Jurnal
Teknologi

Full Paper

FLIGHT PERFORMANCE OF VARIOUS BLENDED WING-BODY SMALL UAV DESIGNS

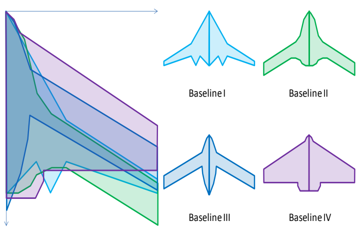
Rizal E. M. Nasir*, Firdaus Mohamed, Ramzyzan Ramly, Aman M. I. Mamat, Wirachman Wisnoe and Wahyu Kuntjoro

Flight Technology and Test Centre, Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

Article history
Received
10 December 2014
Received in revised form
04 May 2015
Accepted
09 June 2015

*Corresponding author
rizal524@salam.uitm.edu.my

Graphical abstract



Abstract

Currently there are four BWB designs that have been tested in the LST-1 wind tunnel at Flight Technology and Test Centre (FTTC), UiTM since 2005. The objective of this paper is to analyse their flight performance of these four BWB UAVs in terms of airspeed flight envelope, endurance, range and rate of climb as a function of the number of batteries and to determine the optimal number of batteries to be carried for 1-hour endurance mission and 3-hour endurance mission. The targeted cruising-loitering airspeed mission for all these BWBS are around 20 to 40 mph (8.9 m/s to 17.8 m/s) and they are to possess the lowest take off/landing speed and the highest maximum speed possible. This paper also seeks to find the best design of the four to explore its maximum potential in the near future where a prototype will be constructed. Unlike conventionally powered aircraft that uses fuel, which burns out thus reducing total weight of aircraft as it flies for long hours, these four BWB electric-powered vehicles carry batteries and the weight shall remain constant throughout the flight.

Keywords: Blended wing-body, flight performance, unmanned aerial vehicle

1.0 INTRODUCTION

While many recent studies focus on large, airline-sized [1,2] or business jet-sized [3] blended wing-body (BWB) aircraft, Flight Technology and Test Centre (FTTC) in Universiti Teknologi MARA looks into application of blended wing-body technology for small unmanned aircraft. Currently there are four BWB designs that have been tested in LST-1 wind tunnel at the centre's vicinity since 2005.

Historically, the earliest BWB design studied (Baseline I) should have wingspan of 13.1 ft. powered by a pair of micro turbojets. It was to be flown at wide range of speed from low to high subsonic with maximum take of weight (MTOW) in excess of 220 lbs. [4]. With its poor flight stability and aerodynamic characteristics, and limited knowledge in electronic control at the time, the design was abandoned in favour of a new, smoother, meticulously designed Baseline II BWB. The Baseline-II has similar wing span as its former but with weight and thrust requirement reduced to suit to low subsonic operation and high aerodynamic efficiency [5]. It was later resized to half of its original span and a quarter of its MTOW to be built as electric propulsion UAV. Baseline III BWB is a version Baseline II with wings moved forward and resembled more like a conventional aircraft (but tail-less) while Baseline IV is a BWB aircraft with delta wing almost similar to the design published in [6] but Baseline IV is designed to have very short take-off and landing distance or possibly vertical take off/land capability in the future.

For the purpose of this study, all BWB designs have the same wingspan of 6.56 ft., wing thickness-to-chord ratio, t/c of 12% and the same MTOW. Figure 1 and Table 1 show the planform design of all four BWBs and their specifications, respectively. All four aircraft can carry up to twelve 3000 mAh six-cell (22.2 V) Lithium-Polymer (LiPo) batteries internally and powered by a single 90-mm electric ducted fan (EDF). All BWBs shall have the same empty weight of 4.43 lbs., shall carry

500 grams (1.11 lbs.) of payloads and the same amount of installed thrust. Baseline IV has the largest wing area while Baseline III has the smallest of all but former has the lowest aspect ratio (AR) while the latter has the largest. Common understanding presumes that the most aerodynamically efficient aircraft (the largest lift-to-drag ratio L/D) shall have the largest aspect ratio [7]. These small UAVs are required to fly for two types of loitering mission – one-hour endurance mission and three-hour endurance mission.

