The Effects of Tail-Tilt on the Yaw Stability of Baseline-V Blended Wing Body Aircraft

Nur Syazwani C.M.
Rizal E.M. Nasir
Flight Technology Test Centre, Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia

ABSTRACT

This paper presents a study on the effects of tilting the tail on yaw stability performance of Baseline-V blended wing body (BWB) aircraft. The study on BWB aircraft began in UiTM in 2005 and a few designs of BWB aircraft have been studied and published. Recent progress on BWB study in UiTM indicates major flaws in BWB technology particularly its stability and issues regarding limited controllability since it is unequipped with any vertical tail to perform directional motion. Some ideas have been proposed generally to overcome the problems such as designing large central elevator on Baseline-I, attaching canard and belly-flap on Baseline-II, general shape mimics flying birds for Baseline-III and birds inspired control surface by adding horizontal tail for Baseline-IV. The results showed that some of the ideas gave positive feedback into stability and some degraded the aerodynamic efficiency. Even to this day, in general the research community and industry have not concluded any solutions or guidelines to overcome some problems of BWB aircraft design. It is proposed that the Baseline-V BWB aircraft to have a horizontal close-coupled tail located at wing trailing edge inspired by bird control surface so that longitudinal (pitch) and lateral-directional (yaw) stability suffered by BWB aircraft are solved. The objective of this study was to determine the effectiveness of close-coupled tail on Baseline-V BWB to overcome the problems regarding stability. This was achieved by conducting wind tunnel tests at low speed tunnels at Universiti Teknologi Malaysia (UTM-LST). The test model was a full scale model of Baseline-V and was tested at actual test speed of 15m/s (54 km/h). The longitudinal and lateral directional aerodynamic characteristics of the aircraft such as coefficients of forces (lift, drag and side forces) and coefficients of moments (roll, pitch and yaw moment) were experimentally measured. Based on the results, tilting tail of Baseline-V gave positive feedback in terms of stability.

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2016-09-30
Accepted for publication: 2017-05-27
Published: 2017-11-15

Keywords: *Blended Wing Body, Stability, Tail-Tilt, Wind Tunnel Experiment*

Introduction

Future air transport vehicle needs to comply with stringent regulations related to fuel consumption, noise and harmful gas emissions. A Blended Wing Body (BWB) aircraft was introduced in the late 1980s and as the name suggested, a BWB aircraft was the aircraft that had configuration where the wing and its body were blended together [1]. By carefully "blending" both wing and body, while at the same time removing the tail and making the body fully airfoil section, one could reduce the wetted-surface area and reduce the skin friction drag, and finally increase lift. Blended wing body aircraft configuration can offer reduction in fuel consumption and noise by reducing drag [2]. It has lifting body, instead of tubular fuselage, blended smoothly to its wing; thus, it increases lift force. The smooth transition between body and wing reduces interference drag and its low wetted surface area compared to conventional aircraft of the same volume reduces skin-friction drag. The combination of high lift and low drag forces increases the lift-to-drag ratio of the blended wing body aircraft of up to 20% more than conventional aircraft [3]. Studies on blended wing body aircraft configuration became favourite topics among researchers in aircraft design and many on them discussed advantages and issues related to its aerodynamics and stability.

An increasing interest exploring the BWB aircraft can be seen over the past years due to its high potential benefits especially in aerodynamic efficiency. Its configuration itself resulted into great enhancement by reduction in wetted area that finally reduced the skin surface area to friction drag associated to conventional aircraft while at the same time preserved the payload as well as other substantial performance [2]. This resulted into high aerodynamic efficiency for some cases BWB aircraft of previous researchers that were around 25, compared to conventional configuration aircraft lift-to-drag ratio that was around 18 while carrying the same amount of payload [4, 5]. Bolsunovsky mentioned that the integration of body and wing of an aircraft shall improve its aerodynamic gain [6]. Besides, compared to the conventional configuration aircraft, BWB aircraft has some other advantages such as noise reduction, greater internal volume and improvement on cost-per-seat-mile.

