduction

Throughout history, humankind has endeavored to subjugate every accessible region of the Earth, including the atmosphere. We have marveled at the awe-inspiring aerial prowess of eagles, storks, and condors, which ultimately culminated in the Wright brothers' groundbreaking flight in 1903, widely regarded as one of the most noteworthy milestones in the annals of aviation. Additional endeavors encompassed the ancient Greeks, Michelangelo, ornithopter flying contraptions, Montgolfier, Sir George Cayley, Otto Lilienthal, and Langley. These individuals have devoted their careers to the quest for avian flight, striving to replicate historical achievements and discover unexplored regions.[1]

Figure 1 NASA conceptual design of BWB aircraft.[2]

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Blended wing bodies (BWB) refer to aircraft that have a seamless integration of wings and fuselage, reducing wetted area and form drag. They are employed in aircraft and submersible gliders and can have or without a tail.[2]

1.1. History

The Blended Wing Body (BWB) design, initially proposed by Nicolas Woyevodsky in the 1920s, underwent significant advancements by NASA during the 1990s. Boeing and NASA are collaborating on developing Blended Wing Body (BWB) designs for the Boeing X-48 unmanned aerial vehicle. Additionally, Airbus is contemplating utilizing a BWB configuration for the A320neo series. The N3-X NASA design integrates superconducting electric motors to minimize fuel use, noise emissions, and contaminants. NASA and its corporate partners are now investigating a blended-wing aircraft design for upcoming air transportation endeavors, with the potential to decrease fuel consumption by 20%.[3]

1.2. Characteristics

NASA is investigating a hybrid wing body (BWB) configuration to tackle structural challenges in expansive internal spaces. The BWB design minimizes the resistance caused by the skin and increases the thickness of the wing root area, leading to a more effective construction and less weight. The design also includes jet engines with Ultra High Bypass ratios, which enhance fuel efficiency.[3]

1.2.1. Advantages

- Significant advantages in carrying heavy loads for purposes such as strategic airlift, aviation freight, and aerial refueling.
- Fuel efficiency has been enhanced by 10.9 percent compared to a regular widebody. Over 20% of similar traditional aircraft
- Noise reduction — NASA audio simulations demonstrate a decrease in noise level of 15 decibels for Boeing 777-class aircraft. In contrast, studies estimate a fall in noise levels ranging from 22 to 42 decibels below the Stage 4 threshold.

1.2.2. Disadvantages

- In an emergency, evacuating a BWB might be difficult. Because of the design of the aircraft, the seats would be theater-style rather than tubular. This thus constrains the number of escape doors.[4]
- Although it has been proposed that BWB interiors will be windowless, more recent research indicates this is untrue. The windows may be positioned differently, but the weight penalties are the same as in a regular airplane.[5]
- The cabin may experience a sense of uneasiness as the wings roll, resembling the Dutch roll phenomenon observed in conventional aircraft such as the 777. To serve as a passenger cabin, the center wing box must have a significant height, necessitating a wider wingspan. Modifying designs to accommodate various sizes incurs higher costs than scaling up or down the airframes and wings.
- A BWB has a higher vacant mass for a comparable payload and may not be cost-effective for short flights of four or shorter hours.[6]

1.2.3. NASA BWB Research

NASA is researching the flying characteristics of the Blended Wing Body (BWB), a military aircraft, to secure commercial permission. The project seeks to analyze the flight and handling characteristics of the design, validate its performance against engineering expectations, develop digital flight controls, and assess the integration of the propulsion system. Experiments using wind tunnels and free-flight models have been carried out to examine the aerodynamic, noise, stability, and control characteristics. Subsequent research will include wind tunnel data in full-scale blended wing body (BWB) models.[7]

2. Stability Criteria

Stability pertains to an aircraft's capacity to counterbalance environmental influences such as turbulence or flight control inputs, enabling the pilot to be less attentive even when the autopilot is deactivated. It aids in maintaining equilibrium while flying in a straight and level manner at a consistent speed. Aircraft designs incorporate stability features to enhance flying performance, which includes maintaining balanced flight, ensuring consistent conditions, recovering from disturbances, and reducing pilot workload. Dynamic stability encompasses positive static stability.

- The Longitudinal Axis maintains stability along the longitudinal axis from the nose to the tail via the fuselage.
- The lateral Axis is responsible for ensuring stability from wingtip to wingtip.
- Vertical Axis maintains stability from top to bottom via the middle of the fuselage.

A few more points to consider, such as the left-turning inclinations, maneuverability vs. controllability, and unfavourable yaw, contribute to this issue.

2.1. Longitudinal Stability

The role of an aircraft is controlled by the longitudinal axis, which is a line that runs from the nose to the tail. Longitudinal stability, on the other hand, refers to the aircraft's ability to return to its trimmed angle of attack.

2.1.1. Lateral Stability

The lateral axis, a hypothetical line extending from one wingtip to the other, impacts an aircraft's nose's upward or downward movement, hence determining its lateral stability.