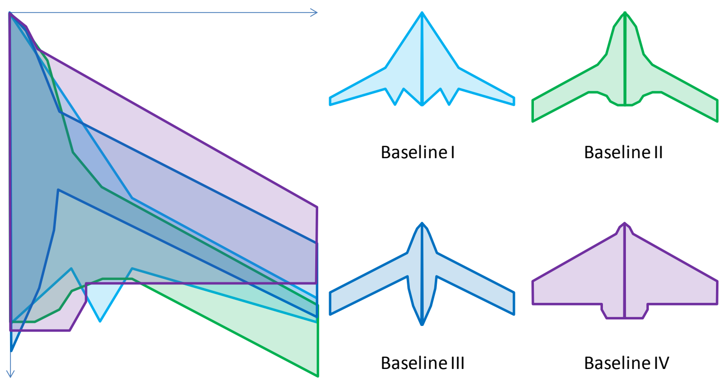


Figure 1 Planform of BWBs in study

Table 1 Catalytic alkylation of resorcinol to 4-*tert*-butyl resorcinol and 4,6-di *tert*-butyl resorcinol [a]

BWB Design	Baseline I	Baseline II	Baseline III	Baseline IV
Wing span, b (ft)	6.56	6.56	6.56	6.56
Wing Area, S (ft^2)	6.00	7.10	5.47	13.61
Wing aspect ratio, AR	7.17	6.11	7.87	3.16
Empty Weight, W_{empty}(lbs)	4.43	4.43	4.43	4.43
Payload Weight, $W_{payload}$ (lbs)	1.11	1.11	1.11	1.11
Weight per battery, $W_{battery}$ (lbs)	1.11	1.11	1.11	1.11
Max. no. of batteries, n_{max}	12	12	12	12
Max. Take-off Weight (lbs)	18.8	18.8	18.8	18.8
Max. Wing Load (lb/ft^2)	3.14	2.65	3.44	1.38
Propulsion	1 x 90-mm EDF with 36mm, 1340rpm/V, 22.2V, 80A brushless motor, rated at 2.4 hp			
Max. Thrust (lbs)	5.54	5.54	5.54	5.54
Installed Thrust (lbs)	4.43	4.43	4.43	4.43
T/W at MTOW	0.24	0.24	0.24	0.24

Unlike conventionally powered aircraft that uses fuel, which burns out thus reducing total weight of aircraft as it flies for long hours, these four BWB electric-powered vehicles carry batteries and the weight shall remain constant throughout the flight. Doubling the number of batteries will not double endurance and range as the aircraft is heavier and the weight does not deplete over battery use. The objective of this paper is to analyse their flight performance of these four BWB UAVs in terms of airspeed flight envelope, endurance, range and rate of climb as a function of number of batteries and to determine suitable number of batteries to be carried for 1-hour endurance mission and 3-hour endurance mission. The targeted cruising-loitering airspeed mission for all these BWBS are around 20 to 40 mph (8.9 m/s to 17.8

m/s) and they are to possess the lowest take off/landing speed and the highest maximum speed possible. This paper also seeks to find the best design of the four to explore its maximum potential in the near future where a prototype will be constructed.

2.0 FLIGHT PERFORMANCE ANALYSES

Figure 2 shows aerodynamic characteristics, namely lift coefficients versus angle of attack, lift versus drag coefficients and lift-to-drag ratio versus angle of attack plots. These plots are data of wind tunnel experiments conducted at FTTC facilities using 1/3rd scale half-aircraft model tested at airspeed ranging from 15 m/s to 45 m/s representing Reynold number equivalent to actual airspeed from 5 m/s to 15 m/s. Although Baseline IV has the highest maximum lift coefficient at, it is the Baseline II that has the highest efficiency at 23.5 compares to 13.8 for the former due to Baseline II low drag. The lowest drag is achieved by Baseline I but it produces low lift and has the lowest efficiency at around 7.

The method of calculation is shown in Figure 3. Since authors have aerodynamic data from wind tunnel tests, airspeed for a given angle of attack (thus for known lift coefficient C_L) can be determined using equation (1) where total weight W is the sum of empty weight W_{empty} (fixed to 4.43 lbs), payload weight $W_{payload}$ (fixed to 1.11 lbs) and battery weight $nW_{battery}$ with n as the number of batteries (as stated above) and $W_{battery}$ is the weight per unit battery. Drag coeffcient C_D data for the said C_L is also available thus one can calculate power required by the aircraft at airspeed determined in equation (1) and is shown in Equation (2). The fan jet is assumed to produce constant thrust (*TA*) at varying speed thus available power is a function of the thrust times airspeed.