However, previous studies have proven that it was hard to achieve and get high aerodynamic efficiency while at the same time maintaining the aircraft stability especially for unconventional aircraft configuration [7, 8]. The control surfaces of BWB aircraft are different from conventional configuration aircraft especially for longitudinal and directional control. Since BWB aircraft is tailless aircraft, it is reported that some BWB aircrafts have the same stability issues just like flying wing [9]. Tailless means this type of aircraft comes with or without vertical and purely without horizontal tail such as B-2 Bomber aircraft that was designed purely without both vertical and horizontal tail [10]. Nevertheless, not all BWB aircraft type comes without vertical tail such as X-48B since UiTM also studied a single vertical tail on Baseline-II [11, 12]. The presence of the vertical tail may be different in terms of configuration and position compared to conventional aircraft since some of the vertical tails of BWB aircraft are located at the wings.

Since attached vertical tail may sometimes not compatible for some BWB aircraft configurations, conventional rudder seems not appropriate to be used for directional control to overcome stability issues. Previous researchers also want to maintain BWB aircraft tailless configuration and some of them mechanically put forward other alternatives to overcome stability problems. The unconventional control surfaces such as split drag flaps, inboard and outboard ailerons, winglet rudders and canard were attached to unconventional configuration aircraft to improve stability for both longitudinal and directional motion [13, 14, 15, 16]. In order to find the best control surfaces for directional control on tailless aircraft, some experiments were carried to identify reliable configuration of yaw control surfaces. Northrop found that split drag flap was the best and reliable configuration for directional control of tailless aircraft. UiTM also carried out a study on split drag flap and it was found that the aircraft was directionally unstable even though the split drag flaps was deployed [17].

While many recent studies focused on large airlines size of BWB aircraft, Flight Technology and Test Centre (FTTC) in UiTM focused on small UAV. BWB UAV study in UiTM began in 2005 by focusing on design and fundamental aerodynamics of a small BWB UAV. Currently there are four designs that have been tested in LST wind tunnel. Figure 1 shows the planform view of all four Baseline designs under UiTM study. Early design has poor lift-to-drag ratio and longitudinal stability on Baseline-1 BWB [18]. The second design known as Baseline-II was developed based on lessons learned from earlier BWB and was able to achieve lift-to-drag ratio of around 24 [19]. However, canard foreplane must be introduced to ensure good longitudinal stability [4]. Baseline-III design was inspired by bird that did not achieve good lift-to-drag ratio and it had poor longitudinal stability. Baseline-IV BWB replaced straight and swept wing of Baseline-III by delta wing with additional close-coupled horizontal tail behind the wing trailing edge [20]. Aerodynamic efficiency was increased compared to Baseline-II with improvement on longitudinal stability. The all-moving horizontal tail stabilized Baseline-IV BWB but it still had no yaw control. Based on the studies, it was found that BWB aircraft having planform published by other established researchers somehow did not guarantee efficient aerodynamics and at the same it had problems regarding stability.

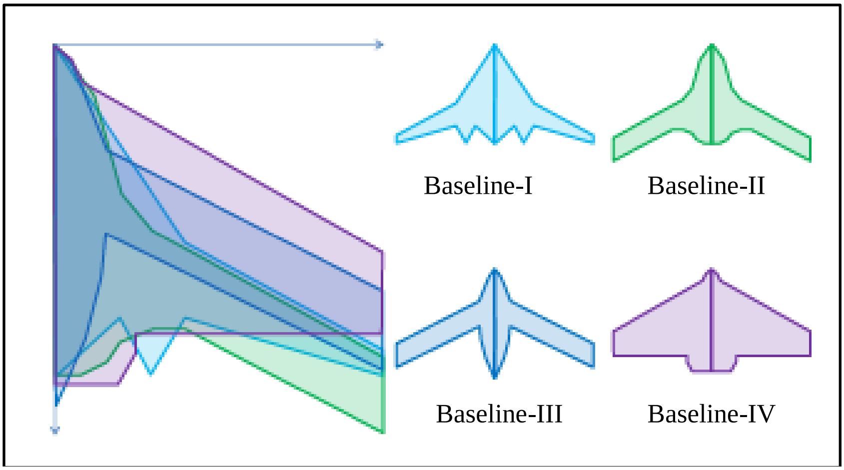


Figure 1: Planform of BWBs in study

It is recommended that inspirations shall come from nature. For millions of years, many researchers have tried to mimic bird's wing and tail movements. It was found that mimicking bird-body and bird-tail planform can be used to stabilize the aircraft. BWB planform configuration is much like a flying wing compared to pure conventional aircraft. There is a gap between BWB and conventional aircrafts that is a configuration in which its planform looks more like a bird. Birds in real life have no vertical tail like flying wing but its planform is similar like conventional aircraft configuration than BWB configuration. Past researchers have studied the behaviour of birds while flying especially related to horizontal tail [21]. Twisting the bird tails along the longitudinal axis can generate yawing moments. Hence, the tail will no longer become control surface that is strictly in horizontal plane but has a component in vertical plan too. Turning or tilting tail in axial axis can function as rudder. Gottfrid et al. concluded that compared with the wing, tail was more effective in producing yawing moment due to sideslip since the wing had a larger aspect ratio compared to the tail [22].