2.2. Dihedral Effect

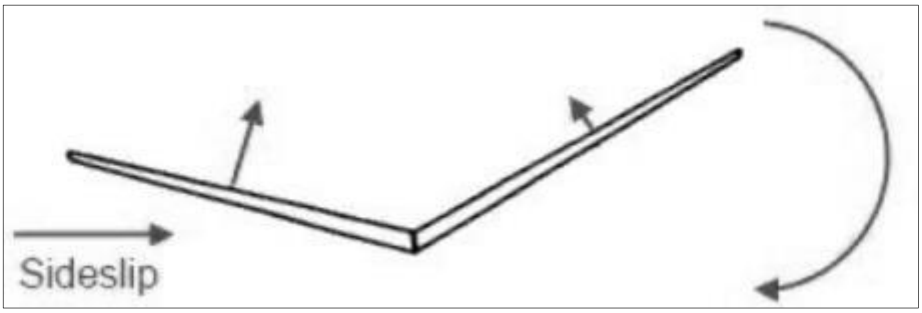

Figure 2 Dihedral effect.[8]

Dihedral is the phenomenon that happens when an aircraft rolls, resulting in a sideways movement. The lower wing elevates by increasing its angle of attack, increasing lift and upward movement. As the wing position increases, the aircraft's roll resistance is enhanced. The rudder is used to improve the turning motion of an airplane and counteract the effects of adverse yaw.

2.3. Swept Wing Effect

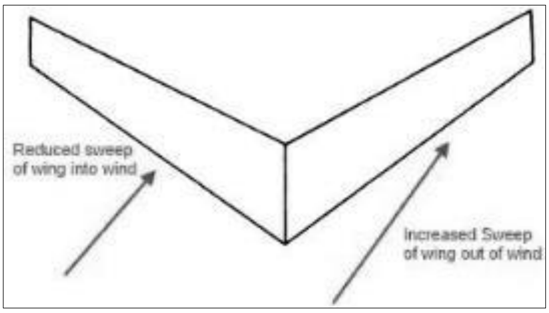

Figure 3 Swept Wing Effect[8]

Side slips create more direct relative wind to the upwind swept wing, which creates a roll toward the wing level.

2.4. Vertical Stability

The vertical axis is a conceptual line extending from the plane's uppermost point to the aircraft's lowermost end. The rudder controls the rotation around this axis, commonly called "yaw."

- The resistance to yawing is determined by the surface area below the center of gravity (CG), which enhances the directional stability.

2.5. Dutch Roll

Dutch roll refers to an aircraft's simultaneous sideways and rolling movement, which can be uncomfortable and potentially hazardous unless the aircraft is permitted to tilt significantly. Turbulence or excessive control inputs can initiate it, while the aircraft's inherent stability can mitigate its effects. The aircraft's poor Dutch roll characteristics can increase its vulnerability to pilot-induced oscillations (PIO), especially while attempting to align in the landing mode.

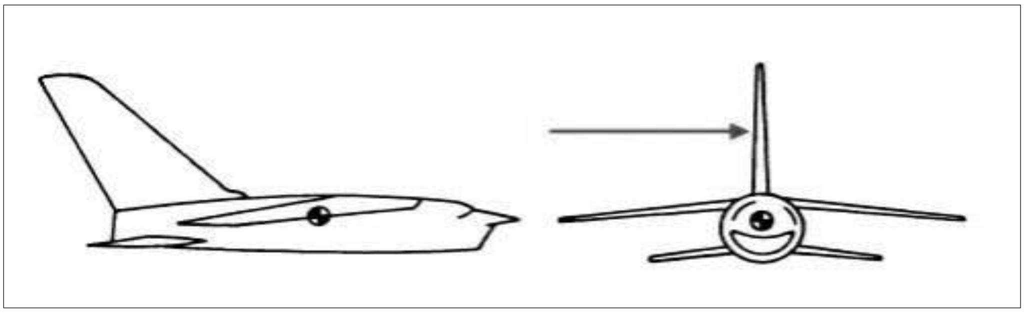

Figure 4 Rudder Effect[8]

2.6. Four Left Turning Tendencies

- Typically, general aviation engines turn clockwise when viewed from the cockpit, looking through the windscreen.
- The principles of p-factor, gyroscopic precession, torque, and slipstream result in a tendency for a clockwise rotating propeller to turn left.
    - In engines where the propeller rotates in the counter-clockwise direction, these principles result in a tendency for the aircraft to turn to the right.

2.7. P-factor

Asymmetric loading, sometimes called P-factor, is an intricate interplay among the aircraft, the direction of the wind, and the rotating direction of the wind, where a higher angle of attack leads to greater thrust.

2.8. Gyroscopic Precession

Gyroscopic precession is when a propeller experiences a 90° force that causes it to rotate 90° in the same direction. This effect is most frequently observed in tailwheel airplanes after take-off, particularly when flying at low and high-power airspeeds.

