Aerodynamic, stability and flying quality evaluation on a small blended wing-body aircraft with canard foreplanes

Rizal E.M. Nasir, Wahyu Kuntjoro, Wirachman Wisnoe

Abstract

Blended wing-body (BWB) concept promises up to 30 percent increase in aerodynamic efficiency and reduction in fuel cost by having planform geometry optimized to increase lift and to reduce drag. Many claimed to have achieved the target of increasing lift-to-drag ratio better than current conventionally-configured airplanes either large airliners or small unmanned airplane. However, achieving good balance of aerodynamic efficiency, stability and flying quality is harder then one might expect. Over years of studying small BWB aircrafts in Universiti Teknologi MARA (UiTM), it is found that unconventional behaviour of aerodynamic characteristics leads to limitations to BWB aircraft’s flight envelope. In this paper, a short overview of aerodynamic, stability and flying quality of UiTM’s BWB aircraft design is highlighted. Lessons learned from its unusual lift-angle of attack curves, stability reversals, the effect of canard to flight stability and poor longitudinal flying quality (short-period mode and phugoid mode) are discussed. A classical control solution to improve it flying quality has been proposed and simulated and the result shows that both short-period and phugoid modes are able to achieve damping ratios within 0.6 to 0.8 exceeding minimum Level 1 damping ratios of 0.35 and 0.04 respectively. Design flaws of this aircraft and recommendations to be implemented on the next evolution of aircraft design conclude this paper.

Keywords: Blended Wing-Body; Unmanned Aerial Vehicle; Flight Dynamics; Aerodynamics
1. Introduction

The challenge of improving flight performance, particularly range and endurance, had been undertaken since the early years of aviation. Flying wing is one of the solutions, introduced in Germany as a concept for long-range bombers [1], its use is limited to short years within the United States Air Force (USAF) in a form of B-49 [2]. Problems related to flight dynamics and control hampered the flying wing to serve in long years unlike its B-52 counterpart until advancement of digital fly-by-wire electronic control allowed the flying wing to be revived again in a form of B-2 stealth bomber [3]. It was also the time, in the late 1980s, when Blended Wing-Body (BWB) concept was introduced – a hybrid of flying wing and conventional tubular fuselage-wing-tail configuration [4].

| Nomenclature |
|---------------|
| OFE Operational Flight Envelope |
| P Phugoid mode |
| SP Short-period mode |
| c Mean chord |
| CD Drag coefficient |
| CL Lift coefficient |
| CM Pitch moment coefficient |
| \(K_n\) static margin, \(K_n = h - h_n\) |
| h 1. Centre of gravity location with respect to datum 2. altitude in feet |
| \(h_n\) neutral point location with respect to datum |
| \(l_c\) pitch moment arm for canard foreplane |
| \(\eta_c\) canard incidence angle w.r.t. body x-axis |
| \(\omega\) Natural frequency |
| \(\zeta\) Damping ratio |

The BWB concept promises up to 30% fuel consumption reduction by improving lift-to-drag ratio. It was found that the current airliners’ conventional planform configuration had reach their limit of efficiency. Proposing flying wing airliners limits the passenger and cargo capacity thus a form of hybrid of the two different planform shape might be the answer. By carefully ‘blending’ the wing and body, removing tail and shaping the body like airfoil sections, one could reduce the wetted-surface area thus reducing skin friction drag, eliminate interference drag and increase lift [4]. This resulted in high lift-to-drag ratio, around 25 for some studies, compared with 18 for conventional configuration airliners while still carrying the same amount of passenger and payload [5, 6, 7, 8]. However, while BWB might poses the efficiency of a flying wing, it also inherit the latter’s problems. Due to lack (or none) of horizontal tail and its relatively high pitch moment from its large lifting body, the BWB have serious problems with its longitudinal static stability and flying qualities [9, 10, 11]. Electronic controllers with advanced algorithm may provide stability augmentation but it may be forced to work all the time creating all sort of dynamically changing trim drag that reduces its aerodynamic efficiency (lift-to-drag ratio) [12].