It is proposed here that a close-coupled horizontal tail with elevator and tilting capability to be integrated with the design of a blended wing body to provide stability and control in pitch and yaw motion just like a bird's tail. Baseline-V blended wing body UAV highlighted in this paper incorporated the close-coupled tail mentioned not only to provide stability in pitch and some control in yawing motion but also to maintain its high lift-to-drag ratio. Figure 2 shows the idea of Baseline-V with close-coupled tail attached behind the wing-body that was inspired by bird control surface so that longitudinal (pitch) and lateral-directional (yaw) stability suffered by flying wing and BWB are solved. As a result, when one takes a look at planform view, Baseline-V still looks like a tailless BWB aircraft configuration.

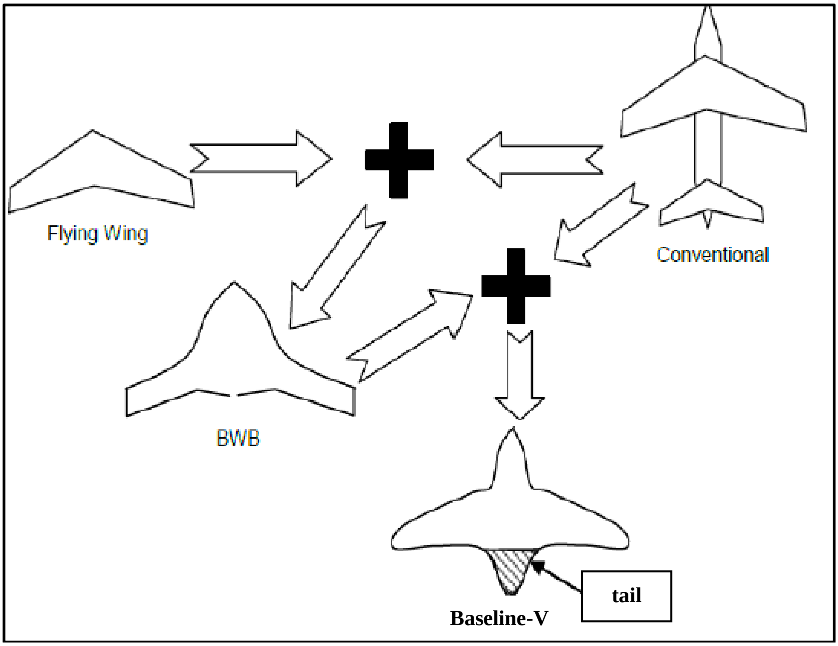
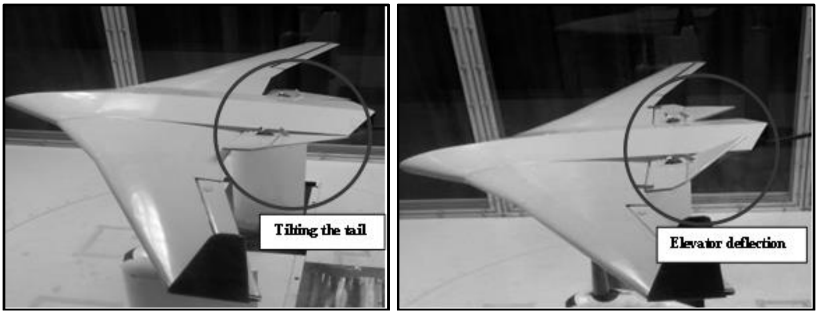


Figure 2: BWB with addition of tail concept

The purpose of additional tail may increase longitudinal moment arm by significant margin; thus, it requires only a small tail pitch angle to trim at cruising condition. This may only slightly increase drag but the penalty on the lift-to-drag ratio may be very small compared to adding proper horizontal tail or canard foreplane. The tail can also be tilted longitudinally (rotational about longitudinal axis) as shown in Figure 3 below to become a combination elevator and rudder diminishing the needs for a proper vertical tail. This looks like an ideal mechanical solution to longitudinal and lateral stability which controls problems without significantly reducing its aerodynamic efficiency. The objective of this paper was to evaluate the stability of Baseline-V Bird-Inspired BWB aircraft by testing full-scaled model inside a low speed wind tunnel.