2.9. Torque

Torque is the force produced by a blade's clockwise rotation, causing the aircraft to rotate counter-clockwise, with its most significant effect at low airspeeds.

2.10. Slipstream

The gusty wind impacts the left side of the tail (rudder) with a twisting motion.

2.11. Maneuver vs. Controllability

The concepts of maneuverability and controllability are inherently contradictory, requiring designers to carefully strike a balance between the two while designing an aircraft. Aviation has no free benefits, and achieving more significant lift always comes at the cost of increased drag.

2.12. Maneuverability

Maneuverability enables easy control and stress resistance of the aircraft.

2.13. Dependent on

- Weight
- Flight control system

- Structural strength
- Thrust

2.13.1. Controllability

The aircraft's responsiveness to control inputs concerning its attitude and flight path.

2.13.2. Adverse Yaw

Adverse yaw arises from the asymmetrical drag experienced by the wings, resulting in a yawing force that opposes the direction of the turn. The rudder adjusts, resulting in the nose turning outward.[9]

3. Background

The BWB is a novel design that combines the wing, fuselage, and engines, resulting in several aerodynamic benefits such as reduced wetted area and decreased interference drag. Additionally, it boasts a 20% greater lift-to-drag ratio.[10] Blended wing body arrangements offer superior aerodynamic performance but are vulnerable to gust loads during take-off and landing, causing near-stall conditions and increased local angle of attack.[11] The Swing wind tunnel model airplane's aerodynamics and control surface efficiency are investigated numerically and physically. The study reveals the presence of non-linearity and instability in the yaw moment.[12] The use of flying wings in commercial aviation shows great potential due to several market, technological, and environmental aspects. Since their introduction in the 1930s and 1940s, they have had stability problems, although providing technical feasibility, operational efficiency, and fuel savings.[13] Boeing conducted wind tunnel research on their own BWB design at low speeds. These experiments aimed to simulate flying conditions near the limit of the aircraft's capabilities and in potentially uncontrollable situations. The results of these experiments were communicated, and valuable insights were gained.[14] This study investigates the departure characteristics of open-loop, twin-finned combat aircraft at different attack angles to identify the required aerodynamic adjustments for reducing resistance during closed-loop flight.[15] Departure prediction indicators for both open- and closed-loop flight control are created using a unified analytical technique, and linear methods are examined for addressing nonlinear difficulties.[16] The flight characteristics of BWB aircraft are determined by analyzing the Dutch roll frequency, damping, roll time constant, and time to double amplitude for spiral.[17] NASA and Boeing are constantly producing BWB prototypes, one after the other, with the X48C being the most recent advancement in the design. Over time, significant advancements have been made in the field of BWB research, which is still ongoing. Aerospace researchers and scientists have already conducted extensive research. R. H. Liebeck pioneered combining the wing, fuselage, and engines into a single lifting surface.[18–27] When designing and developing an aircraft, the high-level requirements of the system (aircraft) drive the design and development of the aircraft's various subsystems. However, as subsystems become more complex, their integration becomes an increasingly important concern due to their interdependence and interaction.[28,29] A concept image of a commercial aircraft with a blended wing body appeared in the November 2003 issue of Popular Science magazine. In 2006, the image was used in an email hoax claiming that Boeing had developed a 1000-passenger jetliner with a radical Blended Wing (the "Boeing 797"). [30–32]

4. Test Model

A detailed figure of the test model design of the blended wing body aircraft can describe the structure and principles vividly. This section summarizes the essential aspects. The analysis will be given later to grasp flying dynamics better. The initial specs are equivalent to a Typical long-distance mission: when mach changes, this mission encompasses several aspects.