Meanwhile, rate of climb for a given speed (thus, power) and total weight can be calculated using Equation (4). During cruise/loiter, thrust available is set to be equal to required thrust hence the motor is required to produce the required power. Electrical current A to be supplied by the motor is based on equation (5) where ηm, ηe and Volt are mechanical efficiency, electrical efficiency and voltage (22.2 V) respectively. The two efficiencies are set at 75% and 80% based on tests made on the actual fan-motor assembly. The current use A can determine the length of time the battery capacity is being drained, hence the endurance and range of flight. Out of 3000 mAh of capacity of each battery, only 2/3rd is being used for cruising-loitering mission and the rest is saved for take-off, climb and landing missions plus some of the will be used to power up controllers, actuators and other auxilliary systems. Instead of using Breguet equations for estimating endurance and range, Equations (6-7) are used based on simple electrical theory for endurance. Different numbers of battery will give different drag, rate of climb and endurance plots and it is from here one can determine minimum airspeed, maximum airspeed, maximum endurance and its optimum cruise airspeed, and maximum rate of climb.

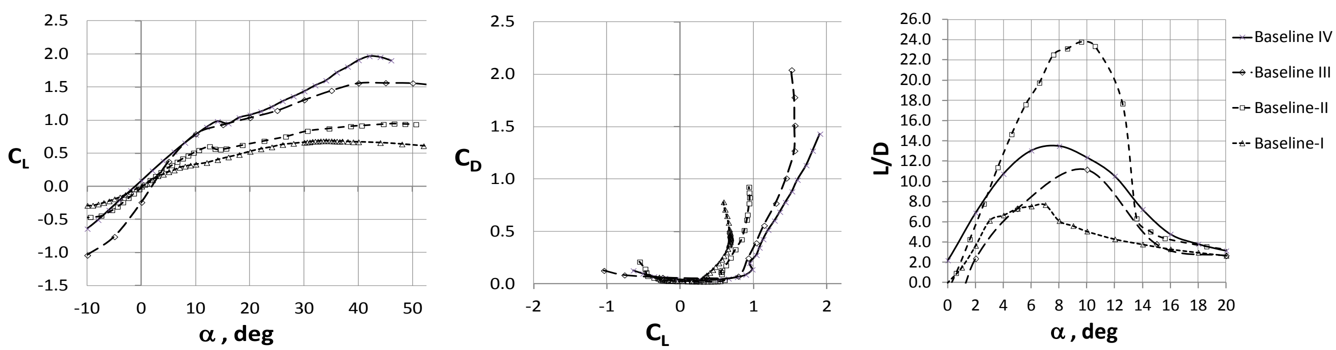


Figure 2 C_L versus α (left), C_D versus C_L (centre) and *L/D* versus *α* (right)