(a) (b)

Figure 3: Baseline-V BWB; (a) tilting the tail (b) elevator deflection

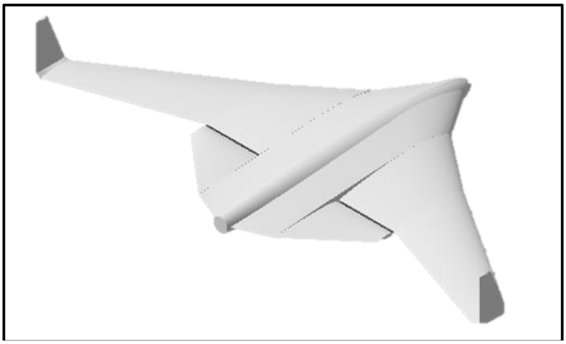


Figure 4: Baseline-V BWB

Baseline-V Model and Test Setup

An experiment was conducted in low speed wind tunnel (UTM-LST) at Aeronautic Laboratory of Universiti Teknologi Malaysia (UTM). The overall test set up is shown in Figure 5. The wind tunnel had a test section of 4.9 ft x 6.6 ft x 19.0 ft (1.5 m x 2 m x 5.8 m) and was of closed circuit type.This tunnel can operate at wind speed between 3 to 80 m/s.

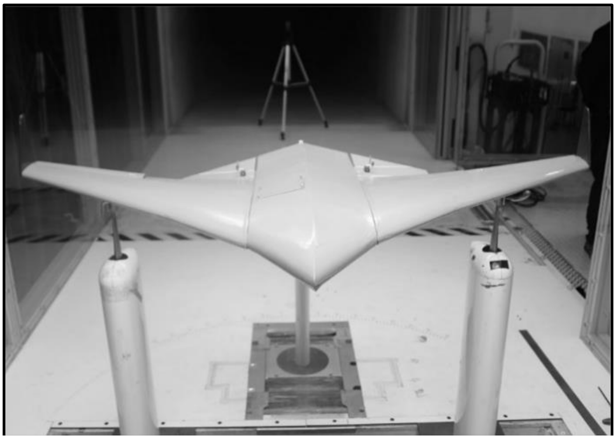


Figure 5: Overall test set up

A full scale wind tunnel model of Baseline-V with control surfaces that can be deflected remotely was mounted on three struts connected to turntable on the floor. The turntable was mounted on balance with sensors to measure forces and moments aircraft varying aircraft angle of attack. The aft pitching strut was connected to the model using a single boom. The model was being tested at actual flight speed of 15 m/s. Since the model was tested in an actual size of flying UAV, the results obtained in this experiment were assumed to be the actual aerodynamic behaviour of Baseline-V BWB. No computational fluid dynamic (CFD) simulation was needed in this case. The model was installed in the wind tunnel using three struts mounting system at the centre of the test section. For aircraft pitching system, the aft pitching strut was connected to the model using a single boom as shown in Figure 6.

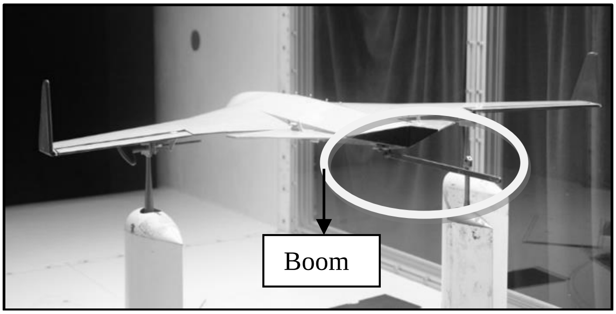


Figure 6: Connecting pitching strut and model using boom

The experiment focused on measuring aerodynamics forces and moments by varying aircraft angle of attack and side-slip angles. The effect of elevator angles and tilting angles of the horizontal tail to lift, drag, pitch moment and yaw moment was to be observed, analysed and concluded. Table 1 summarizes the experiment cases while carrying out the wind tunnel experiments for Baseline-V.