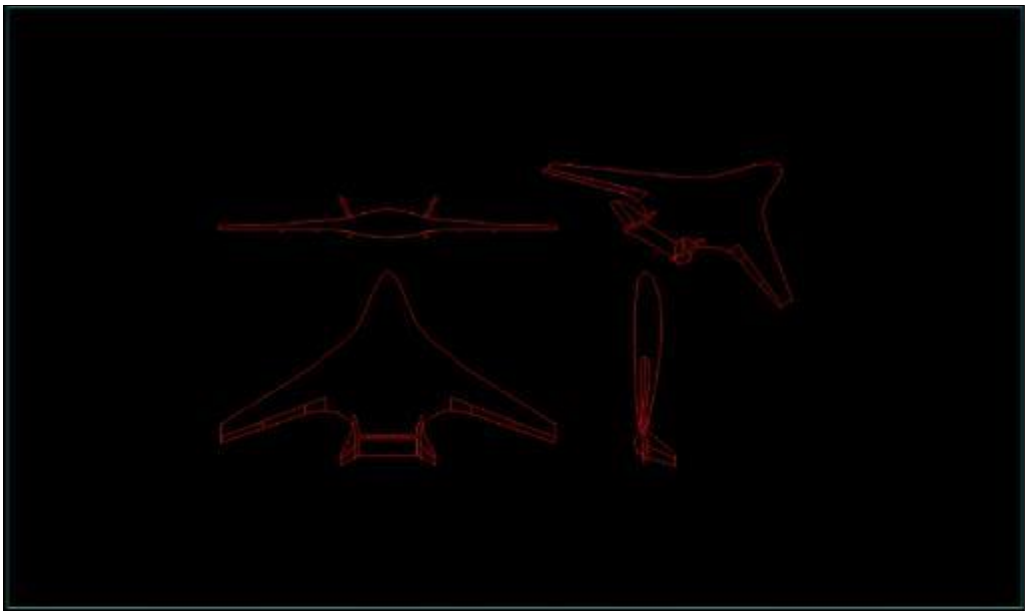

Figure 5 Various views of the blended wing body aircraft, shown in the external arrangements

Table 1 Structural parameters of the experimental model

Parameter	value
Reference area S	$0.067m^2$
Wing span L	0.7m
Mean aerodynamic chord c	0.1m
The rotational inertia of z-axis Iz	0.612
The rotational inertia of the x-axis Ix	0.337

The BWB aircraft is designed with wing loading, take-off weight, and engine thrust (or engine r power) in mind. The weight and wing planform area is expected to be based on the actual weight and size the stability study needs. Aerodynamic selection has been one of the most essential processes since airfoil features influence cabin layout, structural stiffness, and other factors, such as stability and performance.

5. Aerodynamics Characteristics

The aerodynamic characteristics of BWB aircraft are different from those of conventional aircraft. This section aims to analyze the aerodynamic attributes of BWB aircraft from the wind tunnel force measurement data.

Experiments with BWB models revealed axial and regular forces, pitching moment, and lift/drag forces. Non-dimensionalization of these numbers was achieved using aerodynamic coefficients. The resulting L, D, and M values are then non-dimensionalized by finding the aerodynamic coefficients.

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S}$$

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S}$$

$$C_M = \frac{M}{\frac{1}{2}\rho V^2 Sc}$$

5.1. Longitudinal Stability Characteristics

Lift distribution curves may be produced using the axial and regular forces acquired from wind tunnel testing at angles of attack ranging from degrees. These figures may be used to evaluate the performance of the aft- and fore-body models by comparing the slope of the lift curve, C_{La}, the stall angle, C_{Lmax}, the lift coefficient at zero angles of attack, C_L = 0, and the highest lift coefficient~~, α~~C_{Lmax}. Linear regression analysis is used to calculate the slopes of the lift curves ranging from a specific angle.

Two requirements must be met simultaneously to achieve trimmed flying in a longitudinal statically stable airplane: $C_{m0} > 0$ and $C_{m\alpha}<0$. Because BWB aircraft lacks a horizontal tail, trimmed flying conditions can only be met via the excellent design of the whole aircraft platform. A typical BWB aircraft comprises three components: the core body, the wing-body transition portion, and the wing. The central body airfoil of a BWB aircraft is often designed with a trailing-edge reflexed airfoil to meet the limitations of storage needs and a deck angle of less than 3° during cruise flight. The trailing-edge reflexed airfoil can ensure that the whole aircraft has $C_{m0}>0$, but the central body is statically unstable, which means $C_{m\alpha}>0$. Thus, the transition part and the wing need to adopt a sweep and twist design to adjust the position of the Aerodynamic Center (AC) to achieve $C_{m\alpha}<0$ for the whole aircraft.

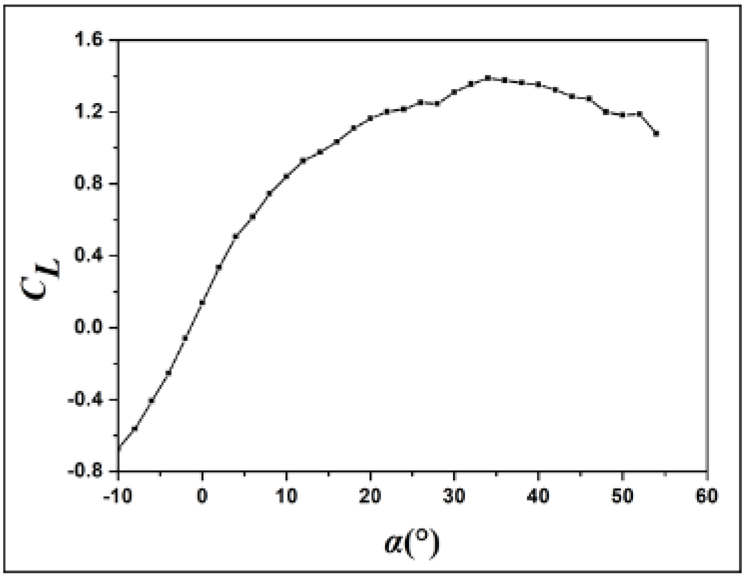

Figure 6 Lift coefficient curves

Figure 6 shows the lift coefficient curve of the BWB. It can be seen that it has linear lift characteristics when the angle of attack is less than 10 °. When the angle of attack is greater than 10 °, the lift line slope decreases gradually with the increase of the angle of attack until the angle of attack reaches 24 °, and a platform area appears. When the angle of attack reaches 28 °, the lift coefficient increases until the stall angle of attack reaches 34 °, and the maximum lift coefficient is 1.388.