BWB research team in Universiti Teknologi MARA was formed in 2005 with the first design, Baseline-I (HANTU), freezed and tested in wind tunnel within a year. The Baseline-I is a mere replica of Liebeck’s planform with inspiration from the B-2 bomber albeit with intended use as a small two to four-metre span unmanned aircraft. It has the body span of 35 percent with body thickness-to-chord length ratio varies from 12 to 22 percent [13]. The study was extended to computational simulations to understand it aerodynamic behavior [14], implications to flight performance and flight stability and the effect of centre elevator to effectiveness of trim flight [15]. The second design took lessons learned from Baseline-I and used Inverse-Twist Method to design its planform and airfoil incidence [16]. The Baseline-II, introduced in 2009, had its body span reduced to just 19 percent, maximum body thickness reduced to 15 percent, larger wing area with high-wing location for lateral stability and smoother planform
shape [17]. Canard foreplanes of various sizes were incorporated to reduce its nose-down stability and improve its agility [18].

This paper evaluates aerodynamics, stability and longitudinal flying quality of Baseline-II BWB. The governing standard for flying quality is based on MIL-F-8785C [20]. There are three issues related to this aircraft. They are:

- **Aerodynamics** - Each BWB design is unique and aerodynamic behaviour may also be unique. Many studies have investigated BWB aircraft dynamics and stability characteristics at high subsonic cruising speed (Mach 0.8 and above). Baseline-II BWB flies much slower (Mach 0.1) making its stability characteristic more vulnerable to aerodynamic parameters such as airspeed and altitude.
- **Stability** - Canard may destabilize an aircraft by shifting neutral point forward.
- **Flying qualities** - This aircraft must satisfy minimum requirement for Level 1 flying quality according to MIL-F-8785C. Small BWB may have similar aerodynamics to the larger BWB but the effect of velocity and altitude to flight dynamics is unknown.

In evaluating Baseline-II BWB behaviour, main questions to be answered are whether or not it adheres to static stability requirements and does so efficiently with small reduction in its maximum lift-to-drag ratio. Baseline-II E-2 BWB aircraft must also satisfy Level 1 flying qualities for both phugoid and short-period modes. If Baseline-II E-2 BWB aircraft need a stability augmentation system to improve its flying qualities what kind of control law shall be applied to the system for this aircraft to have good flying qualities for flight missions within its OFE?

2. Evaluations

2.1. Aerodynamics and Static Stability

![Fig. 1. (a) Baseline-II BWB CAD model; (b) LST-1 Wind Tunnel; (c) Baseline-II wind tunnel model.](image)