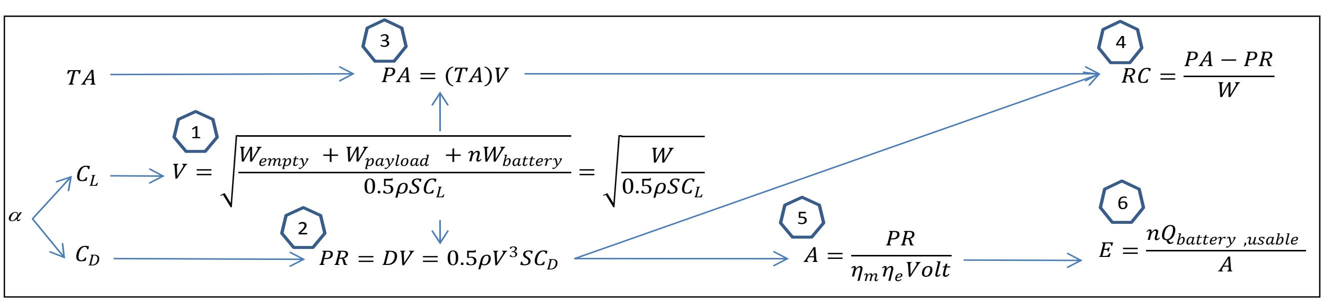


Figure 3 Calculation of flight performance parameter

Figure 4 shows range of airspeed that can be flow by each BWB design with number of batteries carried. Baseline I BWB is the fastest at 107 mph and has the widest airspeed regime (maximum airspeed minus minimum airspeed) of all followed by Baseline II while Baseline IV delta wing BWB is the slowest of all with the shortest spread of airspeed. This is not surprising since it has the largest wing area hence the lowest stall speed at around 11 mph but it also has the largest drag at low airspeed that limits its maximum airspeed to mere 60 mph.

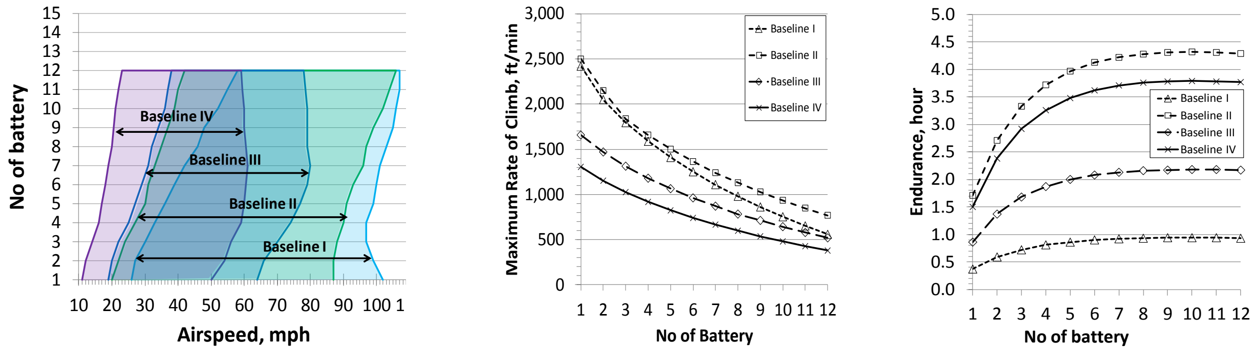


Figure 4 Airspeed versus no of battery hodograph, maximum rate of climb, and endurance

Increasing the number of batteries have increases the minimum airspeed but their maximum airspeed vary according to each individual drag coefficient characteristics curve. For example, Baseline I and II achieve their maximum airspeed at maximum number of batteries, while Baseline III and IV achieve their maximum airspeed if carry only 7 batteries. The trend shown here is unsurprising because, as mentioned earlier, Baseline I is designed to fly at high speed while Baseline IV is suited for V/STOL capability. Baseline II is the most usable at wide range of airspeed; its minimum airspeed is similar to Baseline III and just around 10 mph faster than Baseline-IV but its maximum speed is approaching Baseline I's.

In terms of rate of climb, all BWBs can achieve their highest rate of climb at their lightest weight (with one battery, minimum). Rate of climb reduces as the weight increases. Baseline I and II has the fastest rate of climb at nearly 2500 ft/min while the other two stays around 1200 to 1700 ft/min with Baseline IV has the lowest rate of climb of all.

Doubling the number of batteries does not double the endurance due to increase in weight and required thrust. In this case, there is less than 5 percent increase in endurance time beyond 8 batteries for all BWBs. For Baseline II and IV, it takes just 3 to 4 batteries to achieve 3-hour endurance. Baseline II BWB needs another three batteries to add another hour of endurance while it is impossible for Baseline IV to achieve four-hour endurance even with 12 batteries. The worst case is Baseline I where it cannot even achieve a proper one-hour endurance with maximum amount of batteries.