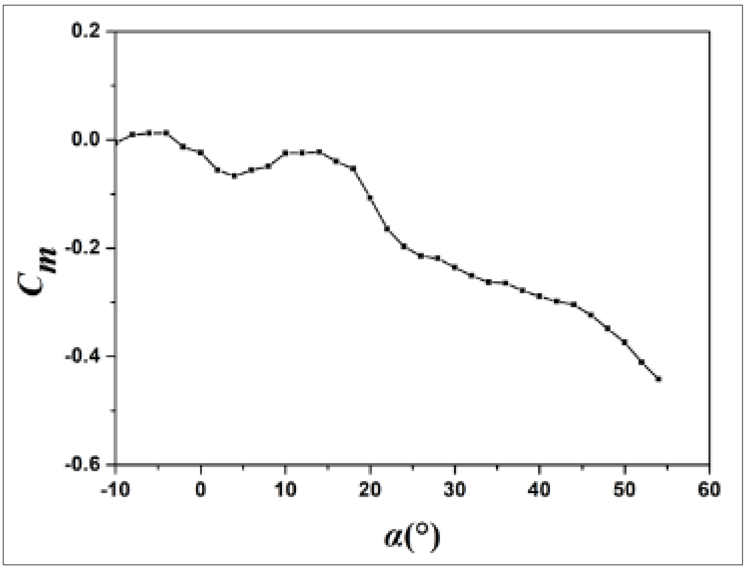

Figure 7 Pitch moment coefficient curves

Figure 7 shows the pitching moment coefficient curve. It can be seen that when the angle of attack is 4 ° ~ 10 °, the longitudinal static stability derivative $C_{m\alpha}$ is positive, the aircraft has a rising trend, and the BWB is longitudinally unstable at this angle of attack. After a 10 ° angle of attack, $C_{m\alpha}$ is negative, and the BWB is longitudinally static stable. After a 24 ° angle of attack, $C_{m\alpha}$ increases, but it is still negative, and its longitudinal static stability decreases.

Based on the force measurement test data of longitudinal lift coefficient and pitch moment coefficient, it can be seen that the BWB aircraft may have apparent changes in longitudinal characteristics at 10 ° angle of attack and 24 ° angle of attack. In the slight angle of attack range of 4 ° ~ 10 °, the aircraft is longitudinally static unstable, while after the 10 ° angle of attack, it is longitudinally static stable.

5.2. Lateral & Directional Stability Characteristics

The term "lateral stability" describes the stability of the plane's longitudinal axis, which is determined by four design parameters: weight distribution, keel effect, dihedral, and sweepback. To attain stability, dihedral-angled wings are frequently employed. When an airplane's wings are banked, the air strikes the low wing at a greater angle of attack due to the dihedral nature of the wing, which returns the aircraft to its initial lateral attitude. Aircraft with rapid roll or banking characteristics are less dihedral than those with less agility, as excessive dihedral can impair lateral maneuverability.

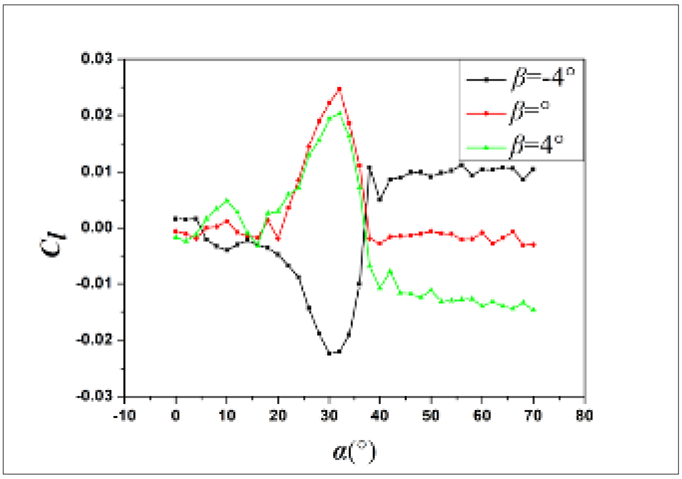

Figure 8 Roll moment coefficient curves

The lateral and directional static stability is the key to measuring whether the aircraft can return to its original state after being disturbed. The curve of the lateral static stability derivative can be used to analyze the stability characteristics of the aircraft. For directional stability, when the directional static stability derivative $C_{n\beta} > 0$, the aircraft is directional stable and tends to automatically restore the original direction after being disturbed. When $C_{n\beta} < 0$, the aircraft will lose directional stability and deviate from the divergence after being disturbed. For lateral stability, when the lateral static stability derivative $C_{l\beta} < 0$, the aircraft is laterally static stable. When $C_{l\beta} > 0$, the aircraft may have roll deviation.