Wind tunnel (WT) experiments is carried out in UiTM LST-1 low speed wind tunnel at Universiti Teknologi MARA with DARCS3D data acquisition (Fig. 1). The experimental setup used 3-component external balance with 1:11 scale half model with 0.35 m span, 0.04 m² wing-body plan form area, 0.114 m mean chord and moment reference centre (or centre of gravity) at 19.8% behind the leading edge of the mean chord. Blockage ratio is calculated at 1.9 percent at zero angle of attack and increases to five percent for maximum angle of attack. All experiments were conducted at average of 35 m/s airspeed (Mach 0.11) with average air density of 1.17 kg/m³ and average temperature of 24 degrees Celsius. The experiment aims to measure the forces and moments acting on the aircraft model for varying angles of attack and canard setting angle. The centre body in mounted on the flat, round, horizontal turn table as shown in Fig. 2. The load cell has been calibrated with maximum error of 0.5 percent at full-scale reading. The load cells are able to measure up to 50 kgf of force for each x and z axis with 25 kgf-m of y-moment. Airspeed is generated by a fan located behind the test section. The type of fan is suction axial flow fan with variable speed.
Fig. 2. (a) shows Baseline-II E2’s CL versus α plots for various Kc. The trend of these plots is linear at $-5^\circ \leq \alpha \leq 10^\circ$ that corresponds to $-0.4 \leq C_L \leq 0.6$ where the change of lift with respect to angle of attack $C_{La}$ is almost constant at around 0.05 to 0.06 per degree. There are reductions of $C_L$ within $10^\circ \leq \alpha \leq 15^\circ$. Beyond these, $C_L$ continues to rise up to their maximum (stall) of $C_{Lmax} = 0.9-1.0$ at $\alpha_{stall} \approx 45^\circ$. The existence of $C_L$ reduction within $5^\circ \leq \alpha \leq 15^\circ$ is unusual but not unique to Baseline-II BWB. Similar trend is also observed on other BWB aircrafts such as studied by Katz et. al. [5]. $C_L$ drops to 0.03 per degree at high D. Fig. 2 (b) shows L/D versus D plots. No-canard case maximum L/D is equals to 23.8. Installation of canard increases drag and reduces aerodynamic efficiency. Large $\eta_c$ brings maximum L/D even further down. Logical comprehension of this is that larger absolute $\eta_c$ causes larger drag, increases downwash and reduces effective lift generated by the wing-body region thus decreases L/D. The best canard angle configuration seem to be near zero $\eta_c$ which gives maximum L/D at $K_{ctrim} = 18.2$. Fig.2 (c) shows $C_{Mcg}$ versus $C_L$ plots. The centre of gravity is at $h = 0.198c$. Within $-5^\circ \leq \alpha \leq 10^\circ$, this aircraft is longitudinally stable as it has negative changes of $C_{Mcg}$ w.r.t. $\alpha$ ($dC_{Mcg}/d\alpha = C_{Ma}$) and $C_L$ ($dC_{Mcg}/dC_L = -K_a$). Canard affects two parameters crucial in determining static stability of an aircraft;

- Effect of $\eta_c$ to $C_{Ma}$ and $K_a$ - Negative $K_a$ means that the centre of gravity is in front of aircraft’s aerodynamic centre. $K_a$ is approximately 31.3% for canard-less case while with-canard cases, $K_a$ drops to around 6.0% to 20.4%. This confirms that a canard shifts aircraft’s aerodynamic centre forward.
- Effect of $\eta_c$ to $C_{Mcg}$ at zero $C_L$ ($C_{Mc}$) - $C_{Mc}$ shall be positive value for stable flight, hence positive $\alpha_{trim}$ ($\alpha$ at zero $C_{Mcg}$). Large $C_{Mc}$ causes large $\alpha_{trim}$ (Fig 2 (c) adn (d)) and this is a standard feature of many conventional aircrafts. Maximum L/D at trim flight ($L/D_{trim}$) can be found at $\eta_c$ slightly below 0.0°. This corresponds to $C_L \approx 0.45$, $\alpha_{trim} \approx 7.5^\circ$ and $L/D_{trim} = 18.2$. This will be the optimum flight condition for cruising. The change of
\[ C_{mo} \] with respect to the change of \( \eta \) is around 0.006 to 0.01 per degree and this is fairly small. Beyond \(-5^\circ \leq \alpha \leq +10^\circ\), stability reversals (unstable where \( K_c < 0 \)) are found on both positive and negative ends.

Baseline-II BWB satisfies the requirement of static stability but only for flight within \(-5^\circ \leq \alpha \leq +10^\circ\). Although canard “spoils” the high \( L/D \) to just mere 18.2, it is efficient enough for a small aircraft. Authors have identified a major flaw in the design of Baseline-II BWB – the location of the wing. The wing is located too far behind that nose-down moment is so strong the outer wing has to be twisted to provide counter moment, and the canard size has to be large and located far forward of the wing. This also causes large downwash on the wing root, reducing its lift.