Table 2 Performance for 1-hour and 3-hour endurance setup

BWB Design	1-hour Endurance				3-hour endurance			
	Baseline I	Baseline II	Baseline III	Baseline IV	Baseline I	Baseline II	Baseline III	Baseline IV
No. of Batteries	12	1	2	1	-	3	-	4
TOW, (lbs)	18.83	6.65	7.75	6.65	-	8.86	-	9.97
T/W	0.24	0.67	0.57	0.67	-	0.50	-	0.44
Wing Load (lb/ft^2)	3.14	0.94	1.42	0.49	-	1.25	-	0.73
Endurance (hr)	0.94	1.71	1.37	1.50	-	3.33	-	3.26

Table 3 Performance at MTOW

BWB Design	Baseline I	Baseline II	Baseline III	Baseline IV
Minimum Airspeed (mph)	26-58	20-42	19-38	11-23
Optimal Airspeed (mph)	39-65	23.8-43.5	24.5-41.2	17-28.6
Maximum Airspeed (mph)	97-107	87-106	64-78	50-59
Maximum Achievable Endurance at MTOW (hr)	0.94	4.32	2.18	3.79
Max. Rate of Climb (ft/min)	557	769	518	377

4.0 CONCLUDING REMARKS

Table 2 and Table 3 show flight performance for one-hour endurance setup, three-hour endurance setup and at MTOW (12 batteries). Baseline II and IV need only one battery for the first setup with theoretical endurance around 1.5 to 1.71 hours but the former stays longer on air. TOWs, thrust-to-weight ratio (T/W) are the same for both but Baseline IV enjoys better manoeuvrability due to low wing pressure (0.49 lb/ft^2). In this case, both are equally good. Baseline I can barely meet an hour endurance even with all twelve batteries while Baseline III needs two. For three-hour endurance setup, Baseline II is the clear winner with less number of batteries needed than Baseline IV, lighter TOW, faster acceleration due to higher T/W and longer theoretical endurance.

Overall performance of all these four BWBs at MTOW can be summarised as follows:

1. Baseline IV has the slowest take-off and landing speed (minimum airspeed) – suitable for V/STOL operation. It also has the slowest loitering/cruising airspeed. While Baseline I is the fastest of all, Baseline II is not much slower than Baseline I but Baseline II can also fly very slow near to the minimum airspeed of Baseline IV. Baseline II has the widest spread of operational airspeed envelope of all making it useful for both high and low speed flight.
2. Baseline II has the longest achievable endurance of 4.3 hours and the fastest rate of climb at 769 ft/min. Baseline IV has the second best endurance but its rate of climb is the slowest of all four BWBs.

In short, if only performance criteria in Table 2 and Table 3 was counted for final selection, Baseline II will be the overall winner.

Acknowledgement

This research is funded by Fundamental Research Grant Scheme (FRGS/1/2014/TK09/UITM/02/1). Authors would like to express our deepest gratitude to Ministry of Education Malaysia, Research Management Institute and Faculty of Mechanical Engineering, Universiti Teknologi MARA for continuous support.

References

[1] Paulus, D., Salmon, T., Mohr, B., Roessler, C., Petersson, O., Stroscher, F., Baier, H. and Hornung, M. 2013. Configuration selection for a 450-passenger ultra-efficient 2020 aircraft. *Progress in Flight Dynamics, GNC, and Avionics* 6: 601-618.

[2] Dommelen, J. v. and R. Vos. 2014. Conceptual design and analysis of blended-wing-body aircraft. *Proceedings of the Institution of Mechanical Engineers.* Part G: J. of Aerospace Engineering published online 29 January 2014.

[3] Mulyanto, T. and Nurhakim, M. L. I. 2013. Conceptual Design of Blended Wing Body Business Jet Aircraft. *Journal of KONES Powertrain and Transport.* 20(4): 299-306.

[4] Nasir, R. E. M., Kuntjoro, W., Wisnoe, W. and Mamat, A. M. I. 2009. 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*. 6(2): 73-96.

[5] Nasir, R. E. M., Kuntjoro, W., Wisnoe, W., Ali, Z., Nor F. Reduan, Mohamad, F. and Suboh, S. 2010. 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 3rd Engineering Conference on Advancement in Mechanical and Manufacturing for Sustainable Environment (EnCon2010),* Kuching, Sarawak, Malaysia. 14-16 April 2010.

[6] Mata, S., Ishak, I. S., Zakaria K. and Ajis Khan, Z. 2014. Manufacturing Process of Blended Delta-Shaped Wing Model. *Advanced Materials Research*. 845: 971-974.

[7] Wildschek, A., Stroscher, F., Hanis, T. and Belschner, T. 2013. Fuel management system for cruise performance optimization on a large blended wing body airliner. *Progress in Flight Dynamics, GNC, and Avionics* 6: 651-670.