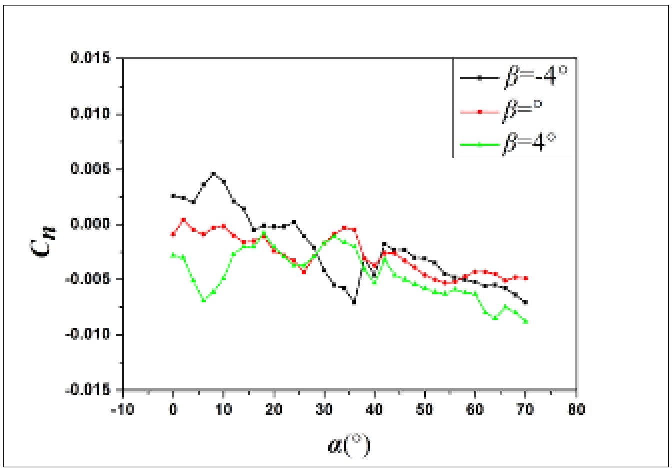

Figure 9 Yaw moment coefficient curves

Figure 8 and Figure 9 show the comparison curve of the roll moment coefficient and yaw moment coefficient under the condition of side slip and without side slip. It is converted into the lateral and directional stability derivatives $C_{l\beta}$ and $C_{n\beta}$, and The results are shown in Figure 10.

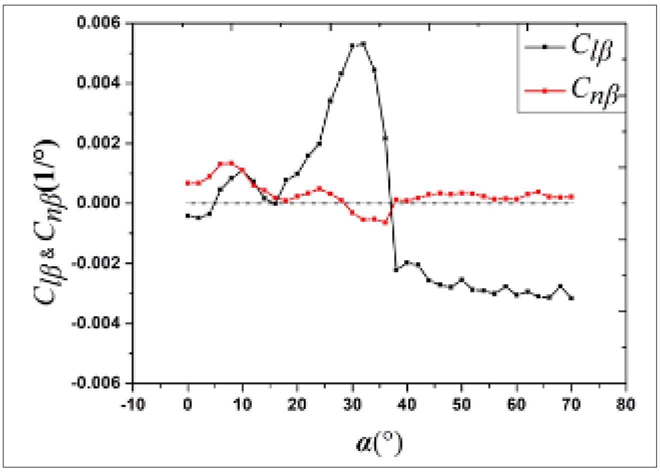

Figure 10 Lateral and directional stability derivatives

It can be seen from Figure 10 that the lateral static stability derivative changes from a negative value to a positive value at a 5 ° angle of attack, and the BWB aircraft changes from lateral static stability to lateral static instability, and its lateral static instability also intensifies with the increase of angle of attack. At 37 ° angle of attack, $C_{l\beta}$ changes from positive to negative value again, and the BWB aircraft regains lateral static stability. For the directional static stability derivative $C_{n\beta}$, when the angle of attack is not greater than 28 °, the BWB aircraft is directional static stability. When the angle of attack is 28 °, $C_{n\beta}$ changes from positive to negative, and the BWB aircraft changes from stability to instability. When the angle of attack is 38 °, $C_{n\beta}$ changes from a negative value to a positive value again, and the BWB aircraft returns to directional static stability.

Through the analysis of the lateral and directional static stability derivative, it can be preliminarily judged that the lateral static stability of the BWB aircraft is poor. It is lateral static instability at a slight angle of attack, and lateral instability motion may occur. The directional static stability is good. It shows static instability only in the range of 28 ° ~ 38 ° angle of attack.

6. Stability Analysis

If the stability of the aircraft is judged only from the static stability derivative, it will be different from the actual flight state. This section predicts the sensitive area of aircraft instability by fully mining the test data and analyzing the dynamic directional stability parameter, lateral control departure parameter, and Weissman chart.

6.1. Dynamic Directional Stability Parameter (Cnβ, Dyn)

The dynamic directional stability parameter ($C_{n\beta,\ Dyn}$) considers the comprehensive influence of the static stability derivative and moment of inertia on the directional stability of the aircraft at different angles of attack when the aileron and rudder are neutral, which can truly reflect the stability of the plane. Its expression is as follows:

$$C_{n\beta,dyn} = C_{n\beta}\cos\alpha - C_{l\beta}\left(\frac{I_z}{I_x}\right)\sin\alpha$$

When $C_{n\beta,\ Dyn}$> 0, it is considered that the aircraft will not produce divergence in the yaw direction.