### 2.2. Flying Qualities

Mathematical model is derived based on results from aerodynamic and static stability plots. Longitudinal dynamics model is derived based on convention shown in Fig. 3 (a). The dynamic state-space representation is shown in Fig. 3 (b). Simulated flight is programmed within MatLab environment and a flight simulator is constructed within X-Plane software. Five airspeeds and three altitudes are chosen to be included in the study, making a total of fifteen (15) flight “points of study” within operational flight envelope limit (OFE). These missions are:

- Minimum cruise airspeed set at about 1.3 times stall speed, level flight.
- Loitering airspeed set at maximum lift-to-drag ratio, level flight.
- Optimum cruise airspeed, set at airspeed for maximum range, level flight.
- Steady climb airspeed set at maximum excess power.
- Maximum cruise airspeed set at maximum airspeed achievable by the amount of available thrust.

![Diagram of flight dynamics](attachment:image.png)

Fig. 3. (a) Longitudinal forces, angles and axes convention (b) flight dynamics representation.
Fig. 4. Shows results of dynamic simulations, in this case, plots of damping ratios for (a) short-period mode and (b) phugoid mode that is crucial for evaluation flying quality. To achieve Level 1 quality standard, $\zeta_{sp} \geq 0.35$ while $\zeta_p \geq 0.04$. Additional requirement comes from short-period natural frequency that must adhere to specific parameter value that is less crucial for unmanned aircraft. In general, the longitudinal flying quality of Baseline-II BWB is poor. For short-period mode (Fig. 4(a)), Baseline-II BWB is unable to achieve Level 1. At near stall speed, $\zeta_{sp}$ decreases with increasing airspeed $U_o$ but stays constant at 60 m/s onward until reaching its maximum $U_o$. Moving the centre of gravity forward, hence increases $K_n$, has only made the $\zeta_{sp}$ to decrease further from 0.1 at $K_n = 0.1$ to 0.075 at $K_n = 0.2$. Shifting the centre of gravity backward towards neutral point reduces $K_n$ and improves $\zeta_{sp}$ but even at $K_n = 0.01$ the $\zeta_{sp}$ is still unable to achieve minimal damping ratio of 0.35 required by MIL-F-8785C. $\zeta_{sp}$ is less affected by altitude $h$.

In the meantime, phugoid mode is affected by both airspeed and altitude. $\zeta_p$ increases parabolically with increasing $U_o$ and increases linearly with increasing altitude. This aircraft has broad region of flight envelope that has Level 1 phugoid mode. Low speed flight, generally at $U_o < 50$ m/s, has Level 2 and 3 phugoid mode. Level 3
technically means unstable oscillation but this is allowed as long as the time to double amplitude is more than 55 seconds. Baseline-II BWB has this unstable phugoid mode for flight $U_o < 40 \text{ m/s}$ at sea level to $U_o < 70 \text{ m/s}$ at 30,000 feet altitudes. $\zeta_p$ is not affected by centre of gravity location. It was concluded that the behaviour of Baseline-II BWB can be summarized in Table 1. It is found that since dynamic pressure $Q_o$ is a function of $U_o$ and air density, which is also a function of altitude, it can be used as the basis to designing stability augmentation system.

### Table 1. Flying quality parameters relationships with $U_o$, $h$ and $Q_o$.  

| Flying quality parameter | Relationship w.r.t. airspeed, $U_o$ | Relationship w.r.t. altitude, $h$ | Relationship w.r.t. dynamic pressure, $Q_o$ |
|--------------------------|-------------------------------------|-----------------------------------|------------------------------------------|
| $\omega_{sp}$            | $\omega_{sp} \propto U_0$           | $\omega_{sp} \propto 1/h$         | $\omega_{sp} \propto \sqrt{Q_o}$        |
| $\zeta_{sp}$             | $\zeta_{sp} \equiv \text{constant for all } U_0$ | $\zeta_{sp} \propto 1/h$         | $\zeta_{sp} \equiv \text{constant for all } Q_0$ |
| $\omega_p$               | $\omega_p \propto 1/U_0$           | $\omega_p \equiv \text{constant for all } h$ | $\omega_p \propto Q_o^{0.5}$           |
| $\zeta_p$                | $\zeta_p \propto U_0^2$            | $\zeta_p \propto 1/h$            | $\zeta_p \propto Q_0$                   |

Fig. 5. (a) Proposed stability augmentation control scheme, (b) $\zeta_{sp}$ versus $U_o$ versus $K_{com}$, (c) $\zeta_p$ versus $U_o$.