Table 1: Experiment cases

Velocity (m/s)	**Yaw**	**Pitch**	**Configurations/Notes**
0, 10, 15, 20	0	0	Bayonet test
0	Ψ	0	Tare Data (Yaw),Zero control surface
15	Ψ	0	Zero control surface
15	Ψ	0	Tail Tilt 15 degree (starboard Down)
15	Ψ	0	Tail Tilt 30 degree (starboard Down)
15	Ψ	0	Tail Tilt 45 degree (starboard Down)
15	0	α	Elevator -20 Degree (Upward)
15	0	α	Elevator -10 Degree (Upward)
15	0	α	Elevator +10 Degree (Downward)
15	0	α	Elevator +20 Degree (Downward)

Yaw Moment Theory

Figure 7 shows the sign convention for aerodynamic forces and moments for Baseline IV BWB aircraft. If we take a summation of side force equation in terms of coefficients form, we have:

$$\xrightarrow{+} \sum F_s = C_S \tag{1}$$

Hence;

$$C_S = C_{S_{WB}} + C_{S_T}\left(\frac{S_T}{S_{WB}}\right)\sin\kappa \tag{2}$$

where ***CS_{WB}*** is side coeffients of wing body, ***CS_T*** is side coefficients of tail, ***S_T*** is area of tail and ***S_{WB}*** is area of wing body. Equation (2) can be rewritten in the form of:

$$C_S = \frac{dC_{S_{WB}}}{d\beta}\beta + \left(\frac{dC_{S_T}}{d\beta}\beta + \frac{dC_{S_T}}{d\eta}\eta\right)\left(\frac{S_T\sin\kappa}{S}\right) \tag{3}$$

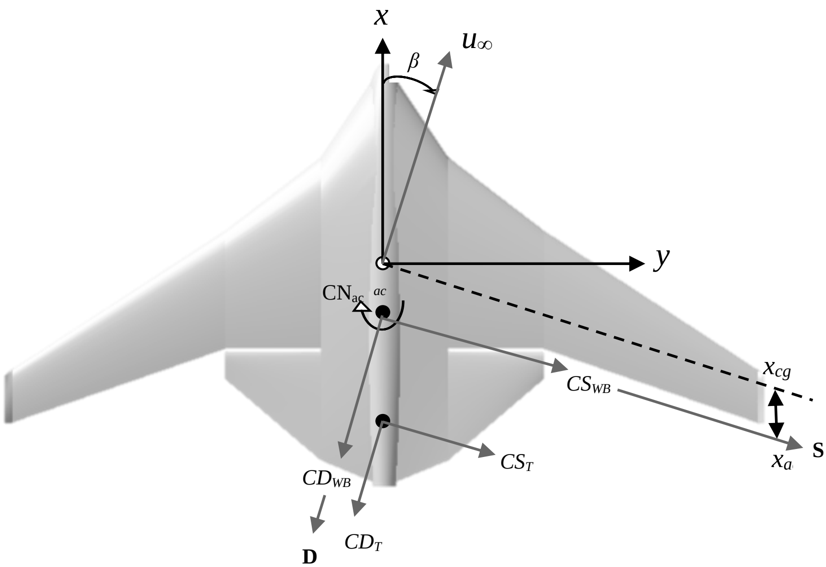


Figure 7: Sign convention for aerodynamic forces and moments

Rearrange equation (3),

$$C_S = \frac{d\left\{C_{S_{WB}} + C_{S_T}\left(\frac{S_T \sin\kappa}{S}\right)\right\}}{d\beta}\beta + \frac{dC_{S_T}}{d\eta}\left(\frac{S_T \sin\kappa}{S}\right)\eta \tag{4}$$

Since in this study elevator angles, η=0, then it can be concluded that;

$$C_S = \frac{d\left\{C_{S_{WB}} + C_{S_T}\left(\frac{S_T \sin\kappa}{S}\right)\right\}}{d\beta}\beta \tag{5}$$

The yaw moment is the moment about the z_{body} axis and a big contributor to the yaw moment is the tail of the aircraft. If we take a yaw moment equation in terms of coefficients form, we have:

$$\sum N_{cg} = C_{N_{cg}} = C_{N_{cg_{WB}}} + C_{N_T} \tag{6}$$

Equation (3) can be rewritten in the form of:

$$C_{N_{cg}} = \frac{dC_{N_{cg_{WB}}}}{d\beta}\beta + \left(\frac{dC_{S_T}}{d\beta}\beta + \frac{dC_{S_T}}{d\eta}\eta\right)\left(\frac{S_T \sin\kappa}{S}\frac{l_T}{c}\right) \tag{7}$$

where $\mathbf{CN_{cg}}$ is yaw moment coefficients at centre of gravity, $\boldsymbol{CNcg_{WB}}$ is yaw moment coefficients at centre of gravity for wig body, $\boldsymbol{CN_T}$ is yaw moment coefficients for tail, $\boldsymbol{l_T}$ is length of the tail and $\boldsymbol{c}$ is mean chord.