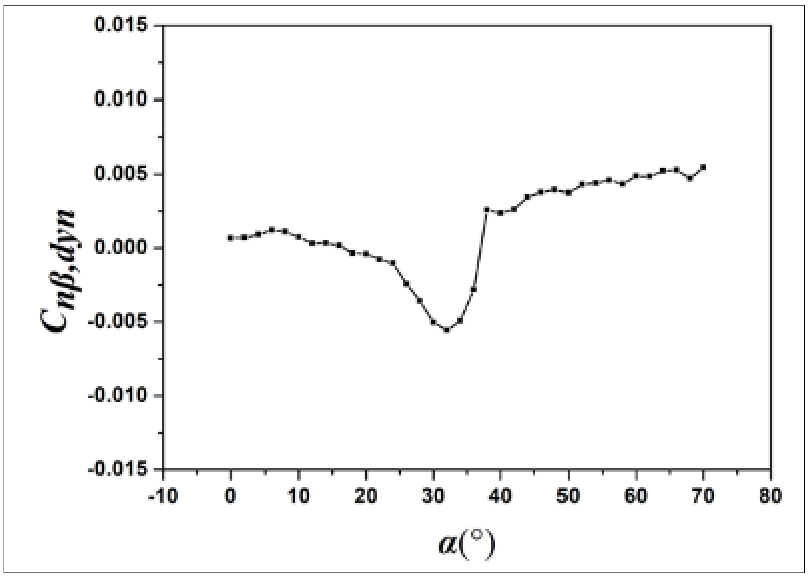

Figure 11 Dynamic directional stability parameter

Figure 11 shows the variation curve of $C_{n\beta,\ Dyn}$ with the angle of attack. It can be seen from the figure that in the range of 16 ° to 37 ° angle of attack, $C_{n\beta,\ Dyn}$ < 0 indicates that the instantaneous response to the sideslip angle will increase the sideslip angle and departure course of BWB aircraft at this angle of attack range. According to its prediction, the critical unstable angle of attack of BWB aircraft is 16 °.

6.2. Lateral Control Departure Parameter (LCDP)

The lateral control departure parameter introduces the influence of aileron control efficiency, mainly used to predict the sensitivity of aircraft yaw divergence during lateral control. It is defined as follows:

$$\mathrm{LCDP} = C_{n\beta} - C_{l\beta}\frac{C_{n\delta_a}}{C_{l\delta_a}}$$

If LCDP > 0, there is a tendency to eliminate the sideslip during lateral control automatically, and the aircraft is stable.

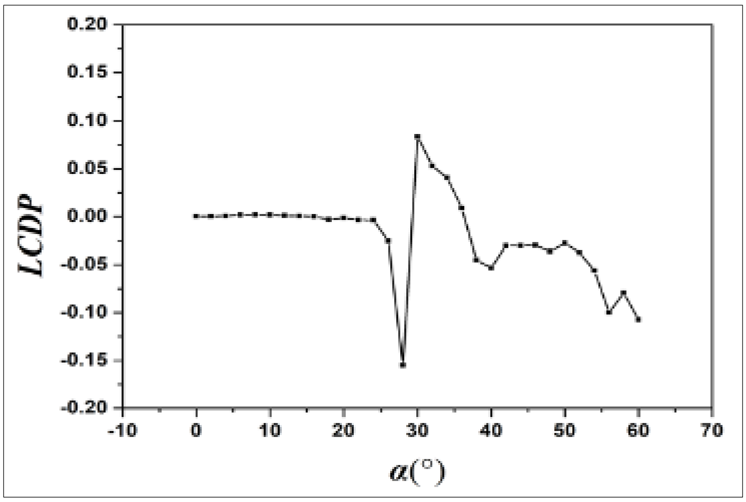

Figure 12 Lateral control departure parameter

As shown in Figure 12, the variation curve of LCDP with the angle of attack is shown. It can be seen from the figure that when the angle of attack is within 16 ° ~ 30 ° and the angle of attack is greater than 36 °, the LCDP is less than 0, and the BWB aircraft may yaw diverge. Therefore, the critical, unstable angles of attack predicted by LCDP are 16 ° and 36 °.

6.3. WEISSMAN chart

$C_{n\beta,\ Dyn,}$ and LCDP have an interactive relationship with certain limitations when used independently. In 1972, Weissman empirically put $C_{n\beta,\ Dyn,}$ and LCDP together, and the Weissman chart was drawn.