Stability augmentation control scheme is proposed not just to achieve Level 1 for both modes but also to have excellent damping ratios for future, more-accurate flight-path control programme. Fig. 5 shows this scheme and the flight dynamic model is surrounded by second order actuator-canard dynamics, two loops of feedback and their governing laws, namely pitch attitude feedback with variable gain $K_\theta$ and pitch rate feedback with variable gain $K_q$, that are also fed by dynamic pressure $Q_o$ data from pitot-static tubes. The command is of pitch rate command, $\delta_{com}(s)$, with mechanical limitations is set on the canard $\eta(s)$ to avoid Baseline-II BWB from going into stability reversal region. The target for this augmentation system is to achieve damping ratios of 0.7 for both short-period and phugoid modes. The feedback gains control laws are determined using root locus computation for every flight missions within OFE coupled with analytical calculations. The required gains $K_\theta$ and $K_q$ are plotted against $Q_o$ to come up with trends and suitable equations that govern them. These equations are simplified for ease of
implementation in the proposed stability augmentation scheme. The results shows that the augmented Baseline-II BWB has $0.6 \leq \zeta_{\text{sp}} \leq 0.8$ and $0.7 \leq \zeta_{p} \leq 0.8$. The slight wider range of $\zeta_{\text{sp}}$ and $\zeta_{p}$ is due to simplication of $K_{\theta}$ and $K_{q}$. This combination of simple pitch rate and pitch attitude feedback governed by classical control law based on dynamic pressure proves to be adequate to provide excellent damping ratios for accurate navigation and more than adequate to achieve Level 1 longitudinal flying qualities.

3. Concluding Remarks

The need to adequately trim the flight and ensuring stability (static) at usable range of angle of attack reduces aerodynamic efficiency of Baseline-II BWB to just mere $L/D = 18.2$. The chosen centre of gravity location gives good static stability but not enough to achieve Level 1 short-period mode damping ratio. The phugoid mode, however, achieve Level 1 in most area within its OFE but this may be due to low specification stated in MIL-F-8785C standard. The proposed stability augmentation scheme based on classical approach that consists of pitch rate and pitch attitude feedbacks with gains governed by dynamic pressure gives good longitudinal flying quality exceeding minimal values stated in the standard.

Despite gaining good flying quality the biggest setback is the loss of $L/D$ value due to installation of canard due to wing location that is at the rear of the body. Several improvements are proposed to improve this, 1. Move the wing forward, reducing its nose-down stability, so smaller canard shall be installed and 2. Move the wing forward even more and have long but thin rear body section as elevator just like some birds having tails ‘blended’ to the body shape. Based on lessons learned from this study, authors chose the second option in which Baseline-III BWB design has been proposed and currently being studied.

Acknowledgements

Authors would like to express gratitude to the UiTM’s Research Management Institute for granting a fund of RM32,000 for this research, the Faculty of Mechanical Engineering UiTM for various support and Mr. Syahriral Subuh, Mrs. Zurriati Ali, Mr. Firdaus Mohamed and Mrs. Fazira Redzuan for assistance in the laboratory.