Let $C_{N_{cg_{WB}}} = C_{N_{acWB}} - C_{S_{WB}}\left(\frac{x_{ac} - x_{cg}}{c}\right)$

where $(x_{ac} - x_{cg})$ is distance between aerodynmic centre and centre of gravity point. Hence;

$$C_{N_{cg_{WB}}} = C_{N_{acWB}} - \frac{dC_{S_{WB}}}{d\beta}\left(\frac{x_{ac} - x_{cg}}{c}\right)\beta\left(\frac{S_T \cos\kappa}{S_{WB}}\right) \tag{8}$$

Substitute equation (8) into equation (7);

$$C_{N_{cg}} = \frac{d\left\{C_{N_{acWB}} - \frac{d\,C_{S_{WB}}}{d\beta}\left(\frac{x_{ac} - x_{cg}}{c}\right)\beta\left(\frac{S_T \sin\kappa}{S_{WB}}\right)\right\}}{d\beta}\beta + \left(\frac{dC_{S_T}}{d\beta}\beta + \frac{dC_{S_T}}{d\eta}\eta\right)\left(\frac{S_T \cos\kappa}{S}\frac{l_T}{c}\right) \tag{9}$$

With this expressions for the stability derivative, equation (9) can be rewritten in convinient form:

$$C_{N_{cg}} = \frac{dC_{N_{acWB}}}{d\beta}\beta - \frac{d^2 C_{S_{WB}}}{d\beta^2}\beta^2\left(\frac{x_{ac} - x_{cg}}{c}\right)\left(\frac{S_T \sin\kappa}{S_{WB}}\right) \tag{10}$$

It can be concluded that good stability in yaw will have the parabolic graph pattern.

Result and Discussion

Side force coefficients versus sideslip angle

Figure 8 shows a trend of side force coefficients versus sideslip for varying tilt angles cases. Basically, all of the tilting tail case trends showed negative slope which means that side force coefficients decreased as the sideslip angles was increased. At negative sideslip angles, all of the cases resulted into positive side force coefficients. As the sideslip angles increased, side force coefficients turned negative. For zero tilt angle, $\kappa = 0$ degree the trend showed almost symmetrical to the origin.

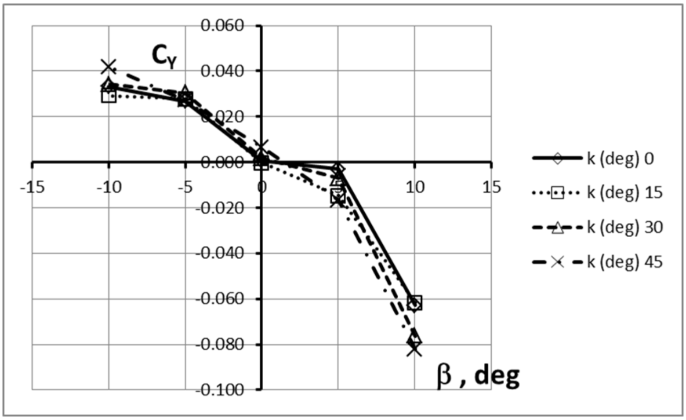


Figure 8: Graph of side force coefficients versus sideslip angle

Drag coefficients versus sideslip angles

Figure 9 shows the results obtained for varying tilt angles on drag coefficients versus sideslip angles. Generally, from the results, it can be concluded that as the side slip angle increased from negative to positive, the drag coefficients recorded for all cases were reduced. However, there were some drag drops at side slip angle, β= -5 degree where all the tail tilt angles experienced the same situation. Further analysis should be done to investigate the real phenomena that occurred at this angle. Basically, for zero tilting angle cases, the trend should be symmetrical as mentioned in the side force coefficients versus side slip angles cases where the value of drag coefficients should be the same for positive and negative side slip angles since at these conditions, the aircraft was symmetrical to the longitudinal axis.