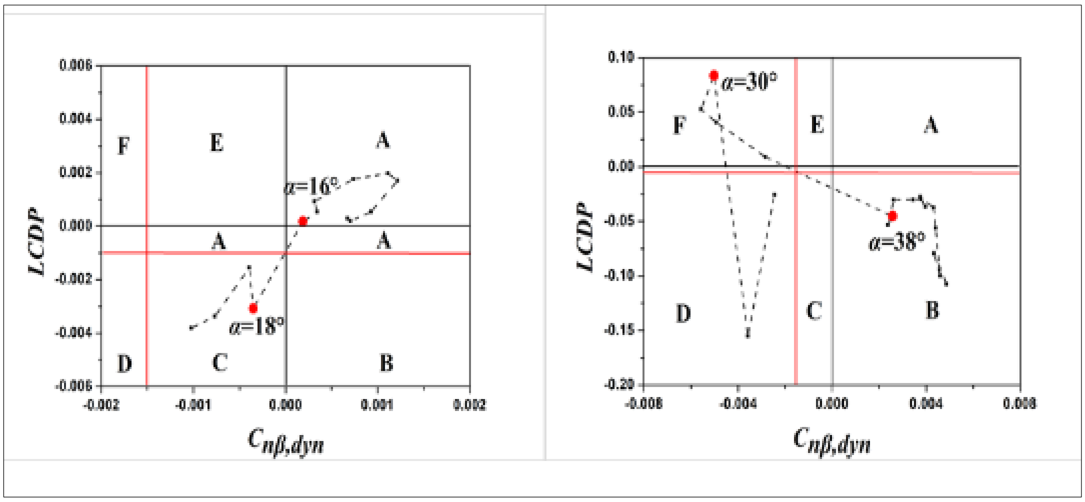

Figure 13 Weissman chart

Figure 13 shows the application of the Weissman chart on BWB aircraft in this paper. Figure 13 (a) and Figure 13 (b) show the parameter distribution after the angle of attack is less than 24 ° and greater than 24 °, respectively. Zone A is a non-departure zone; Zone B is a slight rolling control divergence zone; Zone C is a moderate yaw divergence zone; Area D is a substantial departure area; Zone E is a moderate yaw divergence zone; Area F is a strongly divergent area. It can be seen from Figure 13(a) that between 16 ° and 18 ° angle of attack, the curve enters Zone C from Zone A, and moderate yaw divergence may occur. It can be seen from Figure 13 (b) that when BWB aircraft enters Zone D from Zone C at an angle of attack of 24 ° to 26 °, there may be substantial yaw divergence or roll control divergence. When the angle of attack increases to 30 °, the BWB aircraft begins to enter zone F, and the divergence becomes very rapid. When the angle of attack reaches 38 °, the BWB aircraft enters B from zone F, and slight roll control divergence may occur. According to the Weissman chart, after the angle of attack is greater than 16 °, the BWB aircraft begins to enter different degrees of deviation areas, so it can be predicted that its critical unstable angle of attack is 16 °.

7. Discussion

In this paper, the stability of the aircraft is analyzed in different ways, and the unstable angle of attack under different criteria is obtained.

For this BWB aircraft, significant longitudinal characteristic changes may occur at 10 ° and 24 ° angles of attack. The lift coefficient decreases at these two angles of attack, and the longitudinal static stability derivative increases. In the slight angle of attack range of 4 ° ~ 10 °, the BWB aircraft is longitudinally statically unstable, while it is longitudinally statically stable after 10 °.

The BWB aircraft has poor lateral static stability. After a 16 ° angle of attack, $C_{l\beta}$ increases rapidly, and the lateral static instability increases, which is the main reason for the departure. According to the Weissman chart, after the angle of attack exceeds 24 °, there may be non-strong divergence, which is very rapid. At this angle of attack, it is directional static and stable, and the lateral static instability is great. The side slip caused by rolling makes the aircraft departure rapidly, resulting in the non-commanded movement of the aircraft.

Nomenclature

If they differ, numerals in parentheses are which are used in computing displays.

α = Angle of attack (deg)
β = Angle of sideslip (deg)
m = No. of control variables
n = No. of state variables
Cl = Coefficient of rolling moment
Cm = Coefficient of pitching moment
Cn = Coefficient of yawing moment
Clβ = Rolling moment coefficient derivative to β
Cnβ = Yawing moment coefficient derivative to β
AoA = Angle of Attack
BWB = Blended-wing-body
δ = Vector of system parameters
δa = Aileron defection (deg)
Ix = x body axis moment of inertia (kg m2)
Iz = z body moment of inertia (kg m2)
Cnδa = Rolling moment coefficient derivative to δa
Clδa = Yawing moment coefficient derivative to δa
Cnβ, Dyn =Dynamic Directional Stability Parameter

Subscript

dyn = Directional dynamic

8. Conclusion

In this paper, a series of stability analysis methods are used to analyze the stability of the aircraft, obtain the approximate initial unstable angle of attack and unstable region of the plane, and predict its sensitive region. These stability criteria reflect the unstable motion characteristics of aircraft from different aspects. Some requirements only include longitudinal parameters, lateral parameters, or directional parameters, while others are coupling criteria, including lateral and directional parameters. Therefore, we should comprehensively use various criteria to predict the instability characteristics when analyzing aircraft stability.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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