References

[1] Myhra D. The Horten Brothers and Their All-wing Aircraft. London: Bushwood Books, 1997.
[2] Coleman T. Jack Northrop and the Flying Wing: The Real Story Behind the Stealth Bomber. New York: Paragon House, 1988.
[3] Pace S. B-2 Spirit: The Most Capable War Machine on the Planet. New York: McGraw-Hill, 1999.
[4] Liebeck RH, Page MA, Rawdon BK. Blended Wing Body Subsonic Commercial Transport. AIAA Technical Paper 98-0438, 1998.
[5] Katz J, Byre S, Hahl R. Stall resistance features of lifting body airplane configurations. Journal of aircraft, 1999;36/2: 471-478.
[6] Qin N, Yavalle A, Le Moigne A, Laban M, Hackett K, Weinnerfelt P. Aerodynamic considerations of blended wing body aircraft. Progress in Aerospace Science, 2004:321-343.
[7] Gebbie DA, Reeder MF, Tyler C, Fonov V, Crafton J. Lift and Drag Characteristics of a Blended Wing Body Aircraft. Journal of aircraft, 2007;44(5):1409-1418.
[8] Zhu Z, Wang X, Wu Z, Chen Z. A new type of transport: blended wing body aircraft. Hangkong Xuebaon/Acta Aeronautica et Astronautica Sinica, 2008;29(1):49-59.
[9] Jung DW, Lowenberg MH. Stability and control assessment of a blended-wing-body airliner configuration. AIAA Atmospheric Flight Mechanics Conference and Exhibition. San Francisco, California. 15-18 August 2005.
[10] Saephan S, Van Dam CP. Simulation of the tumbling behaviour of tailless aircraft. 24th Applied Aerodynamics Conference. San Francisco, California. 5-8 June 2008.
[11] Bolsunovsky L, Buzoverya NP, Gurcviceh BI, Denisov VE, Dunacvsky AI, Shkadov LM, Sonin OV, Udzduhu AJ, Zhurihin JP. Flying Wing- Problems and Decisions. Aircraft Design 2001; 4:193-219.
[12] de Castro HV. Flying and handling qualities of a fly-by-wire blended-wing-body civil transport aircraft. PhD. Thesis. Cranfield University, 2003.
[13] Ihsan Mamat AM, Mohd Nasir RE, Ngah Z, Kuntjoro W, Wisnoe W. Aerodynamics Of Blended Wing Body (BWB) Unmanned Aerial Vehicle (UAV) Using Computational Fluid Dynamics (CFD). Proceedings of Conference on Social & Scientific Research, Subang Jaya, Malaysia, 2007.
[14] Ihsan Mamat AM, Mohd Nasir RE, Ngah Z, Kuntjoro W, Wisnoe W, Ramly R. Aerodynamics Of Blended Wing Body (BWB) Unmanned Aerial Vehicle (UAV) Using Computational Fluid Dynamics (CFD). Journal of Mechanical Engineering, UiTM, 2008;5(2):15-26.

[15] Nasir REM, Kuntjoro W, Wisnoe W, Mamat AMI. The Effect of Centre Elevator on Aerodynamics of UiTM Baseline-1 Blended Wing Body (BWB) Unmanned Aerial Vehicle (UAV) at Low Subsonic Speed. Journal of Mechanical Engineering, UiTM, 2009;6(2):73-96.

[16] Nasir REM, Kuntjoro W, Wisnoe W, Ali Z, Reduan NF, Mohamad F, Suboh S. Preliminary Design of “Baseline-II” Blended Wing-Body (BWB) Unmanned Aerial Vehicle (UAV): Achieving Higher Aerodynamic Efficiency Through Planform Redesign and Low-Fidelity Inverse Twist Method. Proceedings of 3rd Engineering Conference on Advancement in Mechanical and Manufacturing for Sustainable Environment, Kuching, Sarawak, Malaysia, April 14-16, 2010.

[17] Wisnoe W, Kuntjoro W, Mohamad F, Nasir REM, Reduan NF, Ali Z. Experimental Results Analysis for UiTM BWB Baseline-I and Baseline-II UAV Running at 0.1 Mach number. International Journal of Mechanics 2010;4(2):23-32.

[18] Nasir REM, Kuntjoro W, Wisnoe W, Ali ZM, Reduan NF, Mohamad F. The Effect of Canard on Aerodynamics and Static Stability of Baseline-II Blended Wing-Body Aircraft at Low Subsonic Speed. Proceedings of the 4th World Engineering Congress, Kuching, Sarawak, Malaysia, August 2-5, 2010.

[19] MIL-F-8785C. Flying Qualities of Piloted Airplanes. Military Standard. 5 Nov. 1980.