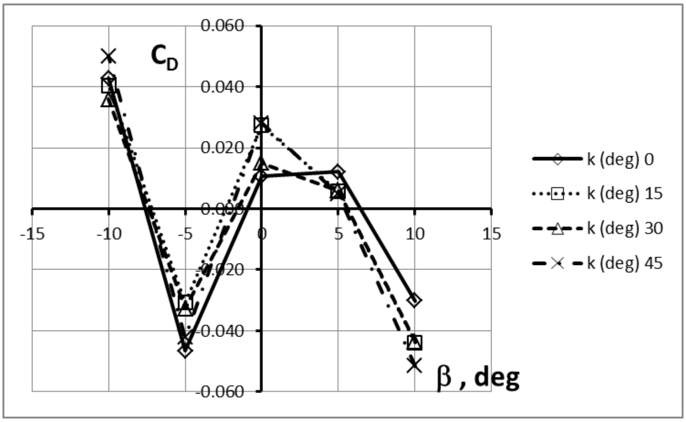


Figure 9: Graph of drag coefficients versus sideslip angle

Yaw moment coefficients versus sideslip angles

Figure 10 shows yaw moment coefficients versus side slip angles for different tail tilt angle cases. Nothing unusual was found on the results obtained. As can be seen from the trend, all of the tilt cases experienced negative yawing moments at negative side slip angles and as the side slip angles increased, yawing moment coefficients became positive. It can be concluded that Baseline-V had the tendency to rectify and balance its position when facing the wind since it had static stability behaviour from any disturbance especially in yaw direction.

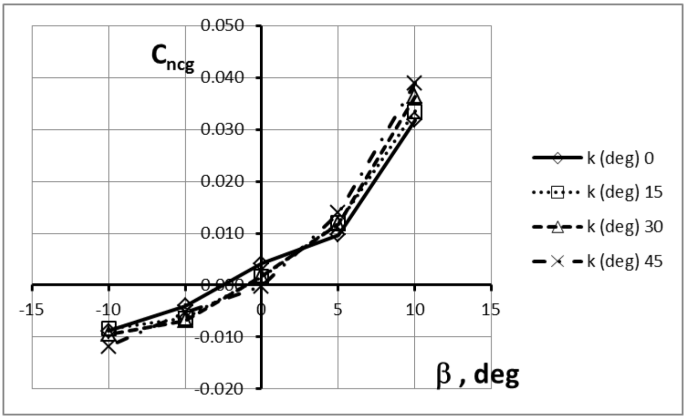


Figure 10: Graph of yaw moment coefficients versus sideslip angles

Conclusion

Design yaw control surface for UiTM's Baseline-IV BWB by attaching close-coupled horizontal tail was performed for this study. Close-coupled tail was chosen to provide stability and control in pitch and yawing motion just like a bird's tail.

The series of wind tunnel experiments of Baseline-V BWB with the effect of various close-coupled tail tilt angle were done at elevator angle in the range of $-10^{o} \leq \beta \leq +10^{o}$. The longitudinal and lateral directional aerodynamic characteristics for selected yaw control surfaces were obtained in terms of dimensionless coefficients such as drag, side force coefficients and yawing moment coefficients. It was observed that Baseline-IV BWB was directionally stable in yaw. Besides, various tail tilt angles also gave some effects on stability trends.

Acknowledgement

The research presented in this paper is a part of continuation research project undertaken by Aviation Technology Research Group (ATR) under Flight Technology Test Centre (FTTC) of Faculty of Mechanical Engineering UiTM Shah Alam. Authors would like to express gratitude to the UiTM's Research Management Institute and Administration of High Education for granting a fund under FRGS GRANT (600-RMI/FRGS 5/3 (103/2014)) for this research and Faculty of Mechanical Engineering UiTM for various support.

References

[1] Liebeck RH, Page MA, Rawdon BK. Blended Wing Body Subsonic Commercial Transport. AIAA Technical Paper 98-0438, 1998.

[2] R. H. Liebeck, "Design of the Blended Wing Body Subsonic Transport," Journal of Aircraft, vol. 41, no. 1, pp. 10–25, 2004.

[3] N. Qin, Vavalle, Le Moigne, M. Laban, K. Hackett, and P. Weinerfelt, "Aerodynamic considerations of blended wing body aircraft," Progression in Aerospace Science, vol. 40, pp. 321–343, 2004.

[4] R. E. M. Nasir, W. Kuntjoro, and W. Wisnoe, "Aerodynamic, Stability and Flying Quality Evaluation on a Small Blended Wing-body Aircraft with Canard Foreplanes," Procedia Technology, vol. 15, pp. 783–791, 2014.

[5] Zhu Z, Wang X, Wu Z, Chen Z. A new type of transport: blended wing body aircraft. Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica, 29(1), 49-59, 2008.

[6] Bolsunovsky, N. Buzoverya, B. Gurevich, V. Denisov, Dunaevsky, L. Shkadov, O.Sonin, Udzhuhu, and J. Zhurihin, "Flying wing - problems and decisions," Aircraft Design, vol. 4, pp. 193–219, 2001.

[7] M. Kanazaki, R. Hanida, T.Nara, M. Shibata, T. Nomura, M. Murayama, and K.Yamamoto, "Challenge of design exploration for small blended wing body using unstructured flow solver," Computational Fluids, vol. 85, pp. 71–77, 2013.

[8] P. Dehpanah and A. Nejat, "The aerodynamic design evaluation of a blended-wing-body configuration," Aerospace and Science Technology, vol. 43, pp. 96–110, 2015.

[9] Abbas, J. De Vicente, and E. Valero, "Aerodynamic technologies to improve aircraft performance," Aerospace and Science Technology vol. 28, no. 1, pp. 100–132, 2013.

[10] Gloria Stenfelt and Ulf Ringertz, "Yaw Control of a Tailless Aircraft Configuration", Journal of Aircraft (0021-8669) Vol. 47 No. 5, pp. 1807-1811, 2010.

[11] Wirachman Wisnoe, Rizal E.M. Nasir, Ramzyzan Ramly, Wahyu Kuntjoro, Firdaus Muhammad, "Aerodynamic Of Uitm's Blended-Wing-Body Unmanned Aerial Vehicle Baseline-II Equipped With One Central Vertical Rudder", Jurnal Teknologi, vol. 12, pp. 133-139, 2015.

[12] Melissa B. Carter, Dan D.Vicroy, and Dharmendra Patel,"Blended-Wing-Body Transonic Aerodynamics: Summary of ground Tests and Sample Results (Invited)", 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, 5 - 8 January 2009, Orlando, Florida, 2009.

[13] F. Cai, M. Qin, and H. Wu, "The Effect of Belly-Flap on Aerodynamic Performance of Blended Wing Body Civil Aircraft," vol. 378, pp. 69–73, 2013.

[14] G. Yingsong, Y. Zhichun, and H. Shun, "Body Freedom Flutter of a Blended Wing Body Model Coupled with Flight Control System," Procedia Engineering, vol. 99, pp. 46–50, 2015.

[15] P. Panagiotou, P. Kaparos, and K. Yakinthos, "Winglet design and optimization for a MALE UAV using CFD," Aerospace in Science Technology, vol. 39, pp. 190–205, 2014.

[16] R. E. M. Nasir and W. Kuntjoro, "Stability augmentation for longitudinal modes of a small blended wing-body aircraft with canard as control surface," Journal of Mechanical Engineering vol. 10, no. 1, pp. 40–54, 2013.

[17] F. Mohamad, W. Wisnoe, Rizal E. M. Nasir, I. Sainan, and N. Jenal, "Yaw Stability Analysis for UiTM's BWB Baseline-II UAV E-4," vol. 393, pp. 323–328, 2013.

[18] W. Wisnoe, R. Effendy, M. Nasir, W. Kuntjoro, and A. Mohd, "Wind Tunnel Experiments and CFD Analysis of Blended Wing Body (BWB) Unmanned Aerial Vehicle (UAV)," 2009.

[19] Rizal E. M. Nasir1, Zurriati Ali, "Investigation on aerodynamic characteristics of baseline-II E-2 blended wing-body aircraft with canard via computational simulation," AIP Conference Proceeding, 2012.

[20] Rizal E. M. Nasir, Firdaus Mohamed, Ramzyzan Ramly, Aman M. I. Mamat, Wirachman Wisnoe and Wahyu Kuntjoro, "Flight Performance Of Various Blended Wing-Body Small UAV Designs", Jurnal Teknologi, vol.122, pp. 133-139, 2015.

[21] T. Muijres, P. Henningsson, M. Stuiver, and A. Hedenström, "Aerodynamic flight performance in flap-gliding birds and bats," Jurnal Biology, vol. 306, pp. 120–128, 2012.

[22] G. Sachs, "Tail effects on yaw stability in birds," Jurnal Biology, vol. 249, pp. 464–472, 2007.